Analysis of Search and Rescue Tactics in Single-Story Single-Family Homes Part I: Bedroom Fires

Craig Weinschenk

UL's Fire Safety Research Institute
Columbia, MD 21045

May 17, 2022

This publication is available free of charge from:
https://dx.doi.org/10.54206/102376/DPTN2682

UNDERWRITERS LABORATORIES™

Analysis of Search and Rescue Tactics in Single-Story Single-Family Homes Part I: Bedroom Fires

Craig Weinschenk

UL's Fire Safety Research Institute
Columbia, MD 21045

May 17, 2022

This publication is available free of charge from:
https://dx.doi.org/10.54206/102376/DPTN2682

Underwriters Laboratories Inc.
Terrence R. Brady, President
Christopher J. Cramer, Chief Research Officer

UL's Fire Safety Research Institute
Steve Kerber, Vice President and Executive Director

UNDERWRITERS LABORATORIES™

In no event shall UL be responsible to anyone for whatever use or non-use is made of the information contained in this Report and in no event shall UL, its employees, or its agents incur any obligation or liability for damages including, but not limited to, consequential damage arising out of or in connection with the use or inability to use the information contained in this Report. Information conveyed by this Report applies only to the specimens actually involved in these tests. UL has not established a factory Follow-Up Service Program to determine the conformance of subsequently produced material, nor has any provision been made to apply any registered mark of UL to such material. The issuance of this Report in no way implies Listing, Classification or Recognition by UL and does not authorize the use of UL Listing, Classification or Recognition Marks or other reference to UL on or in connection with the product or system.

Abstract

Prior full-scale fire service research on the residential fireground has focused on the impact of ventilation and suppression tactics on fire dynamics. This study builds upon prior research by conducting eleven experiments in a purpose-built single-story, single-family residential structure to quantify the impact of how search and rescue tactics are coupled with ventilation and suppression actions and timing. Each fully furnished structure included four bedrooms, 2 bathrooms and an open-floor kitchen and living room. The structures were instrumented to quantify post-ignition toxic gas and thermal conditions. Temperature, velocity, and pressure were measured to evaluate the fire dynamics. Gas concentrations and heat fluxes were measured to quantify toxic and thermal exposures.

Across this series of experiments, the impact of isolation of fire and non-fire compartments, the timing of search actions relative to suppression actions, and the influence of isolation, elevation, and path of travel during rescue were examined with respect to firefighter safety and occupant tenability.

Similar to previous experiments in both purpose-built and acquired structure, the data showed that prior intervention locations lower in elevation and/or behind closed doors had lower toxic gas and thermal exposures compared to locations at higher elevations or locations that were not isolated. Lower elevations were also shown to have lower toxic gas and thermal exposures during the removal of occupants as part of rescue operations.

For scenarios where search operations occurred prior to suppression, isolation of spaces from flow paths connected to the fire compartment was shown to be effective at reducing the thermal operating class for firefighters and the toxic and thermal exposure rates compared to spaces that were not isolated. Following isolation, exterior ventilation was found to further reduce the toxic gas and thermal exposures in the protected space. Suppression, from either interior and exterior positions, was effective at reducing the thermal operating class for searching firefighters and the rate of thermal exposure increase to occupants. Following suppression, additional exterior ventilation increased the rate at which gas concentrations returned to pre-ignition levels.

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-2017-FP-00628). This critical fire service research project would not be possible without this funding and continued support.

The authors thank the members of the project's fire service technical panel, listed in the table on the following page, for providing support during the development and planning phase of this project, and for contributing valuable feedback regarding the project results and conclusions. The enthusiasm of panel members to share their diverse range of knowledge and experience was integral to this project's success and relevance to the fire service.

Thanks to Keith Stakes for his lead role in the development, planning and execution of the experiments conducted.

Thanks to the following individuals from the UL FSRI team for their assistance during all portions of the project: Nick Dow, Phil Gilman, Gavin Horn, Sarah Huffman, Joseph Johnson, Brad Morrissey, Jack Regan, Steven Robert, and Joseph Willi. Thanks for former FSRI team members Julie Bryant and Caleb Cotner for their support of this project. Thanks to Rebekah Schrader for review and edits to the document.

The authors also thank the team from the Illinois Fire Service Institute for their assistance throughout the experimental series. Particularly, their expertise in laser diagnostics improved the measurement capability of the experiments.

Additionally, the authors extend a special thanks to Roy McLane of Thermal Fabrication for his tireless support in both the planning and execution of the experiments involved.

Finally, under the direction of Kerby Kerber, the Delaware County (PA) Emergency Services Training Center provided the much needed logistical support for these experiments. The authors thank Ethan Crivaro, Mark Morrissey, John McGowan, Tyler Boroi, Dennis Gallagher, Gary Thompson, Brian Righter, Tom Chesnut, Joseph Bynum, Anthony Alosi, Bill Norris, and Jerry Fokas for their assistance with fireground operations during the experiments.

Fire Service Technical Panel

Name	Affiliation
Christopher Byrne	Colorado Springs Fire Department, CO
Kristofer DeMattia	Prince George's County Fire & EMS Department, MD
Christopher Finelli	District of Columbia Fire and EMS Department, DC
Hale Fitzgerald	South Portland Fire Department, ME
Russell Gardner	Sacramento Metropolitan Fire District, CA
Kekoa Gonzales	Federal Fire Department Navy Region Hawaii, HI
Tommy Hofland	Seattle Fire Department, WA
Steve Lopez	Dallas Fire Department, TX
Bryan Lynch	Colorado Springs Fire Department, CO
Randall McDermott	NIST Fire Research, MD
Justin McWilliams	Clackamas Fire District #1, OR
Richard Ray	Creedmoor Volunteer Fire Department, NC
Gerard Smith	Baltimore City Fire Department, MD
Ron Smith	Gary Fire Department, IN
Derek Sutherland	Clark County Fire Department, NV
Ryan Tripp	Los Angeles County Fire Department, CA
Jason Truesdale	Sidney Fire & Emergency Services, OH
Samuel Villani	Montgomery County Fire Rescue Service, MD
Eric Wheaton	Winter Park Fire Department, FL
David Wolf	Estes Valley Fire Protection District, CO
David Young	Beavercreek Township Fire Department, OH

Contents

List of Abbreviations

ACHP	Air changes per hour
BR	Bedroom
CO_2	Carbon dioxide
CO	Carbon monoxide
HVAC	Heating ventilation and air conditioning
NFPA	National Fire Protection Agency
O_2	Oxygen
PPE	Personal protective equipment
PWFE	Pressurized water fire extinguisher
SCBA	Self-contained breathing apparatus
FSRI	Fire Safety Research Institute
VEIS	Vent-enter-isolate-search
VES	Vent-enter-search

1 Introduction

The number of fires that occur in the United States have decreased by 3.2% from 2010 to 2019 [1]. Conversely, annual fire deaths during the same time period have increased by 24.1% [1]. The majority of these fires and fire fatalities occur in residential structures; between 2014 and 2018, "69% of the reported home fires were in one- or two-family homes, causing 85% of the home fire deaths [2]." Size-up and search & rescue have long been identified as key components of fireground operations, and the need to study them is further amplified by recent fire data.

This fire dynamics-based study was designed to provide information for firefighters conducting search & rescue tactics. The experiments were conducted in a purpose-built single-story, single-family structure. Each test fixture was designed and built to replicate a fully-furnished home, including a fully functional heating, ventilation, and air conditioning (HVAC) system, windows, insulation, and attic space. This structure type was chosen because in 2019, 68% of the 124 million U.S. households were single family [3], with the ranch style home comprising the largest percentage of single family homes in 34 states in the U.S. [4].

Twenty-one full-scale experiments were conducted to quantify fire department tactics as a function of ignition location (bedroom, kitchen, and living room), isolation of fire and non-fire compartments, location of search origin, search timing relative to suppression timing, and rescue tactics (isolation, elevation, and path of travel). This report focuses on 11 of the 20 experiments which were conducted where the fire was ignited in a bedroom.

1.1 Objectives

The experiments conducted for this study were designed to improve firefighter safety and occupant tenability during residential fires by:

- examining the impact of different search tactics, such as search initiated through the front door or search initiated through a window;
- examining the impact of different rescue tactics such as path of occupant removal or elevation of occupant removal;
- examining the impact of isolation (front door, fire room, or remote bedroom) and ventilation;
- examining the impact of search and rescue operations that occur prior to, during, or post suppression.

2 Literature Review

Size-up and search & rescue have been practiced by the fire service for centuries, but primary considerations for each will vary based on the structure in question. Although life safety, property protection, fire confinement, and suppression are the goals of every fire department, how one goes about completing these objectives can vary between departments and even between calls. The following sections are designed to provide a snapshot on the state of the current literature on these topics.

The International Association of Fire Chiefs (IAFC) adopted the "Rules of Engagement for Structural Firefighting [5]" as a recommended best practice model for fireground procedures. Within that document are lists of factors that the IAFC suggests should be considered before engaging in structural firefighting. Listed below are three of the 11 points of consideration for firefighters:

- Size-up your tactical area of operation
- Determine the occupant survival profile
- Extend vigilant and measured risk to protect and rescue savable lives

These three items simply provide a starting point to discuss the sections that follow: size-up, search, and rescue.

2.1 Size-Up

From NFPA 1006/1700 [6, 7], size-up is defined as "the ongoing observation and evaluation of factors that are used to develop strategic goals and tactical objectives." Sizing-up an incident is not only about identifying problems but also identifying opportunities for engagement and mitigation. There are several factors that build a good size-up with priorities varying based on the situation. One long-standing approach is from John Norman's "Fire Officer's Handbook of Tactics [8]." He suggests that one acronym to consider when performing a fireground size-up is "COAL WAS WEALTH." This acronym represents the following considerations:

- Construction
- Occupancy
- Apparatus and Manpower
- Location and Extent of Fire

- Water Supply
- Auxiliary Applications
- Street Conditions
- Weather
- Exposures
- Area and Height
- Location and Extent of Fire
- Time
- Hazmat

Each of these considerations can have an affect on the development of fireground strategies and tactics. What may present as an attic fire in a two-story, wood-frame structure could be from a basement fire due to balloon-frame construction. Rapidly identifying the occupant status and determining the likelihood that someone may be trapped can help identify whether a primary search should be completed before water application. That decision can become even more critical if the first arriving crew will be operating for several minutes before another crew arrives.

One recurring point of emphasis is the need to conduct a proper 360 degree size-up of the structure in question. Visualizing all sides of the structure is important because it can help the first-arriving officer determine what the problem is, where the problem is, and develop a course of action that can be relayed to incoming units. Taking the time to size-up a structure properly can lead to safer operations conducted in a timely manner [9]. During a 360 degree size-up, potential victim locations, building features (construction and layout), and other hazards such as exterior propane cylinders can also be identified [10]. With modern construction practices focused on energy efficiency through a tighter building envelope, utilizing a thermal imaging camera during the 360 degree size-up may help identify hotspots or potential areas of fire involvement [11].

Chapter 9 of NFPA 1700, "Strategic Considerations," presents a two-pronged approach for conducting an initial and ongoing assessment. This approach is broken down into Initial Arriving Factors and 360-Degree Survey. As part of the initial arriving factors, firefighters should include the following in their assessment:

- Bystander/witness statements
- Access concerns on the property
- Building height, size, and stability
- Occupancy type

- Construction type
- Wind direction relative to the building location and configuration
- Fire location, size, extent
- Civilian and fire fighter life safety
- Suspected direction of fire and smoke travel within the structure (flow path)
- Smoke and fire exposures exterior to the structure
- Presence and status of fixed fire protection system
- Firefighter safety building marking systems
- Resources available

These initial arriving factors should then be combined with on-scene observations [7]. The 360-Degree Survey also includes a number of considerations under the larger directive of focusing on the protection of occupants and controlling the fire:

- Number of stories on side A and side C
- Verify presence of basement and its type
- Presence of occupant escape systems
- Utilities
- Pre-existing structural hazards
- Hazardous grade challenges
- Roof type and construction
- Presence of fire protection features (hydrants, FDC, fire pump, etc.)

The size-up of a structure changes depending on the firefighting assignment for a given crew. Crews with different tactical objectives will inherently have different size-up needs based on their respective roles and will also be likely examining the structure from different vantage points. For example, firefighters assigned to search may size-up the structure differently than firefighters assigned to suppression and/or ventilation. The purpose of the following sections is to provide a high level overview of size-up on the fireground. Size-up for individual tactical objectives is beyond the scope of this report.

2.1.1 Smoke and Fire Presentation on Arrival

The visual presentation of smoke and fire should be analyzed by first arriving crews to help determine the current location and extent of the fire and areas of potential exposure. Sizing-up the smoke and fire presentation on arrival can impact how the first strategies and tactics get employed on the fireground. There are four key attributes to smoke that should be identified and interpreted: volume, velocity, density, and color [12].

The volume of smoke exiting a structure can indicate the amount of fuels burning within a space. The size of a structure is also important to consider in relation to volume because a large volume of smoke escaping from a small structure can indicate a fast moving fire [12].

The velocity with which smoke exits a structure can be indicative of the accumulated pressure within the structure due to the fire [12]. Smoke moves from high pressure to low pressure areas utilizing the path of least resistance. As smoke travels through a structure to reach a door or window, it will lose heat and velocity to other objects.

The density of smoke is a graphic indicator of the amount of heat present within the smoke and potential visibility, or lack thereof, on the interior [9]. Optically thick smoke is comprised of unburned particulates that, given the right heat and oxygen, have the potential to ignite [13]. Dense smoke exiting a structure at a high velocity can ignite if the proper mixture of fuel and oxygen is achieved within the smoke. Smoke traveling with this profile can help expedite the spread of fire because it provides a continuous fuel supply from the fire to an oxygen source [12].

The presence of smoke is just as important as the absence of smoke. Heavy smoke pushing out one window while a window next to it is clear indicates there is a barrier protecting that space, such as a closed door.

Due to elevated temperature and lower relative density compared to air, smoke is buoyant which causes it to rise within structures, travel across ceiling surfaces, and fill compartments from the top down. Typically, tracing the path of travel of smoke can help identify the seat of the fire [8].

Sizing-up the fire presentation from a structure is also important. Fire showing from the structure can help determine the initial strategies and tactics as the incident unfolds [14, 15]. If fire is evident from a ventilation opening (i.e., door, window, chimney), it can be beneficial to determine whether or not the flow through the opening is either bi-directional or uni-directional. If the fire presentation at a vent is uni-directional, the fire could be wind impacted, or could be receiving air from another source within the structure or another open vent. If the fire showing is the exterior finishing materials burning or structural member involvement versus interior contents presenting to the exterior, this could dictate initial water application tactics.

2.1.2 Building Construction

Building construction features are an extremely important component of fireground size-up. The type of construction and the building compartmentalization can affect the fire growth and spread along with fire department access. For example, void spaces can allow for fire to spread undetected and energy efficient building envelopes can lead to a quicker transition to ventilation-limited conditions on the interior. Building construction features and compartmentalization can be determined pre-incident through building surveys and plans. Having pre-incident plans for structures can allow responding crews to orient themselves with the building and begin to develop tactical plans prior to arrival.

Construction Types

There are five building construction classifications, and they are described below using the definitions from the seventh edition of Essentials of Fire Fighting [16]. Type I construction is classified as a fire-resistive structure. Type I buildings use reinforced concrete, precast concrete and protected steel frames to provide the most protection from structural damage and collapse due to fire. Type II is called noncombustible construction. A Type II structure is constructed of materials that will not contribute to fire spread and development, such as a metal frame structure or concrete-block construction. The fire-resistance rating of structural members is what differentiates between a Type II and type I structure. A type II structure does not meet the fire-resistance rating of a Type I structure because the structural members have a lower fire-resistance rating.

Type III construction, also known as ordinary construction, is used in settings such as strip malls, older schools, and residential. Type III structures have an exterior envelope consisting of noncombustible materials such as brick and mortar or stone. Wood can make up the interior compartmentalization and can be used for beams, columns, floors, walls, and roofs. Type IV construction, or heavy timber, utilizes large-dimensioned lumber or laminated wood as the interior structural elements and noncombustible materials for the exterior walls. To be classified as a Type IV structure, the structural wood elements must meet certain requirements put forth in building codes. Type V construction, also known as wood frame construction, utilizes wood members for all walls, beams, columns, floors, and roofs. These wood members are typically dimensional 2x4 or 2x6 inch pieces of lumber. Type V construction does not require noncombustible materials for the building's exterior envelope.

Type III and Type V construction make up the majority of single family residential structures built in the United States, with Type V being the most common for new construction. The structures used in these experiments, described in more detail in Section 3.1, were Type V construction.

Building Layout

In addition to information gained about state of the fire during a size-up, details regarding both the exterior (e.g., entry points, possible cues of interior layout, etc.) and the interior (e.g., compartmentation) can be used to inform subsequent fireground operations such as search.

Modern structures built with lightweight elements (colloquially referred to as lightweight construction) are built with engineered materials that are smaller and lighter than dimensional lumber used in the past, and are therefore more prone to failure when subjected to fire conditions [17]. Further, lightweight construction is often used to create large open areas within a structure. Large open areas can facilitate the flame spread and the spread of combustion gases compared to more compartmentalized interiors.

Firefighters can also use visual details of the structure (e.g., window sill height, roof penetrations, exterior door swing, etc.) to help determine the relative locations of different living spaces. In the first 2000 rescues documented by the Firefighter Rescue Survey [18], it was found that 68% of the occupants were removed from a bedroom, family room, or kitchen, with bedrooms leading the way at 45%.

The size-up literature review was split into smoke and fire presentation on arrival sections and building construction, in practice, however, these topics are inherently linked. Knowledge of the building construction, potential compartmentation or lack thereof, can provide valuable information regarding the smoke and fire presentation. Although size-up is not explicitly examined in this report, the information gained from an effective size-up can improve both search and suppression operations.

2.2 Search

Search and rescue operations on the fireground typically place firefighters inside an IDLH, potentially without the protection of a hoseline as firefighters traverse through the structure looking for occupants [9]. Traditionally, firefighters assigned search and rescue are first guided to locations near fire as this has been thought to generally be the area of highest hazard. As the fire environment has evolved with new construction methods, building materials and fuel loads, ventilation-limited fire conditions present increased hazards to those operating on the fireground. Although improvements to personal protective equipment and self-contained breathing apparatus have allowed firefighters to operate in more severe conditions for longer periods of time, the combination of these factors can lead to firefighters searching in conditions beyond the capability of their protective equipment. Furthermore, risk is a combination of probability and consequence [19]. Even though the number of fire fatalities per year is increasing, the same cannot be said for the number of annual fires [1]. From 2014-2018, US fire departments responded to over 353,000 home structure fires per year [2]. Moreover, there were 14 firefighter line of duty deaths that happened during search and rescue operations between 2011 and 2016 [20].

Although the number of fires in the United States has exhibited a downward trend in recent years, the opposite is true for fire fatalities [1]. In addition, the number of reported rescues per year trended upwards between 2016 and 2020 [18]. From April 2016 to September 2021, over 2000 firefighter rescue surveys were submitted to the Firefighter Rescue Survey [18].

2.2.1 Search Types

The two types of searches conducted routinely at a structure fire are commonly referred to as the primary and secondary search. A primary search is intended to be a rapid search of locations where it is believed savable victims may be present. These locations include common paths of travel, near main entry and egress points of the structure, bedrooms, closets, and bathrooms [8]. The overall goal of a primary search is to locate occupants who are in immediate danger. Occupants can only survive in a hostile smoke filled environment for so long, which is why there is such an emphasis on completing a primary search rapidly [21].

A secondary search is generally slower and more in depth to ensure all spaces within the structure have been covered thoroughly more than once. During the secondary search it is important to check every possible location, including closets, cabinets, under beds, and every other place an occupant could be [8]. During a secondary search, the emphasis should be on ensuring that all spaces were checked thoroughly to confirm that no occupants were missed during the primary search [22]. A secondary search should not be considered complete until the search crew can say with confidence there are no occupants left inside the structure.

2.2.2 Search Methods

In "Searching Smarter [21]," John Coleman presents four of the five types of search methods (#'s 1-4) and Clackamas Fire District #1's presents # 5 in their "Rescue & Search [23]" manual. The five search methods are:

1. Standard search
2. Large area search
3. Oriented search
4. Vent-enter-search
5. Split search

Coleman describes the standard search as your typical firefighter introductory search. In this search method, a crew of firefighters, typically two to four members, all enter a room together and cover the same area as a team before progressing to the next room. This is done by having all members enter and perform either a left-hand or right-hand search. The crew can also split into two groups inside the room with one group performing a left-hand search while the other performs a right-hand search until they meet up again on the other side of the room. In this type of search, every member of the search team is involved in physically searching the room. Coleman notes that an advantage of this type of search is that all team members stay together and are responsible for searching the same area, which theoretically reduces the chances of missing a victim. Disadvantages to this search technique include a longer search time because the entire team is searching each room inside the structure, and that because the officer is physically involved in searching, they may not be thinking about how to best remove a victim should crew members find one.

Large area search requires a team to work together to maintain orientation and search an area effectively. For a large area search, team members will typically maintain their orientation by using a hose line or a search rope. One member of the team is responsible for maintaining the team's orientation by keeping tension on the search line and securing it at changes in direction. The other members of the team proceed to search off the line by one of the following methods. Searchers can side-step away from and then back to the search line, maintaining their body orientation for reference. Searchers can also secure another piece of rope or webbing to the search line and use that to maintain orientation to the search line while extending their reach. An advantage of this search method is that the search line keeps searchers continuously oriented with their egress point. Disadvantages are that this method is time consuming when conducted properly, and that it's not practical for many situations. This search technique is effective for searching large open areas with few reference points but is not applicable in most residential settings.

Oriented search is described by Coleman as the safest and most effective search method [21]. This approach splits the tasks the officer and searching firefighters are focused on. During an oriented search, the officer focuses on crew safety, exit routes for rescue or evacuation, fire conditions, and maintaining crew orientation during the search. The firefighter's focus is limited exclusively to searching a room and monitoring the conditions in that room. In general, an oriented search is completed by the officer leading the search crew to a room entry point and then directing a firefighter to search that room. If there are multiple searching firefighters, the officer can direct each firefighter to search a different room as long as the firefighters can maintain voice contact with the officer. The officer is responsible for maintaining contact with their searching firefighters and staying oriented within the structure, knowing what areas have been searched and where a search is still needed. Advantages of the oriented search are that multiple rooms can be searched at the same time, and that the officer remains oriented to the search team's location within the structure. By having the officer not directly involved in the search, this enables the officer to think about egress routes and monitor fire conditions in the structure. Coleman notes that a disadvantage to the oriented search is that if the officer becomes disoriented, then the entire search team could become disoriented. The oriented search method is applicable for searching large and small residential structures.

To perform a vent-enter-search (VES), firefighters enter a room from the exterior of a structure through a vent (e.g., a window or door). The entry point is typically a window in a room that has been determined to have a high probability of containing an occupant. The firefighter directed to search the specified room will access the room using a ladder or other means after taking the window and clearing out the frame. It is important the firefighter is properly outfitted with PPE and SCBA prior to taking the glass so that the time between introducing oxygen to the room and isolating the room is minimized. After entering the room, the firefighter should work to locate the door to the room and close it to isolate the room. After isolating the room, the firefighter should then perform a primary search of the room. An advantage of this type of search method is that the firefighter can bypass congested areas such as stairwells typically occupied by other crews engaged in suppression or ventilation and go directly to a room with a higher occupant expectancy. A disadvantage of this search method is that the crew could be operating in the exhaust portion of a flow path until the room where entry was made is isolated.

Split search can be defined exactly as it sounds; a crew of firefighters conducting a search will split apart to search unique areas of the structure simultaneously instead of sequentially. According to the Clackamas Fire District #1: Truck Company Manual on Rescue & Search, 'split search is typically performed when at least one of the following three are present: favorable conditions, a comfortable crew, or fire attack is in place [23].' A split search typically occurs on the same floor opposed to splitting to search multiple floors. As Clackamas Fire District #1's manual highlights, that when crews split across floors, 'if a member is in need of assistance or finds a victim, the crew is too far apart to be efficient [23].'

For the purposes of the document, actions performed by firefighting crews are defined directly by the action performed, instead of using any acronyms that may not ubiquitous in the fire service. Search actions are defined by the point of entry to the structure: window initiated search and door initiated search. The direction of travel once inside the structure and subsequent actions of isolation and ventilation are described by the specific experimental scenario. The analysis of the search actions in these experiments is intended to be independent of a fire department's response model and staffing. Thus, terminology such as standard and oriented search are limited to their definitions in the literature review section only. The method of window ventilation —- taking, removing, and opening —– varied based on the specifics of the individual experiments. For more information on the definitions of window ventilation methods, see Appendix A. Spaces within the structure that were isolated or not-isolated also varied based on the experimental scenario. Isolation was defined by the status of the relevant interior or exterior door. Note, the toggling of interior doors was performed remotely by exterior crews using purpose built cabling.

2.2.3 Search Considerations

When conducting a primary search, it has traditionally been taught to search as close to the fire as possible, sometimes going above the fire where you expect to find savable victims, and then work outwards from there [24]. By searching this way, the search team will locate the occupants in the most danger quickest and can then facilitate their removal from the structure. Maintaining the continuity of a search is also important. Ideally every location will be searched once with no overlap and no missed areas.

During a secondary search, the search team needs to be extensive, thorough, and methodical to ensure all occupants are accounted for. In the article "Secondary Search Techniques" by Paul Mastronardi [22], the author identifies several considerations to be made during a secondary search. When conducting a secondary search, it is important to search all the way down to the floor and to the back of every closet and cabinet where someone, especially a child, may be hiding. Although this may seem like a straightforward task, difficulties arise when you encounter a structure with hoarding conditions. Different structures will present with their own challenges and it is important to make sure any building you are going to conduct a secondary search in is structurally sound. Consider the fire severity and location when assessing stability.

Another consideration for search presented by Mike Mason in his article "Residential Search: Applying the Principles [25]" is the type of occupancy and time of day you are searching is important in determining priority search areas. If you are searching a residential occupancy at night then the likelihood of locating an occupant in a bedroom is much higher than finding an occupant in the kitchen.

According to Stephen Marsar's article 'Survivability Profiling: Are the Victims Savable?' [26], firefighters are dying at a disproportionately high rate compared to civilians at incidents where firefighters are killed. Marsar stresses the importance of reading the conditions inside a structure and understanding how the fire will progress before committing to interior operations such as search & rescue. Recognizing when occupant survival chances have disappeared should alter how you prioritize fireground operations and tactics. Firefighters need to utilize the National Fire Academy's risk versus reward approach of "risk a lot to save a lot."

Contrary to Marsar, in his blog post 'Beyond the door, The Risk Analysis' [27], Scott Corrigan argues that "every fire department should make it known to their employees and their customers what their beliefs are". In other words, fire departments should decide whether or not they believe residential occupancies are generally occupied upon arrival; if the answer is yes, "a first alarm should have an offensive mindset before the bell ever hits [27]." Corrigan suggests that this thought process will ensure that firefighters are ready for the task at hand. It eliminates a layer of chaos from the scene by not strictly relying on verbal and radio communications. As the article states, if the fire service and the public "already know what should be done when someone is trapped in a fire, maybe [they] should focus on who should be doing it [27]." Also, in the article 'VES: Victims Expecting Search', Brian Brush emphasizes the fact that if the fire service publicly campaigns messages such as the importance of closed doors and sheltering in place, they must match those initiatives by actively "cooling open spaces, extinguishing fire, and bringing loved ones out [28]." While firefighting is an inherently dangerous job, it is the responsibility of the fire service to search for and locate victims because the public is counting on them to do so.

In John Mittendorf's book "Truck Company Operations 2nd Edition [9]," Mittendorf states that there are several fundamental characteristics to address when discussing search & rescue. One fundamental characteristic is the modern fireground. Several factors are incorporated into the discussion of the modern fireground. New building construction features such as lightweight trusses cause a structure to become unstable earlier in a fire event than older type IV structures. Focus on energy efficiency has lead to tightly sealed rooms with thermal pane windows that can prevent heat from exiting the structure and increase the chance of flashover. New synthetic materials have created a petroleum-rich fuel load that develops a fire much faster than the natural materials of the first half of the 20th century. Improved turnout gear has the ability to absorb more heat before a firefighter feels it on their skin. This improvement can lead to firefighters spending a prolonged time in a dangerous environment without realizing the severity of the conditions. The final point to be made about the modern fireground is that firefighters are running fewer working fires than their predecessors did, resulting in less fireground awareness and experience.

2.3 Rescue

Once an occupant is discovered in need of rescue, firefighters typically decide between removal of the occupant along the path of entry, removal through an alternate egress path, or sheltering in place. Several factors can influence an answer. It is important to remember the occupant is not protected from the environment [29]. The best option for the occupant may not be the quickest or easiest way out of the building. An interior staircase is ideal for occupant removal because it is designed for people under normal conditions [30]. However, if the occupant has to be removed from an isolated room to make the stairs, it may not be worth the exposure.

Should the need to move an unconscious or injured occupant arise, firefighters also need to consider how the occupant should be moved. There are numerous methods for moving a occupant, so to narrow the focus in this report, attention will be given to the elevation of the occupant rather than the method. Data from several previous reports has shown that the temperature difference between 1 ft off the ground and 3 ft can differ by several hundred degrees Fahrenheit [31]. Oxygen concentration as well as other gas concentrations are likely to change at different elevations similar to the temperature. When tasked with removing a occupant, this consideration may be easy to overlook.

In these experiments, the removal of occupants (i.e., rescue) was simulated. This means that there were no occupants or training manikins that were physically removed from the structure during the experiments. Instead, a series of 16 discrete occupant packages (temperature, heat flux and gas concentration) were installed within the structure. In addition to the measurement limitations that would have occurred with a mobile occupant instrumentation package, this implementation would have restricted the analysis of occupant removal to a fixed drag speed and single path of travel for a specific experiment. Although the discrete approach lacks the continuous path of travel a movable occupant would have, this instrument package allows for an analysis of both a range of speeds and different egress pathways based upon a piecewise aggregation of the measurement locations. The analysis can incorporate multiple search tactics, different arrival/search/rescue times, and multiple rescue methods from a single experiment. For more information on the instrumentation locations see Section 3.3.

2.4 Related LoDD/LoDI

Table 2.1 below shows several of the line of duty deaths (LoDDs) that are related to the topics of size-up and search & rescue in residential structures. While reviewing these reports, common factors appeared in multiple reports. To convey these common themes, the column of contributing factors was created. Elements in these reports were grouped into high-level areas of interest. These categories included: Accountability (of crew members), Building construction, Command Structure, Communication, Flow path, Risk versus Reward, Size-up, Tactics, and Ventilation.

Table 2.1: Line of Duty Deaths During Residential Search

Report	Location	Fatalities	Contributing Factors
F2016-18 [32]	New Castle, DE	3	Flow path, Size-up, Tactics
F2015-21 [33]	Sioux Falls, SD	1	Accountability, Tactics, Ventilation
F2015-19 [34]	Hamilton, OH	1	Size-up, Ventilation
F2014-25 [35]	Philadelphia, PA	1	Flow path, Tactics, Ventilation
F2014-09 [36]	Boston, MA	2	Flow path, Tactics, Ventilation
F2014-02 [37]	Toledo, OH	2	Flow path, Size-up, Tactics
F2013-13 [38]	Reisterstown, MD	1	Accountability, Size-up, Tactics
F2013-02 [39]	Owego, NY	1	Communication, Risk versus Reward, Size-up, Tactics
F2012-28 [40]	Chicago, IL	1	Building Construction, Ventilation
F2011-30 [41]	Worcester, MA	1	Risk versus Reward, Size-up, Tactics
F2011-13 [42]	San Francisco, CA	2	Flow path, Size-up, Ventilation
F2011-02 [43]	Towson, MD	1	Flow path, Tactics, Ventilation
F2010-10 [44]	Homewood, IL	1	Size-up, Ventilation
F2009-11 [45]	Houston, TX	2	Flow path, Size-up, Tactics
F2008-34 [46]	Crossville, AL	1	Accountability, Size-up, Tactics
F2008-26 [47]	Forrest, IL	1	Size-up, Tactics
F2008-09 [48]	Colerain Township, OH	2	Size-up, Tactics
F2008-08 [49]	Linwood, PA	1	Risk versus Reward, Size-up, Tactics
F2008-06 [50]	Grove City, PA	1	Communication, Tactics, Ventilation
F2007-29 [51]	Tyler, TX	2	Accountability, Communication, Tactics, Ventilation
F2007-28 [52]	Pleasant Hill, CA	2	Tactics, Ventilation
F2007-16 [53]	Atlanta, GA	1	Size-up, Tactics, Ventilation
F2007-12 [54]	Prince William, VA	1	Size-up, Tactics, Ventilation
F2007-07 [55]	Harrison, TN	1	Building Construction, Size-up, Tactics
F2007-02 [56]	Atlanta, GA	1	Accountability, Risk versus Reward, Size-up, Tactics, Ventilation
F2006-28 [57]	Baltimore, MD	1	Building Construction, Tactics, Ventilation
F2006-26 [58]	Green Bay, WI	1	Building Construction, Tactics, Ventilation

Report	Location	Fatalities	Contributing Factors
F2006-24 [59]	Lafayette, IN	1	Accountability, Building Construction, Risk versus Reward, Tactics, Ventilation
F2005-02 [60]	Baytown, TX	1	Size-up, Ventilation
F2003-12 [61]	Cincinnati, OH	1	Tactics, Ventilation
F2002-12 [62]	Jefferson City, TN	1	Size-up, Tactics, Ventilation
F2002-11 [63]	Harrisburg, NC	1	Flow path, Risk versus Reward, Size-up, Tactics
F2002-06 [64]	Manlius, NY	2	Building Construction, Command Structure, Flow path, Risk versus Reward, Tactics
F2001-16 [65]	Cleves, OH	1	Risk versus Reward, Size-up, Tactics
F2001-15 [66]	Osceola, MO	2	Accountability, Communication, Tactics
F2001-08 [67]	Ashton, IL	2	Accountability, Tactics, Ventilation
F2000-44 [68]	Pensacola, FL	1	Accountability, Tactics, Ventilation
F2000-26 [69]	Center Point, AL	1	Tactics, Ventilation
F2000-23 [70]	Layton, UT	1	Accountability, Flow path, Size-up, Ventilation
F2000-16 [69]	Fraser, MI	1	Accountability, Command Structure, Communication, Flow path, Size-up, Tactics, Ventilation
F2000-04 [71]	Keokuk, IA	3	Command Structure, Communication, Size-up, Tactics, Ventilation
99-F21 [72]	District of Columbia	2	Communication, Flow path, Size-up, Tactics, Ventilation
99-F02 [73]	Worthington, IN	1	Accountability, Communication, Size-up, Tactics

3 Experimental Configuration

3.1 Experimental Structure

Two identical, purpose-built, ranch-style, single-story residential structures were constructed on the grounds of the Delaware County Emergency Services Training Center in Sharon Hill, PA. The design of the structures, fuel loads, and set of experiments were planned during a workshop with the technical panel assembled for this study. Each structure had a footprint of approximately 1600 ft^2 with interior experimental area of approximately 1450 ft^2 and featured four bedrooms, two bathrooms, and an open concept kitchen/living room. Figure 3.1 shows representative photographs of the four sides of the structure with side A as the front.

(a) Side A

(b) Side B

(c) Side C

(d) Side D

Figure 3.1: Representative exterior photographs of the four sides of the experimental structures.

The subfloor of the structure was comprised of 0.72 in. tongue-and-groove, moisture-resistant, engineered wood sheeting. This sheeting was affixed to nominally 2.0 in. by 10.0 in. fir floor joists, spaced at 16.0 in. on center. The entire flooring system of the structure was supported through a series of laminated veneer lumber beams. Each beam location included a pair of 9.5 in. by 1.75 in. beams affixed together, which brought the total size to 9.5 in. by 3.5 in. The beam network supporting the structure was leveled using concrete piers with incorporated rebar connecting to each footing. Each footing was a 2.0 ft by 2.0 ft by 4.0 ft concrete block.

Figure 3.2: Photograph of support assembly for each structure. From the top down, this included the subfloor, floor joists, support beams, and concrete piers.

The exterior walls of the structures were protected by 0.25 in. thick fiber cement board siding, a layer of olefin home wrap, and 0.438 in. oriented strand board (OSB). The walls were constructed from nominally 2.0 in. by 4.0 in. studs spaced 16 in. on center and filled with R-13 fiberglass insulation. The studs were lined on the interior with 0.625 in. gypsum board and finished with two coats of latex paint. A dimensioned floor plan of the structure is included in Figure 3.3.

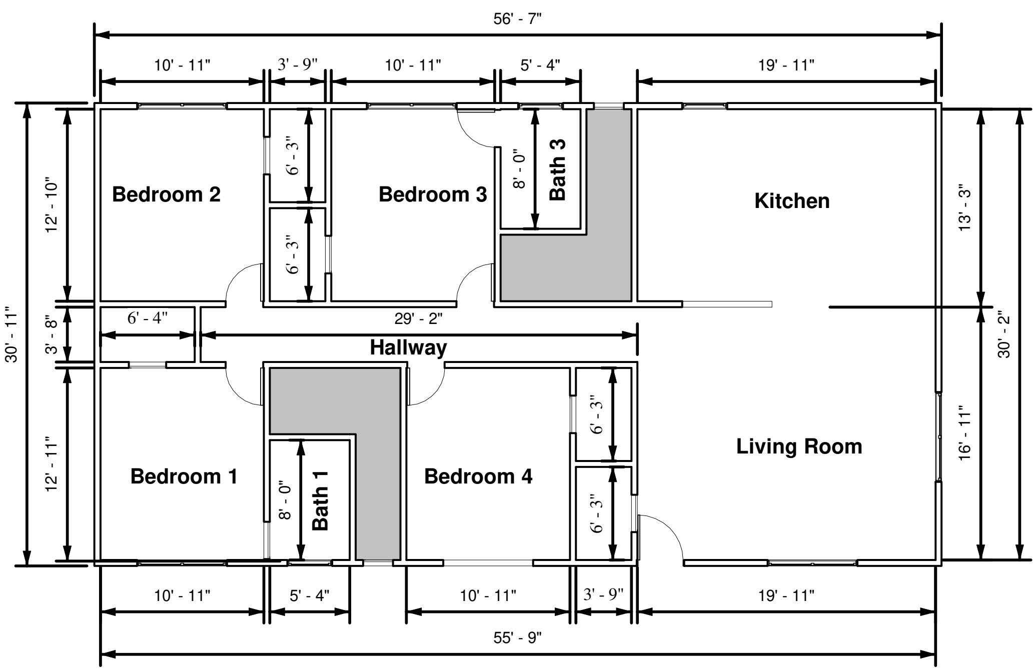
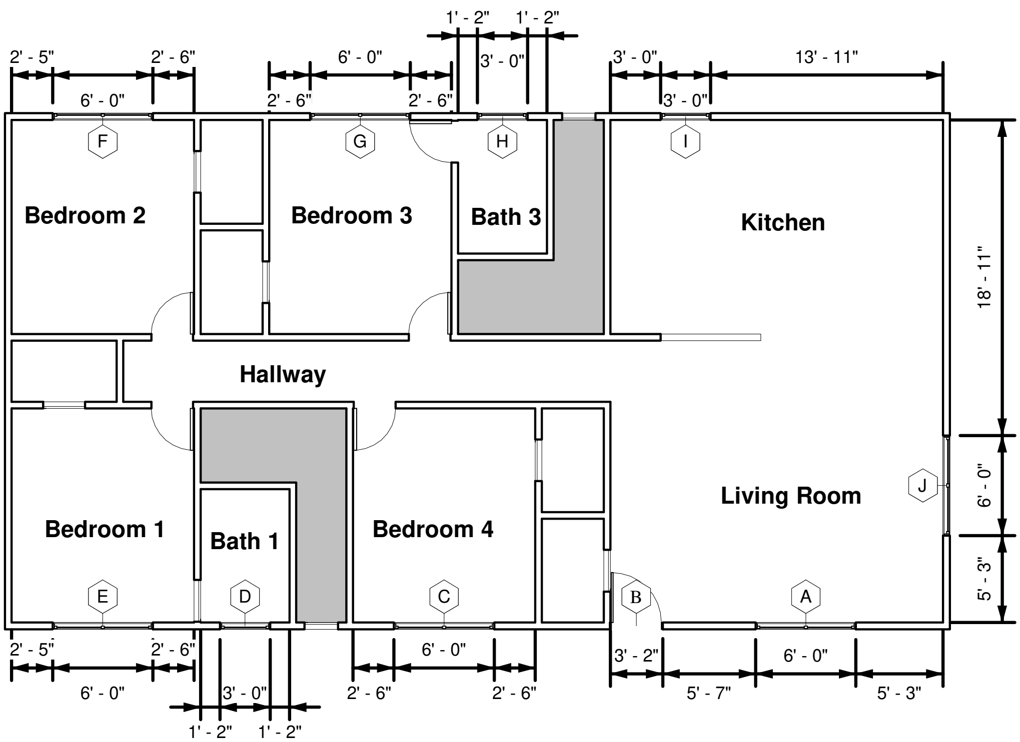


Figure 3.3: Dimensioned layout of structure.

Each structure had one exterior door that was either fiberglass or metal (36 in. by 80 in.) with hollow-core wood frame interior doors to the bedrooms and closets (30 in. by 80 in.). The bedroom windows were comprised of two double-hung, dual pane windows each measuring 3 ft wide by 4 ft high with a center mullion for a total size of 6 ft by 4 ft. Living room windows were similar to the bedroom windows, with two double hung, dual pane windows with a center mullion, except slightly taller with an overhaul size of 6 ft wide by 5 ft high. The bathroom windows were dual-pane, non-operable windows measuring 3 ft wide by 2 ft high. The kitchen window was a double-hung, dual-pane window measuring 3 ft wide by 3 ft high. Figure 3.4 shows the location of the exterior vents.



Vent	Size (width x height)	Sill Height
Living Room Window (A, J)	6 ft x 5 ft	2 ft
Front Door (B)	36 in. x 80 in.	—
Bedroom Window (C, E, F, G)	6 ft x 4 ft	3 ft
Bathroom Window (D, H)	3 ft x 2 ft	5 ft
Kitchen Window (I)	3 ft x 3 ft	4 ft

Figure 3.4: Dimensioned layout of exterior vents.

A residential heating, ventilation, and air conditioning (HVAC) system was also installed in each structure. A closed system (i.e., no fresh air intake on the return) was installed, and thus the system recirculated air within the structure. Although the system was off for each experiment, all supply and return vents were open to allow for the transport of gases throughout the structure. The system originated in the side C instrumentation/mechanical room and extended up through the top of the furnace unit into the attic, where all the duct work was located. The HVAC system used rigid metal ductwork for the main trunk lines, supply lines, and to connect the returns once they reached the attic. Within the living space of the structure, each return was created by the volume between stud bays and the enclosing walls. Each bedroom (x4), bathroom (x2), the living room (x2) and the kitchen (x1) had supplies with surface-mounted registers in the ceiling for a total of nine supplies.

Each bedroom (x4), the hallway (x2), and the living room (x1) had returns with surface-mounted registers along interior walls, 8 in. above the floor, for a total of eight returns. The system included an 18 kW heater with a 0.37 kW (1/2 horsepower), five-speed motor, which resulted in a capacity of approximately 2040 m^3/hr (1200 scfm). R410A refrigerant was used as the cooling fluid that conditions the air in a single stage air handler [74]. The condensing unit for the HVAC system was located along the back side of the structure below the mechanical room.

To characterize the natural ventilation of the structures, a leakage test was conducted with all exterior vents closed. ASTM E 779, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization," was followed to determine the air changes per hour [75]. According to the International Energy Conservation Code (IECC), residential structures within climate zones 3–8 (these experiments were conducted in zone 4), should undergo $\leq$ three air changes per hour (ACPH) at 50 Pa [76]. The average leakage in the test structures across the 21 experiments was 1.58 $\pm$ 0.1 ACPH at 50 Pa (0.007 psi) which falls within the acceptable IECC range.

3.2 Experimental Procedure

A series of procedures was performed before, during, and after each fire. Prior to the start of each experiment, a series of instrumentation checks and measurements were taken. All instruments were tested to ensure proper functionality and gas lag times (discussed in Section 3.3) were determined. Flow rates through the HVAC supply and returns were measured, and the effective leakage area (Section 3.1) was measured to assess whether noticeable changes occurred between experiments and to ensure the leakage was still within the acceptable IECC range. The positions of doors and windows were set based on the experimental scenario, video camera positions were set, and photographs were taken to document the interior and exterior of the structure.

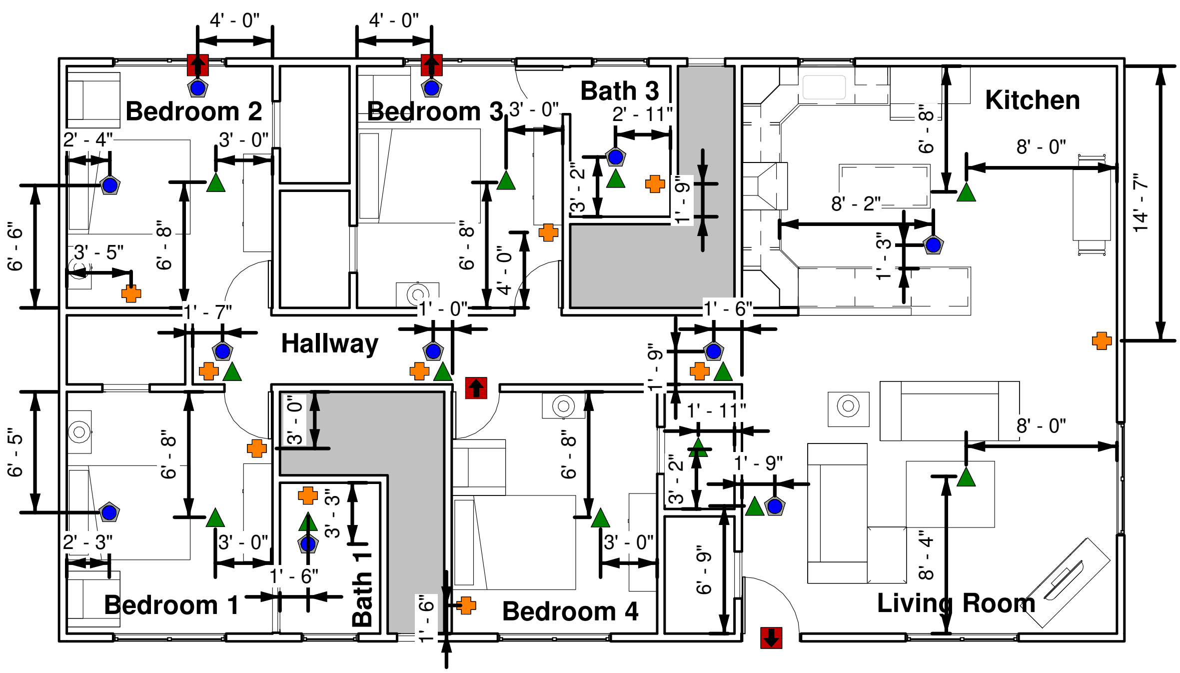
At a minimum, a single crew of three personnel was utilized for suppression, and two crews of two personnel were utilized for exterior horizontal ventilation and interior door manipulation via pre-rigged cables, and/or secondary suppression actions. A standby crew for rapid intervention was present in each experiment. All personnel donned their complete set of PPE and SCBA. Additionally, weather was continuously monitored in case adverse conditions would present a safety hazard to operating personnel, in which case testing would be delayed.

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 set to flow a straight stream at 150 gpm at 50 psi, and the smooth bore nozzle was a 7/8 in. tip set to flow 160 gpm at 50 psi. At the conclusion of primary suppression, hydraulic ventilation was performed at a vent local to the fire room. At the conclusion of hydraulic ventilation, temperatures and gas concentrations within the structure were monitored until conditions returned to near pre-experiment levels.

At the conclusion of each experiment, that respective structure was overhauled to remove damaged furniture, drywall, flooring, and windows. During this phase, those conducting overhaul were in dedicated alternate PPE (i.e., turnout gear outer shells to serve as barrier protection against contaminants), respiratory protection, hardhats, safety toe footwear, and gloves. Following overhaul, each respective structure was rehabilitated, re-furnished, and re-instrumented.

3.3 Instrumentation

Each structure in these experiments was instrumented to measure gas temperature, gas velocity, pressure, total heat flux, and gas concentrations. Instruments utilized during the experiments included thermocouples, bidirectional probes, pressure transducers, Schmidt-Boelter total heat flux gauges, and gas analyzers. Figure 3.5 shows the spatial layout of the instrumentation used during these experiments.



Icon	Instrumentation	Notes
	Thermocouple Array	
	Gas Velocity	Arrow indicates positive flow direction.
	Pressure Tap	6 in. off the wall.
	Heat Flux and Gas Probe	In hallway locations, heat flux was centered in hallway flush with floor and gas probes were 6 in. off the wall at 1 ft and 3 ft.

Figure 3.5: Dimensioned instrumentation layout of structure.

In general, the measurement locations in the two structures were the same for the three ignition locations (bedroom, kitchen, or living room). The instrumentation unique to specific ignition locations included the heat flux gauge and gas sample port in the kitchen and in bathroom 1. For a bedroom or living room ignition, the kitchen heat flux gauge and gas sample port were used, and for kitchen ignitions the bathroom 1 location was used.

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 total expanded uncertainty associated with the temperature measurements from these experiments is estimated to be ± 15% as reported by researchers at NIST [77, 78]. Bare-bead thermocouple arrays were installed throughout the structures in 13 specific spatial locations, which can be found on the floor plan in Figure 3.5. Each thermocouple array consisted of eight thermocouples with the top thermocouple in each array located 1 in. below the ceiling and the remaining seven thermocouples spaced at 1 ft intervals (1 ft below ceiling, 2 ft below ceiling ... 7 ft below ceiling). Single inconel sheathed thermocouples were also installed throughout the HVAC duct network at each of the supplies, returns, and in the main trunk.

Bidirectional probes and sheathed thermocouple arrays were used for gas velocity measurements. To determine magnitude and direction of the flow, the bidirectional probes were connected to both the high and low input of a differential pressure transducer. 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 bidirectional probes similar to those used during this series of tests [79]. At the front door and the doorway to bedroom 4, five bidirectional probes and thermocouples were installed with the first location 4 in. above the floor and subsequent sensors spaced 18 in. apart. At the windows of bedrooms 2 and 3, arrays of five bidirectional probes and thermocouples were installed with the first sensor 4 in. above the window sill and subsequent sensors spaced 10 in. apart.

Pressure measurements were made using differential pressure sensors to determine pressure changes relative to ambient pressure (outside the structure) conditions. Three, 1/4 in. OD copper pressure taps were installed 6 in. off the wall at spatial locations shown in Figure 3.5). At each of the 10 locations, pressure was measured 1 ft, 4 ft, and 7 ft below the ceiling. The differential pressure sensors had an operating range of ± 125 Pa. The total expanded uncertainty associated with pressure measurements obtained from the transducers is estimated as ± 10% [80].

Total heat flux measurements were made with water-cooled Schmidt-Boelter gauges. Each of the 12 heat flux gauges were oriented vertically. The gauges were installed flush with the floor in the hallway and living room, at 1 ft above the floor in the bathrooms and kitchen, at 3 ft above the floor on the beds in the bedrooms, and at 1 ft and 3 ft above the floor at the bedroom 2 and 3 windows. Results from an international study on total heat flux gauge calibration and response demonstrated that the uncertainty of a Schmidt-Boelter gauge is typically ± 8% [81]. Appendix B provides a table of heat flux ranges for several reference thresholds.

Sixteen gas concentration sampling ports were installed in each structure. The sampling ports were installed at 1 ft and 3 ft above the floor in the hallway and living room, at 1 ft above the floor in the bathrooms and kitchen, at 3 ft above the floor in the bedrooms, and at 1 ft and 3 ft above the floor at the bedroom 2 and 3 windows. Gas samples were analyzed through the use of oxygen (paramagnetic alternating pressure) and combination carbon monoxide/carbon dioxide (non-dispersive infrared) analyzers. The gas sampling instruments used throughout the series of tests discussed in this report have demonstrated a relative expanded uncertainty of $\pm$ 1% when compared to span gas volume fractions [82]. Given the non-uniformities and movement of the fire gas environment and the limited set of sampling points in these experiments, an estimated uncertainty of $\pm$ 12 % was applied [83].

To minimize transport time through the system, samples were pulled from the structure through the use of a vacuum/pressure diaphragm pump rated at 0.75 CFM. The sampling ports consisted of 3/8 in. OD stainless steel tubing within the structure. Once outside the structure, the sample was drawn through a condensing trap to remove moisture and filtered through a 5 micron polyester filter and a 3 micron polyester filter. At the exit of these filters, the sample line transitioned from stainless steel to polyethylene tubing until the sample reached the analyzer/pump rack. At the inlet to the rack but before reaching the sample pump, the gas flowed through a 0.3 micron HEPA filter. Downstream of the pump, but upstream of the analyzer, the sample flowed through a drierite filter to remove any remaining moisture, and finally a 0.01 micron filter. Prior to every experiment, the transport time of a known calibration gas from each sample port to each respective analyzer was measured. This time lag was accounted for in post-processing to ensure the gas data was in sync with the other measurements.

3.4 Fuel Packages

Each structure was fully furnished to represent fuel loading typical to a residential structure. This included furnishing each of the four bedrooms, the two bathrooms, the kitchen, and the living room. The overall arrangement and dimensions of a representative furnished structure is presented in Figure 3.6.

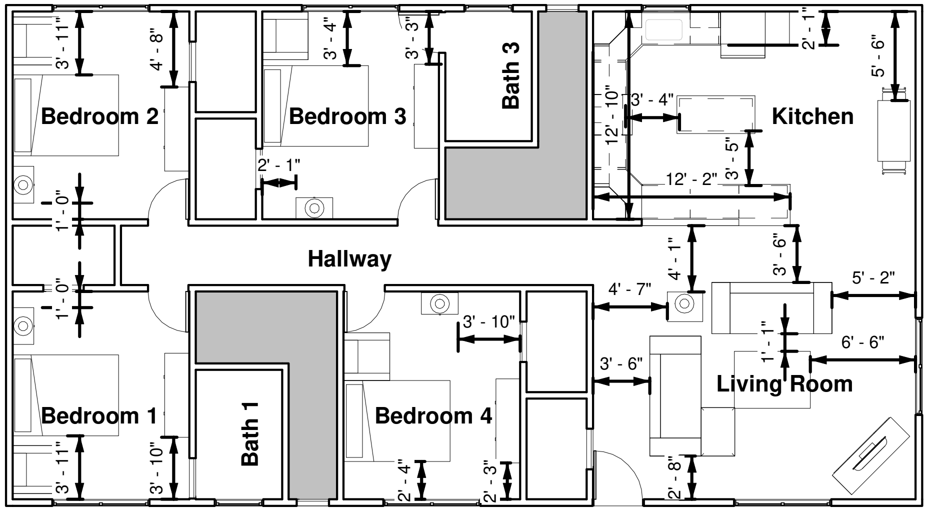


Figure 3.6: Dimensioned layout of bedroom, kitchen, and living room fuels.

The furnishings were dimensioned and weighed, and where possible, 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 Section 3.4.1–3.4.3 along with representative photographs.

3.4.1 Bedroom

Each bedroom's fuel package consisted of a queen mattress set with a foam mattress topper and associated bedding, a dresser, a night stand, a chair, a lamp, window curtains, and a wall painting as shown in Figure 3.7. Additionally, each bedroom floor was lined with polyethylene terephthalate (PET) carpet, polyurethane (PU) foam padding, and an oriented strand board subfloor. Table 3.1 shows the size, material composition, and mass of each of the items that comprised a bedroom fuel load for each experiment. Note: The layout of the furniture was in one of three configurations based on the location of the respective hallway door, closet/bathroom door, and window, as shown in Figure 3.6.

(a) View from Windows Toward Door

(b) View from Door Toward Windows

Figure 3.7: Example layout of fuels from bedroom 3.

Table 3.1: Bedroom Furnishings and Contents

Item	Dimensions (in)	Materials	Mass (lb)
Mattress Topper	75 x 58 x 4	PU foam	15.1
Mattress	79 x 59 x 12	90% PU foam, 10% blended rayon & polyester	66.4
Foundation	79 x 59 x 9	PE padded fabric over wood	34.1
Bedding	Queen size	100% PE	7.7
Pillow(2)	27 x 17 x 4	Shell 52% PE & 48% cotton, fill 100% PE	2.6
Chair	32 x 26 x 34	Fabric 100% PE, fill PU foam & PE	48.5
Dresser	62 x 17 x 36	Vinyl over particle board w/cardboard back	109.2
Nightstand	27 x 15.5 x 27	Vinyl over particle board w/cardboard back	35.0
Lamp	12 x 12 x 25	Body cast vinyl, shade fabric over plastic film	3.2
Painting	30 x 24 x 2	Frame, styrene over MDF, canvas	3.2
Curtains (pair)	84 x 84	100% PE	2.5
Carpet	144 x 144 x 0.5	Fiber 100% PET, backing PP and latex	0.68 lb/ft^2
Padding	144 x 144 x 0.44	PU rebond foam	0.64 lb/ft^2
Oriented Strand Board	0.44 thick	Wood and PF resin	1.4 lb/ft^2

Bedroom fires were ignited with an electric match located in the corner of the upholstered chair where the seat cushion met the armrest nearest the mattress. A slit was made in the fabric and a small amount of the polyester batting was pulled out. Figure 3.8 shows the ignition setup prior to the matchbook being set underneath the batting.

Figure 3.8: Photograph of ignition setup for a bedroom fire.

In addition to the fuel load in each of the bedrooms, the two bathrooms were also furnished with representative items (a vanity and toilet) as shown in Figure 3.9.

Figure 3.9: Photograph of bathroom fuel layout.

3.4.2 Kitchen

The open floor-plan kitchen contained both upper and lower cabinets, a range, a range hood, a refrigerator, an island, a small table, and two chairs. Figure 3.10 shows the layout of the kitchen fuels, and Table 3.2 shows the size, material composition, and mass of each of the items that comprised the primary kitchen fuel load for each experiment.

(a) View Toward Ignition Burner (b) View of Full Kitchen

Figure 3.10: Example layout of kitchen fuels.

Table 3.2: Kitchen Furnishings and Contents

Item	Dimensions (in)	Materials	Mass (lb)
36 in. Wall Cabinet	36 x 12 x 36	MDF w/ wood veneer and door frames	55.9
Corner Wall Cabinet	24 x 12 x 36	MDF w/ wood veneer and door frames	59.9
30 in. Wall Cabinet	30 x 12 x 24	MDF w/ wood veneer and door frames	31.0
21 in. Wall Cabinet	21 x 12 x 36	MDF w/ wood veneer and door frames	34.6
12 in. Wall Cabinet	12 x 12 x 36	MDF w/ wood veneer and door frames	27.1
33 in. Wall Cabinet	33 x 12 x 18	MDF w/ wood veneer and door frames	22.9
36 in. Base Cabinet	36 x 25 x 34.5	Plywood w/ wood veneer and door frames	66.9
24 in. Base Cabinet	24 x 25 x 34.5	Plywood w/ wood veneer and door frames	43.9
27 in. Base Cabinet	27 x 25 x 34.5	Plywood w/ wood veneer and door frames	47.5
Corner Base Cabinet	30 x 30 x 34.5	Plywood w/ wood veneer and door frames	58.4
36 in. Base Cabinet	36 x 25 x 34.5	Plywood w/ wood veneer and door frames	47.0
Tall Cabinet	18 x 24 x 90	Plywood w/ wood veneer and door frames	77.8
Counter Top	27 x 57 x	Plastic laminate over particle board	38.8
Fill Panel	96 x 24 x 1	Veneer over plywood	26.9
Fill Board	48 x 96 x 0.25	Veneer over fiberboard	29.2
Composite Flooring	0.17 thick	IXPE foam, vinyl, PU wear layer	1.49 lb/ft^2
Oriented Strand Board	0.44 thick	Wood and PF resin	1.4 lb/ft^2
Table	45 x 24 x 30	Vinyl covered MDF w/ wood legs	34.9
Chair (2)	22.5 x 19.5 x 39	Wood frame, PU foam, PE fabric	35.7
Picture	30 x 24 x 1	Canvas, styrene over MDF frame, cardboard	3.2
Refrigerator	66.375 x 30 x 30.375	Steel, rigid foam, plastic liner	155.8
Range	47 x 30 x 29	Steel, plastic	130
Range Hood/Fan	5.5 x 30 x 20	Steel nylon	20

In addition to the ignition fuels and furniture, a set of plastics typical to a residential kitchen were included to facilitate flame spread across the counter and through the cabinets. Table 3.3 provides the details of those materials.

Table 3.3: Kitchen Plastics

Item	Dimensions (in)*	Materials	Mass (lb)#
Water Bottles (20)	2.5 dia. x 8	PET	0.40
Milk Jugs (2)	6 x 6 x 10	HDPE	0.14
Recycling Bin	26 x 16 x 15	LDPE	4.7
Two Gallon Bin	8.75 x 9.5 x 9	PC	1.7
7 Piece Utensils	3.5 x 12.5 x 0.5	Nylon	0.75
Small Food Canister	6.5 x 4.75 x 8.75	Polypropylene	0.41
Small Lid	7 x 5 x 2	HDPE	0.17
Medium Food Canister	7.5 x 3.6 x 11	Polypropylene	0.50
Medium Lid	7.9 x 4 x 2	HDPE	0.13
Large Food Canister	9.1 x 5.25 x 9	Polypropylene	0.88
Large Lid	9.75 x 5.3 x 2	HDPE	0.22
Recipe Holders (2)	8.6 x 3.25 x 11	PMMA	1.4
Coffeemaker Body	8 x 12 x 12.5	PP	2.3
Cups (25)	20 oz	EPS	0.28
Cups (50)	20 oz	PLA	0.84
Pipe	1.5 OD x 18 in	PVC	0.79
Electrical Box	4.3 x 3.5 x 6.5	PVC	0.38
Outlet (2)	2.7 x 1.3 x 1.0	PVC	0.23
Outlet Cover Plate	5.4 x 5.3 x 0.3	PVC	0.093
14-2 NM Cable	60 long	PVC over copper	0.29

* Dimensions are provided for single items.
# Mass is provided for the total number of items.

3.4.3 Living Room

The living room contained two three-seat sofas, an ottoman, a coffee table, an end table, a TV stand, and a TV. The space was fully carpeted with padding and oriented strand board subfloor as shown in Figure 3.11. Table 3.4 shows the size, material composition, and mass of each of the items that comprised the living room fuel load for each experiment.

Figure 3.11: Photograph of fuels for a living room fire.

Table 3.4: Living Room Furnishings and Contents

Item	Dimensions (in)	Materials	Mass (lb)
Sofa (2)	87 x 36 x 34	Fabric PE, fill PU foam & PE, frame eng. wood	116.8
Ottoman	29 x 16 x 23	Fabric PE, fill PU foam & PE, frame eng. wood	18.6
Coffee Table	55 x 42 x 16.5	Vinyl over press board	89.5
End Table	26 x 22 x 26	Vinyl over particle board	61.4
TV Stand	50 x 20 x 30	Wood, eng.wood w/ wood veneer, electronic circuits, metal components	144.5
TV	38 x 22 x 4	PE shell, glass screen	17.4
Lamp	12 dia x 25	Body cast vinyl, shade fabric over plastic film	3.2
Curtains (2 pair)	84 x 84	100% PE	5.1
Carpet	0.5 thick	Fiber 100% PET, PP backing with latex	0.68 lb/ft^2
Padding	0.44 thick	PU rebond foam	0.64 lb/ft^2
Oriented Strand Board	0.44 thick	Wood and PF resin	1.4 lb/ft^2

3.5 Experiments Conducted

To evaluate the search and rescue tactics in a single-family, single-story structure, 21 live-fire experiments were conducted with bedroom, kitchen, and living room ignition locations. This report focuses on 11 of the 20 experiments which were conducted with bedroom ignition locations to evaluate:

- the point of origin for search operations (origination through the front door or through a bedroom window)

- the timing of search operations relative to suppression (before, during, or after suppression)
- the impact of isolation during search (closing of the front door and/or bedroom doors)
- the path of travel during occupant rescue (internal path through the front door or through the nearest bedroom window)

Table 3.5 provides a overview of the experiments conducted based on their fire location, the tactic studied, and the timing of the search relative to suppression actions. This report includes the bedroom experiments, numbered 1-10. The kitchen and living room fire experiments can be found in Part II [84].

Table 3.5: List of Experiments

Ignition	Exp #	Search Tactic	Search Timing
Bedroom 4	1	Window Initiated Search in BR2 (Non-Isolated) and BR3 (Isolated)	Pre-Suppression
	2	Window Initiated Search in BR2 (Non-Isolated) and BR3 (Isolated)	During Suppression
	3	Window Initiated Search in BR2 (Non-Isolated) and BR3 (Isolated)	During Suppression
	4	Window Initiated Search in BR2 (Isolated) and BR3 (Non-Isolated)	Pre-Suppression
	5	Window Initiated Search in BR2 (Isolated) and BR3 (Non-Isolated)	During Suppression
	6	Door Initiated Search w/Front Door Control	Pre-Suppression
	7	Door Initiated Search w/BR4 Door Control	Pre-Suppression
	8	Window Initiated Search in BR3 (Non-Isolated) w/BR4 Door Control	Pre-Suppression
	8b	Window Initiated Search in BR3 (Isolated) w/BR4 Door Control	Pre-Suppression
	9	Door Initiated Search	During Suppression
	10	Baseline^{+}	—
Kitchen	11	Window Initiated Search in BR2 (Non-Isolated) and BR3 (Isolated)	Pre-Suppression
	12	Window Initiated Search in BR2 (Non-Isolated) and BR3 (Isolated)	During Suppression
	13	Window Initiated Search in BR2 (Isolated) and BR3 (Non-Isolated)	Pre-Suppression
	14	Door Initiated Search	Post-Suppression
	15	Door Initiated Search w/Front Door Control	Pre-Suppression
	16	Door Initiated Search and Window Initiated Search in BR3 (Non-Isolated) w/Front Door Control	Pre-Suppression
	17	Door Initiated Search	Pre-Suppression
	18	Baseline^{+}	—
Living Room	19	Window Initiated Search in BR2 (Isolated) and BR3 (Non-Isolated)	Pre-Suppression
	20	Door Initiated Search	During Suppression

$^{+}$ Baseline refers to the case where no changes were made from the initial conditions to serve as the comparison point for other experiments.

Examinations of the experimental results are split based on the first intervention action performed (e.g., ventilation of a window, closing a door, suppression, etc.). Given the use of the same structure, fuel packages, and ignition locations for the respective groups of experiments, Section 4 presents a representative example of the fire dynamics from ignition until intervention for a bedroom fire. Sections 5.1—5.11 examine the fire dynamics of each bedroom experiment from prior to intervention through the completion of the experiment. When interpreting the individual experimental results presented below, consider that the order of the data presented begins with the fire room and proceeds based on the path of travel of fireground operations. For example, following an analysis of the fire room, a window initiated search writeup starts with the bedroom(s) where the search began, moves to the hallway, and concludes with the remaining bedrooms. For a door initiated search, the analysis begins with the fire room, moves to the hallway, and concludes with the bedrooms.

4 Experimental Results from Ignition to Intervention

For each of the 11 bedroom ignitions examined in this document, both the measured and visualized fire growth of the individual experiments had varying degrees of uniqueness (e.g., peak temperature, time to peak temperature, and time to exterior visible flames among other characteristics). This variability can primarily be attributed to changes in experimental variables, but was also impacted by weather (e.g., temperature, humidity, and wind) and simply how the flames spread from the ignition source to target fuels. The similarities across measurements grouped by ignition location prior to firefighter intervention (controlling for different interior door closures) allows for the fire dynamics in this time period to be described by a representative example. The following section 4.1 presents a discussion on the fire dynamics from ignition until first intervention through analysis of a singular bedroom 4 experiment (Experiment 10).

4.1 Bedroom Ignition Example

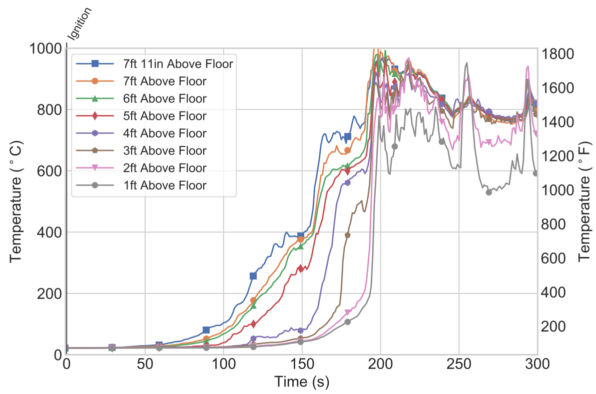
For the bedroom ignition, consider Experiment 10. Prior to ignition, the lower windows of the fire room were removed and the fire room door and front door were open. The door to bedroom 1 and bathroom 1 were closed while the doors to bedroom 2, bedroom 3, and bathroom 3 were open. The fire was ignited in the upholstered chair next to the bed. Flames were first visible from the bedroom 4 window at 172 s (2:52) post ignition, and Figure 4.1a correspondingly shows the interior conditions. Across the 11 bedroom ignition experiments (Table 3.5), flames were visible out of the window at 176 s (2:56) ± 25 s. The fire continued to grow and reached flashover at 197 s (3:17) post ignition as floor-to-ceiling temperatures crossed 600 °F (1100 °F) (Figure 4.1b). Post-flashover, flames extended out of the bedroom 4 windows until suppression.

(a) Flames First Visible Out Window

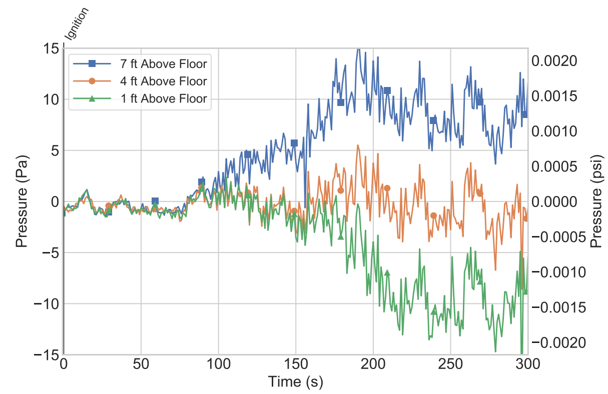
(b) Transition Through Flashover

Figure 4.1: Interior views of fire growth at the time flames were first visible out of bedroom 4 window (172 s post ignition) and as the fire transitioned through flashover (197 s post ignition).

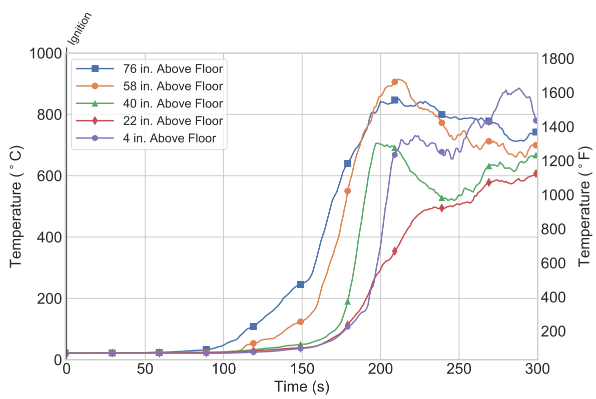
The time history of the fire room data (room temperature, pressure, doorway temperature, and doorway velocity) are presented in Figure 4.2. Gas temperatures at the ceiling in bedroom 4 first began to rise 20 s after ignition, and by 120 s, temperatures began to rise at all elevations (Figure 4.2a). There was a corresponding rise in pressure at the 7 ft elevation due to gas expansion associated with the temperature increase (Figure 4.2b). At the time flames were visible out the fire room windows, temperatures within the fire room ranged from 85 °C (185 °F) 1 ft above the floor to 730 °C (1345 °F) at the ceiling, and pressures ranged from -2.5 Pa (-0.0004 psi) 1 ft above the floor to 9 Pa (0.001 psi) 7 ft above the floor. The continued increase in pressure at 7 ft above the floor was directly related to the accumulation of high-temperature gases within the space through the development of a hot gas layer. As this layer descended below the door header, the higher-pressure gases in the fire room flowed toward areas of lower pressure within the structure as evident by the positive velocities in the doorway (+2.5 m/s (5.6 mph) to +4.5 m/s (10 mph)) shown in Figure 4.2d. The below ambient pressure at the 1 ft elevation was created due to the air entrainment associated with the flow of combustion gases in the fire plume. The below ambient gas pressure under the 4 ft elevation in the fire room led the relatively higher pressure gases in the structure to flow into the fire room as shown by the approximate -1 m/s (-2.2 mph) velocities at the doorway below 22 in. above the floor in Figure 4.2d. The gases that flowed into the fire room were mostly air, which aided further fire growth and enabled the room to transition through flashover 25 s later.



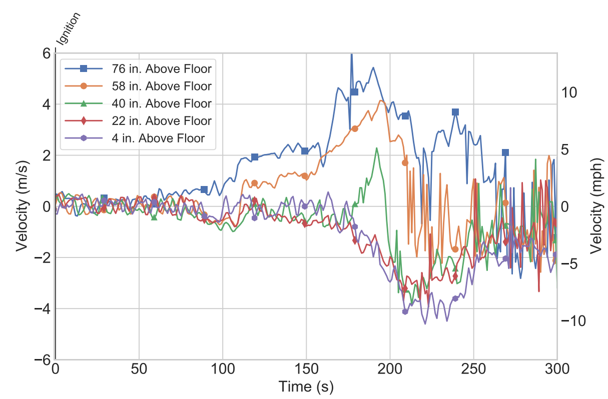
(a) Bedroom 4 Temperature



(b) Pressure (+ Indicates Above Ambient)



(c) Doorway Temperature



(d) Doorway Velocity (+ Indicates Flow Out of Room)

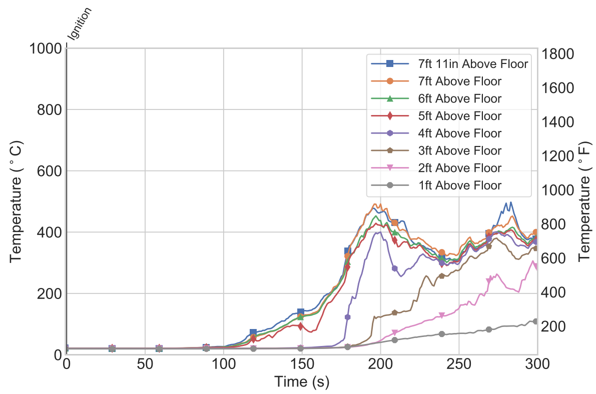
Figure 4.2: Temperature, pressure, and velocity time histories in bedroom 4 (fire room) from ignition (t = 0 s) until firefighter intervention for Experiment 10.

The rise in bedroom doorway temperatures, especially at 58 in. and above, was associated with the higher pressure combustion gases that flowed out of the bedroom into the hallway. Although the velocity data in Figure 4.2d showed intake velocities at 40 in. and below, those doorway temperatures still rose in part due to radiation from the flames out the top of the door and in part due to the ignition of the hallway carpet. Taken from a camera installed in the end hallway wall looking toward the start hallway location, Figure 4.3 shows the flaming combustion of the carpet in the hallway outside bedroom 4 prior to flashover. The temperature and pressure remained nominally steady through flashover, except for the doorway velocity, which fluctuated between intake and exhaust at approximately 260 s due to flaming combustion at the doorway.

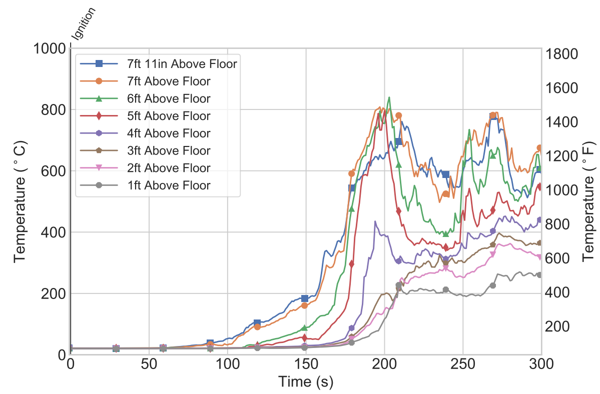
Figure 4.3: Ignition of hallway carpet outside of bedroom 4 just prior to flashover looking from the end hallway location toward the start hallway location.

Hallway and Front Door

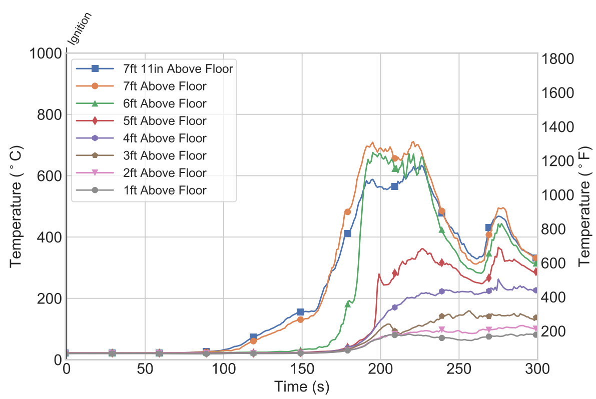
The hallway, bedrooms 2 and 3, and common space were connected (i.e., there were no closed doors between the fire room and these spaces that could restrict gas flow) to bedroom 4, which allowed for the transport of combustion gases to these locations. Consider the changes that occurred in the hallway as a result of the bedroom 4 fire growth. Recall from Figure 4.2d that higher temperature combustion gases started to flow out of the bedroom at 70 s. This directly aligns with the temperature rise at the mid hallway location as it was the closest to bedroom 4 (Figure 4.4b). The start hallway and end hallway ceiling temperatures began to increase 90 s post-ignition due to the further distance from the fire room (Figures 4.4a and 4.4c). Similar to the fire room, peak temperatures at all three hallway locations occurred following flashover in bedroom 4, at approximately 200 s. The mid hallway temperatures were the highest due to the proximity to the fire room, peaking at 800 °C (1472 °F) at the ceiling and 200 °C (392 °F) 1 ft above the floor. Here, proximity mattered because of less distance and time for combustion gases to cool through mixing with quiescent gases and through heat loss to the structure (ceiling, walls, and flooring). Temperatures at the end hallway location reached the lowest peak values of temperatures in the hallway of approximately 490 °C (915 °F) at the ceiling because once the space began to fill with combustion gases, the increase in pressure limited gas flow. The gases that initially filled the space cooled through mixing and heat transfer to the structure.



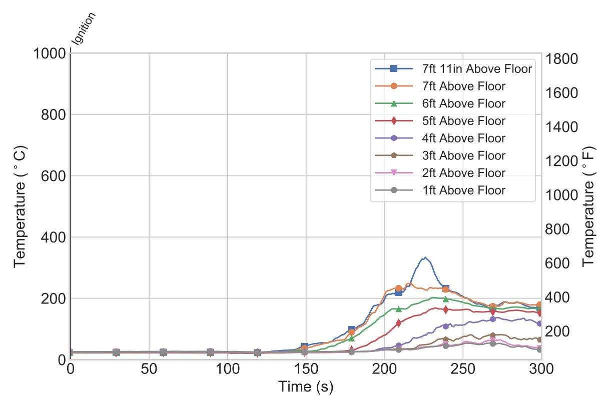
(a) End Hallway Temperature



(b) Mid Hallway Temperature



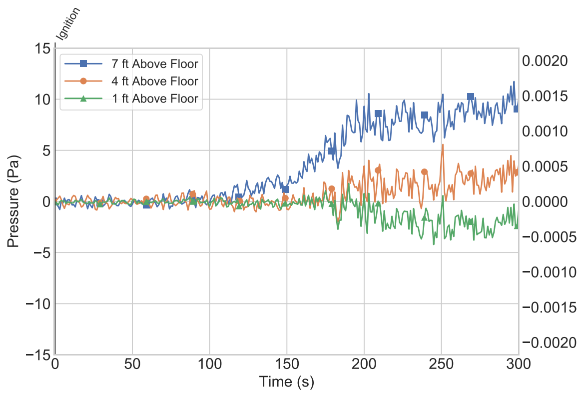
(c) Start Hallway Temperature



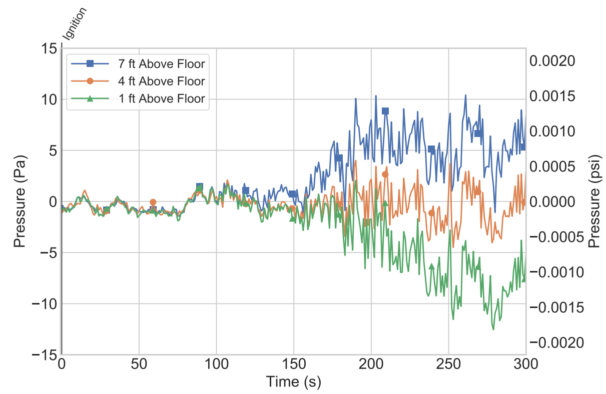
(d) Living Room Entryway Hallway Temperature

Figure 4.4: Temperature time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

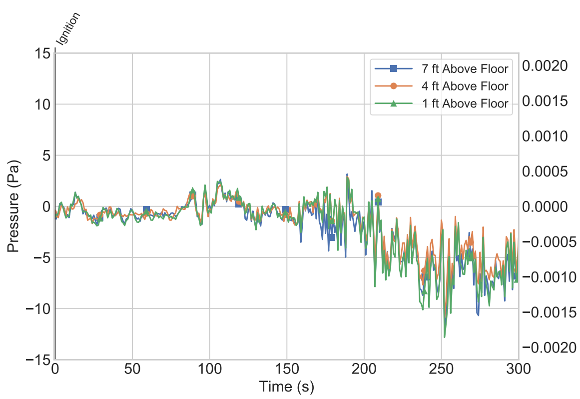
The measured pressures at the 1 ft, 4 ft, and 7 ft elevations (Figure 4.5) provided additional context to the impact of the bedroom fire on conditions within the hallway. At the end hallway location, the accumulation of combustion gases due to a lack of open vents between the fire room and bedroom 3 is shown by the higher pressures at the 4 ft and 7 ft elevations in Figure 4.5a. As the smoke layer descended at the end of the hallway, the pressure first began rise 7 ft above the floor 110 s post ignition. The layer descended to the 4 ft location approximately 150 s post ignition. The pressure at 4 ft and 7 ft remained above ambient level, at approximately 2.5 Pa (0.0004 psi) and 9 Pa (0.001 psi) respectively, until the start of suppression. Pressure at the 1 ft elevation at the end of the hallway dropped below ambient at 192 s, indicating that gases were drawn away from the dead end of the hallway and toward the fire room.



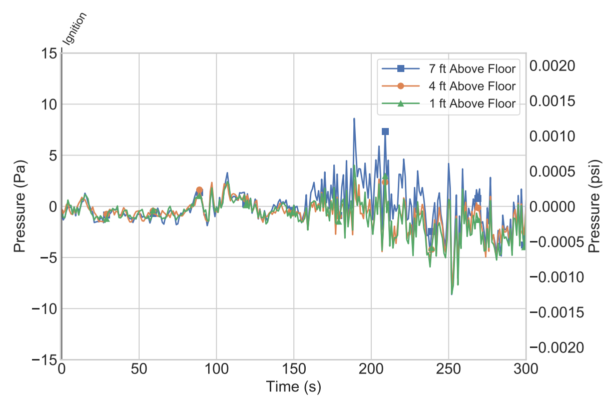
(a) End Hallway Pressure



(b) Mid Hallway Pressure



(c) Start Hallway Pressure



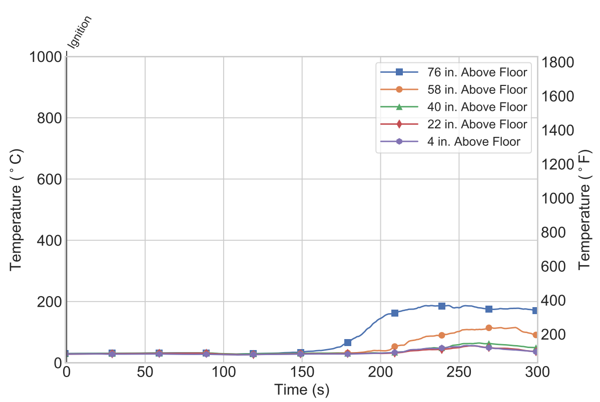
(d) Living Room Pressure

Figure 4.5: Pressure time histories in the hallway and living room due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

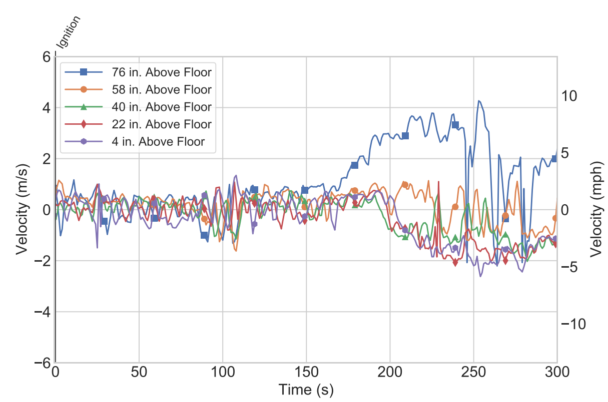
Measured pressures at the mid hallway location were similar to that of the bedroom: above ambient pressure 7 ft above the floor (approximately 7 Pa (0.001 psi)), near ambient 4 ft above the floor, and below ambient 1 ft above the floor (approximately -8 Pa (-0.001 psi)). The pressure at the 7 ft elevation increased 130 s post-ignition, 20 s after the pressure rise at the end of the hallway. This delay was associated with combustion gas accumulation in both the hallway and open bedrooms. The pressure changes 1 ft above the floor were first measured at 150 s, which corresponded to the intake velocities measured at the bedroom 4 door.

At the start hallway location, it is important to recognize that despite the pressure measurements dropping below ambient at approximately 150 s, there is not enough information from Figure 4.5c to determine the direction of gas flow. Here, gases flowed past the pressure probes such that an area of low pressure developed across the measurement probes. The location of the probes where the hallway met the common space, combined with the open front door, limited the development of pressure in contrast to accumulation of expanding high-temperature gases at the end hallway and mid hallway locations. Therefore, to fully understand the movement of gases within the space, the living room pressure (Figure 4.5d) and front doorway temperature and velocity data are also considered (Figure 4.6). The living room pressure showed an increase in pressure at the 7 ft elevation at 160 s, which coincided with the combustion gases that flowed out of bedroom 4 and along the hallway ceiling toward both the end hallway and living room. After the bedroom fire transitioned through flashover (197 s post ignition), the living room pressures began to drop below ambient. The large fluctuations indicate that gases were likely circulating within the open common space.

Temperature and velocity measurements at the front door (Figure 4.6) confirmed the bidirectional flow established at the fire room door persisted through the front door (the exterior vent). The top probe (76 in. above the floor) showed a similar profile to that of the fire room: out flow of 3.5 m/s (7.8 mph) as the bedroom reached flashover until about 260 s. The bottom three probes (40 in. above the floor) recorded inlet velocities of -1.5 m/s (3.4 mph). The probe 58 in. above the floor fluctuated between intake and exhaust of $\pm$ 1 m/s (2.2 mph). The velocity profile was reflected in the temperatures as the 76 in. and 58 in. probes had peak temperatures of 187 °C (367 °F) and 115 °C (239 °F), respectively, compared to the lower three probes, which peaked at approximately 60 °C (140 °F).



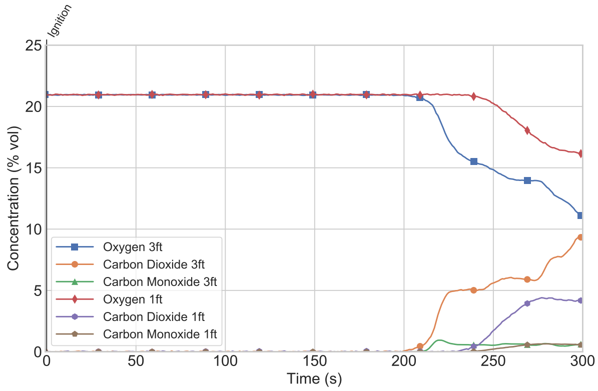
(a) Front Doorway Temperature



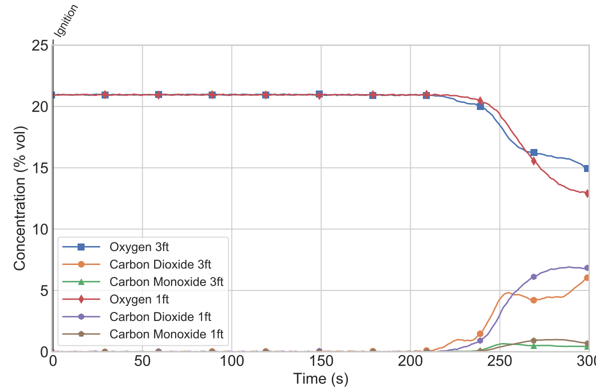
(b) Front Doorway Velocity

Figure 4.6: Front doorway temperature and velocity time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

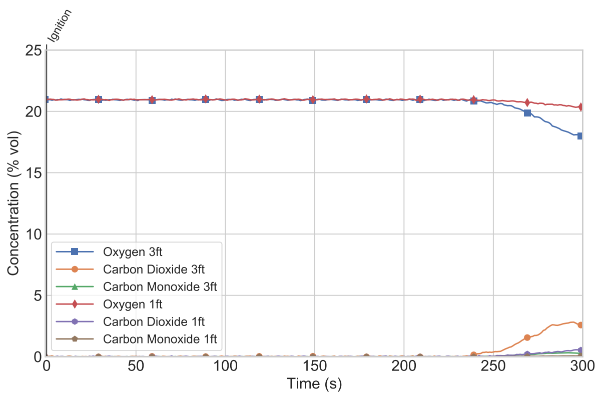
The hallway gas concentrations first began to change (with a drop in oxygen (O_2) and rise in carbon dioxide (CO_2) and carbon monoxide (CO)) at the 3 ft elevations at the end of the hallway 205 s after ignition (Figure 4.7a), at the mid hallway location 216 s after ignition (Figure 4.7b), and at the start of the hallway location 244 s after ignition (Figure 4.7c). As was reflected in the temperature and pressure, the gas concentration data showed the impact of smoke filling due to the lack of vents at the end hallway location compared to the open vent at the front door. The living room entryway hallway location, closest to the open front door, did not see measurable changes in gas concentrations until 254 s after ignition (Figure 4.7d).



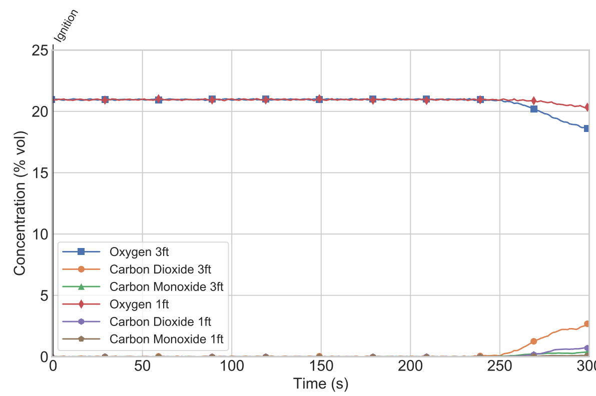
(a) End Hallway Gas Concentration



(b) Mid Hallway Gas Concentration



(c) Start Hallway Gas Concentration



(d) Living Room Entryway Hallway Gas Concentration

Figure 4.7: Gas concentration time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

In general, across the set of bedroom experiments prior to firefighter intervention, gas concentrations within the hallway at the 3 ft elevation had higher concentrations of CO_2 and CO and lower concentrations of O_2 than the corresponding 1 ft elevation. An outlier was Experiment 10, where there were higher gas concentrations measured at the 1 ft elevation at the mid hallway location. In Experiment 10, the nature in which the carpet outside of the bedroom 4 door curled and burned toward the gas probe (the start is visible in Figure 4.3 prior to flashover) impacted the 1 ft measurements differently compared to the other bedroom 4 experiments.

The total heat flux in the hallway floor showed a similar response to the measured temperatures at their respective locations as shown in Figure 4.8. The mid hallway and start hallway locations peaked as the fire room reached flashover with values of 31 kW/m^2 and 20 kW/m^2. As the gas flow out of the fire room decreased, the convective component of heat transfer to the floor began to decrease as shown by the drop in heat flux values at the mid hallway and start hallway locations. At the end hallway where there was minimal gas flow and no flaming combustion, the heat flux peaked at 2.9 kW/m^2 during flashover of bedroom 4, lower than the mid and start hallway locations. The living room location, where the convective heat transfer from the combustion gases that exhausted

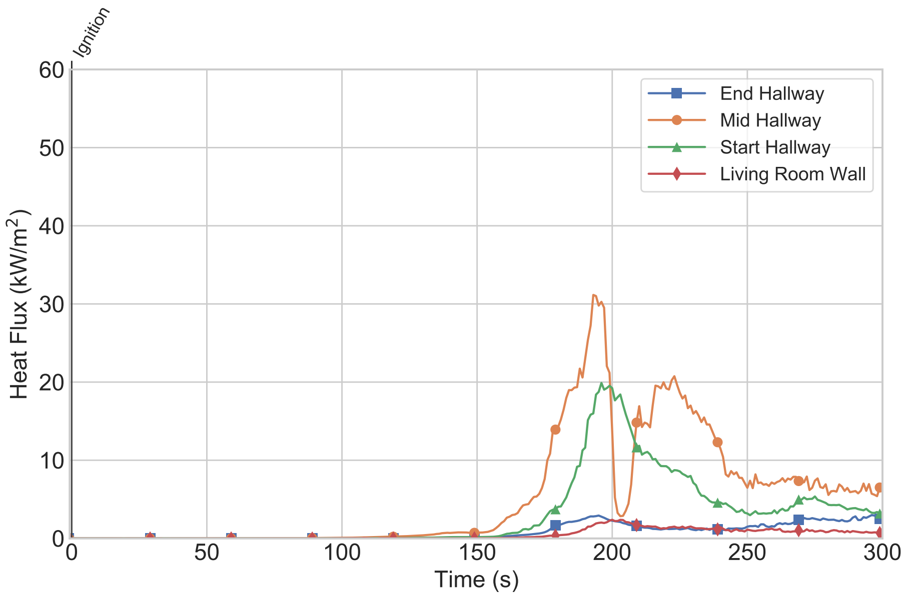


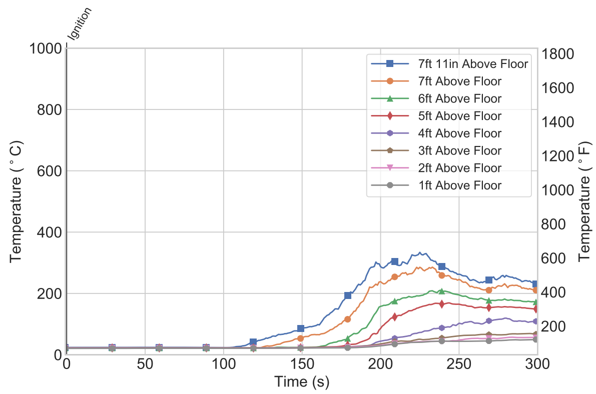
Figure 4.8: Heat flux time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

through the front door was balanced by fresh air intake, peaked at 2.4 kW/m^2 10 s after flashover.

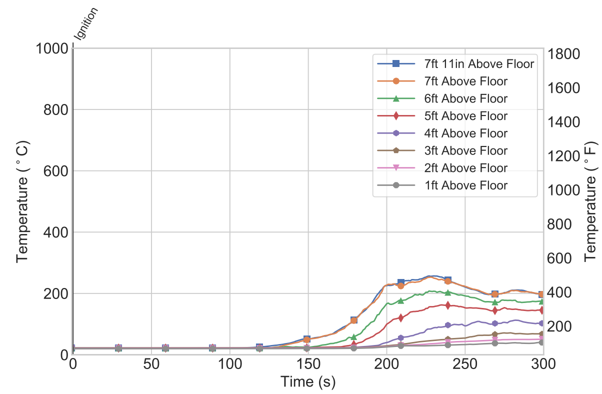
Common Space

The living room and kitchen locations (e.g., the common space) both began to show a temperature rise at the ceiling approximately 110 s after ignition, similar to the hallway temperatures. The peak ceiling temperatures (which occurred 225 s post ignition) were 330 °C (626 °F) and 255 °C (490 °F) for the living room (Figure 4.9a) and kitchen (Figure 4.9b), respectively. Although the timing of the relative temperature increases and magnitude of the peak temperatures varied throughout the bedroom experiments, in general these peaks occurred later and reached lower magnitudes than the hallway as a result of the large volume, distance from the fire room, and closer proximity to the open from door.

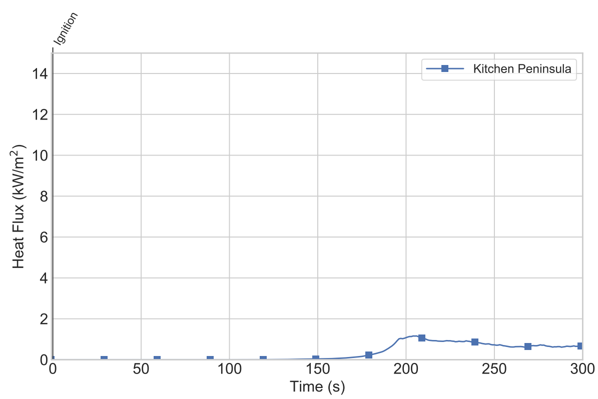
At the 1 ft level between the island and peninsula in the kitchen, the heat flux and gas concentrations had lower magnitude responses compared to the hallway locations located in the exhaust flow between the fire room and front door. The lack of gas flow limited the total heat flux, which reached a peak of 1.2 kW/m^2 in Experiment 10. The open front door limited the accumulation of combustion gases, and the large volume within the common space diluted the accumulated gases through mixing. The kitchen gas concentrations in Experiment 10 did not measure a change until 282 s after ignition.



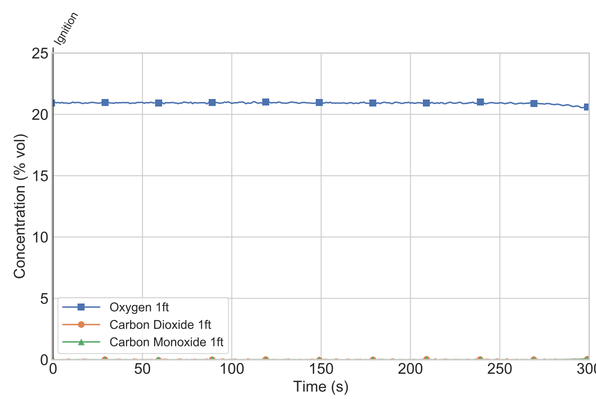
(a) Living Room Temperature



(b) Kitchen Temperature



(c) Kitchen Heat Flux



(d) Kitchen Gas Concentration

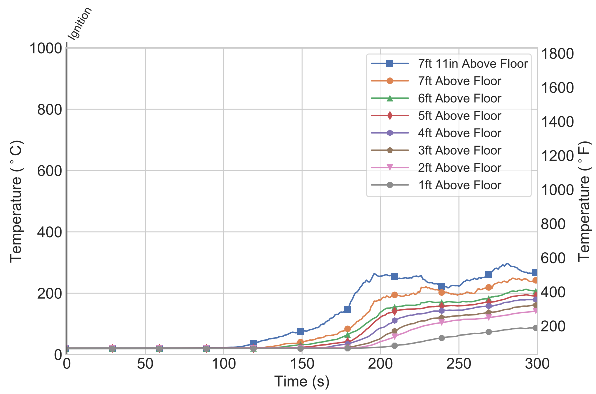
Figure 4.9: Living temperatures and kitchen temperatures, heat flux, and gas concentration time histories in the hallway due to a fire in bedroom 4 from ignition ($t = 0$ s) until firefighter intervention for Experiment 10.

Non-Fire Bedrooms

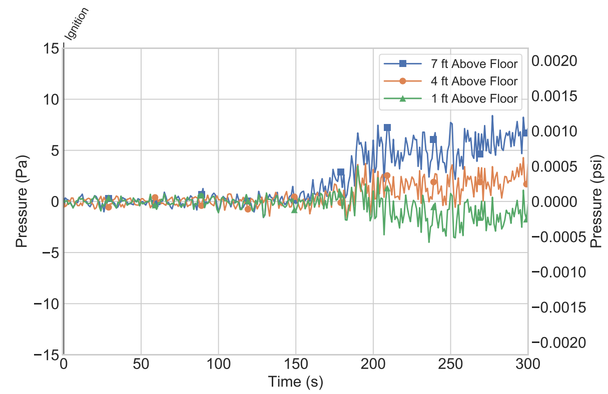
Across the series of bedroom ignition experiments, the initial state of bedroom doors varied based on the specific objective of each experiment. The initial door position impacted the transport of gases to that space, but did not directly impact the fire growth in bedroom 4. The following examination of changes to conditions within the respective bedrooms is based on the initial door positions of Experiment 10. It is therefore important to note that while proximity to the fire room impacted the magnitude of measured quantities across the set of experiments, the amount of ventilation to the bedroom via an open versus closed door was the largest factor for differences.

Open Bedrooms

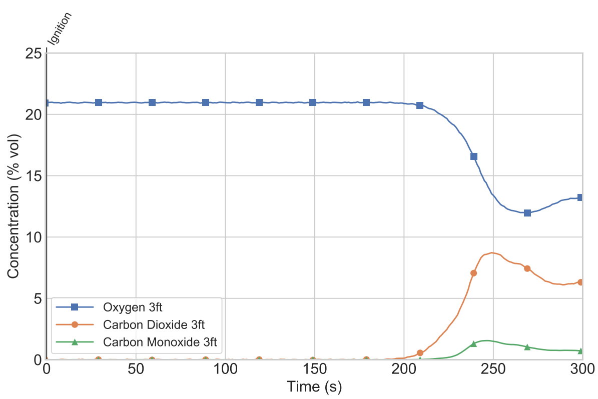
In Experiment 10, the doors to bedroom 2 and bedroom 3 were open prior to ignition. The open door allowed for the transport of combustion from the hallway into the respective bedroom once the smoke layer descended below the door header. In bedroom 2, temperatures first began to rise at the ceiling at 92 s post ignition (Figure 4.10a), shortly after the end hallway temperatures increased. The sharpest rise in temperature occurred in the 30 s prior to flashover in bedroom 4 when temperatures reached 260 °C (500 °F) at the ceiling and 34 °C (93 °F) 2 ft above the floor. Similar to the end hallway location, 1 ft temperatures in bedroom 2 remained lower until the smoke layer descended to the floor. At the time of intervention, bedroom 2 temperatures ranged from 270 °C (518 °F) at the ceiling to 87 °C (189 °F) 1 ft above the floor. The measured pressure in bedroom 2 was also similar to the end hallway location; the lack of an open vent led to the accumulation of higher temperature combustion gases, which led to an increase in pressure at the 7 ft and 4 ft elevations to approximately 6 Pa (0.0009 psi) and 2 Pa (0.0003 psi), respectively (Figure 4.10b). Pressure at the 1 ft elevation was approximately -1 Pa (-0.0001 psi), an indication that gases at that elevation flowed out of bedroom 2 toward the mid hallway location and fire room, which were at lower pressures.



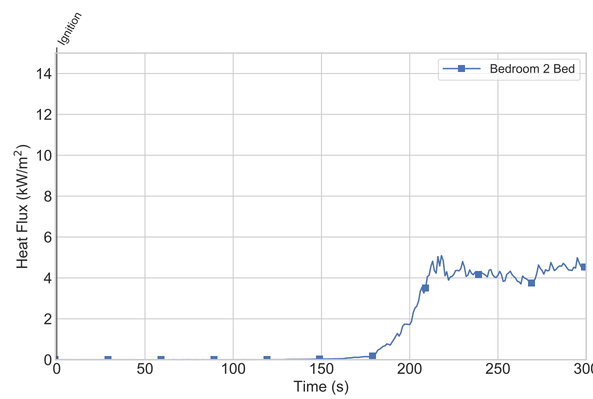
(a) Bedroom 2 Temperature



(b) Bedroom 2 Pressure



(c) Bedroom 2 Gas Concentration

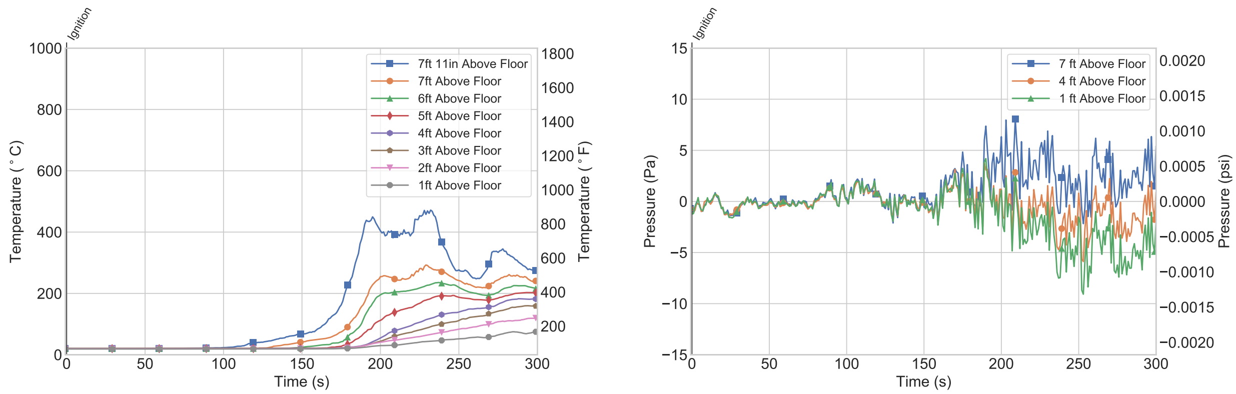


(d) Bedroom 2 Heat Flux

Figure 4.10: Bedroom 2 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

The inflow of combustion gases into bedroom 2 also led to gas concentrations at the bed level (3 ft above the floor) to show measurable change 197 s post-ignition, as the bedroom 4 fire transitioned through flashover. The accumulation of gases in the bedroom led to gas concentrations to peak approximately 250 s after ignition. Additionally, the flow of gases into the room led to a rise in total heat flux at the bed level (3 ft above the floor), which started at 179 s and reached an approximately steady value of 4.5 kW/m^2 by 210 s post ignition.

Similar to bedroom 2, bedroom 3 temperatures first increased at the ceiling 92 s after ignition. Except for a higher peak at the ceiling, the bedroom 3 temperatures showed a similar response to bedroom 2 because neither room had a lower pressure exhaust vent (Figure 4.11a). Combustion gases flowed out of the fire room into the hallway and began to accumulate in bedroom 3 once the smoke layer descended below the door header. Temperatures were lower in the bedroom compared to the hallway because gases that entered the space mixed with the air originally in the room and cooled through mixing. The closer proximity to the fire room compared to bedroom 2 was more noticeable in the pressure measurements. By 230 s post ignition, the 7 ft elevation measured approximately 4 Pa (0.0006 psi) while the 1 ft elevation measured approximately -5 Pa (-0.0007 psi) (Figure 4.11b). The 4 ft elevation fluctuated around 0 Pa. The low pressures generated in the fire room (-10 Pa (-0.001 psi) at 230 s) led to entrainment of gases into the fire room, particularly from gases from bedroom 3 across the hallway. This entrainment led to the lower pressures compared to bedroom 2.

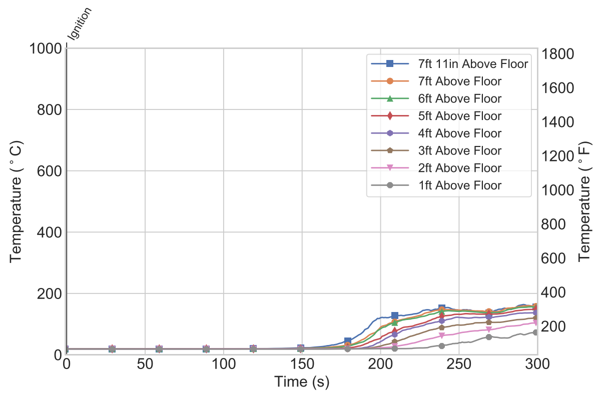


(a) Bedroom 3 Temperature

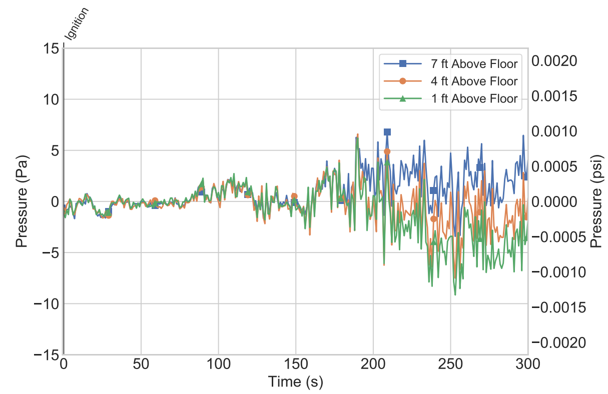
(b) Bedroom 3 Pressure

Figure 4.11: Bedroom 3 temperature and pressure time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

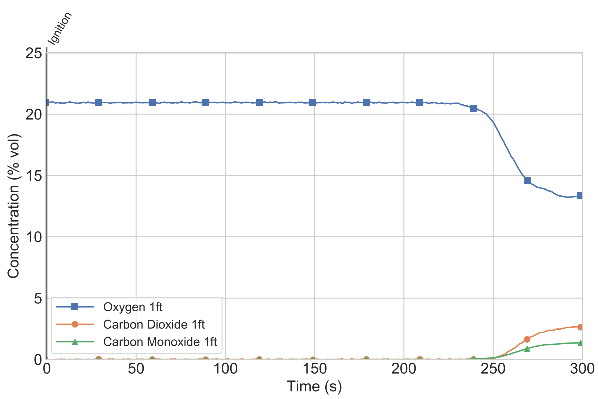
The door to the bathroom within bedroom 3 was open prior to ignition. This setup represented a room within a room configuration and was open for all experiments. Bathroom temperatures and pressures were similar to those of the bedroom, except the magnitudes were less due to the distance from the source and additional volume for mixing with ambient gases. Temperatures in the bathroom measured 160 °C (320 °F) at the ceiling, which was approximately the same magnitude at the 3 ft elevation in the bedroom (Figure 4.12a). Additionally, the 7 ft pressure had an average of approximately 3 Pa (0.0004 psi) and the 1 ft pressure had an average of -4 Pa (-0.006 psi) (Figure 4.12b). In the bathroom, the gas concentration and total heat flux measurements were made at the 1 ft level. The first measured CO and CO_2 concentrations occurred 230 s after ignition and O_2 steadily declined due to the accumulation of combustion gases in the bathroom, as shown in Figure 4.12c. The total heat flux, shown in Figure 4.12d, peaked at 1.6 kW/m^2 but first measured an increase at 185 s due to the combustion gases that began to fill the space with noticeable temperature rises above 5 ft in elevation.



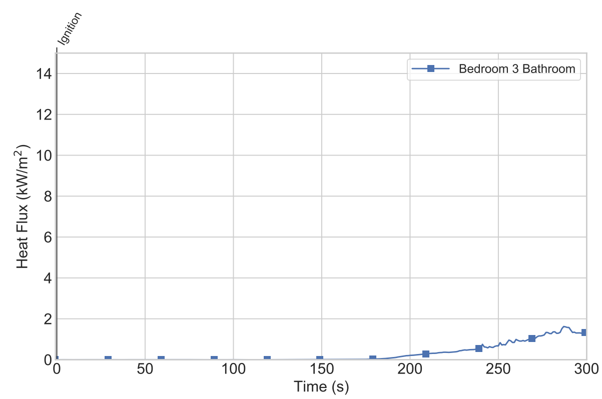
(a) Bathroom 3 Temperature



(b) Bathroom 3 Pressure



(c) Bathroom 3 Gas Concentration

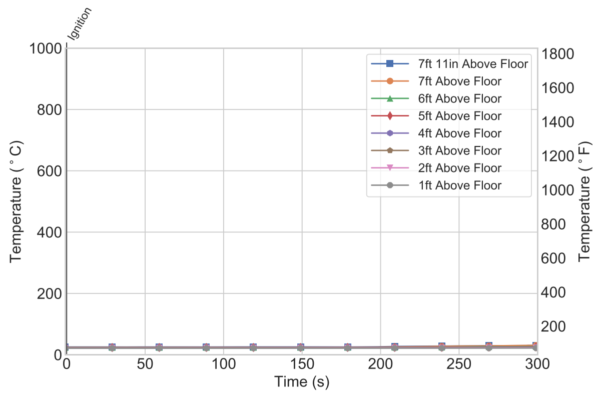


(d) Bathroom 3 Heat Flux

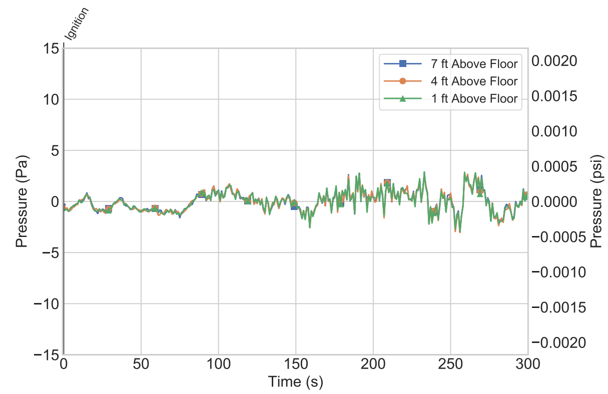
Figure 4.12: Bathroom 3 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

Closed Bedroom

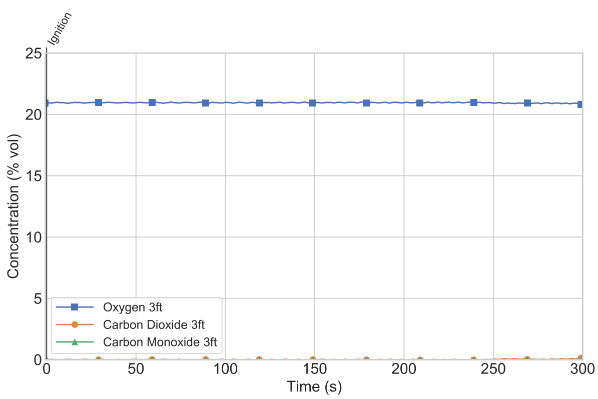
In Experiment 10, only the bedroom 1 door was closed prior to ignition. Additionally, the door in the bathroom attached to bedroom 1 was closed. Figure 4.13 shows the temperature, pressure, gas concentration, and heat flux time histories from ignition until firefighter intervention. The closed door to bedroom 1 limited the transport of gases to the room. The pathways for transports were through small gaps around the door and through the HVAC system. The temperature (Figure 4.13a) and pressure (Figure 4.13b) show there was a negligible influx of combustion gases relative to the open spaces within the structure. The temperatures at 7 ft and above peaked at 30 °C (86 °F) just prior to intervention. No other temperatures in the bedroom exceeded 27 °C (81 °F). At all three elevations, the bedroom 1 pressures remained the same and fluctuated around ambient compared to the split in pressure (above ambient high and below ambient low) measured in the open bedrooms. This also indicated that there was limited flow of gases into the space. As a result, there were no measurable changes to the gas concentrations (Figure 4.13c) and total heat flux (Figure 4.13d).



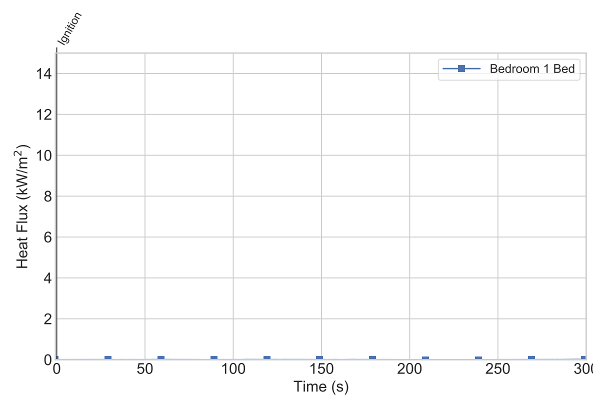
(a) Bedroom 1 Temperature



(b) Bedroom 1 Pressure



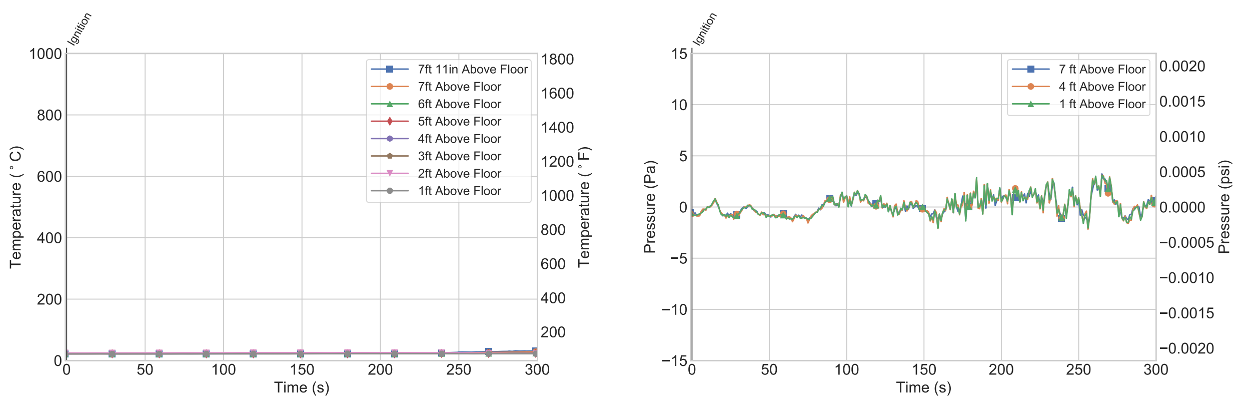
(c) Bedroom 1 Gas Concentration



(d) Bedroom 1 Heat Flux

Figure 4.13: Bedroom 1 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

The bathroom connected to bedroom 1 had a similar temperature and pressure response as the bedroom, as shown in Figure 4.14. In this space, with two closed doors between the bathroom and exhaust gases from the fire room, the majority of transport occurred through the HVAC system. Temperatures at the ceiling peaked at 32 °C (90 °F) and remained below 25 °C (77 °F) below the 6 ft elevation. The bathroom pressures were similar to the bedroom, with minimal measured changes.



(a) Bathroom 1 Temperature

(b) Bathroom 1 Pressure

Figure 4.14: Bedroom 1 temperatures and pressure time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 10.

5 Experimental Results: Post Intervention

For these experiments, interior operations of search crews were simulated by controlling the opening and closing of interior doors by exterior crews and a series of purpose built cables. Window ventilation occurred via one of three actions: take (ventilate with a hook), open (slide the bottom sashes up), or remove (remove entire window from structure). See Appendix A for further description on the window ventilation tactics. Suppression was performed by crews from both interior and exterior positions that was driven by the specific experimental scenario. The *suppression* event marker is an indicator used to identify the time at which the suppression crew was deployed. The start of water flow was at the discretion of the suppression crew and depending on the experimental scenario can lag the event marker by several seconds.

5.1 Experiment 1

The Experiment 1 search tactics were designed to evaluate window initiated operations conducted before interior suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide bedroom 4 window and the bedroom 4 door were removed. The front door to the structure and doors to bedroom 2, bedroom 3, and bathroom 3 were opened. The doors to bedroom 1 and bathroom 1 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 fire flashover, the crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. The crews entered bedrooms 2 and 3 and proceeded toward the doors to the hallway. The crew in bedroom 3 closed the door. This action isolated bedroom 3 from the flow of combustion gases produced by the bedroom 4 fire. The crew in bedroom 2 were unable to close the door and continued their search beyond the room of entry by entering the hallway. Simultaneously, the crew in bedroom 3 removed the remainder of the double-wide window as the crew in the hallway opened the bedroom 1 door. This action allowed combustion gases to flow from the fire room into bedroom 1. The crew in bedroom 1 closed the door, which isolated the bedroom from the flow of combustion gases produced by the bedroom 4 fire. Once isolated, the crew proceeded to remove the bedroom 1 window. At this point, the search tactic comparison was complete and interior suppression began. 116 gallons of water were flowed during suppression. Upon the suppression crew announcement of ‘fire under control,’ hydraulic ventilation occurred out of the failed double-wide bedroom 4 window. The total amount of water flowed during suppression and hydraulic ventilation was 227 gallons. Table 5.1 provides the timing of each event relative to ignition and to the first intervention, which in this experiment was ventilation of the bedroom 2 and bedroom 3 windows.

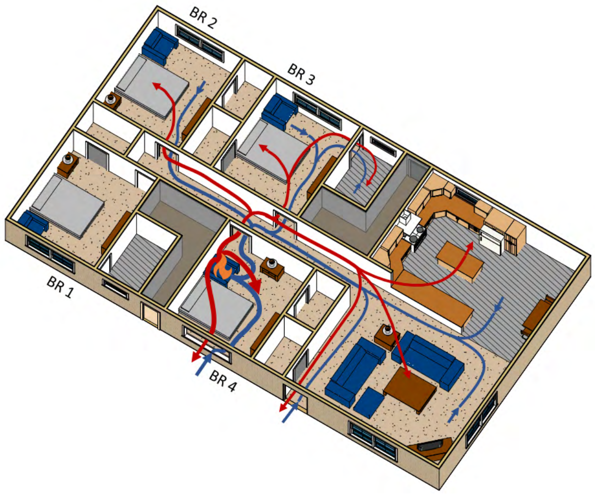
Figures 5.1 through 5.3 show the changes in gas flow before and after each intervention over the course of Experiment 1. Prior to intervention (Figure 5.1a), the bedroom 4 fire reached a post-

Table 5.1: Experiment 1 Event Times

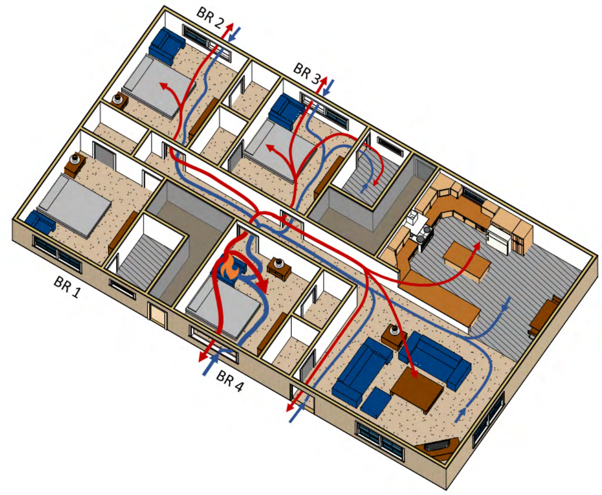
Event	Elapsed Time From Ignition (mm:ss)	(s)	From Intervention (mm:ss)	(s)
Ignition	00:00	0	—	—
Take BR2 & BR3 Windows	05:10	310	00:00	0
Close BR3 Door	05:55	355	00:45	45
Remove BR3 Window, Open BR1 Door	06:07	367	00:57	57
Close BR1 Door	06:19	379	01:09	69
Remove BR1 Window	06:35	395	01:25	85
Suppression	06:50	410	01:40	100
Hydraulic Ventilation	09:08	548	03:58	238

flashover state. Air entrained and combustion gases exhausted through side A window and front door. Bidirectional flow had established between the fire room and bedroom 2, bedroom 3, and bathroom 3 through their respective open doorways.

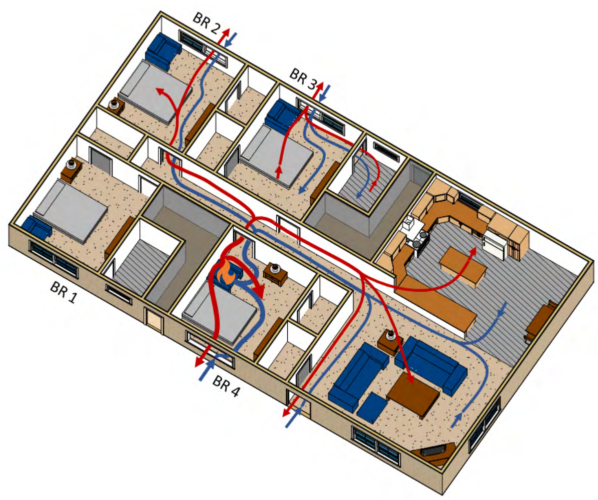
Figure 5.1b shows the impact on gas flows due to the ventilation of the bedrooms 2 and 3 windows. Ventilation of half the double-wide windows created exterior vents in bedrooms 2 and 3, which established two new flow paths between the fire room and the exterior of the structure. Bidirectional flow established through these vents. Closure of the bedroom 3 door isolated the bedroom from gas exchange with the higher-temperature, higher-pressure hallway, as shown in Figure 5.1c. This action further limited accumulation of combustion gases in bedroom 3 and bathroom 3. However, prior accumulation of combustion gases continued to drive bidirectional flow through the bedroom 3 window. Higher-temperature gases were exhausted out the top of the bedroom window and were replaced by cooler air.



(a) Flows Prior to Intervention



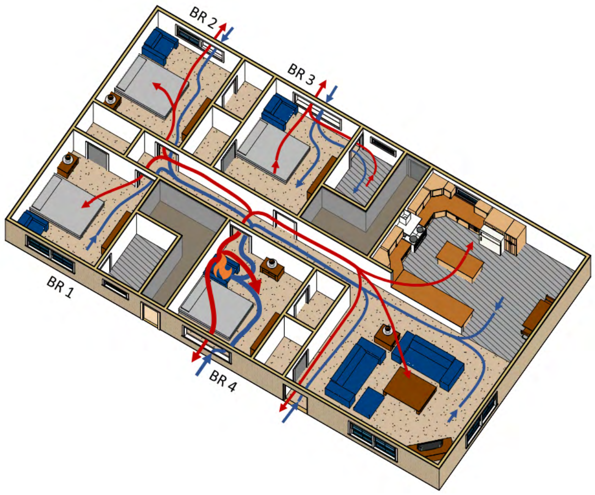
(b) Take BR2 & BR3 Windows



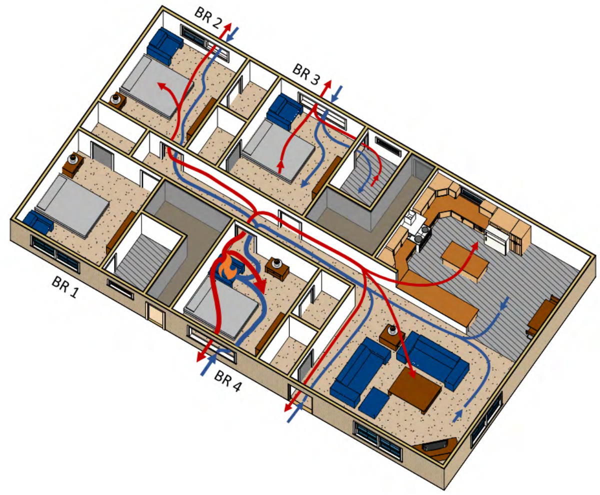
(c) Close BR3 Door

Figure 5.1: Changes in gas flows in the structure following fire department interventions in Experiment 1.

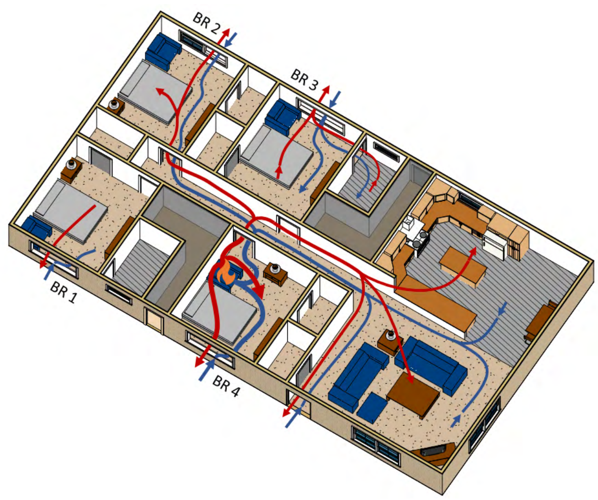
Simultaneously, the remainder of the bedroom 3 window was removed and the bedroom 1 door was opened, as shown in Figure 5.2a. A new flow path established between the fire room and bedroom 1. Air from bedroom 1 flowed toward the fire room and combustion gases from the fire room flowed toward bedroom 1. This bidirectional flow was momentary, as the bedroom door was closed approximately 12 s later. Closure of the bedroom 1 door isolated the bedroom from gas exchange with the hallway, as shown in Figure 5.2b. Removal of the bedroom 1 window created an exterior vent, which established a new flow path between bedroom 1 and the exterior of the structure. Higher-temperature, higher-pressure gases were exhausted from the bedroom through the vent and were replaced by lower-temperature, lower-pressure air as shown in Figure 5.2c.



(a) Remove BR3 Window, Open BR1 Door



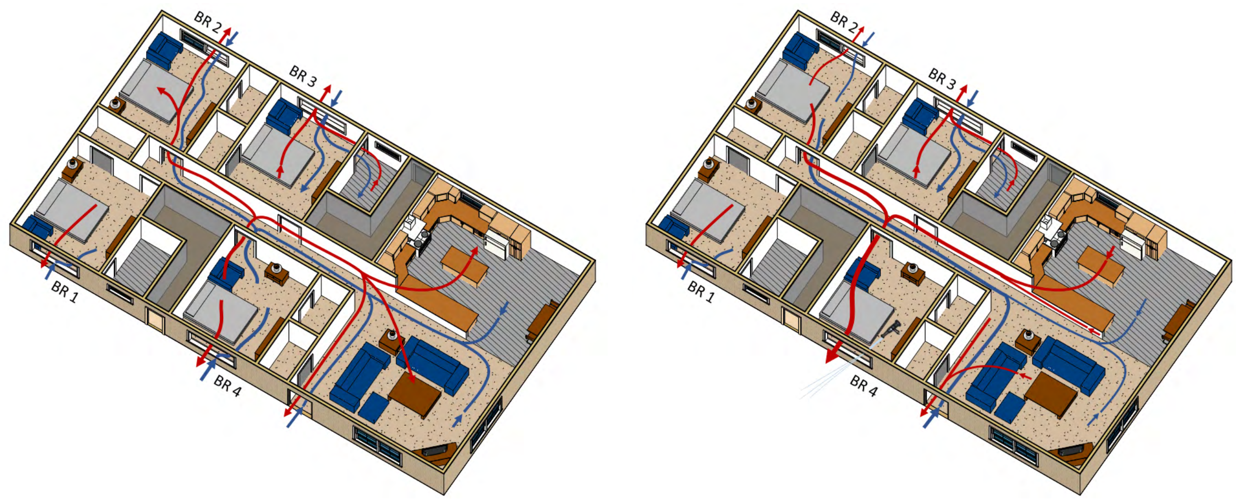
(b) Close BR1 Door



(c) Remove BR1 Window

Figure 5.2: Changes in gas flows in the structure following fire department interventions in Experiment 1.

Interior suppression was conducted with a smooth bore nozzle with a 7/8 in. tip, set to flow 160 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline. Although suppression reduced the production of combustion gases, gas flow throughout the structure continued (Figure 5.3a). Hydraulic ventilation occurred out of the failed, double-wide bedroom 4 window with the tip on, at half bale, in an O-pattern (Figure 5.3b). Flow through the window became unidirectional exhaust, which caused air to entrain through open exterior vents in bedroom 2 and the common space. Spaces isolated by closed interior doors (bedroom 1 and bedroom 3) were minimally impacted by hydraulic ventilation.



(a) Suppression

(b) Hydraulic Ventilation

Figure 5.3: Changes in gas flows in the structure following fire department interventions in Experiment 1.

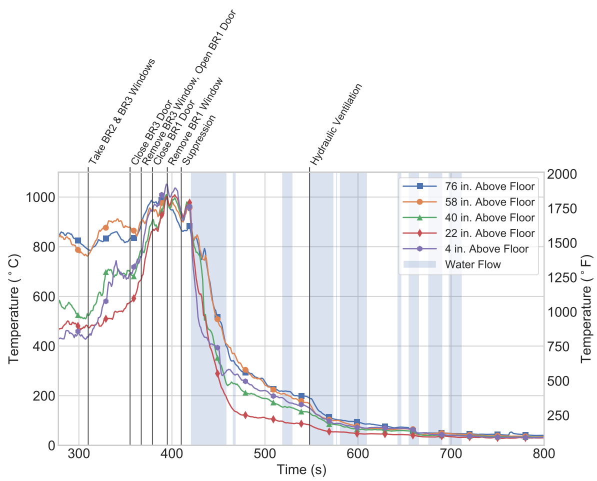
5.1.1 Bedroom 4

Approximately 225 s post-ignition, prior to flashover, falling debris damaged the thermocouple array in bedroom 4. Data from this thermocouple after this time stamp are not representative of temperatures throughout the space, rather flashover was determined from visual cues captured with standard and IR cameras. Flashover of the fire room occurred approximately 210–220 s post-ignition, after the side A windows began to fail and flames were visible.

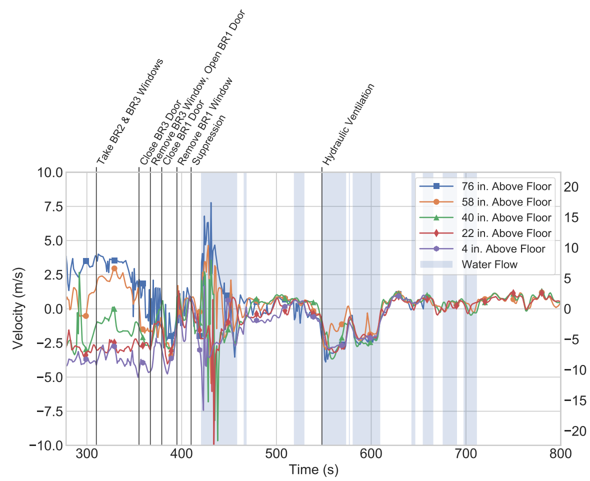
At the time of intervention, conditions within bedroom 4 were consistent with a steady post-flashover state, as shown by Figures 5.4a and 5.4b. Doorway temperatures 76 in. to 58 in. above the floor exceeded 800 °C (1472 °F). Temperatures below 40 in. above the floor were less than 600 °C (1112 °F). The temperature gap is reflected in the velocity data, which indicated bidirectional flow through the doorway. The top two probes measured outflow (into the hallway) and velocities ranged between 2 m/s and 4 m/s (5 mph to 7.5 mph). The bottom three probes measured inflow (into the bedroom), and velocities ranged between -2 m/s to -4 m/s (-5 mph to -7.5 mph). As additional vents were made to the structure, the available oxygen for combustion in the hallway increased. As a result, flaming combustion occurred at the bedroom 4 doorway and in the hallway. All temperatures at the doorway exceeded 1000 °C (1832 °F) 394 s post-ignition and velocities correspondingly fluctuated around $\pm$ 1 m/s ($\pm$ 2 mph).

Suppression of the bedroom 4 fire reduced doorway temperatures below 335 °C (635 °F). Note: Thermocouples which are part of the bidirectional probe array typically take longer to cool down as the attached stainless steel velocity probe transfers heat to the thermocouple despite a drop in the local gas temperature. Hydraulic ventilation caused unidirectional inflow through the doorway into bedroom 4 with velocities between -2 m/s to -4 m/s (-5 mph to -7.5 mph), which decreased temperatures below 100 °C (212 °F).

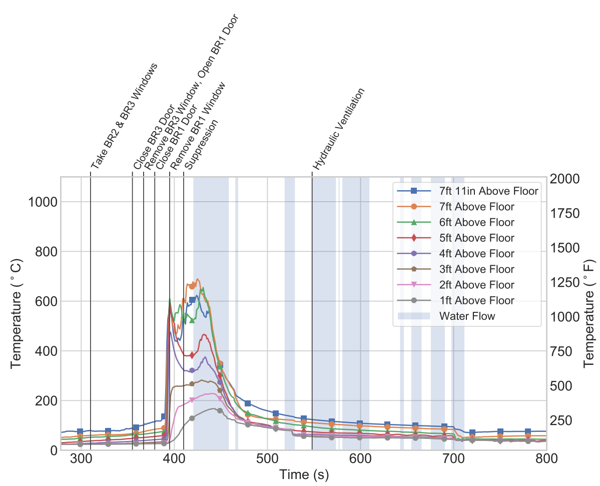
Bedroom 4 closet temperatures at the time of intervention were below 80 °C (176 °F) and steadily increased to 144 °C (291 °F) 390 s post-ignition, independently of changes in ventilation (Figure 5.4c). Over the next 5 s, closet temperatures rapidly increased to 610 °C (1130 °F) at the ceiling and 475 °C (887 °F) 4 ft above the floor. This was an indication that the top of the closet door burned through, which allowed combustion gases to accumulate in the closet. Localized burning occurred as the remaining air behind the door reacted with the high-temperature fuel gases. Approximately 10 s after the onset of suppression, as the crew made entry to bedroom, closet temperatures dropped. Hydraulic ventilation through the fire room window caused closet temperatures to decrease below 100 °C (212 °F).



(a) Bedroom 4 Doorway Temperature



(b) Bedroom 4 Doorway Velocity



(c) Bedroom 4 Closet Temperature

Figure 5.4: Temperature and velocity time histories in the doorway and closet of bedroom 4 for the period following fire department intervention in Experiment 1.

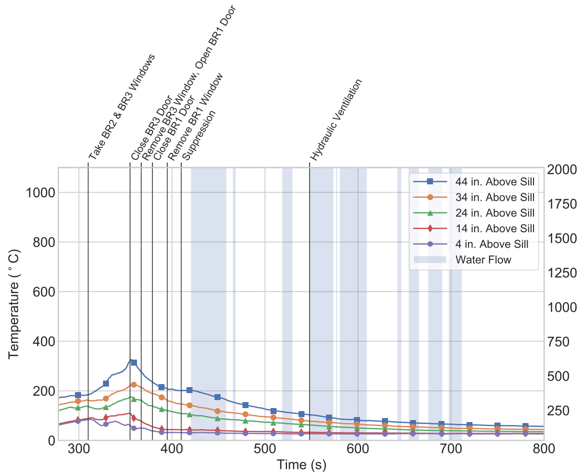
5.1.2 Bedroom 3

Figure 5.5 shows the bedroom 3 time histories of temperature, velocity, heat flux, and gas concentrations during Experiment 1. The bedroom 3 door was opened prior to ignition, which allowed combustion gases to flow into the bedroom. The smoke layer had descended to the floor and visibility was lost, approximately 278 s post-ignition.

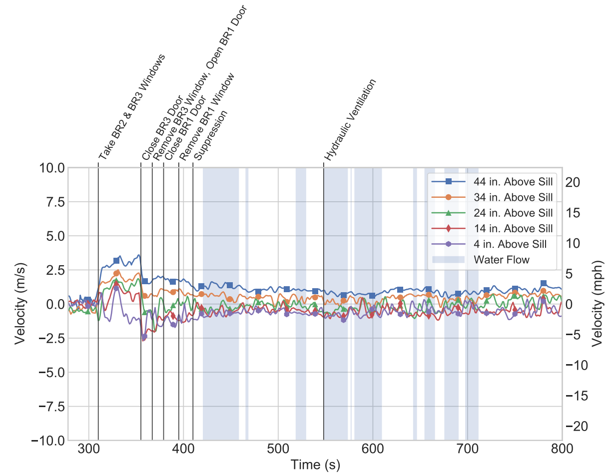
At the time of initial fire department intervention, window temperatures ranged from 183 °C to 85 °C (361 °F to 185 °F) from top to bottom through the window. Figure 5.5a shows that immediately following ventilation of the bedroom 3 window, temperatures at the top 4 measurement locations recorded a temperature increase and the bottom measurement location recorded a temperature decrease. Figure 5.5b shows that bidirectional flow established in the window. Higher-temperature gases exhausted through the upper portion of the window and lower-temperature air entrained through the lower of the window.

Prior to bedroom isolation, window temperatures peaked to 325 °C (617 °F) at the top of the window and to 65 °C (149 °F) at the bottom of the window. Correspondingly, the top four velocity probes recorded exhaust flows between 3.6 m/s and 0.8 m/s (8.0 mph and 1.8 mph). The bottom velocity probe (4 in. above the sill) recorded an inflow of -1.0 m/s (-2.2 mph). Closure of the bedroom 3 door isolated the room from the flow of combustion gases, which led to a steady decrease in window temperatures. The door closure also changed the profile of gas exchange at the window. The top two probes continued to measure outflow, but the bottom three probes measured inflow. The respective magnitude (inflow and outflow) of the velocities decreased with time. As temperatures cooled, gases contracted, and pressure decreased, which was the primary driver for gas exchange between the bedroom and the exterior.

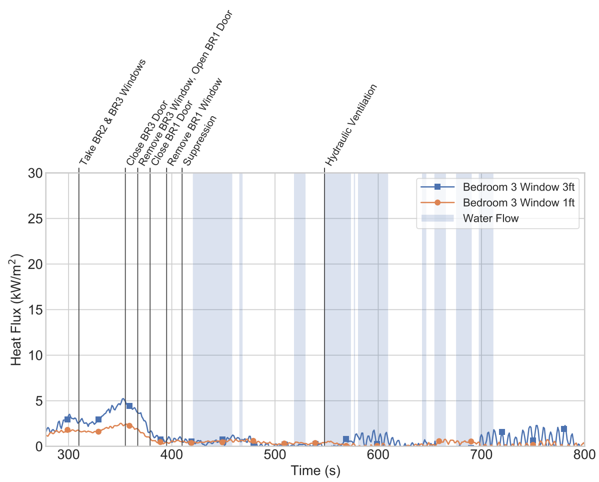
The bedroom 3 door remained closed, which minimized the effect of suppression and hydraulic ventilation. Window temperatures and velocities were not noticeably affected.



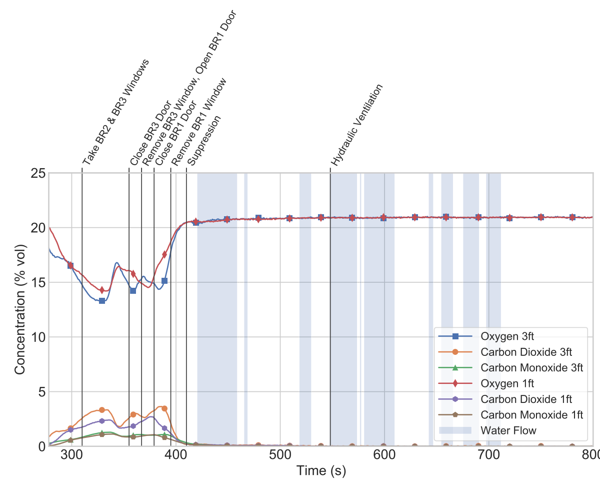
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.5: Post-intervention window temperature and velocity, heat flux, and gas concentration in bedroom 3 during Experiment 1.

Heat fluxes at the window showed an overall increase between the time of window ventilation and room isolation (Figure 5.5c), though there was a temporary decrease immediately following the window ventilation. Prior to intervention, the 3 ft heat flux had peaked at 3.5 kW/m^2 and dropped to 2.2 kW/m^2 due the exhaust of of accumulated combustion gases in the space and corresponding inflow of air from the exterior. However, opening the window increased gas flow from the fire room through the bedroom vent, and the 3 ft heat flux increased to 5.2 kW/m^2 prior to the closure of the bedroom 3 door. There was less impact to the 1 ft heat flux measurement because it was lower in elevation and consequently further from the flow of gases through the window. Prior window ventilation, the 1 ft heat flux was 1.8 kW/m^2, dropped to 1.5 kW/m^2 immediately following ventilation before ultimately peaking at 2.5 kW/m^2 prior to the closure of the bedroom 3 door. The closed door reduced the flow of higher-temperature gases through the bedroom and the heat flux decreased at both elevations and reached negligible values.

Gas concentrations at the time of intervention below the bedroom 3 window were characterized by elevated concentrations of CO and CO_2 and low concentrations of O_2, consistent with a smoke layer that had descended below the 1 ft measurement location. The gas concentration time histories at the 1 ft and 3 ft measurement locations below the bedroom 3 window are shown in Figure 5.5d. Following ventilation of the bedroom 3 window, CO and CO_2 concentrations increased and O_2 concentrations decreased. Entrainment through the lower portion of the window lifted the smoke layer near the window 332 s post-ignition, which caused gas concentrations to recover. A temporary change in this trend occurred shortly after wind caused a period of unidirectional exhaust through the window. After the room was isolated from higher-pressure hallway gases, gas concentrations recovered to near pre-ignition levels.

The temperatures measured in the center of bedroom 3, shown in Figure 5.6, ranged from 290 °C to 53 °C (554 °F to 127 °F) at the time of intervention. Bedroom 3 temperatures responded to interventions in a consistent manner to the conditions at the bedroom 3 window. Immediately following first intervention, combustion gases flowed from the fire room into bedroom 3 toward the exterior vent. Temperatures throughout the bedroom increased. However, the magnitude of increase for temperatures nearest the floor (4 ft and below) was less than temperatures nearest the ceiling, as air entrained through the ventilated window cooled gases through mixing. Temperatures at the ceiling exceeded 555 °C (1031 °F).

Isolation of the bedroom by closing the door to the hallway decreased the flow of combustion gases into the bedroom. As a result, temperatures at all elevations decreased. Approximately 35 s after isolating the room, flames were observed within bedroom 3 at the top of the door. Temperatures at the ceiling of bedroom 3 increased approximately 400 s post-ignition, as these flames rapidly grew. Suppression extinguished flaming combustion and temperatures at the ceiling immediately decreased. Approximately 60 s post-suppression, visibility fully returned to the bedroom 3 camera. Temperatures within the space decreased below 100 °C (212 °F) after hydraulic ventilation.

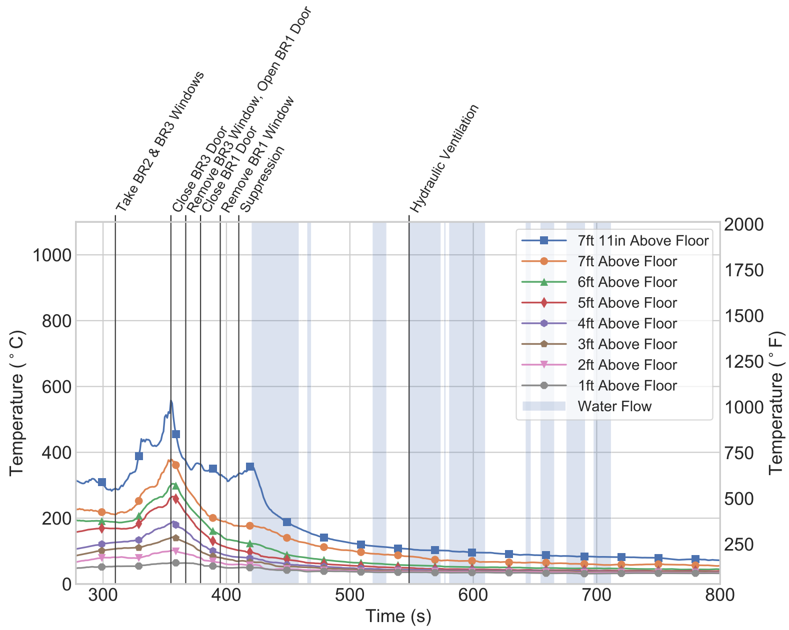
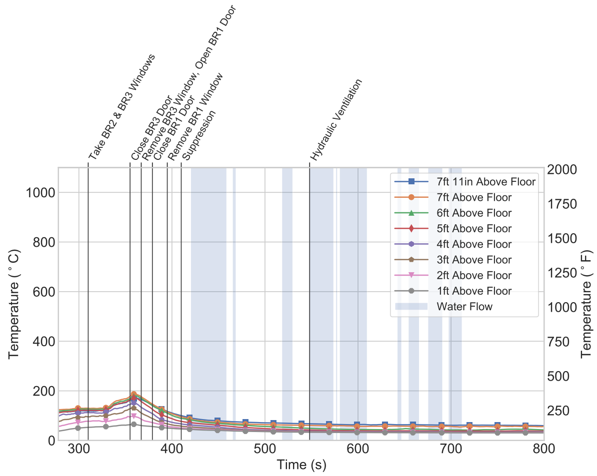


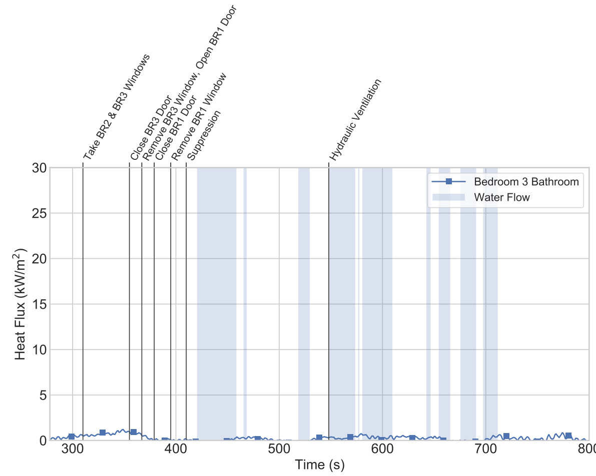
Figure 5.6: Post-intervention temperature in bedroom 3 during Experiment 1.

Bathroom 3 visibility was lost approximately 15–30 s before bedroom 3 visibility. Temperature and heat flux followed similar trends to those in bedroom 3, although at lower magnitudes (Figures 5.7a and 5.7a). Ventilation of the bedroom 3 window caused bathroom temperature and heat flux to increase as combustion gases flowed toward the exterior vent. Temperatures peaked to 190 °C (374 °F) at the ceiling and 65 °C (149 °F) 1 ft above the floor. Heat flux peaked to 1.2 kW/m^2 1 ft above the floor. Following isolation, the temperatures and heat flux steadily decreased.

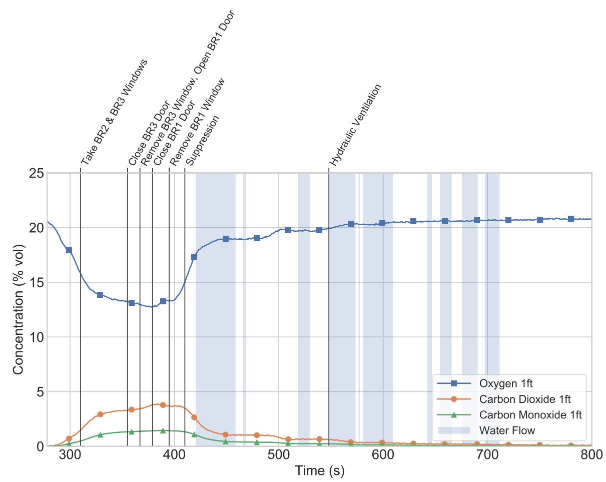
Bathroom 3 gas concentrations had a maximum change from ambient after the removal of bedroom 3 window to 12.9% O_2, 3.8% CO_2, and 1.4% CO as combustion gases cooled and dropped in elevation. Bathroom 3 concentrations did not recover to pre-ignition levels until 900 s post ignition (352 s after hydraulic ventilation). The higher gas concentrations, later peak, and longer recovery time show the impact of proximity to vent. Although in a connected space (i.e., open bathroom 3 door), the bathroom 3 location was adjacent to but not part of the flow path between the bedroom and the exterior, which limited the gas exchange within the bathroom.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



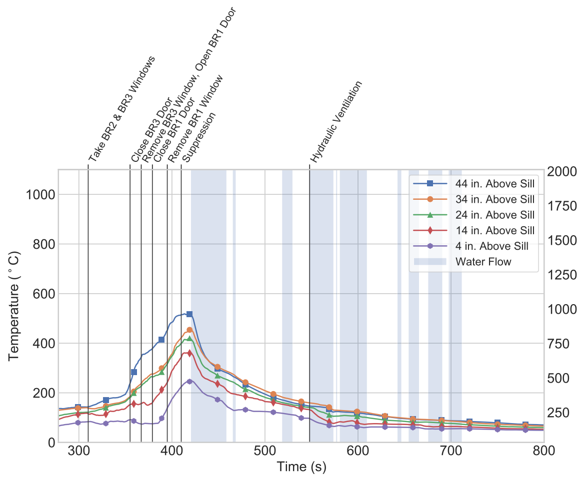
(c) Bathroom 3 Gas Concentration

Figure 5.7: Post-intervention temperature, heat flux, and gas concentration in bathroom 3 during Experiment 1.

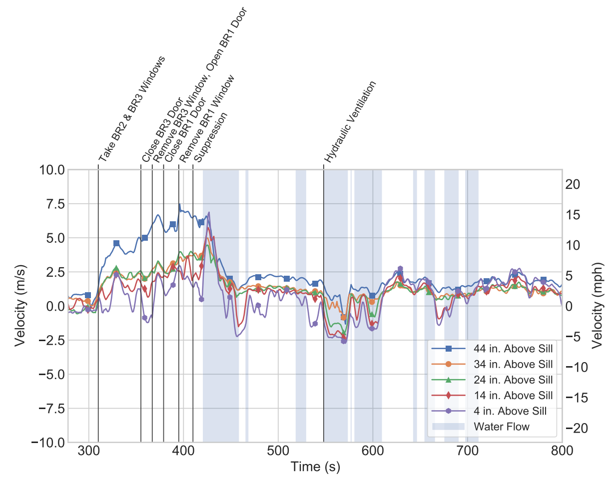
5.1.3 Bedroom 2

The smoke layer in bedroom 2 descended to the bed approximately 224 s post-ignition, which caused an increase in heat flux and a change in gas concentrations. Prior to intervention, the smoke layer had descended to the floor and visibility was lost.

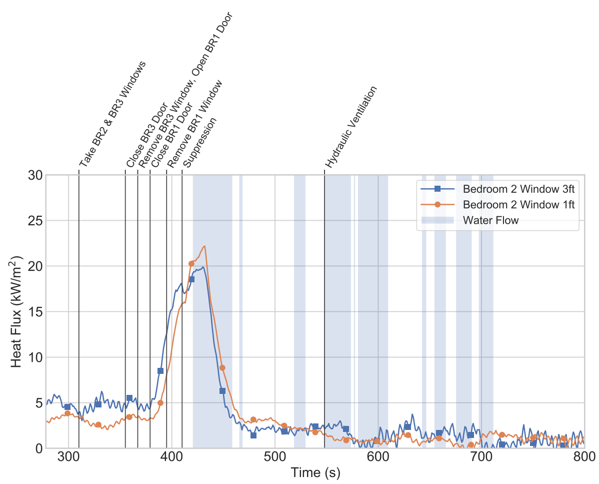
Figure 5.8 shows the temperatures, velocities, heat fluxes, and gas concentrations measured below the bedroom 2 window. Ventilation of half the double-wide bedrooms 2 window created an exterior vent. A flow path was created between the fire room and the exterior of the structure. In the 60 s that followed ventilation, bidirectional flow through the window established, as velocity 4 in. above the window sill fluctuated between inflow and outflow. After which, there was unidirectional outflow through the vent.



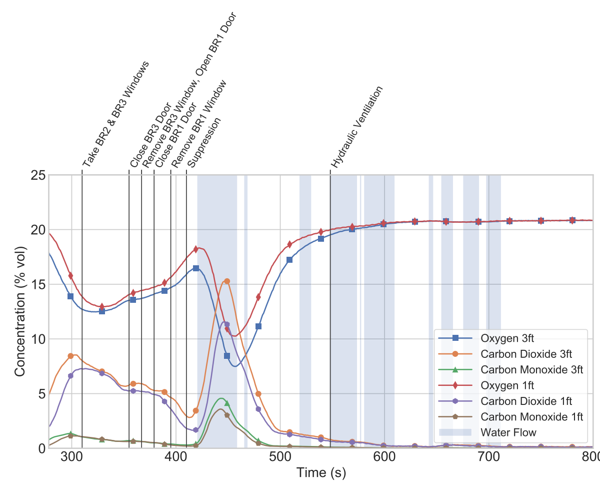
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

Figure 5.8: Post-intervention window temperature and velocity, heat flux, and gas concentration bedroom 2 during Experiment 1.

Bedroom 3 was isolated from the flow of fire room combustion gases, which led to an increase in gas flow through bedroom 2. As a result, entrainment through the bottom of the window increased to 1.2 m/s (2.7 mph) and exhaust through the top of the window increased to 6.0 m/s (13.4 mph). Window temperatures increased from 230 °C to 355 °C (446 °F to 671 °F) near the top of the window and from 180 °C to 230 °C (356 °F to 446 °F) near the bottom of the window.

Opening and closing the bedroom 1 door increased the available oxygen for combustion within the hallway. As a result, flaming combustion occurred in the hallway and at the bedroom 2 doorway. Heat and flames traveled along the flow path between the fire room and the exterior of the structure through bedroom 2. Figure 5.9 shows the changes in visual conditions in bedroom 2 following the opening of the bedroom 1 door. Temperatures increased from 380 °C to 516 °C (716 °F to 961 °F) at the top of the window and from 80 °C to 250 °C (176 °F to 482 °F) at the bottom of the window.

(a) Side C IR At Close BR1 Door

(b) Bedroom 2 At Close BR1 Door

(c) Side C IR 15 s After Close BR1 Door

(d) Bedroom 2 15 s After Close BR1 Door

(e) Side C IR 30 s After Close BR1 Door

(f) Bedroom 2 30 s After Close BR1 Door

Figure 5.9: Post-intervention, side C view of bedroom 2 (right window) and view of bedroom 2 doorway showing change in conditions following bedroom 1 door open/close in Experiment 1.

The suppression crew's first water flow application was in the hallway to extinguish the fire along the carpet, which cooled combustion gases in the hallway and knocked back the fire at the bedroom 4 doorway. The O-pattern water application resulted in air movement that caused unidirectional hallway gas flows toward the end hallway. As a result, flow through the bedroom 2 open vent became unidirectional exhaust between 4.5 m/s to 6.5 m/s (10 mph to 14.5 mph), as shown in Figure 5.8b. Following suppression, the velocity profile through the window continued to be unidirectional exhaust, as higher-temperature, higher-pressure combustion gases remained in the bedroom and connected spaces. Hydraulic ventilation reversed the flow of gases through the bedroom 2 window, which caused unidirectional inflow at -2.0 m/s (-4.4 mph). Temperatures decreased to 120 °C (248 °C) at the top of the window and 60 °C (140 °F) at the bottom of the window. Window temperatures dropped below 50 °C (122 °F) at 1125 s post-ignition (577 s after hydraulic ventilation started).

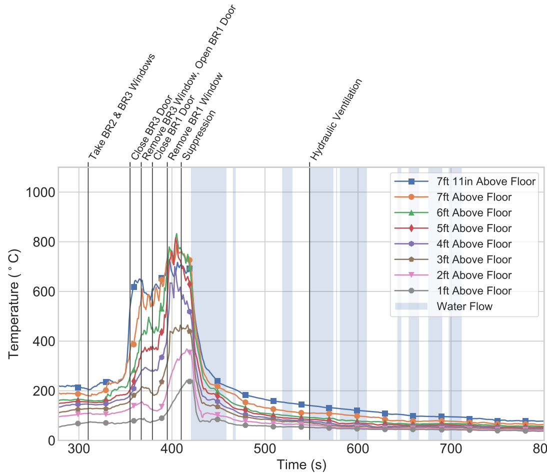
Heat flux below the window at the 3 ft and 1 ft elevations followed similar trends to the window temperatures. At the time of intervention, heat flux was 5.0 kW/m^2 and 3.5 kW/m^2 at the 3 ft and 1 ft elevations, respectively. As a result of flaming combustion at the bedroom 2 doorway, heat flux at both elevations subsequently increased to approximately 18 kW/m^2. In contrast to temperature, which decreased during suppression, heat flux at both elevations continued to increase during the first 10 s of water flow and peaked to 22 kW/m^2 and 20 kW/m^2 at the 3 ft and 1 ft elevation, respectively. Hallway suppression increased the gas velocity through the window, which increased the convective heat flux despite lower temperatures. The gas velocity through the window decreased as the suppression crew made entry to bedroom 4 and extinguished the fire. As a result, the heat fluxes dropped to 2 kW/m^2. Hydraulic ventilation lifted the smoke layer in the bedroom and the heat flux decreased below 1 kW/m^2.

Figure 5.8d shows the gas concentration time history below the bedroom 2 window. At the time of intervention, gas concentrations were 12.7% O_2, 8.1% CO_2, and 1.1% CO at the 3 ft elevation and 13.9% O_2, 7.3% CO_2, and 1.1% CO at the 1 ft elevation. Following ventilation of the bedroom 2 window, air was entrained through the lower portion of the window, decreasing CO and CO_2 concentrations and increasing O_2 concentrations at both elevations. Gas concentrations continued to improve until the start of suppression. O_2 concentrations at 3 ft and 1 ft were approximately 15.9% and 17.4%, respectively; CO_2 concentrations were approximately 3.4% and 1.7%, respectively; and CO concentrations were 0.5% and 0.3%, respectively. The change in window flow from bidirectional to unidirectional exhaust resulted in an increase in CO_2 and CO, and a decrease in O_2 concentrations. Concentrations reached 7.5% O_2, 15.3% CO_2, and 4.6% CO at the 3 ft elevation and 10.3% O_2, 11.6% CO_2, and 3.6% CO at the 1 ft elevation. The completion of suppression and subsequent hydraulic ventilation improved gas concentrations, which returned to pre-ignition levels by 700 s (152 s after the start of hydraulic ventilation).

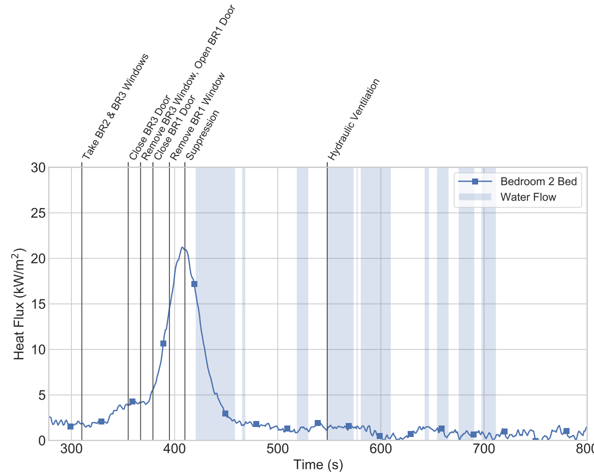
Figure 5.10 shows the temperature, heat flux, and gas concentrations in the center of bedroom 2. Figure 5.10a shows that temperatures within the room at the time of intervention ranged from 206 °C (403 °F) at the ceiling to 72 °C (162 °F) 1 ft above the floor. Ventilation of the bedroom 2 window increased temperatures. Isolation of bedroom 3 caused a sharp increase in temperature, as it led to increased flow of combustion gases through bedroom 2. Toggling the bedroom 1 door caused air isolated in bedroom 1 door to flow into the hallway, which supported flaming combustion at both the end hallway and bedroom 2 doorway. Temperatures peaked to 835 °C (1535 °F) at the ceiling and 405 °C (761 °F) 1 ft above the floor. The suppression crew flowed water into the hallway and bedroom 4, which reduced the production of high-temperature combustion gases; as such, temperatures in bedroom 2 decreased to 140 °C (284 °F). Temperatures decreased below 115 °C (239 °F) after hydraulic ventilation.

A similar trend was observed at the bed heat flux location, shown in Figure 5.10b. At the time of intervention, the heat flux on the bed was increasing. Flaming combustion at the bedroom 2 doorway caused the heat flux to peak to 21.2 kW/m^2. Suppression caused heat flux to decrease to

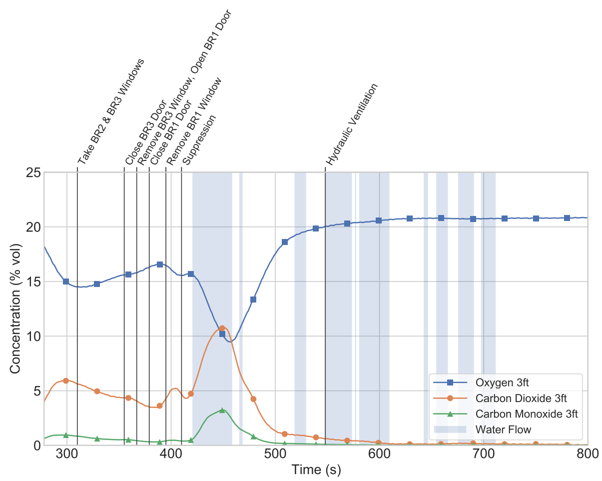
2.1 kW/m^2 and hydraulic ventilation caused heat flux to decrease to below 1 kW/m^2. The behavior was different than the window heat flux locations as the bed heat flux was offset from the flows through the door and window.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

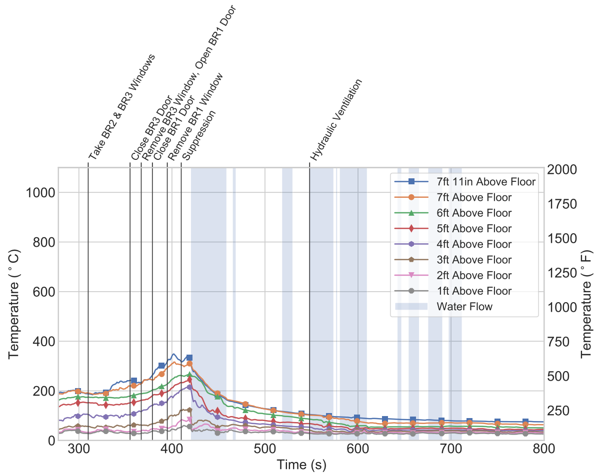
Figure 5.10: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 1.

The gas concentrations on the bed followed a similar trend to the 3 ft location at the window. Following the initial intervention, the exchange of gases through the ventilated bedroom 2 window caused gas concentrations to recover toward pre-ignition levels. When hallway suppression actions caused the flow through the bedroom 2 window to change to unidirectional exhaust, O_2 concentrations decreased and the CO_2 and CO concentrations increased (9.5% O_2, 10.7% CO_2, and 3.2% CO). The completion of suppression and subsequent hydraulic ventilation improved gas concentrations, which returned to pre-ignition levels by 700 s (152 s after the start of hydraulic ventilation).

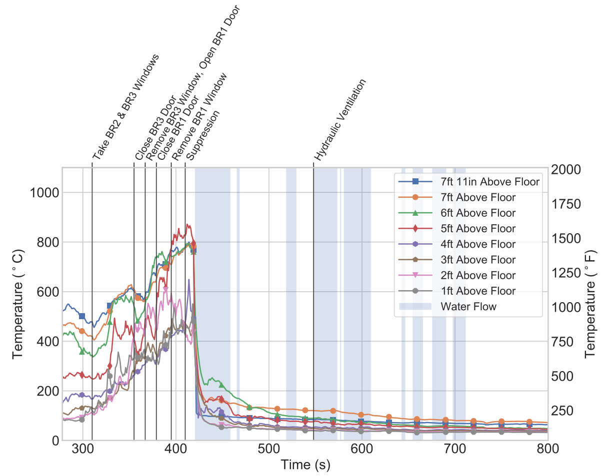
5.1.4 Hallway

At the time of intervention, there was zero visibility within the hallway. Higher-temperature, higher-pressure combustion gases flowed from bedroom 4 into the hallway and lower-temperature, lower-pressure air flowed from the hallway into the fire room. The relative magnitude of temperature, heat flux, and gas concentration increase was as a function of proximity to the fire room. Figure 5.11 shows the temperatures throughout the hallway and egress path to the front door. At the time of intervention, temperatures in the mid hallway location were the greatest, followed by the end hallway, start hallway, and living room entryway locations, respectively. Flow through the open front door combined with the large volume of the common space limited the accumulation of combustion gases in the entryway. Additionally, inflow of air at the front door cooled gases through mixing. As a result, the temperatures at the living room entryway and start hallway locations were generally lower than temperatures at the mid hallway and end hallway locations.

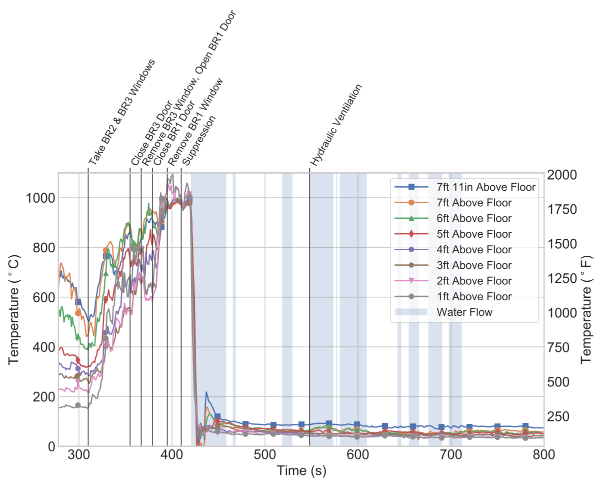
Ventilation of the bedroom 2 and 3 windows led to additional outflow of combustion gases from bedroom 4 into the hallway. Hallway temperatures increased. Most notably, mid hallway temperatures increased from 515 °C to 895 °C (959 °F to 1643 °F) at the ceiling and 150 °C to 530 °C (302 °F to 986 °F) 1 ft above the floor.



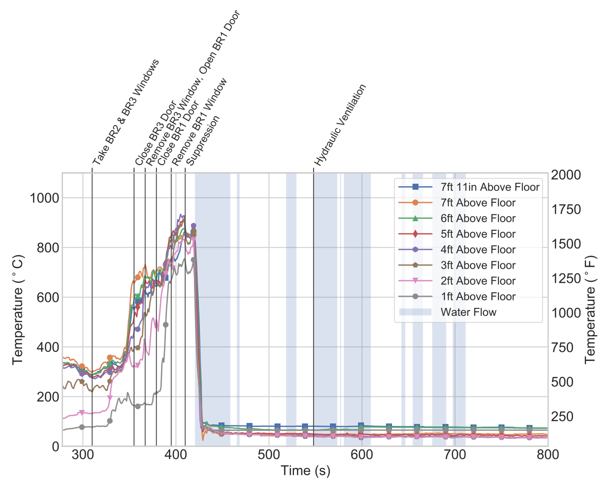
(a) Living Room Entryway Hallway Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature

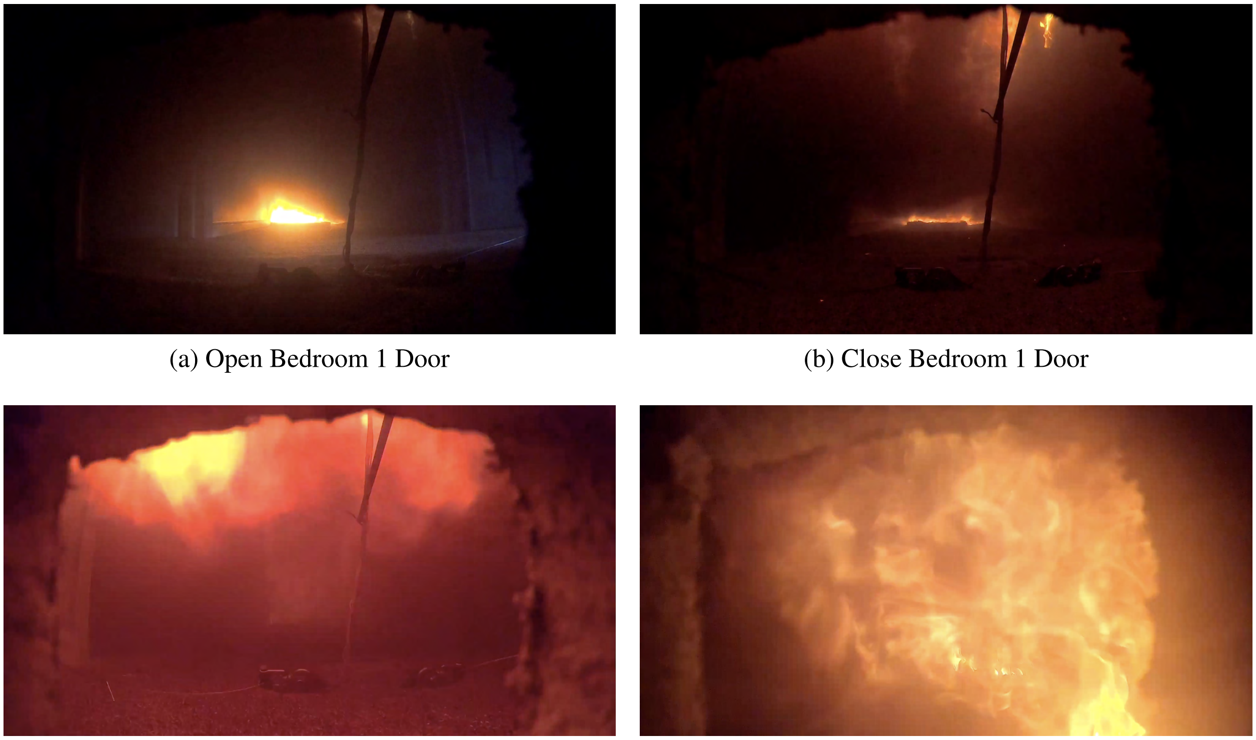


(d) End Hallway Temperature

Figure 5.11: Temperature time histories in the hallway in the period following fire department intervention in Experiment 1.

Closure of the bedroom 3 door stopped the flow of combustion gases between bedrooms 3 and 4, which subsequently reduced the rate of rise of hallway temperatures. This impact was limited in duration because the bedroom 1 door was opened 22 s later. Opening the bedroom 1 door increased the available oxygen for combustion along the flow path between bedroom 4 and bedroom 2. Higher-temperature combustion gases that accumulated within the hallway mixed with oxygen and ignited. Figure 5.12 depicts flaming combustion in the hallway after the toggling of the bedroom 1 door. At this point, temperatures at the mid hallway and end hallway locations exceeded the criteria for flashover as shown by the tabular data in Figure 5.12. Temperatures 5 ft above the floor at the start hallway location exceeded 800 °C (1472 °F). Temperatures at lower elevations remained below 600 °C (1112 °F), as inflow through the front door cooled gases through mixing. Living room entryway temperatures peaked to 310 °C (590 °F) at the ceiling but remained near

40 °C (104 °F) 1 ft above the floor, due to its proximity to the open front door.



(a) Open Bedroom 1 Door

(b) Close Bedroom 1 Door

(c) Close Bedroom 1 Door (+15 s)

(d) Close Bedroom 1 Door (+35 s)

	Mid Hallway		End Hallway	
Time	3 ft Temperature	Heat Flux	3 ft Temperature	Heat Flux
Open Bedroom 1 Door	654 °C (1209 °F)	68 kW/m^2	538 °C (1000 °F)	7.7 kW/m^2
Close Bedroom 1 Door	683 °C (1261 °F)	68 kW/m^2	531 °C (988 °F)	8.5 kW/m^2
Close Bedroom 1 Door (+15 s)	704 °C (1299 °F)	70 kW/m^2	660 °C (1220 °F)	16 kW/m^2
Close Bedroom 1 Door (+35 s)	992 °C (1818 °F)	80 kW/m^2	880 °C (1616 °F)	51 kW/m^2

Figure 5.12: Post-intervention, hallway increased burning after Bedroom 1 door open and close in Experiment 1.

Figure 5.13 shows the heat flux throughout the hallway and egress path to the front door. Ventilation of bedrooms 2 and 3 increased the flow of combustion gases from the fire room into the hallway. The end hallway and start hallway heat fluxes increased increased from less than 1 kW/m^2 to 4.4 kW/m^2 and 7.3 kW/m^2 prior to the closure of the bedroom 3 door. The living room wall heat flux increased to 1.5 kW/m^2 as inflow through the open front door minimized the effects of the combustion gas flows. The mid hallway heat flux increased to 68 kW/m^2, an indication that the carpet near the heat flux gauge had ignited. Isolation of bedroom 3 caused the flow through the bedroom 3 doorway to be redirected through the bedroom 2 doorway and into the common space. Heat flux measured at the start hallway and end hallway locations increased. Opening the bedroom 1 door increased the available oxygen for combustion in the hallway, which resulted in additional flaming combustion. As flames traveled throughout the hallway, heat flux within the

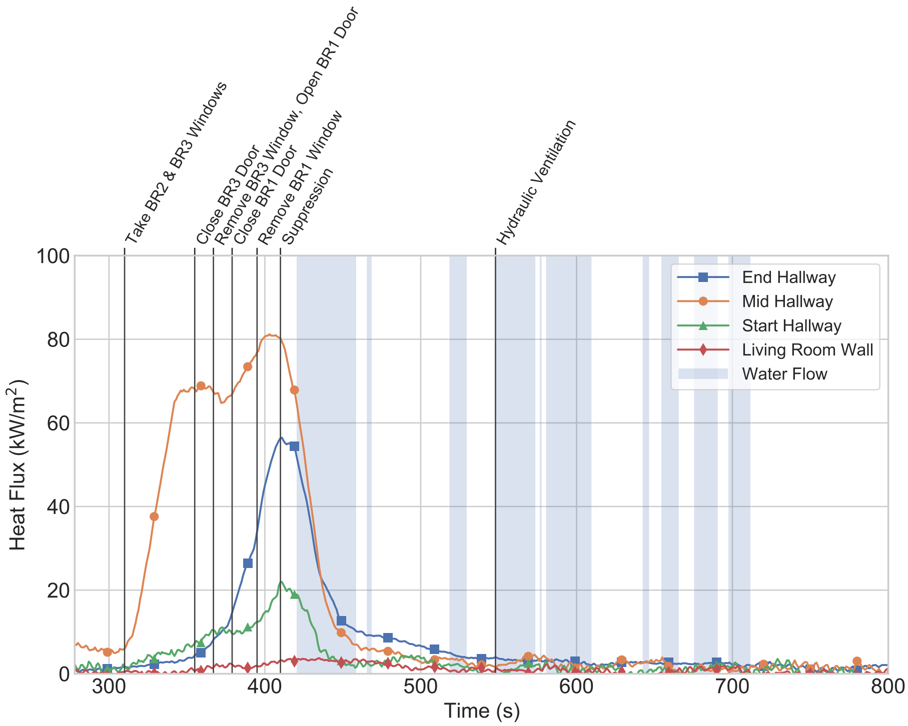


Figure 5.13: Heat flux time histories in the hallway in post-intervention period during Experiment 1.

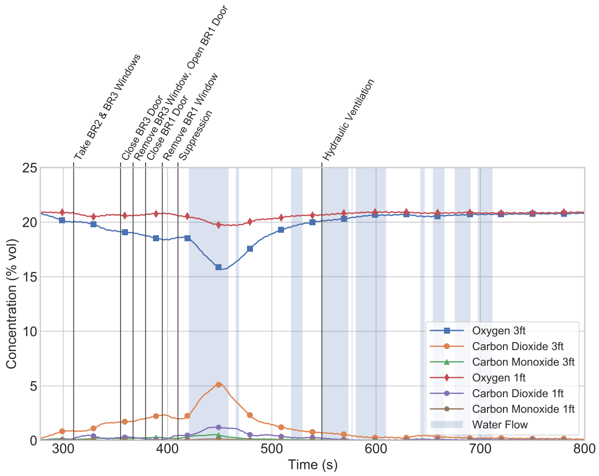
hallway increased. The end hallway heat flux peaked to 56.5 kW/m^2, the mid hallway heat flux peaked to 81.2 kW/m^2, and start hallway heat flux peaked to 21.9 kW/m^2. Suppression of the bedroom 4 fire caused all heat fluxes within the hallway to decrease.

Table 5.2 shows the gas concentrations measured in the hallway and egress path to the front door at the time of intervention. Gas concentrations indicated that at the time of intervention, the smoke layer had descended past the 1 ft measurement location at the mid hallway location and past the 3 ft measurement location at the end hallway, start hallway, and living room entryway.

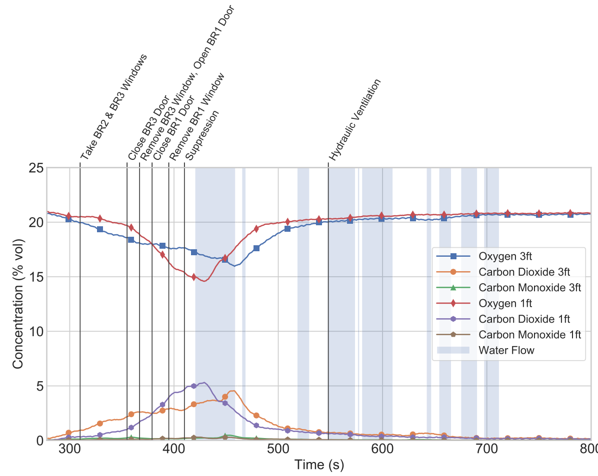
Table 5.2: Hallway Gas Concentrations at Intervention for Experiment 1

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway Hallway	3 ft	20.0	0.9	0.1
	1 ft	20.8	0.1	0.0
Start Hallway	3 ft	20.0	1.0	0.1
	1 ft	20.1	0.3	0.1
Mid Hallway	3 ft	17.6	3.8	0.5
	1 ft	15.9	5.5	0.9
End Hallway	3 ft	15.2	5.6	1.6
	1 ft	19.9	1.5	0.3

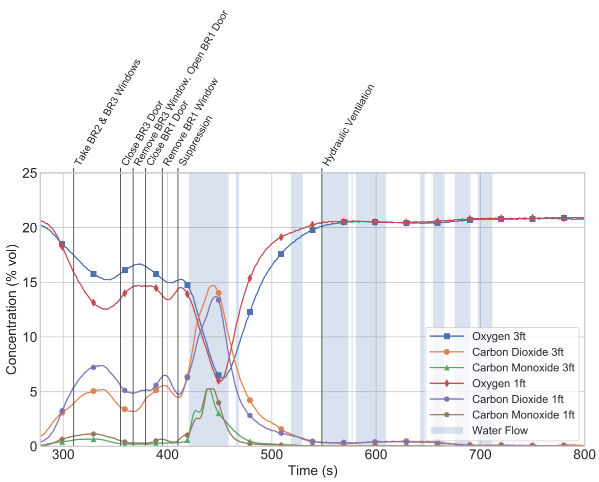
Figure 5.14 shows the gas concentrations throughout the hallway and egress path to the front door. Following first intervention, gas concentrations at the mid hallway and end hallway locations were most impacted, as the measurement locations were in the flow paths established between the fire room and the exterior of the structure through the ventilated windows. Gas concentrations at the start hallway and living room entryway were less affected, as they were along the established flow path to the open front door, which minimized the accumulation of combustion gases.



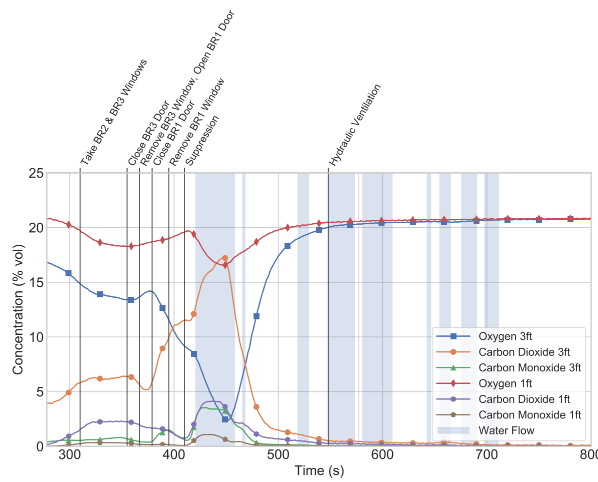
(a) Living Room Entryway Hallway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.14: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 1.

Low-level burning outside of bedroom 4 approximately 295–300 s post-ignition caused mid hallway gas concentrations 1 ft above the floor to exceed gas concentrations 3 ft above the floor. Ventilation through the bedrooms 2 and 3 windows caused an influx of fresh air into the hallway, temporarily improving mid hallway gas concentrations. End hallway, start hallway, and living room entryway gas concentrations indicated increased accumulation of combustion gases despite flow through the ventilated bedroom windows. Isolation of bedroom 3 limited the influx of fresh air in the hallway, which caused mid hallway gas concentrations to deteriorate.

Opening the bedroom 1 door also caused an influx of fresh air into the hallway, however it led to the ignition of combustion gases between bedroom 4 and the end hallway location. The mid hallway and end hallway locations showed a resulting increase in CO_2 and CO concentrations and decrease in O_2 concentrations. Both the mid hallway and end hallway locations showed a sharp response to the start of suppression. The O-pattern water application and the resulting air movement caused the combustion gases in the hallway to flow toward the end hallway and through the open bedroom 2 vent.

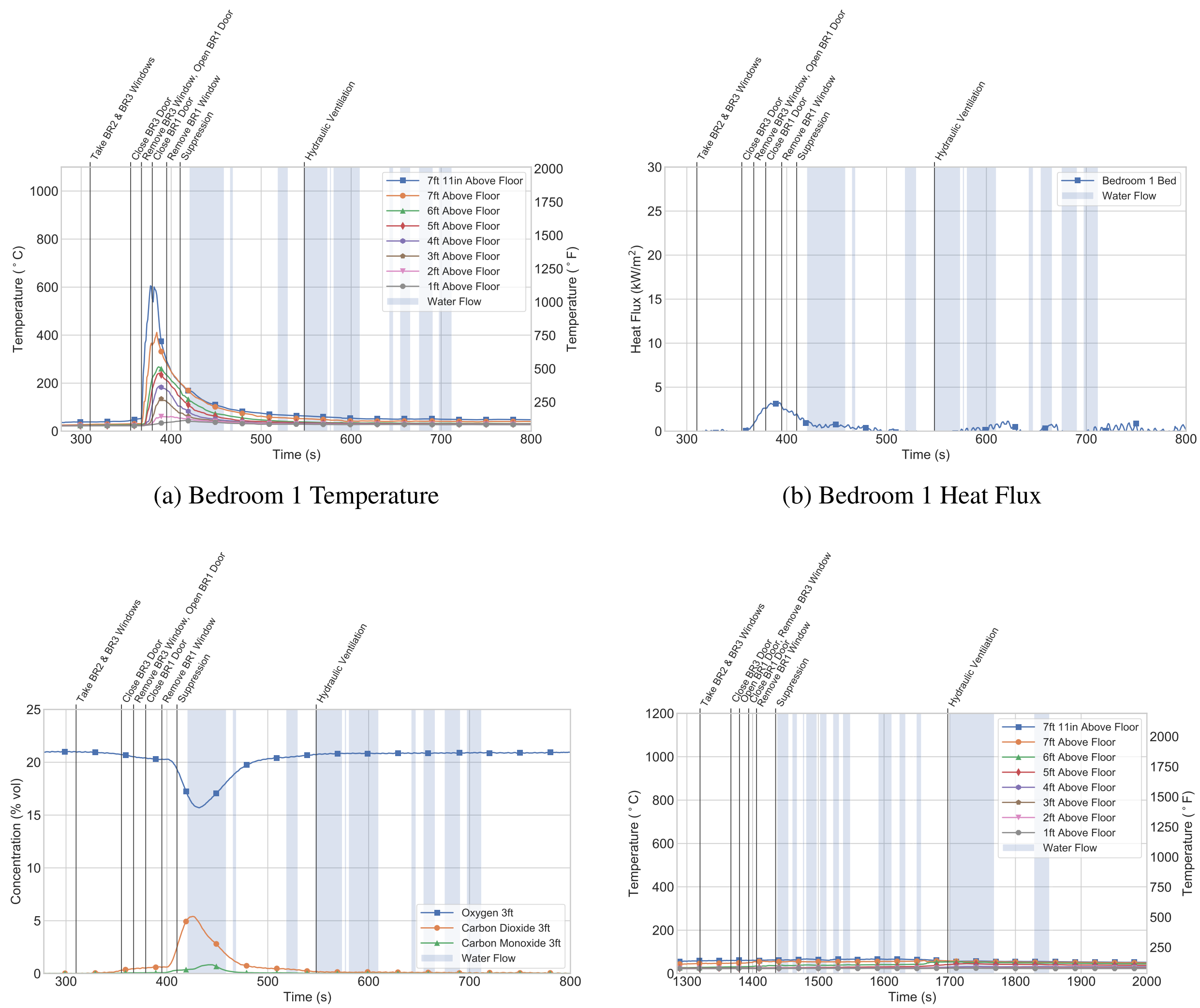
The start hallway and living room entryway hallway locations also showed an increase in combustion gas accumulation during suppression. Here, suppression both reduced the production of combustion gases and cooled gases in the hallway. As gases cooled and contracted, the pressure dropped, which caused the gases to become more dense and drop in elevation. As a result, gas concentrations worsened. Consequently, the exhaust velocity slowed and the gases also descended in the space. At all locations, the combination of suppression and hydraulic ventilation caused gas concentrations to recover to pre-ignition conditions.

5.1.5 Bedroom 1

The bedroom 1 door was closed prior to ignition, which isolated the bedroom from the flow of combustion gases from the fire room. Smoke entered the bedroom through the leakage area around the door. Figure 5.15 shows the temperature, heat flux, and gas concentrations measured within bedroom 1. Prior to ventilation, temperatures within the bedroom remained below 55 °C (131 °F), heat flux remained below 1.5 kW/m^2, and gas concentrations remained near ambient.

The bedroom 1 door was opened for approximately 12 s and then closed, which allowed higher-pressure combustion gases to flow from the hallway into the bedroom and displace the lower-pressure air. As a result, bedroom 1 air flowed into the hallway. Bedroom 1 temperatures 2 ft and above immediately increased with peak values of 600 °C (1112 °F) at the ceiling. Bedroom 1 heat flux at the bed immediately peaked to 3.2 kW/m^2. Bedroom 1 gas concentrations began to worsen.

Removal of the bedroom 1 window created an exterior vent and a flow path within the bedroom. Combustion gases flowed toward the vent and within 5 s bedroom 1 temperatures and heat flux decreased. Flow through the window cooled accumulated combustion gases. As gases cooled, they dropped in elevation, which caused gas concentrations to deteriorate. Flow through the window continued to exhaust gases, which lead to gas concentration recovery to pre-ignition levels.



(a) Bedroom 1 Temperature

(b) Bedroom 1 Heat Flux

(c) Bedroom 1 Gas Concentration

(d) Bathroom 1 Temperature

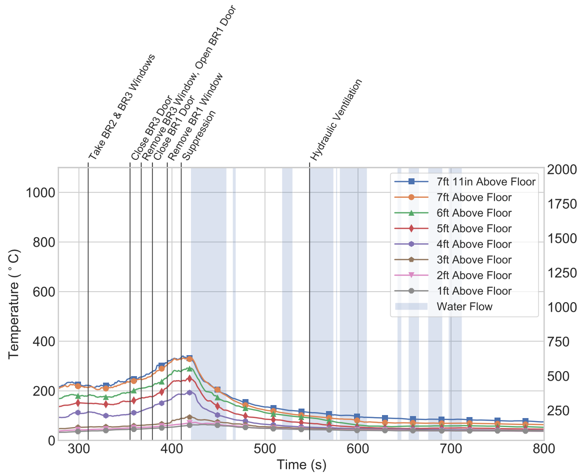
Figure 5.15: Post-intervention temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 1.

The door to bathroom 1 was closed prior to ignition, which prevented the flow of gases between the bedroom and the bathroom. However, bathroom 1 had an HVAC supply vent and no return vent. Smoke that filled the duct network flowed into the closed bathroom until the pressure within the room sufficiently increased to prevent additional flow. As a result, smoke filled the space and limited visibility prior to fire department intervention. Due to heat losses within the duct network and gas mixing with the bathroom, temperatures within the bathroom remained below 60 °C (140 °F) throughout the duration of the experiment (Figure 5.15d).

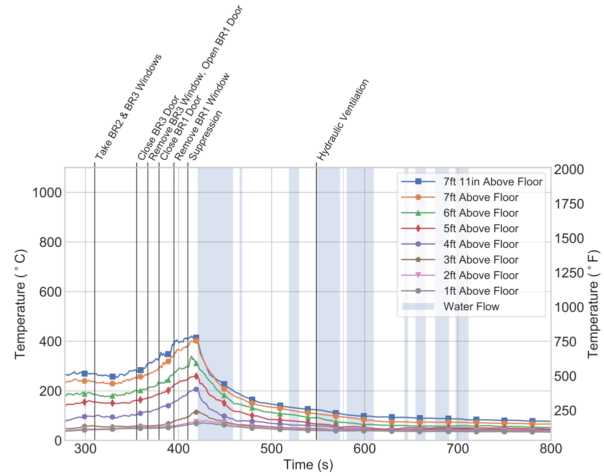
5.1.6 Common Space

Figure 5.16 shows the living room and kitchen temperature, kitchen heat flux, and kitchen gas concentrations. Temperature and heat flux within the common space gradually increased and gas concentrations gradually deteriorated throughout the experiment. The front door remained open throughout the experiment, and combined with the large volume of the common space, limited the effects of changes in ventilation. Living room and kitchen temperatures gradually increased regardless of ventilation. Temperatures peaked to 420 °C (788 °F) in the living room and to 340 °C (644 °F) in the kitchen. Suppression reduced temperatures in the common space below 180 °C (356 °F). Hydraulic ventilation reduced temperatures below 95 °C (203 °F).

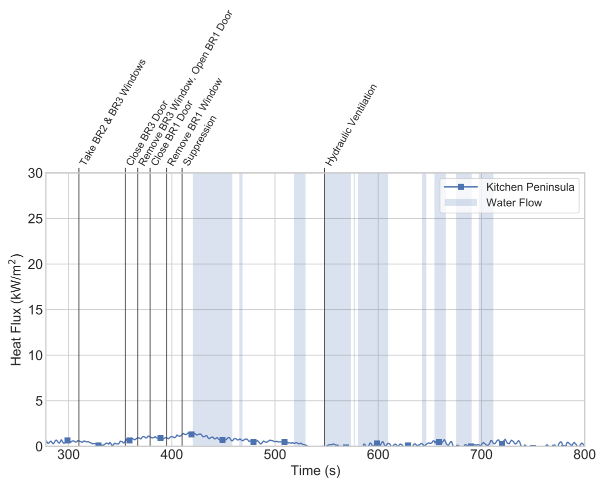
Heat flux and gas concentrations followed a similar trend to temperature and gradually increased throughout the experiment, as combustion gases spread and accumulated at the ceiling of the common space. Heat flux peaked to 1.5 kW/m^2 prior to suppression. However, gas concentrations increased to 18.3% O_2, 1.2% CO_2, and 0.5% CO after suppression, as combustion gases cooled and descended toward the floor.



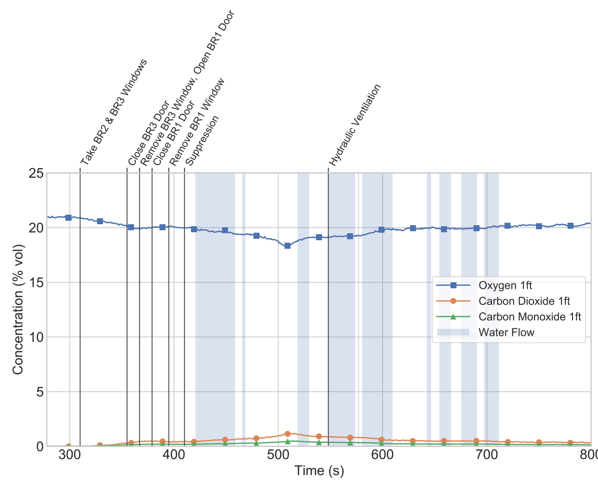
(a) Kitchen Temperature



(b) Living Room Temperature



(c) Kitchen Heat Flux

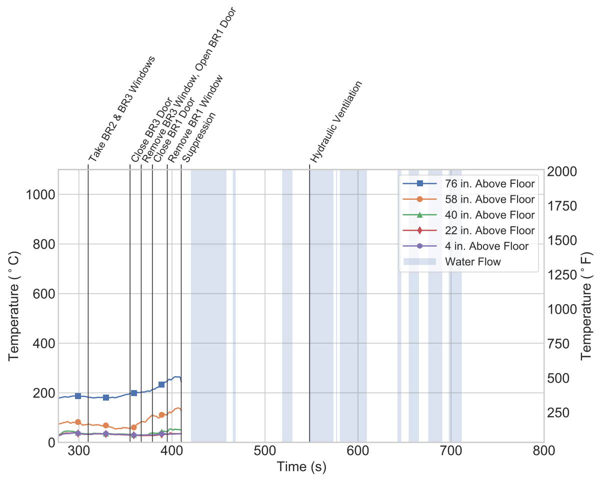


(d) Kitchen Gas Concentration

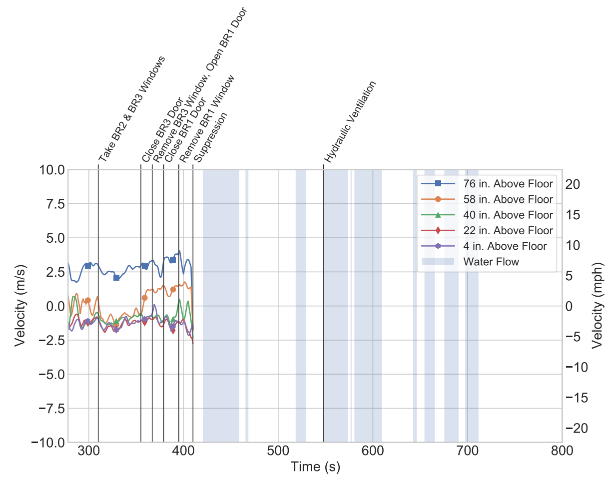
Figure 5.16: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 1.

Prior to intervention, a flow path was established between bedroom 4 and the exterior through the open front door. Figure 5.17 shows the front doorway temperature and velocity measurements. Bidirectional flow through the door was indicated by velocities of 3.0 m/s (6.7 mph) 76 in. above the floor, exhaust, and -1.0 m/s (-2.2 mph) below 22 in. above the floor, entrainment. Ventilation of the bedrooms 2 and 3 windows caused additional entrainment through the front door. Velocities 58 in. and 40 in. above the floor decreased from 0.0 m/s to -1.0 m/s (0 mph to -2.2 mph). At this point, only the 76 in. probe measured an exhaust velocity.

Isolation of bedroom 3 cutoff the exhaust flow through the bedroom 3 window. As a result, there was a corresponding increase in exhaust through the front door. The velocity 58 in. above the floor increased to 1.0 m/s (2.2 mph) and temperature increased to 85 °C (185 °F). The bidirectional probes were removed 410 s post-ignition, prior to crew entry into the structure for interior suppression. Data recorded after this time stamp are not reflective of flow through the doorway.



(a)



(b) Front Doorway Velocity

Figure 5.17: Post-intervention temperatures and velocities in the front doorway during Experiment 1.

5.2 Experiment 2

The search tactics in Experiment 2 were designed to evaluate window initiated operations conducted during interior suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide bedroom 4 window were removed and the door to bedroom 4 was opened. The front door and doors to bedroom 2, bedroom 3, and bathroom 3 were opened. The doors to bedroom 1 and bathroom 1 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post-flashover in bedroom 4, interior suppression occurred as crews on side C of the structure ventilated half the double-wide windows in bedroom 2 and bedroom 3. The crews entered bedrooms 2 and 3 and proceeded toward the doors to the hallway. The crew in bedroom 3 closed the door, which isolated the bedroom from the flow of combustion gases. The crew in bedroom 2 were unable to isolate the bedroom and entered the hallway to continue their search beyond the room of entry. Simultaneously, the crew in bedroom 3 removed the remainder of the double-wide window and the crew that entered bedroom 2 opened the bedroom 1 door. The crew then entered bedroom 1 and closed the door behind them. Once isolated in bedroom 1, the crew proceeded to remove the double-wide bedroom 1 window. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed double-wide bedroom 4 window. 91 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 272 gallons. Table 5.3 provides the timing of each event relative to ignition and the first fire department intervention, which was simultaneous suppression and ventilation of the bedroom 2 and 3 windows.

Table 5.3: Experiment 2 Event Times

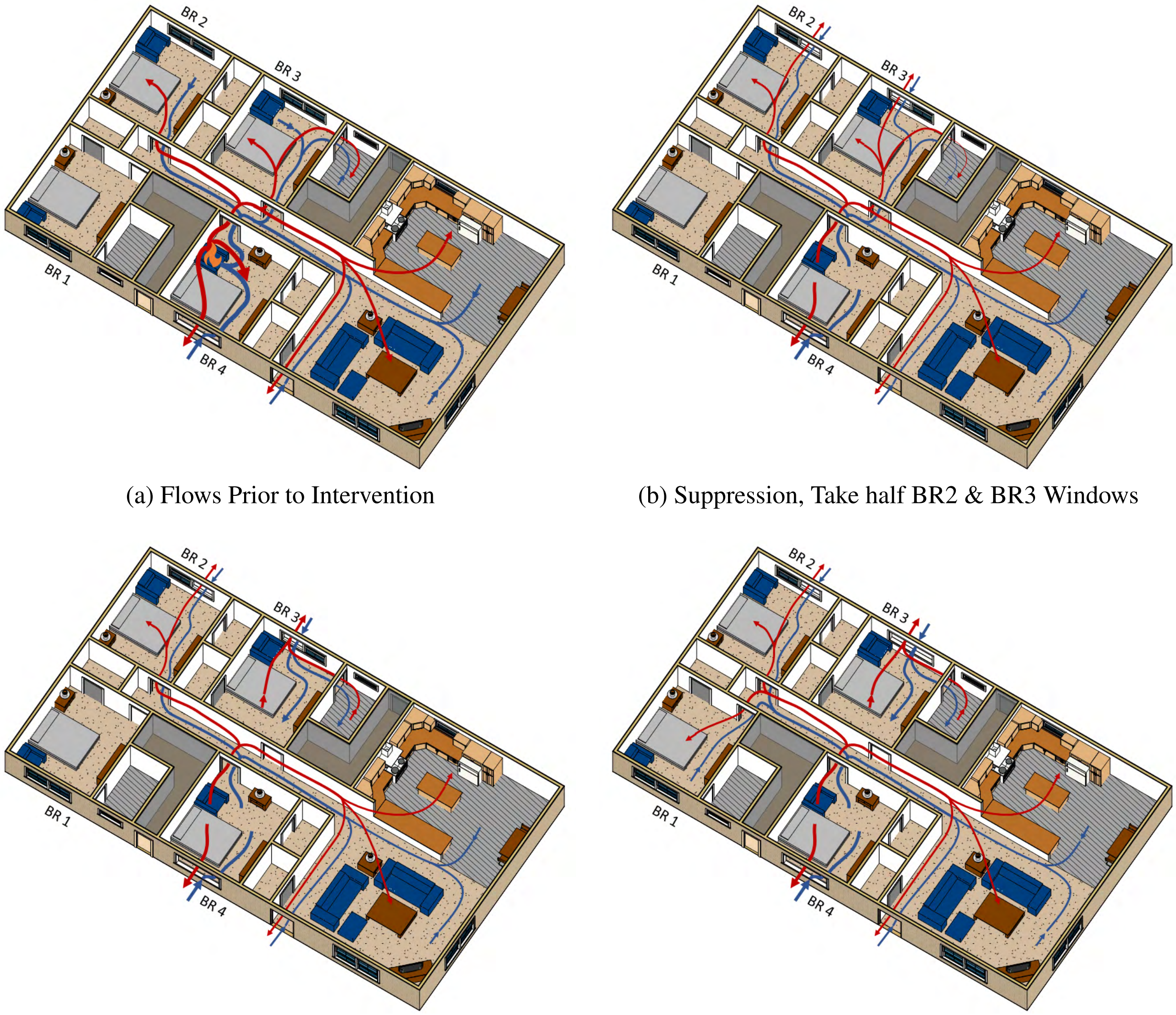
Event	Elapsed Time			
	From Ignition		From Intervention	
	(mm:ss)	(s)	(mm:ss)	(s)
Ignition	00:00	0	—	—
Suppression, Take BR2 & BR3 Windows	05:16	316	00:00	0
Close BR3 Door	05:56	356	00:40	40
Remove BR3 Window, Open BR1 Door	06:07	367	00:51	51
Close BR1 Door	06:17	377	01:01	61
Remove BR1 Window	06:29	389	01:13	73
Hydraulic Ventilation	07:10	430	01:54	114

Figures 5.18 and 5.19 show the changes in flow in the time period before and after each fire department intervention over the duration of Experiment 2. At the time of intervention, bedroom 4 was in a steady post-flashover state. The bedroom 4 fire entrained lower-temperature, lower-pressure air and exhausted higher-temperature, higher-pressure combustion gas, which generated bidirectional flows through the bedroom 4 vents. Flow paths were established through the bedroom 4 window to the exterior of the structure and through the bedroom 4 doorway to open volumes of

the structure (bedroom 2, bedroom 3 and bathroom 3, and through the open front door), as shown in Figure 5.18a.

Interior suppression was conducted with a combination nozzle set to flow a straight stream at 150 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline. Suppression of the bedroom fire reduced the production of combustion gases and decreased the heat release rate of the fire. Ventilation of half the bedrooms 2 and 3 double-wide windows created two new exterior vents (Figure 5.18b), which established flow paths between the fire room and the exterior of the structure through each open bedroom. The flows through both bedroom windows were predominately bidirectional, except for approximately 5 s in the bedroom 3 window after it was opened and for approximately 15 s in the bedroom 2 window after water flow. During these time periods, flow through the vent was unidirectional exhaust.

Closing the bedroom 3 door isolated the bedroom from the flow of combustion gases from the fire room (bedroom 4). Figure 5.18c depicts the change in flows that resulted from closing the bedroom 3 door. Air continued to be entrained through the exterior vent but then terminated in the bedroom and bathroom rather than the fire room. Combustion gases continued to be exhausted from of the structure but now originated from bedroom 3 and bathroom 3 rather than the fire room. The removal of the bedroom 3 window increased the surface area for ventilation, which increased gas flows (Figure 5.18d).



(a) Flows Prior to Intervention

(b) Suppression, Take half BR2 & BR3 Windows

(c) Close BR3 Door

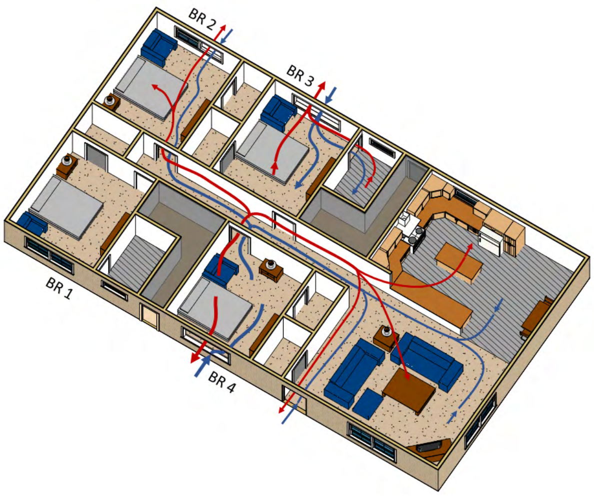
(d) Remove BR3 Window, Open BR1 Door

Figure 5.18: Changes in gas flows in the structure following fire department interventions in Experiment 2.

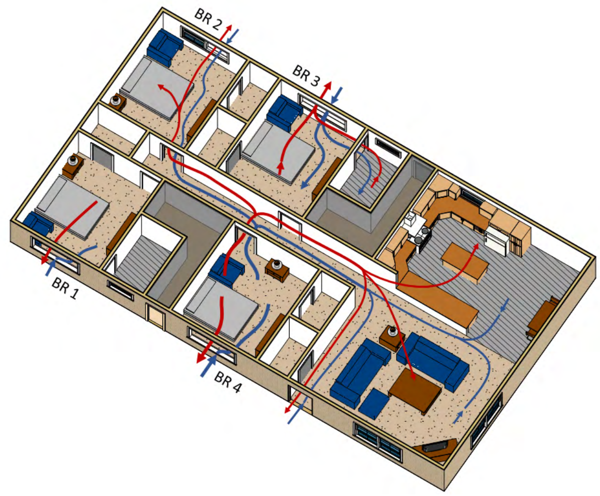
Opening the bedroom 1 door established a new flow path between the fire room and bedroom 1 (Figure 5.18d). Bidirectional flow at the doorway was established as bedroom 1 air and hallway combustion gases were exchanged. This bidirectional flow was momentary, as the room was isolated approximately 12 s later. Closing the bedroom 1 door prevented further accumulation of combustion gases in the bedroom, but also trapped accumulated combustion gases within the bedroom (Figure 5.19a). The removal of the bedroom 1 window created a new exterior vent, which established a new flow path between the bedroom and the exterior. Air was entrained into the bedroom and combustion gases were exhausted from the bedroom, as shown in Figure 5.19b.

Hydraulic ventilation occurred out of the failed, double-wide bedroom 4 window with a straight stream in an O-pattern. Figure 5.19c shows the changes in flows due to hydraulic ventilation.

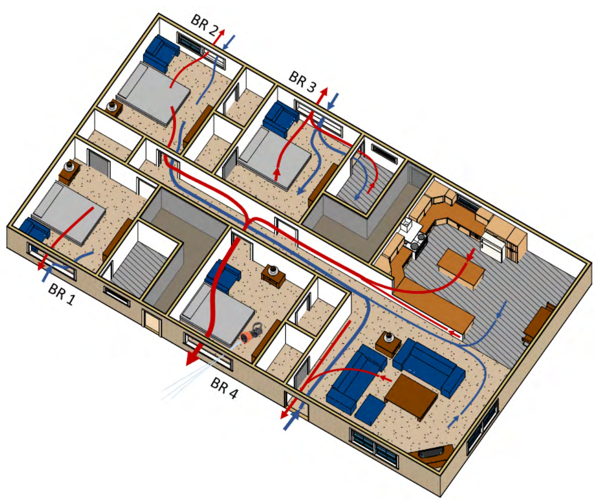
Water flow through the bedroom 4 window generated an area of low pressure in the bedroom. Gases in the structure connected to bedroom 4 via an open doorway (hallway, bedroom 2, kitchen, and living room) flowed toward the lower-pressure bedroom, which caused gas flow through the bedroom 4 doorway to become unidirectional inflow and gas flow through the bedroom 4 window to become unidirectional exhaust. Gas flows in spaces isolated by a closed door (bedroom 1 and bedroom 3) remained unchanged.



(a) Close BR1 Door



(b) Remove BR1 Window



(c) Hydraulic Ventilation

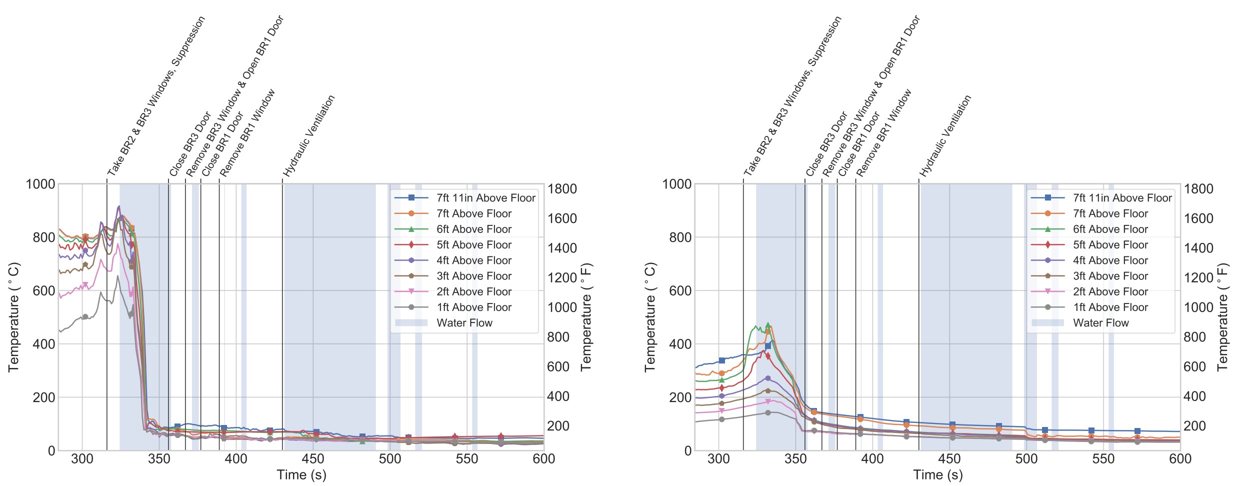
Figure 5.19: Changes in gas flows in the structure following fire department interventions in Experiment 2.

5.2.1 Bedroom 4

The bedroom 4 fire transitioned through flashover approximately 220 s post-ignition. The fire was in a steady, post-flashover, ventilation-limited state prior to intervention, as temperatures ranged from 850 °C (1562 °F) at the ceiling to 560 °C (1040 °F) 1 ft above the floor. Figure 5.20a shows the temperature time history in bedroom 4.

Simultaneous with crew entry for suppression, ventilation created two new exterior vents in bedrooms 2 and 3, which established flows path between the fire room and the exterior of the structure. This action resulted in an increase in combustion gas flow from the fireroom and correspondingly, air entrainment to the fire room, which increased the oxygen available for combustion. During the 8 s between ventilation and suppression the heat release rate increased, which increased ceiling temperatures to 920 °C (1688 °F). Suppression decreased fire room temperatures, which stratified to 100 °C (212 °F) above 5 ft above the floor and 60 °C (140 °F) below 4 ft above the floor. Additional water flows decreased fire room temperatures below 80 °C (176 °F) and hydraulic ventilation decreased fire room temperatures below 55 °C (131 °F).

As the heat release rate of fire increased and the bedroom transitioned through flashover, higher-pressure combustion gases pushed around the closed closet door. Combustion gases flowed through the leakage area around the closed door and accumulated in the closet, which increased closet temperatures to 360 °C (680 °F) at the ceiling and 130 °C (266 °F) 1 ft above the floor at the time of intervention (Figure 5.20b). The closed door limited the flow of gases, but delayed temperature recovery compared to bedroom 4. Post-suppression temperatures remained elevated and stratified between 150 °C (302 °F) at the ceiling to 75 °C (167 °F) 1 ft above the floor. Hydraulic ventilation decreased all closet temperatures below 100 °C (212 °F), which was greater than the respective elevations in the center of the room.

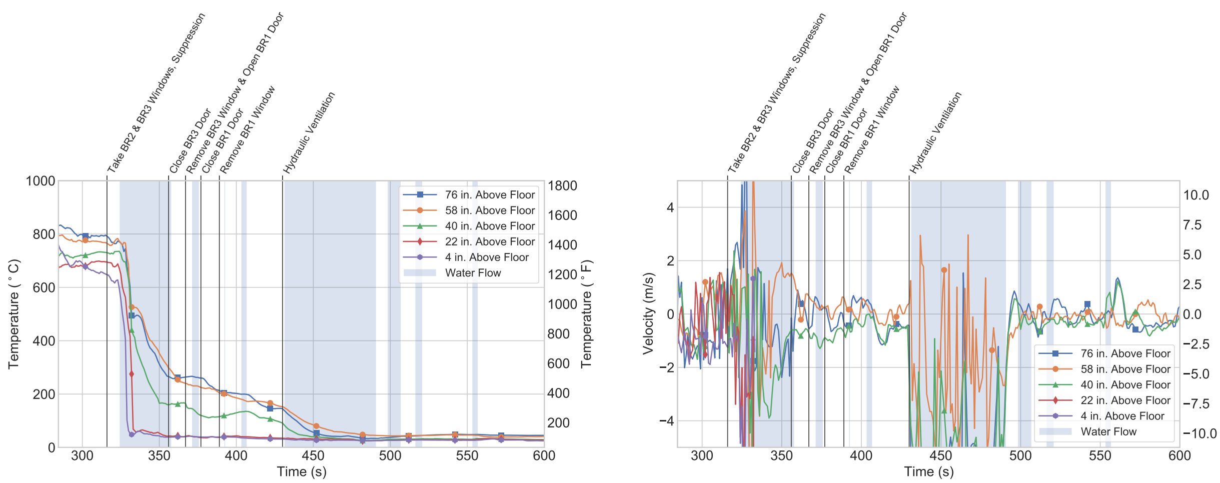


(a) Bedroom 4 Temperature

(b) Closet Temperature

Figure 5.20: Temperature time histories in bedroom 4 and closet for the period following fire department intervention in Experiment 2.

Figures 5.21a and 5.21b show the temperature and velocity time history at the bedroom 4 doorway, respectively. Prior to intervention, bedroom 4 doorway temperatures were nominally steady and ranged from 795 °C (1463 °F) at the top of the door frame to 650 °C (1202 °F) near the floor. Door velocities fluctuated between intake and exhaust (1.5 m/s to -2 m/s (3.4 mph to -4.5 mph)), as combustion occurred at the doorway. Following suppression, temperatures at the top of the door frame decreased to 280 °C (536 °F) and temperatures near the floor decreased to 40 °C (104 °F). Door velocities 40 in. and above decreased to near 0 m/s (0 mph) and door velocities 22 in. and below were negative (-4 m/s (8.9 mph)), which indicated no exhaust from the fire room into the hallway and entrainment from the hallway into the fire room, respectively. Hydraulic ventilation resulted in unidirectional inflow through the bedroom 4 door, which dropped all doorway temperatures to below 45 °C (113 °F).



(a) Bedroom 4 Doorway Temperature

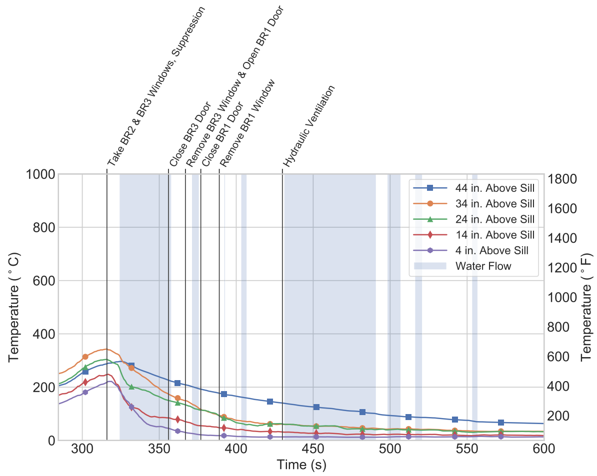
(b) Bedroom 4 Doorway Velocity

Figure 5.21: Temperature and velocity time histories in bedroom 4 door for the period following fire department intervention in Experiment 2.

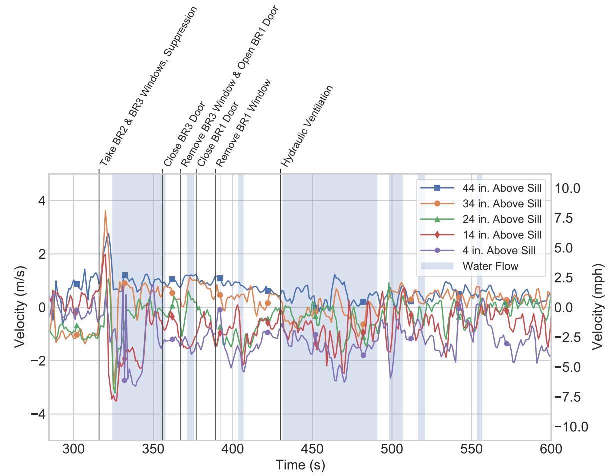
5.2.2 Bedroom 3

The door between bedroom 3 and the hallway was open prior to ignition. Combustion gases accumulated in the room and visibility was completely lost approximately 18 s prior to fire department interventions. Figure 5.22a shows bedroom 3 window temperatures. At intervention, temperatures within the bedroom 3 window ranged from 345 °C (653 °F) 44 in. above the sill to 220 °C (428 °F) 4 in. above the sill. The initial fire department intervention was ventilation of half of the bedroom 2 and bedroom 3 windows simultaneous with suppression. Ventilation resulted in temperature decrease, as combustion gases at all elevations exhausted from the structure between 0.4 m/s to 3.5 m/s (0.9 mph to 7.8 mph), as shown in Figure 5.22b. Suppression furthered temperature decrease and caused the pressure within the space, which drove unidirectional exhaust, to decrease. As a result, the velocity profile through the window became bidirectional. The bedroom 3 door was closed 40 s after the start of suppression, which isolated the bedroom from the flow of combustion gases. Bidirectional flows through the window persisted after the bedroom door was closed. Combustion gases exhausted at approximately 1.0 m/s (2.2 mph) and air was entrained at approximately -1.2 m/s (2.7 mph). Following isolation, window temperatures ranged from 225 °C (437 °F) 44 in. above the sill to 45 °C (113 °F) 4 in above the sill. Temperatures decreased below 100 °C (212 °F) during the duration of the experiment. The door to bedroom 3 remained isolated during hydraulic ventilation, therefore hydraulic ventilation did not impact the rate of temperature decrease.

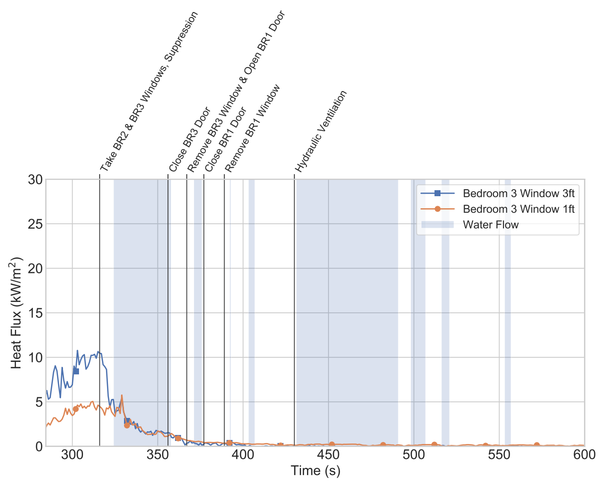
Heat flux below the window followed a similar trend as the window temperatures. Prior to ventilation of the bedroom 3 window, heat flux was approximately 10.5 kW/m^2 3 ft above the floor and 4.5 kW/m^2 1 ft above the floor (Figure 5.22c). Window ventilation, which allowed accumulated gases to exhaust through the window and air to be entrained, resulted in a steady decrease in heat flux 3 ft above the floor. Suppression decreased the heat release rate of the bedroom 4 fire and cooled combustion gases. As a result, heat flux at both elevations below the window steadily decreased. At the time that bedroom 3 was isolated, heat flux at both elevations had decreased to 1.3 kW/m^2. As combustion gases continued to exhaust from the space, heat flux steadily decreased for the remainder of the experiment and values were negligible within 90 s of initial intervention.



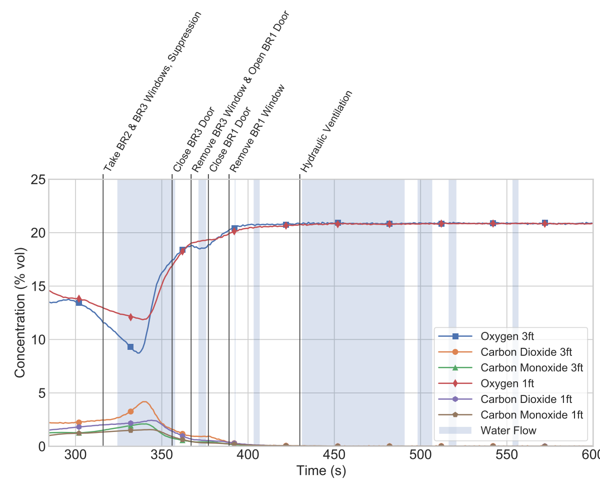
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.22: Post-intervention window temperature, heat flux, gas concentration, and velocity in bedroom 3 during Experiment 2.

At the time of intervention, gas concentrations below the window 3 ft above the floor were 11.6% O_2, 2.5% CO_2, and 1.5% CO, and 1 ft above the floor were 13.0% O_2, 2.0% CO_2, and 1.3% CO, as shown in Figure 5.22d. Ventilation of the bedroom 3 window and resulting unidirectional exhaust increased the flow of combustion gases through bedroom 3. This led to increased CO_2 and CO concentrations and decreased O_2 concentrations at both elevations. Concentrations at the window began to improve within 20 s of intervention (12 s after the start of water flow), as suppression decreased pressure and caused unidirectional gas flows to transition to bidirectional flows. Bidirectional flow through the window continued after isolation of the bedroom, which lifted the smoke layer and improved gas concentrations. Gas concentrations continued to improve for the duration of the experiment and reached pre-ignition levels prior to the start of hydraulic ventilation.

Prior to intervention, bedroom 3 temperatures ranged from 495 °C (923 °F) at the ceiling to 120 °C (243 °F) 1 ft above the floor, as shown in Figure 5.23. Immediately following window ventilation, bedroom temperatures gradually decreased. Water flow caused temperatures to decrease more rapidly. The closed bedroom 3 door isolated the bedroom from gas exchange with the hallway, which reduced temperatures from 208 °C to 100 °C (406 °F to 212 °F) at the ceiling and from 48 °C to 30 °C (118 °F to 86 °F) 1 ft above the floor, as bidirectional flow through the ventilated window lifted the smoke layer.

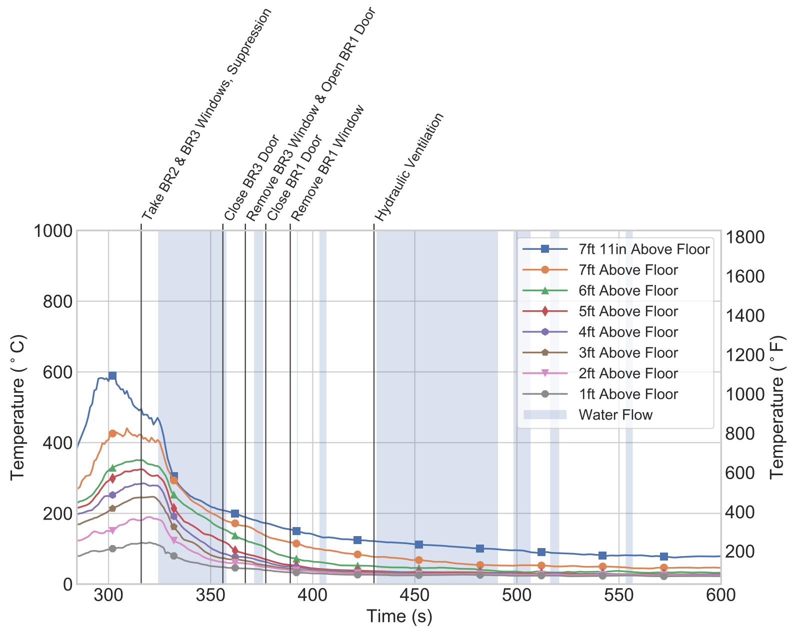
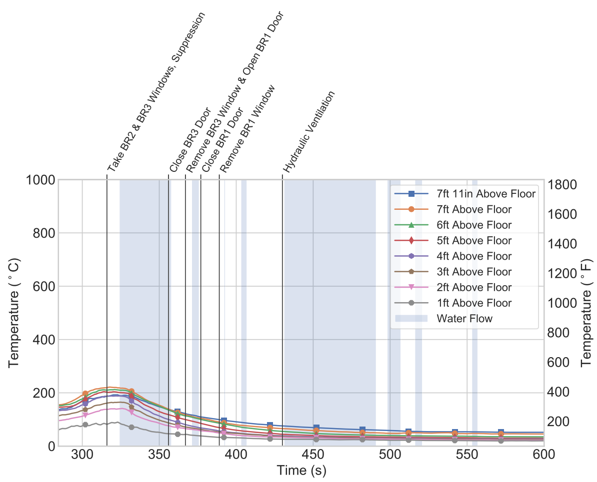


Figure 5.23: Post-intervention temperature in bedroom 3 during Experiment 2.

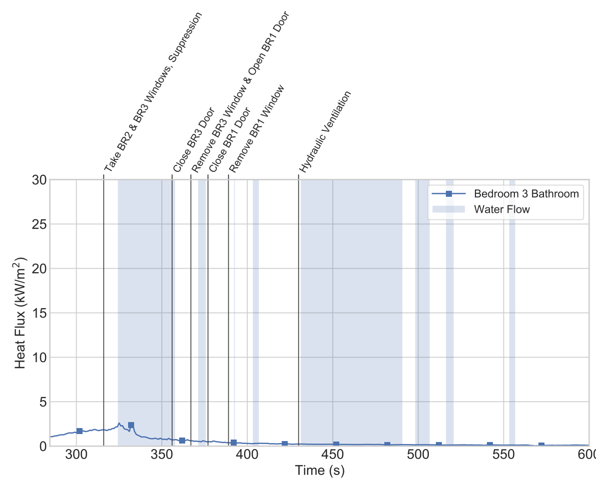
The door between bedroom 3 and bathroom 3 was opened prior to ignition. Visibility in bathroom 3 was lost approximately 70 s prior to complete visibility loss in bedroom 3. At the time of intervention, bathroom temperatures ranged from 220 °C (428 °F) at the ceiling to 80 °C (176 °F) 1 ft above the floor (Figure 5.24). Bathroom temperatures were less than adjacent bedroom temperatures, as the bathroom was offset from the flow of gases between the hallway and bedroom 3. Ventilation of half the bedroom 3 window led to increased flow of combustion gases from the hallway into the bedroom. As a result of being offset from the flow path, bathroom temperatures remained steady. Water flow decreased bathroom temperatures from 220 °C to 140 °C (392 °F to 284 °F) at the ceiling and from 90 °C to 45 °C (194 °F to 113 °F) 1 ft above the floor. Temperatures reduced below 60 °C (140 °F) following bedroom 3 isolation.

Heat flux in the bathroom had a similar response to temperature during the duration of the experiment. Following ventilation of the bedroom 3 window, heat flux increased from 1.8 kW/m^2 to 2.6 kW/m^2, as shown in Figure 5.24b. Suppression of bedroom 4 fire resulted in less gas flow from the hallway and heat flux decreased to 0.7 kW/m^2. Bidirectional flow through the bedroom 3 window lifted the smoke layer in the bedroom and bathroom, and heat flux continued to decrease for the remainder of the experiment.

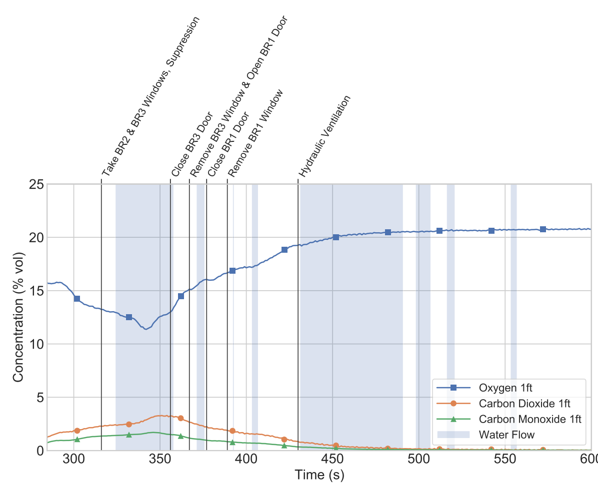
Figure 5.24c shows bathroom gas concentrations 1 ft above the floor, which were comparable to the same elevation in the adjacent bedroom at the time of intervention: 13.2% O_2, 2.3% CO_2, and 1.4% CO. Following bedroom 3 window ventilation, combustion gases continued to accumulate in the bathroom due to the increased flow of gases toward the exterior vent. Gases in the bathroom peaked in concentration 26 s after ventilation (6 s after the bedroom). Suppression and subsequent isolation of bedroom 3 led to a recovery in concentrations, as gases were exchanged through the bedroom 3 window. However, since the bathroom was offset from the primary flow path established through the window and lacked a local exterior vent, gas concentration recovery was slower than in the bedroom. Concentrations did not recover to pre-ignition levels until 214 s after intervention.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

Figure 5.24: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 2.

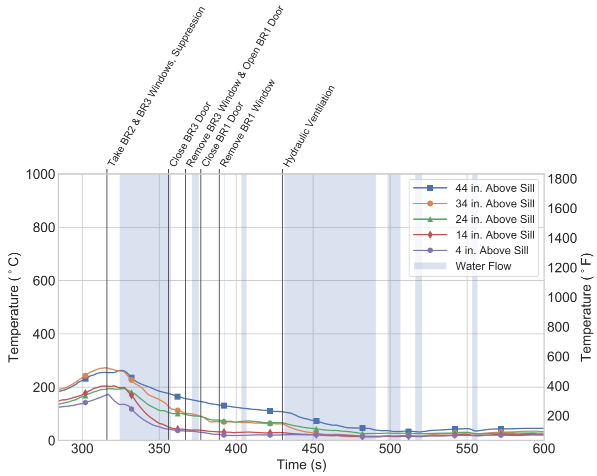
5.2.3 Bedroom 2

The door between bedroom 2 and the hallway was opened prior to ignition, which allowed combustion gases to fill the bedroom. Visibility in bedroom 2 was lost approximately 97 s prior to fire department intervention. Figure 5.25 shows the time histories of temperature, velocity, heat flux, and gas concentrations through and below the bedroom 2 window. At the time of intervention, temperatures at the window ranged from 270 °C (518 °F) 44 in. above the sill to 170 °C (338 °F) 4 in. above the sill (Figure 5.25a).

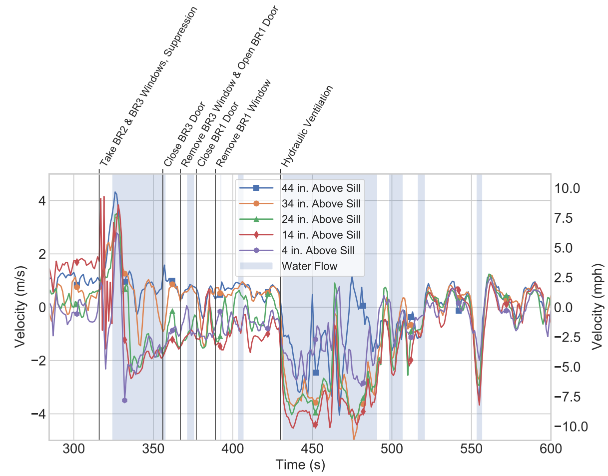
Immediately following window ventilation, unidirectional exhaust flow through the window was established as higher-temperature, higher-pressure gases accumulated in bedroom 2 flowed toward the lower-pressure exterior. The unidirectional exhaust flow continued through the start of the suppression. Air entrainment from the hoseline, directed toward the end hallway location, was manipulated in an O-pattern. This resulted in an area of increased pressure ahead of the stream. Gases flowed from the area of higher-pressure to lower-pressure, which increased gas flows through the hallway and through the open bedroom 2 window between 2.8 m/s and 4.3 m/s (6.2 mph and 9.6 mph) (Figure 5.25b).

As suppression continued in bedroom 4, the unidirectional gas flow through the window transitioned to bidirectional flow. Combustion gas exhausted approximately 0.7 m/s (1.6 mph) and air entrained approximately -1.2 m/s (2.7 mph), which decreased temperatures to 110 °C (230 °F) at the ceiling and 20 °C (68 °F) 1 ft above the floor. Gas flows remained nominally steady until hydraulic ventilation, which created unidirectional inflow with peaks flows of -4 m/s (9 mph) through the window. Temperatures decreased all temperatures below 40 °C (104 °F).

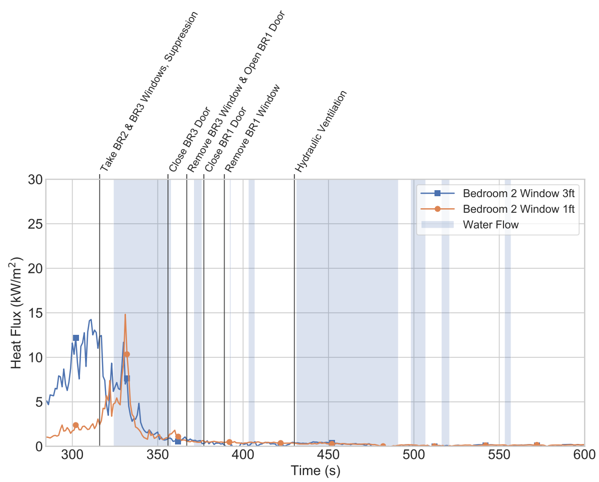
At the time of intervention, heat flux below the bedroom 2 window was 12.4 kW/m^2 3 ft above the floor and 2.4 kW/m^2 1 ft above the floor, as shown in Figure 5.25c. In the 5 s immediately following the bedroom 2 window ventilation, the 3 ft heat flux decreased and the 1 ft heat flux increased to approximately 5.0 kW/m^2. The decrease at the 3 ft elevation was temporary, driven by the influx of air associated with window ventilation. Heat flux at both elevations subsequently spiked to 12 kW/m^2 and 15 kW/m^2 at the 3 ft elevation and 1 ft elevation, respectively, despite the concurrent drop in window temperature. Increased gas velocity through the window increased the convective heat transfer; therefore, the peak heat flux corresponded to the peak exhaust flow. Once gas flow through the lower portion of the window transitioned to inflow, heat flux decreased at both elevations. Prior to hydraulic ventilation, magnitudes at both elevations had dropped below 0.4 kW/m^2, which minimized its impact.



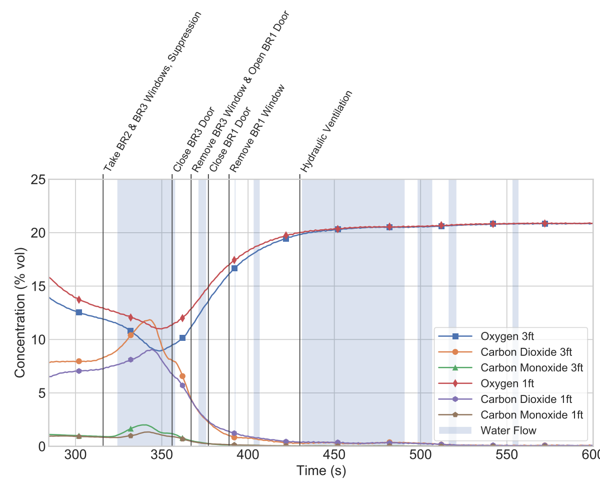
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux

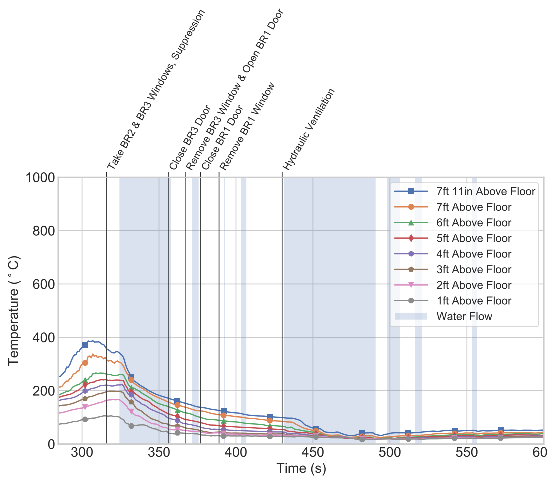


(d) Bedroom 2 Window Gas Concentration

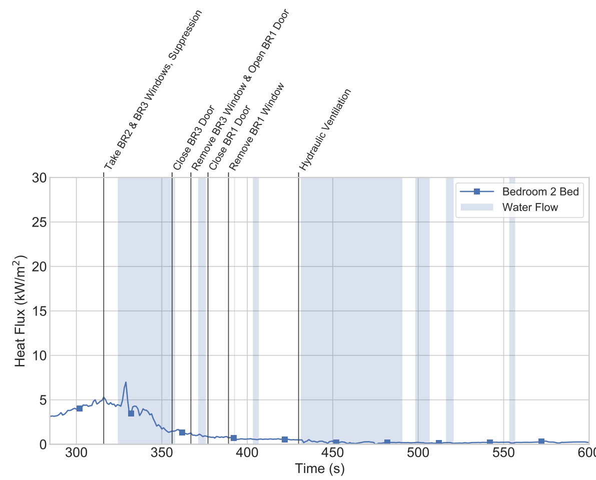
Figure 5.25: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 2.

The gas concentration time histories below the bedroom 2 window are shown in Figure 5.25d. At the time of intervention, gas concentrations 3 ft above the floor were 11.9% O_2, 8.3% CO_2, and 0.9% CO, and gas concentrations 1 ft above the floor were 13.0% O_2, 7.2% CO_2, and 0.9% CO. These values indicated that the smoke layer had descended past the 1 ft level. After ventilation, gas flows through the bedroom increased during the period of unidirectional exhaust, which peaked gas concentrations to 8.9% O_2, 11.9% CO_2, and 2.0% CO 3 ft above the floor and 11.0% O_2, 9.1% CO_2, and 1.3% CO_2 1 ft above the floor. Flow through the bedroom window became bidirectional, which, similar to temperature and heat flux, reduced gas concentrations. After suppression, gas concentrations began to steadily improve. During hydraulic ventilation, gas concentrations returned to pre-ignition levels.

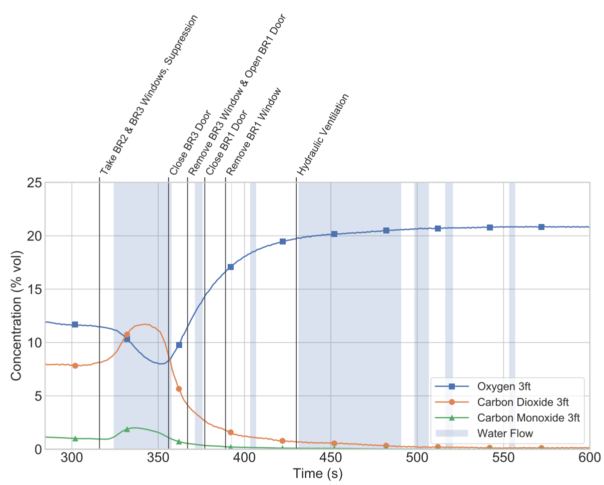
At the time of intervention, bedroom 2 temperatures ranged from 360 °C (860 °F) at the ceiling to 105 °C (221 °F) 1 ft above the floor (Figure 5.26a). Bedroom temperatures remained steady following ventilation of the bedroom window and began to uniformly decrease with the onset of hallway suppression. In contrast to the isolated bedroom 3, hydraulic ventilation reduced bedroom temperatures from 100 °C to 35 °C (212 °F to 95 °F) at the ceiling and from 29 °C to 20 °C (84 °F to 68 °F) 1 ft above the floor.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

Figure 5.26: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 2.

Heat flux at the bed was 5.3 kW/m^2 at the time of intervention, as shown in Figure 5.26b. Similar to the 3 ft heat flux below the window, the heat flux on the bed initially decreased following ventilation. Within 4 s of water flow, the bed heat flux, like the window heat fluxes but to a lesser degree due to its offset location from the flow path, had a temporary increase. Heat flux peaked to 7.0 kW/m^2, as increased flow through the window during unidirectional exhaust increased the convective hat transfer. Following this peak, the gas velocities decreased, and heat flux steadily decreased for the remainder of the experiment. Hydraulic ventilation caused heat flux at the bed to decrease from 0.5 kW/m^2 to 0.2 kW/m^2.

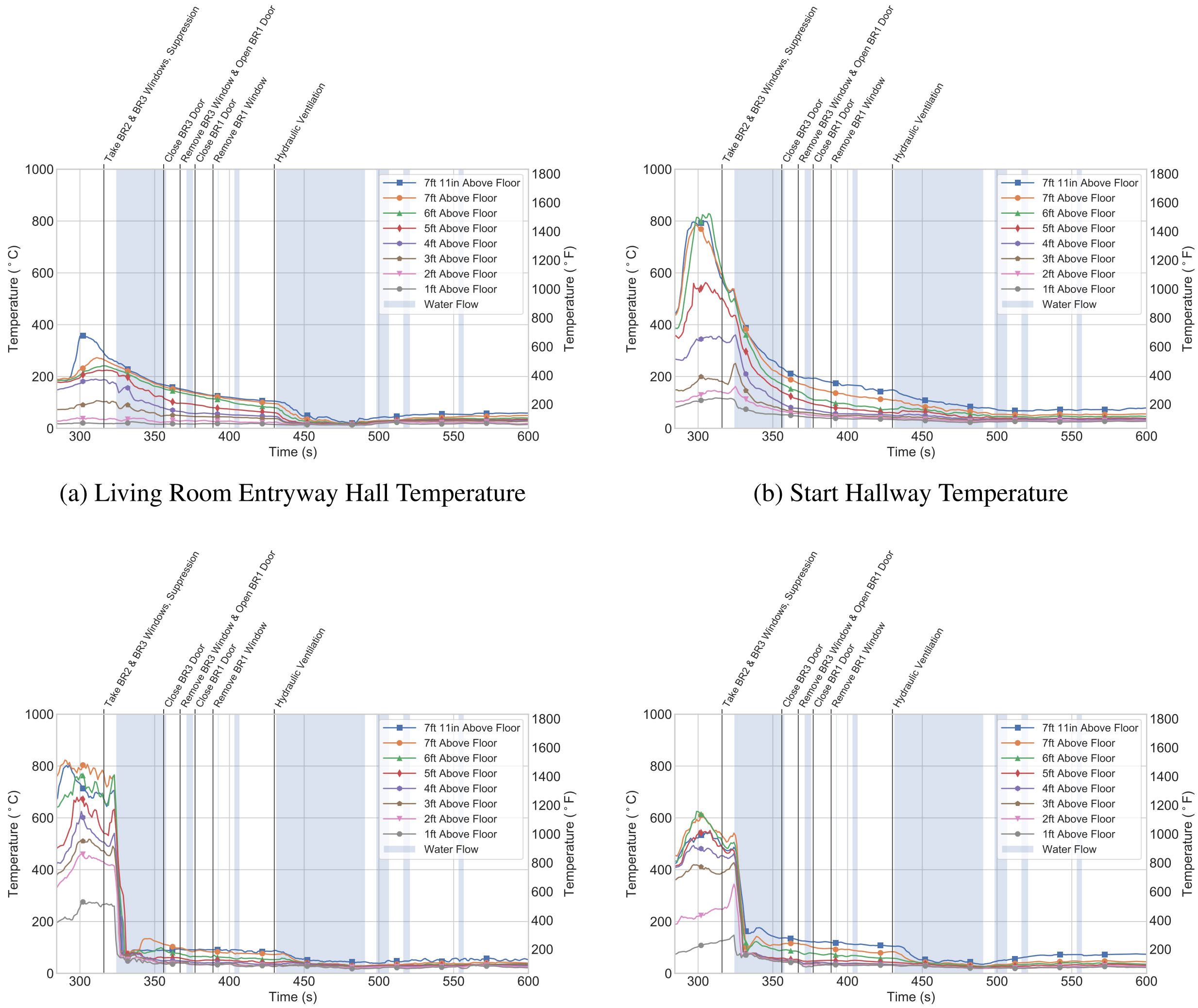
Gas concentrations at the bed 3 ft above the floor were increasing prior to window ventilation as combustion gases accumulated in the bedroom. Concentrations were 11.5% O_2, 8.2% CO_2, and 0.9% CO at the time of intervention, as shown in Figure 5.26c. Similar to window gas concentrations, gas concentrations at the bed continued to increase following window ventilation, as gases flowed through the bedroom toward the exterior vent. Gas flow through the window transitioned to bidirectional flow, which improved gas concentrations to 19.7% O_2, 0.7% CO_2 and 0.1% CO. Hydraulic ventilation further improved gas concentrations to pre-ignition levels.

5.2.4 Hallway

Figure 5.27 shows the temperature time histories for each hallway location. Hallway temperatures at the time of intervention were dependent on proximity to the fire room (bedroom 4). The mid hallway location was closest to the fire room and had the greatest temperatures, which ranged from 775 °C (1427 °F) at the ceiling to 265 °C (509 °F) 1 ft above the floor. The end hallway and start hallway locations were similar in distance to the fire room and had similar temperatures, which ranged from 535 °C to 605 °C (995 °F to 1121 °F) at the ceiling and 125 °C to 115 °C (257 °F to 257 °F) 1 ft above the floor, respectively. The living room entryway location was the furthest from the fire room and had the lowest temperatures, which ranged from 365 °C (689 °F) at the ceiling to 60 °C (140 °F) 1 ft above the floor. The open volume of the common space and flow through the front door prevented the accumulation of combustion gases in the living room entryway, which caused temperatures to be lower than the hallway.

Window ventilation in bedrooms 2 and 3 created two new exterior vents. As gas flow from bedroom 4 toward the vents increased, temperatures at the start hallway, mid hallway, and end hallway locations increased. The end hallway and mid hallway locations had the greatest temperature increase, as the measurement locations were within the flow paths between the fire room and the exterior vents.

The suppression crew flowed water in the hallway in an O-pattern to cool gases and suppress flaming combustion, which reduced mid hallway and end hallway temperatures, as both locations were ahead of the hoseline. Temperatures at the mid hallway location decreased below 70 °C (158 °F) in approximately 7 s and temperatures at the end hallway location decreased below 165 °C (329 °F) in approximately 8 s (5 ft and below dropped to 75 °C (167 °F)). The start hallway and living room entryway locations decreased as the initial water flow cooled gases in the hallway, but as these locations were behind the hoseline, temperatures decreased more gradually than the mid and end hallway locations. At the start hallway location temperatures decreased below 220 °C (428 °F) and at the living room entryway location temperatures decreased below 190 °C (374 °F). Hydraulic ventilation occurred through the fire room window, which increased the rate of temperature decrease at all four locations. Temperatures reduced below 80 °C (176 °F).



(a) Living Room Entryway Hall Temperature

(b) Start Hallway Temperature

(c) Mid Hallway Temperature

(d) End Hallway Temperature

Figure 5.27: Temperature time histories in the hallway in the period following fire department intervention in Experiment 2.

Figure 5.28 shows the heat flux time histories for each hallway location. Similar to hallway temperatures, hallway heat fluxes were dependent on proximity to the fire room at the time of intervention. The mid hallway heat flux was 22.0 kW/m^2, the start hallway heat flux was 8.3 kW/m^2, the end hallway heat flux was 3.6 kW/m^2, and the living room entryway heat flux was 1.4 kW/m^2. Following ventilation, the flow of higher-temperature combustion gases from bedroom 4 into the hallway increased, which increased heat flux at the end hallway and mid hallway locations to 40.7 kW/m^2 and 6.4 kW/m^2, respectively. During suppression, the heat flux at these locations were coated with water, which impacted the measurement accuracy. Therefore, post-suppression heat flux data at the mid hallway and end hallway locations are not an accurate representation of heat flux. The start hallway and living room entryway heat flux sensors were not impacted by water flow. Suppression decreased heat flux to 0.8 kW/m^2 and 0.5 kW/m^2, respectively. Hallway heat fluxes steadily

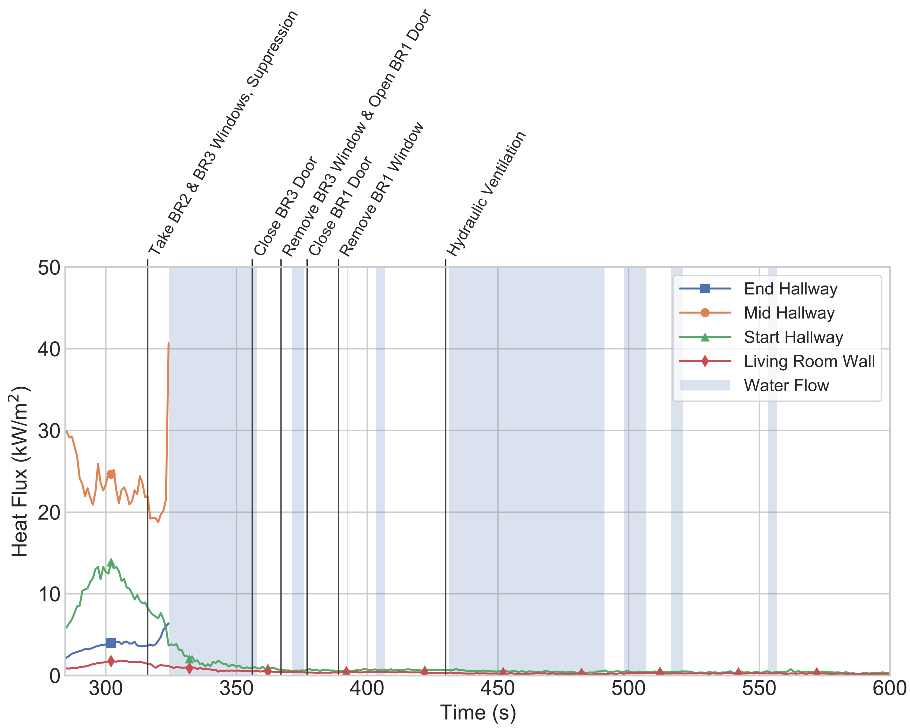


Figure 5.28: Heat flux time histories in the hallway in post-intervention period during Experiment 2.

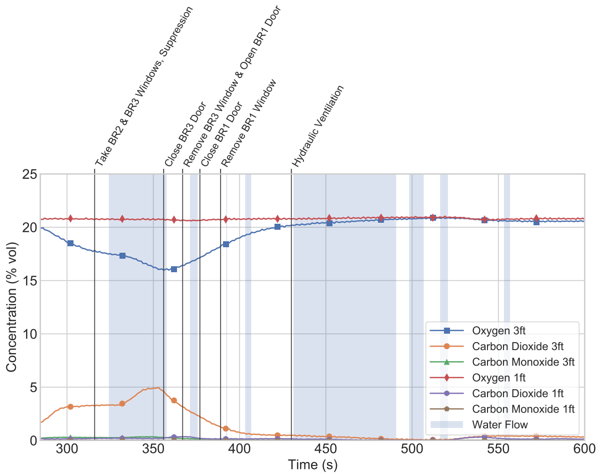
decreased for the duration of the experiment.

Table 5.4 shows the gas concentrations measured in the hallway at the time of intervention. The end hallway and mid hallway were similarly characterized by low O_2 concentrations and elevated CO and CO_2 concentrations, which indicated that prior to intervention the smoke layer had descended past the 1 ft level at these measurement locations. The lack of open vent between the fire room and bedroom 2 led to combustion gas accumulation along this flow path. The large volume of the common space and flow through the open front door limited the accumulation of gas concentrations at the start hallway and living room entryway, particularly relative to the other hallway locations.

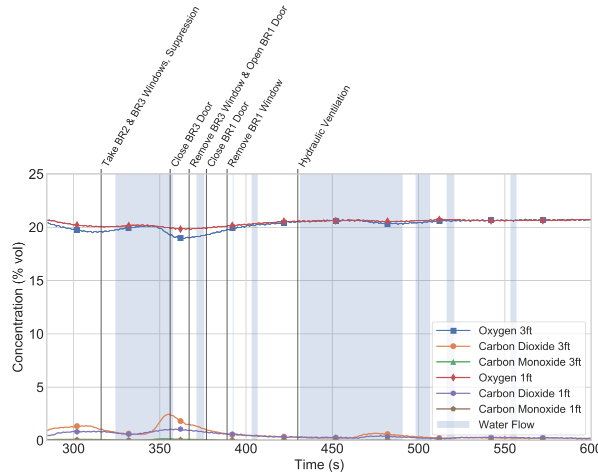
Table 5.4: Hallway Gas Concentrations at Intervention for Experiment 2

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	17.8	3.2	0.3
	1 ft	20.7	0.2	0.0
Start Hallway	3 ft	19.6	1.1	0.1
	1 ft	20.1	0.8	0.1
Mid Hallway	3 ft	12.5	8.1	0.7
	1 ft	14.7	5.6	0.7
End Hallway	3 ft	9.5	11.7	1.5
	1 ft	19.0	2.0	0.3

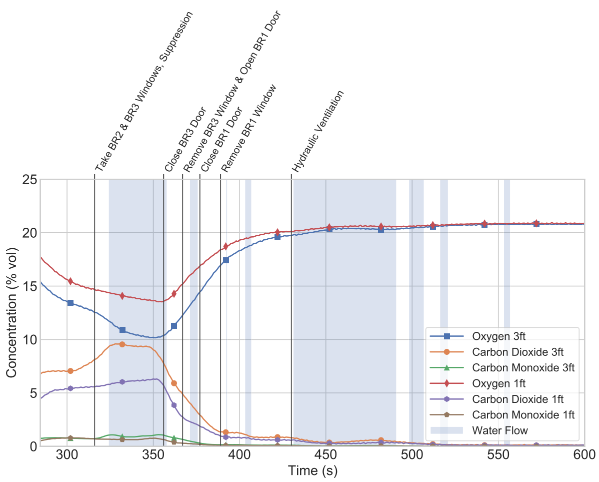
Figure 5.29 shows the gas concentration time histories for each hallway location. The flow of combustion gases from the fire room into the hallway increased after ventilation of half the bedroom 2 and 3 windows, which worsened gas concentrations at the mid hallway and end hallway locations. Gas concentrations throughout the hallway improved by the completion of suppression. The timing and rate of recovery toward pre-ignition levels was driven by the proximity to an exterior vent and proximity to the flow paths that terminated at the bedroom 2 window, bedroom 4 window, or front door. Concentrations at the 3 ft elevation at the living room entryway remained elevated post-suppression, in contrast to the start hallway, as the accumulated gases in the common space exhausted through the front door, past the entryway location. All concentrations returned to pre-ignition levels by the completion of hydraulic ventilation.



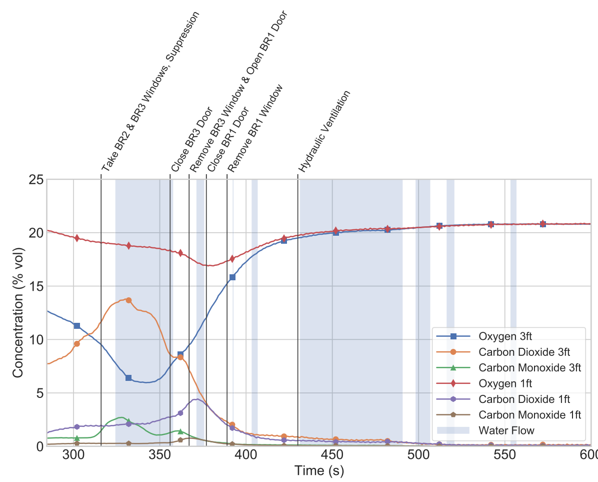
(a) Living Room Entryway Hall Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.29: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 2.

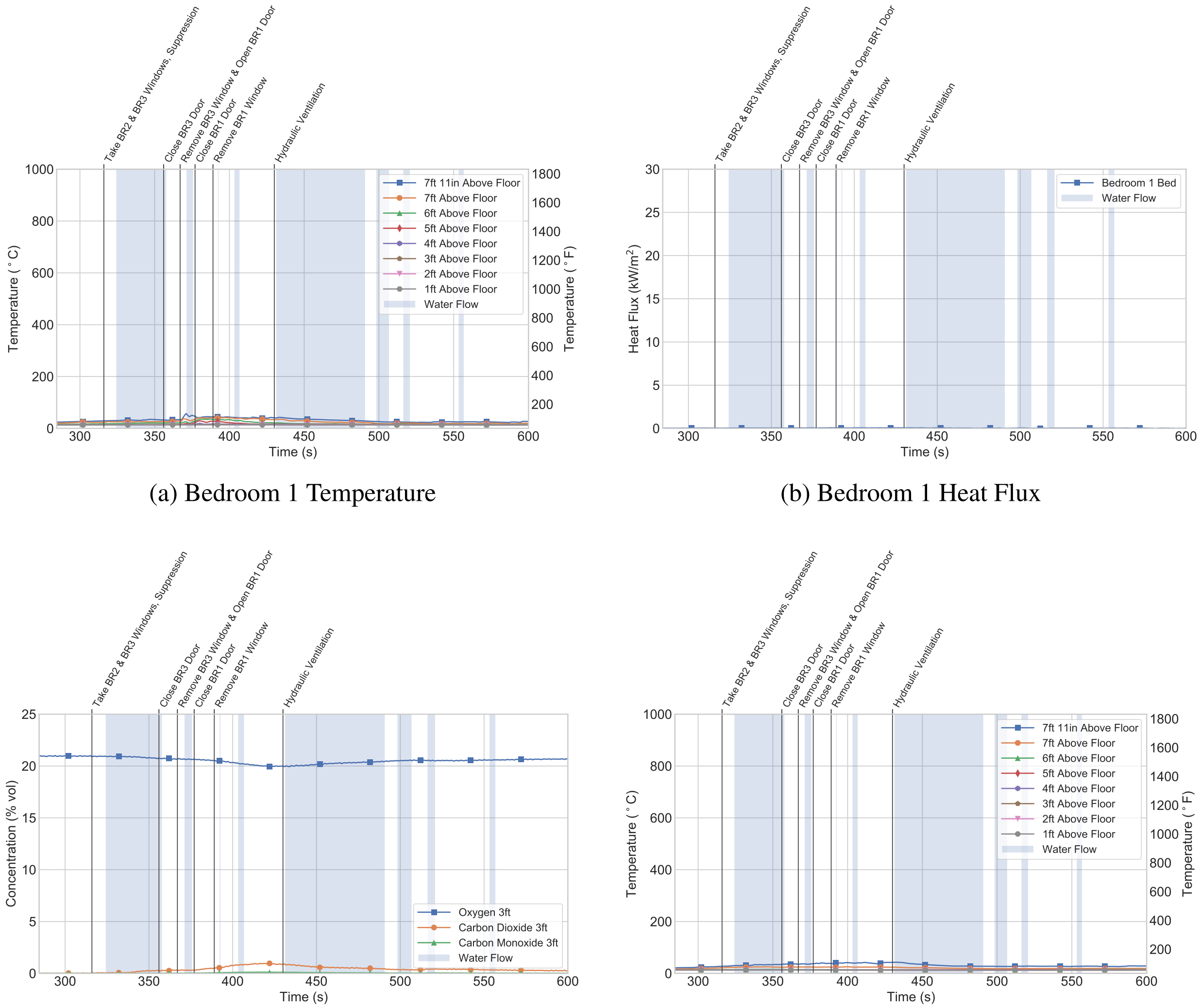
5.2.5 Bedroom 1

In contrast to bedrooms 2 and 3, the bedroom 1 door was closed prior to ignition. The closed door limited the exchange of combustion gases and air between bedroom 1 and the hallway. Figure 5.30 shows the time histories of the bedroom 1 temperatures, heat flux, and gas concentrations as well as bathroom 1 temperatures. Combustion gases entered the room through a combination of higher-pressure gases flowing through the leakage area around the closed door and through the HVAC supply vents.

Bedroom 1 temperatures ranged from 30 °C (86 °F) at the ceiling to 15 °C (59 °F) 1 ft above the floor at the time of intervention (Figure 5.30a). During the 10 s that the bedroom 1 door was opened, temperatures increased to 60 °C (140 °F) at the ceiling and 20 °C (68 °F) 5 ft above the floor. After the door was closed, temperatures became steady between 45 °C (113 °F) at the ceiling to 30 °C (86 °F) 1 ft above the floor. Once the bedroom window was removed, temperatures began to decrease, as gases were exchanged between the bedroom and the exterior. The door to bedroom 1 remained closed for the duration of the experiment, which minimized the impact of hydraulic ventilation.

The lack of gas flow into the bedroom from ignition, which resulted in low temperatures, limited the heat flux to the bed when the door was opened and closed. Figure 5.30b shows that heat flux increased to 0.1 kW/m^2 during the 10 s duration that the door was opened.

Similar to temperature and heat flux, gas concentrations remained near pre-ignition levels until the bedroom 1 door was opened. Toggling the bedroom door caused gas concentrations to slightly worsen and peak to 20.0% O_2, 1.0% CO_2, and 0.1% CO (Figure 5.30c). Removal of the bedroom 1 window caused bidirectional flow to establish between the bedroom and the exterior. The resulting gas exchange led to pre-ignition gas concentration levels.



(a) Bedroom 1 Temperature

(b) Bedroom 1 Heat Flux

(c) Bedroom 1 Gas Concentration

(d) Bathroom 1 Temperature

Figure 5.30: Post-intervention temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 2.

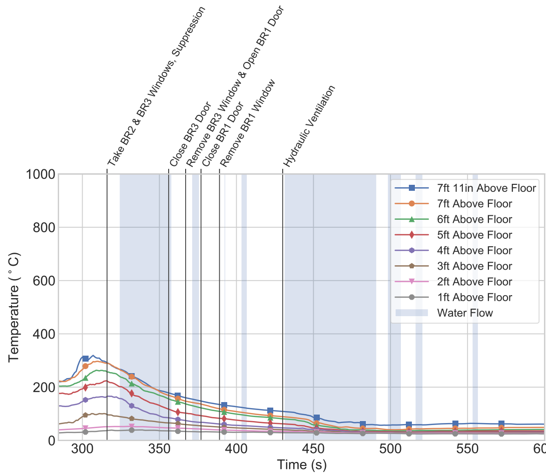
Figure 5.30d shows the temperature time history within bathroom 1. The door between bedroom 1 and bathroom 1 was closed at the time of ignition. As a result, the only path for products of combustion to flow into bathroom 1 were via leakage around the closed door and through the HVAC supply vent. Temperatures in bathroom 1 were comparable to those observed in bedroom 1 at the time of intervention: 30 °C (86 °F) at the ceiling and 15 °C (50 °F) 1 ft above the floor. Temperatures gradually increased for the duration of the experiment, peaking to 45 °C (113 °F) at the ceiling prior to hydraulic ventilation. The door to bathroom 1 remained closed, so the impact of hydraulic ventilation was minimal.

5.2.6 Common Space

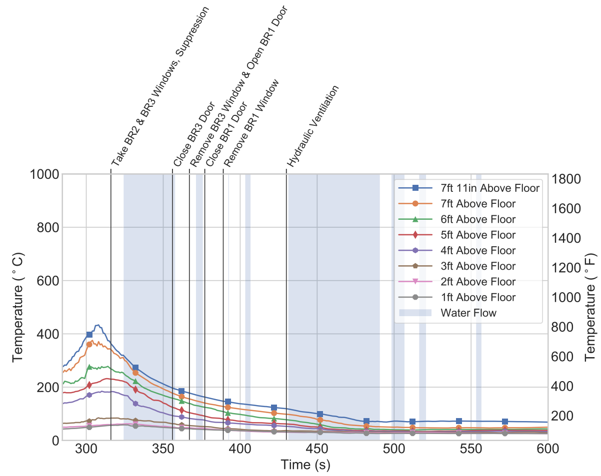
Figure 5.31 shows the time histories for the kitchen and living room temperatures, kitchen heat flux, and kitchen gas concentrations. Prior to intervention, kitchen and living room temperatures had peaked to 320 °C and 435 °C (608 °F and 815 °F), respectively, and were decreasing. Air entrainment through the front door prevented the smoke layer from descending to the floor, which caused temperatures 2 ft and below to remain near pre-ignition levels. Temperatures continued to decline, as suppression reduced the production of combustion gases and remained gases exhausted out of open exterior vents.

Figure 5.31c shows the heat flux time history 1 ft above the kitchen floor. Heat flux in the kitchen followed a similar trend to temperature and had peaked to 1.2 kW/m^2 before decreasing prior to intervention. Following suppression, heat flux decreased below 0.4 kW/m^2. Heat flux decreased to negligible values prior to hydraulic ventilation, which minimized its impact.

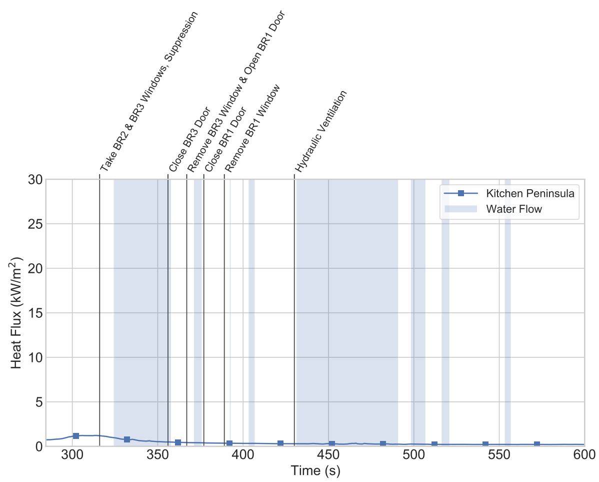
At the time of intervention, kitchen gas concentrations were near pre-ignition levels (20.5% O_2, 0.1% CO_2, and 0.1% CO), as the smoke layer had not descended to the 1 ft measurement location (Figure 5.31d). During the first 20 s of suppression, gas concentrations worsened, as combustion gases cooled and dropped in elevation. At the completion of suppression, gas concentrations reached concentrations of 19.1% O_2, 0.7% CO_2, and 0.3% CO. Note: These concentrations were less than those in open spaces closer to bedroom 4 at the same elevation. Gas concentrations recovered following hydraulic ventilation.



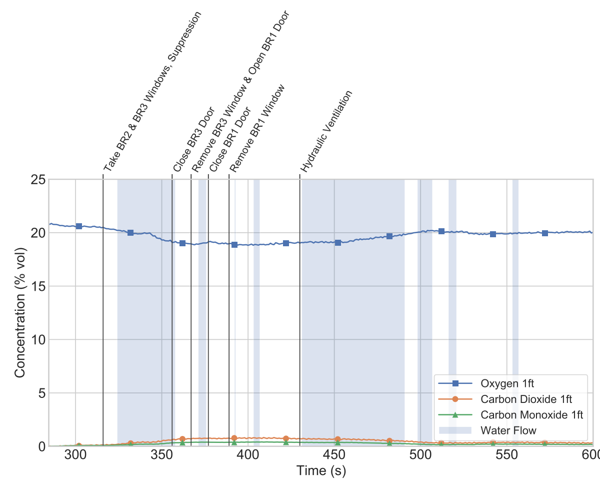
(a) Kitchen Temperature



(b) Living Room Temperature



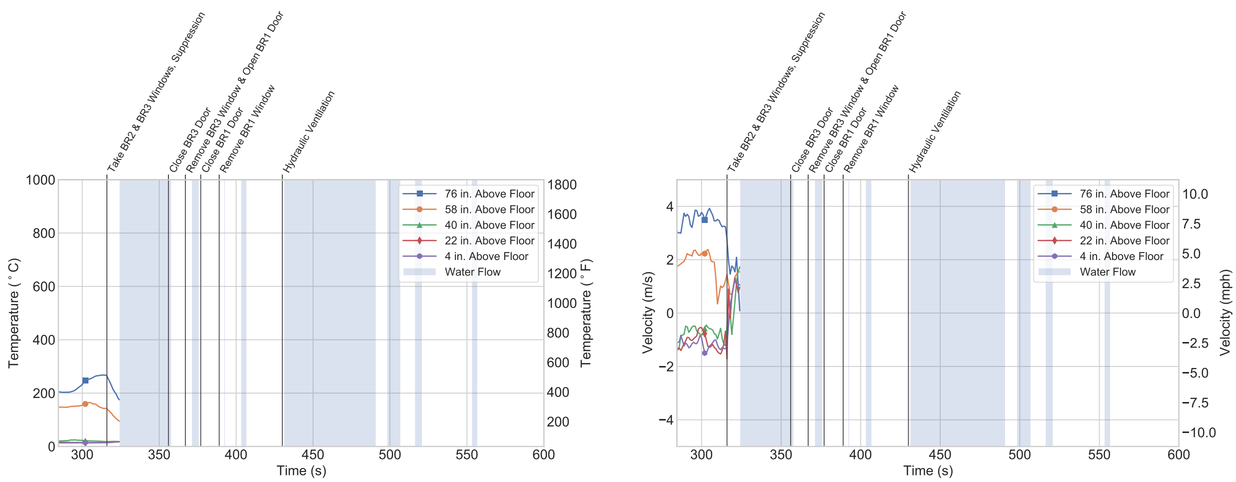
(c) Kitchen Heat Flux



(d) Kitchen Gas Concentration

Figure 5.31: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 2.

Figure 5.32 shows the temperature and velocity time histories for the front door. Front doorway temperatures at the time of intervention were stratified between 265 °C and 145 °C (509 °F and 293 °F) at the top of the frame and between 14 °C and 18 °C (58 °F and 65 °F) near the floor, as shown in Figure 5.32a. Front door velocities were between 2.8 m/s and 1.4 m/s (6.3 mph and 3.1 mph) near the top of the frame and -0.5 m/s and -1.7 m/s (-1.1 mph and -3.8 mph) near the floor, which indicated bidirectional flow through the door (Figure 5.32b). The bidirectional probes were removed 324 s post-ignition, prior to crew entry into the structure for interior suppression. Data recorded after this time stamp are not reflective of flow through the doorway.



(a)

(b) Front Doorway Velocity

Figure 5.32: Post-intervention temperatures and velocities in the front doorway during Experiment 2.

5.3 Experiment 3

The search tactics in Experiment 3 were designed to evaluate window initiated operations conducted during exterior suppression. Prior to ignition, the lower panes of the double-wide bedroom 4 window and the bedroom 4 door were removed. The front door and doors to bedroom 2, bedroom 3, and bathroom 3 were opened. The doors to bedroom 1 and bathroom 1 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 flashover, crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. At the onset of ventilation, exterior suppression began through the failed bedroom 4 window. After an initial knockdown, the suppression crew shut down the stream and moved to the interior of the structure for final extinguishment. The crews entered bedrooms 2 and 3 and proceeded toward the doors to the hallway. The crew in bedroom 3 closed the door, which isolated bedroom 3 from the flow of combustion gases. The crew in bedroom 2 were unable to close the door and continued across the hallway. The crew opened the closed bedroom 1 door and entered the bedroom. The crew closed the bedroom 1 door. Simultaneously, the bedroom 1 and bedroom 3 windows were removed. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed bedroom 4 window. 50 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 309 gallons. Table 5.5 provides the timing of each event relative to ignition and the first fire department intervention, which was ventilation of half the bedrooms 2 and 3 double-wide windows.

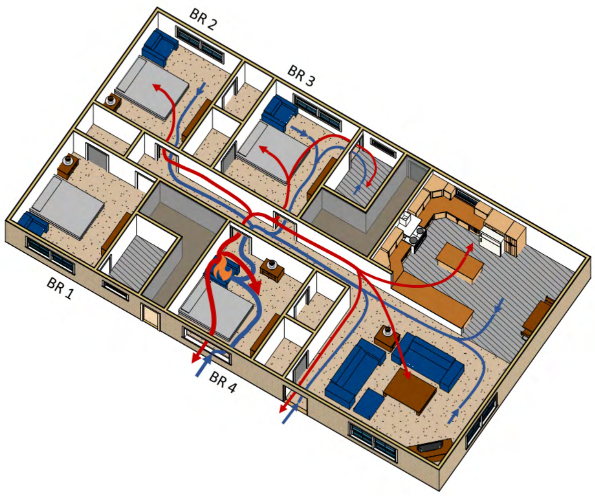
Table 5.5: Experiment 3 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Ignition	00:00	0	—	—
Take BR2 & BR3 Windows	05:00	300	00:00	0
Exterior Suppression	05:09	309	00:09	9
Close BR3 Door	05:35	335	00:35	35
Open BR1 Door	05:50	350	00:50	50
Close BR1 Door	06:05	365	01:05	65
Remove BR1 & BR3 Windows	06:20	380	01:20	80
Hydraulic Ventilation	06:40	400	01:40	100

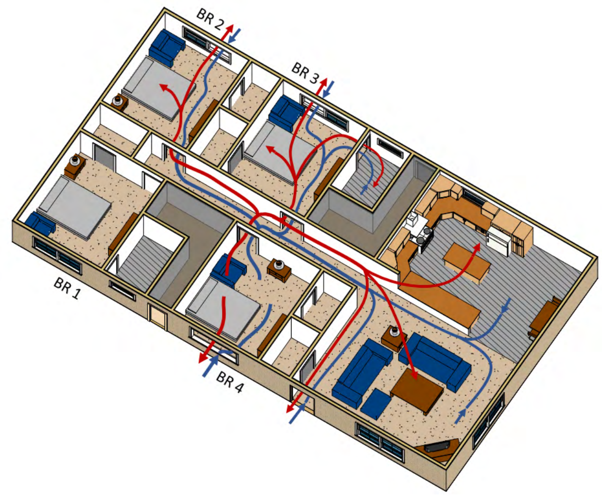
Figures 5.33 and 5.34 show the changes in gas flow in the time period immediately preceding and following each fire department intervention over the duration of Experiment 3. Prior to initial intervention, bedroom 4 was in a steady post-flashover state, as higher-pressure combustion gases were exhausted and lower-pressure air was entrained through the bedroom 4 vents. Flow paths were established between the fire room and the exterior of the structure, through the bedroom 4 window, and between the fire room and open volumes of the structure (bedroom 2, bedroom 3, bathroom 3, and common space), through the bedroom 4 doorway, as shown in Figure 5.33a.

Ventilation of half the double-wide windows in bedrooms 2 and 3 created two new exterior vents. As a result, two flow paths were established between the fire room and the exterior of the structure, through each bedroom (Figure 5.33b). Flow through these vents was initially unidirectional exhaust, due to accumulated pressure within the respective bedrooms. As the pressure decreased, flow through these windows became bidirectional.

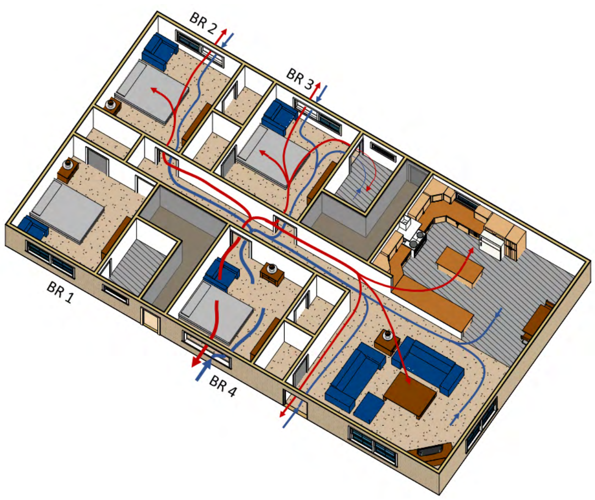
Exterior suppression was conducted through the failed double-wide bedroom 4 window from a smooth bore nozzle with a 7/8 in. tip, set to flow 160 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline. Exterior suppression reduced the heat release rate of the fire and reduced the production of higher-temperature, higher-pressure combustion gases. This reduced the flow of smoke and heat throughout the structure (Figure 5.33c). Isolation of the bedroom 3 door terminated the flow path between the fire room and the exterior of the structure, which prevented further flow of combustion gases into bedroom 3 and bathroom 3 (Figure 5.33d). Accumulated combustion gases continued to drive flow through the open bedroom 3 window. In contrast, the bedroom 2 door was not isolated and the flow path through the bedroom persisted.



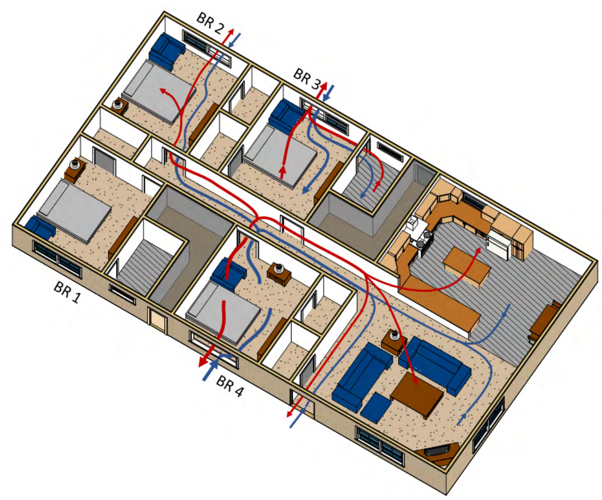
(a) Flows Prior to Intervention



(b) Take BR2 & BR 3 Windows



(c) Exterior Suppression



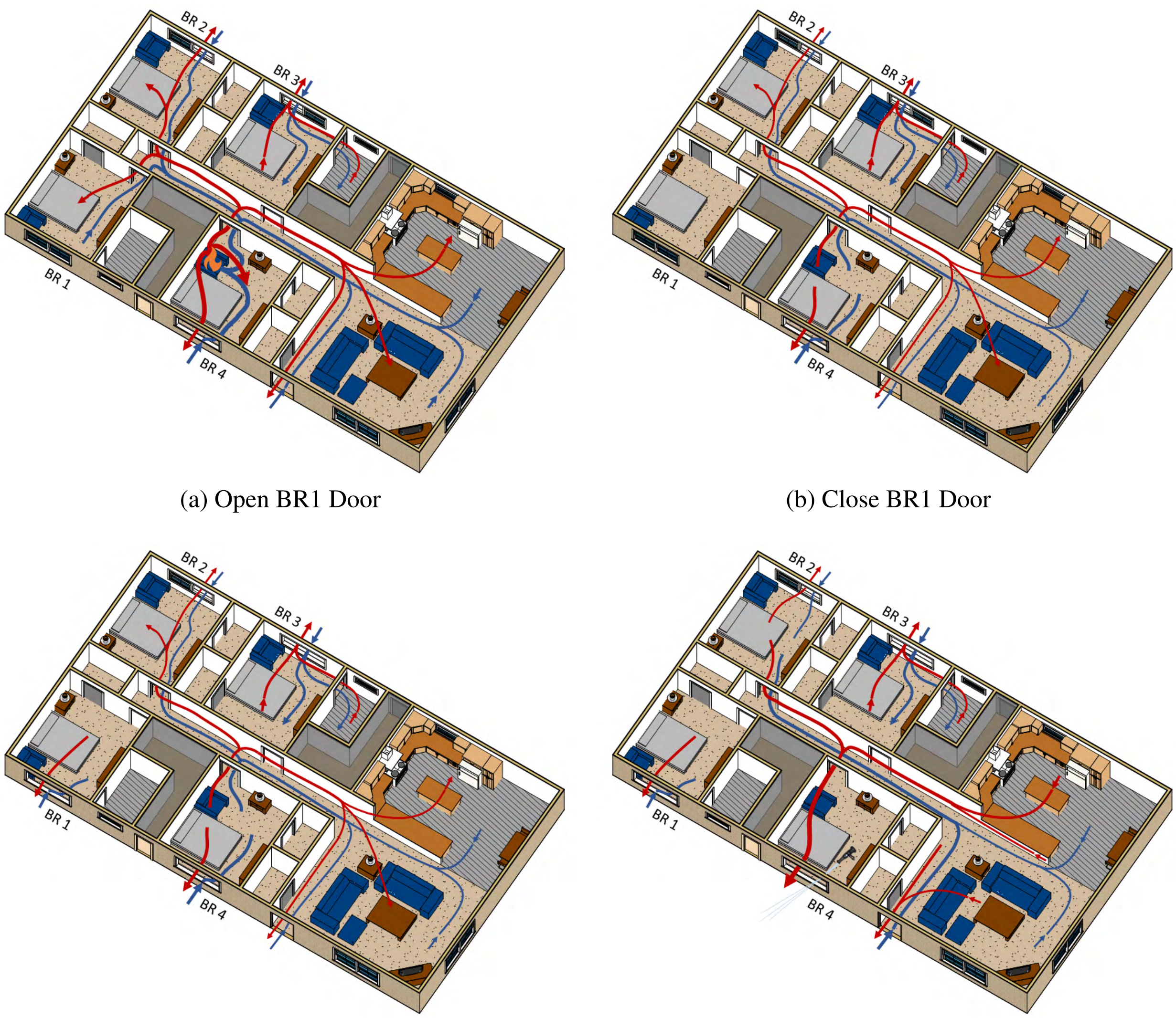
(d) Close BR3 Door

Figure 5.33: Changes in flow in structure following fire department interventions in Experiment 3.

Opening the bedroom 1 door established a new flow path between the fire room and the bedroom through the open doorway (Figure 5.34a). The bidirectional flow through the bedroom 1 doorway was momentary, as the door was closed approximately 15 s later. Closing the bedroom 1 door terminated the flow path between the fire room and bedroom 1, which prevented further accumulation of combustion gases and trapped any previously accumulated combustion gases in the bedroom (Figure 5.34b).

The bedroom 1 window was removed 15 s after the bedroom was isolated (Figure 5.34c). This created a new flow path between the bedroom and the exterior, which allowed trapped combustion gases to exhaust through the upper portion and fresh air to entrain through the lower portion of the bedroom 1 window. At the same time, the remaining half of the bedroom 3 window was removed. The surface area for ventilation increased, which increased the flow through the vent.

Hydraulic ventilation occurred out of the failed, double-wide bedroom 4 window with a full-open bale in an O-pattern. Flow through the bedroom 4 window became unidirectional exhaust. The flowing hose stream created an area of lower pressure in bedroom 4. Gases from spaces not isolated by a closed door (hallway, bedroom 2, kitchen, and living room) flowed toward the fire room and exhausted through the bedroom 4 window (Figure 5.34d). Correspondingly, air was entrained through the exterior vents in the structure (the half-ventilated bedroom 2 window and open front door). Closed volumes of the structure, spaces isolated by a closed door (bedroom 1, bathroom 1, and bedroom 3), were not impacted by hydraulic ventilation.



(a) Open BR1 Door

(b) Close BR1 Door

(c) Remove BR1 & BR3 Windows

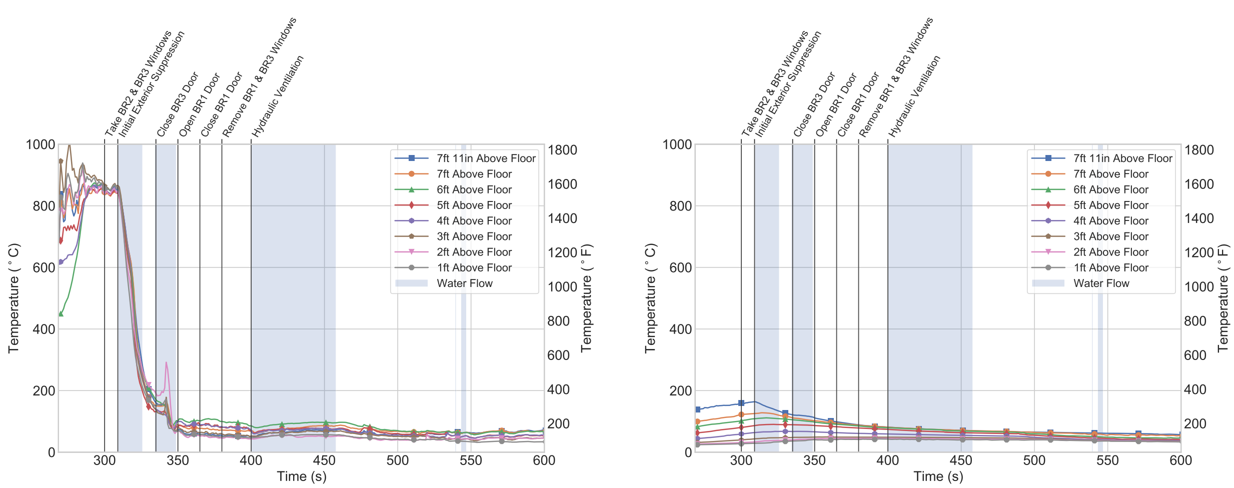
(d) Hydraulic Ventilation

Figure 5.34: Changes in flow in structure following fire department interventions in Experiment 3.

5.3.1 Bedroom 4

The bedroom 4 fire had reached a post-flashover, ventilation-limited state prior to intervention, as shown by Figure 5.35a. Temperatures at the time of intervention ranged between 865 °C (1589 °F) at the ceiling to 840 °C (1544 °F) 1 ft above the floor. Ventilation of the bedroom 2 and 3 windows, 300 s after ignition, created two additional flow paths, which began in the fire room and terminated at the exterior vents in the respective bedrooms. This change in ventilation had minimal impact on the post-flashover temperatures in bedroom 4. A steep, exterior water stream was directed off the bedroom ceiling and subsequently off the window lintel, 10 s after the bedroom 2 and 3 windows were ventilated. This water flow decreased temperatures below 250 °C (482 °F). Temperatures continued to decrease as the crew moved into the structure for interior suppression. Following interior suppression, temperatures decreased below 110 °C (230 °F); following hydraulic ventilation, temperatures decreased below 100 °C (212 °F).

Figure 5.35b shows the temperature time history in the bedroom 4 closet. Although the bedroom 4 closet was protected by a closed door, temperatures gradually increased as the fire transitioned through flashover and higher-pressure gases flowed through the leakage area around the closed door. At the time of intervention, closet temperatures ranged from 160 °C (320 °F) at the ceiling to 30 °C (86 °F) 1 ft above the floor. Temperatures in the closet began to decrease following exterior suppression, with the highest elevation decreasing first and the lower elevations (which were at lower temperatures) decreasing progressively later. Hydraulic ventilation decreased all temperatures below 70 °C (158 °F).



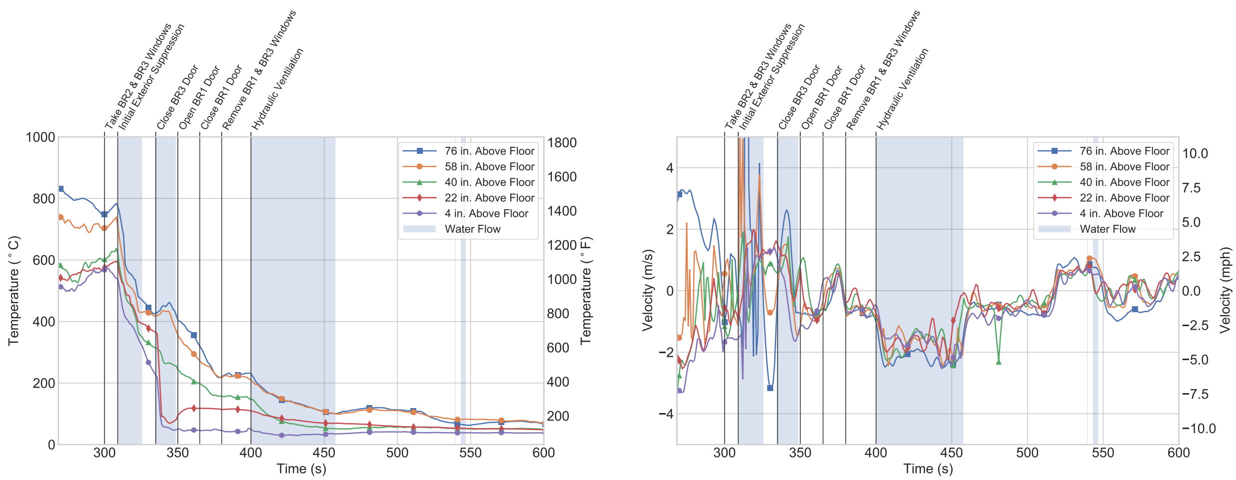
(a) Bedroom 4 Temperature

(b) Closet Temperature

Figure 5.35: Temperature time histories in bedroom 4 and closet post-intervention period during Experiment 3.

Bedroom 4 doorway temperatures at the time of intervention were between 750 °C and 705 °C (1382 °F and 1301 °F) at the 76 in. and 58 in. elevations and under 600 °C (1112 °F) at elevations 40 in. and below, as shown in Figure 5.36a. This gap in temperature was reflected by the inflow and outflow of gases through the doorway. Velocities measured at the bedroom 4 doorway indicated exhaust near the top of the frame and entrainment near the floor, as shown in Figure 5.36b. The probe 58 in. above the floor fluctuated between inflow and outflow. Following ventilation, doorway temperatures 22 in. above the floor and higher increased by approximately 30 °C (86 °F) and the temperature 4 in. above the floor decreased by approximately 40 °C (104 °F). The temperature changes were reflected by the changes in velocity. The 4 in. probe measured inflow of -1.5 m/s (-3.4 mph) and probes above 22 in. fluctuated between ± 1.0 m/s (± 2.2 mph).

Exterior suppression decreased doorway temperatures to 465 °C (104 °F) at the top of the frame and 305 °C (581 °F) 4 in. above the floor. Following interior suppression, doorway temperatures further decreased, particularly at the lower elevations. During hydraulic ventilation, temperatures continued to decrease as flow through the doorway became unidirectional inflow with an approximate velocity of -2.0 m/s (-4.5 mph).



(a) Bedroom 4 Doorway Temperature

(b) Bedroom 4 Doorway Velocity

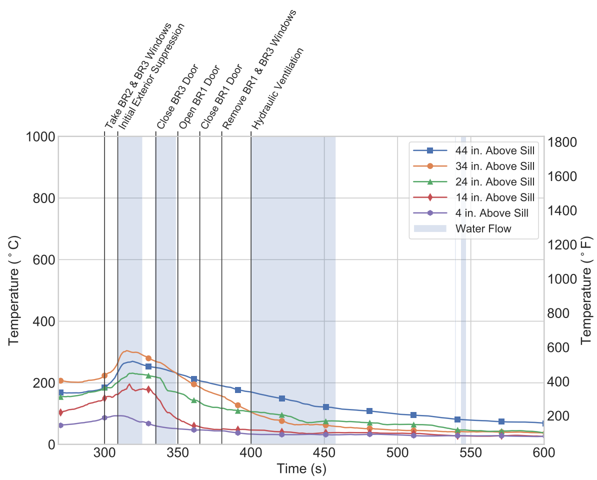
Figure 5.36: Temperature and velocity time histories in the doorway of bedroom 4 for the period following fire department intervention in Experiment 3.

5.3.2 Bedroom 3

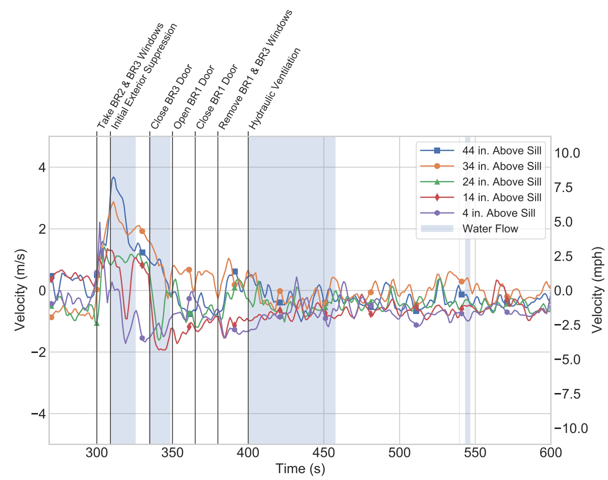
The bedroom 3 door was opened prior to ignition, which led to an accumulation of combustion gases within the bedroom due to the lack of a local exterior vent. Figure 5.37a shows the temperature time history through the bedroom 3 window. At the time of intervention, window temperatures ranged from 224 °C to 87 °C (435 °F to 189 °F). The highest elevations experienced the largest temperature increase, due to the increased flow of combustion gases through the bedroom and out the window. This is shown by the period of unidirectional exhaust through the bedroom 3 window (Figure 5.37b). During exterior suppression, temperatures peaked to 305 °C (581 °F) near the top of the frame and 95 °C (203 °F) near the bottom of the frame. As the bedroom 4 exhaust flows decreased, flow through the bedroom 3 window became bidirectional. Combustion gases were exhausted at 3.7 m/s (8.3 mph) from the top of the window and air was entrained at -1.7 m/s

(-3.8 mph) from the bottom of the window.

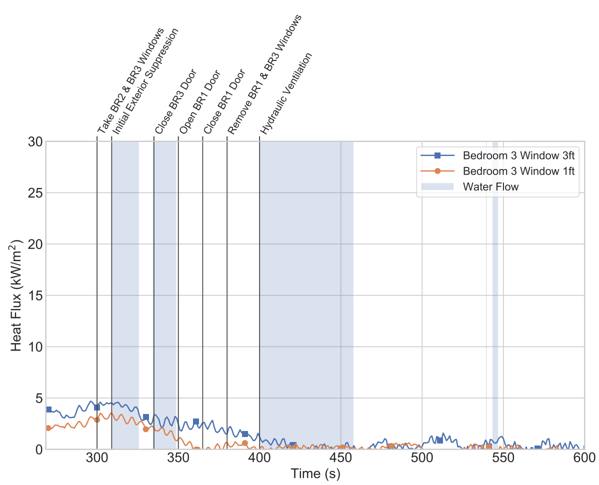
Isolation of bedroom 3 decreased the exhaust through the top of the window and increased the entrainment through the bottom of the window, leading combustion gases to decrease more rapidly. Removal of the window increased the surface area for gas exchange between the bedroom and the exterior. As the temperatures and pressures decreased within the bedroom, the gas velocity through the window also decreased. Hydraulic ventilation had minimal impact on the conditions within the bedroom because the bedroom was isolated from the hallway.



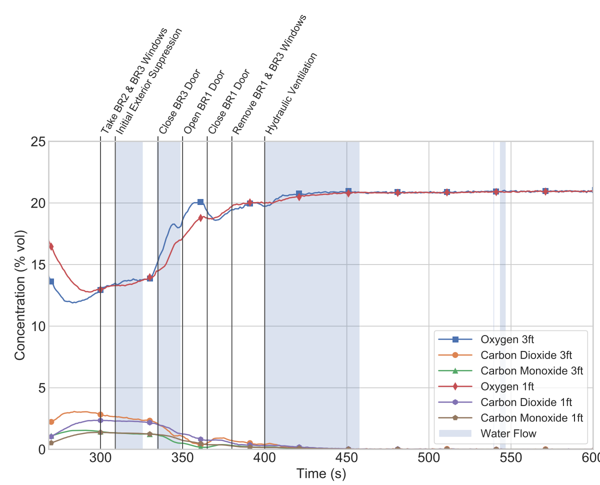
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.37: Post-intervention window temperature, heat flux, and gas concentrations at bedroom 3 window during Experiment 3.

Heat fluxes below the bedroom 3 window at the time of intervention were 4.5 kW/m^2 and 3.5 kW/m^2 at 3 ft and 1 ft above the floor, respectively as shown in Figure 5.37c. The heat flux at both elevations remained nominally steady following ventilation, similar to the temperature nearest the bottom of the window sill. Through the combination of ventilation and the onset of exterior suppression, bidirectional flow through the window was established. The air entrained through the bottom portion of the window caused the heat flux at both elevations below the bedroom 3 window to decrease to 3.0 kW/m^2 and 2.5 kW/m^2 at 3 ft and 1 ft above the floor, respectively. The bedroom was subsequently isolated and heat flux decreased to below 1 kW/m^2 due to increased air intake and exhaust of accumulated combustion gases through the window .

Gas concentrations below the bedroom 3 window at the time of intervention were 12.8% O_2, 2.8% CO_2, and 1.4% CO 3 ft above the floor and 13.1% O_2, 2.4% CO_2, and 1.4% CO 1 ft above the floor, as shown in Figure 5.37d. Ventilation of the window improved conditions near the window, as air was entrained into the bedroom. Isolating the bedroom from the flow of combustion gases further improved conditions to concentrations of 19.4% O_2, 0.7% CO_2, and 0.3% CO 3 ft above the floor and 19.8% O_2, 0.5% CO_2, and 0.3% CO 1 ft above the floor. Removing the window increased the surface area for ventilation and flow through the window. Gas concentrations improved to pre-ignition levels.

Bedroom temperatures in the center of the room ranged from 370 °C (698 °F) at the ceiling to 85 °C (185 °F) 1 ft above the floor at the time of intervention, as shown in Figure 5.38. Ventilation of the bedroom 3 window created a new exterior vent. Combustion gases flowed through the bedroom toward the vent, which increased the rate of temperature rise. The ceiling temperature peaked to 575 °C (1067 °F). Exterior suppression decreased temperatures to 350 °C (662 °F) at the ceiling and to 80 °C (176 °F) 1 ft above the floor, as cooler bedroom 4 exhaust gases flowed into bedroom 3. After bedroom isolation, temperatures continued to decrease at a steady rate due to gas exchange with the exterior through the open bedroom 3 window.

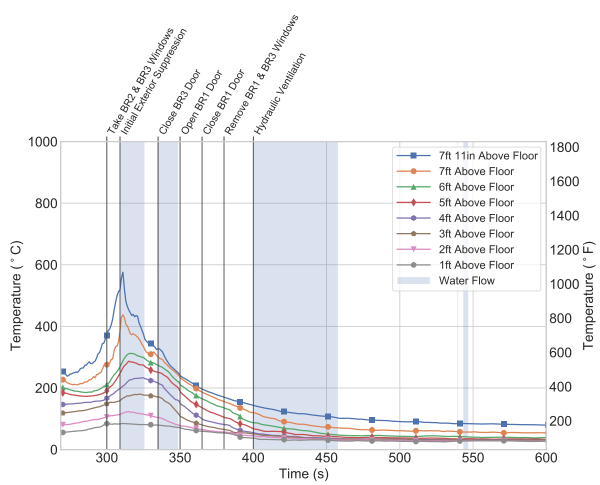
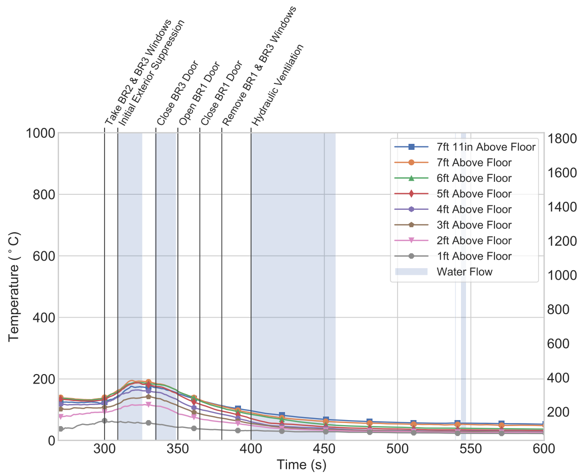


Figure 5.38: Post-intervention temperature in bedroom 3 during Experiment 3.

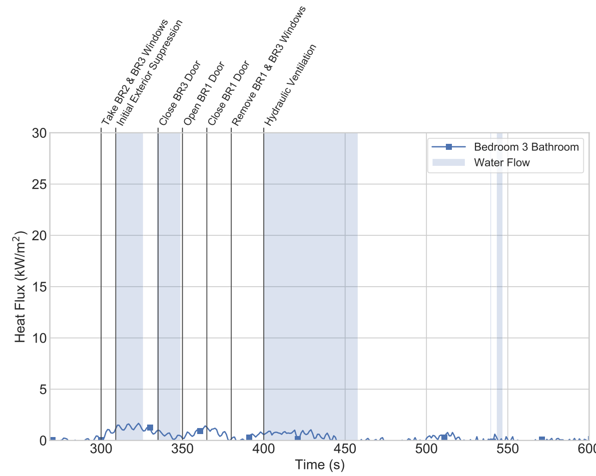
The door to bathroom 3 was opened prior to ignition, which allowed combustion gases to accumulate in the bathroom. Prior to intervention, temperatures were 140 °C (284 °F) at the ceiling and 65 °C (150 °F) 1 ft above the floor (Figure 5.39a). Following bedroom 3 window ventilation, bathroom temperatures increased. The bathroom was not directly a part of the flow path between the fire room and the open bedroom 3 window; therefore, temperatures remained less than those in the adjacent bedroom. Temperatures peaked during exterior suppression, 8 s after peak temperatures in the adjacent bedroom, to 195 °C (383 °F) at the ceiling and 60 °C (140 °F) 1 ft. above the floor. The slower response was again a result of the bathroom's adjacent location to the established flow path. Similar to bedroom 3, bathroom 3 temperatures steadily decreased for the remainder of the experiment.

The lower temperatures and lack of gas flows in bathroom 3 resulted in a lower heat flux at the same elevation in bedroom 3 compared to the window location (Figure 5.39b). Heat flux 1 ft above the floor in bathroom 3 was 0.2 kW/m^2 when the bedroom 3 window was ventilated. Similar to temperature, heat flux increased to 1.6 kW/m^2 before steadily decreasing after exterior suppression and isolation of bedroom 3 from the hallway.

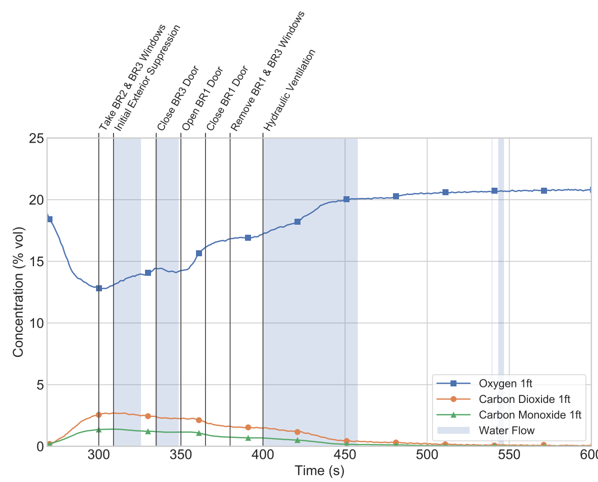
Gas concentrations 1 ft above the bathroom 3 floor were 12.8% O_2, 2.6% CO_2, 1.4% CO when the bedroom 3 window was ventilated, as shown in Figure 5.39c. This indicated that the smoke layer had descended below the 1 ft level in the bathroom. Gas concentrations gradually improved during exterior suppression and continued following bedroom 3 isolation. Concentrations reached pre-ignition magnitudes 675 s post-ignition. The lack of a local exterior vent in the bathroom slowed the recovery time of gas concentrations to pre-ignition levels compared to bedroom 3.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

Figure 5.39: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 3.

5.3.3 Bedroom 2

The bedroom 2 door was opened prior to ignition, which allowed combustion gases to flow into the bedroom. Combustion gases accumulated at the ceiling of the bedroom, which increased temperatures within the space. Window temperatures at the time of intervention ranged from 190 °C (374 °F) 44 in. above the sill to 105 °C (221 °F) 4 in. above the sill, as shown in Figure 5.40a.

Following ventilation of half the bedroom 2 window, the combustion gases that had accumulated in the bedroom flowed toward and through the exterior vent. Unidirectional outflow at 2.5 m/s (5.6 mph) established through the window for approximately 10 s (Figure 5.40b), which increased window temperatures to 225 °C (437 °F) by the onset of exterior suppression.

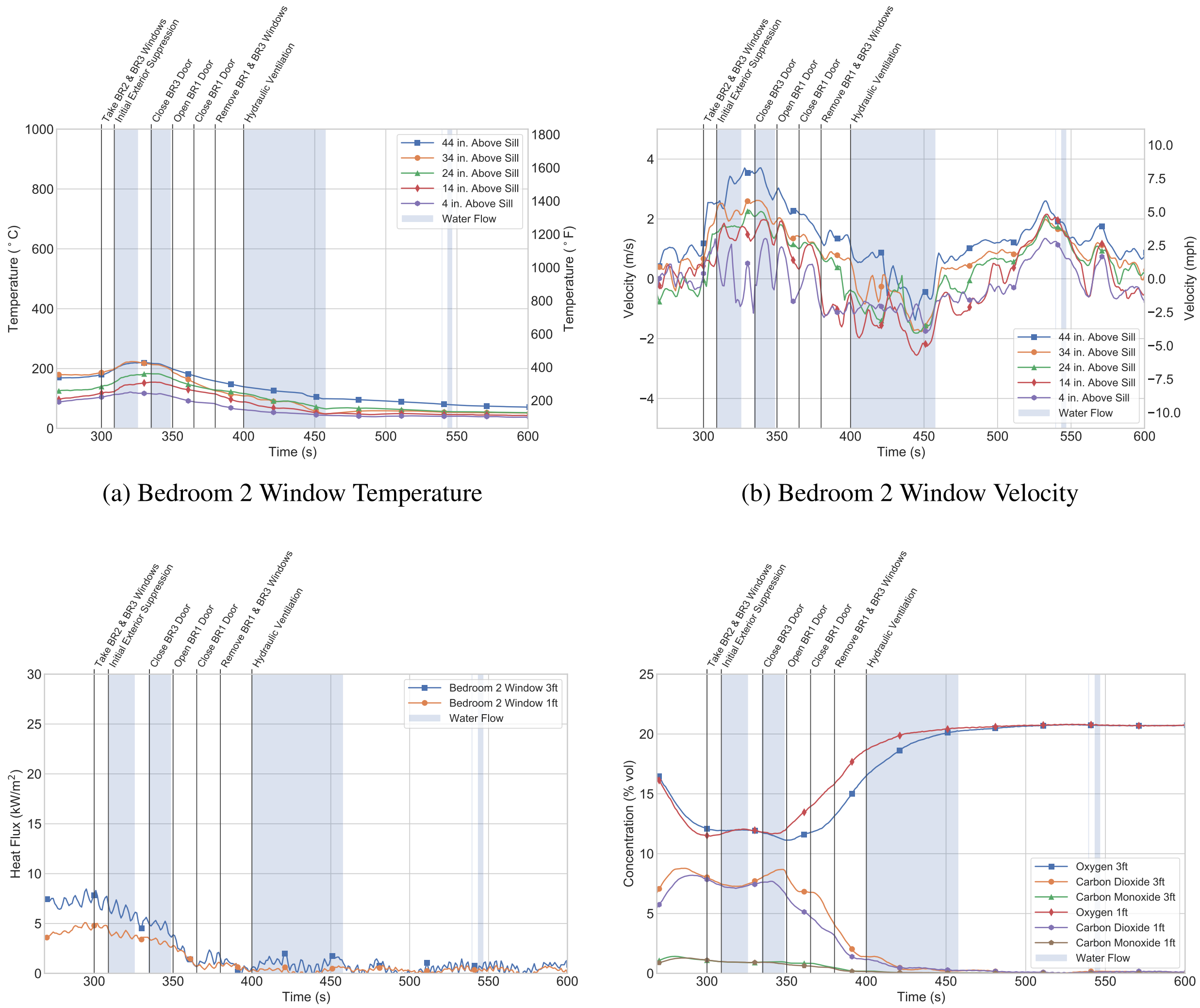
Exterior suppression reduced the heat release rate of the bedroom 4 fire and cooled combustion gases, which caused bidirectional flow between 3.7 m/s and -0.9 m/s (8.3 mph and 2.0 mph) to establish through the window. Window temperatures decreased below 270 °C (518 °F). As the crew shut down the line and moved inside the structure for interior suppression, gas flow through the window became unidirectional exhaust between 3.6 m/s and 0.5 m/s (8.1 mph and 1.1 mph). Temperatures 24 in. to 14 in. above the sill increased. Interior suppression extinguished the bedroom 4 fire and further cooled combustion gases. Flow through the bedroom 2 window remained unidirectional exhaust and window temperatures decreased below 215 °C (419 °F).

Post-suppression exhaust flow through the window decreased until bidirectional flow established. Temperatures continued to decrease, as combustion gases exhausted between 1.1 m/s and 0.6 m/s (2.5 mph and 1.3 mph) and air entrained between -0.9 m/s and -0.4 m/s (2.0 mph and 0.9 mph). Hydraulic ventilation caused unidirectional inflow at -2.6 m/s (5.8 mph) through the bedroom 2 window, which reduced window temperatures below 100 °C (212 °F).

Heat flux at the time of intervention indicated that the smoke layer in bedroom 2 had descended below the 1 ft level as the heat flux below the bedroom window was nominally 8 kW/m^2 3 ft above the floor and 5 kW/m^2 1 ft above the floor, as shown in Figure 5.40c. Following ventilation, flow through the bedroom window was unidirectional exhaust for approximately 10 s, until water flowed from the exterior. As a result, the heat flux below the window remained steady. Exterior suppression decreased the heat release rate of the bedroom 4 fire and caused bidirectional flow through the ventilated bedroom 2 window. As a result, heat flux below the window decreased. Interior suppression extinguished the bedroom 4 fire, which further reduced heat flux below the window. Post-suppression bidirectional flow through the window reduced heat flux below 1 kW/m^2,.

Gas concentrations below the window also indicated that the smoke layer in bedroom 2 had descended below the 1 ft level at the time of intervention. Gas concentrations were 12.1% O_2, 8.0% CO_2, and 1.1% CO 3 ft above the floor and 11.5% O_2, 7.8% CO_2, and 1.1% CO 1 ft above the floor, as shown in Figure 5.40d. Flow through the ventilated bedroom 2 window improved gas concentrations. However, suppression caused higher-temperature combustion gases to cool and drop in elevation. As a result, gas concentrations began to worsen during exterior suppression. As a result, gas concentrations reached 11.1% O_2, 8.7% CO_2, and 1.0% CO 3 ft above the floor and 11.7% O_2, 7.7% CO_2, 0.9% CO 1 ft above the floor during interior suppression. Post-suppression gas flow through the ventilated window improved gas concentrations to 16.5% O_2, 1.4% CO_2, and 0.1% CO 3 ft above the floor and 18.7% O_2, 1.2% CO_2, and 0.1% CO 1 ft above the floor. Hydraulic ventilation caused unidirectional inflow through the ventilated window, which improved gas concentrations to pre-ignition conditions.

Temperatures in the center of bedroom 2 were consistent with window temperatures at the time of intervention, as shown in Figure 5.41a. Combustion gases in the hallway flowed through bedroom 2 toward the ventilated window, which increased temperatures in the center of bedroom 2 to 360 °C (680 °F). Exterior suppression reduced temperatures in bedroom 2 to 290 °C (554 °F) and interior suppression reduced temperatures to 215 °C (419 °F). Post-suppression bidirectional flow cooled the bedroom to 125 °C (257 °F). Unidirectional inflow through the ventilated window caused by hydraulic ventilation reduced the temperature of the bedroom below 100 °C (212 °F).



(a) Bedroom 2 Window Temperature

(b) Bedroom 2 Window Velocity

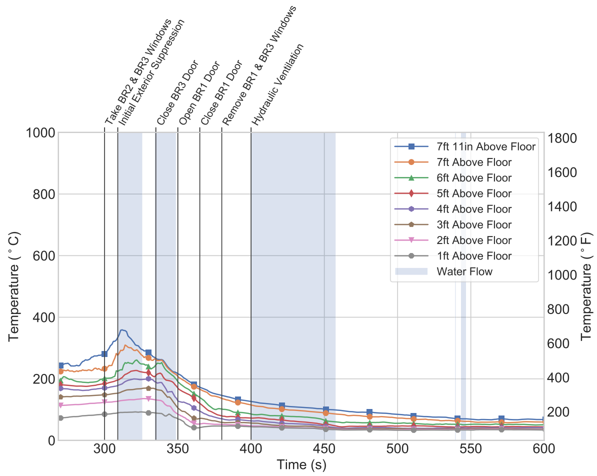
(c) Bedroom 2 Window Heat Flux

(d) Bedroom 2 Window Gas Concentration

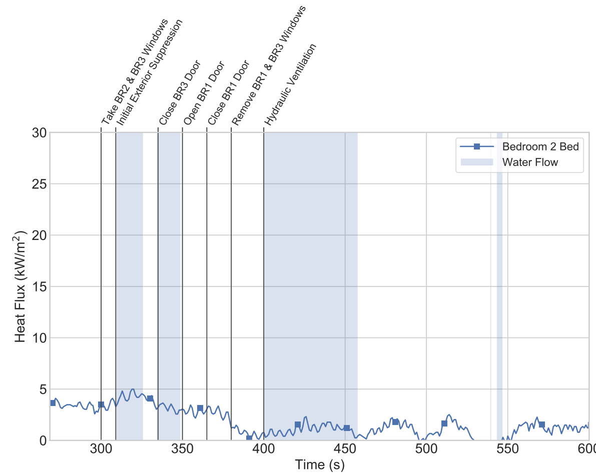
Figure 5.40: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 3.

Heat flux to the bed at the time of intervention was approximately 3.5 kW/m^2, as shown in Figure 5.41b. Ventilation of the bedroom 2 window resulted in an increased in heat flux to approximately 5 kW/m^2 as combustion gases flowed across the hallway toward the ventilated bedroom 2 window. Both exterior and interior suppression reduced the heat release rate of the bedroom 4 fire, which caused the heat flux to bed 2 to decrease. Since the bedroom 2 heat flux location was offset from the flow of gases through the window, the reduction in magnitude post-suppression compared to the window location was slower.

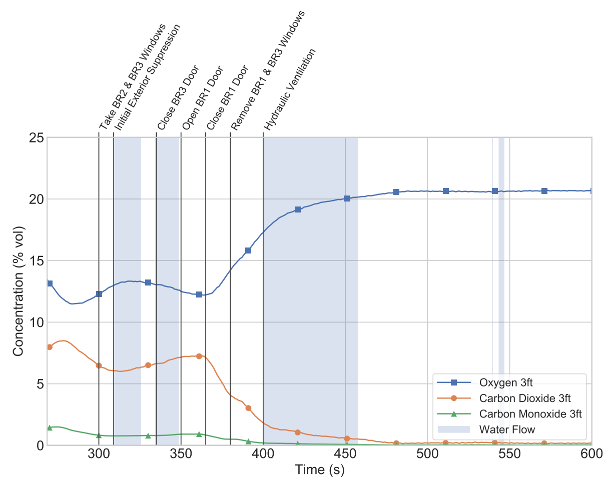
Gas concentrations at the bed at the time of intervention were 12.3% O_2, 6.4% CO_2, and 0.8% CO, as shown in Figure 5.41c. Gas concentrations continued to improve until suppression. Suppression caused higher-temperature gases to cool and drop in elevation, which worsened gas concentrations to 12.2% O_2, 7.3% CO_2, and 0.9% CO. Post-suppression gas flow through the ventilated window improved gas concentrations to 17.3% O_2, 1.7% CO_2, and 0.2% CO. Hydraulic ventilation further improved gas concentrations to 20.2% O_2, 0.5% CO_2, and 0.1% CO 3 ft above the floor.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



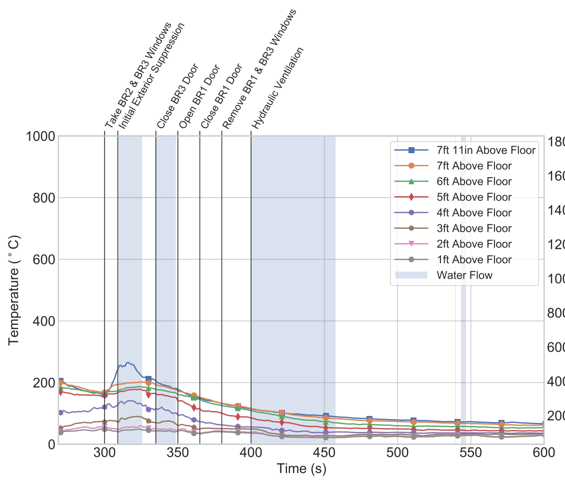
(c) Bedroom 2 Gas Concentration

Figure 5.41: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 3.

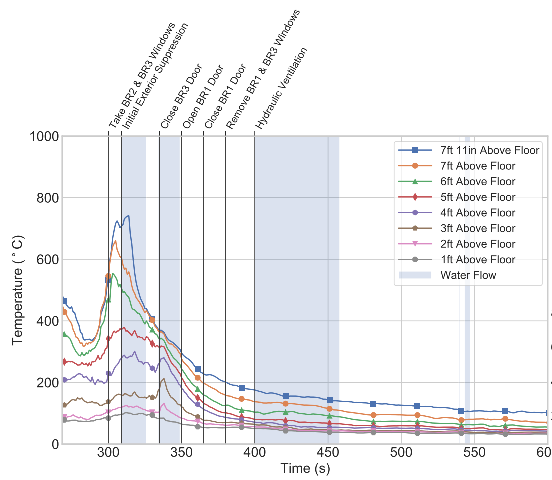
5.3.4 Hallway

Figure 5.42 shows the temperature time histories for the hallway and living room entryway locations. At the time of intervention, hallway temperatures were a function of proximity to the fire room. Temperatures at the mid hallway location were the greatest and exceeded 690 °C (1274 °F), followed by the start hallway (545 °C (1013 °F)), end hallway (460 °C (860 °F)), and living room entryway (170 °C (338 °F)) locations. The flow of combustion gases from the fire room into each bedroom increased following bedroom 2 and bedroom 3 window ventilation. Hallway temperatures increased to 835 °C (1535 °F) at the mid hallway location, 740 °C (1364 °F) at the start hallway location, 560 °C (1040 °F) at the end hallway location, and 265 °C (509 °F) at the living room entryway location.

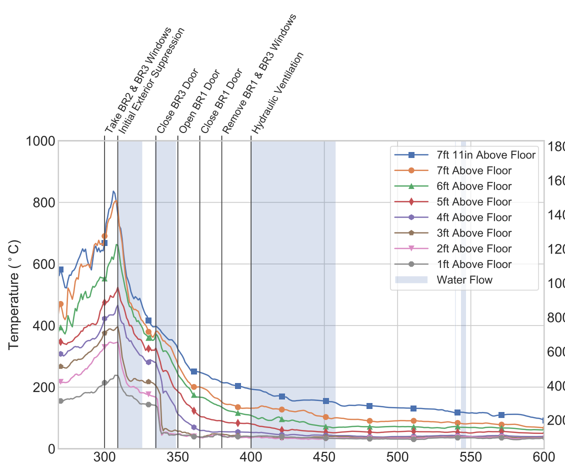
Exterior suppression decreased the heat release rate of the bedroom 4 fire, which decreased the temperature of combustion gases that flowed into the hallway. Interior suppression began in the hallway, which caused hallway temperatures ahead of the hoseline (end hallway) to decrease rapidly 340 s post-ignition. Post-suppression hallway temperatures were below 325 °C (617 °F). Bidirectional flow through the exterior vents lifted the smoke layer in the structure and hallway temperatures decreased below 195 °C (383 °F). Hydraulic ventilation further reduced hallway temperatures to 145 °C (293 °F).



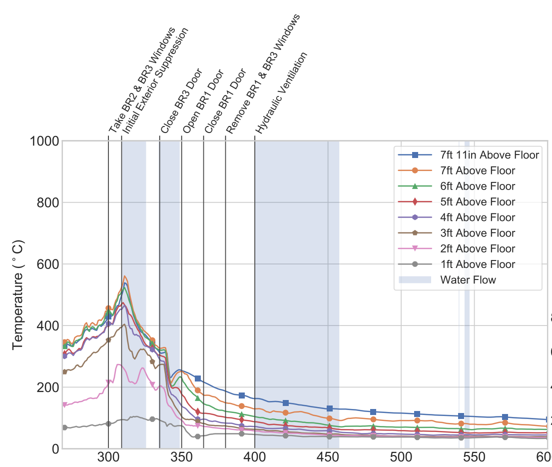
(a) Living Room Entryway Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.42: Temperature time histories in the hallway in the period following fire department intervention in Experiment 3.

Prior to intervention, combustion gases and flames flowed from the fire room into the hallway, which caused ignition of the carpet near the mid hallway location. Flames spread along the carpet toward bedrooms 1, bedroom 2, and the common area. However, the lack of an exterior vent in bedrooms 1 and 2 limited flame spread toward the end hallway location. As a result, heat flux at the time of intervention was 9.4 kW/m^2 at the start hallway location, 5.9 kW/m^2 at the mid hallway location, 3.1 kW/m^2 at the end hallway location, and 0 kW/m^2 at the living room entryway location, as shown in Figure 5.43.

Combustion gas flow from the fire room into the hallway increased after ventilation of the bedrooms 2 and 3 windows, which increased heat flux outside the fire room (mid hallway location) to 13.1 kW/m^2. Exterior suppression decreased the heat release rate of the bedroom 4 fire and cooled the fire room. Heat flux at the mid hallway location decreased and heat flux at the mid hallway and end hallway locations remained constant. Interior suppression extinguished the bedroom 4 fire, which decreased heat flux throughout the structure. Post-suppression heat flux decreased to 0 kW/m^2 in the hallway, which minimized the effect of hydraulic ventilation.

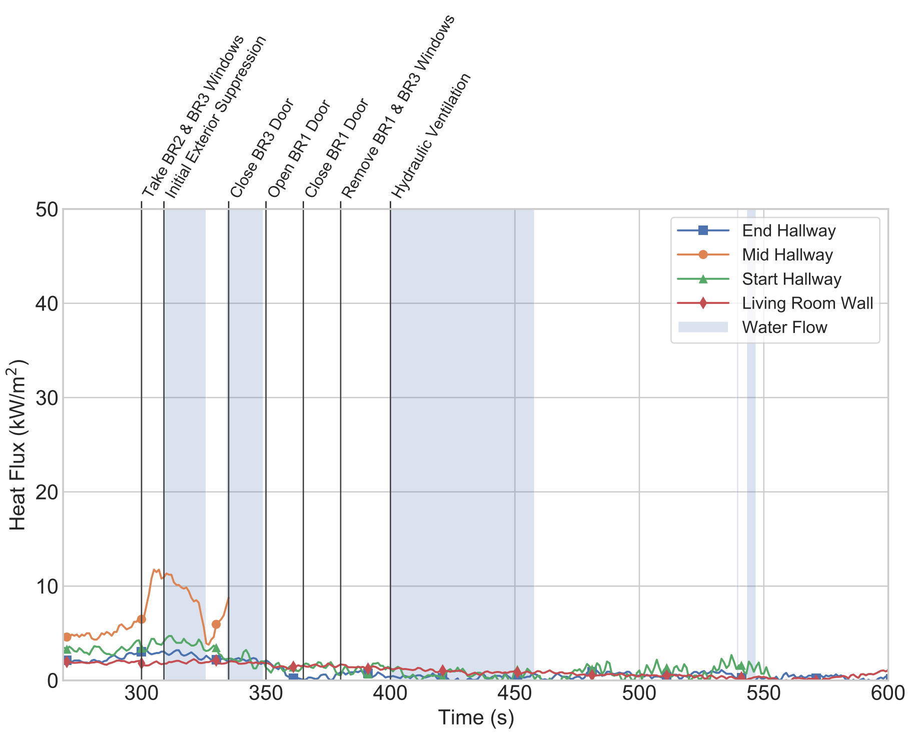


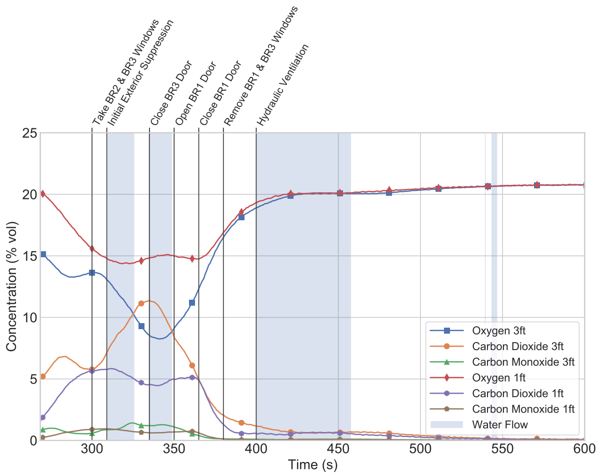
Figure 5.43: Heat flux time histories in the hallway in post-intervention period during Experiment 3.

Table 5.6 shows the gas concentration time history throughout the hallway and living room entryway locations at the time of intervention during Experiment 3. Gas concentrations indicated that the smoke layer had descended past the 1 ft level at the end hallway and mid hallway locations and past the 3 ft level at the start hallway and living room entryway locations. Gas concentrations in the living room entryway had higher concentrations of O_2 and lower concentrations of CO_2 and CO when compared to the hallway, as the large volume of the common space and bidirectional flow through the front door prevented the smoke layer from descending in the entryway.

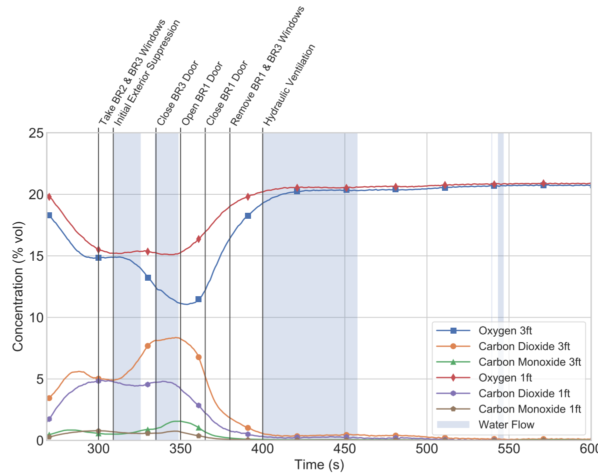
Table 5.6: Hallway Gas Concentrations at Intervention for Experiment 3

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	19.7	1.2	0.2
	1 ft	20.6	0.3	0.1
Start Hallway	3 ft	19.4	0.4	0.1
	1 ft	20.4	1.8	0.2
Mid Hallway	3 ft	14.8	4.8	0.6
	1 ft	15.5	5.0	0.8
End Hallway	3 ft	13.6	5.6	0.6
	1 ft	15.5	5.8	0.9

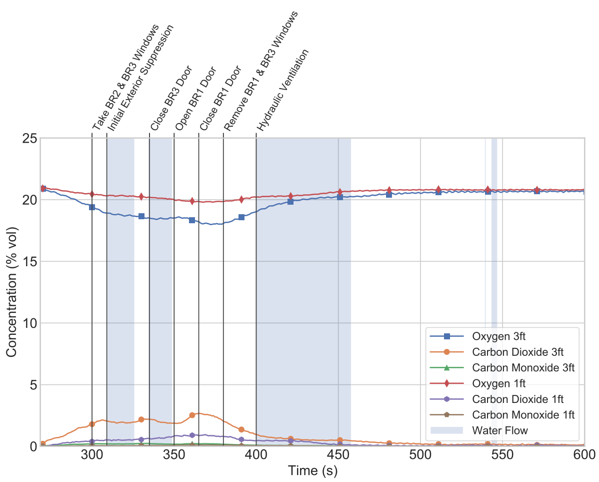
Figures 5.44a and 5.44d show the gas concentration time histories in the hallway and living room entryway. Gas concentrations remained steady after ventilation. Exterior suppression cooled higher-temperature combustion gases throughout the structure, which caused combustion gases to drop in elevation. As a result, gas concentrations deteriorated to 8.2% O_2, 11.4% CO_2, and 1.4% CO at the end hallway location and and 11.1% O_2, 8.4% CO_2, and 1.6% CO at the mid hallway location during interior suppression. However, interior suppression terminated the production of combustion gases, which caused gas concentrations to improve. As bidirectional flow through the exterior vents lifted the smoke layer, gas concentrations at the end hallway and mid hallway locations improved. The start hallway location was adjacent to the flows established between the fire room and the exterior through the bedrooms 2 and 3 windows. As a result, gas concentrations at this location were slower to recover than the end hallway and mid hallway locations. Hydraulic ventilation caused combustion gases in the hallway to flow toward and through the bedroom 4 vents to the exterior. Gas concentrations returned to pre-ignition levels.



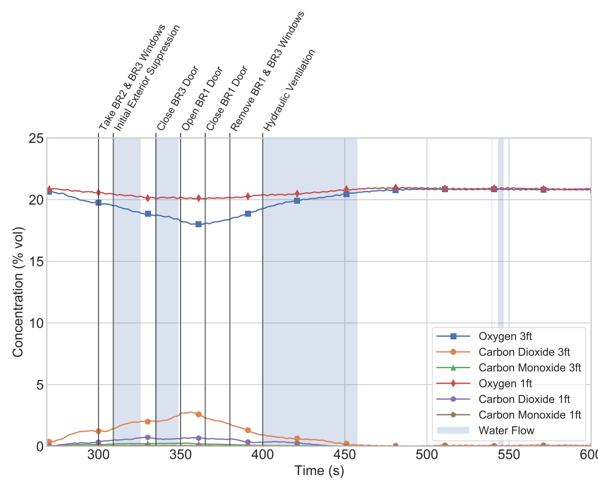
(a) End Hallway Gas Concentration



(b) Mid Hallway Gas Concentration



(c) Start Hallway Gas Concentration



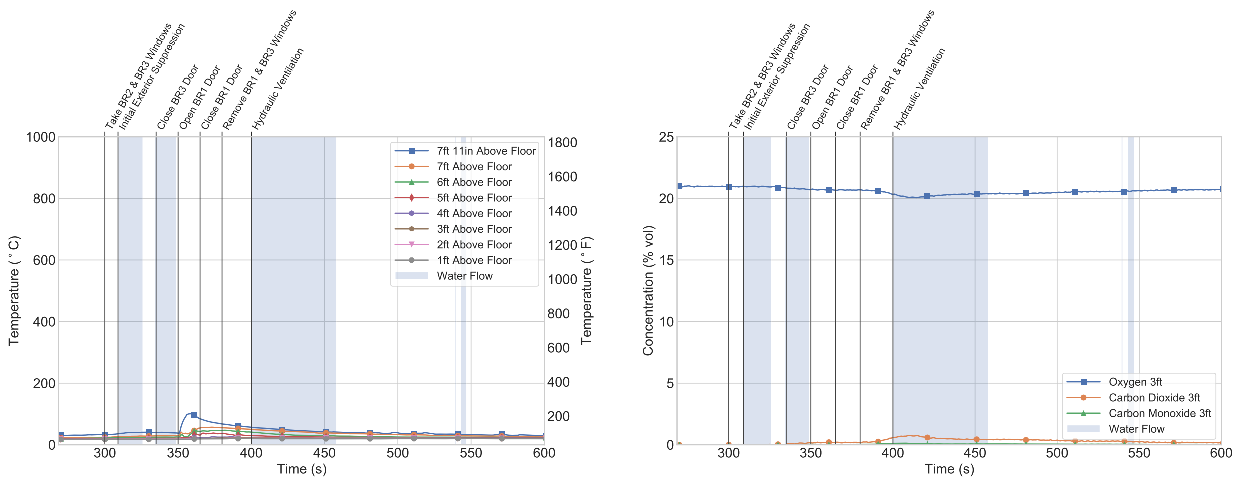
(d) Living Room Entryway Hall Gas Concentration

Figure 5.44: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 3.

5.3.5 Bedroom 1

The bedroom 1 door was closed prior to ignition, which prevented the flow of combustion gases from the fire room into the bedroom. However, higher-pressure combustion gases flowed through the leakage area around the closed door and through the HVAC supply vents into the bedroom. At the time of intervention, bedroom 1 temperatures were below 35 °C (95 °F), as shown in Figure 5.45a. Within 8 s of opening the bedroom 1 door, ceiling temperatures exceeded 100 °C (212 °F), as combustion gases flowed into the previously isolated bedroom. Closure of the bedroom door stopped the flow of combustion gases into the bedroom and trapped previously accumulated gases in the bedroom. Bedroom temperatures decreased to 65 °C (149 °F). The bedroom window was removed, which established a new flow path between the bedroom and the exterior of the structure. Bedroom temperatures continued to decrease. The bedroom 1 door remained closed during hydraulic ventilation, however bidirectional flow through the window decreased temperatures below 40 °C (104 °F).

Gas concentrations at the bed level were 21.0% O_2, 0% CO_2, and 0% CO at the time of intervention, as shown in Figure 5.45b. Combustion gases flowed through the open bedroom 1 door and accumulated at the ceiling. However, the smoke layer did not descend from the ceiling and gas concentrations remained constant. After the removal of the bedroom window, combustion gases exhausted to the exterior and air entrained into the bedroom. As a result, combustion gases near the ceiling cooled and dropped in elevation, which caused gas concentrations to deteriorate to 20.1% O_2, 0.7% CO_2, 0.1% CO. Bidirectional flow through the window continued to lift the smoke layer, which improved gas concentrations to pre-ignition levels.



(a) Bedroom 1 Temperature

(b) Bedroom 1 Gas Concentration

Figure 5.45: Post-intervention bed level temperature and gas concentrations in bedroom 1 during Experiment 3.

The bathroom 1 door was closed prior to ignition, which prevented the flow of gases between the bedroom and bathroom. However, higher-pressure combustion gases flowed through the HVAC supply vent to the lower-pressure bedroom. At the time of intervention, bathroom temperatures exceeded 30 °C (86 °F), as shown in Figure 5.46. Bathroom temperatures continued to increase as combustion gases flowed through the HVAC supply vents. Bathroom temperatures exceeded 40 °C (104 °F) at the end of the experiment.

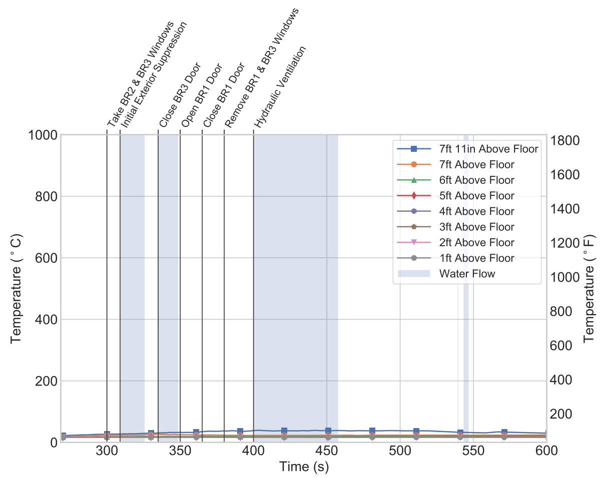


Figure 5.46: Post-intervention temperatures in bathroom 1 during Experiment 3.

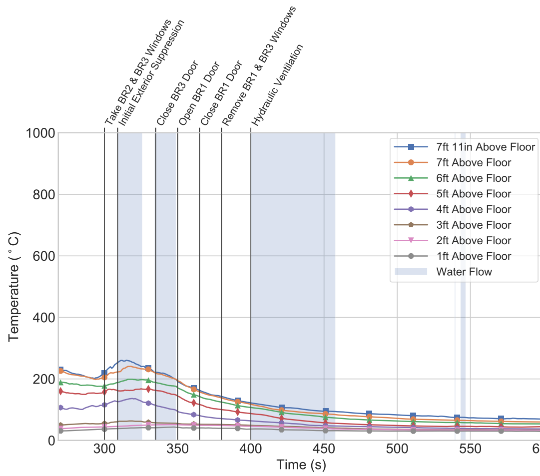
5.3.6 Common Space

Figure 5.47a shows the temperature time histories for the kitchen and living room. At the time of intervention, common space gas temperatures indicated that the smoke layer had descended past the 4 ft level. Temperatures above 4 ft above the floor exceeded 290 °C (554 °F) in the living room and 220 °C (428 °F) in the kitchen. Temperatures below 3 ft above the floor were less than 60 °C (140 °F). As a result of window ventilation, temperatures in the common space increased to 335 °C (635 °F) in the living room and 260 °C (500 °F) in the kitchen. Exterior suppression reduced the heat release rate of the bedroom 4 fire, which gradually decreased temperatures in the common space. Interior suppression extinguished the bedroom 4 fire and bidirectional flow though the exterior vents exhausted accumulated combustion gases from the structure. As a result, common space temperatures decreased to 135 °C (275 °F) in the living room and 120 °C (248 °F) in the kitchen. Hydraulic ventilation caused combustion gases in the structure to flow toward bedroom 4, which reduced common space temperatures below 105 °C (221 °F).

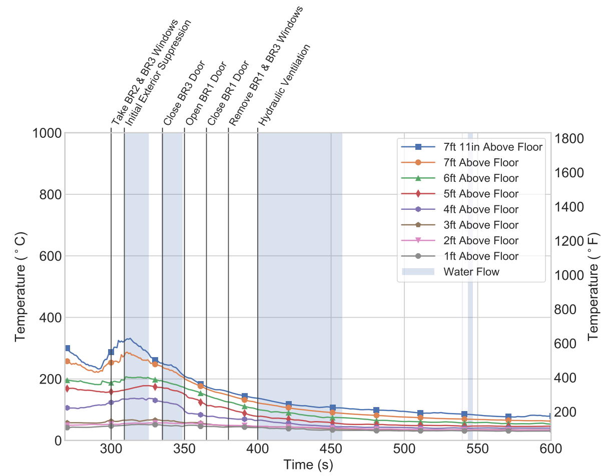
Kitchen heat flux at the time of intervention was approximately 1.5 kW/m^2 1 ft above the floor, as shown in Figure 5.47c. The window ventilation had minimal impact on the heat flux but exterior suppression followed by interior suppression decreased heat flux to below 1 kW/m^2 for the duration of the experiment.

At the time of intervention, kitchen gas concentrations were consistent with pre-ignition conditions, which indicated that the smoke layer had not descended to the 1 ft level. Figure 5.47d shows the gas concentration time history for the kitchen. Exterior and interior suppression cooled combustion gases in the structure. As combustion gases cooled and dropped in elevation, gas concentrations in the kitchen worsened to 19.7% O_2, 0.5% CO_2, and 0.2% CO. The kitchen was adjacent to the flow of gases caused by hydraulic ventilation, which limited its impact on gas concentrations.

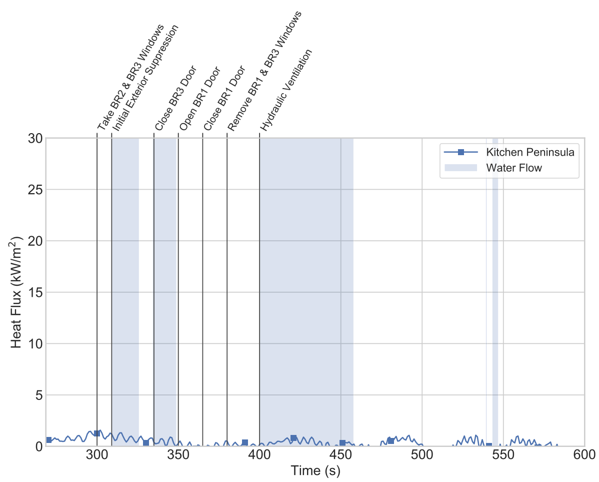
Bidirectional flow through the front door stratified gas temperatures at the time of intervention,



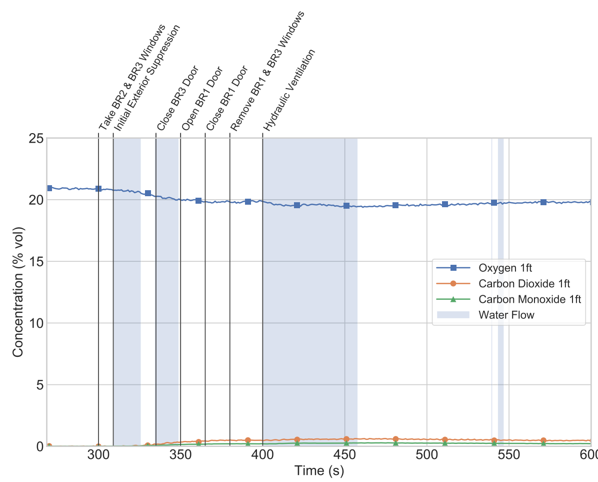
(a) Kitchen Temperature



(b) Living Room Temperature



(c) Kitchen Heat Flux

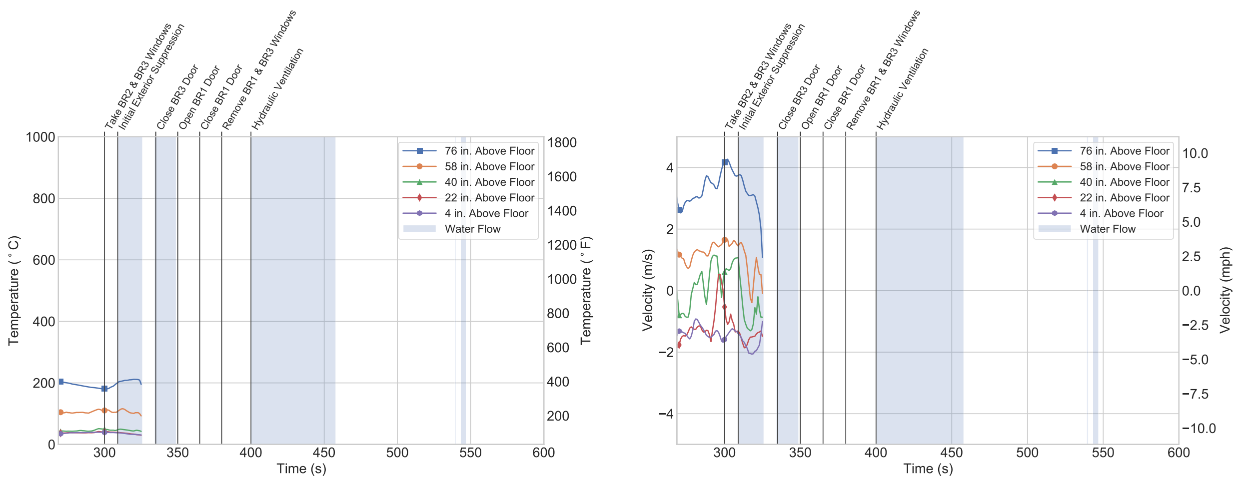


(d) Kitchen Gas Concentration

Figure 5.47: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 3.

as shown in Figures 5.48a and 5.48b. Combustion gases exhausted between 4.2 m/s and 0.6 m/s (9.4 mph and 1.3 mph) 76 in. to 40 in. above the floor, which caused temperatures near the top of the door frame to exceed 185 °C (365 °F). Air was entrained between -0.5 m/s and -1.6 m/s (-1.1 mph and -3.6 mph) 22 in. and 4 in. above the floor, which kept temperatures below 40 °C (104 °F).

Ventilation of the bedrooms 2 and 3 windows, followed by exterior suppression, caused flow through the front door to decrease. Combustion gas exhaust decreased to 1.1 m/s (2.5 mph) 76 in. above the floor, and temperatures increased to 210 °C (410 °F). Air was entrained between -0.4 m/s and -2.1 m/s (-0.9 mph and -4.7 mph) 58 in. to 4 in. above the floor. As a result, temperatures decreased below 58 in. above the floor. The bidirectional probes were removed 325 s post ignition, prior to crew entry into the structure for interior suppression. Data recorded after this time stamp are not reflective of flow through the doorway.



(a) Front Doorway Temperature

(b) Front Doorway Velocity

Figure 5.48: Post-intervention temperatures and velocities in the front doorway during Experiment 3.

5.4 Experiment 4

The search tactics in Experiment 4 were designed to evaluate window initiated operations conducted prior to suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide bedroom 4 window and the bedroom 4 door were removed. The front door to the structure and doors to bedrooms 2, bedroom 3, and bathroom 3 were opened. The doors to bedroom 1 and bathroom 1 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 flashover, the crews on side C of the structure ventilated half of the double-wide window in bedroom 2 and bedroom 3. The crews entered bedrooms 2 and 3 and proceeded toward the doors to the hallway. The crew that entered bedroom 3 was unable to close the door to the hallway. The crew that entered bedroom 2 proceeded into the hallway and closed the bedroom 2 door behind them. This crew crossed the hallway and opened the door to bedroom 1. After entry into the bedroom, the crew closed the door and removed the double-wide bedroom 1 window. The search tactic comparison was then complete, and suppression began with entry into the structure through the front door. Upon the suppression crew announcement of 'fire under control', hydraulic ventilation occurred out of the failed double-wide bedroom 4 window. 157 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 353 gallons. Table 5.7 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was ventilation of half the bedrooms 2 and 3 double-wide windows.

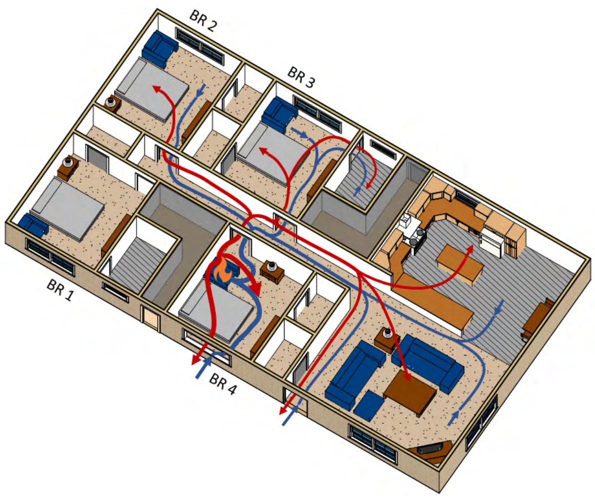
Table 5.7: Experiment 4 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Ignition	00:00	0	—	—
Take BR2 & BR3 Windows	04:30	270	00:00	0
Close BR2 Door	05:14	314	00:44	44
Open BR1 Door	05:24	324	00:54	54
Close BR1 Door	05:39	339	01:09	69
Remove BR1 Window	05:54	354	01:24	84
Suppression	06:33	393	02:03	123
Hydraulic Ventilation	09:26	566	02:53	173

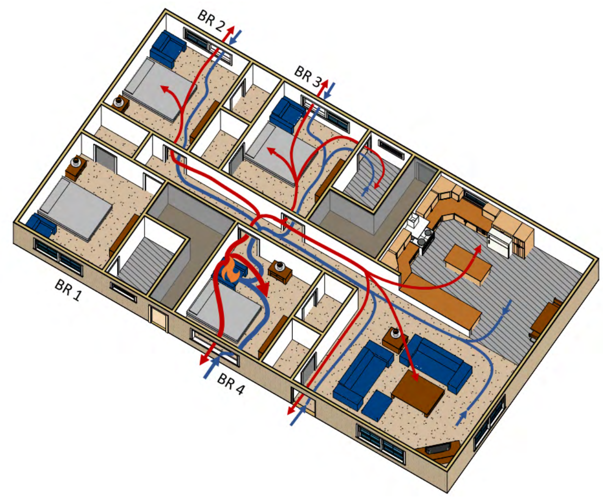
Figures 5.49, 5.50, and 5.51 show the changes in gas flow within the structure caused by each fire department intervention during Experiment 4. Prior to intervention, the bedroom 4 fire was entraining air and exhausting combustion gases, which generated bidirectional flow through the open bedroom 4 vents, as shown in Figure 5.49a. Flow paths were established between the higher-pressure fire room and lower-pressure open volumes of the structure and the exterior.

Ventilation of the bedrooms 2 and 3 windows created an exterior vent in each bedroom. A flow path established between the higher-pressure fire room and the lower-pressure exterior through each bedroom, as shown in Figure 5.49b. Bidirectional flow through each window exhausted combustion gases and entrained air to each bedroom.

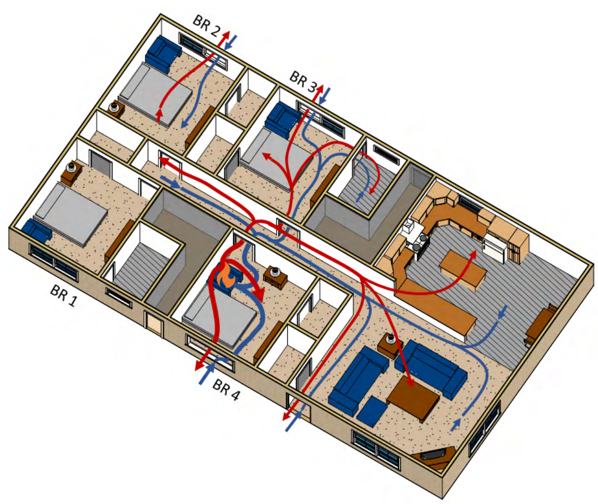
Closure of the bedroom 2 door stopped the flow of combustion gases from the fire room to the bedroom, which limited further accumulation of combustion gases in bedroom 2 (Figure 5.49c). Bidirectional flow through the window exhausted previously accumulated combustion gases.



(a) Flows Prior to Intervention



(b) Take BR2 & BR3 Windows



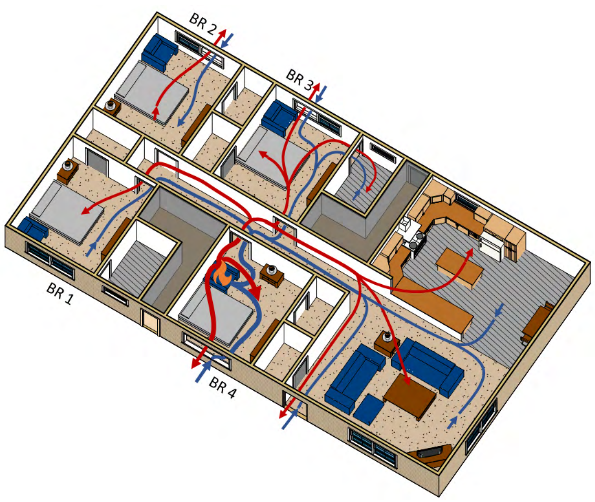
(c) Close BR2 Door

Figure 5.49: Changes in flow in structure following fire department interventions in Experiment 4.

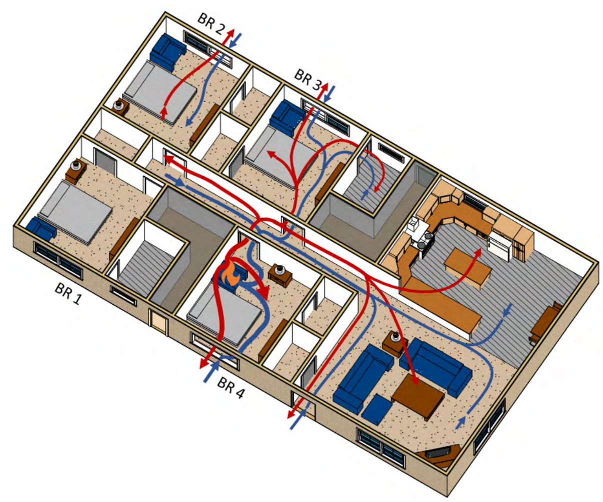
The open bedroom 1 door established a new flow path between the higher-pressure fire room and lower-pressure bedroom, as shown in Figure 5.50a. Bidirectional flow through the doorway exchanged bedroom air with hallway combustion gases. Closure of the bedroom 1 door isolated the bedroom from the flow of combustion gases, which trapped combustion gases in the bedroom (Figure 5.50b).

The bedroom 3 window failed, as high-temperature combustion gases caused the window frame to warp (Figure 5.50c). A larger exterior vent was created in the bedroom, which increased the flow of combustion gases from the fire room.

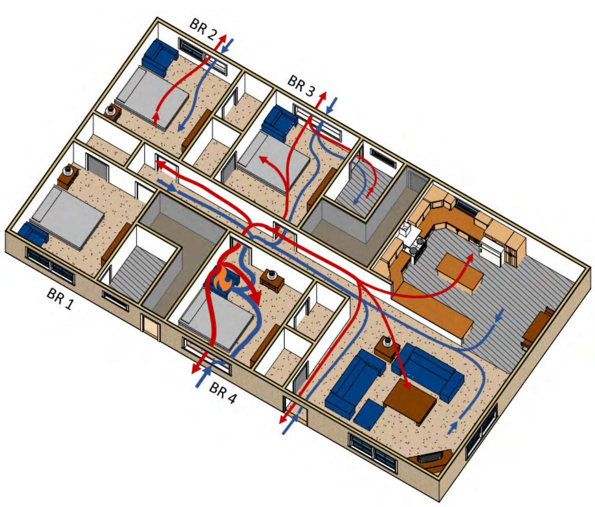
Removal of the bedroom 1 window created an exterior vent, which established a new flow path between the higher-pressure bedroom and the lower-pressure exterior (Figure 5.50d). Bidirectional flow through the window exhausted previously accumulated combustion gas and entrained air to the bedroom.



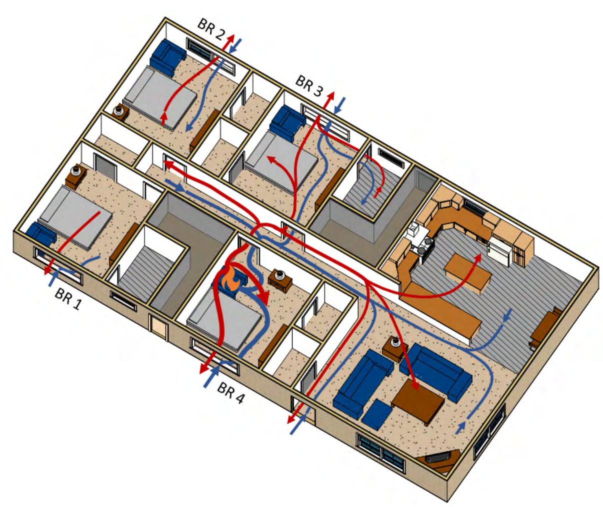
(a) Open BR1 Door



(b) Close BR1 Door



(c) BR3 Window Failure

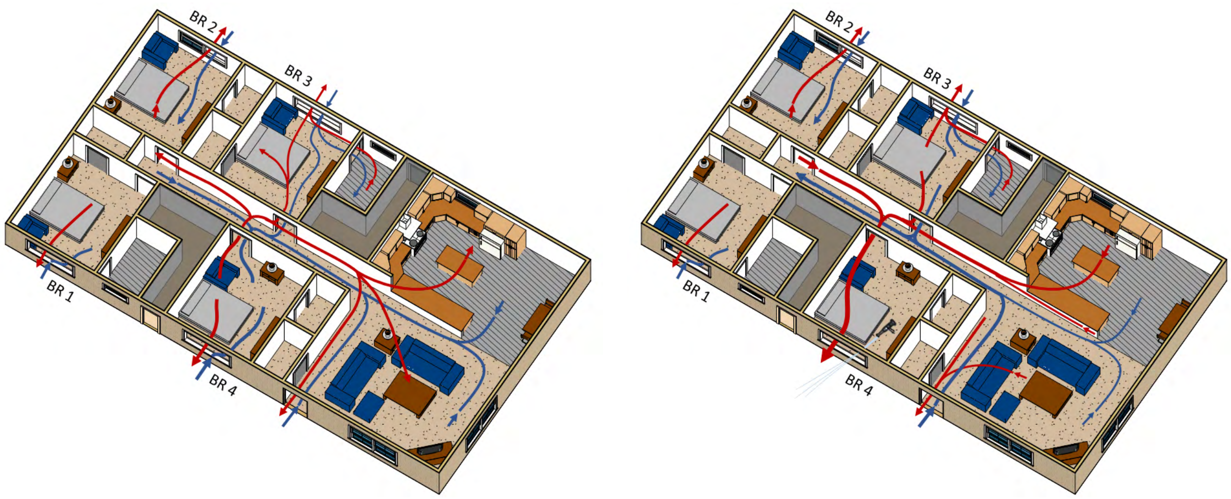


(d) Remove BR1 Window

Figure 5.50: Changes in flow in structure following fire department interventions in Experiment 4.

Interior suppression was conducted through the front door with a smooth bore nozzle with a 7/8 in. tip, set to flow 160 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline. Suppression terminated the production of combustion gases in bedroom 4, however the presence of higher-temperature, higher-pressure gases continued to drive flow to open volumes of the structure

(Figure 5.51a). Hydraulic ventilation occurred out the bedroom 4 window with the tip on, full bale, and in an O-pattern. Flow through the bedroom 4 window became unidirectional exhaust and flow through the bedroom 4 doorway became unidirectional intake, as shown in Figure 5.51b.



(a) Suppression

(b) Hydraulic Ventilation

Figure 5.51: Changes in flow in structure following fire department interventions in Experiment 4.

5.4.1 Bedroom 4

Approximately 178 s post-ignition, falling debris damaged the thermocouple array in bedroom 4. Data from this thermocouple after this time stamp are not representative of temperatures within bedroom 4. Flashover was determined from visual cues captured with standard and IR cameras. Flashover of the fire room occurred approximately 215 s post ignition, after flames extended from the failed side A window.

Figures 5.52a and 5.52b show the temperature and velocity time histories through the bedroom 4 doorway. At the time of first intervention, the bedroom 4 fire had reached a steady post-flashover state. Combustion gases exhausted from the fire room between 2.4 m/s and 0.6 m/s (5.4 mph and 1.3 mph) and air entrained to the fire room doorway between -0.6 m/s and -1.7 m/s (-1.3 mph and -3.8 mph), which increased doorway temperatures to 740 °C (1364 °F) 76 in. above the floor and 510 °C (950 °F) 4 in. above the floor.

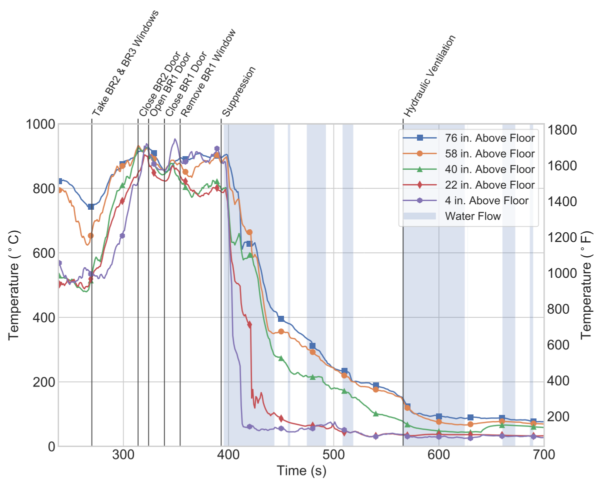
Ventilation of the bedrooms 2 and 3 windows established flow paths between the fire room and the exterior through each bedroom. Air flowed along these paths to the fire room and increased the available oxygen for combustion in the hallway and in bedroom 4. The heat release rate of the bedroom 4 fire increased, which increased doorway temperatures to 930 °C (1706 °F) 76 in. above the floor and 820 °C (1508 °F) 4 in. above the floor, as the mid hallway transitioned through flashover.

The closed bedroom 2 door stopped the flow of gases into and out of the bedroom, which limited the available oxygen for combustion. As a result, flaming combustion in the hallway retreated toward the fire room and flow through the bedroom 4 doorway became unidirectional intake at -3.5 m/s (-7.8 mph).

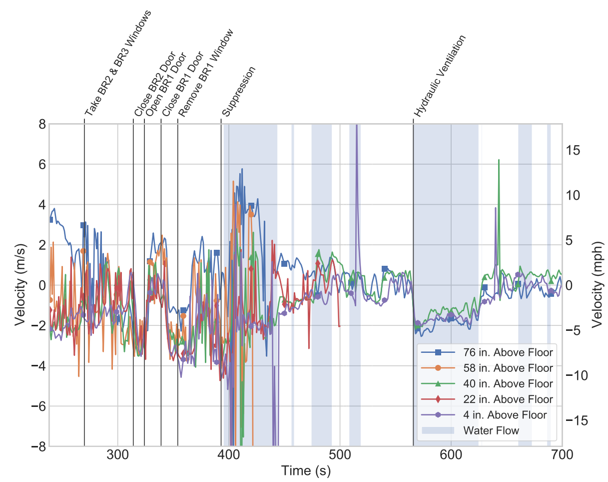
The open bedroom 1 door established a new flow path between the fire room and the bedroom. Flow through the bedroom 4 doorway became bidirectional, which increased the available oxygen for combustion in the hallway. Bedroom 4 doorway temperatures increased to 950 °C (1742 °F) as the mid hallway, again, transitioned through flashover. Similar to bedroom 2, the closed bedroom 1 door isolated the bedroom from the flow of combustion gases and flow through the bedroom 4 doorway became unidirectional intake at -3.7 m/s (-8.3 mph). Although changes in ventilation impacted the flow through the bedroom 4 doorway, the temperatures through the bedroom 4 fire remained at a steady state, near 900 °C (1652 °F).

Suppression decreased the heat release rate of the bedroom 4 fire and cooled combustion gases that flowed into the hallway. Initial suppression reduced doorway temperatures below 420 °C (788 °F). Additional water flows cooled doorway temperatures below 200 °C (392 °F). Water flow damaged bidirectional probes located in the bedroom 4 doorway. Data recorded from the 58 in. and 22 in. probes are not representative of gas flow through the doorway. Hydraulic ventilation created an area of lower pressure in the bedroom, which caused higher-pressure combustion gases to flow into the bedroom. Flow through the bedroom 4 doorway became unidirectional inflow and flow through the bedroom 4 window became unidirectional exhaust. Temperatures through the doorway decreased below 90 °C (194 °F).

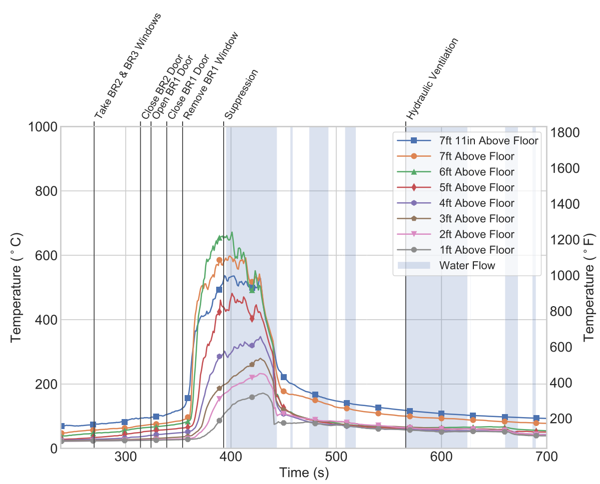
The bedroom 4 closet door was closed prior to ignition, which prevented the flow of higher-temperature, higher-pressure combustion gases into the closet. However, higher-pressure combustion gases flowed through the leakage area around the closed door and increased temperatures as the bedroom 4 fire transitioned through flashover. Closet temperatures at the time of intervention exceeded 80 °C (176 °F), as shown in Figure 5.52c. Approximately 360 s post-ignition, rapid temperature increase in the closet indicated door failure, as temperatures exceeded 670 °C (1238 °F). The closet was adjacent to the flows established in the fire room during suppression. As a result, temperatures decreased gradually until water was flown directly into the closet. Initial suppression decreased temperatures below 255 °C (491 °F). Additional water flows decreased temperatures below 130 °C (266 °F). The closet lacked an exterior vent, which minimized the effect of hydraulic ventilation. Closet temperatures decreased below 100 °C (212 °F).



(a) Bedroom 4 Doorway Temperature



(b) Bedroom 4 Doorway Velocity



(c) Closet Temperature

Figure 5.52: Temperature and velocity time histories in the doorway and closet of bedroom 4 for the period following fire department intervention in Experiment 4.

5.4.2 Bedroom 3

The bedroom 3 door was opened prior to ignition. Higher-temperature, higher-pressure combustion gases flowed from the fire room to the lower-temperature, lower-pressure bedroom and accumulated at the ceiling. The smoke layer descended to the floor and impaired visibility approximately 215 s post-ignition.

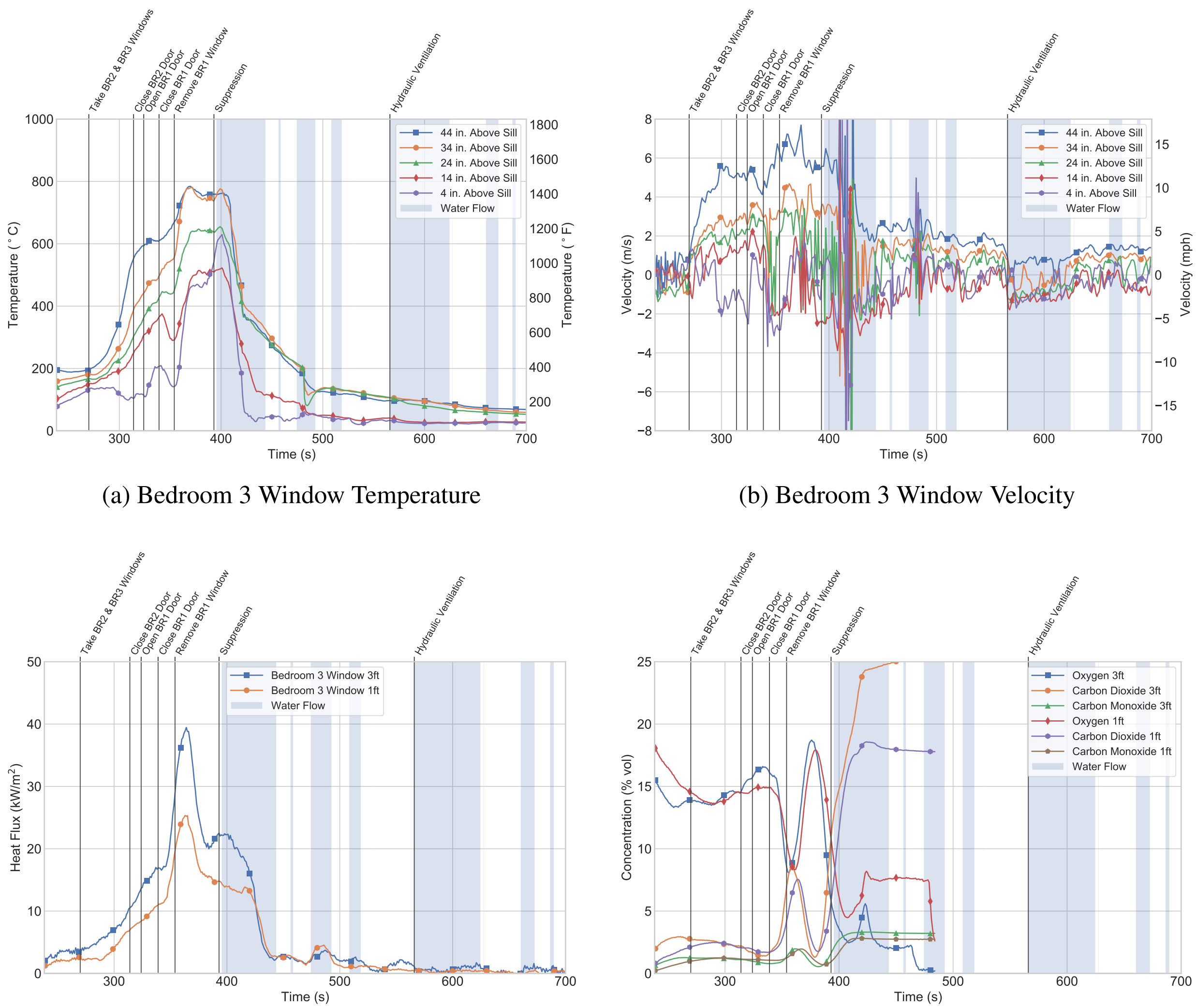
At the time of intervention, bedroom 3 window temperatures exceeded 200 °C (392 °F), as shown in Figure 5.53a. Ventilation of half the window created an exterior vent in the bedroom and established a new flow path between the fire room and the exterior. Combustion gases and flames flowed from the hallway toward the bedroom 3 window. Combustion gases exhausted to the exterior between 44 in. to 14 in. above the sill between 5.6 m/s and 1.0 m/s (12.5 mph and 2.2 mph). As a result, window temperatures exceeded 560 °C (1040 °F). Air entrained from the bedroom 3 window toward the hallway at 4 in. above the sill at -2.1 m/s (4.7 mph), which decreased temperature to 105 °C (221 °F), as shown in Figure 5.53b. Flow through the open bedroom 1 door decreased air entrainment through the bedroom 3 window, which caused temperature 4 in. above the sill to increase from 110 °C to 210 °C (230 °F to 410 °F).

The remaining non-vented bedroom 3 window failed approximately 340 s post-ignition. Combustion gases exhausted 44 in. to 24 in. above the sill between 6.3 m/s and 2.2 m/s (14.1 mph and 4.9 mph), which increased temperatures to 675 °C (1247 °F). Air entrained 14 in. to 4 in. above the sill at -3.1 m/s (-6.9 mph), which decreased temperatures to 140 °C (284 °F). The available oxygen for combustion increased, which caused flames to spread into the bedroom. Exhaust flow through the window increased as the bedroom ignited, which corresponds to peak window temperatures of 785 °C (1445 °F). Temperature 4 in. above the sill exceeded temperature 14 in. above the sill, as flames exhausted from the window.

The suppression crew flowed water into bedroom 3 during their advancement to the fire room. Initial suppression decreased the heat release rate of the bedroom 3 fire and reduced temperatures below 315 °C (599 °F). An additional water flow into bedroom 3 reduced window temperatures below 140 °C (284 °F). Hydraulic ventilation caused combustion gases to flow from bedroom 3 into bedroom 4 and air to entrain from the exterior into bedroom 3, which reduced temperatures below 85 °C (185 °F).

Heat flux below the window at the time of first intervention was 3.5 kW/m^2 3 ft above the floor and 2.5 kW/m^2 1 ft above the floor, as shown in Figure 5.53c. As additional combustion gases flowed from the hallway toward the ventilated bedroom 3 window, heat flux steadily increased to 17.5 kW/m^2 and 11.9 kW/m^2 at the 3 ft and 1 ft elevation, respectively. Failure of the bedroom 3 window increased the available oxygen for combustion in the bedroom, which led to flame spread from the hallway into the bedroom. Heat flux peaked at 41.1 kW/m^2 and 26.4 kW/m^2 3 ft and 1 ft above the floor, respectively as the bedroom transitioned through flashover. Post flashover, heat flux decreased to 20 kW/m^2 and 15 kW/m^2 as inflow through the bedroom window increased. Initial suppression decreased heat flux below 3.0 kW/m^2 at both elevations. Additional water flow into the bedroom coated the heat flux gauge with water, which resulted in a spurious peak at 485 s post-ignition.Hydraulic ventilation lifted the smoke layer in the bedroom and heat flux reduced below 0.5 kW/m^2.

Gas concentrations below the window at the time of first intervention indicated that the smoke layer had descended past the 1 ft level. Gas concentrations were 13.9% O_2, 2.7% CO_2, and 1.2% CO 3 ft above the floor and 14.5% O_2, 2.1% CO_2, and 1.0% CO 1 ft above the floor, as shown in Figure 5.53d. Bidirectional flow through the ventilated window improved gas concentrations at the 3 ft level. Failure of the bedroom 3 window rapidly deteriorated gas concentrations to 8.0% O_2, 8.5% CO_2, and 2.0% CO 3 ft above the floor and 8.3% O_2, 7.6% CO_2, and 2.0% CO 1 ft above the floor, as combustion gases mixed within the bedroom. Inflow through the failed window improved gas concentrations, but also increased flaming combustion in the bedroom. As the bedroom transitioned through flashover, gas concentrations worsened. The sampling ports became clogged with soot, which affected the accuracy of the measurements.



(a) Bedroom 3 Window Temperature

(b) Bedroom 3 Window Velocity

(c) Bedroom 3 Window Heat Flux

(d) Bedroom 3 Window Gas Concentration

Figure 5.53: Post-intervention window temperature, heat flux, and gas concentrations in bedroom 3 during Experiment 4.

Temperatures in the center of the bedroom were consistent with window temperatures at the time of first intervention, as shown in Figure 5.54. Combustion gases and flames flowed along the flow path between the fire room and the exterior through bedroom 3, which caused bedroom temperatures to exceed 780 °C (1436 °F). After the bedroom 3 window failed, the bedroom fuels ignited and the fire transitioned through flashover 375 s post-ignition. Temperatures ranged between 1000 °C and 640 °C (1832 °F and 1184 °F). Suppression extinguished the bedroom 3 fire, which reduced temperatures below 85 °C (185 °F). Hydraulic ventilation caused combustion gases in bedroom 3 to flow into bedroom 4, which reduced temperatures below 80 °C (176 °F).

The bathroom 3 door was opened prior to ignition. Higher-temperature, higher-pressure gases flowed from the fire room to bathroom 3 and accumulated at the ceiling. The smoke layer de-

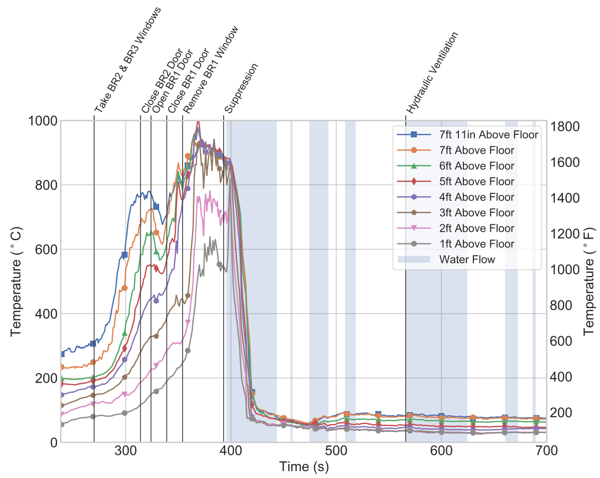


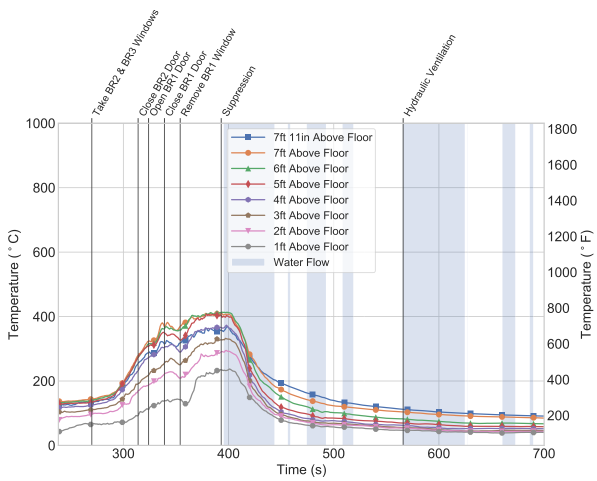
Figure 5.54: Post-intervention temperature in bedroom 3 during Experiment 4.

scended to the floor prior to intervention, which impaired visibility approximately 200 s post-ignition.

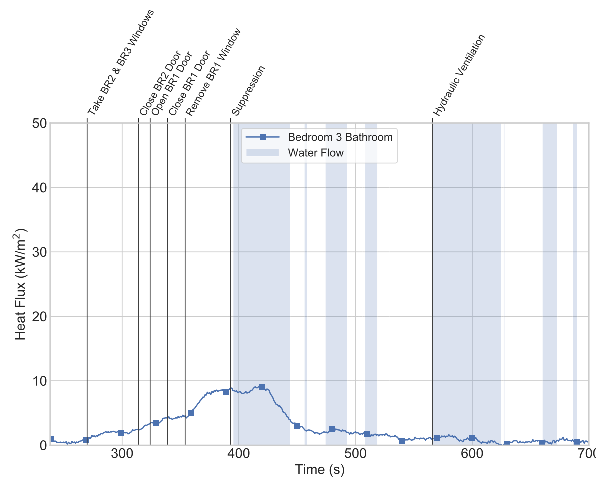
Temperatures in bathroom 3 were below 145 °C (293 °F) at the time of intervention, as shown in Figure 5.55a. Combustion gases flowed toward the ventilated window in bedroom 3. As a result, combustion gases flowed into bathroom 3 and increased temperatures above 325 °C (617 °F). Flame spread toward the exterior vent in bedroom 3 increased bathroom temperatures to 380 °C (716 °F). Bedroom 3 window failure caused bathroom combustion gases to flow into bedroom 3, which decreased bathroom temperatures to 360 °C (680 °F). After the bedroom fuels ignited, bathroom temperatures increased to 415 °C (779 °F). Initial suppression extinguished the bedroom 3 fire, which reduced bathroom temperatures below 200 °C (464 °F). Additional water flows decreased bathroom temperatures below 125 °C (257 °F). The bathroom was adjacent to the flows established in bedroom 2, which minimized the impact of hydraulic ventilation. However, temperatures decreased below 100 °C (212 °F).

Heat flux 1 ft above the bathroom floor at the time of intervention was 1.2 kW/m^2, as shown in Figure 5.55b. Heat flux gradually increased to 4.6 kW/m^2, as combustion gases and flames flowed along the flow path between the fire room and the exterior through bedroom 3. Heat flux peaked to 9.1 kW/m^2 as the bedroom transitioned through flashover. Initial suppression in bedroom 3 increased the gas flows in the bathroom. The increased gas velocity caused the heat flux in the bathroom to temporarily peak to 9.4 kW/m^2. Suppression and additional water flows cooled combustion gases, which decreased heat flux below 1.7 kW/m^2. Hydraulic ventilation decreased heat flux below 0.3 kW/m^2.

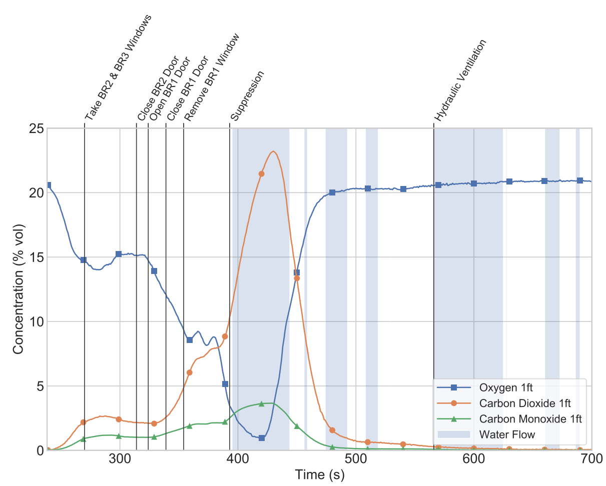
At the time of intervention, gas concentrations 1 ft above the bathroom floor indicated that the smoke layer had descended past the 1 ft elevation, as shown in Figure 5.55c. Gas concentrations were 14.8% O_2, 2.2% CO_2, and 0.9% CO. Air entrainment through the exterior vent in bedroom 3 improved gas concentrations in the bathroom. However, as combustion gas and flames flowed into the bedroom, gas concentrations in the bathroom worsened. Gas concentration peaked during suppression to 1.0% O_2, 23.2% CO_2, and 3.7% CO, as combustion gases cooled and dropped in elevation. Bidirectional flow through the window during and after suppression improved gas concentrations to pre-ignition levels prior to hydraulic ventilation.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

Figure 5.55: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 4.

5.4.3 Bedroom 2

The bedroom 2 door was opened prior to ignition. Higher-temperature, higher-pressure combustion gases flowed from the fire room to the lower-temperature, lower-pressure bedroom. Combustion gases accumulated at the ceiling of bedroom 2 and descended to the floor, which limited visibility approximately 190 s post-ignition.

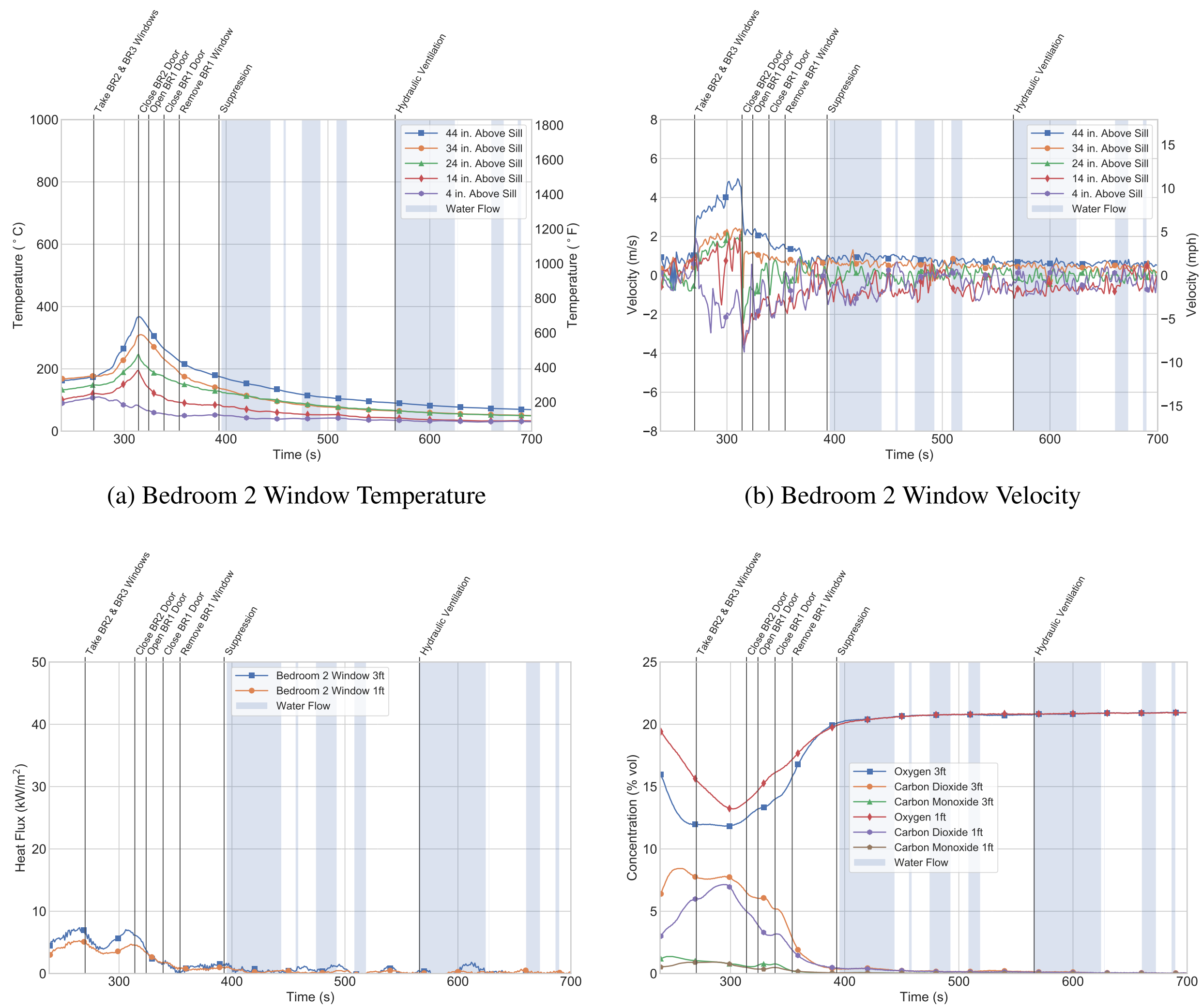
At the time of intervention, window temperatures ranged from 175 °C to 105 °C (347 °F to 221 °F), as shown in Figure 5.56a. Ventilation of half the bedroom 2 window created an exterior vent and established a new flow path between the fire room and the exterior of structure. Flow through the window was initially unidirectional exhaust, but became bidirectional flow after 4 s. Combustion gases flowed along this path and exhausted from the bedroom window between 44 in. to 14 in. above the sill at 3.1 m/s (6.9 mph). Air was entrained 4 in. above the sill at -3.0 m/s (-6.7 mph), as shown in Figure 5.56b. As a result, temperatures 44 in. to 14 in. above the sill increased to 370 °C (698 °F) and temperature 4 in. above the sill decreased to 85 °C (185 °F).

The bedroom 2 door was then closed, which isolated the bedroom from the flow of combustion gases from the fire room. Combustion gases that had accumulated in bedroom 2 continued to drive bidirectional flow through the window. Exhaust flow 44 in. to 34 in. above the sill decreased from 5.0 m/s to 2.2 m/s (11.2 mph to 4.9 mph). Inflow 24 in. to 4 in. above the sill increased to -3.9 m/s (8.7 mph), which decreased window temperatures 44 in. to 14 in. above the sill. The bedroom 2 door remained closed during suppression and hydraulic ventilation. Bidirectional flow through the window decreased temperatures below 75 °C (167 °F).

Heat flux below the bedroom 2 window was 7.3 kW/m^2 3 ft above the floor and 5.3 kW/m^2 1 ft above the floor at the time of intervention, as shown in Figure 5.56c. Immediately following ventilation, combustion gases flowed through the upper portion of the vent and an air was entrained through the lower portion. The air entrainment reduced the heat flux to 3.5 kW/m^2 3 ft above the floor and 3.0 kW/m^2 1 ft above the floor. The decrease was temporary as the exterior vents in bedroom 2 and bedroom 3 led to increased gas flows and a subsequent rise in heat flux to 7.0 kW/m^2 and 4.9 kW/m^2, respectively. Isolation of the bedroom stopped the flow of combustion gases from the fire room into the bedroom, which decreased heat flux. Bidirectional flow through the ventilated window lifted the smoke layer in the bedroom and further reduced heat flux. However, as combustion gases cooled and dropped in elevation, heat flux 3 ft above the floor peaked twice after isolation.

Gas concentrations at the time of intervention indicated that the smoke layer had descended past the 1 ft level in bedroom 2. Gas concentrations were 12.0% O_2, 7.7% CO_2, and 1.0% CO 3 ft above the floor and 15.6% O_2, 6.0% CO_2, and 0.9% CO 1 ft above the floor, as shown in Figure 5.56d. Flow through the window improved gas concentrations 3 ft above the floor, as accumulated combustion gases were exhausted from the bedroom. Air entrainment through the window continued to improve gas concentrations at both measurement locations. After the bedroom 2 door was closed, gas concentrations improved to 20.0% O_2, 0.4% CO_2, and 0.1% CO 3 ft above the floor and 19.9% O_2, 0.5% CO_2, and 0% CO 1 ft above the floor.

At the time of intervention, temperatures in the center of bedroom 2 were consistent with temperatures at the window, as shown in Figure 5.57a. Creation of the exterior vent increased bedroom temperatures as combustion gases and flames flowed from the fire room toward the bedroom 2 window. Temperatures peaked to 630 °C (1166 °F) at the ceiling and 100 °C (212 °F) 1 ft above the floor. Isolation of the bedroom stopped the flow of gases from the fire room into the bedroom. As a result, bedroom temperatures decreased. Bidirectional flow through the window, driven by accumulated combustion gases, decreased temperatures to 150 °C (302 °F) at the ceiling and 50 °C



(a) Bedroom 2 Window Temperature

(b) Bedroom 2 Window Velocity

(c) Bedroom 2 Window Heat Flux

(d) Bedroom 2 Window Gas Concentration

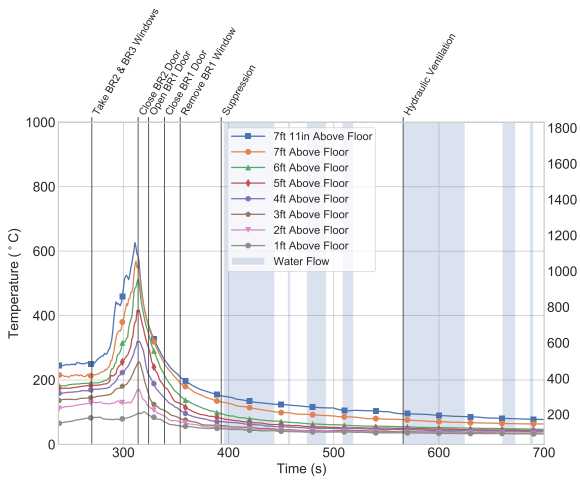
Figure 5.56: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 4.

(122 °F) 1 ft above the floor.

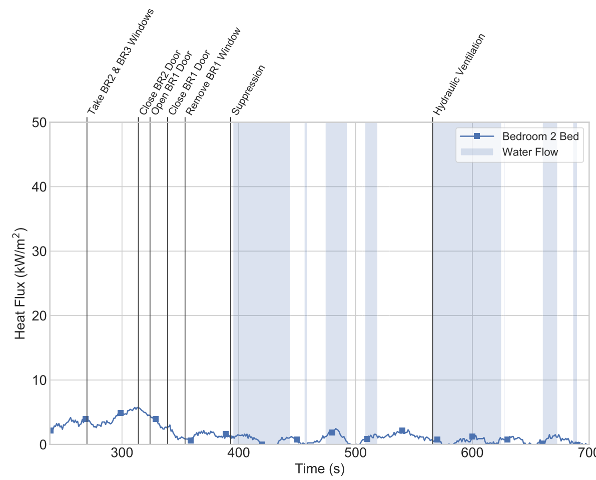
Heat flux to the bed at the time of intervention was 4.1 kW/m^2, as shown in Figure 5.57b. Immediately following window ventilation, accumulated combustion gases flowed toward the exterior vent and heat flux to the bed temporarily decreased to 2.6 kW/m^2. As combustion gases and flames flowed from the hallway into the bedroom, heat flux increased to 5.9 kW/m^2. Isolation of the bedroom and bidirectional flow through the window caused heat flux to decrease. Similar to heat flux below the window, bidirectional flow caused combustion gases to mix with air. Heat flux to the bed peaked after the bedroom was isolated.

Gas concentrations at the bed were 13.2% O_2, 6.4% CO_2, and 0.8% CO at the time of intervention, which indicated the smoke layer had descended past the 3 ft elevation (Figure 5.57c).

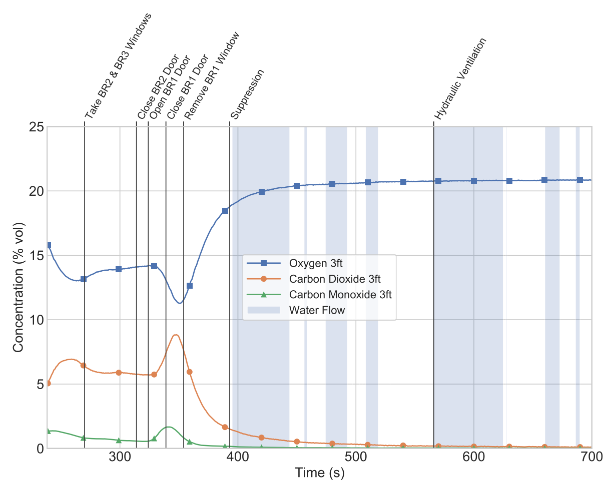
Although combustion gas flow through the bedroom increased temperatures and heat flux, air flow through the ventilated window prevented gas concentrations from worsening. Gas concentrations became steady at approximately 14.0% O_2, 6.0% CO_2, and 0.7% CO. After bedroom isolation, bidirectional flow mixed combustion gases and air within the bedroom. Correspondingly, heat flux reached 2.7 kW/m^2, and gas concentrations rose 11.3% O_2, 8.8% CO_2, and 1.7% CO. Eventually the smoke layer in the bedroom lifted, which improved gas concentrations to 18.8% O_2, 1.5% CO_2, and 0.2% CO.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

Figure 5.57: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 4.

5.4.4 Hallway

Prior to intervention, flames flowed through the top of the fire room doorway into the hallway, which ignited the carpet on the floor. Flames spread toward bedroom 1, bedroom 2, and the common space. However, the lack of a local exterior vent in bedrooms 1 or 2 limited the flame spread toward the end hallway. Figure 5.58 shows the temperature time histories for the hallway and living room entryway locations.

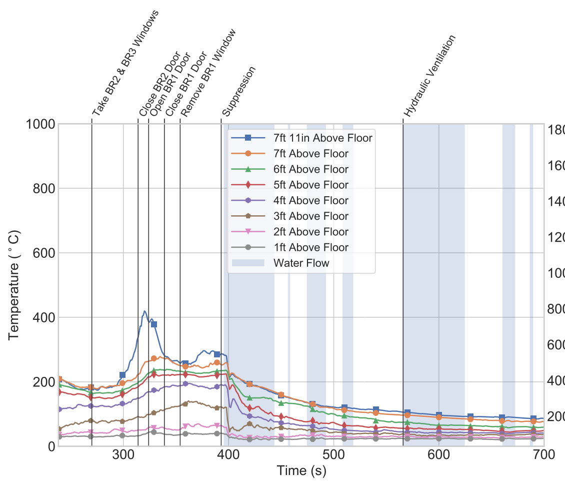
At the time of intervention, hallway temperatures were a function of proximity to the fire room. Mid hallway temperatures were the greatest and exceeded 500 °C (932 °F), followed by start hallway temperatures (450 °C (842 °F)), end hallway temperatures (370 °C (698 °F)), and living room entryway temperatures (180 °C (356 °F)). The large volume of the common space accompanied by bidirectional flow through the front door prevented the smoke layer from descending in the entryway, which caused living room entryway temperatures to be less than hallway temperatures. Temperatures below 2 ft above the floor at the start hallway location were greater than temperatures 4 ft above the floor due to low-level burning of the carpet.

Air entrainment through the ventilated bedrooms 2 and 3 windows increased the available oxygen for combustion along the flow paths to the fire room. The heat release rate of the bedroom 4 fire increased, which increased the temperature of combustion gases flowing into the hallway. The mid hallway location transitioned through flashover as temperatures exceeded 990 °C (1814 °F) at the ceiling and 670 °C (1238 °F) 1 ft above the floor, which caused combustion gases throughout the hallway to ignite.

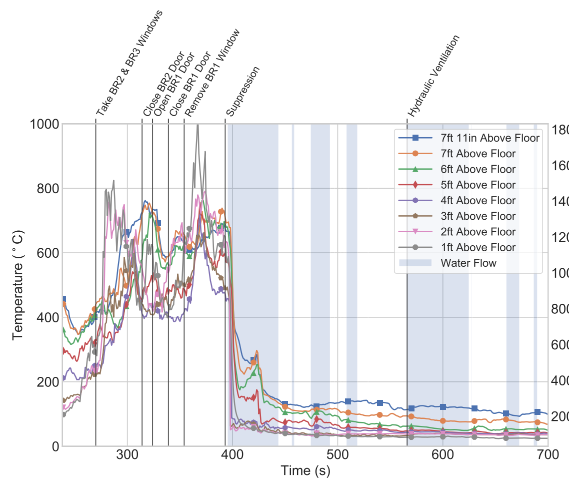
Isolation of bedroom 2 stopped the exchange of gases between the bedroom and the hallway, which decreased the available oxygen for combustion at the end hallway location. Flaming combustion retreated down the hallway toward the fire room and end hallway temperatures decreased from 725 °C to 630 °C (1328 °F to 1337 °F).

The open bedroom 1 door created an exterior vent in the hallway and established a new flow path between the fire room and the bedroom. Higher-temperature combustion gases flowed from the hallway into the bedroom, which decreased temperatures above 5 ft at the start hallway and living room entryway locations. Lower-temperature air entrained from the bedroom into the hallway, which decreased temperature below 5 ft at the end hallway and mid hallway locations. The available oxygen for combustion increased along the flow path to the fire room. The closed bedroom 1 door had a similar effect as the closed bedroom 2 door. End hallway temperatures decreased from 630 °C to 515 °C (1377 °F to 959 °F). Combustion gases and flames retreated down the hallway and flowed toward the exterior vent in bedroom 3, which transitioned the mid hallway through flashover approximately 365 s post-ignition. The bedroom fuels ignited and the bedroom 3 fire transitioned through flashover approximately 370 s post-ignition.

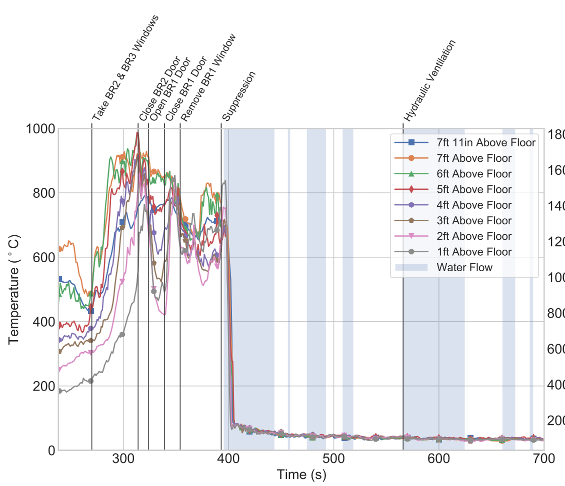
The suppression crew began flowing water in the hallway. Initial suppression caused temperatures ahead of the hoseline (end hallway and mid hallway locations) to decrease more than temperatures behind the hoseline (start hallway and living room entryway locations). Additional water flows decreased temperatures throughout the hallway below 135 °C (275 °F). Hydraulic ventilation caused unidirectional inflow through the bedroom 4 doorway and unidirectional exhaust flow through the bedroom 4 window. Hallway combustion gases flowed into the fire room, which decreased temperatures below 120 °C (248 °F).



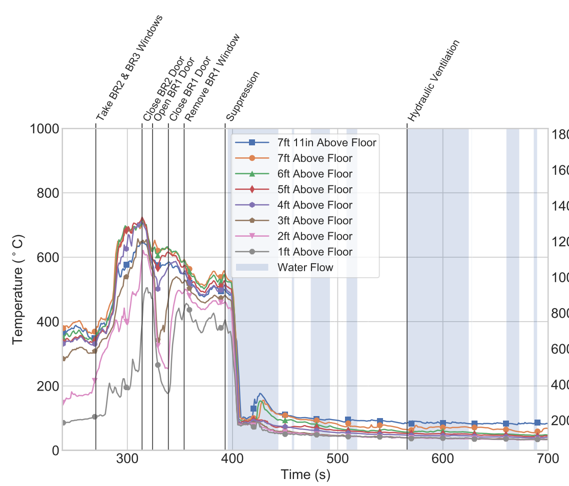
(a) Living Room Entryway Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.58: Temperature time histories in the hallway in the period following fire department intervention in Experiment 4.

Heat flux to the hallway floor at the time of intervention ranged from 1.5 kW/m^2 to 3.5 kW/m^2, expect for the start hallway heat flux which exceeded 35.5 kW/m^2 (Figure 5.59). Low-level burning of the carpet at the start hallway location produced larger heat fluxes and temperatures nearest the floor when compared to the mid hallway, end hallway, and living room entryway locations.

Increased burning in the hallway, as a result of the ventilated bedrooms 2 and 3 windows, increased hallway heat fluxes. The end hallway location peaked at 16.8 kW/m^2 prior to the closure of the bedroom 2, which limited the oxygen available for combustion and the end hall heat flux dropped to 8.9 kW/m^2. The magnitude subsequently recovered to 13.2 kW/m^2 following the opening of

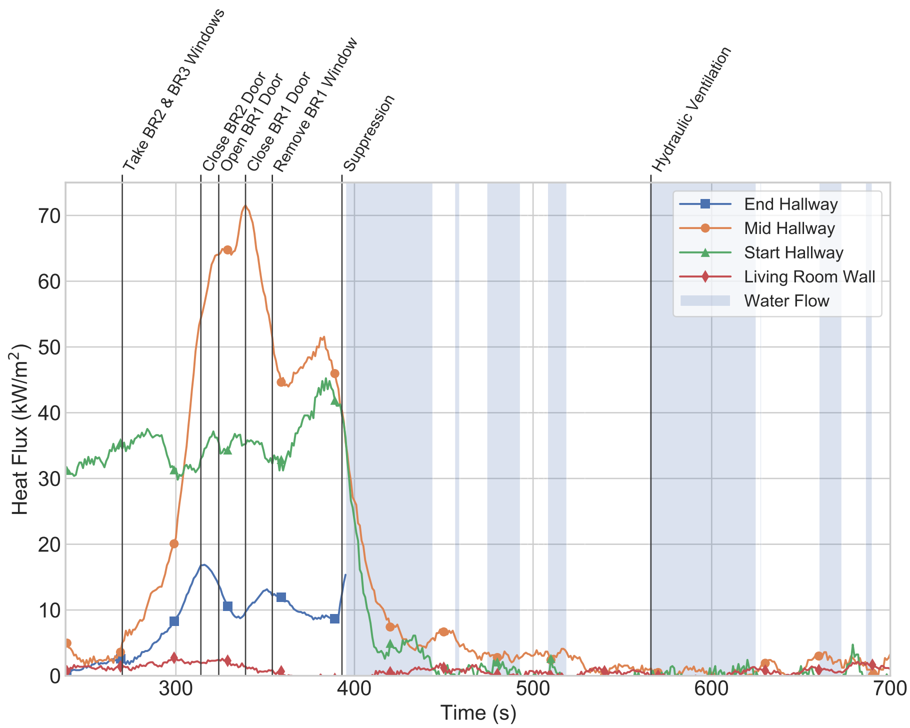


Figure 5.59: Heat flux time histories in the hallway in post-intervention period during Experiment 4.

bedroom 1 which led to increased burning at the end hallway. Closing the bedroom 1 door resulted in a second decay that continued until suppression.

The mid hallway heat flux steadily increased due to the flaming combustion outside of the hallway and peaked at 70 kW/m^2 following the temporary opening of the bedroom 1 door which provided additional air for combustion in the hallway. The mid hallway decreased to 44 kW/m^2 following the closure of bedroom 1 but a secondary peak of 51.6 kW/m^2 was reached and flames spread into bedroom 3 following the failure of the non-vented portion of the bedroom 3 window.

The start hallway heat flux remained nominally steady of approximately 35 kW/m^2 as air entrained through the open front door supported the flaming combustion along the hallway carpet. Similar the mid hallway location, as bedroom 3 transitioned through flashover and start hallway heat flux peaked at 45.2 kW/m^2.

The suppression crew flowed water in the hallway to extinguish flaming combustion on the carpet, which decreased start hallway and mid hallway heat fluxes. Water coated the heat flux gauge at the end hallway location, which affected the accuracy of the measurement. At this point, the end hallway heat flux data are not representative of heat flux during suppression. Initial suppression decreased hallway heat fluxes below 7.0 kW/m^2 and additional water flows decreased hallway heat fluxes below 4.0 kW/m^2. Hydraulic ventilation increased flows through the hallway and through bedroom 4 vents to the exterior, which decreased heat fluxes below 3.0 kW/m^2.

Table 5.8 shows the gas concentrations measured throughout the hallway and living room entryway locations at the time of intervention in Experiment 4. Gas concentrations indicated that prior to intervention, the smoke layer had descended past the 1 ft level at the mid hallway and end hallway locations. Low-level burning at the start hallway location caused lower concentrations of O_2 and higher concentrations of CO and CO_2 at the 1 ft level compared to the 3 ft level.

Prior to intervention, the only exterior vents in the structure were the bedroom 4 window and the front door. Gas concentrations worsened as distance to an exterior vent increased, resulting in higher concentrations of O_2 and lower concentrations of CO_2 and CO in the common area and lower concentrations of O_2 and higher concentrations of CO_2 and CO at the end hallway location.

Table 5.8: Hallway Gas Concentrations at Intervention for Experiment 4

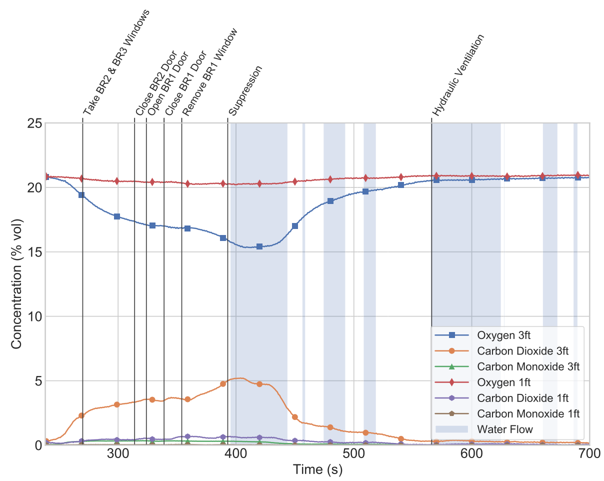
Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	19.4	2.3	0.3
	1 ft	20.7	0.3	0
Start Hallway	3 ft	20.3	0.8	0.1
	1 ft	20.1	1.0	0.1
Mid Hallway	3 ft	14.9	5.3	0.6
	1 ft	17.5	3.2	0.5
End Hallway	3 ft	12.9	6.8	0.8
	1 ft	17.8	3.0	0.5

Figures 5.60a through 5.60d show the gas concentration time histories for the hallway and living room entryway locations. Ventilation of the bedrooms 2 and 3 windows created flow paths between the fire room and the exterior through each bedroom. Air entrainment toward the fire room improved gas concentrations 1 ft above the floor at the end hallway and mid hallway locations, but also increased the available oxygen for combustion along the flow paths. As the heat release rate of the bedroom 4 fire increased, the temperature of combustion gases flowed into the hallway increased. The mid hallway location transitioned through flashover and gas concentrations 3 ft above the floor at all hallway locations worsened.

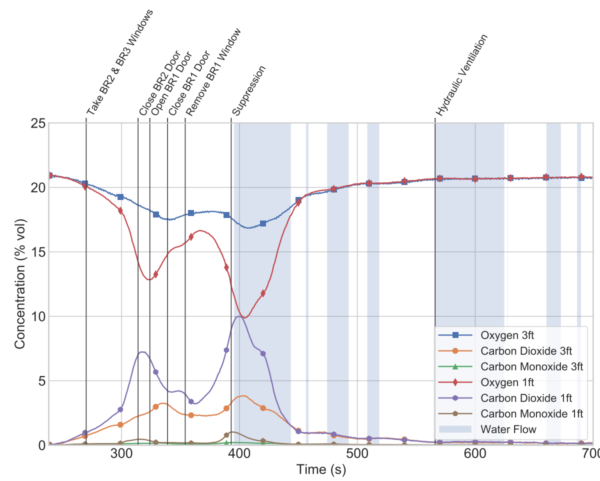
Isolation of bedroom 2 limited the available oxygen for combustion, which decreased hallway burning. Gas concentrations continued to worsen, but at a slower rate. Without a local exterior vent, the end hallway gas concentrations deteriorated to 2.3% O_2, 17.0% CO_2, and 3.6% CO 3 ft above the floor.

Air flowed through the bedroom 1 door into the hallway, which improved gas concentrations 3 ft above the floor at the end hallway and mid hallway locations. Combustion gases flowed from the hallway to bedroom 1, which improved gas concentrations at the start hallway location. Isolation of bedroom 1 had a similar effect as isolation of bedroom 2, as hallway burning decreased and gas concentrations worsened. Flames flowed into bedroom 3 toward the exterior vent and ignited bedroom 3 fuels. As a result, start hallway gas concentrations worsened to 9.9% O_2, 10.0% CO_2, and 1.0% CO 1 ft above the floor.

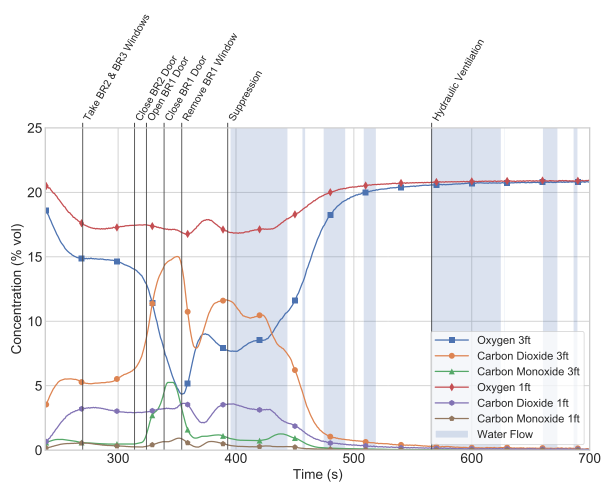
Suppression terminated the production of combustion gases in the hallway and bedroom 4, which caused gas concentrations to improve as bidirectional flow through exterior vents continued. Gas concentrations improved to pre-ignition levels, which minimized the impact of hydraulic ventilation.



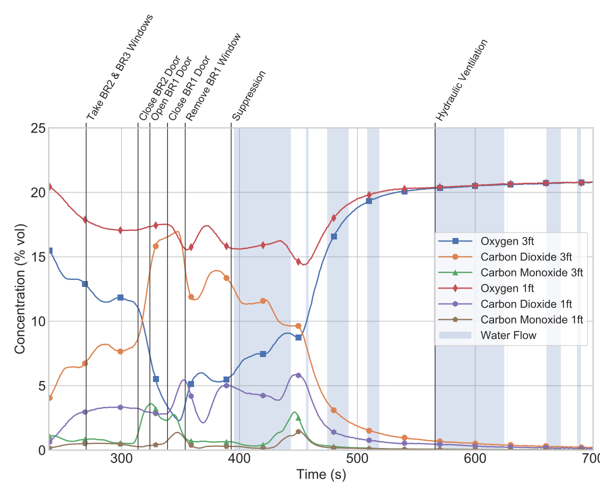
(a) Living Room Entryway Hall Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.60: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 4.

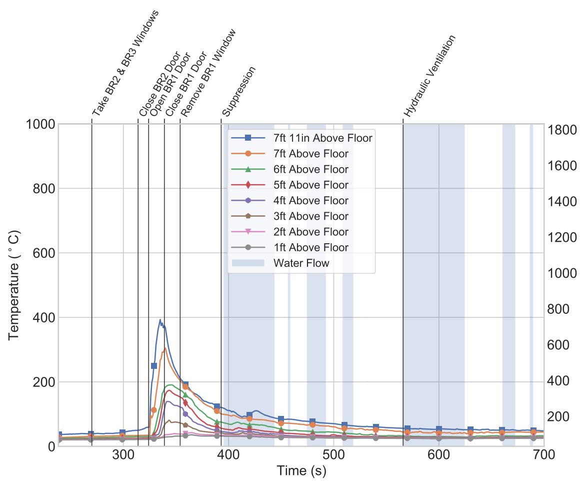
5.4.5 Bedroom 1

The bedroom 1 door was closed prior to ignition, which limited the flow of combustion gases from the fire room into the bedroom. However, higher-pressure combustion gases flowed through the leakage area around the closed door and through the HVAC supply vents, which increased bedroom 1 ceiling temperatures to 40 °C (104 °F) at the time of intervention (Figure 5.61a). The open bedroom 1 door allowed higher-temperature combustion gases to flow from the hallway into the previously isolated bedroom, which increased ceiling temperatures from 60 °C to 395 °C (140 °F to 743 °F). The bedroom was isolated from the flow of combustion gases approximately 15 s later, which caused bedroom temperatures to decrease.

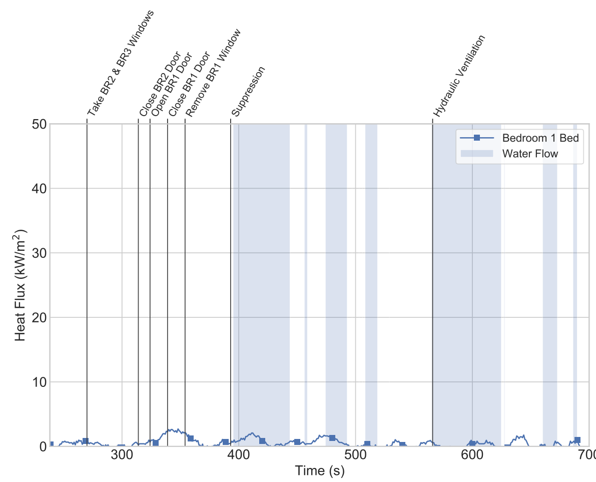
The removal of the bedroom window created an exterior vent and established a new flow path between the higher-pressure bedroom and the lower-pressure exterior. Flow through the window exhausted combustion gases from the bedroom and entrained air to the bedroom. Bedroom temperatures decreased below 120 °C (250 °F). The bedroom door remained closed during suppression and hydraulic ventilation, which minimized the impact of both interventions. However, water flow in bedroom 4 caused additional flow of higher-temperature combustion gases through the HVAC supply vents located in the ceiling. Bedroom 1 ceiling temperature increased from 95 °C to 110 °C (203 °F to 230 °F). Suppression extinguished the bedroom 4 fire, which decreased the temperature of gases flowing through the HVAC supply vents; therefore, temperatures in bedroom 1 decreased. Temperatures decreased below 50 °C (122 °F) by the end of the experiment.

Heat flux to bed 1 at the time of intervention was less than 1 kW/m^2, as shown in Figure 5.61b. After the bedroom 1 door was opened, heat flux peaked to 2.7 kW/m^2. After the bedroom 1 door was closed, the flow of combustion gases into the space stopped and heat flux decreased below 0.5 kW/m^2. Post-suppression heat flux decreased below 1.0 kW/m^2.

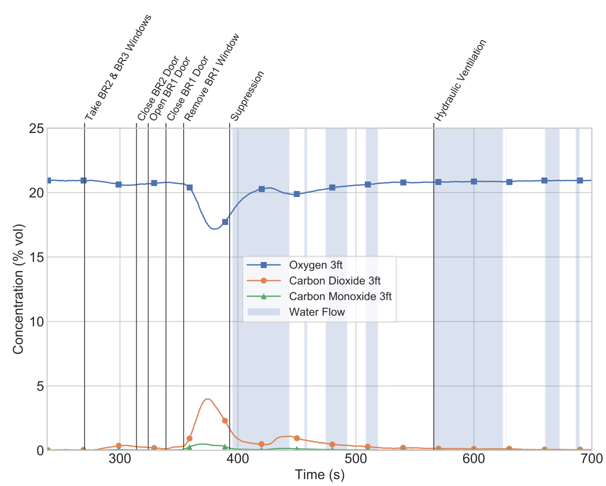
Gas concentrations at the time of intervention were consistent with pre-ignition levels, as shown in Figure 5.61c. Although the open bedroom 1 door allowed combustion gases to flow into the bedroom, gas concentrations did not increase, as the smoke layer did not descend to the bed level. Removal of the bedroom 1 window caused combustion gases to exhaust to the exterior, which caused mixing of combustion gases and air. As mixing cooled combustion gases, they dropped lower in elevation. Gas concentrations worsened to 17.2% O_2, 4.0% CO_2, and 0.5% CO. Gas concentrations improved as bidirectional flow through the window lifted the smoke layer in the bedroom. Similar to bedroom 1 temperature and heat flux, gas concentrations temporarily worsened during suppression. However, gas concentrations improved to pre-ignition conditions of 20.9% O_2, 0.1% CO_2, and 0% CO by the end of the experiment.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



(c) Bedroom 1 Gas Concentration

Figure 5.61: Post-intervention bed level temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 4.

The bathroom 1 door was closed prior to ignition, which prevented the flow of combustion gases between the bedroom and the bathroom. However, higher-pressure combustion gases flowed through the HVAC supply vents and increased bathroom temperatures to 30 °C (86 °F) at the time of first intervention (Figure 5.62). The bathroom was isolated from flow paths established in bedroom 1. As a result, temperatures increased regardless of ventilation changes and exceeded 50 °C (122 °F) at the onset of suppression. Suppression caused temperatures 7 ft and below to decrease, but temperatures near the ceiling continued to increase, as water flow caused additional gas flow through the HVAC supply vents. Bathroom temperatures decreased under 50 °C (122 °F) by the end of the experiment.

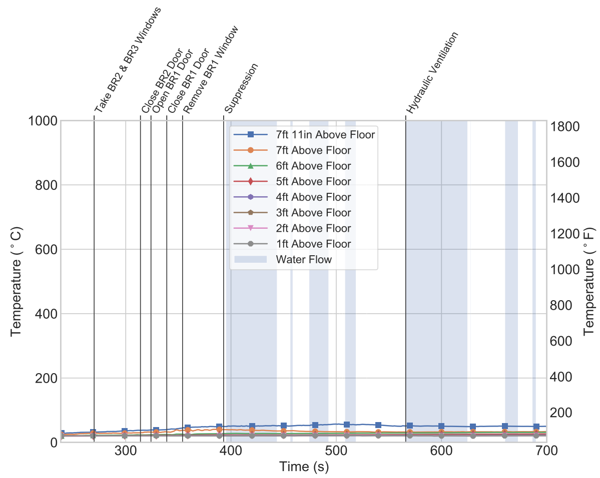


Figure 5.62: Post-intervention temperatures in bathroom 1 during Experiment 4.

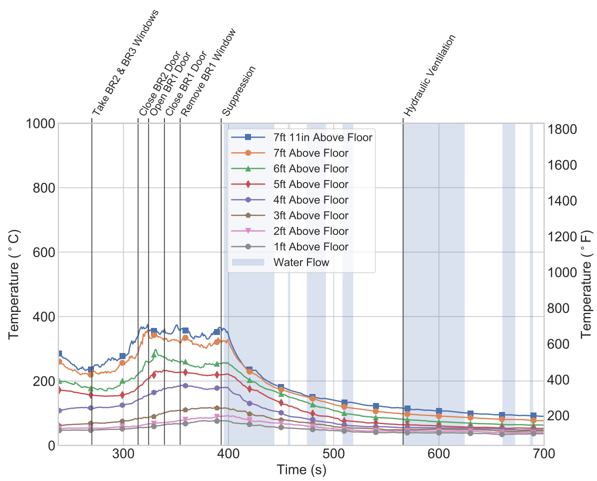
5.4.6 Common Space

Figures 5.63a and 5.63b show the temperature time histories in the living room and kitchen, respectively. Common space temperatures at the time of intervention ranged from 240 °C to 50 °C (464 °F to 122 °F) in the living room and 210 °C to 40 °C (410 °F to 104 °F) in the kitchen. Ventilation of the bedrooms 2 and 3 windows increased the available oxygen for combustion in the fire room, which increased the heat release rate of the bedroom 4 fire. As gas temperatures increased and flames spread down the hallway, temperatures in the common space exceed 375 °C (707 °F) in the living room and 360 °C (680 °F) in the kitchen.

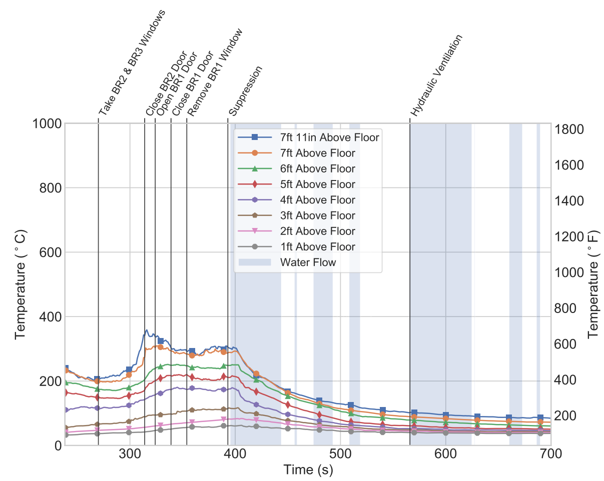
Closure of the bedroom 2 door limited the available oxygen for combustion in the hallway. As a result, flaming combustion in the hallway stopped and the temperature of combustion gases flowing into the common space decreased. Temperatures in the common space remained constant until suppression. Suppression extinguished the fire in bedrooms 3 and 4, and common space temperatures reduced below 125 °C (257 °F). Hydraulic ventilation created an area of lower pressure in bedroom 4, which caused higher-pressure combustion gases to flow into bedroom 4. Temperatures in the common space reduced below 100 °C (212 °F) in the living room and 90 °C (194 °F) in the kitchen.

Heat flux 1 ft above the kitchen floor was 1.2 kW/m^2 at the time of first intervention, as shown in Figure 5.63c. Following flame spread and subsequent flashover of bedroom 3, heat flux increased to 2.0 kW/m^2 due to increased flaming combustion down the hallway toward the common space. Suppression reduced the heat release rate of the hallway and bedroom fires, which reduced kitchen heat flux. Hydraulic ventilation further reduced heat flux by causing combustion gases to flow from the kitchen toward bedroom 4. Heat flux decreased below 0.5 kW/m^2.

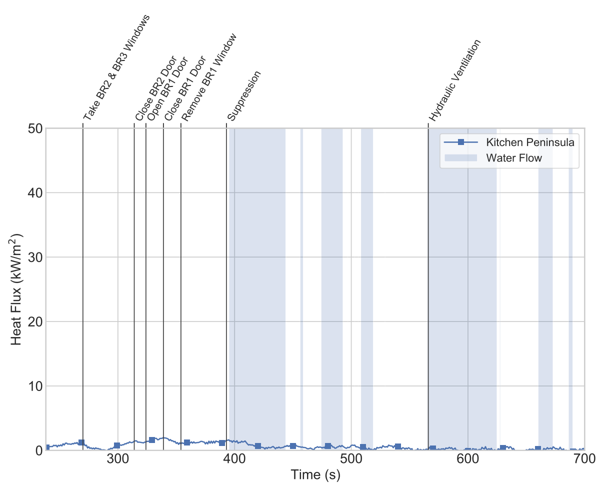
Gas concentrations 1 ft above the kitchen floor were consistent with pre-ignition levels at the time of intervention, as shown in Figure 5.63d. Similar to heat flux, gas concentrations worsened as the smoke layer descended from the ceiling in the kitchen. Suppression cooled combustion gases near the ceiling. Combustion gases dropped in elevation as they cooled, which worsened kitchen gas concentrations to 18.0% O_2, 1.0% CO_2, and 0.5% CO. Post-suppression flow through the exterior vents exhausted combustion gases from the structure, which improved gas concentrations. Hydraulic ventilation further improved gas concentrations to pre-ignition conditions.



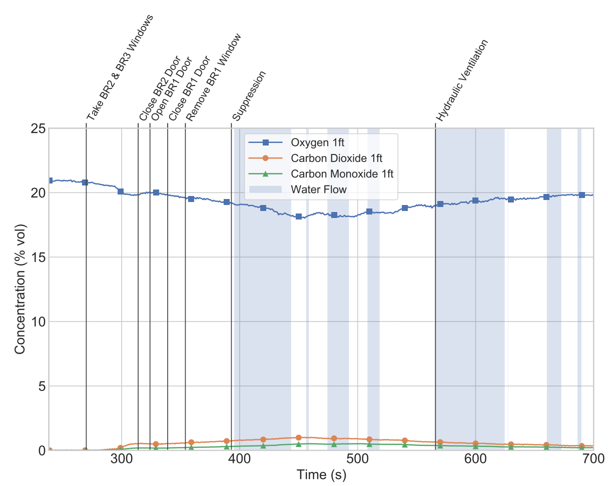
(a) Living Room Temperature



(b) Kitchen Temperature



(c) Kitchen Heat Flux



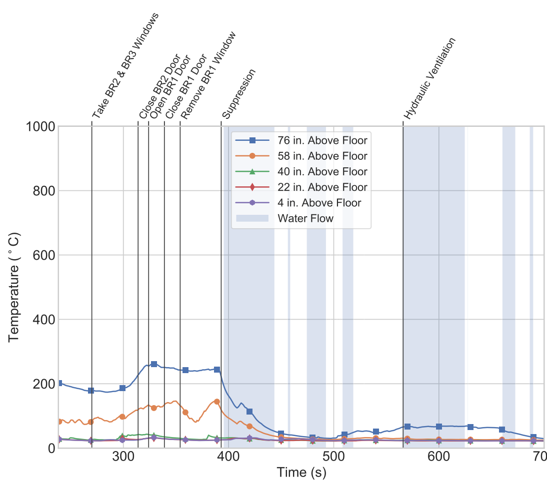
(d) Kitchen Gas Concentration

Figure 5.63: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 4.

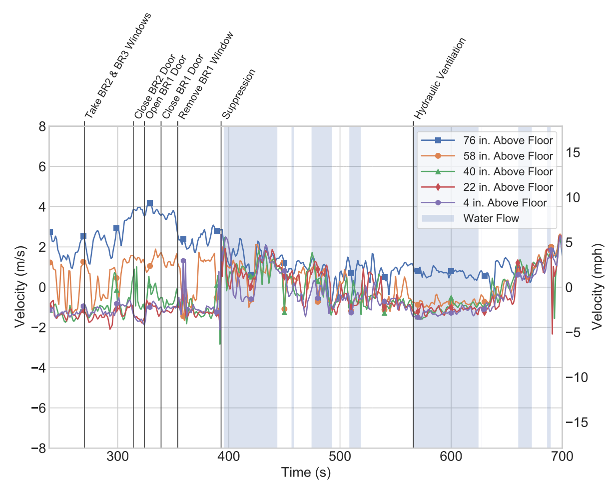
Figures 5.64a and 5.64b show the temperature and velocity time histories through the front door. Front doorway temperatures at the time of first intervention were reflective of the velocity profile through the door. Higher-temperature, higher-pressure combustion gases were exhausted to the exterior 76 in. and 58 in. above the floor between 2.5 m/s and 1.3 m/s (5.6 mph and 2.9 mph), which increased doorway temperatures above 180 °C (356 °F). Lower-temperature, lower-pressure air was entrained below 58 in. at approximately 1.0 m/s (2.2 mph). Temperatures ranged from 30 °C to 20 °C (86 °F to 68 °F).

Ventilation of the bedroom windows caused the heat release rate of the bedroom 4 fire to increase, which increased the temperature of combustion gases that flowed out of the front door. Front door exhaust peaked to 4.2 m/s (9.4 mph) and temperatures exceeded 260 °C (500 °F). Conditions at the front door remained stable until after bedroom 1 was isolated. Bedroom 3 window failure caused front door exhaust 58 in. above the floor to entrain air approximately -2.0 m/s (-4.5 mph) and temperature to decrease from 150 °C to 80 °C (302 °F to 176 °F). As the bedroom fuels ignited and the fire transitioned through flashover, exhaust 58 in. above the floor increased to 1.7 m/s (3.8 mph) and temperatures exceeded 150 °C (302 °F).

The front door bidirectional probes were removed prior to suppression for crew entry into the structure. Data recorded between approximately 385 s post-ignition and 505 s post-ignition are not representative of flow through the front door. Hydraulic ventilation caused velocity 76 in. above the floor to exhaust combustion gases at approximately 1.0 m/s (2.2 mph), and velocities 58 in. and below to entrain air between -1.5 m/s and -0.5 m/s (-3.6 mph and -1.1 mph). Front doorway temperatures reduced below 65 °C (149 °F).



(a) Front Doorway Temperature



(b) Front Doorway Velocity

Figure 5.64: Post-intervention temperatures and velocities in the front doorway during Experiment 4.

5.5 Experiment 5

The search tactics in Experiment 5 were designed to evaluate window initiated operations conducted during interior suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide, bedroom 4 window and the bedroom 4 door were removed. The front door to the structure and doors to bedroom 2, bedroom 3, and bathroom 3 were opened. The doors to bedroom 1 and bathroom 1 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 flashover, the suppression crew entered the structure through the front door and began suppression. Simultaneously, the crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. The crews entered each bedroom and proceeded toward the hallway doors. The crew in bedroom 3 were unable to close the door. The crew bedroom 2 entered the hallway and closed the door behind them. The crew crossed the hallway and opened the door to bedroom 1. After entry into the space the crew closed the door and removed the bedroom 1 double-wide window. At this point, the search tactic comparison was complete. Upon the suppression crew announcement of 'fire under control', hydraulic ventilation occurred out of the failed bedroom 4 window. 106 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 281 gallons. Table 5.9 provides the timing of each event relative to ignition and to the first intervention, which in this experiment was simultaneous interior suppression and ventilation of the bedrooms 2 and 3 windows.

Table 5.9: Experiment 5 Event Times

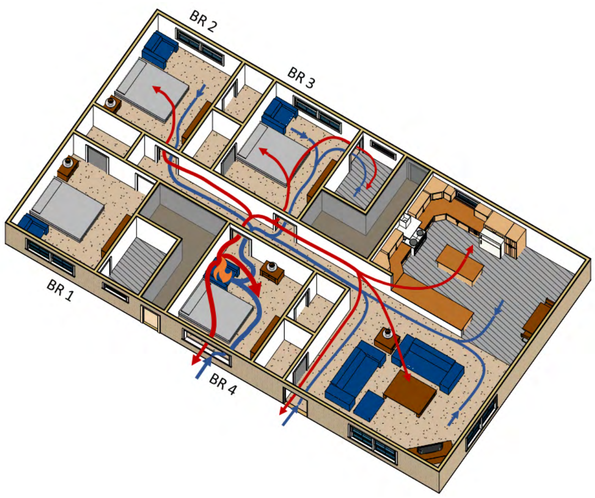
Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Ignition	00:00	0	—	—
Suppression, Take BR2 & BR3 Windows	05:01	301	00:00	0
Close BR2 Door	05:44	344	00:43	43
Open BR1 Door	05:53	353	00:52	52
Close BR1 Door	06:02	362	01:01	61
Remove BR1 Window	06:19	379	01:18	78
Hydraulic Ventilation	07:19	439	02:18	138

Figures 5.65 and 5.66 show the changes in flow throughout the structure as a result of fire department intervention during Experiment 5. At the time of intervention, the bedroom 4 fire was in a post flashover state. Bidirectional flow through the bedroom 4 vents was generated, as air was entrained and combustion gases were exhausted (Figure 5.65a). Flow paths were established between the higher-pressure fire room and the lower-pressure open volumes of the structure and the exterior of the structure.

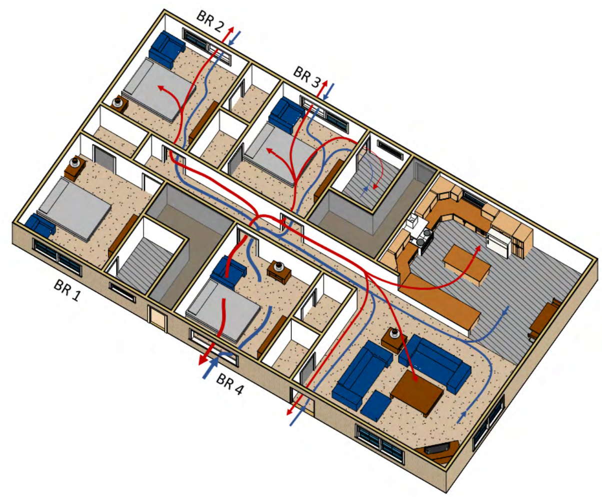
Ventilation of the bedrooms 2 and 3 windows created an exterior vent within each bedroom.

Flow paths were established between the higher-pressure fire room and the lower-pressure exterior through each bedroom, as shown in Figure 5.65b. Interior suppression began 9 s after ventilation and was conducted through the front door using a smooth bore nozzle with a 7/8 in. tip, set to flow 160 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline. Suppression reduced the heat release rate of the fire and reduced the production of combustion gases. The presence of higher-temperature, higher-pressure combustion gases within the structure continued to drive flow throughout the structure.

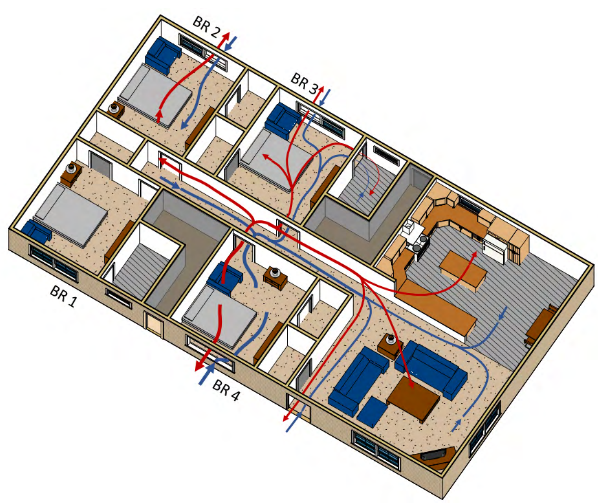
Closure of the bedroom 2 door isolated the bedroom from the flow of combustion gases from the fire room, as shown in Figure 5.65c. Accumulated combustion gases in bedroom 2 continued to drive bidirectional flow through the window.



(a) Flows Prior to Intervention



(b) Suppression, Take BR2 & BR3 Windows

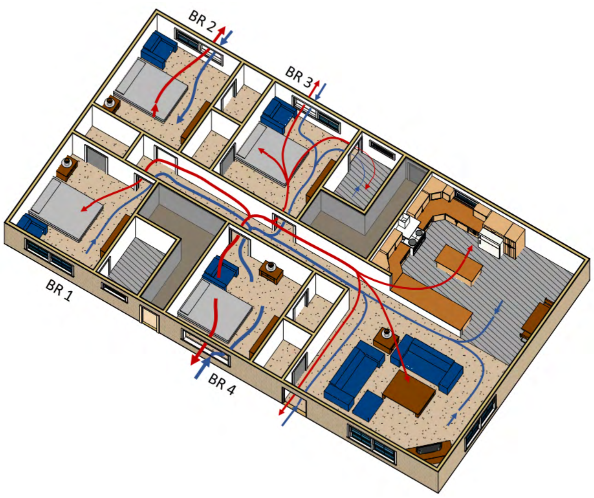


(c) Close BR2 Door

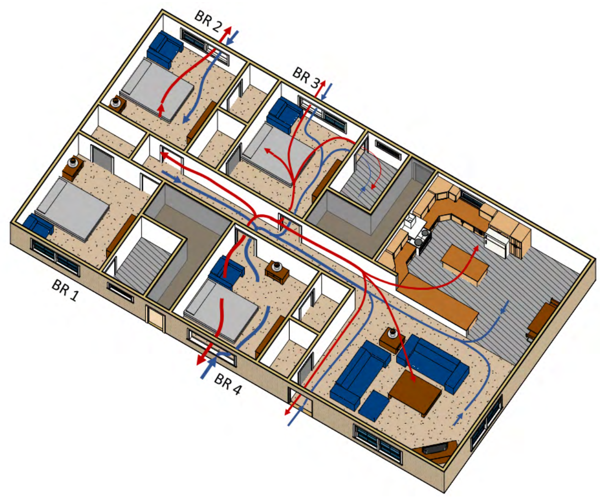
Figure 5.65: Changes in flow in structure following fire department interventions in Experiment 5.

The open bedroom 1 door established a new flow path between the higher-pressure fire room and the lower-pressure bedroom, as shown in Figure 5.66a. Bidirectional flow through the doorway exchanged hallway combustion gases with bedroom air. Closure of the bedroom 1 door isolated the bedroom from the flow of combustion gases from the fire room, as shown in Figure 5.66b. The removal of the bedroom 1 window created an exterior vent and a flow path established between the bedroom and the exterior (Figure 5.66c). Bidirectional flow through the window exhausted previously accumulated combustion gases and entrained cool air to the bedroom.

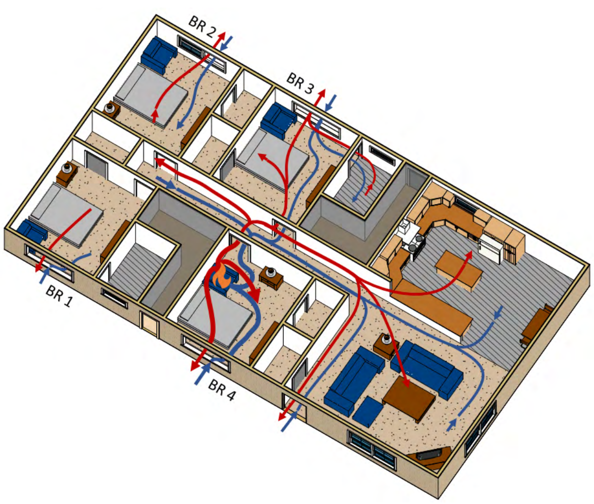
Hydraulic ventilation occurred out of the double-wide bedroom 4 window with the tip on, full bale, in an O-pattern. Flow through the bedroom 4 vents became unidirectional toward the exterior (Figure 5.66d).



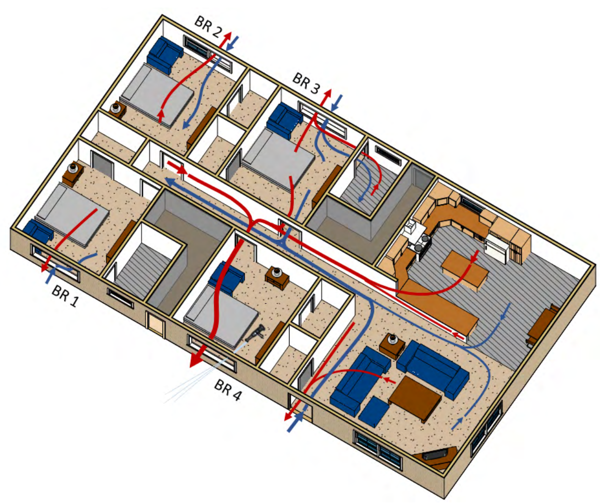
(a) Open BR1 Door



(b) Close BR1 Door



(c) Remove BR1 Door



(d) Hydraulic Ventilation

Figure 5.66: Changes in flow in structure following fire department interventions in Experiment 5.

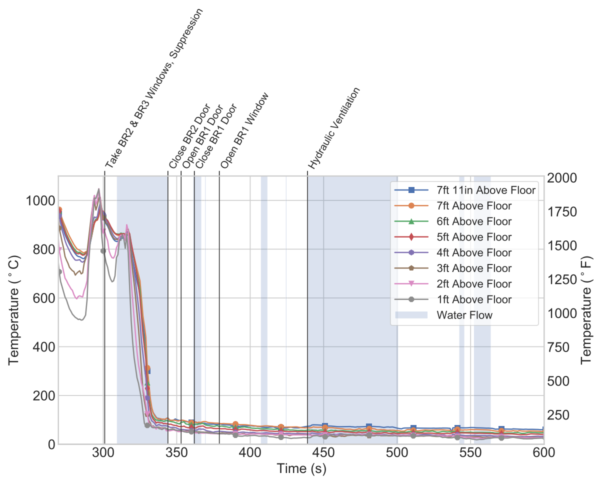
5.5.1 Bedroom 4

The bedroom 4 fire transitioned through flashover approximately 220 s post ignition. Bedroom 4 temperatures at the time of intervention ranged from 930 °C (1706 °F) at the ceiling to 770 °C (1418 °F) 1 ft above the floor (Figure 5.67a). Ventilation of the bedrooms 2 and 3 windows established flow paths between the higher-pressure fire room and the lower-pressure exterior through each bedroom. Suppression occurred approximately 10 s after ventilation and reduced the heat release rate of the fire. Fire room temperatures reduced below 100 °C (212 °F) after initial suppression and below 70 °C (158 °F) after five additional water flows in the fire room and bedroom 3. Hydraulic ventilation occurred out of the double-wide window in bedroom 4. An area of low pressure was created by the flowing hose stream, which caused flow through the bedroom 4 vents to become unidirectional toward the exterior. Combustion gases exhausted outside of the structure, which decreased fire room temperatures below 65 °C (149 °F).

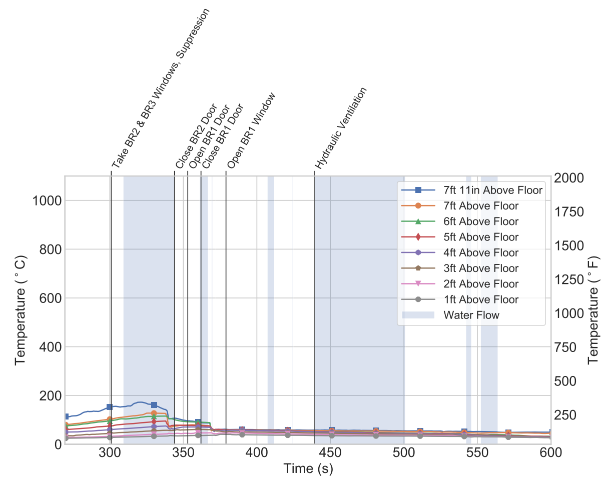
The door to the bedroom 4 closet was closed prior to ignition, which isolated the closet from the flow of higher-temperature, higher-pressure combustion gases. However, combustion gases flowed through the leakage area around the closed door and increased closet temperatures to 150 °C (302 °F) at the ceiling to 30 °C (86 °F) 1 ft above the floor at the time of intervention, as shown in Figure 5.67b. Closet temperatures exceeded 170 °C (338 °F) when suppression caused gradual temperature decrease in the closet. Water flow failed the closet door and immediately reduced closet temperatures to 105 °C (221 °F). Additional water flows decreased closet temperatures below 60 °C (140 °C). The closet lacked an exterior vent and was adjacent to the flows established from hydraulic ventilation in the fire room. The impact of hydraulic ventilation on closet temperatures was minimal, and temperatures decreased below 55 °C (131 °F).

Figures 5.67c and 5.67d show the temperature and velocity time histories through the fire room door. Temperature of the gas flow through the bedroom 4 doorway was stratified at the time of intervention, as flow was bidirectional. Temperatures at the top of the doorway exceeded 820 °C (1508 °F), as combustion gases exhausted between 3.2 m/s and 1.2 m/s (7.2 mph and 2.7 mph). Temperatures near the floor of the doorway exceeded 560 °C (1040 °F), as air entrained between -3.8 m/s and -2.1 m/s (-8.5 mph and -4.7 mph). Air entrained through the ventilated bedrooms 2 and 3 windows along the flow paths to the fire room, which decreased fire room doorway temperatures below 40 in. to 275 °C (527 °F).

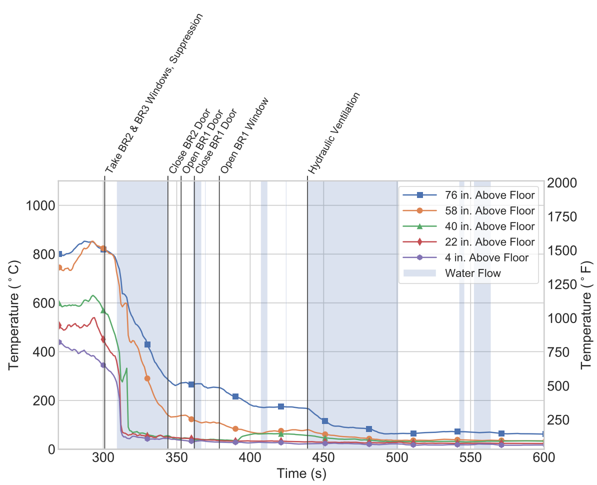
The suppression crew began flowing water the in hallway; as the crew turned into the bedroom, flow from the hoseline damaged the velocity probes in the doorway. Therefore, velocity measurements 58 in. to 22 in. above the floor are not accurate representations of gas flow. Initial suppression reduced the heat release rate of the bedroom 4 fire and reduced the production of higher-pressure, higher-temperature combustion gases. Cooler combustion gases flowed through the doorway, which reduced temperatures below 280 °C (536 °F). Additional water flows further reduced temperatures to 175 °C (347 °F). Hydraulic ventilation caused combustion gas flow through the doorway to become unidirectional exhaust toward the window. Gas flow was approximately -1.5 m/s (-3.6 mph) and temperatures reduced below 65 °C (149 °F).



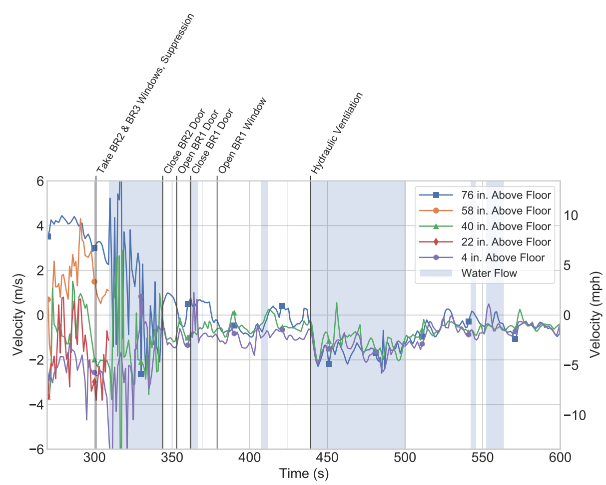
(a) Bedroom 4 Temperature



(b) Closet Temperature



(c) Bedroom 4 Doorway Temperature



(d) Bedroom 4 Doorway Velocity

Figure 5.67: Heat flux time histories in bedroom 4 in post-intervention period during Experiment 5.

5.5.2 Bedroom 3

The bedroom 3 door was opened prior to ignition, which allowed higher-temperature, higher-pressure combustion gases to flow from the fire room into the lower-pressure bedroom. Combustion gases accumulated at the ceiling of bedroom 3 and descended to the floor. Visibility was lost approximately 230 s post-ignition.

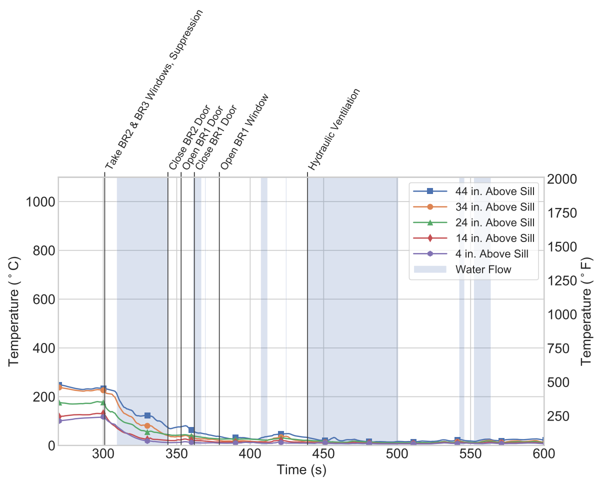
Bedroom 3 window temperatures ranged from 230 °C (446 °F) 44 in. above the sill to 120 °C (248 °F) 4 in. above the sill at the time of intervention, as shown in Figure 5.68a. Ventilation of the window created an exterior vent in the bedroom and established a new flow path between the fire room and the exterior. Flow through the window was bidirectional, as combustion gases exhausted at 1.4 m/s (3.1 mph) and air entrained at -2.7 m/s (-6.0 mph) (Figure 5.68b). Combustion gas flow through the top of the window caused temperatures 44 in. to 34 in. above the sill to remain constant and air flow through the bottom of the window decreased temperatures 24 in. to 4 in. above the sill.

Water flow in the hallway and fire room increased entrainment through the window. Air entrained at -3.9 m/s (-8.7 mph) and reduced window temperatures below 70 °C (158 °F). Post suppression, exhaust flow reestablished through the top of the window between 1.8 m/s and 1.5 m/s (4.0 mph and 3.6 mph), which increased temperature 44 in. above the sill to 80 °C (176 °F). Generally, time periods of water flow increased entrainment through the window and time periods without water flow decreased entrainment through the window. Window temperatures decreased below 30 °C (86 °F).

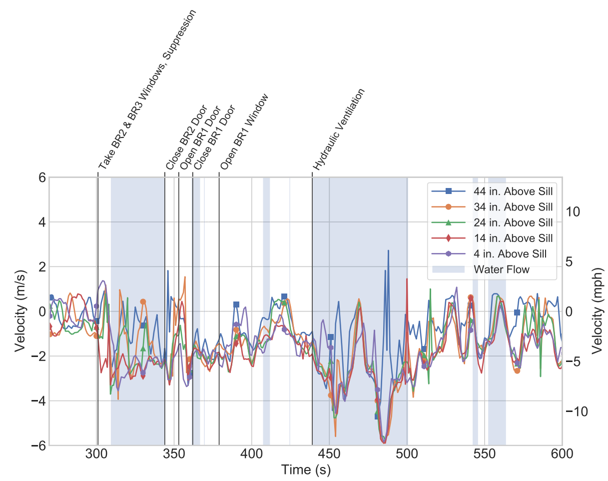
Hydraulic ventilation created an area of lower pressure in the fire room, which caused flow through the bedroom 4 vents to become unidirectional. Increased air entrainment through bedroom 3 resulted in unidirectional inflow through the bedroom 3 window. Wind blowing from side C toward side A, with gusts between 7.7 m/s and 10.9 m/s (17.2 mph and 24.4 mph), caused inflow through the window to exceed -5.9 m/s (-13.2 mph). This inflow over-pressurized the bedroom. Decreased wind gusts decreased the inflow through the window. As the pressure in bedroom 3 pressure equalized to the environment, there was temporary exhaust flow through the window.

At the time of intervention, heat flux below the bedroom 3 window was 4.9 kW/m^2 3 ft above the floor and 1.4 kW/m^2 1 ft above the floor, as shown in Figure 5.68c. Combustion gas flow through the ventilated window exhausted accumulated combustion gases from the bedroom, which decreased heat flux below the window. Air flow through the ventilated window mixed with combustion gases, which caused a temporary rise in heat flux to 3.3 kW/m^2 and 2.1 kW/m^2 3 ft and 1 ft above the floor, respectively. Suppression reduced the heat release rate of the bedroom 4 fire and increased entrainment through the bedroom 3 vent, which reduced heat flux to 0.2 kW/m^2 below the window. Hydraulic ventilation caused unidirectional inflow through the window, which reduced heat flux to 0 kW/m^2.

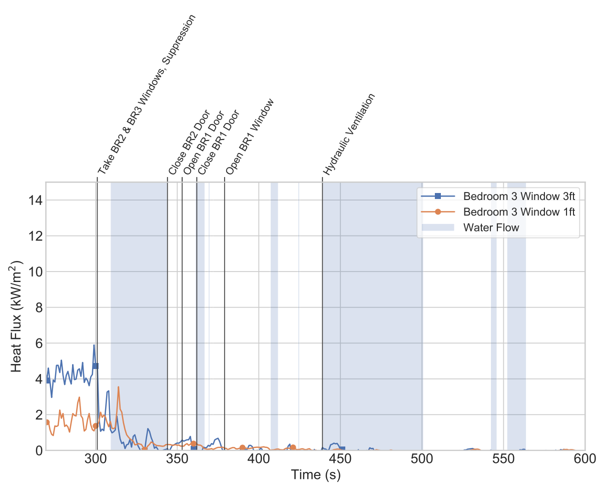
Gas concentrations below the window at the time of intervention were 13.5% O_2, 2.7% CO_2, and 1.4% CO 3 ft above the floor and 13.4% O_2, 2.1% CO_2, and 1.3% CO 1 ft above the floor, as shown in Figure 5.68d. Air flow through the exterior vent mixed with combustion gases below the window, which prevented gas concentrations from worsening. Suppression caused unidirectional inflow through the window. Gas concentrations improved to 19.8% O_2, 0.5% CO_2, and 0.2% CO 3 ft above the floor and 20.0% O_2, 0.6% CO_2, and 0.4% CO 1 ft above the floor, which minimized the impact of hydraulic ventilation.



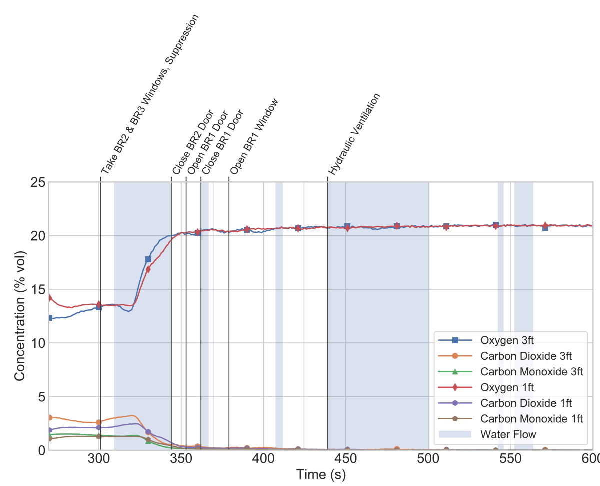
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.68: Post-intervention window temperature, heat flux, and gas concentrations in bedroom 3 during Experiment 5.

Temperatures in the center of bedroom 3 were consistent with window temperatures at the time of intervention, as shown in Figure 5.69. Temperatures ranged from 290 °C (554 °F) at the ceiling to 60 °C (140 °F) 1 ft above the floor. Ventilation of the bedroom window created an exterior vent. As higher-pressure combustion gases flowed toward and through the window, bedroom temperatures decreased. Suppression cooled combustion gases that flowed into the bedroom and temperatures reduced below 80 °C (176 °F). Hydraulic ventilation caused higher-pressure combustion gases in bedroom 3 to flow through the doorway into bedroom 4 and lower-pressure air to flow through the window into bedroom 3. Temperatures decreased below 40 °C (104 °F).

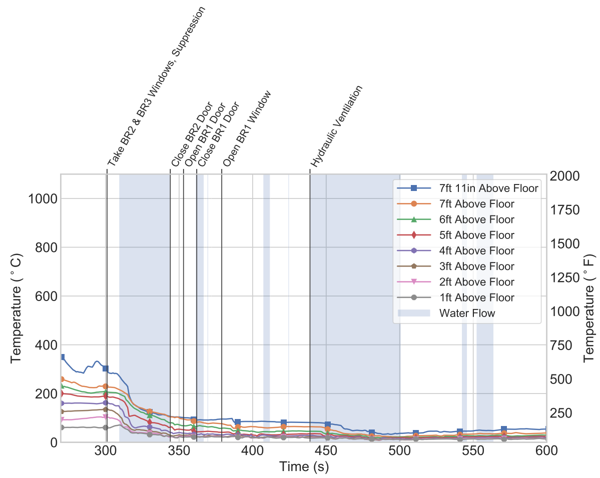
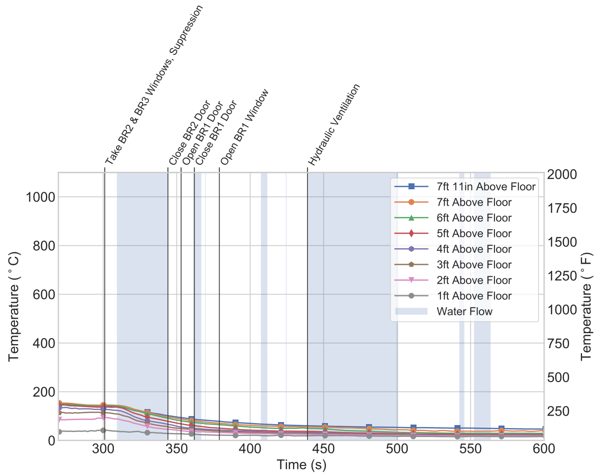


Figure 5.69: Post-intervention temperature in bedroom 3 during Experiment 5.

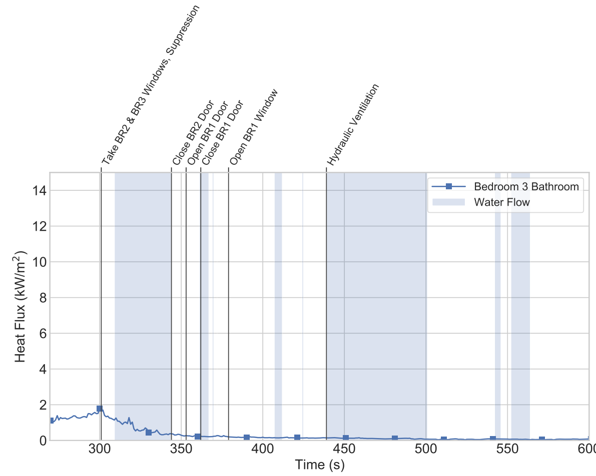
The bathroom 3 door was opened prior to ignition. Higher-temperature, higher-pressure combustion gases flowed from the fire room into the bathroom. However, the bathroom was two rooms removed from the fire, which limited temperature increase compared to the bedroom. At the time of first intervention, bathroom temperatures ranged from 150 °C (302 °F) at the ceiling to 40 °C (104 °F) 1 ft above the floor, as shown in Figure 5.70a. The bathroom was adjacent to, but not part of the flow path established between the bedroom and the exterior through the ventilated window. As a result, temperatures in the bathroom were slower to decrease than the bedroom; however they eventually reduced below 60 °C (140 °F). The bathroom lacked an exterior vent, which limited the impact of hydraulic ventilation. Even so, bathroom temperatures reduced below 50 °C (122 °F).

Heat flux 1 ft above the bathroom floor was 1.8 kW/m^2 at the time of intervention, as shown in Figure 5.70b. Air flow through the ventilated bedroom 3 window cooled combustion gases in the bathroom, though less efficiently than local to the bedroom. Heat flux in the bathroom immediately reduced. Flow through the window continued and heat flux decreased to 0.1 kW/m^2 as the smoke layer lifted.

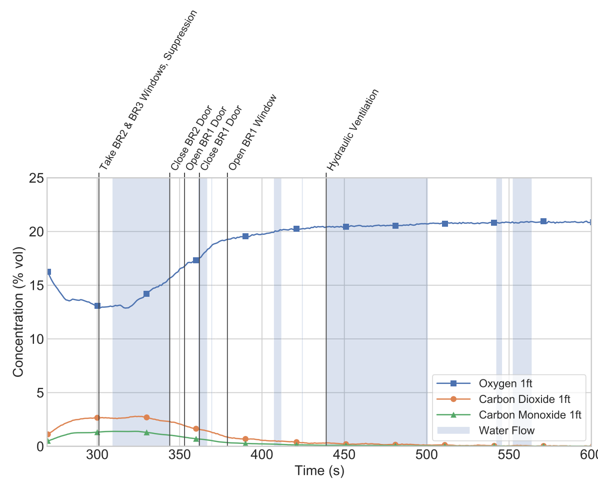
Gas concentrations at the time of first intervention indicated that the smoke layer in the bathroom had descended past the 1 ft level, as shown in Figure 5.70c. Flow through the ventilated window caused gas concentrations to remain at approximately 13.0% O_2, 2.7% CO_2, and 1.3% CO. Suppression reduced the production of combustion gases in the fire room and increased air intake through the bedroom 3 window, which improved bathroom gas concentrations as the smoke layer lifted. Bathroom gas concentrations improved to 20.4% O_2, 0.3% CO_2, and 0.1% CO, which minimized the impact of hydraulic ventilation.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

Figure 5.70: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 5.

5.5.3 Bedroom 2

The bedroom 2 door was opened prior to ignition. Higher-temperature, higher-pressure combustion gases flowed from the fire room and accumulated in the lower-pressure bedroom. The smoke layer descended from the ceiling and visibility was lost approximately 200 s post-ignition.

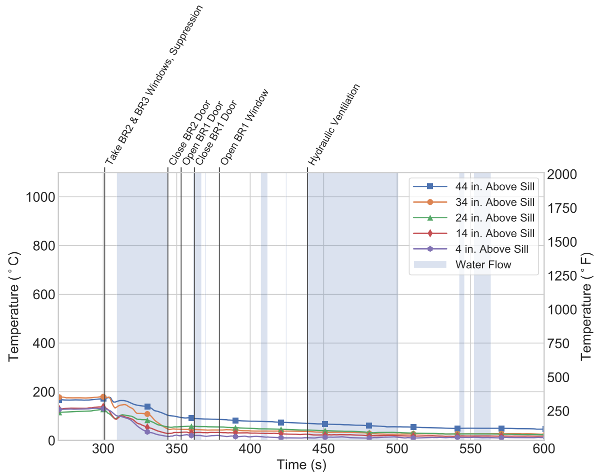
Bedroom 2 window temperatures ranged from 170 °C (338 °F) 44 in. above the sill to 120 °C (348 °F) 4 in. above the sill at the time of intervention, as shown in Figure 5.71a. Ventilation of the bedroom window created an exterior vent in the bedroom and established a new flow path between the bedroom and the exterior. Gas flow through the bedroom 2 window was bidirectional; combustion gases exhausted from the bedroom at 1.6 m/s (3.6 mph) and air entrained to the bedroom at -3.2 m/s (-7.2 mph). Temperatures decreased below 155 °C (311 °F) (Figure 5.71b).

Suppression caused flow through the bedroom window to become unidirectional exhaust for approximately 10 s. Combustion gases exhausted between 3.7 m/s and 2.2 m/s (8.3 mph and 4.9 mph), which caused a temporary rise in temperature to approximately 165 °C (329 °F). Gas temperatures decreased, which caused combustion gases to contract and decrease bedroom 2 pressure. Flow through the window became bidirectional and temperatures reduced to 100 °C (212 °F).

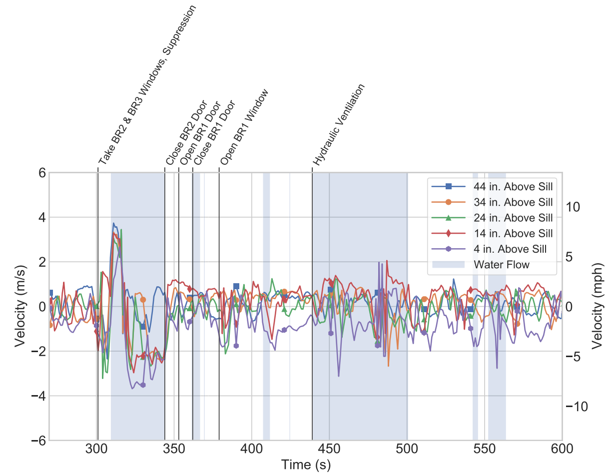
The bedroom 2 door was closed, which isolated the bedroom from the flow of combustion gases. Accumulated combustion gases exhausted from the bedroom at 1.0 m/s (2.2 mph) and air entrained to the bedroom at -1.0 m/s (-2.2 mph). Window temperatures reduced below 55 °C (131 °F). The bedroom door remained closed during hydraulic ventilation.

At the time of intervention, heat flux below the bedroom 2 window measured to 5.8 kW/m^2 3 ft above the floor and 2.0 kW/m^2 1 ft above the floor (Figure 5.71c). After ventilation of the bedroom window, flow through the window cooled combustion gases, which reduced heat flux. Following the onset of suppression, exhaust flow immediately increased heat flux to 7.2 kW/m^2 and 8.3 kW/m^2, respectively. Bidirectional flow through the window before and after the bedroom 2 door was closed reduced heat flux below 0.1 kW/m^2.

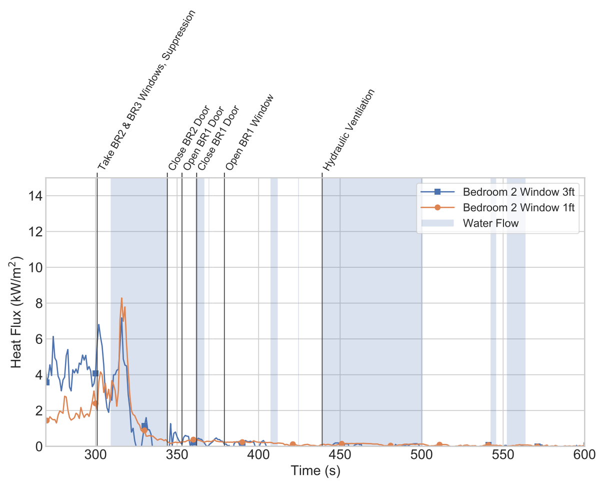
Gas concentrations below the bedroom 2 window at the time of first intervention indicated that the smoke layer in bedroom 2 had descended below the 1 ft level, as shown in Figure 5.71d. Gas concentrations were 13.8% O_2, 5.6% CO_2, and 0.6% CO 3 ft above the floor and 14.7% O_2, 5.2% CO_2, and 0.6% CO 1 ft above the floor. Gas concentrations remained constant until flow through the ventilated window became bidirectional during suppression. Bidirectional flow exhausted combustion gases from the bedroom and entrained cool air to the bedroom, which improved gas concentrations. Isolation of the bedroom limited further accumulation of combustion gases. Bidirectional flow continued and gas concentrations improved to pre-ignition levels.



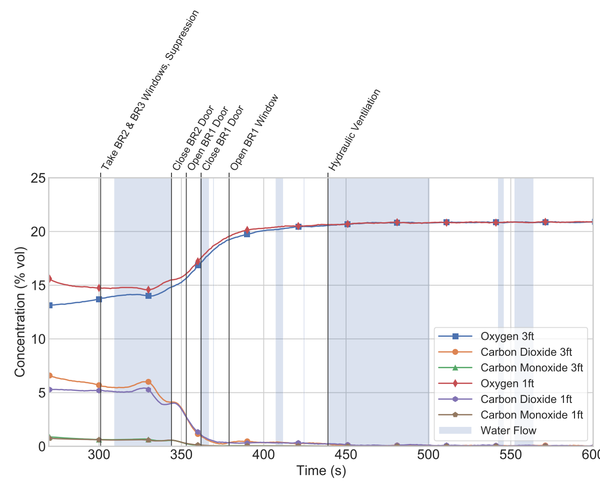
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



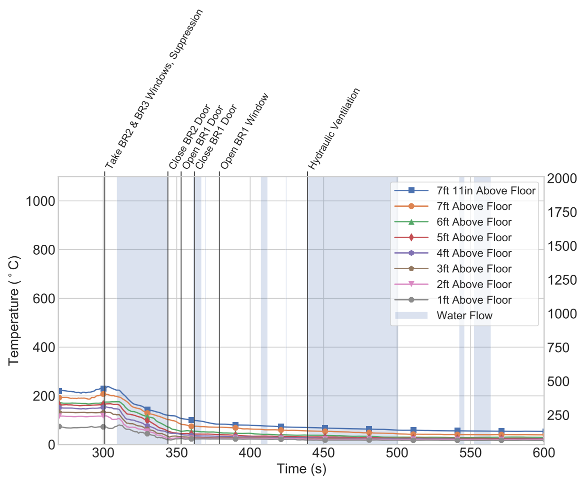
(d) Bedroom 2 Window Gas Concentration

Figure 5.71: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 5.

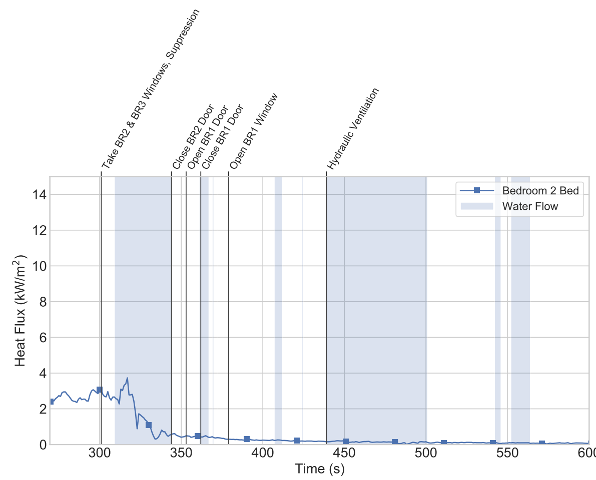
Temperatures in the center of the bedroom were consistent with window temperatures at the time of intervention, as shown in Figure 5.72a. Bidirectional flow through the ventilated bedroom 2 window decreased bedroom temperatures. Suppression decreased the heat release rate of the bedroom 4 fire and caused flow through the window to become unidirectional exhaust for approximately 10 s. Cooler combustion gases flowed from the fire room and exhausted through the vent, which further decreased temperatures. Bidirectional flow through the window established and bedroom temperatures continued to decrease. The bedroom 2 door was closed, which isolated the bedroom from the flow and further accumulation of combustion gases. Bidirectional flow through the window exhausted accumulated combustion gases and entrained air, which decreased temperatures below 60 °C (140 °F).

Heat flux to the bed was 3.1 kW/m^2 at the time of intervention, as shown in Figure 5.72b. Bidirectional flow through the ventilated window caused heat flux to decrease to 2.3 kW/m^2. During suppression, heat flux peaked to 3.7 kW/m^2 as flow through the window became unidirectional exhaust. As the production of combustion gases stopped and flow through the window became bidirectional, heat flux decreased. Heat flux reduced below 0.2 kW/m^2 after the bedroom was isolated.

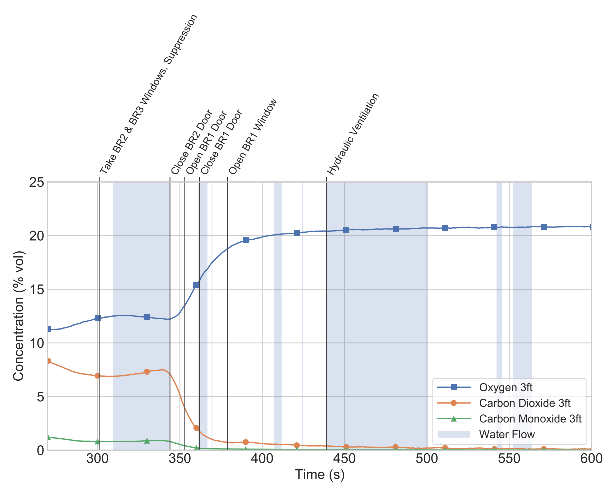
Gas concentrations at the bed level were 12.3% O_2, 6.9% CO_2, and 0.8% CO at the time of intervention, as shown in Figure 5.72c. Flow through the ventilated bedroom window prevented gas concentrations at the bed from worsening. However, gas concentrations did not begin to improve until after the bedroom was isolated. The closed bedroom 2 door prevented further accumulation of combustion gases in the space, which allowed bidirectional flow through the window to lift the smoke layer. Gas concentrations improved to pre-ignition levels.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

Figure 5.72: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 5.

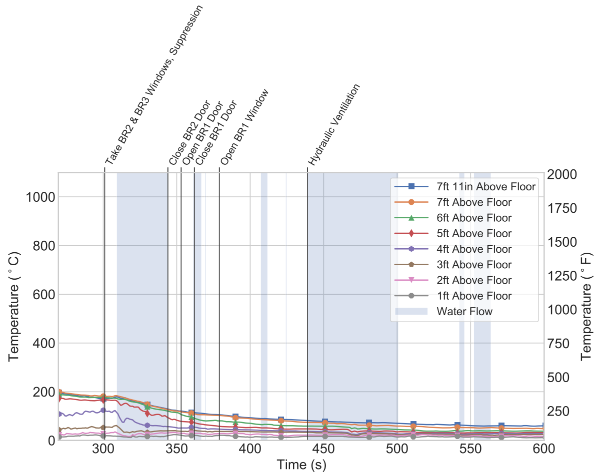
5.5.4 Hallway

Figure 5.73 shows the temperature time histories for the hallway and living room entryway locations. At the time of intervention, hallway temperatures were a function of proximity to the fire room. Mid hallway temperatures were the greatest and exceeded 700 °C (1292 °F), followed by the start hallway, end hallway, and living room entryway locations. The large volume of the common space and flow through the front door caused living room entryway temperatures to generally be less than hallway temperatures.

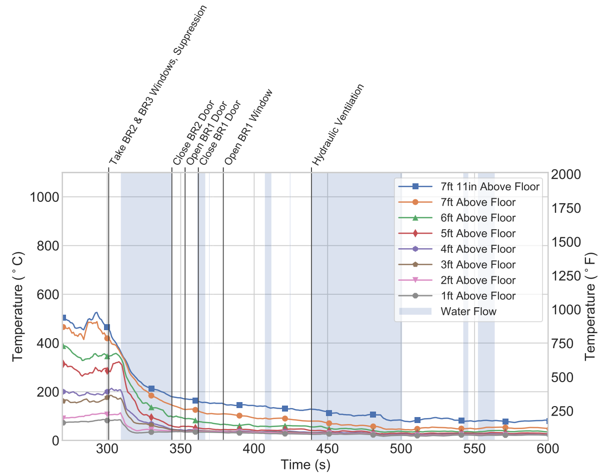
Ventilation of the bedrooms 2 and 3 windows established flow paths between the fire room and the exterior. Cool air entrained along these flow paths to the fire room and combustion gases exhausted along these flow paths to the exterior, which decreased hallway temperatures.

Initial suppression began in the hallway and immediately cooled mid hallway and end hallway temperatures below 100 °C (212 °F), as these locations were ahead of the hoseline. At the start hallway and living room entryway locations, initial suppression gradually cooled temperatures below 180 °C (356 °F) because the locations were behind the hoseline. Suppression decreased the heat release rate of the fire and reduced the production of higher-temperature combustion gases, and temperatures continued to decrease. Post-suppression water flows in the fire room and bedroom 3 reduced end hallway, mid hallway, and living room entryway temperatures below 85 °C (185 °F) and start hallway temperatures below 130 °C (266 °F). Temperatures at the start hallway location were the greatest following suppression, as this location was most removed from an exterior vent and was behind the hoseline.

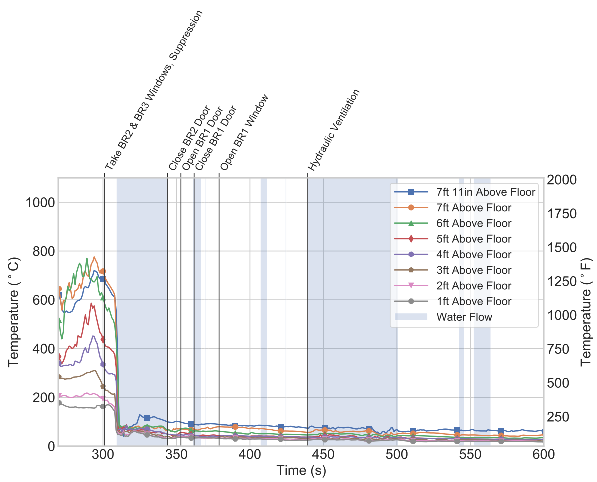
Hydraulic ventilation caused flow from open volumes of the structure through the bedroom 4 vents toward the exterior. Temperatures reduced below 60 °C (140 °F) at the end hallway and mid hallway locations. Temperatures reduced below 80 °C (176 °F) at the start hallway and the living room entryway locations.



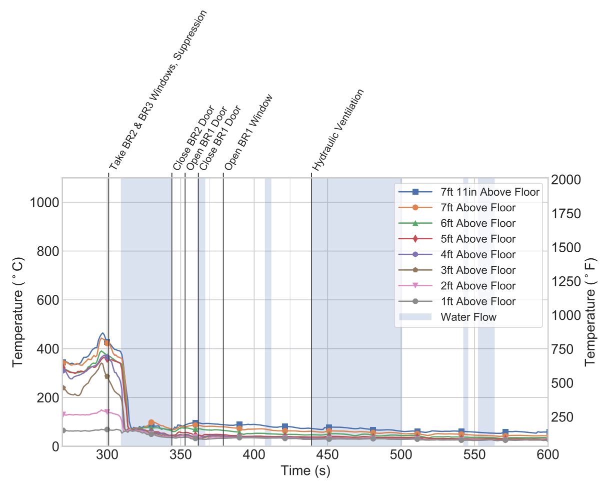
(a) Living Room Entryway Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.73: Temperature time histories in the hallway in the period following fire department intervention in Experiment 5.

Figure 5.74 shows the heat flux time histories in the hallway and living room entryway locations. Prior to intervention, flames exhausted from the fire room into the hallway, which ignited the carpet at the mid hallway location. Flames spread toward both the end hallway location and the start hallway location. However, the lack of an exterior vent in bedrooms 2 limited flame spread to the end hallway location. As a result, heat flux at the time of intervention was greatest at the mid hallway location and exceeded 10.7 kW/m^2, followed by the start hallway (5.5 kW/m^2), end hallway (1.9 kW/m^2), and living room entryway (0.8 kW/m^2) locations.

Ventilation of the bedrooms 2 and 3 windows established flow paths between the fire room and the exterior. Flow through along these paths converged at the mid hallway location. Increased gas velocity increased heat flux to 27.3 kW/m^2.

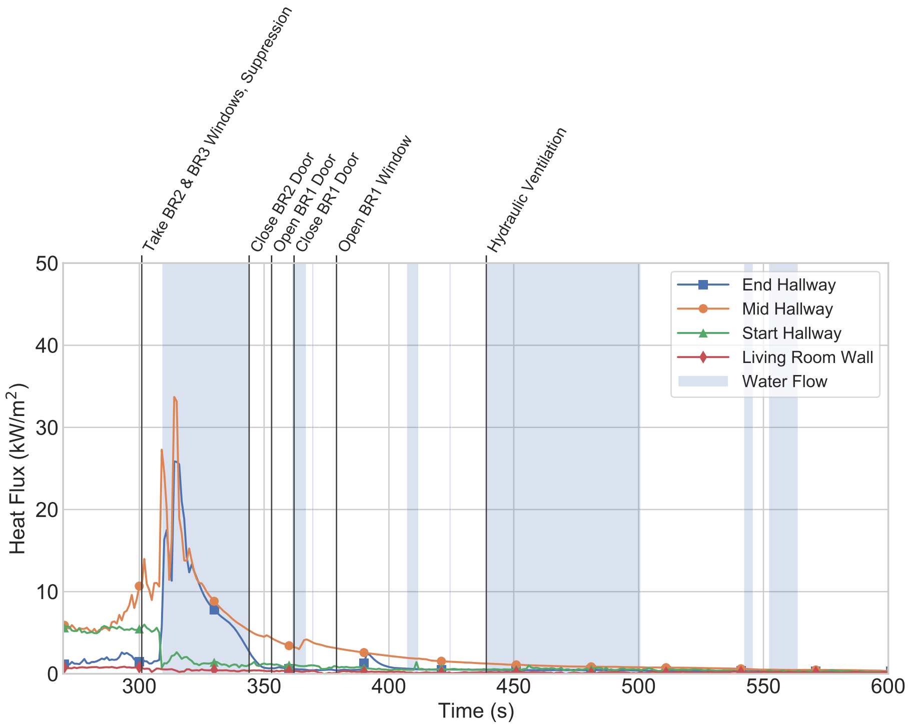


Figure 5.74: Heat flux time histories in the hallway in post-intervention period during Experiment 5.

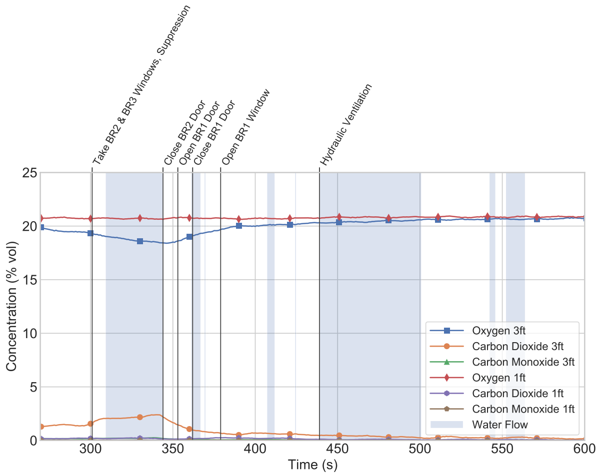
The suppression crew began flowing water in the hallway to cool the carpet before they advanced to the fire room. The O-pattern coated the heat flux gauges at the end hallway and mid hallway locations with water, which impacted the measurement accuracy. Therefore, the end hallway and mid hallway peaks during suppression are not accurate representations of heat flux. Suppression decreased the heat release rate of the fire and cooled gases, which decreased heat fluxes throughout the hallway and living room entryway. Hydraulic ventilation caused combustion gases from the hallway to flow into bedroom 4, which reduced the range of heat flux values from 1.2 kW/m^2—0.5 kW/m^2 to 0.8 kW/m^2—0.1 kW/m^2 after hydraulic ventilation.

Table 5.10 shows the gas concentrations measured throughout the hallway and at the living room entryway at the time of intervention in Experiment 5. Gas concentrations indicated that the smoke layer had descended past the 3 ft level throughout the structure and past the 1 ft level at the mid hallway and end hallway locations.

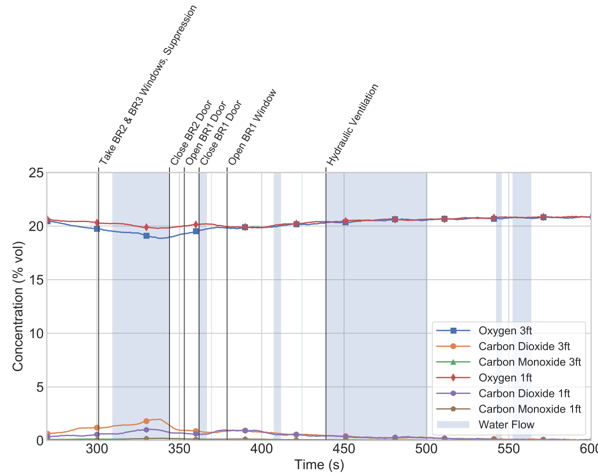
Table 5.10: Hallway Gas Concentrations at Intervention for Experiment 5

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	19.3	1.6	0.2
	1 ft	20.7	0.2	0
Start Hallway	3 ft	19.7	1.2	0.1
	1 ft	20.3	0.6	0.1
Mid Hallway	3 ft	14.5	5.2	0.6
	1 ft	15.4	4.5	0.6
End Hallway	3 ft	12.3	7.7	0.3
	1 ft	19.2	1.7	0.9

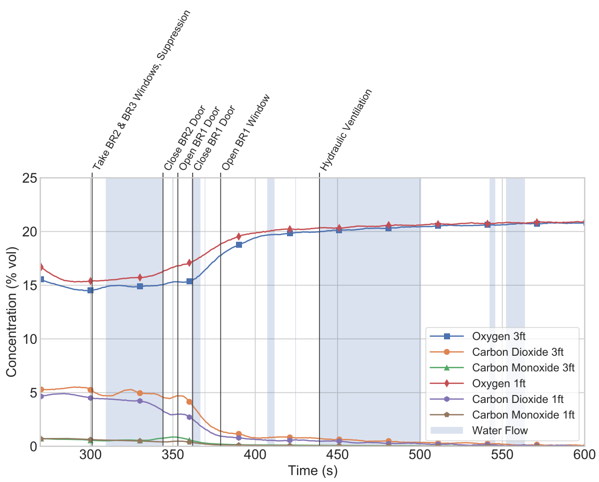
Figure 5.10 shows the gas concentration time histories in the hallway and living room entryway locations. Ventilation of the bedroom windows established flow paths between the fire room and the exterior. Suppression decreased the production of combustion gases in bedroom 4 and impacted the flow through the bedrooms 2 and 3 windows. Flow through the bedroom 2 window was initially unidirectional exhaust, which worsened end hallway gas concentrations 3 ft above the floor. Flow through the bedroom 3 window was initially unidirectional inflow, which improved mid hallway gas concentrations. As flow through the windows became bidirectional, gas concentrations throughout the hallway improved. Gas concentrations improved to pre-ignition concentrations, which minimized the impact of hydraulic ventilation.



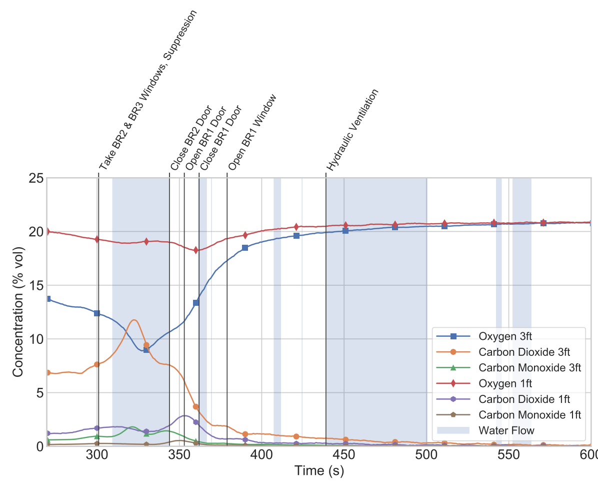
(a) Living Room Entryway Hall Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.75: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 5.

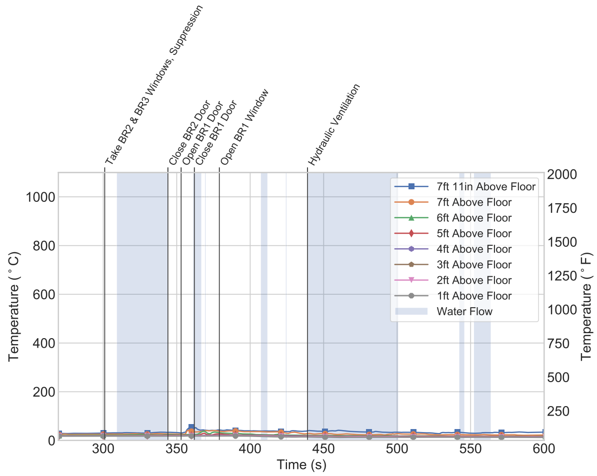
5.5.5 Bedroom 1

The bedroom 1 door was closed at the time of ignition, which isolated the bedroom from the flow of higher-temperature, higher-pressure combustion gases produced in bedroom 4. However, higher-pressure combustion gases flowed through the leakage area around the closed door and the HVAC supply vents into the bedroom. Temperatures at the time of intervention ranged from 30 °C (86 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor, as shown in Figure 5.76a.

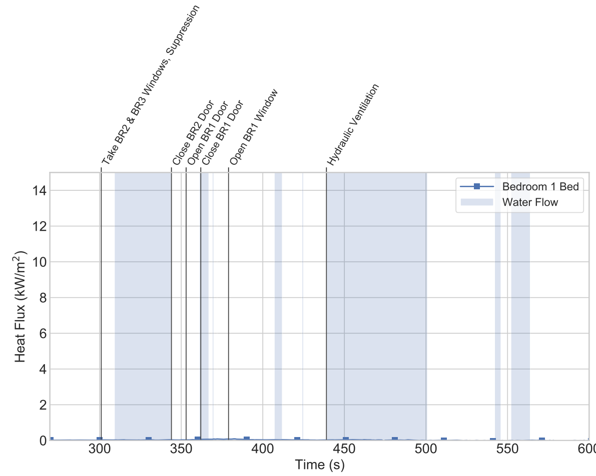
The bedroom 1 door was then opened, which allowed higher-temperature, higher-pressure combustion gases to flow into the bedroom. Temperatures increased to 55 °C (131 °F) near the ceiling and 30 °C (86 °F) below 5 ft above the floor. The bedroom 1 door was closed, which stopped the flow of combustion gases into the bedroom and temperatures decreased. The removal of the bedroom 1 window created an exterior vent. Higher-pressure gases flowed toward and through the window, which decreased temperatures from 45 °C to 35 °C (113 °F to 95 °F).

Heat flux to the bed at the time of intervention was 0 kW/m^2, as shown in Figure 5.76b. Post-suppression, the bedroom 1 door was opened. Due to the low temperature of the bedroom and hallway, combustion gas flow into the bedroom minimally increased heat flux to 0.1 kW/m^2. Flow through the window decreased heat flux to 0 kW/m^2.

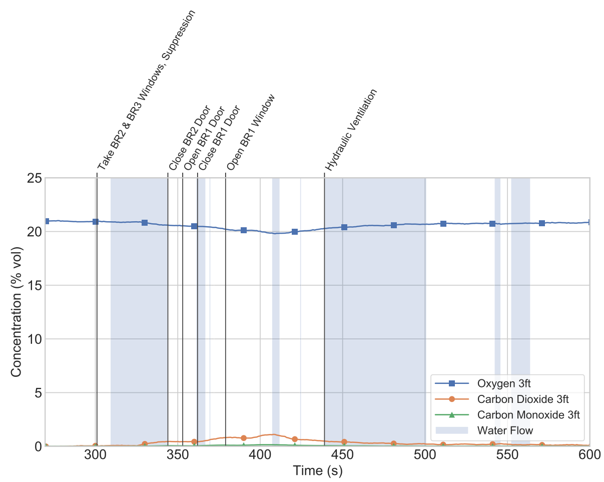
Gas concentrations at the bed at the time of fire department intervention were 20.9% O_2, 0% CO_2, and 0% CO, as shown in Figure 5.76c. Gas concentrations increased as combustion gases flowed into the bedroom through the leakage area around the closed door and through the HVAC supply vent. Gas concentrations peaked at values above ambient 19.8% O_2, 1.1% CO_2, and 0.2% CO after the bedroom 1 door was opened. After the bedroom 1 window was removed, gas concentrations improved.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



(c) Bedroom 1 Gas Concentration

Figure 5.76: Post-intervention bed level temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 5.

The bathroom 1 door was closed prior to ignition, which prevented the flow of combustion gases between the bedroom and the bathroom. Although the space was protected by two closed doors, higher-pressure combustion gases flowed into the space through the HVAC supply vents. Temperatures exceeded 30 °C (86 °F) at the time of intervention, as shown in Figure 5.77. The bathroom lacked an exterior vent; therefore, temperatures continued to increase and peaked to 45 °C (113 °F).

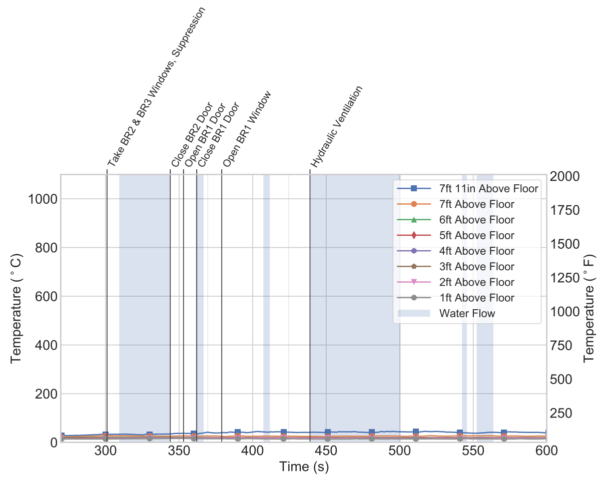


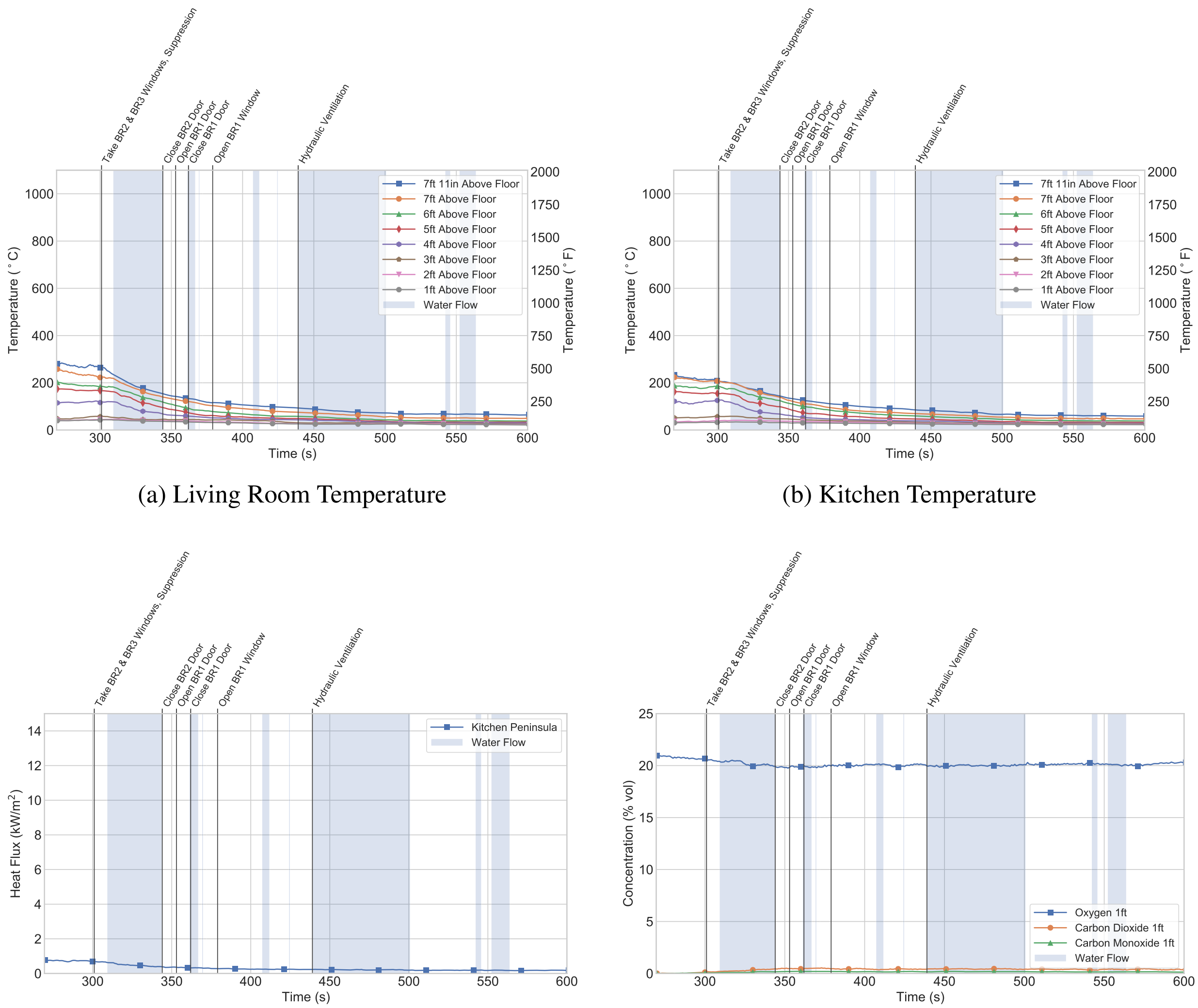
Figure 5.77: Post-intervention temperatures in bathroom 1 during Experiment 5.

5.5.6 Common Space

Figures 5.78a and 5.78b show the temperature time histories in the living room and kitchen, respectively. At the time of intervention, living room temperatures exceeded 260 °C (500 °F) and kitchen temperatures exceeded 205 °C (401 °F). Ventilation of the bedrooms 2 and 3 windows caused unidirectional inflow through the front door. Cool air entrained into the common space and decreased temperatures. The kitchen was adjacent to the flow path between the fire room and the front door; therefore, temperature decrease in the kitchen was less than in the living room. Suppression decreased the heat release rate of the bedroom 4 fire, which decreased the temperature of combustion gases that flowed into the common space along the flow path to the front door. Temperatures decreased to 95 °C (203 °F) in the living room and 85 °C (185 °F) in the kitchen. Hydraulic ventilation caused combustion gases to flow toward and through the bedroom 4 vents. As a result, common space temperatures decreased below 70 °C (158 °F).

Heat flux 1 ft above the kitchen floor was 0.7 kW/m^2 at the time of intervention, as shown in Figure 5.78c. Heat flux decreased after the ventilation of the bedrooms 2 and 3 windows, as cool air entrained into the common space. Heat flux decreased to 0.2 kW/m^2, which minimized the impact of hydraulic ventilation.

Gas concentrations 1 ft above the kitchen floor were consistent with pre-ignition conditions at the time of intervention, as shown in Figure 5.78d. Gas concentrations worsened to 19.8% O_2, 0.5% CO_2, and 0.2% CO during suppression, as combustion gases flowed toward the open front door. The kitchen was adjacent to the flow path established between the front door and the fire room, which minimized the impact of hydraulic ventilation.



(a) Living Room Temperature

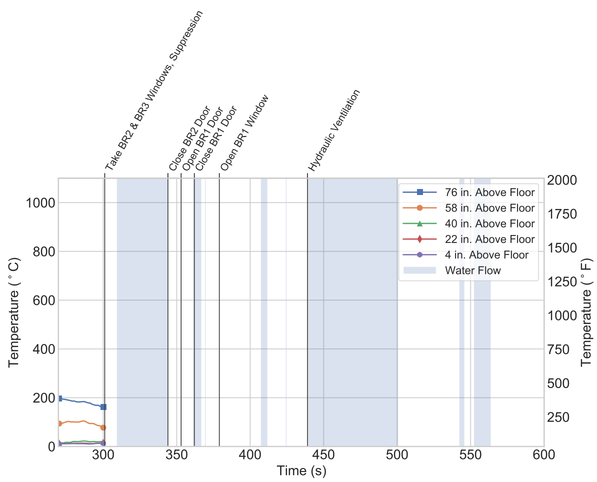
(b) Kitchen Temperature

(c) Kitchen Heat Flux

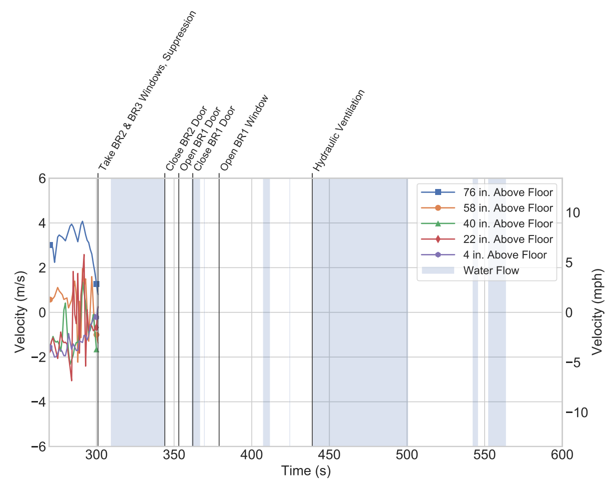
(d) Kitchen Gas Concentration

Figure 5.78: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 5.

Front doorway temperatures at the time of intervention ranged from 155 °C (311 °F) 76 in. above the floor to 15 °C (59 °F) 4 in. above the floor, as shown in Figure 5.79a. Front door velocities indicated bidirectional flow through the doorway, as combustion gases exhausted at approximately 3.5 m/s (7.8 mph) and cool air entrained at approximately -2.5 m/s (5.6 mph), as shown in Figure 5.79b. The bidirectional probes were removed from the doorway approximately 300 s post-ignition for suppression crew entry into the structure. Data recorded after this time period are not reflective of flow through the doorway.



(a) Front Doorway Temperature



(b) Front Doorway Velocity

Figure 5.79: Post-intervention temperatures and velocities in the front doorway during Experiment 5.

5.6 Experiment 6

The search tactics in Experiment 6 were designed to evaluate door initiated operations following front door control conducted prior to suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide, bedroom 4 window and the bedroom 4 door were removed. The front door to the structure, doors to bedrooms 2 and 3, and doors to bathrooms 1 and 3 were open. The door to bedroom 1 was closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

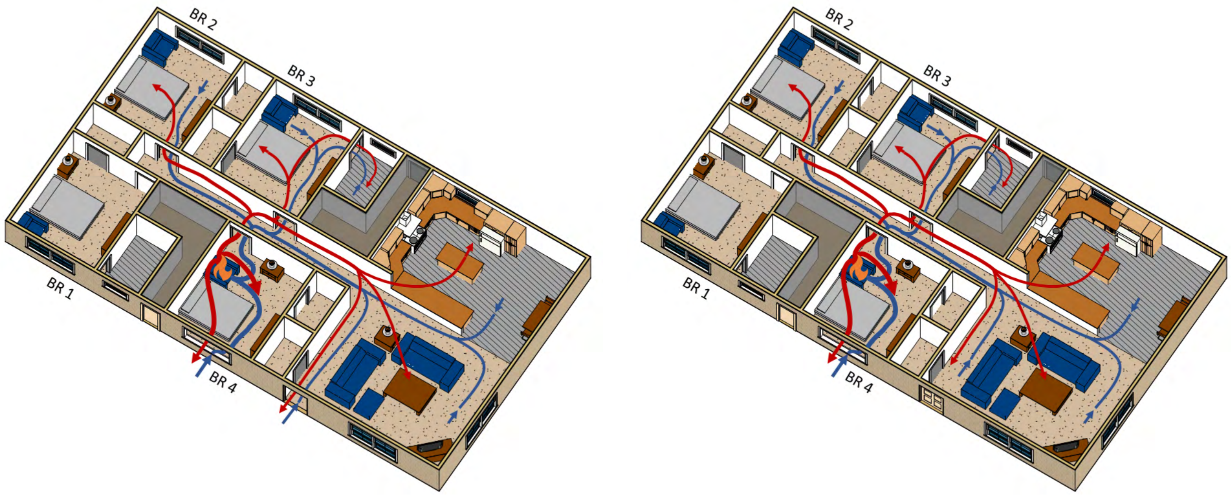
Post bedroom 4 flashover, the crew on side A entered the structure through the front door and closed the door behind them. The crew proceeded through the structure and entered bedroom 3. The crew closed the bedroom 3 door and then removed the bedroom 3 window. The bedroom 3 door was opened for reentry into the hallway and subsequently closed. The crew proceeded down the hall toward bedrooms 1 and 2. The crew split to enter both bedrooms. Simultaneously, the door to bedroom 1 was opened and the door to bedroom 2 was closed. The bedroom 1 door was closed after the crew entered the bedroom. The double-wide window in each bedroom was removed. At this point, the search tactic comparison was complete. The front door was opened and the suppression crew proceeded to the fire room. Upon the suppression crew announcement of 'fire under control', hydraulic ventilation occurred out of the failed bedroom 4 window. 75 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 245 gallons. Table 5.11 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was the closing the front door.

Table 5.11: Experiment 6 Event Times

Event	Elapsed Time			
	From Ignition		From Intervention	
	(mm:ss)	(s)	(mm:ss)	(s)
Ignition	00:00	0	—	—
Close Front Door	05:17	317	00:00	0
Close BR3 Door	06:00	360	00:43	43
Remove BR3 Window	06:16	376	00:59	59
Open BR3 Door	06:50	410	01:33	93
Close BR3 Door	07:02	422	01:45	105
Open BR1 Door & Close BR2 Door	07:47	467	02:30	150
Close BR1 Door	07:58	478	02:41	161
Remove BR1 Window	08:13	493	02:56	176
Remove BR2 Window	08:24	504	03:10	190
Open Front Door & Suppression	08:47	527	03:30	210
Hydraulic Ventilation	11:04	664	05:47	347

Figures 5.80 through 5.82 show the changes in gas flow as a result of fire department intervention during Experiment 6. At the time of intervention, the bedroom 4 fire was in a post-flashover state.

Lower-pressure air was entrained and higher-pressure combustion gases were exhausted through the bedroom 4 vents (Figure 5.80a). Flow paths were established between the fire room and open volumes of the structure and the exterior. Closure of the front door stopped the flow of higher-pressure combustion gases from the fire room to the lower-pressure exterior of the structure, as shown in Figure 5.80b.



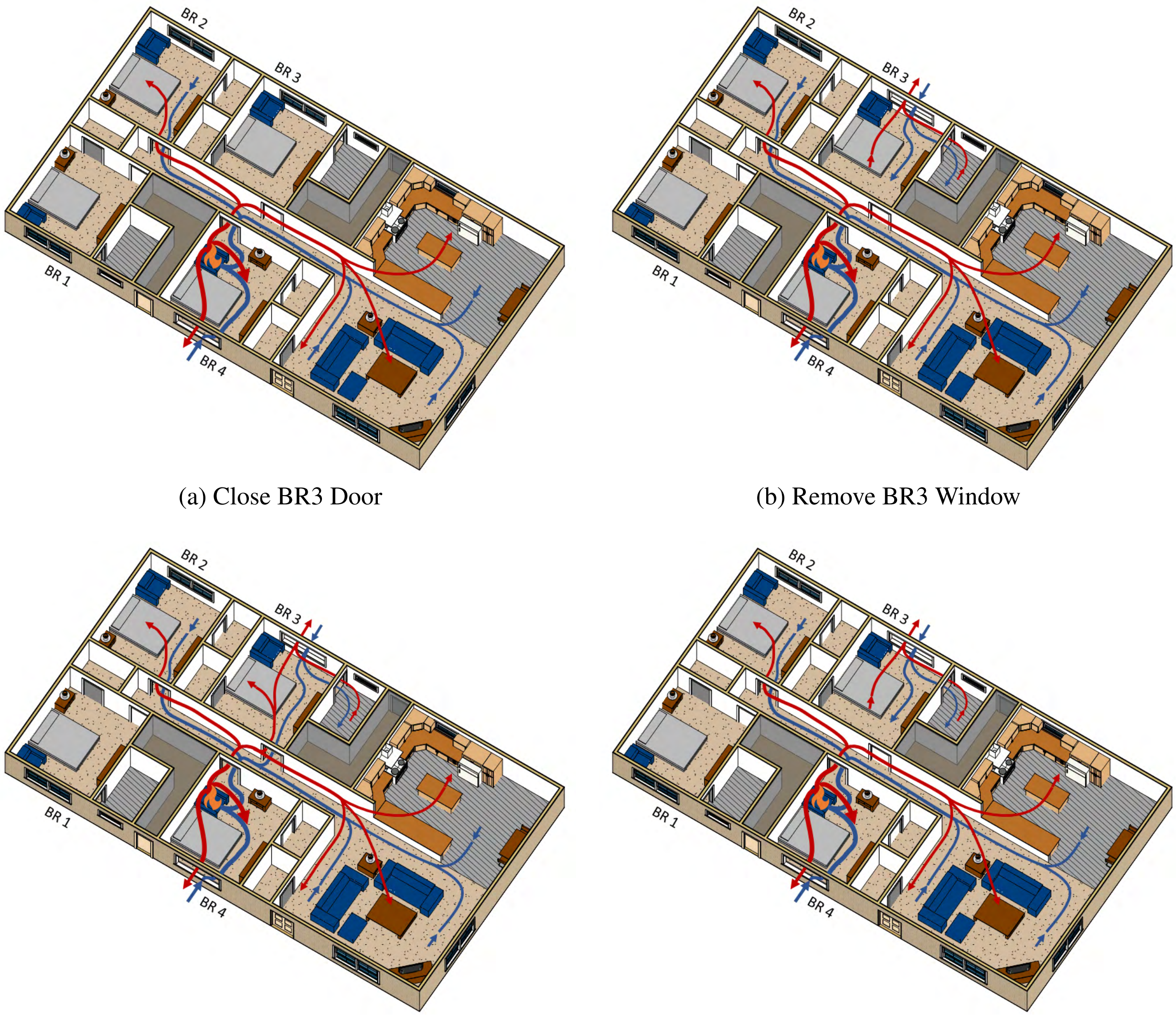
(a) Flows Prior to Intervention

(b) Close Front Door

Figure 5.80: Changes in flow in structure following fire department interventions in Experiment 6.

Closure of the bedroom 3 door isolated the bedroom from the flow of combustion gases, as shown in Figure 5.81a. The bedroom 3 window was then removed, which created an exterior vent in the bedroom (Figure 5.81b). Accumulated combustion gases in bedroom 3 and bathroom 3 exhausted through the vent.

The bedroom 3 door was then opened, which created a flow path between the higher-pressure fire room and the lower-pressure exterior, as shown in Figure 5.81c. Combustion gases flowed from the fire room toward the window, which facilitated further accumulation of combustion gases in bedroom 3 and bathroom 3. Approximately 12 seconds after the bedroom 3 door was opened, it was then closed, which stopped the flow of combustion gases from the fire room into the bedroom (Figure 5.81d). Bidirectional flow through the window continued due to the accumulation of combustion gases in the bedroom while the door was open.



(a) Close BR3 Door

(b) Remove BR3 Window

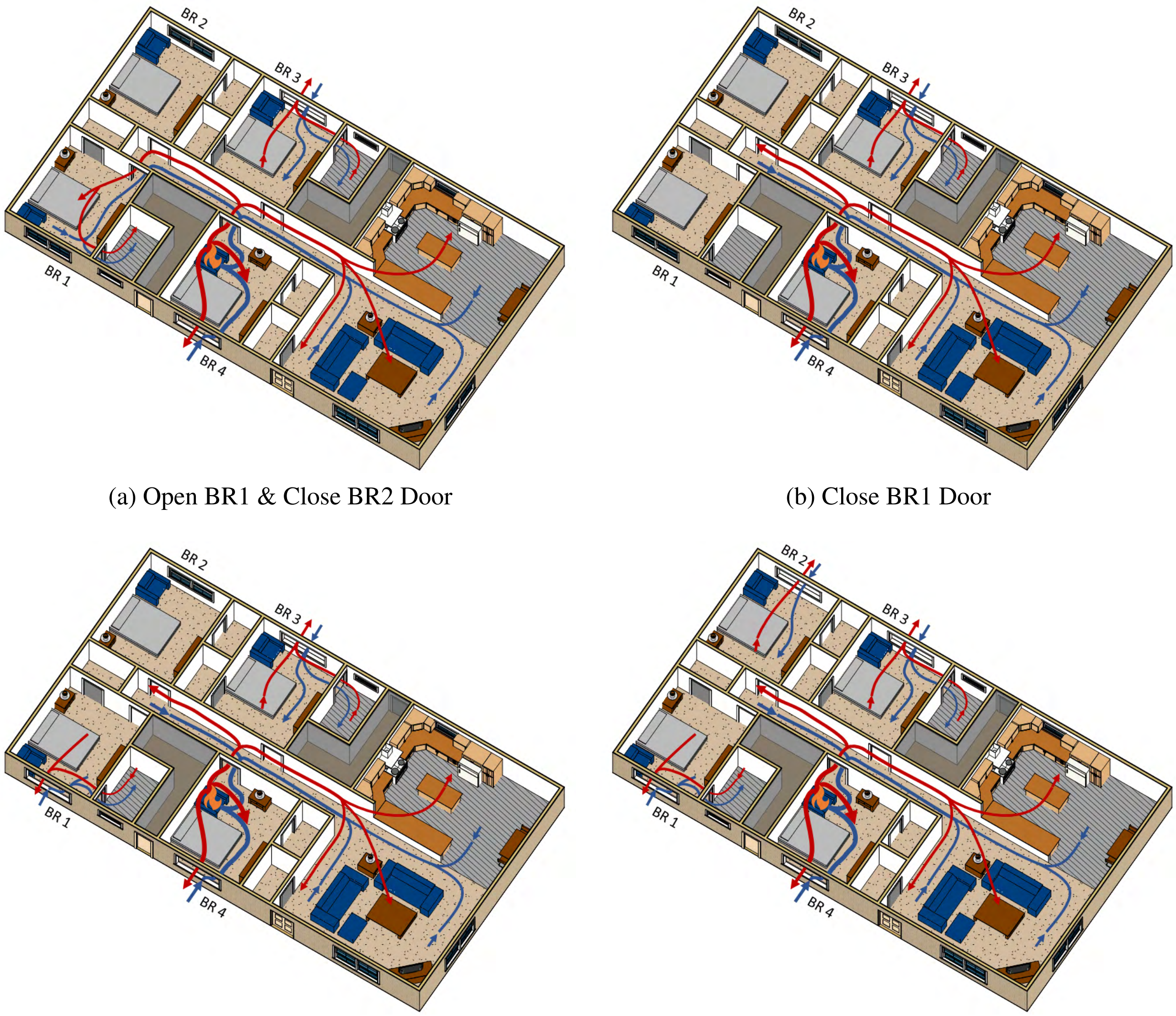
(c) Open BR3 Door

(d) Close BR3 Door

Figure 5.81: Changes in flow in structure following fire department interventions in Experiment 6.

The bedroom 1 door was opened at the same time that the bedroom 2 door was closed, as shown in Figure 5.82a. The open bedroom 1 door allowed higher-pressure combustion gases to flow into the bedroom. A flow path established between the fire room and bedroom 1. The closed bedroom 2 door isolated the bedroom from the flow of combustion gases. Closure of the bedroom 1 door stopped the flow of combustion gases into the bedroom, as shown in Figure 5.82b. The double-wide windows in bedrooms 1 and 2 were removed, which created exterior vents in each isolated bedroom (Figures 5.82c and 5.82d). Accumulated combustion gases exhausted from each bedroom to the exterior.

The front door was opened and suppression began, as shown in Figure 5.83a. A flow path established between the fire room and the exterior. Interior suppression was conducted with a smooth bore nozzle with a 7/8 in. tip, set to flow 160 gpm with a nominal nozzle pressure of 50 psi,



(a) Open BR1 & Close BR2 Door

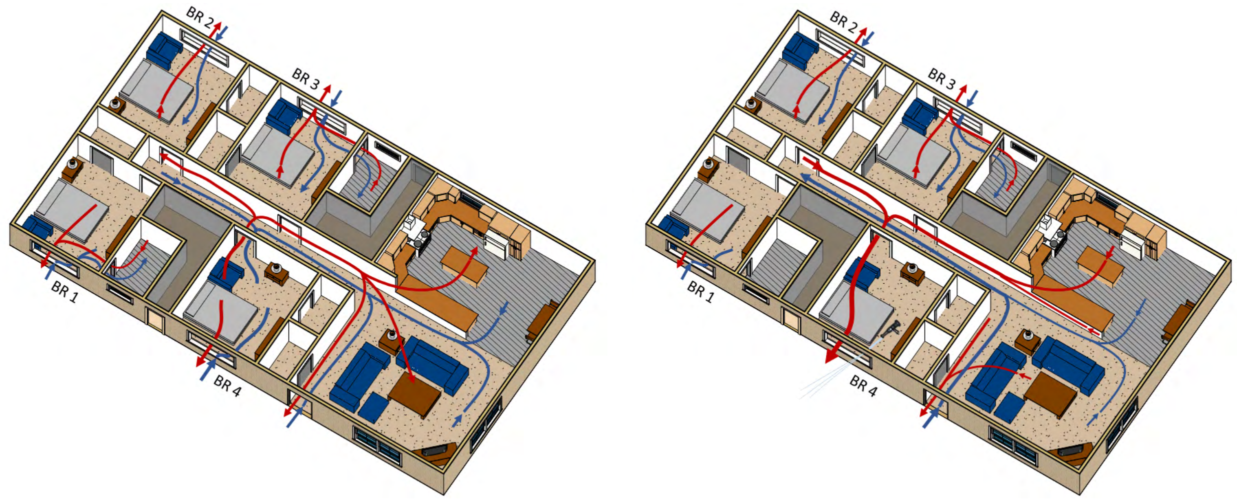
(b) Close BR1 Door

(c) Remove BR1 Window

(d) Remove BR2 Window

Figure 5.82: Changes in flow in structure following fire department interventions in Experiment 6.

connected to an 1 3/4 in. hoseline. Hydraulic ventilation occurred out of the failed bedroom 4 window with the tip off, half bale, in an O-pattern, as shown in Figure 5.83b. Flow through the bedroom 4 vents became unidirectional toward the exterior, which entrained combustion gas and air from open volumes of the structure into bedroom 4.



(a) Open Front Door & Suppression (b) Hydraulic Ventilation

Figure 5.83: Changes in flow in structure following fire department interventions in Experiment 6.

5.6.1 Bedroom 4

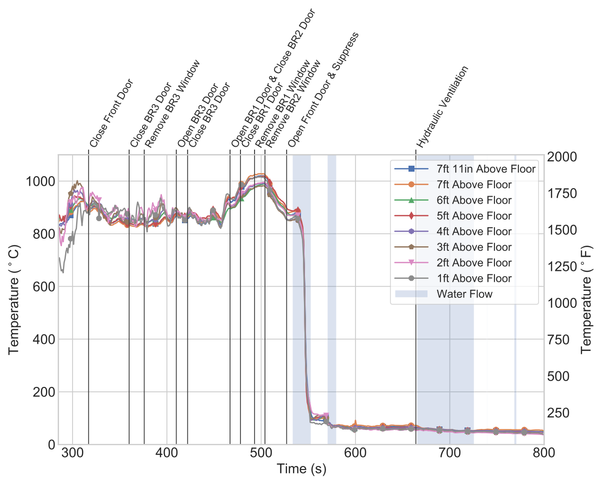
The bedroom 4 fire transitioned through flashover approximately 210 s post-ignition. Temperatures at the time of intervention ranged between 910 °C and 880 °C (1670 °F and 1616 °F), as shown in Figure 5.84a. Closure of the front door stopped the flow of gases between the fire room and the exterior. The fire remained in a steady post-flashover state with temperatures ranging from 850 °C to 1030 °C (1562 °F to 1886 °F). Suppression extinguished the bedroom 4 fire and decreased temperatures below 120 °C (248 °F). An additional water flow decreased temperatures below 80 °C (176 °F). Hydraulic ventilation created an area of lower pressure in the fire room, which caused unidirectional exhaust flow through the bedroom 4 vents. Fire room temperatures decreased below 60 °C (140 °F).

Prior to ignition, the closet 4 door was closed, which isolated the space from the flow of combustion gases. However, higher-pressure combustion gases flowed through the leakage area around the closed door into the closet. Temperatures at the time of first intervention ranged from 140 °C (284 °F) at the ceiling to 30 °C (266 °F) 1 ft above the floor, as shown in Figure 5.84b. The closet door burned through, which allowed combustion gases to flow into the closet and temperatures exceeded 780 °C (1436 °F). Initial suppression of the bedroom 4 fire decreased closet temperatures below 300 °C (572 °F) and a secondary water flow decreased temperatures below 70 °C (158 °F). The closet was adjacent to the flows created by hydraulic suppression in bedroom 4 and lacked an exterior vent, however temperatures still reduced below 50 °C (122 °F).

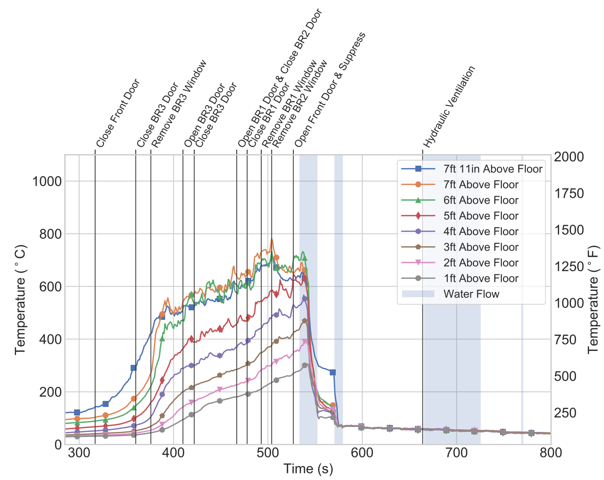
At the time of intervention, bedroom 4 doorway temperatures ranged from 770 °C (1418 °F) 76 in. above the floor to 420 °C (788 °F) 4 in. above the floor, as shown in Figure 5.84c. Door velocities were consistent with doorway temperatures. Combustion gases exhausted at 3.9 m/s (8.7 mph) 76 in. to 58 in. above the floor and air entrained at -0.9 m/s (-2.0 mph) 40 in. to 4 in. above the floor (Figure 5.84d).

Closure of the front door stopped the flow of gases between the fire room to the exterior, which limited the oxygen available for combustion along the flow path. Oxygen concentrations in the hallway decreased below the minimum threshold for combustion, which caused flaming combustion of the carpet outside the fire room to extinguish. Doorway temperatures 22 in. to 4 in. above the floor decreased. Combustion gases exhausted through the doorway at 1.5 m/s (3.4 mph), which increased temperature 40 in. above the floor.

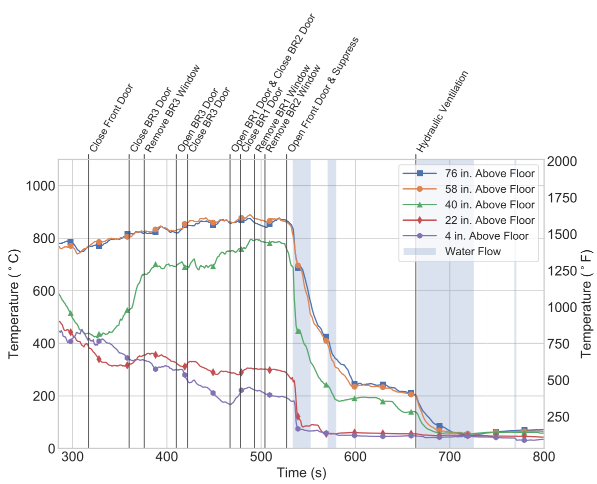
At the time of suppression, combustion gases exhausted between 3.9 m/s and 1.3 m/s (8.7 mph and 2.9 mph) and air entrained at -2.0 m/s (-4.5 mph) through the doorway, which caused temperatures to exceed 850 °C (1562 °F). Initial suppression cooled combustion gases that flowed out of the doorway below 520 °C (968 °F) and secondary water flows cooled combustion gases below 430 °C (644 °F). Door velocities decreased to approximately 1.0 m/s (2.2 mph) exhaust and -1.0 m/s (-2.2 mph) entrainment. Hydraulic ventilation created an area of lower pressure in the fire room, which caused flow through the bedroom 4 vents to become unidirectional exhaust. Door velocities ranged from -2.0 m/s to -5.0 m/s (-4.5 mph and -11.2 mph), which decreased temperatures below 60 °C (140 °F).



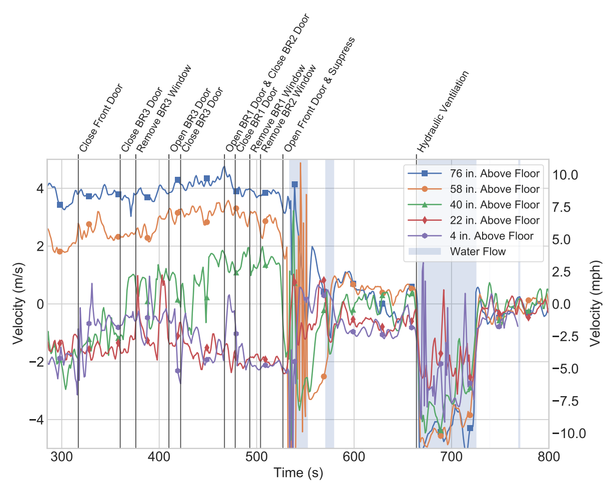
(a) Bedroom 4 Temperature



(b) Closet Temperature



(c) Bedroom 4 Doorway Temperature



(d) Bedroom 4 Doorway Velocity

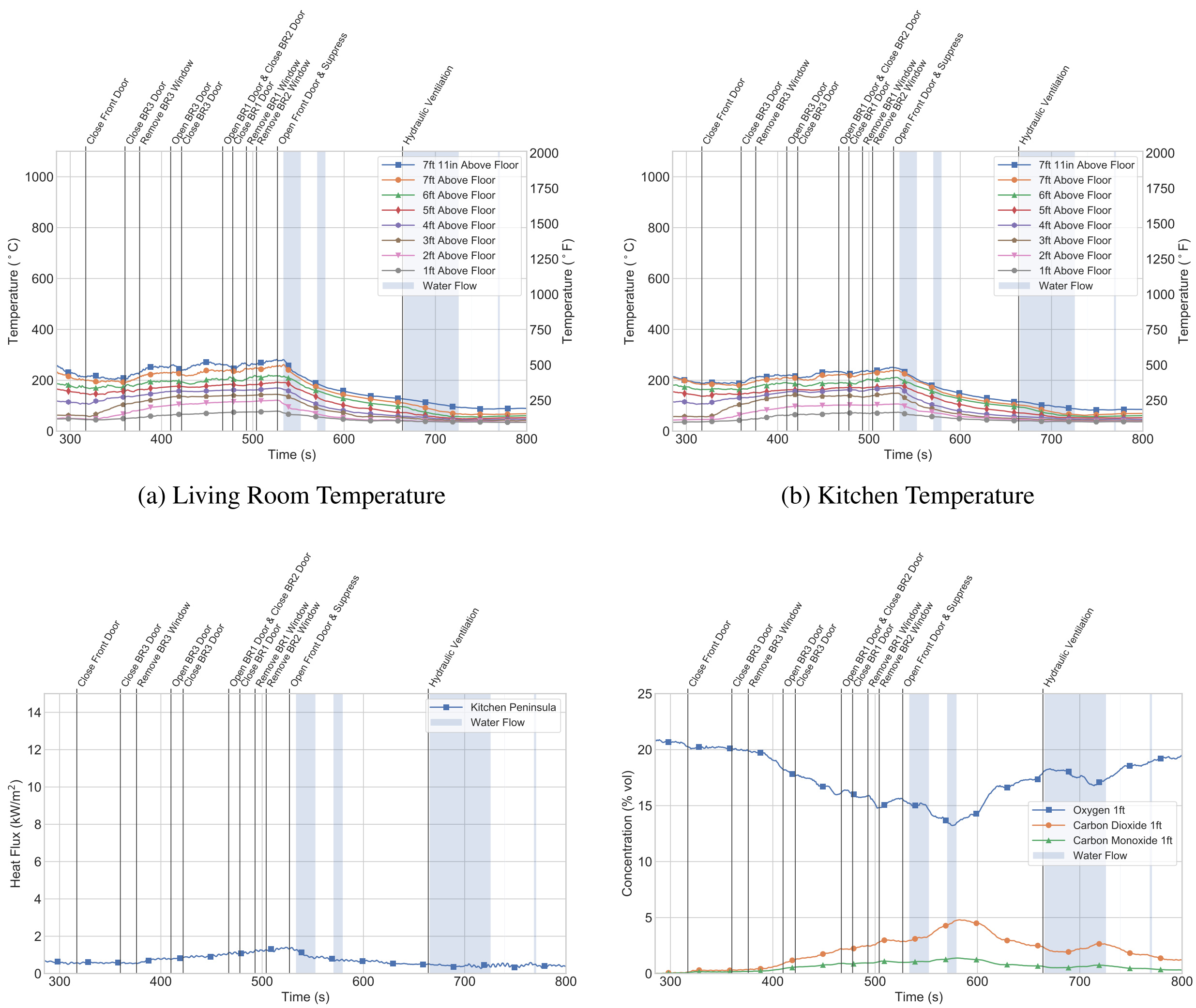
Figure 5.84: Temperature and velocity time histories in bedroom 4 in post-intervention period during Experiment 6.

5.6.2 Common Space

The front door was opened prior to ignition, which allowed higher-pressure combustion gases to flow from the fire room to the exterior of the structure through the hallway and common space. Figures 5.85a and 5.85b show the temperature time histories in the living room and kitchen, respectively. At the time of intervention, common space temperatures exceeded 215 °C (419 °F). Front door closure stopped the bidirectional flow of gases through the doorway. Without the cooling effect of air entrainment, temperatures 4 ft and below in the common space increased. Temperatures exceeded 280 °C (536 °F) when the front door was opened, which established a new flow path between the fire room and the exterior. Air entrained through the doorway, which decreased common space temperatures below 4 ft. Initial suppression decreased common space temperatures below 215 °C (419 °F) and secondary water flows decreased temperatures below 170 °C (338 °F). Hydraulic ventilation decreased temperatures below 95 °C (203 °F), as air entrainment through the front door increased.

Heat flux 1 ft above the kitchen floor was 0.6 kW/m^2 at the time of first intervention, as shown in Figure 5.85c. After the front door was closed, the smoke layer in the common space descended toward the floor and heat flux steadily increased to 1.4 kW/m^2 prior to the front door being opened. After the front door was opened, bidirectional flow through the front door and initial fire room suppression decreased heat flux to 0.8 kW/m^2. Additional water flows in the fire room cooled combustion gases and heat flux decreased to 0.7 kW/m^2. Entrainment through the front door further cooled gases in the common space through mixing, which decreased heat flux to 0.5 kW/m^2. The kitchen was adjacent to the flow paths established by hydraulic ventilation, which minimized its impact on heat flux.

Kitchen gas concentrations were near pre-ignition levels at the time of intervention, which indicated that the smoke layer had not descended to the 1 ft level (Figure 5.85d). Similar to heat flux, gas concentrations worsened as the smoke layer descended to the floor after the front door was closed. Gas concentrations peaked at values above ambient to 13.2% O_2, 4.8% CO_2, and 1.4% CO. However, gas concentrations did not improve until the front door was opened and suppression had extinguished the bedroom 4 fire. Post-suppression entrainment through the front door improved gas concentrations to 18.1% O_2, 2.3% CO_2, and 0.6% CO. The kitchen was adjacent to the flow paths established by hydraulic ventilation, which minimized the impact on gas concentrations.



(a) Living Room Temperature

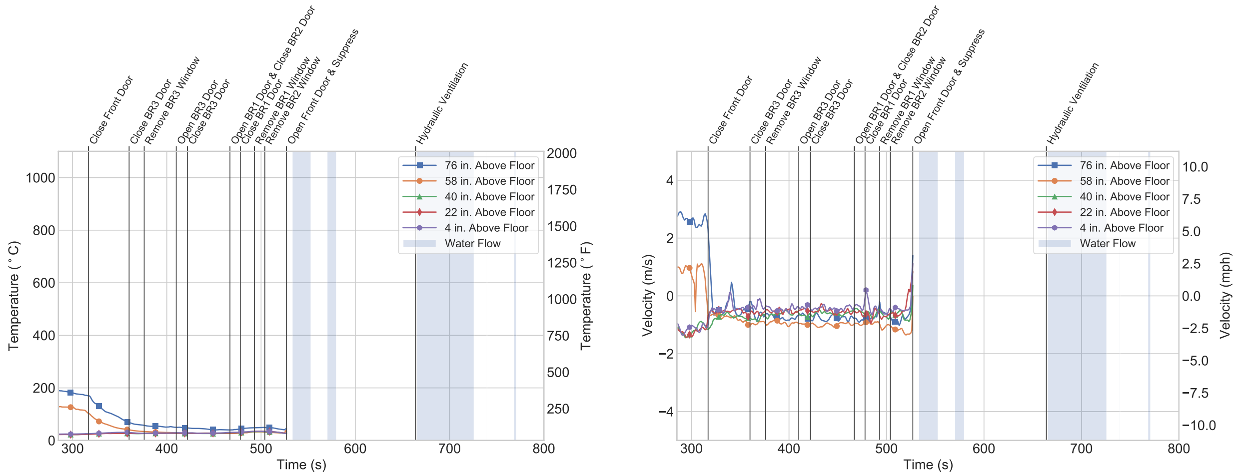
(b) Kitchen Temperature

(c) Kitchen Heat Flux

(d) Kitchen Gas Concentration

Figure 5.85: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 6.

Prior to intervention, flow through the front door was bidirectional. Combustion gases exhausted between 2.8 m/s and 1.0 m/s (6.3 mph and 2.2 mph) 76 in. to 58 in. above the floor, which increased temperatures above 170 °C (338 °F), as shown in Figure 5.86. Cool air entrained at -1.0 m/s (-2.2 mph) below 40 in. above the floor, which caused temperatures of approximately 25 °C (77 °F). Closure of the front door stopped gas flow through the doorway. Flow through the doorway reestablished after the door was opened, however the bidirectional probes were removed for suppression crew entry and were not replaced. As a result, data recorded after this time period are not reflective of flow through the doorway.



(a) Front Doorway Temperature

(b) Front Doorway Velocity

Figure 5.86: Post-intervention temperatures and velocities in the front doorway during Experiment 6.

5.6.3 Hallway

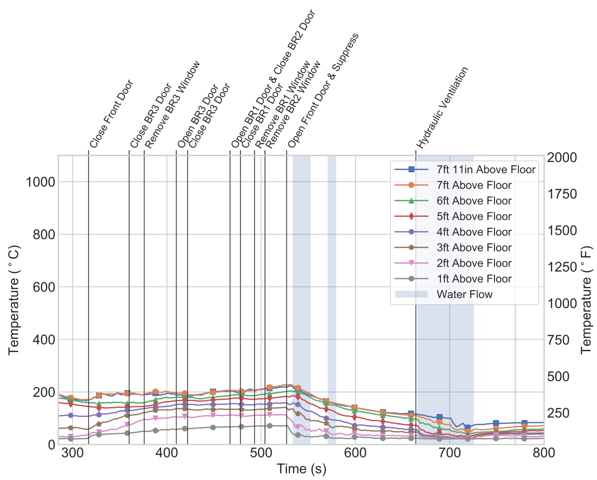
Figures 5.87a through 5.87d show the temperature time histories in the hallway and living room entryway. At the time of first intervention, hallway temperatures were a function of proximity to the fire room. Temperatures at the mid hallway location were the greatest and exceeded 590 °C (1094 °F), followed by the start hallway (345 °C (653 °F)), end hallway (340 °C (644 °F)), and the living room entryway (170 °C (338 °F)) locations. The large volume of the common space limited the accumulation of combustion gases, and bidirectional flow through the open doorway cooled the gases through mixing. As a result, living room entryway temperatures were generally less than the hallway locations.

Closure of the front door stopped the flow of gases between the fire room and the exterior of the structure. As a result combustion gases accumulated along the previous flow path from the fire room to the front door (mid hallway, start hallway, and living room entry). Temperatures nearest the floor increased.

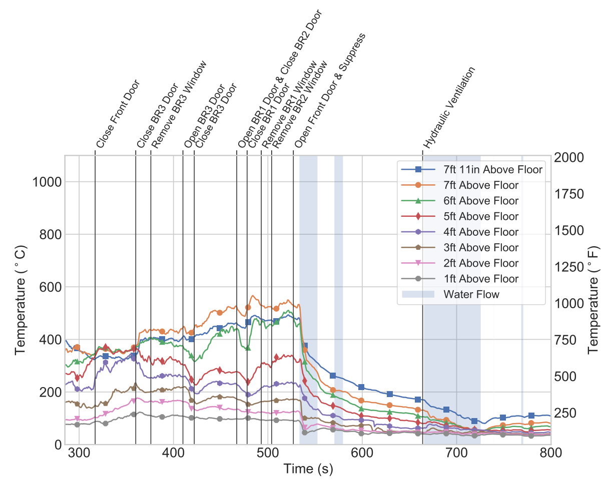
The closed bedroom 3 door stopped the flow of combustion gases from the fire room into the bedroom. Similarly, combustion gases flowed along other flow paths to open volumes of the structure, which increased ceiling temperatures in the hallway. Opening the bedroom 3 door allowed for gas flow between the bedroom and the exterior. Gases entrained along the flow path to the fire room, which decreased start hallway temperatures 6 ft and below. Closure of the bedroom 3 door stopped the flow between the hallway and the bedroom. Temperatures nearest the floor at the start hallway location increased.

The bedroom 2 door was closed as the bedroom 1 door was opened. Flow between bedroom 2 and the hallway stopped as flow between bedroom 1 and the hallway began. Air entrained along the flow path between bedroom 1 and the fire room, which decreased hallway temperatures below 5 ft. The bedroom 1 door was closed and flow between the bedroom and the fire room stopped. Temperatures nearest the floor at the mid hallway and end hallway locations increased.

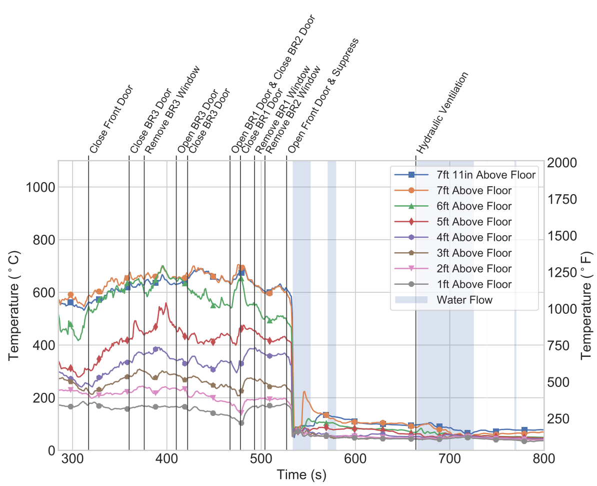
The front door was opened, which reestablished flow between the fire room and the exterior. Suppression began in the hallway, which immediately cooled the end hallway, mid hallway, and start hallway temperatures, as these locations were ahead of the hoseline. Extinguishment of the bedroom 4 fire reduced the temperature of combustion gases that flowed from the fire room to open volumes of the structure. Living room entryway temperatures decreased. Hydraulic ventilation created an area of lower pressure in the fire room, which caused flow through the bedroom 4 vents to become unidirectional toward the exterior. Combustion gases flowed from the hallway into bedroom 4 and temperatures reduced below 125 °C (257 °F).



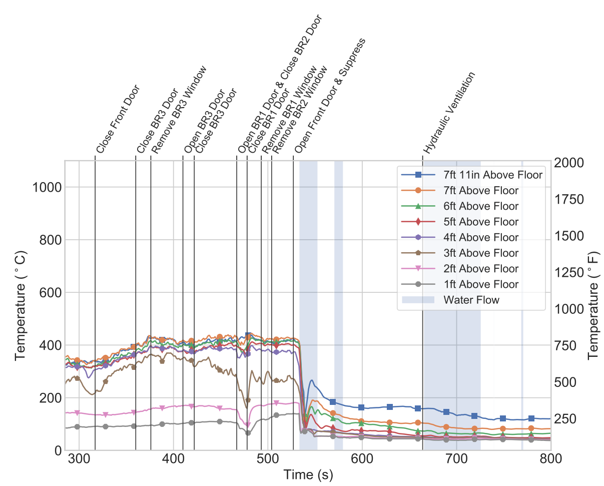
(a) Living Room Entryway Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.87: Temperature time histories in the hallway in the period following fire department intervention in Experiment 6.

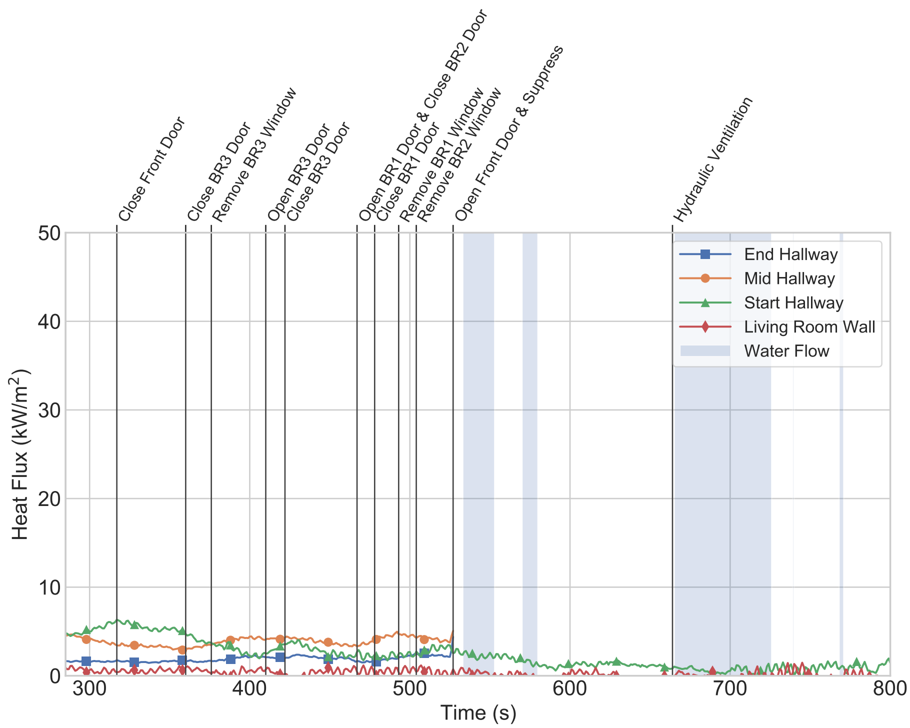


Figure 5.88: Heat flux time histories in the hallway in post-intervention period during Experiment 6.

Prior to intervention, flames extended from bedroom 4 into the hallway and ignited the carpet outside of the fire room (mid hallway location). Flames traveled in both directions down the hallway. However, the lack of an exterior vent in bedroom 2 limited flame spread toward the end hallway location. At the time of intervention, hallway heat fluxes were 6.2 kW/m^2, 3.7 kW/m^2, 1.6 kW/m^2, and 0.5 kW/m^2 at the start hallway, mid hallway, end hallway, and living room entryway locations, respectively (Figure 5.88). The closed front door resulted in the accumulation of combustion gases in the hallway and a corresponding decrease in O_2 concentrations which limited flaming combustion of the carpet. The lack of exterior vents reduced the gas flows from the from the fire room into the hallway which reduced the convective component of the heat flux. As a result, the hallway heat fluxes remained nominally constant. The start hallway location decreased to approximately 2.5 kW/m^2 within 60 s of the door closure as the flaming combustion along the carpet near the start hallway location self extinguished.

Prior to water flow, the ventilation of the front door increased gas flows along the flow path to bedroom 4. The smoldering combustion of the carpet outside the bedroom 4 door was provided O_2 and transitioned to flaming combustion. As a result, the heat flux at the mid hallway and end hallway location increased to 14.2 kW/m^2 and 12.7 kW/m^2, respectively before the start of water flow. However, during suppression, the end hallway and mid hallway heat flux gauges were coated with water, which impacted the measurement accuracy. Therefore, the mid hallway and end hallway peaks following suppression may not be accurate representations of heat flux. The start hallway and living room heat flux dropped below 1 kW/m^2 following suppression.

Table 5.12 shows the gas concentrations measured throughout the hallway and living room entryway locations at the time of intervention during Experiment 6. Gas concentrations indicated that the smoke layer had descended past the 3 ft level throughout the structure and past the 1 ft level at the mid hallway location.

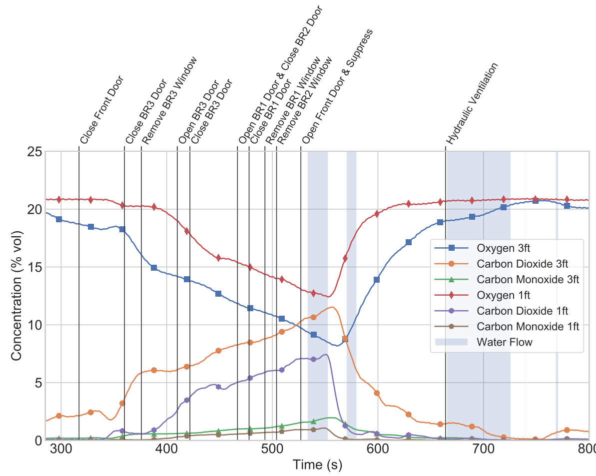
Table 5.12: Hallway Gas Concentrations at Intervention for Experiment 6

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	18.7	2.1	0.2
	1 ft	20.8	0.1	0
Start Hallway	3 ft	19.4	1.4	0.1
	1 ft	20.2	0.6	0.1
Mid Hallway	3 ft	14.3	5.1	0.5
	1 ft	14.2	5.4	0.7
End Hallway	3 ft	11.7	9.1	1.2
	1 ft	19.1	1.6	0.2

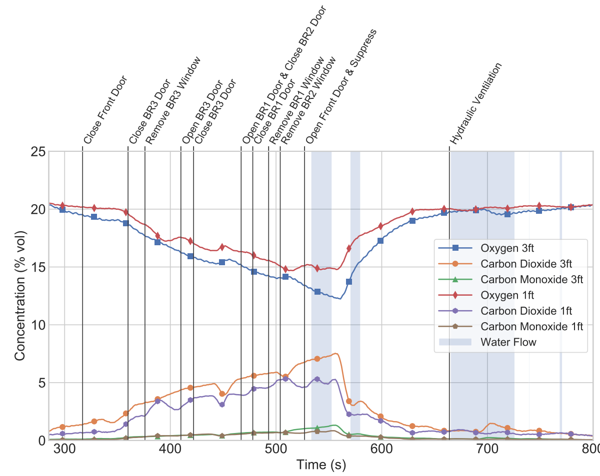
Figures 5.89a through 5.89d show the gas concentration time histories for the living room entryway, start hallway, mid hallway, and end hallway locations. Closure of the front door stopped the flow of gases between the fire room and the exterior of the structure. The smoke layer in the common space descended from the ceiling, which steadily worsened gas concentrations at the start hallway and the living room entryway locations.

The smoke layer in bedroom 3 had descended to the floor prior to intervention, which minimized the impact of air entrainment into the hallway on gas concentrations when the bedroom 3 door was closed. The bedroom 1 door was closed prior to ignition, which prevented the accumulation of combustion gases in the bedroom. The open bedroom 1 door allowed air to be entrained into the hallway along the flow path between bedrooms 1 and 4. Gas concentrations at the end hallway and mid hallway locations improved. The closed bedroom 1 door stopped the flow of gases between bedrooms 1 and 4, which caused gas concentrations at the end hallway and mid hallway locations to stop improving.

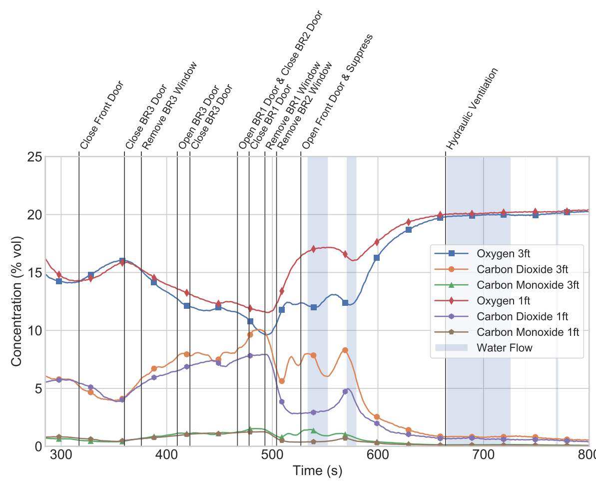
The front door was opened and flow between the fire room and the exterior reestablished. Suppression entrained air through the front door and hallway gas concentrations improved. Hydraulic ventilation created an area of lower pressure in the fire room, which caused flow through the bedroom 4 vents to become unidirectional toward the exterior. As a result, hallway gas concentrations improved.



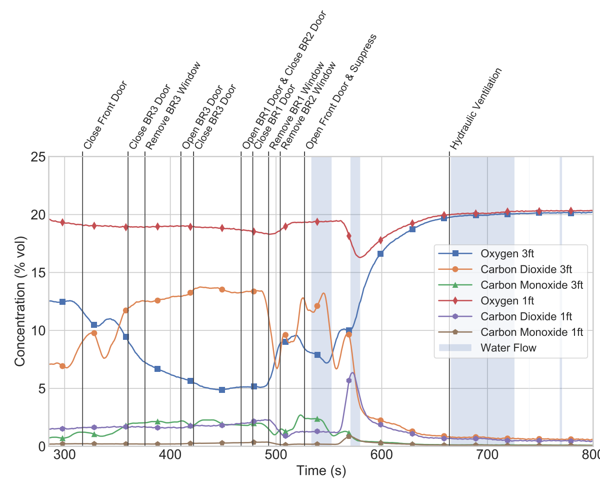
(a) Living Room Entryway Hall Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.89: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 6.

5.6.4 Bedroom 3

The bedroom 3 door was opened prior to ignition, which allowed higher-pressure combustion gases to flow from the fire room into the bedroom. Bedroom temperatures at the time of intervention ranged from 260 °C (500 °F) at the ceiling to 70 °C (158 °F) 1 ft above the floor, as shown in Figure 5.90.

After the front door was closed, combustion gas flow into the bedroom increased temperatures to 320 °C (608 °F) at the ceiling and 75 °C (167 °F) 1 ft above the floor. Closure of the bedroom 3 door isolated the bedroom from the flow of combustion gases, which prevented further accumulation of combustion gases in the bedroom. Temperatures in the bedroom decreased. Removal of the bedroom 3 window created an exterior vent in the isolated bedroom. Accumulated combustion gases flowed toward and through the vent, which further decreased bedroom temperatures to 150 °C (302 °F) at the ceiling and 40 °C (104 °F) 1 ft above the floor.

The bedroom door was opened, which established a new flow path between the higher-pressure fire room and the lower-pressure exterior. Combustion gases flowed along the path, which increased bedroom 3 temperatures above 5 ft. The bedroom door was closed, which isolated the bedroom from the flow of combustion gases. Accumulated combustion gases exhausted through the vent, which decreased temperatures below 85 °C (185 °F). The bedroom 3 door remained closed during suppression and hydraulic ventilation, which minimized the impact of each action on conditions within the bedroom.

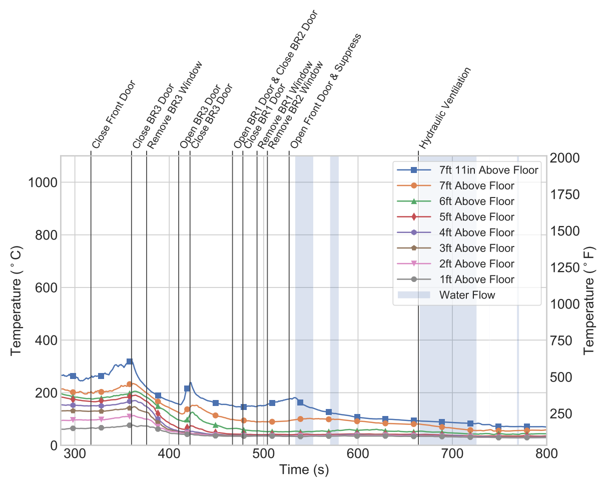


Figure 5.90: Post-intervention temperature in bedroom 3 during Experiment 6.

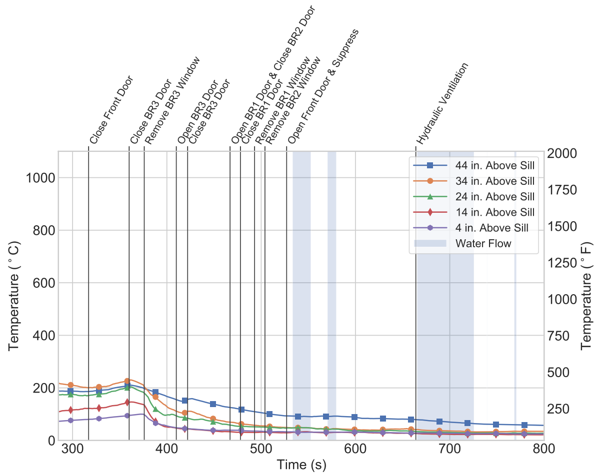
Bedroom 3 window temperatures were consistent with temperatures in the center of the room at the time of intervention, as shown in Figure 5.91a. Combustion gases continued to flow into the bedroom after the front door was closed, which increased window temperatures to 230 °C (446 °F). Window temperatures decreased after the bedroom was isolated from the flow of combustion gases.

Removal of the bedroom 3 window caused bidirectional flow through the vent. Accumulated combustion gases exhausted from the bedroom between 1.6 m/s and 1.3 m/s (3.6 mph and 2.9 mph) above 34 in. above the sill and air entrained to the bedroom between -1.4 m/s and -2.3 m/s (-3.1 mph and -5.1 mph) below 24 in. above the sill (Figure 5.91b). Window temperatures decreased below 155 °C (311 °F).

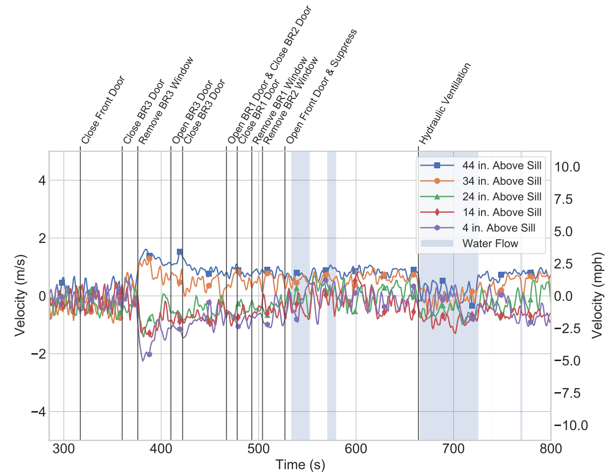
Combustion gases flowed through the open bedroom 3 door toward and through the exterior vent. Exhaust through the window increased, which increased temperatures 44 in. to 34 in. above the sill to 160 °C (320 °F). Closure of the bedroom 3 door stopped the flow of combustion gases into the bedroom from the hallway. Bidirectional flow through the window continued due to the accumulation of combustion gases in the bedroom, which decreased temperatures below 65 °C (149 °F).

Heat flux below the bedroom 3 window was 3.5 kW/m^2 3 ft above the floor and 2.6 kW/m^2 1 ft above the floor at the time the front door was closed, as shown in Figure 5.91c. Heat flux followed a similar trend to temperature after the front door was closed as combustion gases continued to fill the bedroom, and increased to 4.3 kW/m^2 and 2.8 kW/m^2, respectively. Isolation of the bedroom from the flow of fire room combustion gases decreased the bedroom 3 heat flux. Removal of the bedroom 3 window caused bidirectional flow through the exterior vent, which lifted the smoke layer in the bedroom and further decreased heat flux. Bidirectional flow through the window continued as the bedroom door was opened and closed. Heat flux decreased below 0.5 kW/m^2 within 30 s of removing the bedroom 3 window.

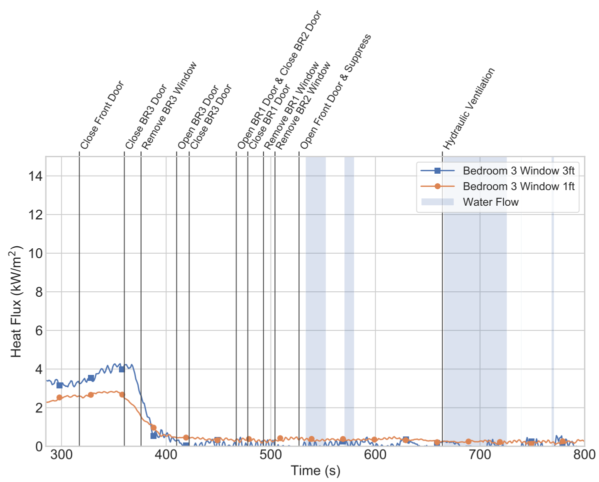
At the time of intervention, gas concentrations below the window indicated that the smoke layer had descended below the 1 ft level. Gas concentrations were 13.5% O_2, 2.8% CO_2, and 1.3% CO 3 ft above the floor and 13.2% O_2, 2.3% CO_2, and 1.3% CO 1 ft above the floor (Figure 5.91d). Gas concentrations remained constant until the bedroom window was removed. Bidirectional flow through the window caused combustion gases and air to mix, which temporarily worsened gas concentrations at the 3 ft elevation. The smoke layer in the bedroom ascended to the ceiling and gas concentrations improved to pre-ignition levels at both elevations.



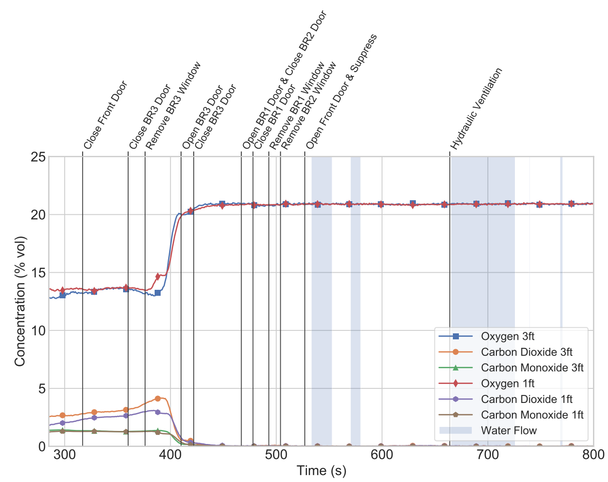
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

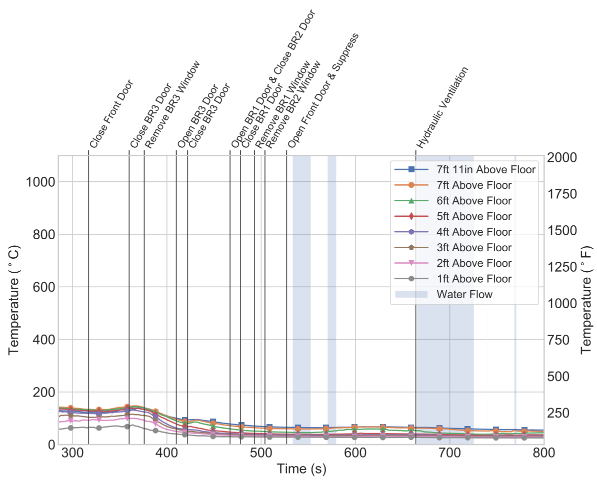
Figure 5.91: Post-intervention window temperature, heat flux, and gas concentrations in bedroom 3 during Experiment 6.

Although the bathroom 3 door was opened prior to ignition, the bathroom was two rooms removed from the fire. Temperatures in the bathroom were generally less than those in the bedroom. Bathroom 3 temperatures at the time of intervention exceeded 135 °C (275 °F), as shown in Figure 5.92a. Bathroom temperatures followed a similar trend to bedroom temperatures and increased to 150 °C (302 °F) after the front door was closed. Closure of the bedroom 3 door and removal of the bedroom 3 window both caused bathroom temperatures to decrease. Bathroom temperatures increased after the bedroom 3 door was opened, as additional combustion gases flowed into the bathroom. However, temperature increase in the bathroom was delayed compared to the bedroom. Bidirectional flow through the window decreased temperatures below 60 °C (140 °F) by the end of the experiment.

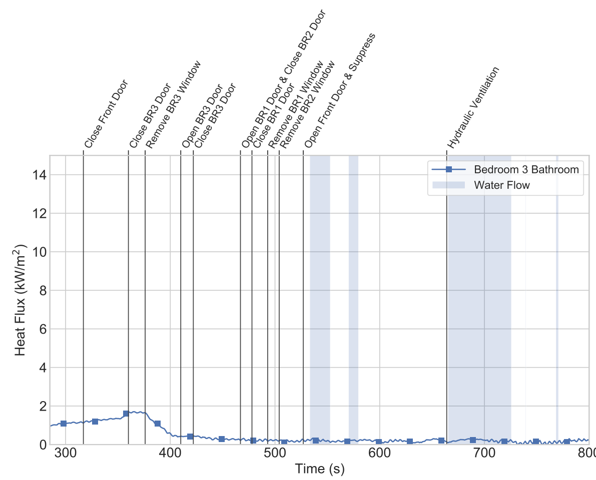
Heat flux 1 ft above the bathroom floor was 1.2 kW/m^2 at the time of first intervention, as shown in

Figure 5.92b. Heat flux increased after the front door was closed, peaking at 1.7 kW/m^2. However, heat flux did not immediately decrease after the bedroom 3 door was closed as the bathroom was adjacent to, but not part of the flow path that had existed while the door was open. The removal of the bedroom 3 window resulted in a lift in the combustion gases that had accumulated in the space due to the bidirectional flow through the open window. As a result, the heat flux decreased to negligible magnitudes.

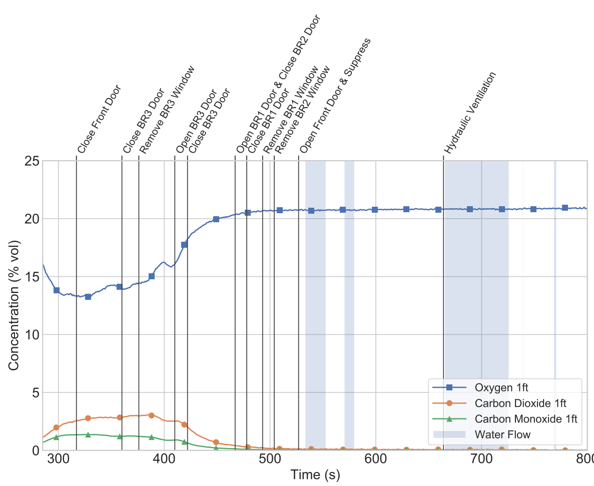
Gas concentrations 1 ft above the bathroom floor indicated that the smoke layer had descended past the 1 ft level at the time of intervention. Gas concentrations were 13.4% O_2, 2.6% CO_2, and 1.4% CO, as shown in Figure 5.92c. Gas concentrations remained constant until the bedroom 3 window was removed. Bidirectional flow through the window lifted the smoke layer, which improved gas concentrations to pre-ignition levels.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

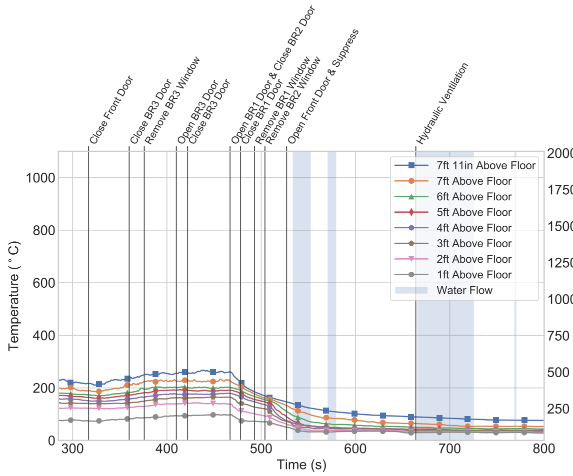
Figure 5.92: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 6.

5.6.5 Bedroom 2

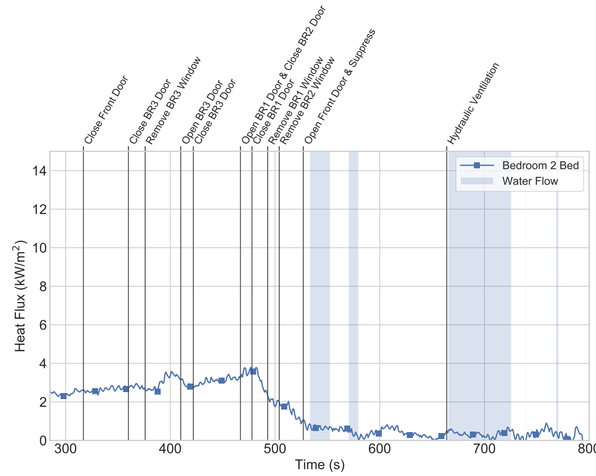
The bedroom 2 door was opened prior to ignition, which allowed combustion gases from the fire room to flow into the bedroom. Bedroom 2 temperatures at the time of first intervention ranged from 220 °C (428 °F) at the ceiling to 75 °C (167 °F), as shown in Figure 5.93a. Temperatures exceeded 260 °C (500 °F) when the bedroom 2 door was closed. Isolation of the bedroom stopped the flow of combustion gases into the bedroom and temperatures decreased. The bedroom 2 window was removed. Accumulated combustion gases in the bedroom flowed toward and through the exterior vent, which further decreased bedroom temperatures. The bedroom door remained closed during suppression and hydraulic ventilation, however bidirectional flow through the window decreased bedroom temperatures below 80 °C (176 °F).

Heat flux to the bed was 2.6 kW/m^2 at the time of bedroom 2 intervention, as shown in Figure 5.93b. The heat flux steadily increased as combustion gases continued to flow into the open bedroom peaking at 3.8 kW/m^2 shortly after the bedroom 2 door was closed. The closure of the bedroom door isolated the room from the gas flows which originated from the fire room and the heat flux began to decrease, dropping to 2.0 kW/m^2. Removal of the bedroom 2 window created an exterior vent in the bedroom and the accumulated combustion gases flowed toward the vent, which resulted in further decrease in heat flux. The bidirectional flow through the window lifted the smoke layer in the bedroom and decreased heat flux below 0.5 kW/m^2.

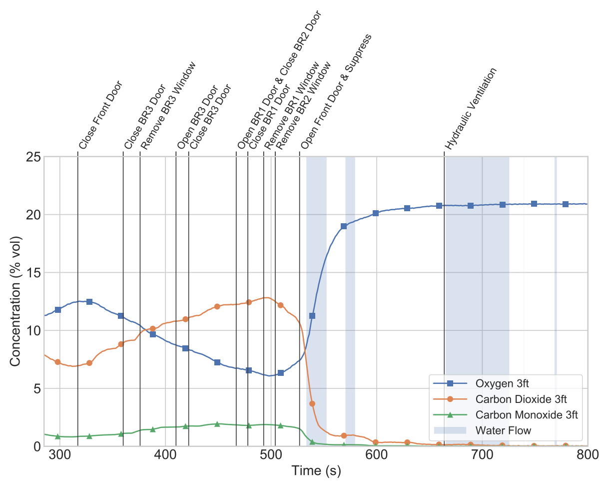
At the time of bedroom 2 intervention, gas concentrations indicated that the smoke layer had descended past the bed. Gas concentrations were 6.8% O_2, 12.2% CO_2, and 1.8% CO, as shown in Figure 5.93c. Closure of the bedroom 2 door stopped the flow of combustion gases into the bedroom, which caused gas concentrations to improve. Bidirectional flow through the window lifted the smoke layer in the bedroom, which improved gas concentrations to pre-ignition levels.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



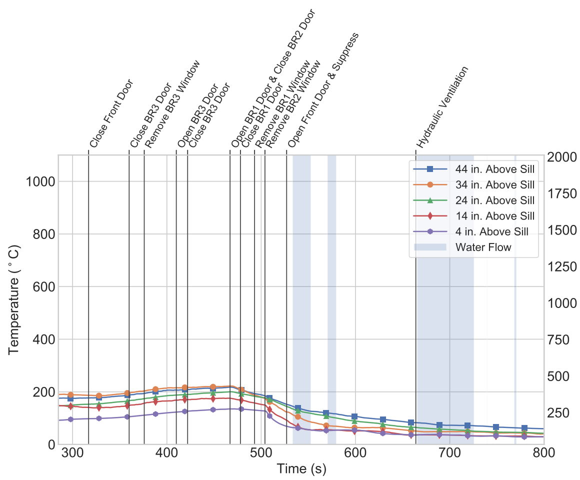
(c) Bedroom 2 Gas Concentration

Figure 5.93: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 6.

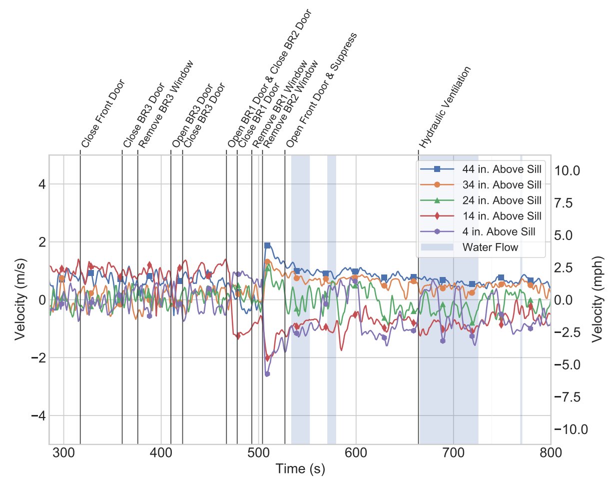
Bedroom 2 window temperatures were consistent with temperatures in the center of the room at the time of first intervention, as shown in Figure 5.94a. Window temperatures followed a similar trend to bedroom temperatures and exceeded 220 °C (428 °F) when the bedroom 2 door was closed. Isolation of the bedroom decreased window temperatures, but removal of the bedroom 2 window decreased temperatures more quickly. Combustion gases exhausted between 1.9 m/s and 1.2 m/s (4.3 mph and 2.7 mph) above 24 in. above the sill and air entrained between -2.0 m/s and -2.6 m/s (-4.5 mph and -5.8 mph) below 24 in. above the sill (Figure 5.94b). Bidirectional flow through the window continued and reduced window temperatures below 70 °C (158 °F).

Heat flux below the bedroom 2 window was 4.2 kW/m^2 at both 3 ft above the floor and 1 ft above the floor at the time of front door closure, as shown in Figure 5.94c. Similar to the heat flux to the bed, the heat flux continued to rise, peaking above 6 kW/m^2 prior to the closure of the bedroom 2 door. The isolation of the bedroom from the combustion gases in the hallway resulted in a steady decrease in heat flux which was decreased further following the removal of the bedroom 2 window. Both heat flux magnitudes dropped below 1.0 kW/m^2 within 15 s of window removal.

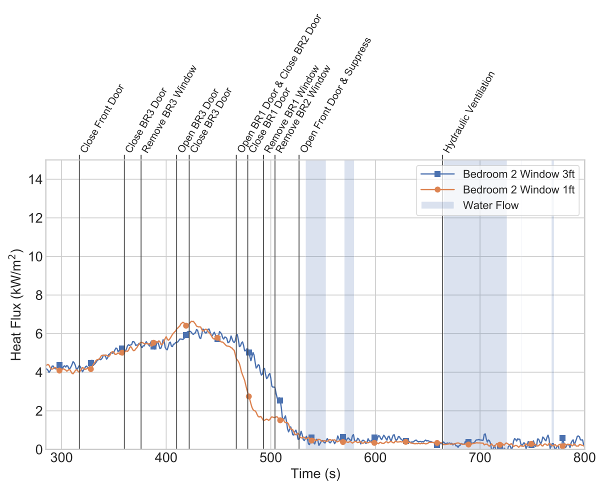
At the time of bedroom 2 intervention, gas concentrations indicated that the smoke layer had descended below the 1 ft elevation. Gas concentrations below the bedroom 2 window were 7.2% O_2, 12.3% CO_2, and 1.9% CO 3 ft above the floor and 7.7% O_2, 11.6% CO_2, and 1.8% CO 1 ft above the floor, as shown in Figure 5.94d. Gas concentrations below the window followed a similar trend to gas concentrations at the bed level and improved after the bedroom was isolated. Bidirectional flow through the window improved gas concentrations to pre-ignition levels.



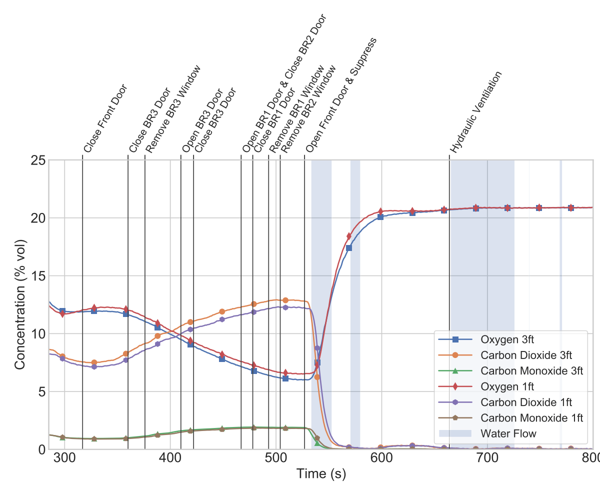
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

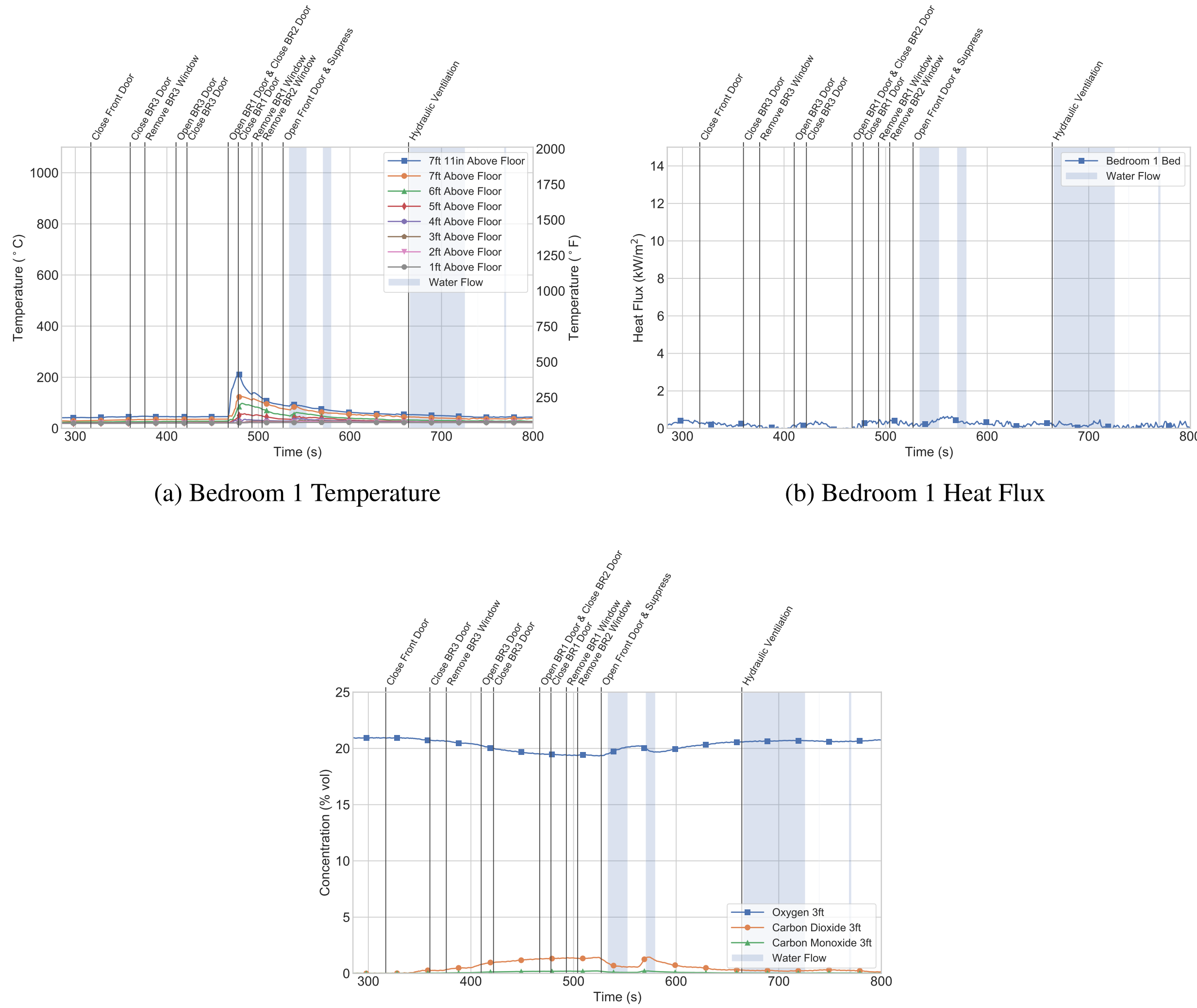
Figure 5.94: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 6.

5.6.6 Bedroom 1

The closed bedroom 1 door prevented the flow of combustion gases from the fire room into the bedroom. However, higher-pressure combustion gases flowed through the leakage area around the closed door and through the HVAC supply vents into bedroom 1. At the time of first intervention, bedroom 1 temperatures exceeded 40 °C (104 °F) at the ceiling and 20 °C (68 °F) 1 ft above the floor, as shown in Figure 5.95a. The open bedroom 1 door established a new flow path between the higher-pressure fire room and the lower-pressure bedroom. Combustion gases flowed into the bedroom, which increased temperatures to 220 °C (428 °F). Closure of the bedroom 1 door isolated the bedroom from the flow of combustion gases and temperatures decreased. Removal of the bedroom 1 window established a new flow path between the bedroom and the exterior. Bidirectional flow through the window further decreased bedroom temperatures. During suppression, combustion gases flowed through the HVAC supply vents, located in the ceiling, into bedroom 1. As a result, temperatures in bedroom 1 temporarily increased during suppression. Bidirectional flow through the window continued and temperatures decreased below 50 °C (122 °F).

Heat flux to the bed was 0.1 kW/m^2 at the time of fire department intervention, as shown in Figure 5.95b. The bedroom 1 door was opened and closed, which allowed combustion gases to flow into the bedroom. However, due to the low temperature of the room, a measurable heat flux increase to the bed was not recorded.

At the time of first intervention, gas concentrations at the bed were consistent with pre-ignition conditions, as shown in Figure 5.95c. Combustion gases flowed into the bedroom through the open bedroom 1 door and gas concentrations steadily worsened to 19.3% O_2, 1.4% CO_2, and 0.2% CO. Following isolation, gas flow through the removed bedroom 1 window improved gas concentrations. Although protected by a closed door, suppression of the bedroom 4 fire caused gas concentrations to worsen due to continued gas flow through the HVAC supply vents. Bidirectional flow through the window improved gas concentrations.



(a) Bedroom 1 Temperature

(b) Bedroom 1 Heat Flux

(c) Bedroom 1 Gas Concentration

Figure 5.95: Post-intervention bed level temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 6.

The bathroom 1 door was opened prior to ignition. Combustion gases flowed into the bathroom through the HVAC supply vents, which increased bathroom temperatures to 36 °C (97 °F) at the time of intervention (Figure 5.96). Combustion gas flow through the open bedroom 1 door increased bathroom temperatures to 65 °C (149 °F). The bathroom was adjacent to, but not part of the flow paths established in bedroom 1. As a result, temperature increase in the bathroom was delayed and less than in the bedroom. Closing the bedroom 1 door and removing the bedroom 1 window decreased bathroom temperatures. However, combustion flow through the HVAC supply vents during suppression limited the temperature decrease to 50 °C (122 °F).

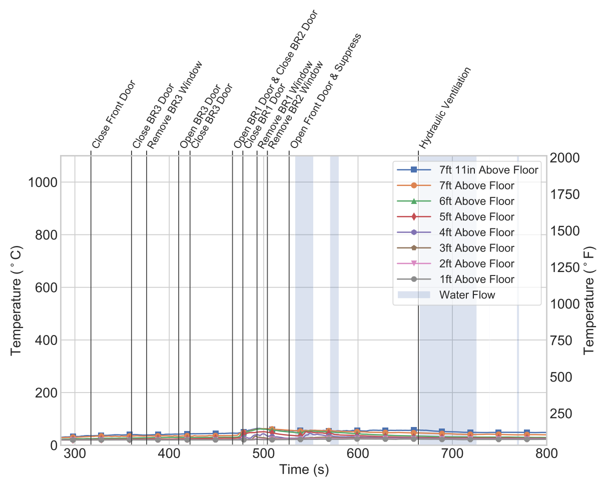


Figure 5.96: Post-intervention temperatures in bathroom 1 during Experiment 6.

5.7 Experiment 7

The search tactics in Experiment 7 were designed to evaluate door initiated operations following fire room door control conducted before suppression of a bedroom fire (bedroom 4). Prior to ignition the lower panes of the double-wide, bedroom 4 window were removed. The front door to the structure and doors to bedroom 4, bedroom 3, bedroom 2, bathroom 3 and bathroom 1 were open. The door to bedroom 1 was closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 flashover, the crew on side A of the structure entered the common space with a 2 1/2 gallon pressurized water fire extinguisher. The crew suppressed flaming combustion in the hallway and proceeded to the fire room. The crew closed the bedroom 4 door, which terminated the flow of higher-pressure combustion gases from the fire room to lower-pressure, open volumes of the structure. The crew proceeded into bedroom 3 and closed the door behind them. The bedroom 3 window was removed. The door to bedroom 3 was opened for entry into the hallway and subsequently closed. The crew proceeded down the hall toward bedrooms 1 and 2, then split to enter both bedrooms. Simultaneously, the door to bedroom 1 was opened and the door to bedroom 2 was closed. The bedroom 1 door was closed after the crew entered the bedroom. The double-wide window in each bedroom was removed. At this point, the search tactic comparison was complete. The suppression crew entered the structure through the front door, flowing water as needed to advance to the fire room. The suppression crew began flowing water as the fire room door was opened. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed bedroom 4 window. During hydraulic ventilation the bedroom 1 door was opened. 84 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 317 gallons. Table 5.13 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was water flow from a pressurized water fire extinguisher.

Table 5.13: Experiment 7 Event Times

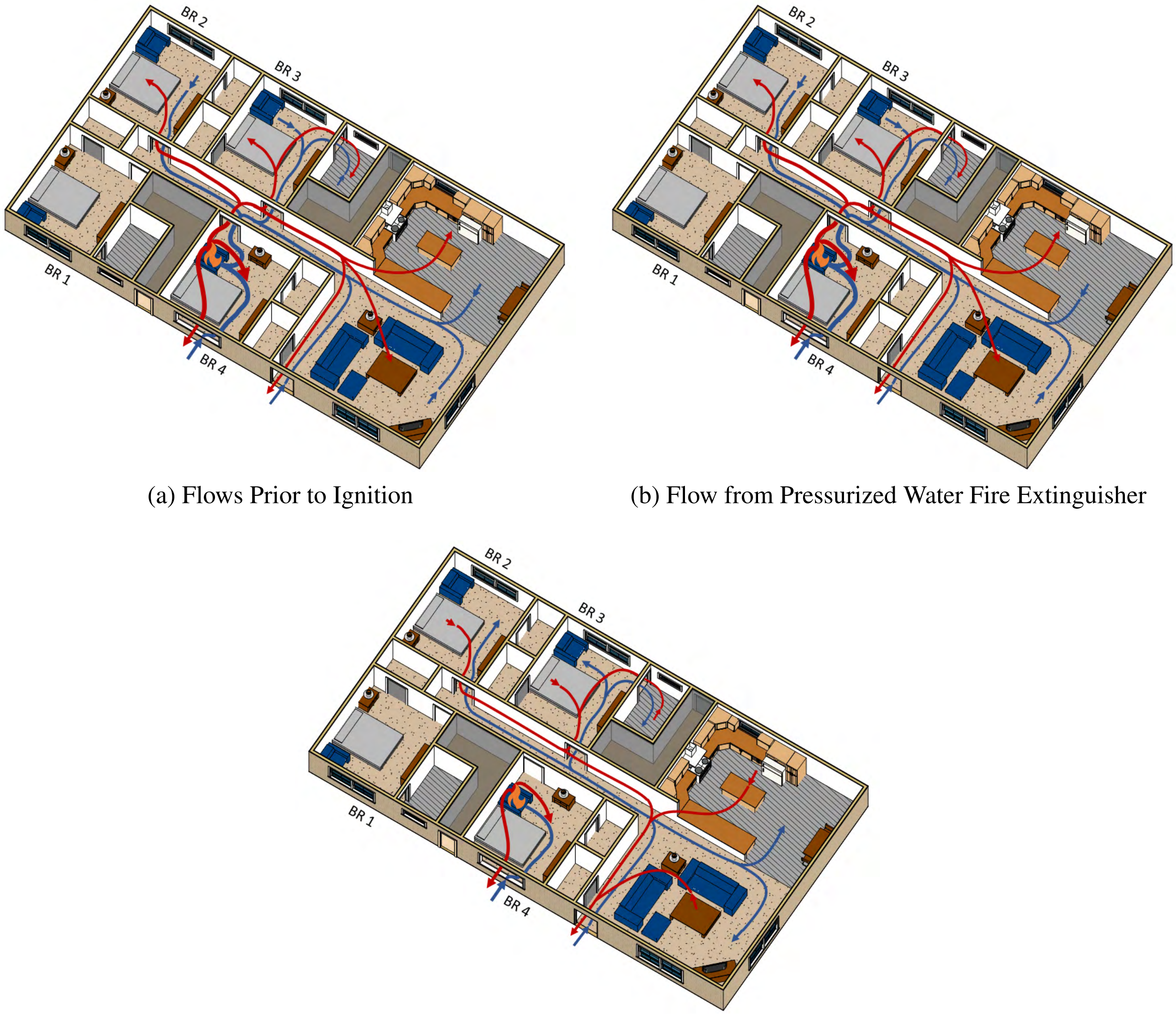
Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Ignition	00:00	0	—	—
Flow from Pressurized Water Fire Extinguisher	05:19	319	00:00	0
Close BR4 Door	05:30	330	00:11	11
Close BR3 Door	05:38	338	00:19	19
Remove BR3 Window	05:50	350	00:31	31
Open BR3 Door	06:20	380	01:01	61
Close BR3 Door	06:31	391	01:12	72
Open BR1 Door & Close BR2 Door	06:46	406	01:27	87
Close BR1 Door	06:55	415	01:36	96
Remove BR2 Window	07:26	446	02:07	127
Remove BR1 Window	07:36	456	02:17	137
Suppression	07:52	472	02:33	153
Open BR4 Door	08:23	503	03:04	184
Hydraulic Ventilation	09:46	586	04:27	267
Open BR1 Door	10:23	623	05:04	304

Figures 5.97 through 5.100 show the changes in flow as a result of fire department interventions. At the time of intervention, the bedroom 4 fire was in a post-flashover state. Lower-temperature, lower-pressure air flowed to the fire room and higher-temperature, higher-pressure combustion gases flowed from the fire room, which generated bidirectional flow through the open bedroom 4 vents (Figure 5.97a). Flow paths were established between the higher-pressure fire room and the lower-pressure open volumes of the structure and to the exterior.

The crew entered the structure and flowed water from a pressurized water fire extinguisher in the hallway, which extinguished flaming combustion on the floor. Water was not flown into bedroom 4 and bulk flows through the structure were minimally affected, as shown in Figure 5.97b.

The crew closed the bedroom 4 door, which stopped the flow of higher-pressure combustion gases from the fire room to the lower-pressure open volumes of the structure (Figure 5.97c). However, existing gas flows continued throughout the structure, due to the previous accumulation of gases while the door was open.

Closure of the bedroom 3 door isolated the bedroom from the flow of combustion gases, which limited further accumulation of combustion gases in bedroom 3 and bathroom 3 (Figure 5.98a). The crew removed the bedroom 3 window. A flow path between the higher-pressure bedroom and lower-pressure exterior established through the exterior vent (Figure 5.98b). Bidirectional flow through the open window exhausted previously accumulated combustion gases from and entrained cool air to the bedroom.



(a) Flows Prior to Ignition

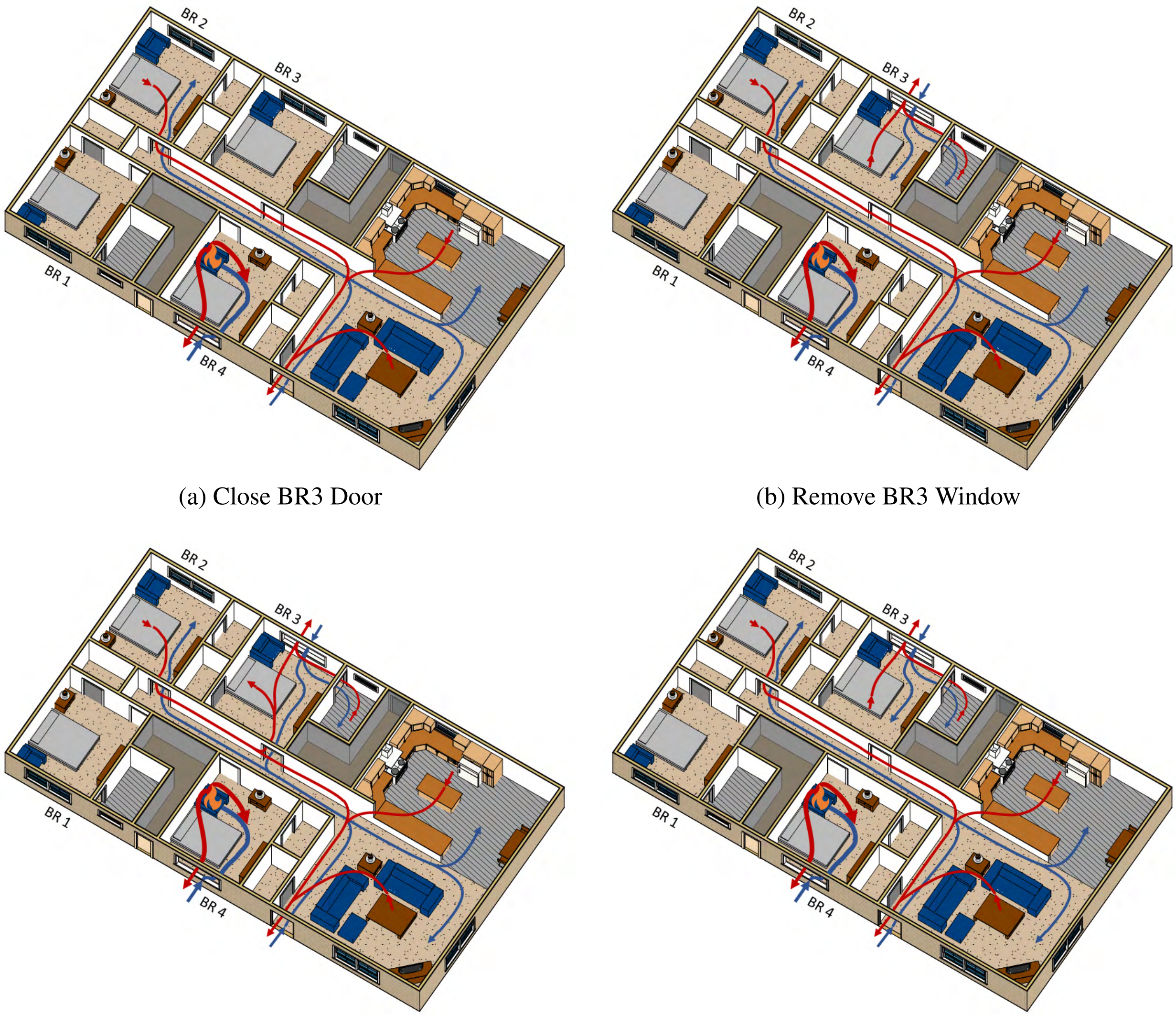
(b) Flow from Pressurized Water Fire Extinguisher

(c) Close BR4 Door

Figure 5.97: Changes in flow in structure following fire department interventions in Experiment 7.

The crew opened the bedroom 3 door, which allowed combustion gases to flow from the hallway into the bedroom and exhaust through the open window (Figure 5.98c). A flow path between the higher-pressure open volume of the structure and the lower-pressure exterior established. The crew closed the bedroom 3 door, which stopped the flow of combustion gases from the hallway into the bedroom (Figure 5.98d). Accumulated combustion gases in the bedroom flowed toward the exterior vent and the flow path between the bedroom and exterior of the structure reestablished.

The crew continued down the hallway and split to enter bedrooms 1 and 2 simultaneously. The bedroom 1 door was opened, which allowed combustion gases to flow from the hallway into the bedroom (Figure 5.99a). A flow path between the higher-pressure hallway and lower-pressure bedroom established. The bedroom 2 door was closed, which stopped the flow of combustion gases from the hallway into the bedroom (Figure 5.99a). Closure of the bedroom 1 door stopped



(a) Close BR3 Door

(b) Remove BR3 Window

(c) Open BR3 Door

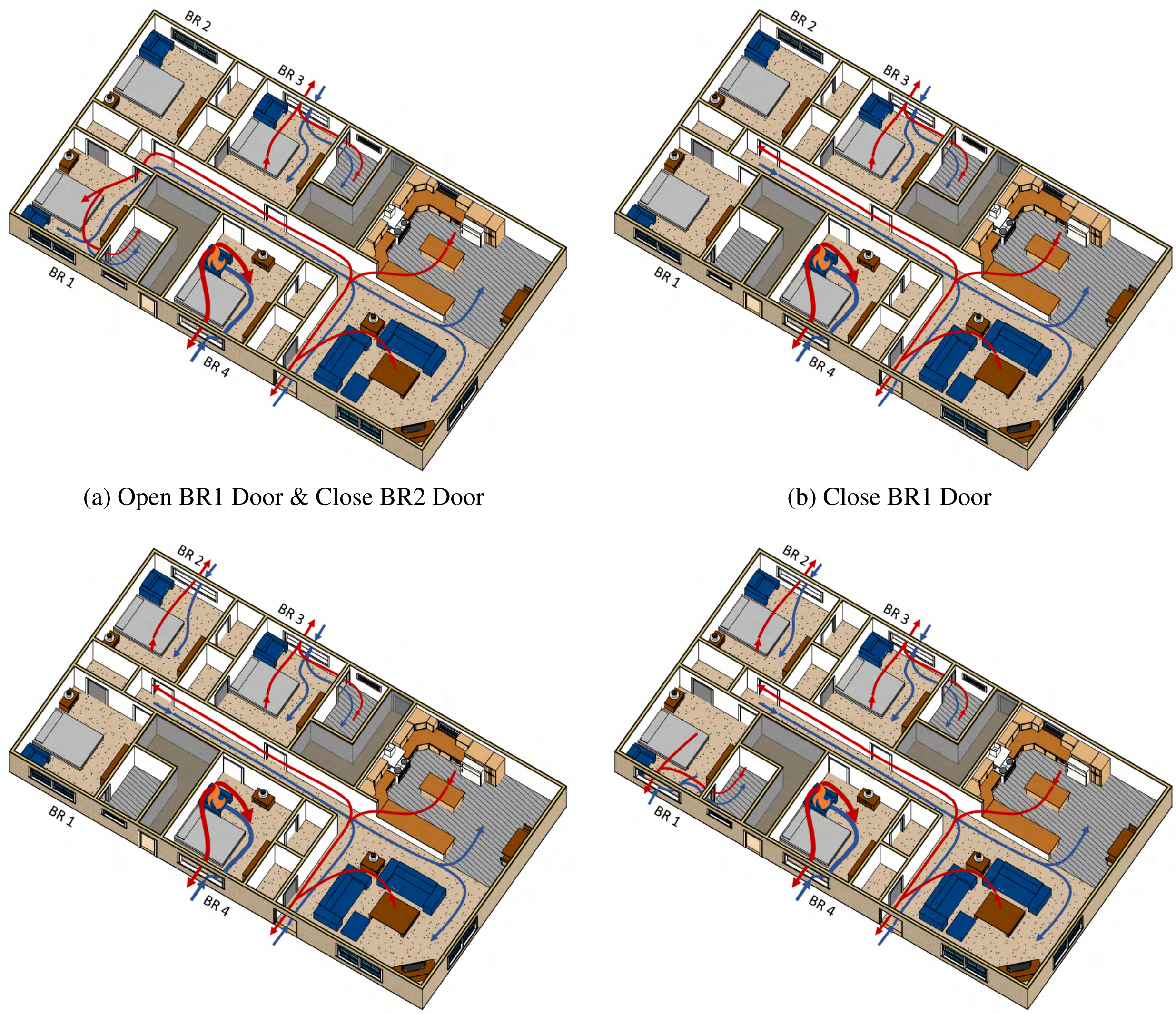
(d) Close BR3 Door

Figure 5.98: Changes in flow in structure following fire department interventions in Experiment 7.

the flow of combustion gases into the bedroom, which limited the accumulation of combustion gases in bedroom 1 and bathroom 1 (Figure 5.99b).

Removal of the bedrooms 1 and 2 windows created an exterior vent in each isolated bedroom. Flow paths were established between each bedroom and the exterior of the structure, as shown in Figures 5.99c and 5.99d.

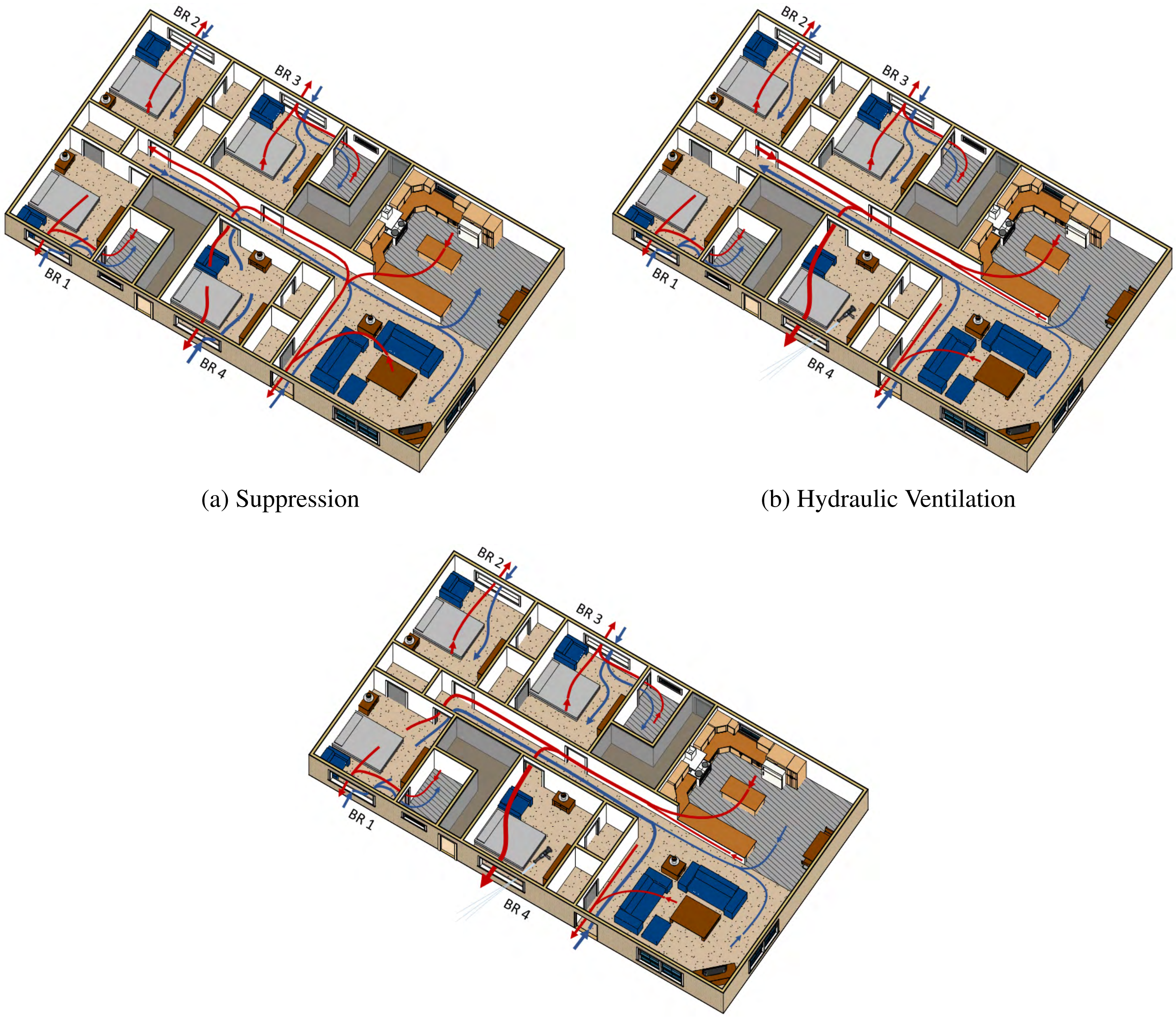
Interior suppression was conducted through the front door with a smooth bore nozzle with a 7/8 in. tip, set to flow 160 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline (Figure 5.100a). The suppression crew advanced down the hallway and flowed water as needed. The door to bedroom 4 was opened and suppression began in the fire room, which allowed higher-pressure combustion gases to flow toward lower-pressure open volumes of the structure.



(a) Open BR1 Door & Close BR2 Door
(b) Close BR1 Door
(c) Remove BR2 Window
(d) Remove BR1 Window

Figure 5.99: Changes in flow in structure following fire department interventions in Experiment 7.

Hydraulic ventilation occurred out of the double-wide bedroom 4 window with the tip off, at half bale, in an O-pattern (Figure 5.100b). Hydraulic ventilation created an area of lower pressure in the fire room, which caused unidirectional exhaust flow through the bedroom 4 vents. The door to bedroom 1 was opened during hydraulic ventilation, which caused previously accumulated combustion gases to flow from the bedroom into the hallway (Figure 5.100c).



(a) Suppression

(b) Hydraulic Ventilation

(c) Open BR1 Door

Figure 5.100: Changes in flow in structure following fire department interventions in Experiment 7.

5.7.1 Bedroom 4

Approximately 147 s post-ignition, falling debris damaged the thermocouple array in bedroom 4. After this time stamp, data from this thermocouple are not representative of temperatures throughout the bedroom. Flashover was determined from visual cues captured with standard and IR cameras. Flashover of the fire room occurred approximately 160—180 s post-ignition, after flames were visible from the failed fire room window.

At the time of fire department intervention, bedroom 4 doorway temperatures ranged between 770 °C (1418 °F) 76 in. above the floor to 300 °C (572 °F) 4 in. above the floor, as shown in Figure 5.101a. Combustion gases exhausted from the fire room at approximately 3.0 m/s (6.7 mph) through the top of the doorway and air entrained into the fire room at approximately -2.1 m/s (-

4.7 mph) near the floor, as shown in Figure 5.101b.

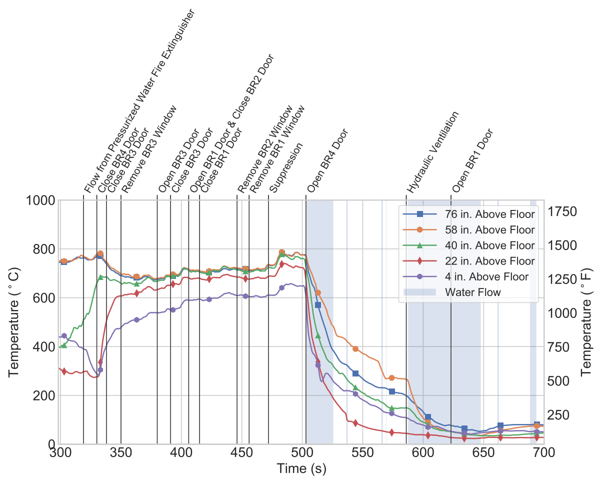
The suppression crew extinguished flaming combustion with a pressurized water fire extinguisher, which cooled gases in the hallway. As cooler gases entrained into the fire room, bedroom 4 doorway temperatures below 22 in. decreased to 280 °C (536 °F).

The suppression crew advanced to the fire room and closed the bedroom 4 door, which stopped bidirectional flow through the doorway and limited heat loss. Without air entrainment from open volumes of the structure, doorway temperatures 22 in. to 4 in. above the floor increased. Data recorded from bidirectional probes during the time the door was closed are not representative of flow through the doorway. Bedroom 4 doorway temperatures reached a steady state and ranged from 735 °C to 610 °C (1355 °F to 1130 °F).

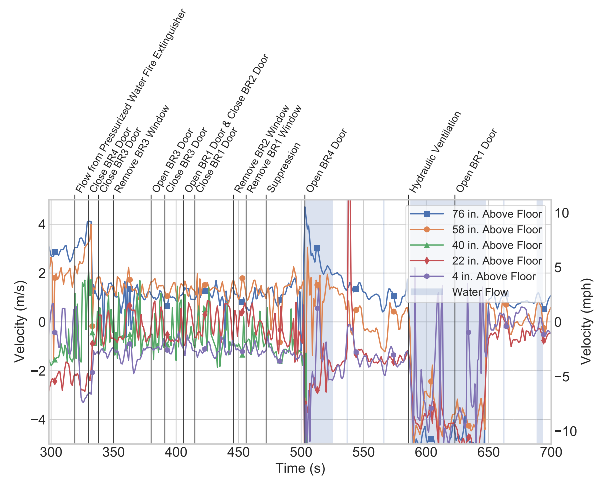
The suppression crew opened the bedroom 4 door simultaneously with the onset of suppression, which allowed gas flow from the fire room to open volumes of the structure. Bidirectional flow through the doorway exhausted combustion gases at approximately 4.7 m/s (10.5 mph) and entrained air at approximately -6.6 m/s (-14.8 mph). Initial water flow decreased the heat release rate of the fire and doorway temperatures decreased below 450 °C (842 °F). Three additional water flows extinguished the fire and temperatures decreased below 270 °C (518 °F).

Hydraulic ventilation occurred out of the bedroom 4 window, which caused flow through the doorway and window to become unidirectional toward the exterior of the structure. Combustion gases exhausted through the window at approximately -4.0 m/s (-8.9 mph), which decreased fire room temperatures below 80 °C (176 °F).

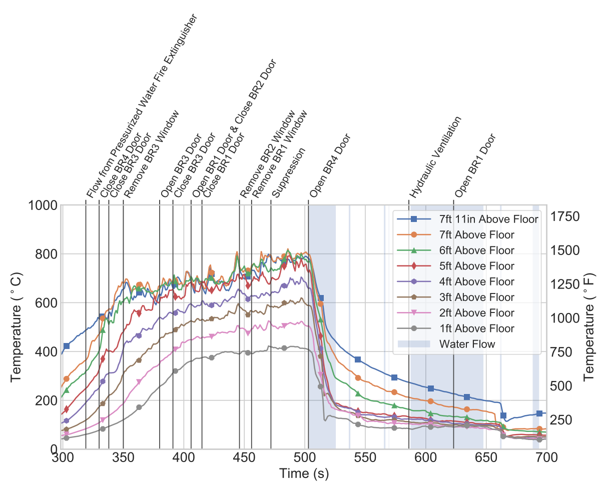
The closet door in bedroom 4 was closed prior to ignition, which isolated the closet from the flow of higher-temperature, higher-pressure combustion gases from the fire room. Approximately 202 s post-ignition, the top of the closet door burned through, which allowed higher-pressure combustion gases to flow into the closet. At the time of intervention, closet temperatures ranged from 490 °C to 60 °C (914 °F to 140 °F), as shown in Figure 5.101c. Prior to suppression, closet temperatures exceeded 810 °C (1490 °F). Initial suppression decreased closet temperatures below 425 °C (797 °F), while additional water flows decreased closet temperatures below 300 °C (572 °F). The closet was one room removed from the flows created by hydraulic ventilation and without a local exterior vent, which minimized the impact of hydraulic ventilation. Temperatures decreased below 200 °C (392 °F).



(a) Bedroom 4 Doorway Temperature



(b) Bedroom 4 Doorway Velocity



(c) Closet Temperature

Figure 5.101: Temperature and velocity time histories in the doorway of bedroom 4 and temperature time histories in the bedroom 4 closet for the period following fire department intervention in Experiment 7.

5.7.2 Common Space

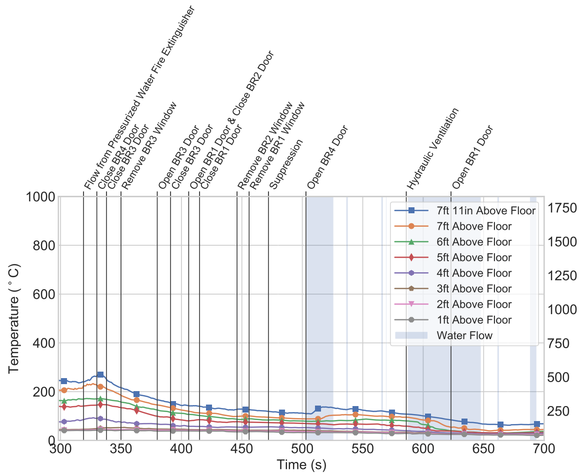
The kitchen was further from the flow path between the fire room and the front door than the living room, which caused kitchen temperatures to generally be less than living room temperatures. At the time of intervention, the smoke layer in the common space had descended to approximately 4 ft. Living room temperatures ranged from 240 °C (464 °F) at the ceiling to 40 °C (104 °F) 1 ft above the floor, as shown in Figure 5.102a. Kitchen temperatures ranged from 200 °C (392 °F) at the ceiling to 35 °C (95 °F) 1 ft above the floor, as shown in Figure 5.102b.

Flaming combustion in the hallway was extinguished with a pressurized water fire extinguisher. As cooler gases flowed throughout the structure, common space temperatures below 6 ft decreased. Ceiling temperatures in the common space decreased after the fire room was isolated. The bedroom 4 door was opened for suppression, which allowed higher-pressure combustion gases to flow from the fire room toward the common space. Living room ceiling temperatures peaked to 135 °C (275 °F) and kitchen temperatures peaked to 115 °C (239 °F). Suppression decreased the heat release rate of the fire, which decreased the temperature of combustion gases that flowed into the common space. As a result, common space temperatures decreased. Hydraulic ventilation caused flow through the bedroom 4 vents to become unidirectional toward the exterior of the structure and flow through the front door to become unidirectional inflow. Common space temperatures decreased below 70 °C and 60 °C (158 °F and 140 °F) in the living room and kitchen, respectively.

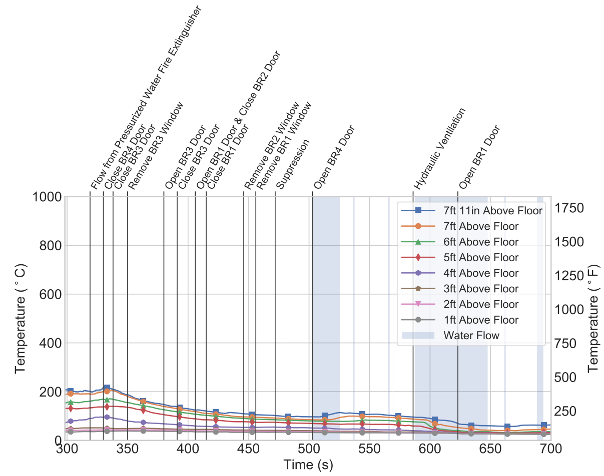
Heat flux 1 ft above the kitchen floor was 0.6 kW/m^2 at the time of intervention, as shown in Figure 5.102c. Water flow in the hallway decreased heat flux from 0.7 kW/m^2 to 0.3 kW/m^2. During suppression, combustion gases flowed from the fire room to open volumes of the structure. However, kitchen heat flux minimally increased. The kitchen was adjacent to flows established between the fire room and the front door, which caused the impact of hydraulic ventilation to be negligible.

Gas concentrations 1 ft above the kitchen floor were 20.4% O_2, 0.2% CO_2, and 0.1% CO at the time of intervention, as shown in Figure 5.102d. Water flow in the hallway extinguished flaming combustion and cooled combustion gases flowing toward the kitchen. Combustion gases dropped in elevation as they cooled, which caused gas concentrations in the kitchen to worsen to 19.9% O_2, 0.5% CO_2, and 0.2% CO. Fire room suppression had a similar effect; gas concentrations worsened to 19.4% O_2, 0.8% CO_2, and 0.3% CO. Hydraulic ventilation caused flow through the bedroom 4 vents to become unidirectional toward the exterior of the structure and flow through the front door to be unidirectional inflow, which improved gas concentrations.

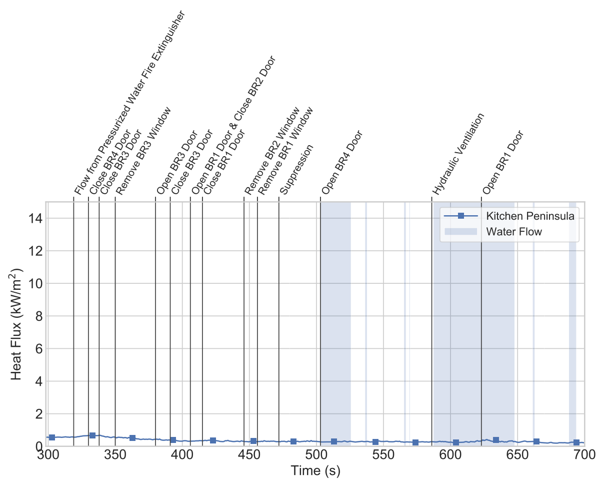
Approximately 293 s post-ignition, the suppression crew removed the bidirectional probes from the front door to gain entry into the structure. Measurements recorded during this time are not representative of flow through the doorway. The bidirectional probes were replaced approximately 344 s post-ignition. Temperatures ranged from 110 °C (230 °F) 76 in. above the floor to 30 °C (86 °F) 4 in. above the floor, as shown in Figure 5.103a. The velocity profile through the door mirrored temperature disparity, as combustion gases exhausted 76 in. above the floor at approximately 2.5 m/s (5.6 mph) and air entrained 58 in. and below at approximately -1.5 m/s (-3.6 mph) (Figure 5.103b). Flow through the front door became unidirectional inflow at -2.0 m/s (-4.5 mph),



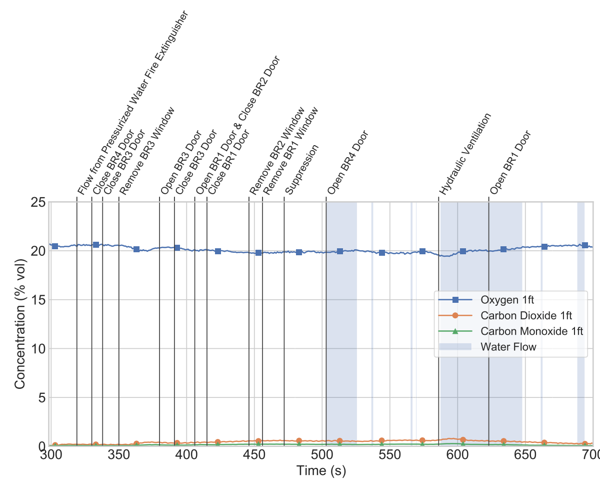
(a) Living Room Temperature



(b) Kitchen Temperature



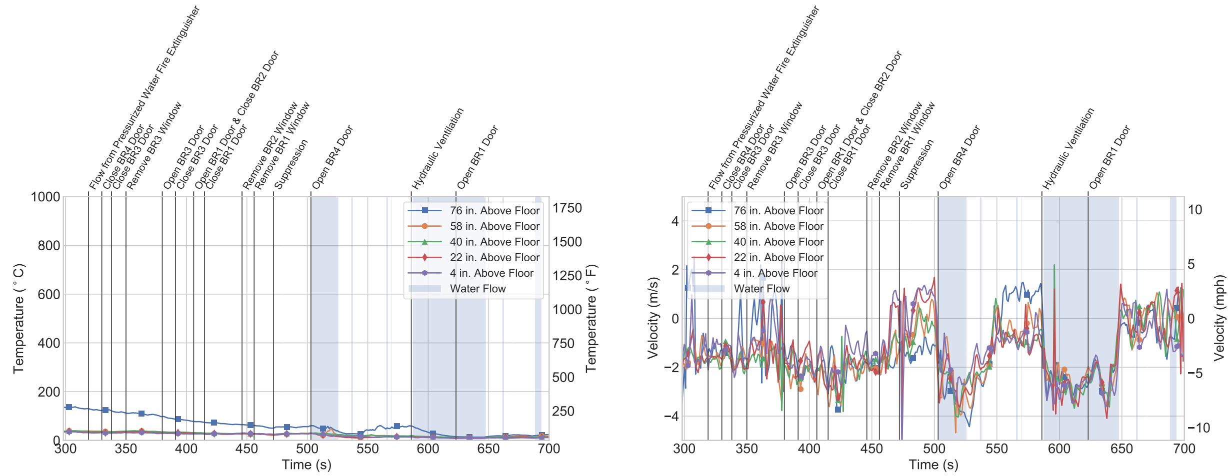
(c) Kitchen Heat Flux



(d) Kitchen Gas Concentration

Figure 5.102: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 7.

which decreased temperature 76 in. above the floor. The bidirectional probes were removed as the crew entered the structure for fire room suppression. The bidirectional probes were replaced approximately 556 s post-ignition. Hydraulic ventilation caused flow through the front door to become unidirectional inflow between -0.6 m/s and -4.7 m/s (-1.3 mph and -10.5 mph), which decreased doorway temperatures below 20 °C (68 °F).



(a) Front Doorway Temperature

(b) Front Doorway Velocity

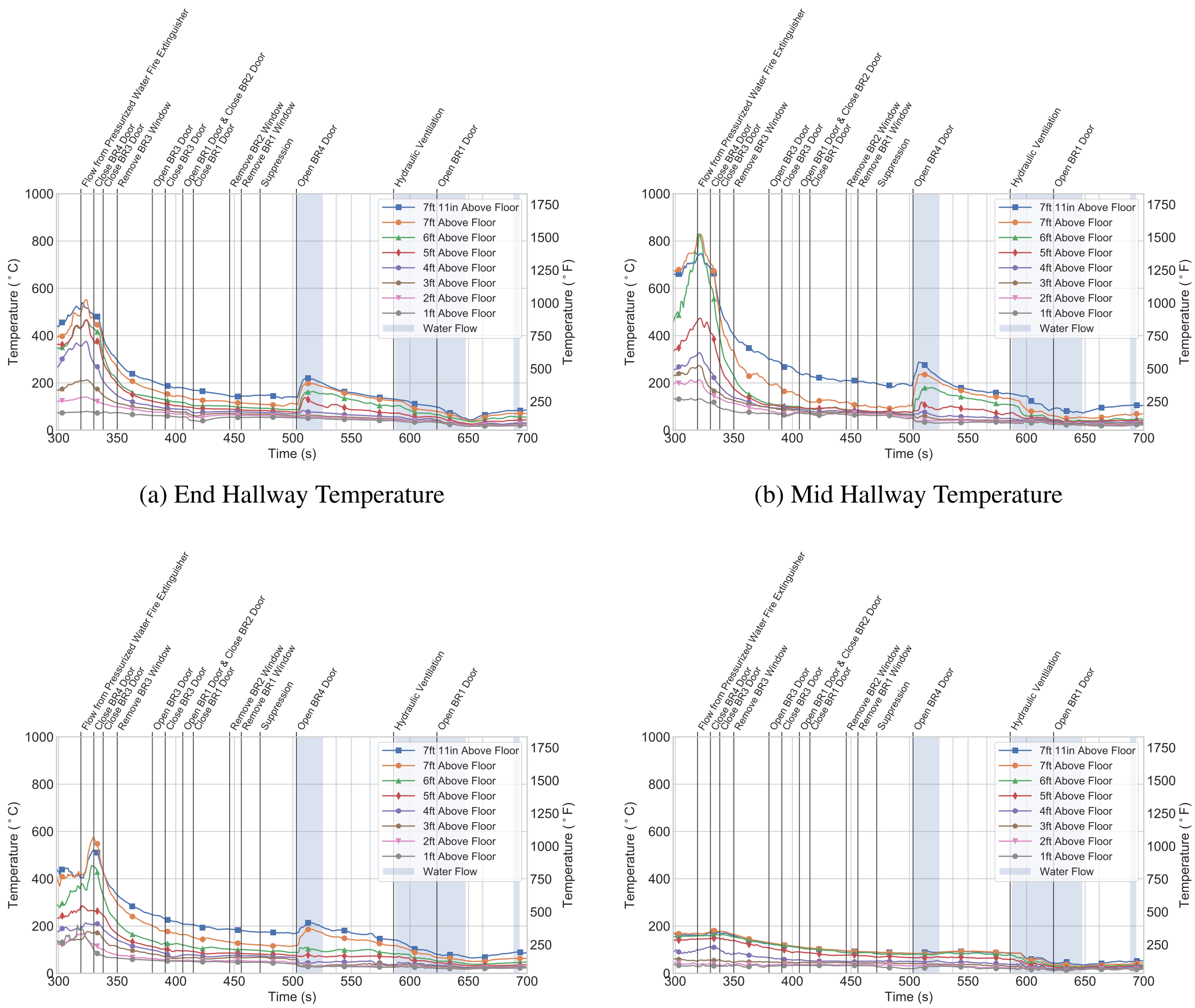
Figure 5.103: Post-intervention temperatures and velocities in the front doorway during Experiment 7.

5.7.3 Hallway

Figure 5.104 shows the temperature time history in the hallway. Prior to intervention, flames extended from the fire room into the hallway, which ignited the carpet at the mid hallway location. Flames spread toward both ends of the hallway, however without an exterior vent in bedroom 2, flame spread was limited toward the end hallway location. At the time of intervention, temperatures nearest the floor indicated low-level burning at the mid hallway and start hallway locations. Ceiling temperatures were a function of proximity to the fire room. Mid hallway temperatures were the greatest and exceeded 830 °C (1526 °F), followed by end hallway (520 °C (968 °F)), start hallway (415 °C (779 °F)), and living room entryway (170 °C (338 °F)) locations. The large volume of air in the common space and open front door prevented the smoke layer from descending to the floor in the entryway, which caused living room entryway temperatures to be less than hallway temperatures.

Flaming combustion on the floor near the start hallway was extinguished with a pressurized water fire extinguisher, which decreased temperatures throughout the hallway. Closure of the bedroom 4 door stopped the flow of combustion gases from the fire room into the hallway, which further decreased hallway temperatures. The open bedroom 1 door allowed gas exchange between the hallway and the bedroom, which decreased end hallway temperatures 4 ft and below.

The bedroom 4 door was opened simultaneously with the onset of suppression. Combustion gases flowed from the fire room into the hallway, which increased hallway temperatures. Mid hallway temperatures exceeded 290 °C (554 °F). Multiple water flows during suppression extinguished the bedroom 4 fire and hallway temperatures decreased below 160 °C (320 °F). Hydraulic ventilation created an area of lower pressure in bedroom 4, which caused flow through the bedroom 4 vents to become unidirectional toward the exterior of the structure. Combustion gases that had accumulated in the hallway flowed into bedroom 4 and temperatures decreased. The proximity of the living room entryway to an exterior vent maximized the impact of hydraulic ventilation; as such, living room entryway temperatures decreased below 35 °C (95 °F). Temperatures in the hallway decreased below 75 °C (167 °F).



(a) End Hallway Temperature

(b) Mid Hallway Temperature

(c) Start Hallway Temperature

(d) Living Room Entryway Hall Temperature

Figure 5.104: Temperature time histories in the hallway in the period following fire department intervention in Experiment 7.

Figure 5.105 shows the heat flux time histories in the hallway and living room entryway.

Heat fluxes at the time of intervention were 36.8 kW/m^2, 3.6 kW/m^2, 1.5 kW/m^2, and 0.5 kW/m^2 at the start hallway, mid hallway, end hallway, and living room entryway locations, respectively. The larger heat flux at the start hallway location indicated low-level burning. Hallway extinguishment from a pressurized water fire extinguisher decreased start hallway heat flux to 7.2 kW/m^2. Isolation of bedroom 4 stopped the flow of combustion gases from the fire room into the hallway,

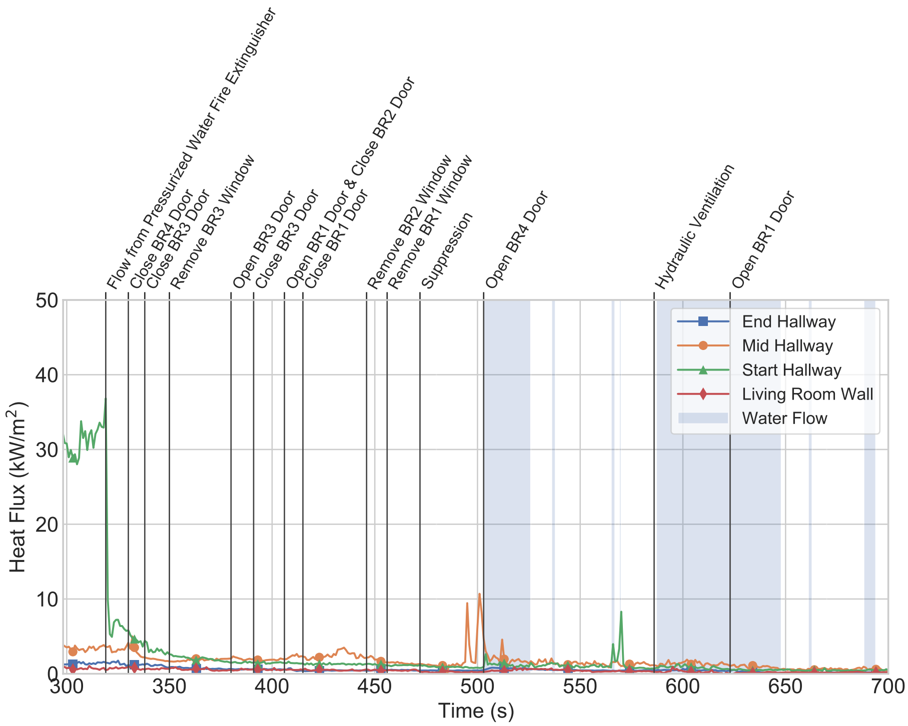


Figure 5.105: Heat flux time histories in the hallway in post-intervention period during Experiment 7.

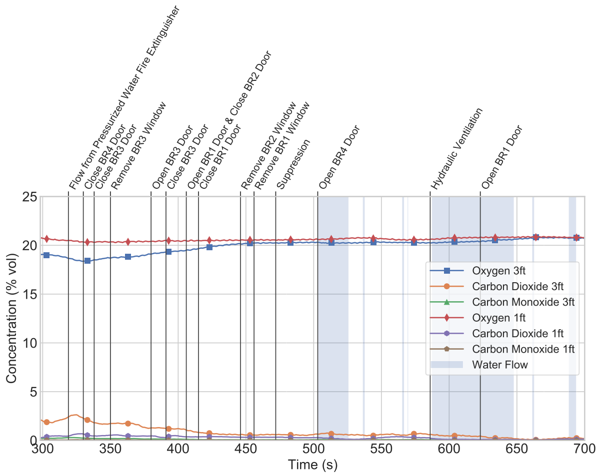
which decreased start hallway and mid hallway heat flux. Heat flux remained stable until the bedroom 1 door was opened. Carpet nearest the fire room reignited and the mid hallway heat flux peaked to 3.5 kW/m^2 before decreasing. The bedroom 4 door was opened concurrently with suppression. As flames rolled out of the bedroom, the heat flux at the mid hallway location increased to 10.7 kW/m^2. Suppression decreased the heat release rate and extinguished the fire, which decreased heat flux. Hydraulic ventilation caused unidirectional gas flow through the bedroom 4 vents toward the exterior of the structure, which reduced hallway heat flux below 0.7 kW/m^2.

Table 5.14 shows the gas concentrations measured throughout the hallway and living room entryway locations at the time of first intervention. Gas concentrations indicate that the smoke layer had descended to the 1 ft level at the mid hallway and end hallway locations. Higher concentrations of CO_2 and CO and lower concentrations of O_2 at the 1 ft elevation compared to the 3 ft elevation indicate low-level burning at the mid hallway location.

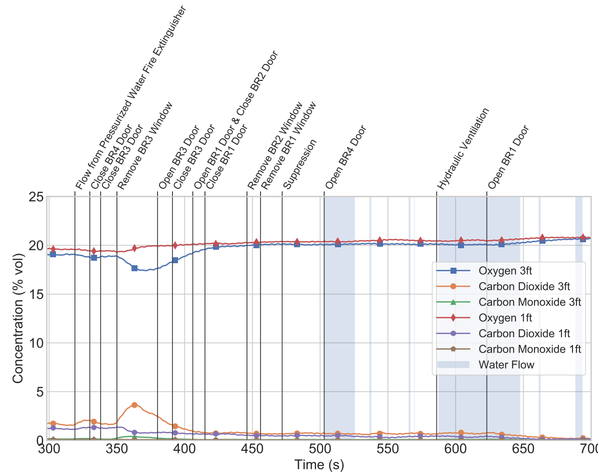
Table 5.14: Hallway Gas Concentrations at Intervention for Experiment 7

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	18.7	2.4	0.3
	1 ft	20.5	0.4	0
Start Hallway	3 ft	19.0	1.2	0.2
	1 ft	19.6	1.7	0.1
Mid Hallway	3 ft	15.6	3.8	0.4
	1 ft	13.1	5.7	0.7
End Hallway	3 ft	12.3	6.8	0.9
	1 ft	14.1	5.6	0.9

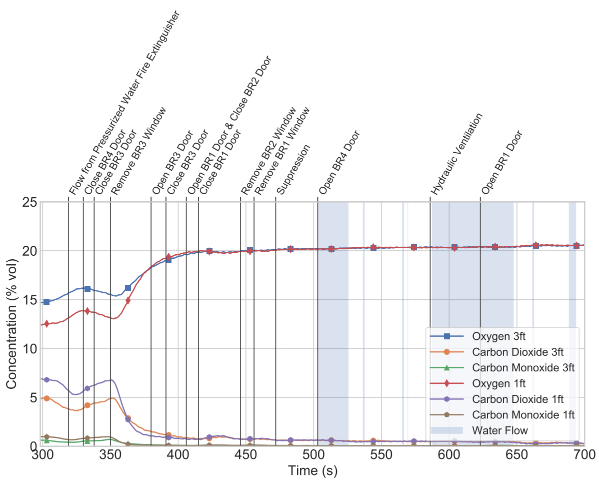
Figure 5.106 shows the gas concentration time histories in the hallway and living room entryway locations. Flaming combustion in the hallway was extinguished with a pressurized water fire extinguisher, which decreased hallway temperatures. Combustion gases in the hallway dropped in elevation as they cooled, which caused gas concentrations in the hallway to worsen. Isolation of the fire room stopped the flow of combustion gases into the hallway, which improved gas concentrations in the hallway. Gas concentrations improved to pre-ignition conditions, which limited the impact of hydraulic ventilation.



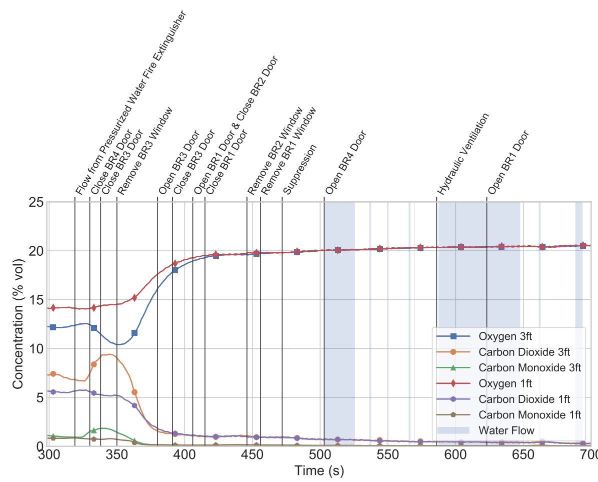
(a) Living Room Entryway Hall Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.106: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 7.

5.7.4 Bedroom 3

The bedroom 3 door was open prior to ignition, which allowed higher-pressure combustion gases to flow from the fire room into the lower-pressure bedroom. Bedroom 3 temperatures at the time of intervention exceeded 280 °C (536 °F), as shown in Figure 5.107. Flaming combustion in the hallway was extinguished with a pressurized water fire extinguisher, which cooled local combustion gases. As cooler combustion gases flowed into bedroom 3, temperatures in the center of the room stopped increasing and became steady.

Bedroom 3 temperatures decreased as the fire room was isolated, which prevented further flow of combustion gases into the hallway. Isolation of bedroom 3 also stopped the flow of combustion gases from the hallway into the bedroom, which caused bedroom temperatures to decrease. The bedroom 3 window was removed, which created an exterior vent in the bedroom. A flow path between the bedroom and the exterior was established. As combustion gases flowed along the flow path toward the open window, bedroom temperatures continued to decrease.

The bedroom 3 door was opened, which allowed higher-pressure combustion gases from the hallway to flow into the bedroom toward the exterior vent. However, water flow in the hallway reduced mid hallway temperatures and bedroom temperatures did not increase during the short duration at which the door was reopened. Accumulated combustion gases in the bedroom caused bidirectional flow through the window to continue after isolation. Higher-pressure combustion gases exhausted from and lower-pressure air entrained to the bedroom, which decreased temperatures below 85 °C (185 °F). The bedroom door remained closed during suppression and hydraulic ventilation, however bidirectional flow decreased bedroom temperatures below 70 °C (158 °F).

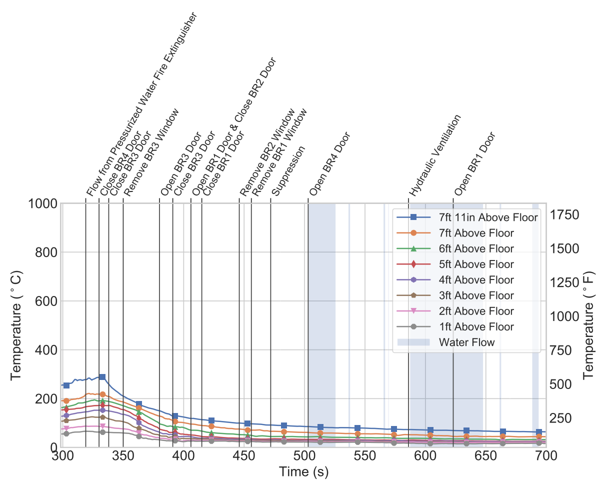


Figure 5.107: Post-intervention temperature in bedroom 3 during Experiment 7.

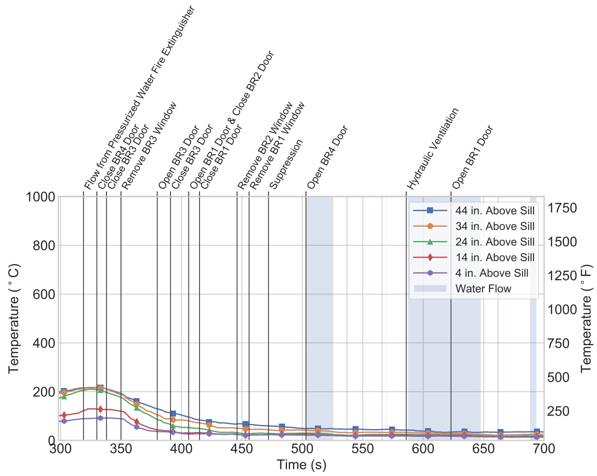
Bedroom 3 window temperatures were consistent with temperatures in the center of the room at the time of first intervention and exceeded 215 °C (419 °F) (Figure 5.108a). Water flow in the hallway cooled combustion gases that flowed into bedroom 3, which caused window temperatures to become steady. Closure of the bedroom 4 door stopped the flow of combustion gases into the hallway. As cooler combustion gases flowed into bedroom 3 from the hallway, window temperatures decreased. Closure of the bedroom 3 door stopped the flow of combustion gases from the hallway and window temperatures continued to decrease. Removal of the bedroom 3 window created an exterior vent in the bedroom. Combustion gases flowed toward and exhausted through the open window at 1.8 m/s (4.0 mph) and air entrained through the window at -2.0 m/s (-4.5 mph) (Figure 5.108b). Window temperatures decreased to 130 °C (266 °F). The bedroom 3 door was then opened, which allowed hallway combustion gases to flow into the bedroom toward the exterior vent. Bidirectional flow through the window decreased after the bedroom 3 door was closed. Temperatures decreased below 50 °C (122 °F). The bedroom 3 door remained closed during suppression and hydraulic ventilation, however window temperatures decreased below 35 °C (95 °F).

At the time of intervention, heat flux below the bedroom 3 window at both 3 ft and 1 ft above the floor was approximately 3.0 kW/m^2, which indicated that the smoke layer had descended past the 1 ft level (Figure 5.108c). Initial hallway suppression from a pressurized water fire extinguisher cooled the combustion gases that flowed into bedroom 3, which prevented heat flux from increasing. Although the closed bedroom 4 door stopped bidirectional flow through the bedroom 4 doorway, flow through the bedroom 3 doorway continued. Combustion gas flows between the hallway and bedroom decreased, which caused heat flux at the 3 ft level to remain steady and heat flux at the 1 ft level to decrease. The closed bedroom 3 door stopped the flow through the doorway and heat flux decreased. Removal of the bedroom 3 window created an exterior vent. Accumulated combustion gases in bedroom 3 flowed toward and through the open window, momentarily increasing heat flux below the window to 2.7 kW/m^2 and 2.4 kW/m^2 3 ft and 1 ft above the floor, respectively. Bidirectional flow through the window lifted the smoke layer below the window, which decreased heat flux below 0.2 kW/m^2. Heat flux was unaffected by the flow of combustion gases into the bedroom when the door was opened. The bedroom remained isolated during suppression and hydraulic ventilation, however bidirectional flow through the window decreased heat flux below 0.1 kW/m^2.

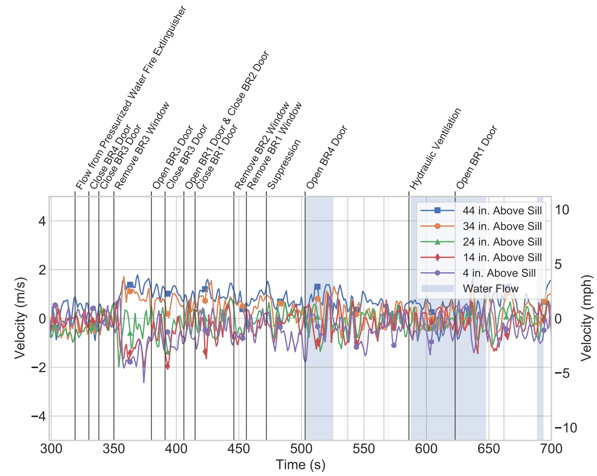
Figure 5.108d shows the gas concentration time histories below the bedroom 3 window. At the time of first intervention, gas concentrations 3 ft and 1 ft above the floor were similar, which indicated that the smoke layer had descended past the 1 ft level. O_2 and CO concentrations were approximately equal at both elevations, measuring 13.5% O_2 and 1.3% CO. CO_2 concentrations were 4.3% CO_2 and 3.5% CO_2 3 ft and 1 ft above the floor, respectively. Gas concentrations were unaffected by water flow or isolation of the fire room and bedroom 3, as the smoke layer had fully descended from the ceiling. The removal of the bedroom 3 window created an exterior vent in the isolated bedroom. As combustion gases flowed toward and exhausted through the open window, gas concentrations at the 3 ft level momentarily worsened to 13.3% O_2, 5.0% CO_2, and 1.3% CO. As air was entrained into the bedroom gas concentrations at both levels improved. Gas concentrations were unaffected by the flow of combustion gases into the bedroom after the door was opened. Bidirectional flow improved gas concentrations to 20.9% O_2, 0% CO_2, and 0% CO 3 ft and 1 ft above the floor.

The bathroom 3 door was opened prior to ignition, which allowed higher-pressure, higher-temperature combustion gases to flow from the fire room into the bathroom. The bathroom was two rooms removed from the fire room. As a result, bathroom temperatures followed similar trends to bedroom temperatures, but at lesser magnitudes. Bathroom temperatures exceeded 140 °C (284 °F) at the time of first intervention, as shown in Figure 5.109a. Initial hallway suppression with a pressurized water fire extinguisher caused bathroom temperatures to become steady. Fire room and bedroom 3 isolation caused bathroom temperatures to decrease. The bathroom was adjacent to, but not part of the flow path established between the bedroom and the exterior, which limited the impact of bidirectional flow through the open window. Temperatures decreased below 40 °C (104 °F).

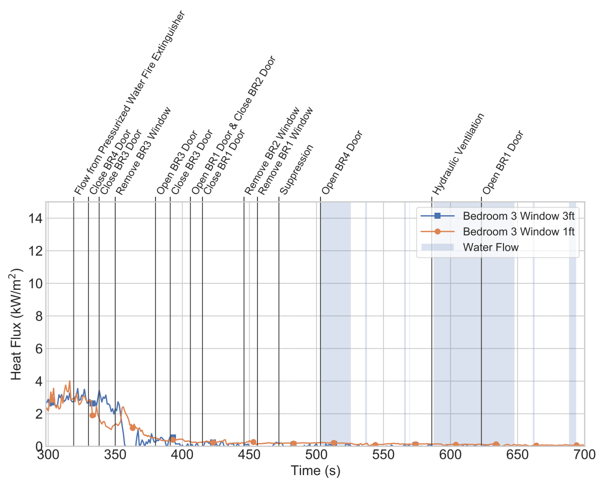
At the time of intervention, the bathroom 3 smoke layer had descended below the 1 ft level, as indicated by a heat flux of 1.4 kW/m^2 (Figure 5.109b). Heat flux increased to 1.6 kW/m^2 before initial water flow in the hallway decreased heat flux. Isolation of the fire room and bedroom 3 limited further accumulation of combustion gases in the bathroom, which further decreased heat flux. Combustion gas flow toward the open window caused heat flux in the bathroom to momentarily



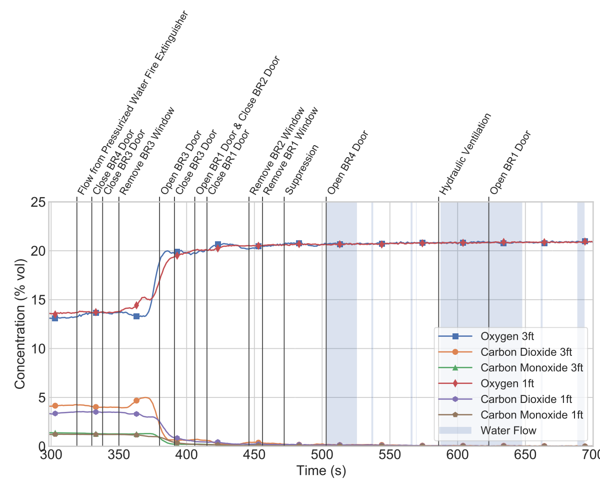
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux

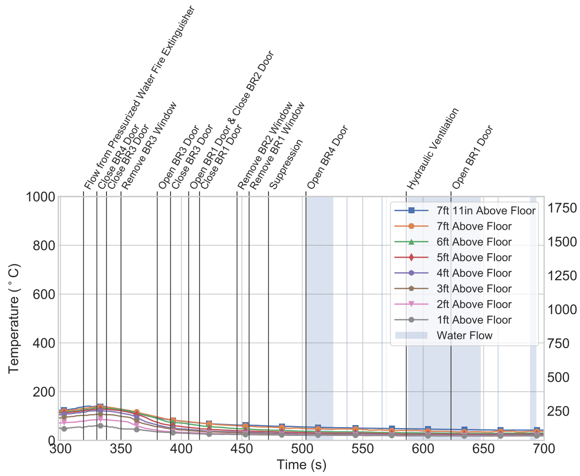


(d) Bedroom 3 Window Gas Concentration

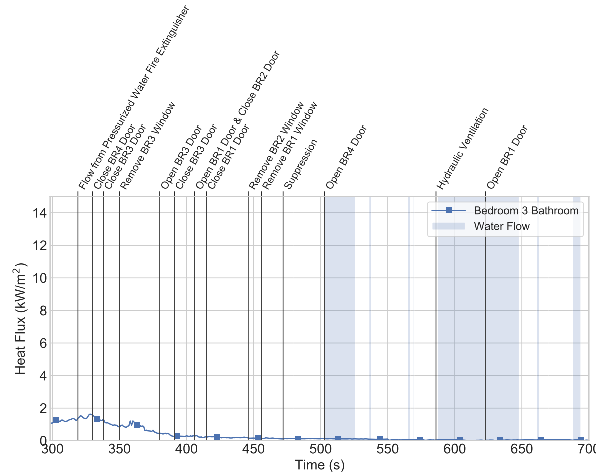
Figure 5.108: Post-intervention window temperature, heat flux, and gas concentrations in bedroom 3 during Experiment 7.

increase to 1.2 kW/m^2. Bidirectional flow through the window decreased heat flux to 0 kW/m^2.

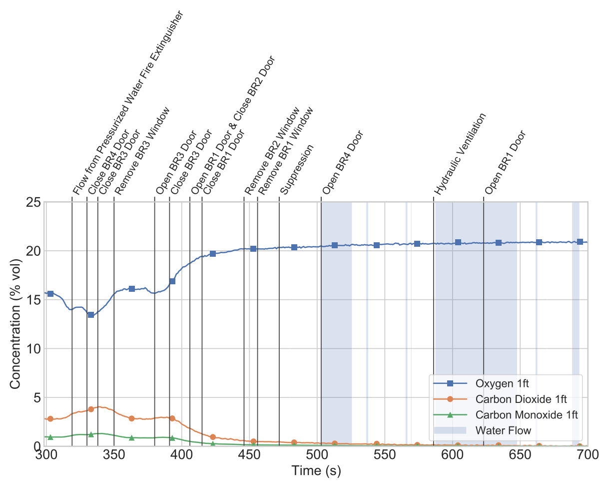
Bathroom gas concentrations at the time of first intervention were 14.0% O_2, 3.3% CO_2, and 1.1% CO, which indicated that the smoke layer had descended below the 1 ft level (Figure 5.109c). Gas concentrations within the bathroom worsened to 13.4% O_2, 4.0% CO_2, and 1.3% CO. Gas concentrations improved after the bedroom 3 door was isolated, which stopped the flow of combustion gases into the bathroom. Bidirectional flow through the open bedroom 3 window improved gas concentrations to 20.8% O_2, 0.1% CO_2, and 0% CO.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

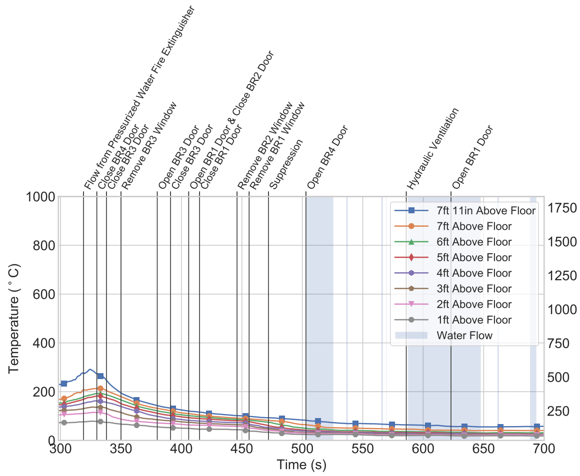
Figure 5.109: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 7.

5.7.5 Bedroom 2

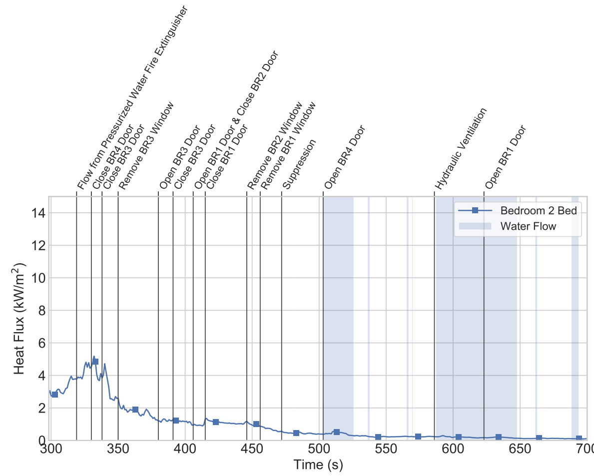
The bedroom 2 door was opened prior to ignition, which allowed higher-pressure, higher-temperature combustion gases to flow from the fire room to the lower-temperature, lower-pressure bedroom. At the time of first intervention, temperatures in the center of bedroom 2 exceeded 280 °C (536 °F), as shown in Figure 5.110a. Flaming combustion in the hallway was extinguished with a pressurized water fire extinguisher, which cooled local combustion gases. As cooler combustion gases flowed into bedroom 2, bedroom 2 ceiling temperatures decreased. Closure of the bedroom 4 door stopped the flow of combustion gases from the fire room to the hallway. However, accumulated combustion gases continued to flow throughout the structure. As cooler combustion gases flowed into bedroom 2, temperatures decreased. Closure of the bedroom 2 door stopped the flow of combustion gases from the hallway into the bedroom; as a result, bedroom 2 temperatures continued to decease. The bedroom 2 window was removed, which created a exterior vent in the bedroom. A flow path established between the bedroom and the exterior. Cool air entrained through the window, which decreased temperatures 5 ft above the floor. The bedroom 2 door remained closed during suppression and hydraulic ventilation, but bidirectional flow through the window decreased temperatures below 55 °C (131 °F).

Heat flux had increased to 3.8 kW/m^2 at the time of intervention, as shown in Figure 5.110b. Water flow in the hallway cooled combustion gases that flowed into bedroom 2, which decreased the heat flux from 5.2 kW/m^2 to 3.7 kW/m^2. Isolation the fire room stopped the flow of higher-pressure combustion gases into the hallway, however existing flows within the structure continued. Cooler combustion gases flowed into bedroom 2, which decreased heat flux to 0.9 kW/m^2. Isolation of bedroom 2 stopped the flow of combustion gases from the hallway into the bedroom, which further decreased heat flux. The removal of the bedroom 2 window created an exterior vent within the bedroom. Accumulated combustion gases flowed toward and through the open window and a flow path between the bedroom and the exterior established. Bidirectional flow through the open window lifted the smoke layer and heat flux decreased below 0.1 kW/m^2.

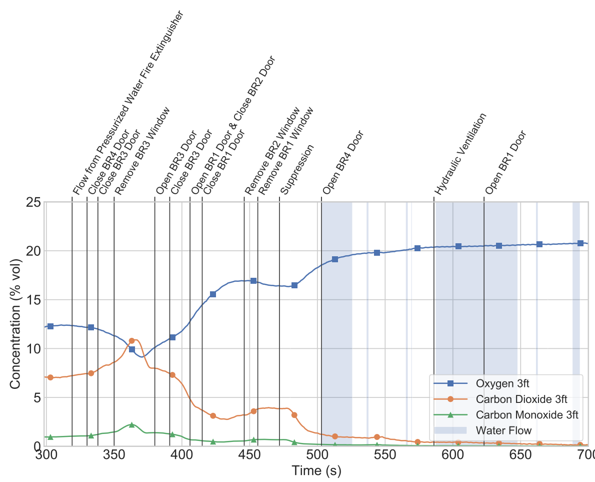
Gas concentrations at the bed were 12.4% O_2, 7.1% CO_2, and 1.0% CO at the time of intervention, as shown in Figure 5.110c. Flaming combustion in the hallway was extinguished with a pressurized water fire extinguisher, which cooled temperatures in bedroom 2. Combustion gases in bedroom 2 dropped in elevation as they cooled, which caused gas concentrations to worsen to 9.1% O_2, 10.9% CO_2, and 2.2% CO. As the products of combustion gases in the hallway fire decreased, gas concentrations improved. Isolation of bedroom 4 stopped the flow of combustion gases from the fire room to bedroom 2, which improved the CO_2 concentration. The removal of the bedroom 2 window created an exterior vent in the bedroom. Combustion gases flowed toward and through the vent, which caused gas concentrations to become steady. Bidirectional flow through the open window lifted the smoke layer, which improved gas concentrations to 20.6% O_2, 0.3% CO_2, and 0% CO.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



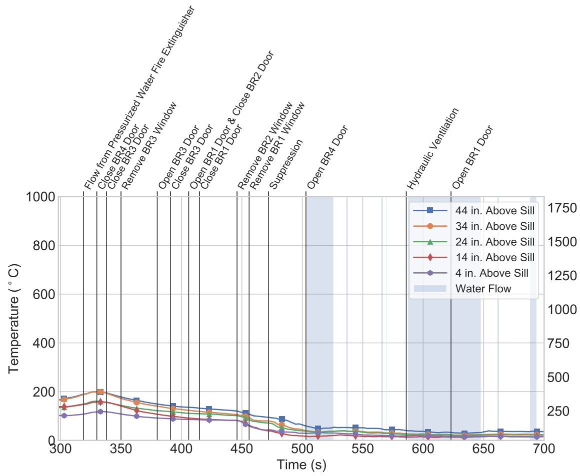
(c) Bedroom 2 Gas Concentration

Figure 5.110: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 7.

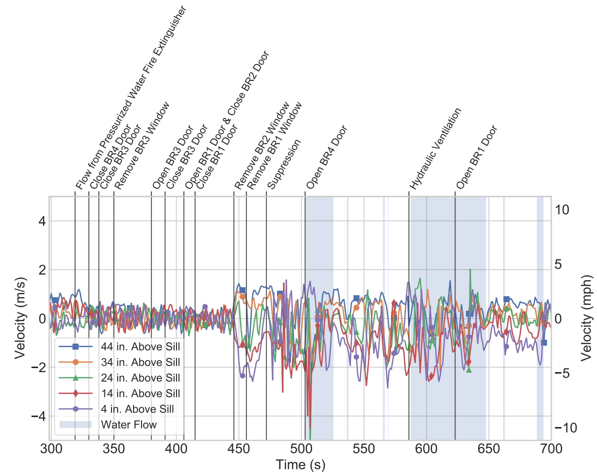
Bedroom 2 window temperatures were consistent with temperatures in the center of the bedroom at the time of intervention and ranged from 190 °C to 110 °C (374 °F to 230 °F), as shown in Figure 5.111a. Following a similar trend, window temperatures decreased after flaming combustion in the hallway was extinguished. Temperatures gradually decreased below 120 °C (248 °F). Flow through the removed bedroom 2 window further decreased window temperatures, as combustion gases exhausted at 1.4 m/s (3.1 mph) and air entrained -2.4 m/s (-5.4 mph) (Figure 5.111b). Bidirectional flow through the window decreased temperatures below 40 °C (104 °F).

At the time of intervention, heat flux below the bedroom 2 window was 4.6 kW/m^2 3 ft above the floor and 3.2 kW/m^2 1 ft above the floor, as shown in Figure 5.111c. Heat flux 3 ft above the floor peaked to 8.5 kW/m^2 as combustion gases flowed into the open bedroom. Heat flux 1 ft above the floor was steady near 3.0 kW/m^2, as the smoke layer had not fully descended. Isolating the fire room limited the flow of combustion gases to open volumes of the structure and heat flux below the window decreased. Heat flux continued to decrease as the bedroom 2 door was isolated, but it decreased more quickly as the bedroom 2 window was removed. Bidirectional flow exhausted combustion gases and entrained cool air into the bedroom. Heat flux 3 ft above the floor decreased from 1.0 kW/m^2 to 0 kW/m^2 in 6 s. Heat flux 1 ft above the floor decreased below 0.1 kW/m^2 post hydraulic ventilation.

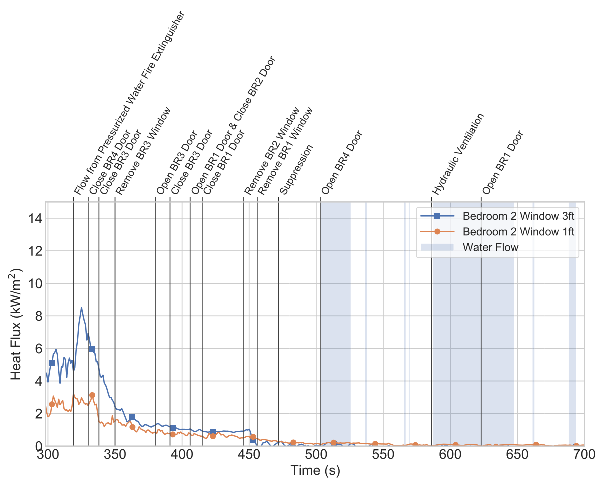
At the time of first intervention, gas concentrations below the window were 12.4% O_2, 7.1% CO_2, and 1.0% CO 3 ft above the floor and 14.3% O_2, 5.4% CO_2, and 0.8% CO 1 ft above the floor (Figure 5.111d). Following a similar trend to gas concentrations on the bed, gas concentrations worsened to 9.2% O_2, 10.5% CO_2, and 2.2% CO 3 ft above the floor and 12.9% O_2, 7.1% CO_2, and 1.3% CO 1 ft above the floor, following hallway suppression. As the production of combustion gases from the hallway fire decreased and the fire room was isolated, gas concentrations improved. Bidirectional flow through the open bedroom 2 window lifted the smoke layer in the bedroom. Gas concentrations improved to 20.8% O_2, 0.1% CO_2, and 0% CO 3 ft and 1 ft above the floor.



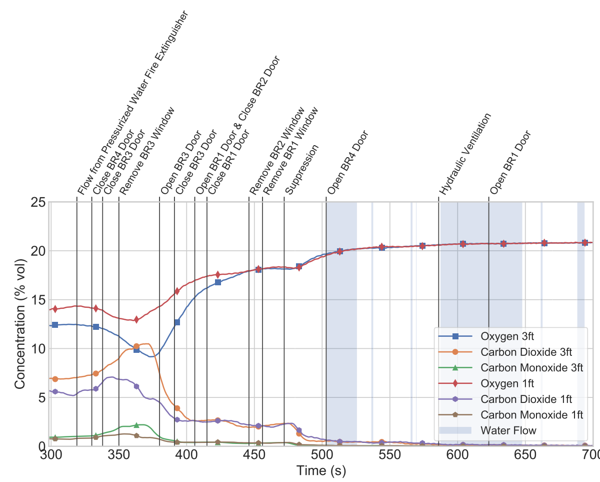
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

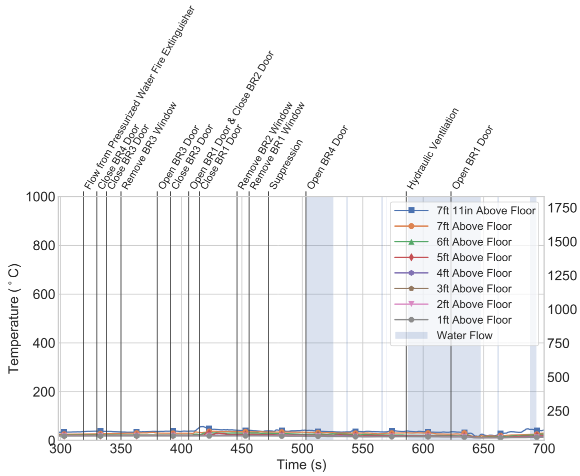
Figure 5.111: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 7.

5.7.6 Bedroom 1

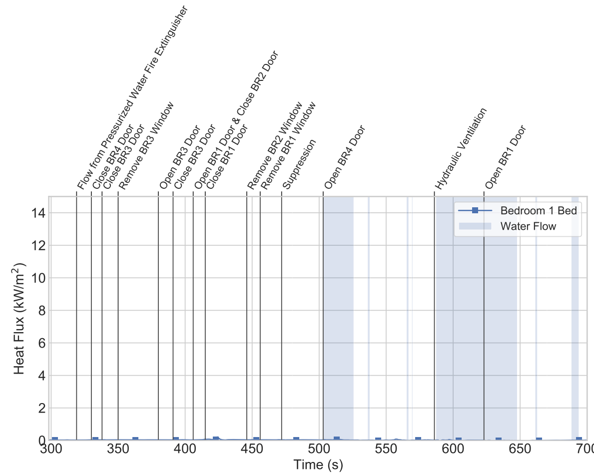
The bedroom 1 door was closed prior to ignition. The closed bedroom 1 door prevented the flow of higher-temperature, higher-pressure combustion gases from the fire room into the lower-temperature, lower-pressure bedroom. However, higher-pressure combustion gases flowed through the leakage area around the closed door and through the HVAC supply vents. Bedroom 1 temperatures at the time of first intervention ranged from 40 °C (104 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor, as shown in Figure 5.112a. The bedroom 1 door was opened, which allowed higher-pressure combustion gases to flow from the hallway into the lower-pressure bedroom. Ceiling temperatures peaked to 60 °C (140 °F) and temperatures nearest the floor remained approximately 20 °C (68 °F). Closure of the bedroom 1 door stopped the flow of combustion gases from the hallway into the bedroom, which decreased bedroom temperatures. The removal of the bedroom 1 window created an exterior vent. Accumulated combustion gases flowed toward and through the window and a flow path between the bedroom and the exterior established. Ceiling temperatures decreased from 40 °C to 35 °C (104 °F to 95 °F) in 167 s. The bedroom 1 door was opened during hydraulic ventilation, which caused gases to flow toward the lower-pressure fire room. Ceiling temperatures decreased from 35 °C to 25 °C (95 °F to 77 °F) in 24 s.

Heat flux to the bed was 0 kW/m^2 at the time of fire department intervention, as shown in Figure 5.112b. Combustion gases flowed into the bedroom after the door was opened, however due to the low temperature of the bedroom, heat flux increase was minimal.

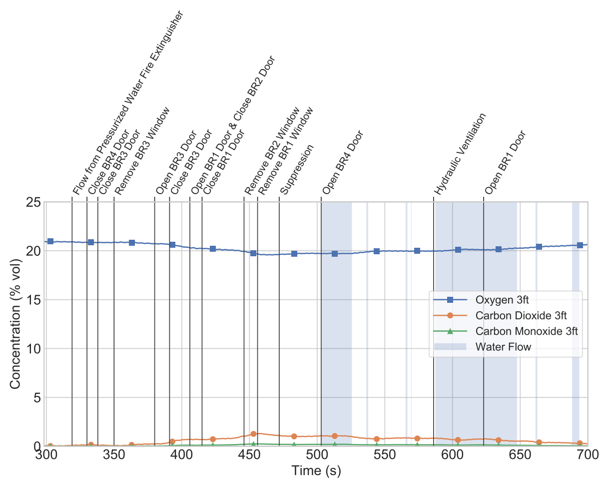
Gas concentrations at the bed were 20.9% O_2, 0.1% CO_2, and 0% CO at the time of intervention, as shown in Figure 5.112c. Similar to heat flux, gas concentrations did not increase until after the bedroom 1 door was opened and peaked to 19.6% O_2, 1.3% CO_2, and 0.2% CO. The closed bedroom 1 door prevented further accumulation of combustion gases in the bedroom. Bidirectional flow through the open window improved gas concentration to pre-ignition conditions, which minimized the impact of opening the door during hydraulic ventilation.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



(c) Bedroom 1 Gas Concentration

Figure 5.112: Post-intervention bed level temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 7.

The bathroom 1 door was opened prior to ignition, which allowed gas flow between bedroom 1 and bathroom 1. Higher-pressure combustion gases flowed through the HVAC vents into bathroom 1, which increased bathroom temperatures to 35 °C (95 °F) at the ceiling and 20 °C (68 °F) 1 ft above the floor at the time of intervention (Figure 5.113). The bathroom was adjacent to, but not part of the flow path established between the hallway and the bedroom, which minimized temperature increase to 40 °C (104 °F), after the bedroom 1 door was opened.

Similarly, the closure of the bedroom 1 door minimally impacted temperature decrease. The bathroom was also adjacent to, but not part of the flow path between the bedroom and the exterior. Bidirectional flow decreased temperatures 6 ft and below, however flow through the HVAC supply vents continued to increase ceiling temperatures. Suppression in the fire room caused additional flow through the HVAC supply vents, which increased ceiling temperatures to 50 °C (122 °F) post-suppression. The bathroom was two rooms removed from the flows caused by hydraulic ventilation, which minimized the impact of hydraulic ventilation.

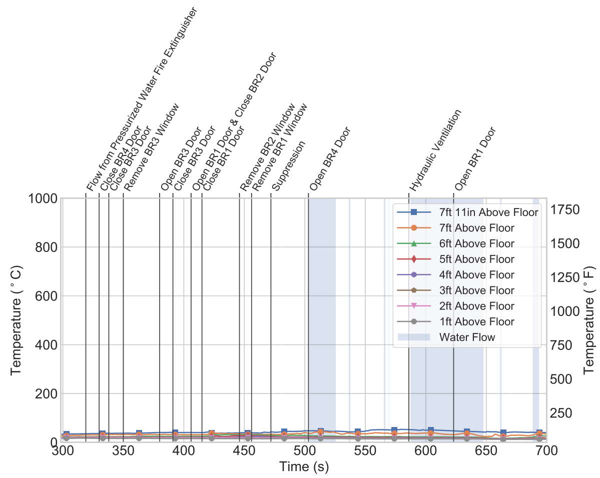


Figure 5.113: Post-intervention temperatures in bathroom 1 during Experiment 7.

5.8 Experiment 8

The search tactics in Experiment 8 were designed to evaluate window initiated operations following fire room door control conducted before suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide, bedroom 4 window were removed. The front door to the structure, doors to bedroom 4, bedroom 3, bedroom 2, bathroom 3, and bathroom 1 were open. The door to bedroom 1 was closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 flashover, the crew on side C of the structure ventilated half of the double-wide window in bedroom 3. The crew entered bedroom 3 and proceeded toward the hallway door. The crew was unable to close the bedroom 3 door. The crew crossed the hallway and closed the bedroom 4 door. The crew proceeded down the hall toward bedrooms 1 and 2. The crew split to enter both bedrooms. Simultaneously, the door to bedroom 1 was opened and the door to bedroom 2 was closed. The bedroom 1 door was closed after the crew entered the bedroom. The double-wide window in each bedroom was removed. At this point, the search tactic comparison was complete. The suppression crew entered the structure through the front door, flowing water as needed to advance to the fire room. The suppression crew began flowing water as the fire room door was opened. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed bedroom 4 window. 75 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 275 gallons. Table 5.15 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was ventilation of half the bedroom 3 double-wide window.

Table 5.15: Experiment 8 Event Times

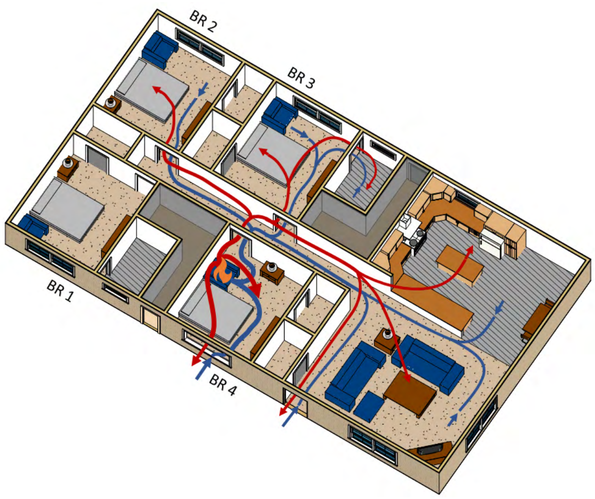
Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Ignition	00:00	0	—	—
Take BR3 Window	04:45	285	00:00	0
Close BR4 Door	05:30	330	00:45	45
Open BR1 Door, Close BR2 Door	05:48	348	00:57	57
Close BR1 Door	05:59	359	01:09	69
Remove BR2 Window	06:28	388	01:25	85
Remove BR1 Window	06:37	397	01:25	85
Suppression	06:58	418	01:40	100
Open BR4 Door	07:38	458	02:20	140
Hydraulic Ventilation	09:23	553	03:57	237

Figures 5.114 through 5.116 show the changes in flows during the time period immediately preceding and following fire department intervention over the duration of Experiment 8. At the time of intervention, the bedroom 4 fire was in a post-flashover state. Lower-pressure, lower-temperature air was entrained and higher-temperature, higher-pressure combustion gases were exhausted through

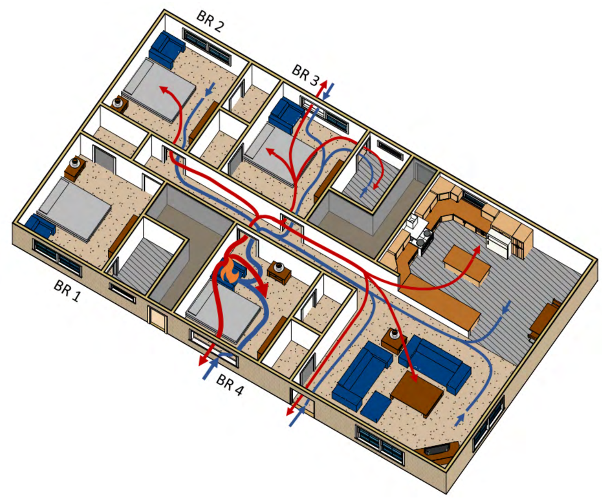
the open bedroom 4 vents (Figure 5.114a). Flow paths were established between the fire room and lower-pressure open volumes of the structure and exterior of the structure.

The first intervention was the ventilation of half the double-wide bedroom 3 window, which created an exterior vent. Higher-pressure combustion gases accumulated in bedroom 3 and bathroom 3 flowed toward and through the vent to the exterior of the structure (Figure 5.114b).

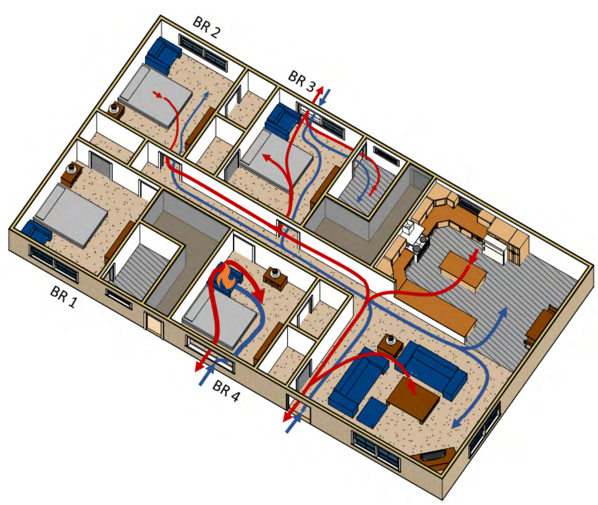
The bedroom 4 door was closed 45 s later, which stopped the flow of higher-pressure combustion gases from the fire room to the lower-pressure, open volumes of the structure (Figure 5.114c). However, previously accumulated combustion gases continued to drive gas flows throughout the structure.



(a) Flows Prior to Intervention



(b) Take BR3 Window

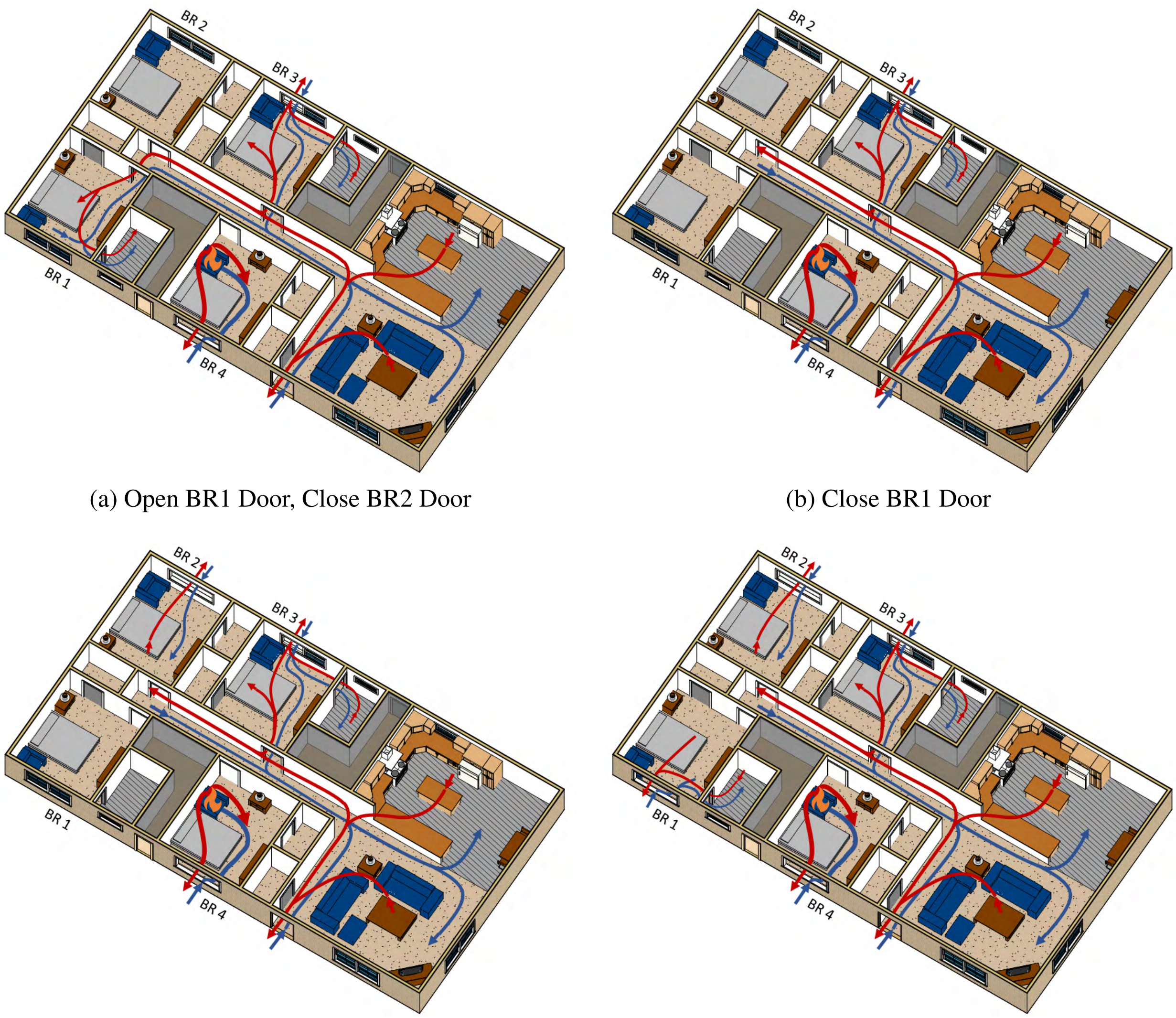


(c) Close BR4 Door

Figure 5.114: Changes in flow in structure following fire department interventions in Experiment 8.

The search crew continued down the hallway to bedrooms 1 and 2. The crew split and simultaneously opened the bedroom 1 door and closed the bedroom 2 door, as shown in Figure 5.115a. The open bedroom 1 door allowed higher-pressure combustion gases and lower-pressure air to exchange between the hallway and bedroom. The closed bedroom 2 door isolated the bedroom from the flow of combustion gases from the hallway. The crew closed the bedroom 1 door after entry into the space, which similarly isolated the bedroom from the flow of combustion gases from the hallway (Figure 5.115b).

The crew in bedroom 2 removed the window, which created an exterior vent, as shown in Figure 5.115c. Higher-pressure combustion gases that had accumulated in bedroom 2 when the door was open flowed toward the lower-pressure exterior. The crew in bedroom 1 removed the window, which also created an exterior vent, as shown in Figure 5.115d. Similarly, higher-pressure combustion gases that had accumulated in bedroom 1 when the door was open flowed toward the lower-pressure exterior.



(a) Open BR1 Door, Close BR2 Door

(b) Close BR1 Door

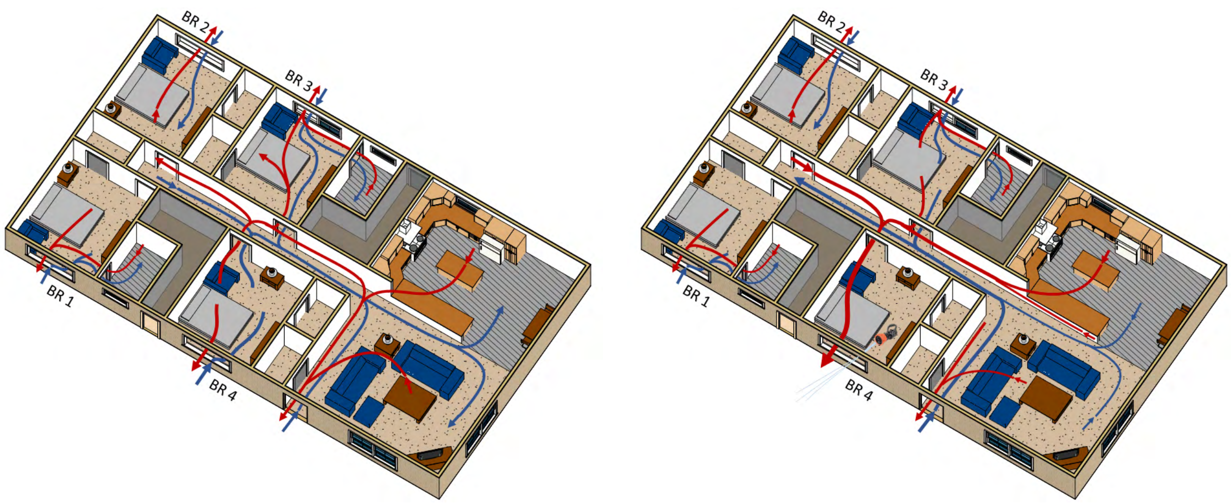
(c) Remove BR2 Window

(d) Remove BR1 Window

Figure 5.115: Changes in flow in structure following fire department interventions in Experiment 8.

Interior suppression was conducted with a combination nozzle set to flow a straight stream at 150 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline (Figure 5.116a). The suppression crew advanced down the hallway, flowing as needed, and opened the bedroom 4 door. The open bedroom 4 door allowed higher-pressure combustion gases to flow from the fire room to lower-pressure, open volumes of the structure. Suppression began immediately as the door was opened. The fire was extinguished and the production of higher-temperature, higher-pressure combustion gases stopped. However, existing gases continued to flow throughout the structure.

Hydraulic ventilation occurred out of the failed, bedroom 4 window with a straight stream in an O-pattern (Figure 5.116b). An area of low pressure was created in the fire room, which caused unidirectional flow from open volumes (bedroom 3, hallway, and common space) through the bedroom 4 vents toward the exterior of the structure. Closed volumes of the structure (bedroom 1, bedroom 2, and bedroom 3) were minimally impacted by hydraulic ventilation.



(a) Suppression

(b) Hydraulic Ventilation

Figure 5.116: Changes in flow in structure following fire department interventions in Experiment 8.

5.8.1 Bedroom 4

The bedroom 4 fire transitioned through flashover approximately 185 s post-ignition. Although temperatures were declining, fire room temperatures indicated a post-flashover state at the time of intervention. Bedroom 4 temperatures ranged from 900 °C (1652 °F) at the ceiling to 580 °C (1076 °F) 1 ft above the floor, as shown in Figure 5.118a.

Ventilation of half the bedroom 3 window created an exterior vent in bedroom 3. Higher-pressure combustion gases flowed from the fire room toward bedroom 3 along the flow path created between the fire room and the exterior. For approximately 20 s, the wind, with an average velocity of 7.6 m/s (17.0 mph) and gusts of 12.6 m/s (28.2 mph), caused flow through the bedroom 4 window to become unidirectional intake and flow through the bedroom 3 window to become unidirectional exhaust. Inflow through the bedroom 4 window was indicated by retreating window flames in Figures 5.117a through 5.117b. The available oxygen for combustion in the fire room increased, which increased the heat release rate of the bedroom 4 fire. Bedroom 4 temperatures exceeded 1010 °C (1850 °F).

As wind velocities slowed, bidirectional flow through the bedrooms 3 and 4 windows established, as indicated by exhaust flow from the bedroom 4 window (Figure 5.117c). The available oxygen for combustion in the fire room decreased, which decreased the heat release rate of the bedroom 4 fire. Bedroom 4 temperatures decreased to to approximately 830 °C (1526 °F).

(a) Take BR3 Window

(b) 19 s post Take BR3 Window

(c) 19 s post Take BR3 Window

Figure 5.117: Changes in flow through the bedroom 4 window following ventilation of bedroom 3 window in Experiment 8.

The crew closed the bedroom 4 door. Bidirectional flow through the bedroom 4 doorway stopped, which minimized the heat loss from the bedroom to open volumes of the structure. Fire room temperatures increased and exceeded 950 °C (1742 °F).

The suppression crew entered the structure through the front door and advanced to the fire room, flowing as needed in the hallway. The fire room door was opened approximately 459 s post-ignition and the suppression crew immediately began flowing water. Suppression extinguished the bedroom 4 fire and temperatures in the fire room decreased below 90 °C (194 °F). Two additional water flows in the bedroom decreased temperatures below 70 °C (158 °F). Hydraulic ventilation created an area of lower pressure in the fire room, which caused higher-pressure combustion gases and cool air to flow through the bedroom 4 vents to the exterior of the structure. Suppression damaged the thermocouple array in the fire room, which impacted measurement accuracy. As a result, temperatures recorded during hydraulic ventilation in bedroom 4 are not an accurate representation of the temperatures in the room at that time.

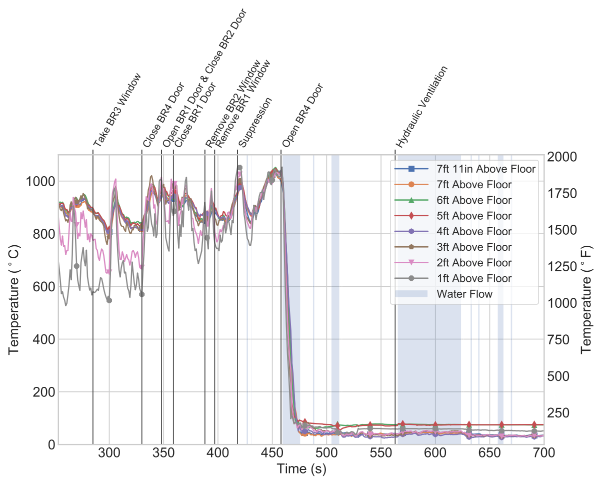
The bedroom 4 closet door was closed prior to ignition. The door burned through approximately 190 s post-ignition, which allowed higher-temperature, higher-pressure combustion gases to flow into the closet. Temperatures ranged from 680 °C (1256 °F) at the ceiling to 265 °C (509 °F) 1 ft above the floor at the time of intervention (Figure 5.118b). The temporary wind-driven unidirectional intake through the bedroom 4 window resulted in a brief spike in closet temperatures. The closet was adjacent to the fire room flow paths and partially isolated due to the remnants of the closet door, which limited temperature increase in the closet. Temperatures in the closet gradually increased until suppression.

Initial suppression cooled combustion gases in the closet below 450 °C (842 °F), while additional water flows decreased temperatures below 300 °C (572 °F). The closet was adjacent to the flows caused by hydraulic ventilation and lacked a local exterior vent, which minimized the impact of hydraulic ventilation on temperature as temperatures only reduced below 180 °C (356 °F).

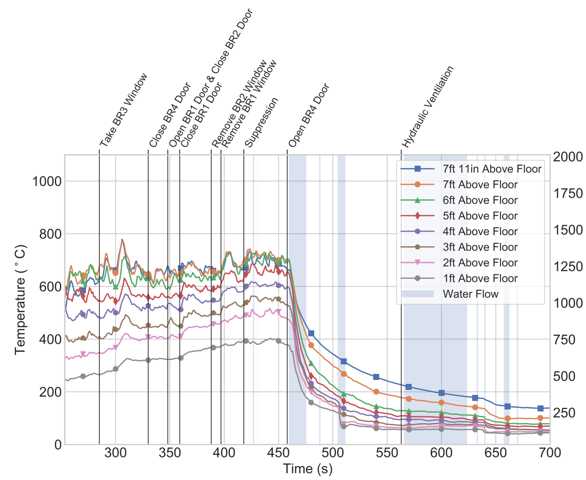
At the time of intervention, bedroom 4 doorway temperatures ranged from 720 °C (1328 °F) 76 in. above the floor to approximately 460 °C (860 °F) 4 in. above the floor, as shown in Figure 5.118c. Bidirectional flow through the doorway exhausted combustion gases into the hallway at 2.7 m/s (6.0 mph) 76 in. to 58 in. above the floor and entrained air to the fire room at -3.1 m/s (-6.9 mph) 40 in. to 4 in. above the floor, as shown in Figure 5.118d. Wind-driven flow following bedroom 3 window ventilation increased the combustion gas flow into the hallway. Exhaust through the doorway increased temperatures 40 in. to 22 in. above the floor to 690 °C and 595 °C (1274 °F and 1103 °F), respectively.

Similar to bedroom 4 temperatures, doorway temperatures increased following bedroom 4 isolation. Without air entrainment into the bedroom, doorway temperatures 22 in. to 4 in. above the floor increased. Data recorded from bidirectional probes during the time the door was closed are not representative of flow through the doorway.

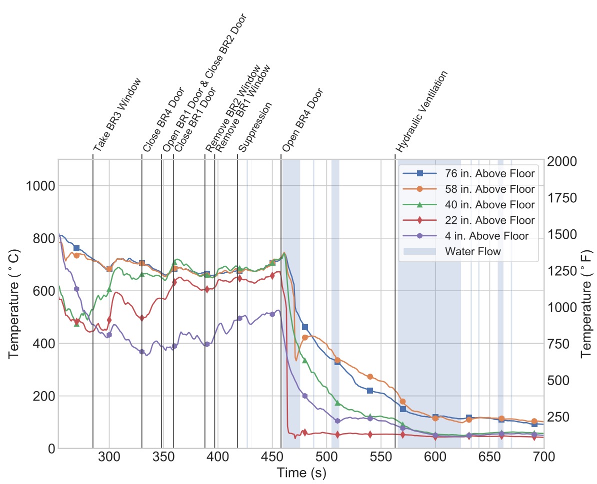
The bedroom 4 door was opened and suppression began immediately. Initial suppression decreased doorway temperatures below 490 °C (914 °F). Additional water flows and bidirectional flow through the doorway decreased temperatures below 330 °C (626 °F). Hydraulic ventilation caused flow through the bedroom 4 vents to become unidirectional toward the exterior as gases exhausted at -1.0 m/s (-2.2 mph). Doorway temperatures decreased below 115 °C (239 °F).



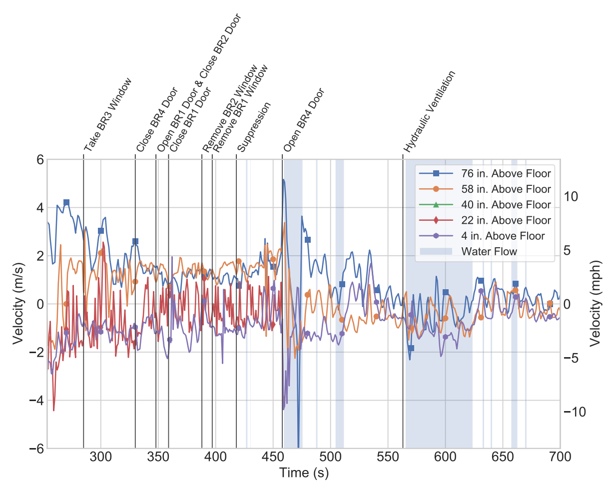
(a) Bedroom 4 Temperature



(b) Closet Temperature



(c) Bedroom 4 Doorway Temperature



(d) Bedroom 4 Doorway Velocity

Figure 5.118: Temperature and velocity time histories in bedroom 4 in post-intervention period during Experiment 8.

5.8.2 Bedroom 3

The bedroom 3 door was opened prior to ignition, which allowed higher-pressure combustion gases to flow from the fire room into the lower-pressure bedroom. At the time of intervention, bedroom 3 window temperatures ranged from 220 °C (428 °F) 44 in. above the sill to 105 °C (221 °F) 4 in. above the sill (Figure 5.119a). Ventilation of half the bedroom 3 window created an exterior vent, which caused fire room combustion gases to flow into the bedroom.

Wind through the side A, bedroom 4 window resulted in unidirectional exhaust flow (velocity of 5.5 m/s (12.3 mph)) through the bedroom 3 window for approximately 20 s, as shown in Figure 5.119b. Window temperatures exceeded 400 °C (752 °F) 44 in. above the sill and 175 °C (347 °F) 4 in. above the sill. As wind-driven flows within the structure slowed, bidirectional flow established through the window. Cool air entrained into the bedroom at -2.7 m/s (6.0 mph), which decreased window temperatures to 80 °C (176 °F) 4 in. above the sill. Combustion gases exhausted from the bedroom at 4.1 m/s (9.2 mph), which increased temperatures 44 in. above the sill to 425 °C (797 °F).

The closed bedroom 4 door stopped the flow of higher-pressure combustion gases from the fire room into the lower-pressure bedroom, which limited further accumulation of combustion gases. Bidirectional flow through the bedroom 3 window continued and window temperatures decreased.

The open bedroom 4 door allowed combustion gases to flow from the fire room to the bedroom. However, suppression increased air inflow through the bedroom 3 window, which decreased window temperatures. As the crew moved into the fire room for final extinguishment and stopped flowing water, gas flow through the bedroom 3 window became unidirectional exhaust at 3.2 m/s (7.2 mph). Combustion gas flow through the window increased window temperatures 24 in. to 4 in. above the sill. Hydraulic ventilation created an area of lower pressure in the fire room, which caused unidirectional inflow through the bedroom 3 window at -3.6 m/s (-8.1 mph). Window temperatures decreased below 80 °C (176 °F).

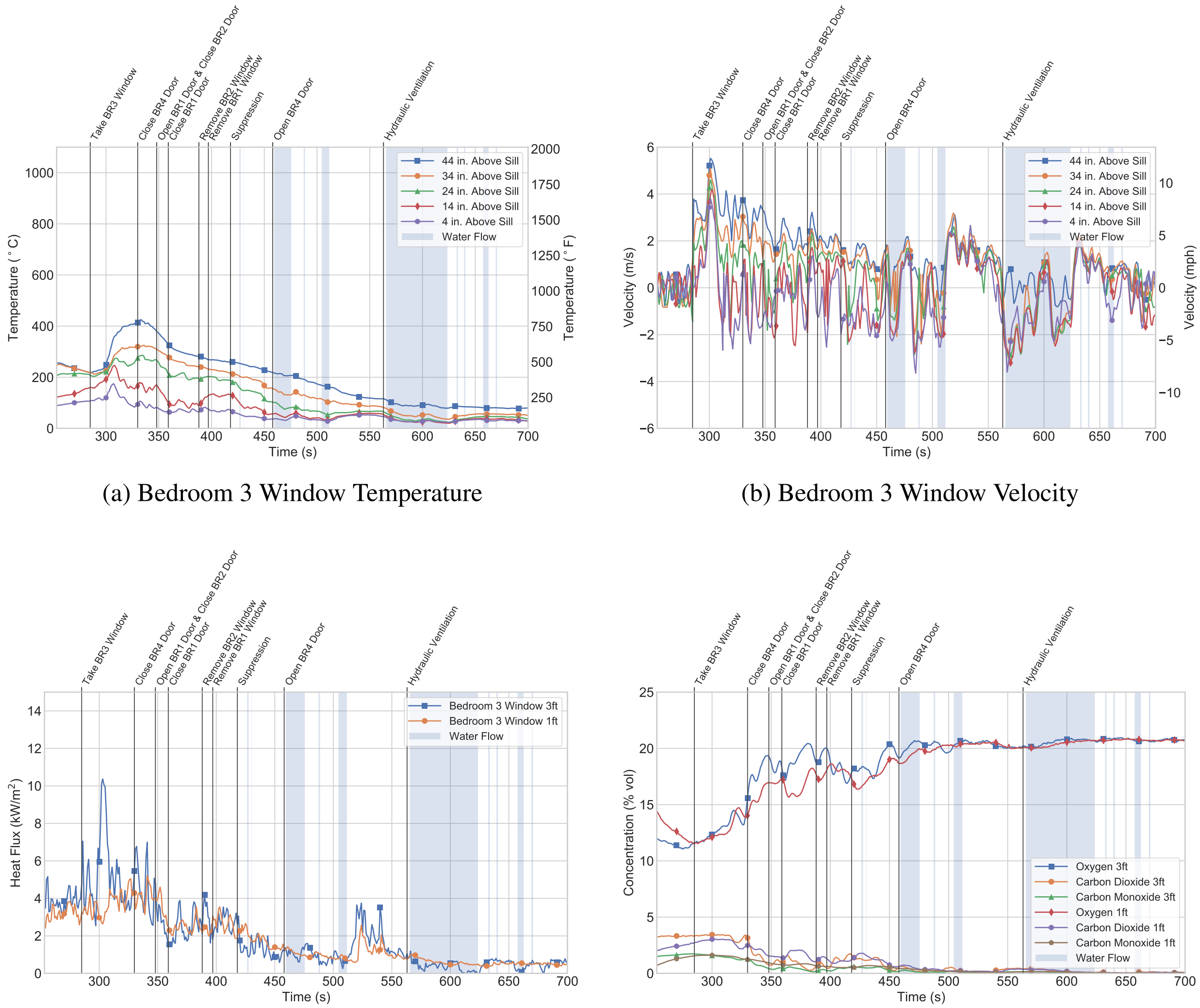
At the time of intervention, heat flux below the bedroom 3 window was 7.1 kW/m^2 3 ft above the floor and 3.2 kW/m^2 1 ft above the floor, which indicated that the smoke layer had descended below the 1 ft level in bedroom 3 (Figure 5.119c). Following bedroom 3 window ventilation, wind-driven flows within the structure increased the combustion gas flow from the fire room to open volumes of the structure. Heat flux 3 ft above the floor peaked to 10.4 kW/m^2. As wind driven flows decreased, bidirectional flow through the window established, which decreased heat flux 3 ft above the floor to 4.4 kW/m^2.

Isolation of the fire room stopped the flow of combustion gases from the fire room to bedroom 3, which limited further accumulation of combustion gases in the space. Bidirectional flow through the window continued and lifted the smoke layer, which decreased heat flux.

Fire room suppression increased the air entrainment through the bedroom 3 window. Entrained air cooled combustion gases in bedroom 3, which decreased heat flux below the window to 2.0 kW/m^2. Post-suppression, combustion gases flowed toward the exterior vent, which increased heat flux to 3.7 kW/m^2 and 2.6 kW/m^2, respectively. The influx of cool air during hydraulic ventilation decreased heat flux below 0.8 kW/m^2.

At the time of intervention, gas concentrations below the bedroom 3 window were 11.6% O_2, 3.3% CO_2, and 1.7% CO 3 ft above the floor and 11.6% O_2, 2.7% CO_2, and 1.5% CO 1 ft above the floor (Figure 5.119d), which indicated that the smoke layer had descended below the 1 ft level. The ventilated bedroom 3 window allowed wind-driven flows within the structure to increase the combustion gas and air flow into bedroom 3. Although flow through the bedroom 3 window was unidirectional exhaust, gas concentrations below the window improved. As wind-driven flows decreased, bidirectional flow established through the window, which further improved gas concentrations below the bedroom 3 window.

The closed bedroom 4 door stopped the flow of combustion gases from the fire room into bedroom 3. Previously accumulated combustion gases continued to drive bidirectional flow through the window, which further improved gas concentrations. During suppression, air entrainment through the bedroom 3 window prevented gas concentrations below the window from worsening. Post-suppression, combustion gases dropped in elevation as they cooled and flowed toward the exterior vent in bedroom 3, which worsened gas concentrations below the window. Air entrainment through the bedroom 3 window during hydraulic ventilation improved gas concentrations to approximately 20.8% O_2, 0.1% CO_2, and 0.1% CO at both the 3 ft and 1 ft levels.



(a) Bedroom 3 Window Temperature

(b) Bedroom 3 Window Velocity

(c) Bedroom 3 Window Heat Flux

(d) Bedroom 3 Window Gas Concentration

Figure 5.119: Post-intervention window temperature, heat flux, and gas concentrations in bedroom 3 during Experiment 8.

At the time of intervention, bedroom 3 temperatures ranged from 260 °C (500 °F) at the ceiling to 70 °C (158 °F) 1 ft above the floor, as shown in Figure 5.120. The ventilated bedroom 3 window created a flow path between the fire room and the exterior. Wind-driven flows through the bedroom 4 window increased combustion gas flow from the fire room into bedroom 3. Bedroom temperatures exceeded 600 °C (1112 °F). Bedroom 3 temperatures decreased following fire room isolation, as bidirectional flow through the bedroom 3 window lifted the smoke layer.

During suppression, increased entrainment through the ventilated bedroom 3 reduced bedroom temperatures. Post-suppression, fire room combustion gases flowed toward the exterior vent in bedroom 3, which increased bedroom temperatures below 5 ft. The area of low pressure created by hydraulic ventilation caused unidirectional inflow through the bedroom 3 window. Temperatures decreased below 110 °C (230 °F).

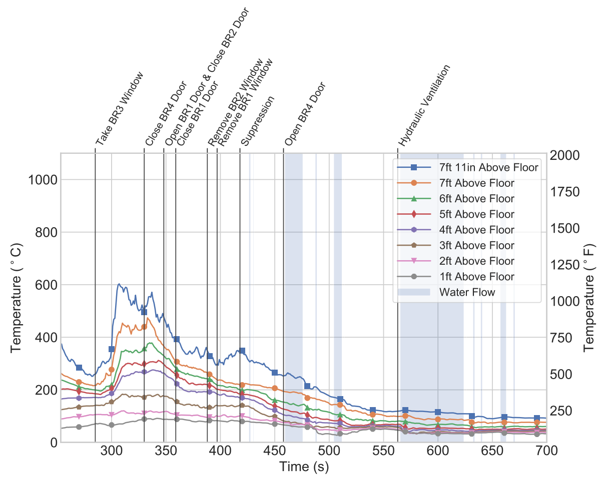


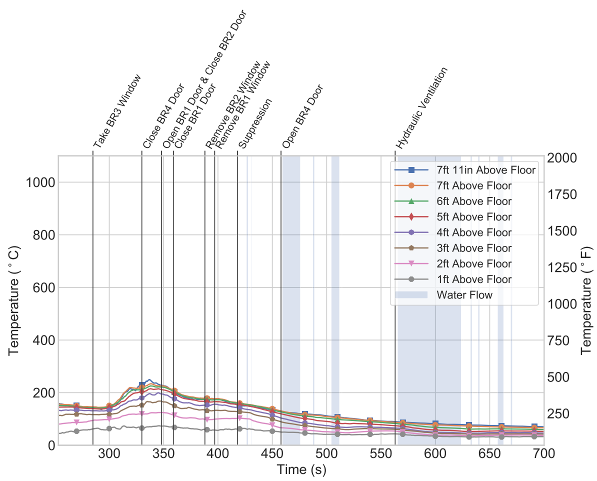
Figure 5.120: Post-intervention temperature in bedroom 3 during Experiment 8.

The bathroom 3 door was opened prior to ignition, which allowed higher-pressure, higher-temperature combustion gases to flow from the fire room to the lower-temperature, lower-pressure bathroom. At the time of intervention, bathroom temperatures ranged from 145 °C (293 °F) at the ceiling to 60 °C (140 °F) 1 ft above the floor, as shown in Figure 5.121a. Bathroom temperature increase was less than bedroom temperature increase, as the bathroom was adjacent to, but not part of the flow paths established through bedroom 3. Wind through the side A bedroom 4 window resulted in additional combustion gas flow into the bathroom. Temperatures exceeded 250 °C (482 °F).

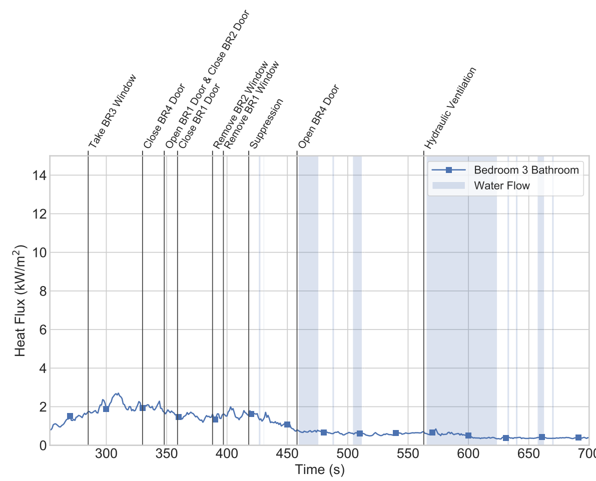
Fire room isolation prevented further accumulation of combustion gases in bedroom 3. Bidirectional flow through the bedroom 3 window reduced bathroom temperatures. During suppression, flow through the bedroom 3 window was bidirectional, which decreased bathroom temperatures. Initial suppression decreased temperatures below 120 °C (248 °F), while additional water flows decreased temperatures below 90 °C (194 °F). Post-suppression flow through the window was unidirectional exhaust, which caused temperatures nearest the floor to increase. The bathroom was adjacent to the flows caused by hydraulic ventilation, which limited temperature decrease to 80 °C (176 °F).

At the time of intervention, heat flux 1 ft above the bathroom floor was 1.8 kW/m^2, as shown in Figure 5.121b. Wind through the side A bedroom 4 window caused combustion gas flow toward the ventilated bedroom 3 window, which increased heat flux in the bathroom to 2.7 kW/m^2. Closing the bedroom 4 door stopped the flow of combustion gases into the bedroom and bathroom. Bidirectional flow established through the window and lifted the smoke layer. Heat flux in the bathroom decreased. Bidirectional flow during suppression exhausted combustion gases and entrained cool air into the bathroom, which further decreased heat flux. Unidirectional inflow through the bedroom 3 window during hydraulic ventilation caused air to flow into the bathroom. As the smoke layer exhausted, heat flux decreased below 0.4 kW/m^2.

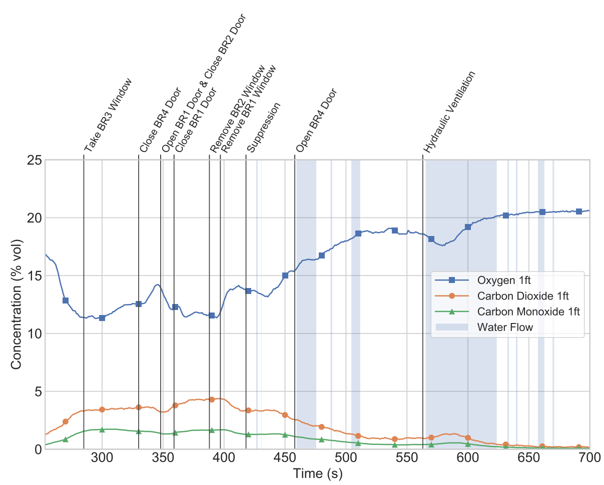
Gas concentrations 1 ft above the bathroom 3 floor were 11.4% O_2, 3.3% CO_2, and 1.6% CO at the time of intervention, which indicated that the smoke layer had descended past the 1 ft elevation (Figure 5.121c). Wind-driven flows within the structure increased combustion gas flow into bedroom 3, which caused gas concentrations to worsen. Bidirectional flow during suppression entrained air into the bathroom, which improved gas concentrations to 19.9% O_2, 0.9% CO_2, and 0.1% CO. Unidirectional inflow during hydraulic ventilation caused air to flow into the bathroom. Gas concentrations improved to 20.4% O_2, 0.5% CO_2, and 0.1% CO.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

Figure 5.121: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 8.

5.8.3 Hallway

Figures 5.122a through 5.122d show the temperature time history for each hallway location. At the time of intervention, hallway temperatures were a function of proximity to the fire room. Temperatures at the mid hallway location were the greatest, followed by the end hallway, start hallway, and living room entryway locations. The open front door combined with the large volume of the common space limited the accumulation of combustion gases in the kitchen and living room. Additionally, entrainment through the front door cooled gases through mixing. Living room entryway temperatures were generally less than the start hallway, mid hallway, and end hallway locations.

Ventilation of the bedroom 3 window established a new flow path between the fire room and the exterior. Wind through the side A bedroom 4 window resulted in increased combustion gas flow from the fire room into the hallway. Hallway temperatures exceeded 715 °C (1319 °F), 600 °C (1112 °F), and 590 °C (1094 °F) at the mid hallway, start hallway, and end hallway locations, respectively.

Isolation of bedroom 4 stopped the flow of combustion gases from the fire room to open volumes of the structure, which caused hallway temperatures to decrease. However, flaming combustion spread down the hallway toward bedroom 3 and the common space, which caused start hallway temperatures nearest the floor to increase.

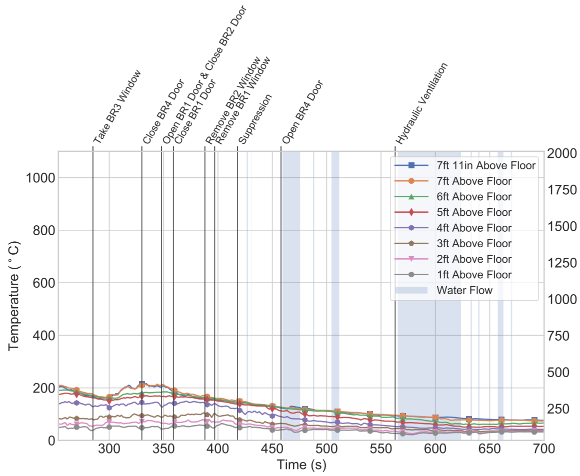
The open bedroom 1 door allowed gases to exchange between the bedroom and hallway. An influx of cool air into the hallway decreased temperatures below 3 ft at the end hallway and mid hallway locations. The closed bedroom 1 door stopped this gas exchange, which caused the end hallway and mid hallway temperatures to increase.

The suppression crew flowed water in the hallway prior to advancing to the fire room. Flaming combustion on the floor was extinguished, which decreased hallway temperatures nearest the floor. The bedroom 4 door was opened, which allowed combustion gases from the fire room to flow into the hallway. Hallway temperatures peaked to 420 °C (788 °F), 300 °C (572 °F), and 285 °C (545 °F) at the mid hallway, end hallway, and start hallway locations, respectively. Suppression began immediately after the bedroom 4 door was opened and extinguished the fire. Cooled combustion gases flowed into the hallway, which decreased hallway temperatures.

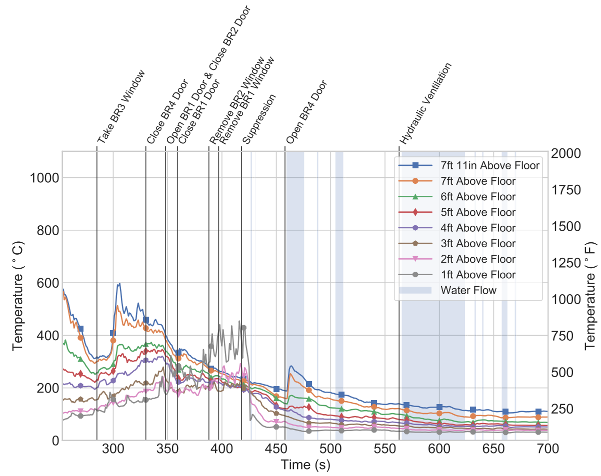
Hydraulic ventilation created an area of lower pressure in the fire room, which caused higher-pressure combustion gases to flow into the fire room. Hallway temperatures decreased below 140 °C (284 °F), 130 °C (266 °F), and 115 °C (239 °F) at the mid hallway, end hallway, and start hallway locations and 85 °C (185 °F) in the living room entryway.

Prior to intervention, flames had extended from the fire room and ignited the hallway carpet. Flames spread along the carpet toward both ends of the hallway. However, due to the lack of an exterior vent in bedroom 2, flame spread was limited toward the end hallway location. Heat flux at the time of intervention indicated flaming carpet combustion at the mid hallway and start hallway locations. Heat flux to the hallway floor was 27.0 kW/m^2, 13.4 kW/m^2, 1.8 kW/m^2, and 1.3 kW/m^2 at the mid hallway, start hallway, end hallway, and living room entryway locations, respectively (Figure 5.123). Bidirectional flow through the open front door and the large volume of air in the common space prevented the smoke layer from descending in the living room entryway, which caused heat flux in the living room entryway to be lower than the hallway.

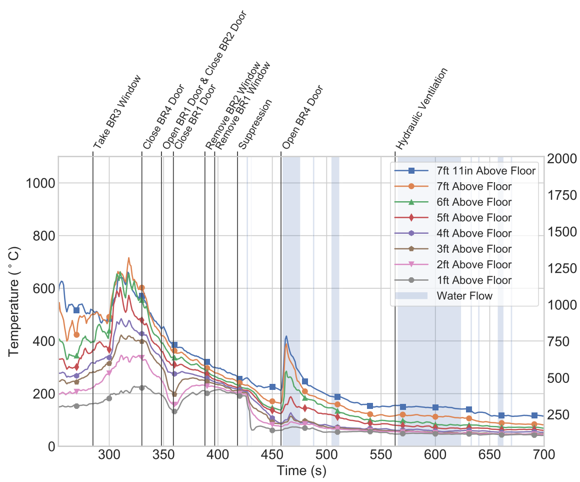
Wind through the side A bedroom 4 door increased the combustion gas flow into the hallway toward the exterior vent in bedroom 3. Additionally, flames spread along this flow path, which



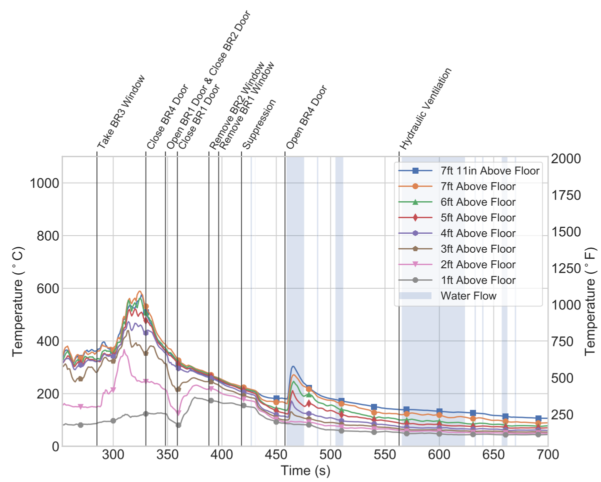
(a) Living Room Entryway Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.122: Temperature time histories in the hallway in the period following fire department intervention in Experiment 8.

decreased mid hallway heat flux and increased start hallway heat flux. Isolation of the fire room stopped flames from extending into the hallway. As flames retreated toward the fire room, start hallway heat flux decreased and mid hallway heat flux increased. Air entrained through the open bedroom 1 door toward the fire room. Flames spread toward the location of entrainment, which increased the mid hallway heat flux to 46.4 kW/m^2. The closed bedroom 1 door stopped the flow of gases between the hallway and the bedroom, which caused mid hallway heat flux to decrease. Two water flows in the hallway extinguished flaming combustion on the carpet. Mid hallway and start hallway heat flux decreased below 15.0 kW/m^2 and 6.6 kW/m^2, respectively. The open bedroom 4 door allowed flames to extend into the hallway, which caused mid hallway heat flux to peak to 13.3 kW/m^2 during suppression. Suppression extinguished the bedroom 4 fire, which decreased the heat flux in the hallway to 1.8 kW/m^2. The impact of hydraulic ventilation was minimal.

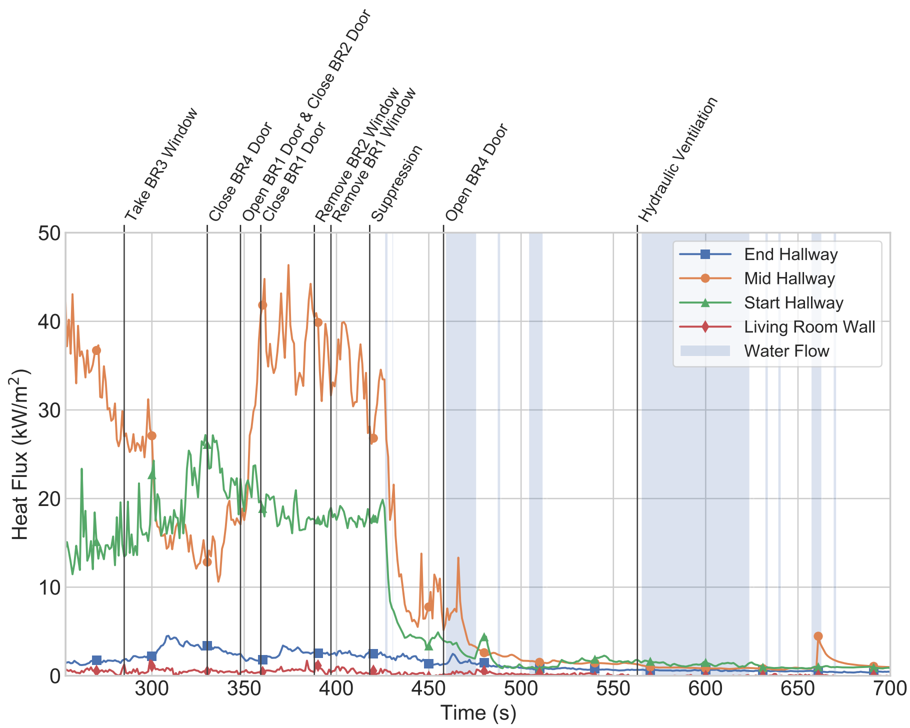


Figure 5.123: Heat flux time histories in the hallway in post-intervention period during Experiment 8.

Table 5.16 shows the gas concentrations measured throughout the hallway and living room entryway locations at the time of fire department intervention. Gas concentrations indicated low-level burning at the mid hallway location and that the smoke layer had descended to the 1 ft level at the mid hallway and end hallway locations. The large volume of the common space and entrainment through the front door prevented the smoke layer from descending to the floor at the start hallway and living room entryway locations.

Table 5.16: Hallway Gas Concentrations at Intervention for Experiment 8

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	17.9	3.1	0.4
	1 ft	20.1	0.9	0.1
Start Hallway	3 ft	18.3	2.8	0.4
	1 ft	19.8	1.1	0.1
Mid Hallway	3 ft	13.4	6.2	1.0
	1 ft	13.4	6.6	0.7
End Hallway	3 ft	11.9	8.2	1.0
	1 ft	15.8	4.7	0.7

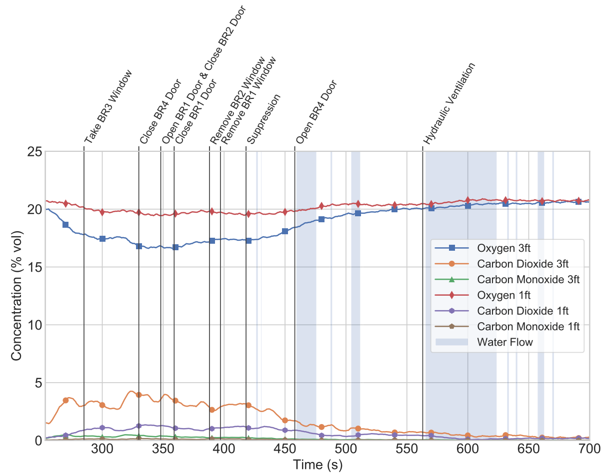
Figures 5.124a though 5.124d show the gas concentration time histories in the hallway. Wind

through the side A bedroom 4 window increased the flow of gases into the hallway. Air inflow through the window temporarily improved gas concentrations at the mid hallway location. Combustion gas flow into the hallway and flame spread along the carpet worsened mid hallway and start hallway gas concentrations.

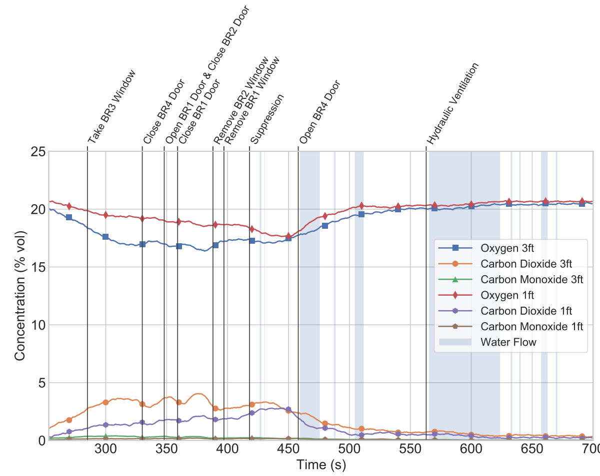
The closed bedroom 4 door stopped the flow of combustion gases from the fire room to the hallway, however existing gas flows continued throughout the structure. Without a local exterior vent, gas concentrations at end hallway and mid hallway locations worsened. The large volume of air and open front door prevented the gas layer from descending in the common space, which kept gas concentrations at the start hallway and living room entryway locations from worsening.

Flow through the open bedroom 1 door allowed an exchange of combustion gases and air between the bedroom and the hallway. End hallway and mid hallway gas concentrations improved 3 ft above the floor. Carpet combustion at the mid hallway location continued to worsen gas concentrations 1 ft above the floor.

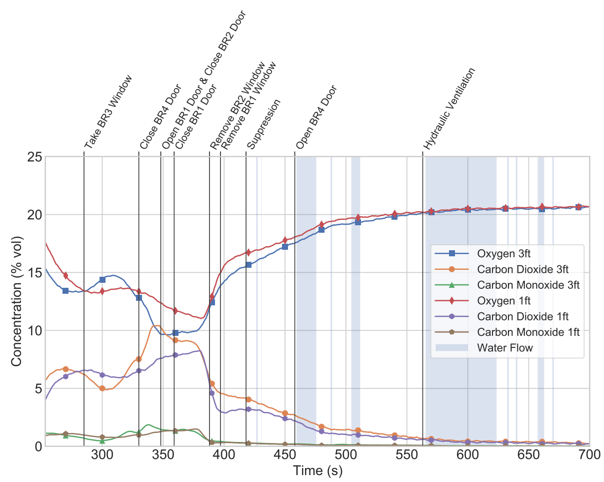
The bedroom 4 door was opened simultaneously with suppression of the bedroom 4 fire. The production of higher-pressure combustion gases was terminated, which limited further accumulation of combustion gases in open volumes of the structure. Flow through exterior vents exhausted accumulated combustion gases and entrained cool air, which caused gas concentrations in the hallway to improve. Gas concentrations improved to pre-ignition conditions prior to hydraulic ventilation.



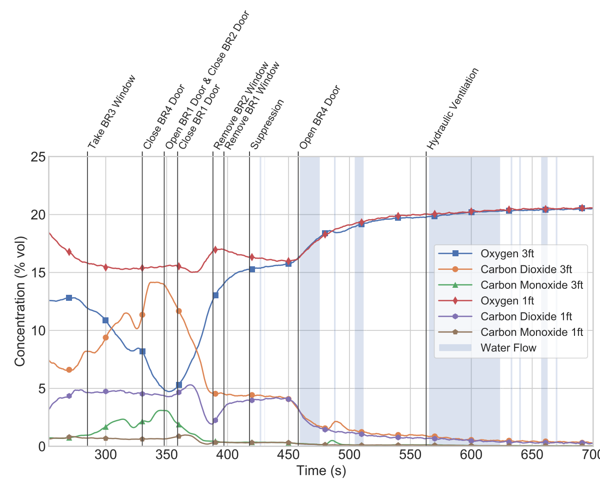
(a) Living Room Entryway Hall Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.124: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 8.

5.8.4 Bedroom 2

The bedroom 2 door was opened prior to ignition, which allowed higher-pressure, higher-temperature combustion gases to flow from the fire room to the lower-pressure, lower-temperature bedroom. Bedroom 2 temperatures ranged from 235 °C (455 °F) at the ceiling to 85 °C (185 °F) 1 ft above the floor at the time of intervention, as shown in Figure 5.125a. Following ventilation of the bedroom 3 window, wind-driven flows within the structure caused additional flow of fire room combustion gases into bedroom 2. Temperatures increased to 350 °C (662 °F) at the ceiling and 110 °C (230 °F) 1 ft above the floor.

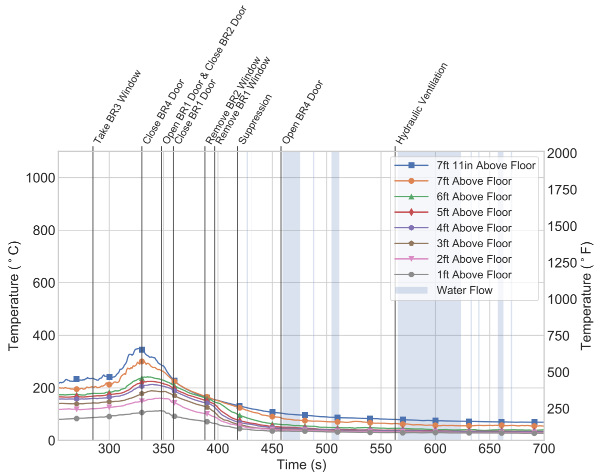
The closed bedroom 4 door stopped the flow of combustion gases from the fire room into the hallway. As existing gas flows continued throughout the structure, combustion gases flowing into bedroom 2 steadied bedroom 2 temperatures. The closed bedroom 2 door stopped the flow of combustion gases from the hallway into the bedroom, which reduced bedroom 2 temperatures. The removal of the bedroom 2 window created an exterior vent and established a new flow path between the bedroom and the exterior. Accumulated combustion gases exhausted from the vent to the exterior and air entrained into the bedroom. Temperatures decreased to 75 °C (167 °F) at the ceiling and 30 °C (86 °F) 1 ft above the floor. The bedroom 2 door remained closed during suppression and hydraulic ventilation, which limited temperature recovery in the bedroom.

Heat flux to the bed was 3.5 kW/m^2 at the time of intervention, as shown in Figure 5.125b. Combustion gas flow into bedroom 3 increased after window ventilation, due to wind-driven flow through the side A bedroom 4 window. Heat flux increased to 5.5 kW/m^2. Although isolation of the fire room stopped the flow of combustion gases to the hallway, combustion gases continued to flow into bedroom 2 and heat flux became steady. Isolation of bedroom 2 stopped the flow of combustion gases into the bedroom, which limited further accumulation of combustion gases in the bedroom. Heat flux decreased. The bedroom 2 window was removed, which created an exterior vent. Accumulated combustion gases flowed toward the window, momentarily increasing heat flux to the bed to 3.2 kW/m^2. Bidirectional flow through the window lifted the smoke layer in the bedroom, which decreased heat flux below 0.3 kW/m^2.

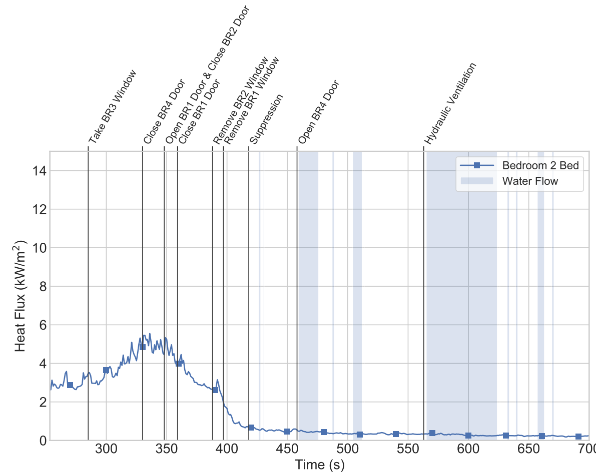
Gas concentrations at the time of intervention indicated that the smoke layer had descended to the bed, as shown in Figure 5.125c. Following bedroom 3 window ventilation, gas concentrations worsened to 9.9% O_2, 11.4% CO_2, and 2.3% CO, as wind-driven flows within the structure increased combustion gas flow from the fire room to open volumes of the structure. Isolation of the fire room limited the flow of combustion gases into bedroom 2 and gas concentrations became steady. Isolation of bedroom 2 prevented further accumulation of combustion gases, which improved gas concentrations. Bidirectional flow through the removed bedroom 2 window lifted the smoke layer in the bedroom. As a result, gas concentrations improved to 20.7% O_2, 0.2% CO_2, and 0% CO.

Window temperatures were consistent with temperatures in the center of the room from the time of first intervention to the time the window was removed (Figure 5.126a). The removal of the bedroom 2 window created an exterior vent in the bedroom. Bidirectional flow through the window immediately decreased window temperatures. Higher-pressure combustion gases exhausted from the top of the window between 1.8 m/s and 1.4 m/s (4.0 mph and 3.1 mph). Lower-pressure air entrained through the bottom of the window between -1.0 m/s and -3.2 m/s (-2.2 mph and -7.2 mph) (Figure 5.126b). Bidirectional flow through the window continued, which decreased window temperatures below 55 °C (131 °F).

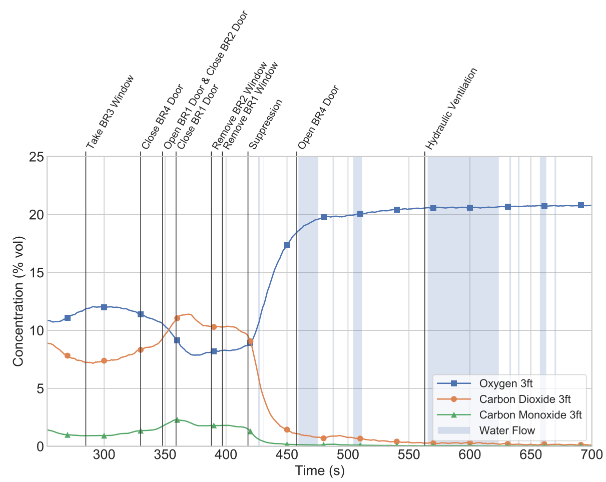
At the time of intervention, heat flux below the window was greater than heat flux at the bed level. Heat flux was 5.6 kW/m^2 3 ft above the floor and 4.6 kW/m^2 1 ft above the floor, as shown in Figure 5.126c. Wind-driven flow within the structure caused heat flux below the window to follow a similar trend to heat flux to the bed. Heat flux increased to 9.0 kW/m^2 and 8.0 kW/m^2, respectively. Fire room isolation caused heat flux to become steady and bedroom 2 isolation caused heat flux to decrease. As accumulated combustion gases in bedroom 2 flowed toward the exterior



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux

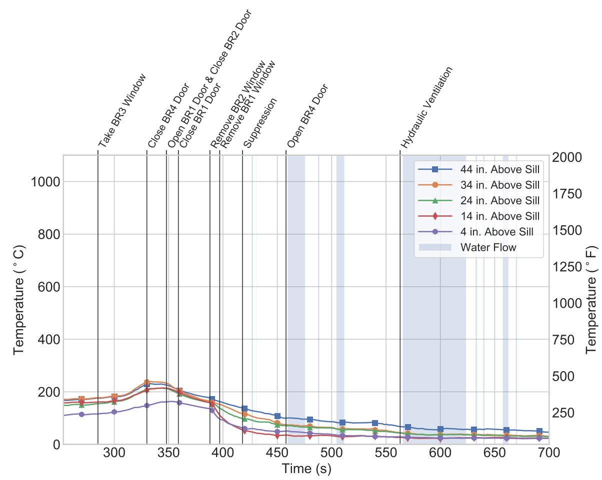


(c) Bedroom 2 Gas Concentration

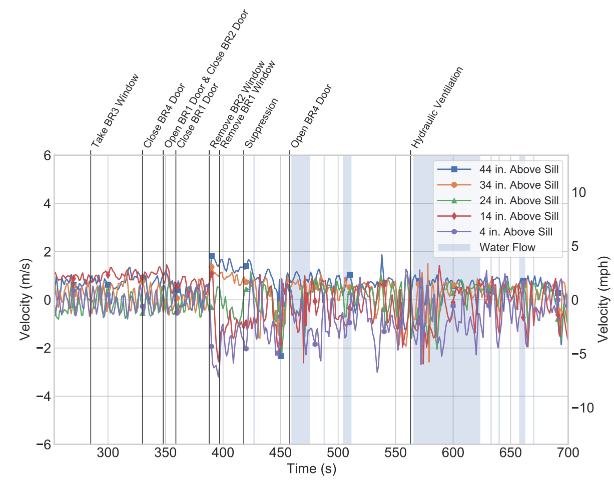
Figure 5.125: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 8.

vent created by the removal of the bedroom 2 window, heat flux momentarily peaked to 4.0 kW/m^2 and 1.8 kW/m^2, respectively. Bidirectional flow through the window decreased heat flux below 0.2 kW/m^2 at both elevations below the window.

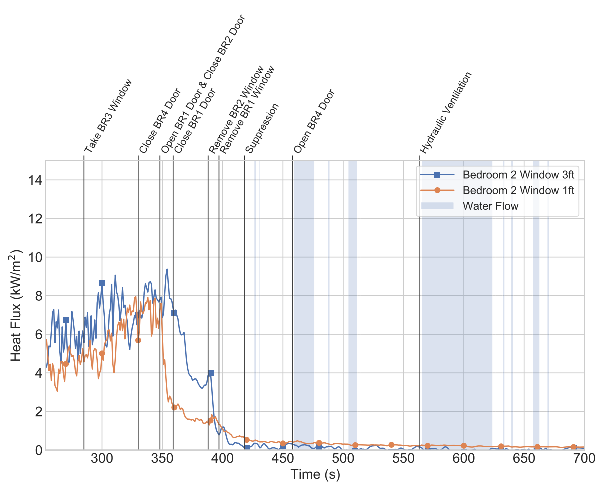
Gas concentrations below the bedroom 2 window at the time of first intervention indicated that the smoke layer had descended past the 1 ft level, as shown in Figure 5.126d. Following bedroom 3 window ventilation, wind-driven flows increased the combustion gas flow into bedroom 2. As a result, gas concentrations below the window followed a similar trend to gas concentrations at the bed and worsened to 7.5% O_2, 11.8% CO_2, and 2.3% CO 3 ft above the floor and 12.1% O_2, 7.7% CO_2, and 1.5% CO 1 ft above the floor. Isolation of the fire room caused gas concentrations to become steady, while isolation of bedroom 2 caused gas concentrations to improve. Bidirectional flow through the window immediately improved gas concentrations at the 3 ft level and gradually improved gas concentrations at the 1 ft level. Gas concentrations improved to approximately 20.8% O_2, 0.1% CO_2, and 0% CO below the window.



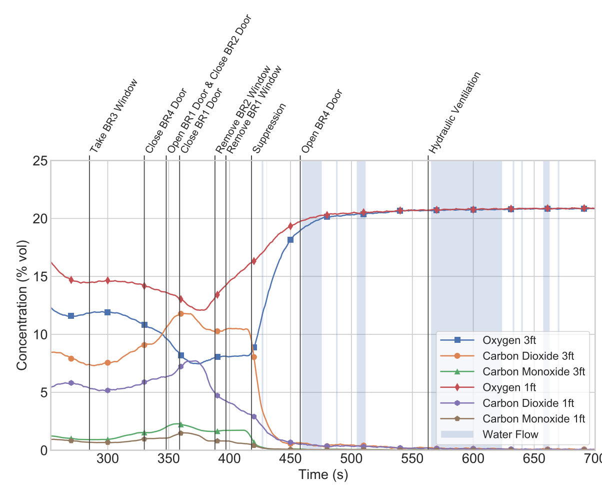
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

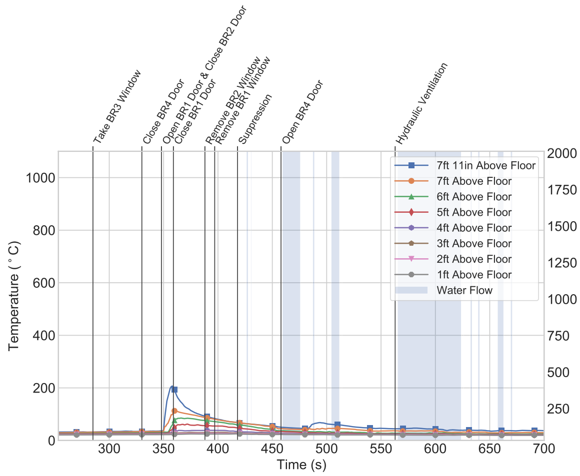
Figure 5.126: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 8.

5.8.5 Bedroom 1

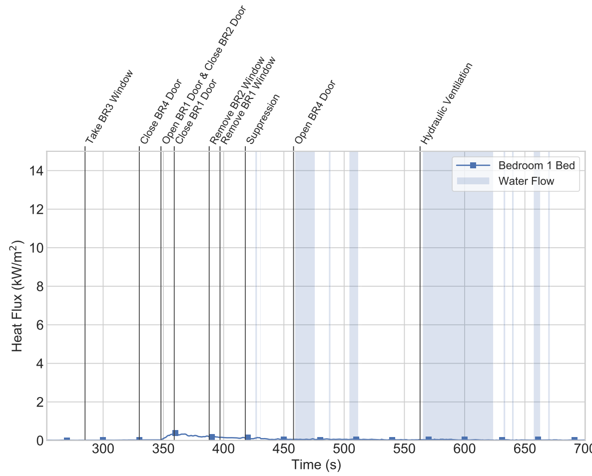
The bedroom 1 door was closed prior to ignition. The closed door prevented the flow of higher-pressure combustion gases from the fire room into the lower-pressure bedroom. However, combustion gases flowed into the bedroom through the leakage area around the closed door and through the HVAC supply vents. At the time of intervention, bedroom 1 temperatures had increased to 30 °C (86 °F) at the ceiling and 20 °C (68 °F) 1 ft above the floor (Figure 5.127a). The open bedroom 1 door established a new flow path between the fire room and bedroom 1. Higher-pressure combustion gases flowed through the open door into the lower-pressure bedroom, which increased temperatures to 205 °C (401 °F) at the ceiling and 40 °C (104 °F) 4 ft above the floor. The closure of the bedroom 1 door stopped the flow of higher-pressure combustion gases from the fire room into the bedroom, which reduced temperatures. The removal of the bedroom 1 window created an exterior vent and established a new flow path between the bedroom and the exterior. Bidirectional flow through the window reduced temperatures below 40 °C (104 °F), as combustion gases cooled and exhausted through the window. The bedroom 1 door remained closed during suppression and hydraulic ventilation. However, suppression in the fire room caused additional gas flow through the HVAC supply vent, which increased ceiling temperatures during suppression.

Heat flux to the bed was 0 kW/m^2 at the time of intervention, as shown in Figure 5.127b. The open bedroom 1 door allowed combustion gases to flow into the bedroom. However, due to the low temperature of the bedroom, heat flux increase was negligible.

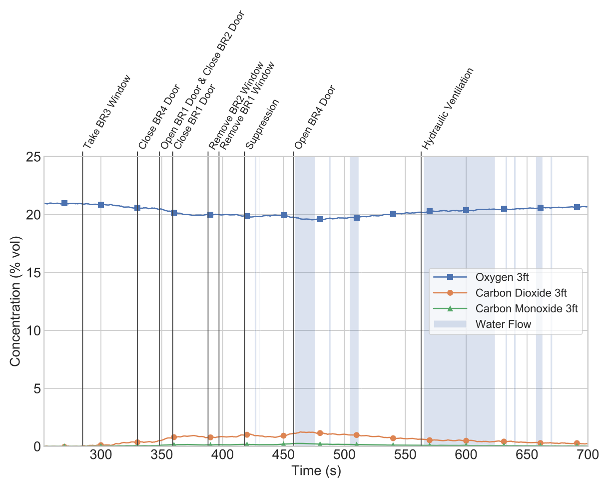
At the time of first intervention, gas concentrations at the bed level were 20.9% O_2, 0.1% CO_2, and 0% CO (Figure 5.127c). Combustion gas flow through the open bedroom 1 door worsened gas concentrations to 19.9% O_2, 1.0% CO_2, and 0.2% CO. Bidirectional flow through the open bedroom 1 window improved gas concentrations.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



(c) Bedroom 1 Gas Concentration

Figure 5.127: Post-intervention bed level temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 8.

The bathroom 1 door was opened prior to ignition, which allowed gases to flow between the bedroom and bathroom. Combustion gases flowed through the HVAC supply vent into bathroom 1, which increased temperatures to 30 °C (86 °F) at the ceiling and 20 °C (68 °F) 1 ft above the floor at the time of intervention (Figure 5.128). Flow through the open bedroom door increased bathroom temperatures to 70 °C (158 °F). The bathroom was adjacent to, but not part of the flow path between the fire room and the bedroom, therefore temperature increase in the bathroom was less than in the bedroom. Similarly, temperature recovery in the bathroom was slower than in the bedroom. Temperatures decreased below 40 °C (104 °F).

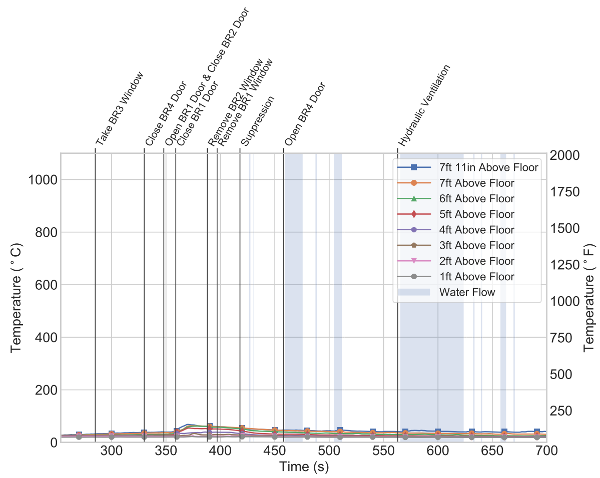


Figure 5.128: Post-intervention temperatures in bathroom 1 during Experiment 8.

5.8.6 Common Space

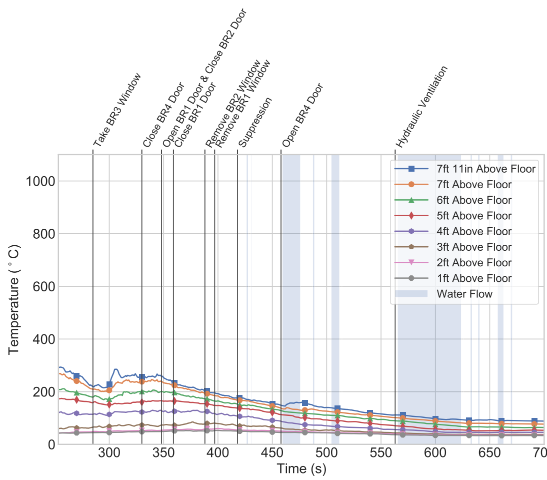
At the time of intervention, living room temperatures ranged from 220 °C (428 °F) at the ceiling to 45 °C (113 °F) 1 ft above the floor (Figure 5.129a) and kitchen temperatures ranged from 195 °C (383 °F) at the ceiling to 40 °C (104 °F) 1 ft above the floor (Figure 5.129b). Wind-driven flows increased combustion gas flow between bedroom 4 and open volumes of the structure following bedroom 3 window ventilation. As a result, common space temperatures increased. The closed bedroom 4 door stopped the flow of combustion gases from the fire room to open volumes of the structure, however previously accumulated combustion gases continued to drive existing flows within the structure. Common space temperatures stopped increasing and became steady. As combustion gases flowed toward the open bedroom, common space temperatures decreased.

As the bedroom 4 door was opened for suppression, higher-pressure combustion gases flowed toward the common space, which increased ceiling temperatures in the common space. Suppression extinguished the bedroom 4 fire, which reduced common space temperatures below 135 °C (275 °F). During hydraulic ventilation, flow through the bedroom 4 vents became unidirectional toward the exterior and flow through the front door became bidirectional. Common space temperatures decreased below 90 °C (194 °F).

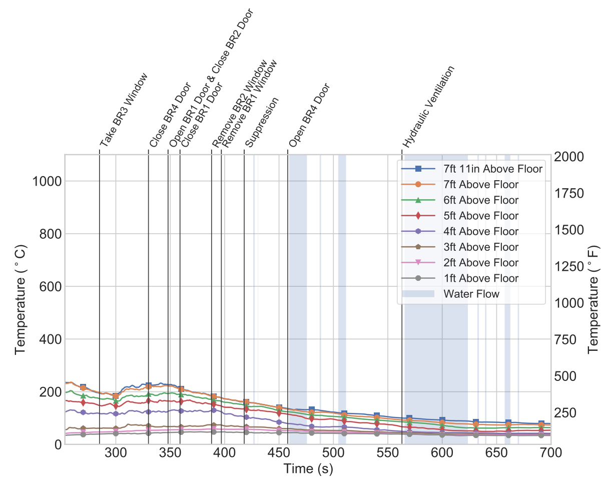
Heat flux 1 ft above the kitchen floor was 0.6 kW/m^2 at the time of intervention (Figure 5.129c). After the bedroom 3 window was ventilated, additional combustion gas flow from the fire room to open volumes of the structure increased heat flux to 0.8 kW/m^2. After the bedroom 4 door was closed, existing gas flows within the structure caused a temporary rise in heat flux to 0.9 kW/m^2 before heat flux decreased. During suppression, combustion gas flow through the open bedroom 4 door increased kitchen heat flux to 0.5 kW/m^2, before the fire was extinguished. Hydraulic ventilation caused combustion gases to flow from the common space into the fire room, which decreased heat flux below 0.3 kW/m^2.

The kitchen was adjacent to the flow path established between the fire room and the front door.

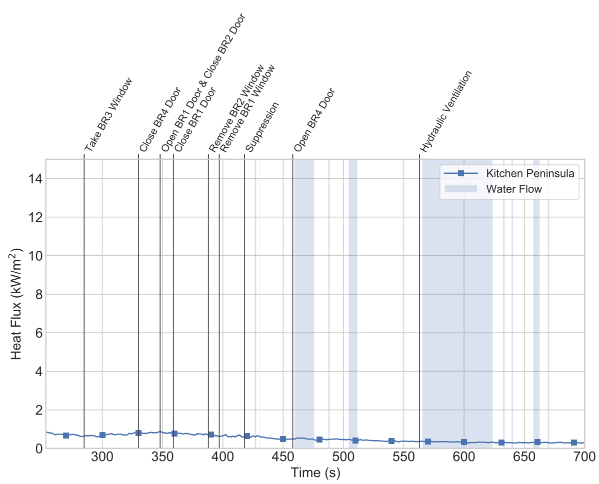
The influence of air entrainment in the kitchen was less than in the living room, as the smoke layer descended to the floor. Gas concentrations steadily worsened to 19.2% O_2, 0.7% CO_2, and 0.3% CO as combustion gases flowed into the kitchen. Hydraulic ventilation caused flow through the bedroom 4 vents to become unidirectional toward the exterior and flow through the front door to become bidirectional. As a result, gas concentrations improved to 20.0% O_2, 0.4% CO_2, and 0.2% CO.



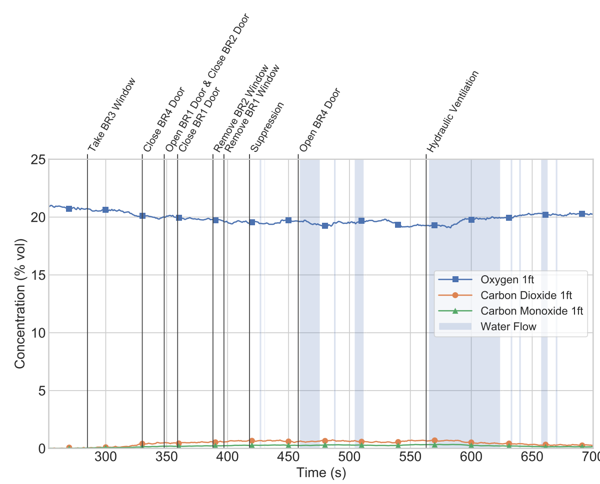
(a) Living Room Temperature



(b) Kitchen Temperature



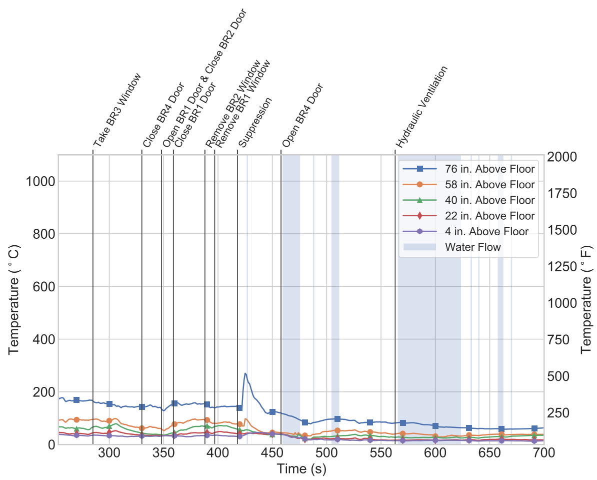
(c) Kitchen Heat Flux



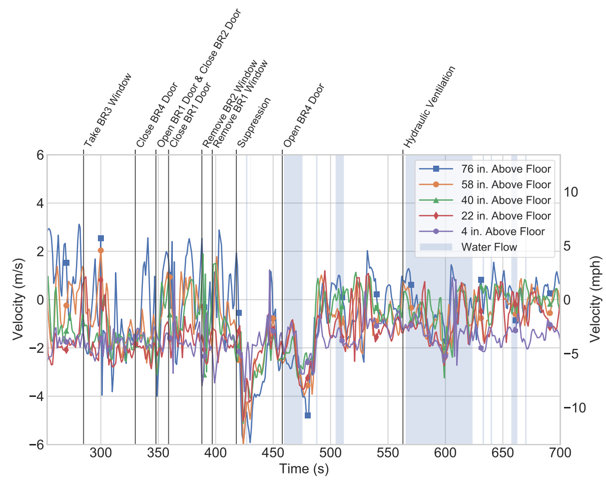
(d) Kitchen Gas Concentration

Figure 5.129: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 8.

Front doorway temperatures at the time of intervention ranged from 165 °C (329 °F) 76 in. above the floor to 35 °C (95 °F) 4 in. above the floor, as seen in Figure 5.130a. Higher temperatures near the top of the doorway reflect combustion gas exhaust at approximately 1.3 m/s (2.9 mph) and lower temperatures near the floor reflect cool air entrainment at approximately -1.6 m/s (-3.6 mph), as seen in Figure 5.130b. The bidirectional probes were removed from the front door approximately 307 s post-ignition, as the suppression crew entered the structure to monitor hallway conditions during bedroom 4 door closure. The probes were replaced 487 s post-ignition. Measurements recorded during this time are not reflective of flow through the doorway. Hydraulic ventilation created an area of lower pressure in the fire room, which caused higher-pressure combustion gases in open volumes of the structure to exhaust through the bedroom 4 vents. Flow through the front door remained bidirectional, but entrainment increased from -1.0 m/s to -3.2 m/s (-2.2 mph to -7.2 mph), which reduced temperatures below 65 °C (149 °F).



(a) Front Doorway Temperature



(b) Front Doorway Velocity

Figure 5.130: Post-intervention temperatures and velocities in the front doorway during Experiment 8.

5.9 Experiment 8b

The search tactics in Experiment 8b were designed to evaluate window initiated operations following fire room door control conducted before suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide, bedroom 4 window were removed, but the screens were left installed. The front door to the structure and doors to bedroom 4, bedroom 2, bathroom 3, and bathroom 1 were opened. The doors to bedroom 2 and bedroom 3 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 flashover, crews on side C of the structure ventilated half of the double-wide windows in bedroom 3. The crew entered bedroom 3 and proceeded toward the hallway door. Thew crew opened the bedroom 3 door and flowed water from a 2 1/2 gallon pressurized water fire extinguisher to suppress flaming combustion in the hallway. After expending the contents of the extinguisher, the crew entered the hallway and closed the bedroom 3 door behind them. The crew attempted to close the fire room door, however the door had burned through. The crew then proceeded down the hall toward bedroom 1 and bedroom 2. The crew split to enter both bedrooms. The door to bedroom 1 was opened for entry and subsequently closed as the crew entered. The door to bedroom 2 remained open. The windows in the respective rooms were then removed. At this point, the search tactic comparison was complete and the suppression crew entered the structure through the front door. The suppression crew flowed water in the hallway during their advance to the fire room door. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed bedroom 4 windows. 68 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 223 gallons. Table 5.17 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was ventilation of half the bedroom 3 double-wide window.

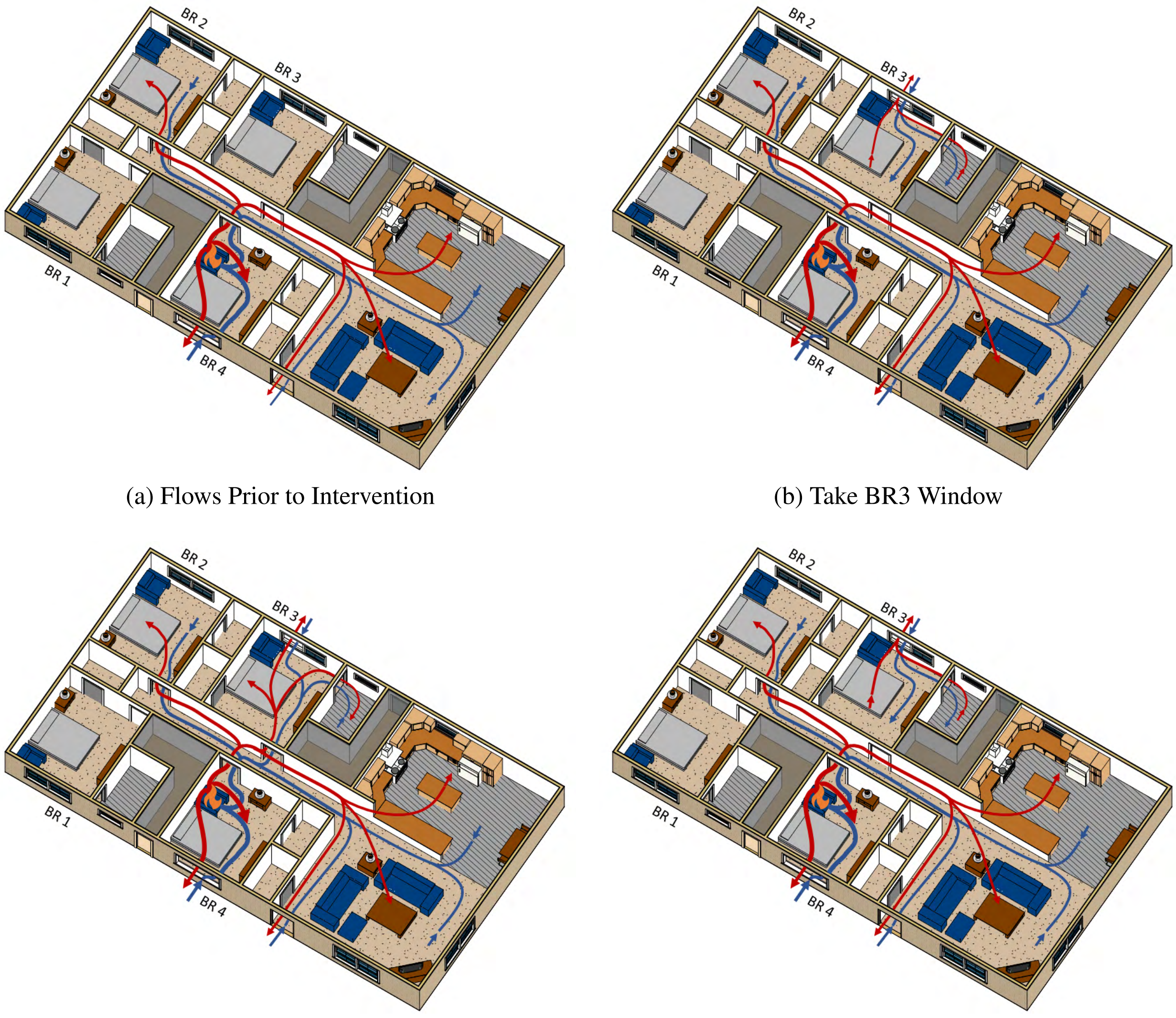
Table 5.17: Experiment 8b Event Times

Event	Elapsed Time			
	From Ignition		From Intervention	
	(mm:ss)	(s)	(mm:ss)	(s)
Ignition	00:00	0	—	—
Take BR3 Window	04:30	270	00:00	0
Open BR3 Door	05:00	300	00:30	30
Flow From Pressurized Water Fire Extinguisher	05:04	304	00:34	34
Close BR3 Door	05:16	316	00:46	46
Open BR1 Door	06:10	370	01:40	100
Close BR1 Door	06:21	381	01:51	111
Remove BR2 Window	06:41	401	02:11	131
Remove BR1 Window	06:53	413	02:23	143
Suppression	07:04	424	03:34	154
Hydraulic Ventilation	09:00	540	04:30	270

Figures 5.131 through 5.133 show the changes in flow in the period immediately preceding and following fire department intervention over the duration of Experiment 8b. At the time of first intervention, the bedroom 4 fire was in a post-flashover state. Lower-pressure, lower-temperature air was entrained and higher-pressure, higher-temperature combustion gases were exhausted through the open bedroom 4 vents (Figure 5.131a). Flow paths were established between the higher-pressure fire room and the lower-pressure open volumes of the structure and the exterior of the structure.

Although bedroom 3 was isolated prior to ignition, higher-pressure combustion gases in the hallway flowed into the lower-pressure bedroom through the leakage area around the closed door and through the HVAC supply vents. The first intervention was ventilation of half the double-wide bedroom 3 window. The ventilated window created an exterior vent in the bedroom. As a result, accumulated higher-pressure combustion gases flowed toward the vent to the exterior of the structure, as shown in Figure 5.131b.

The bedroom 3 door was opened 30 s later, which allowed combustion gases to flow from the fire room to the exterior of the structure through the bedroom, as shown in Figure 5.131c. After the bedroom 3 door was opened, flaming combustion in the hallway was extinguished with a pressurized water fire extinguisher. Water flow into bedroom 4 was minimal and bulk flows through the structure were similar to those prior to use of the extinguisher. The search crew then closed the bedroom 3 door, which isolated the bedroom from the flow of combustion gases (Figure 5.131d). Gas flows between bedroom 3 and the exterior continued due to the additional accumulation of gases while the door was opened.



(a) Flows Prior to Intervention

(b) Take BR3 Window

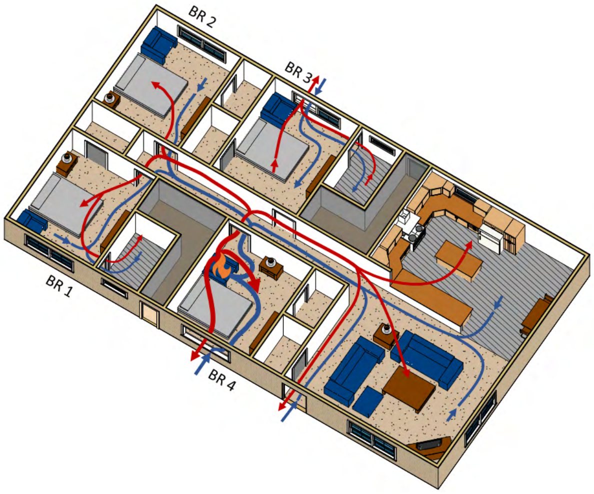
(c) Open BR3 Door

(d) Close BR3 Door

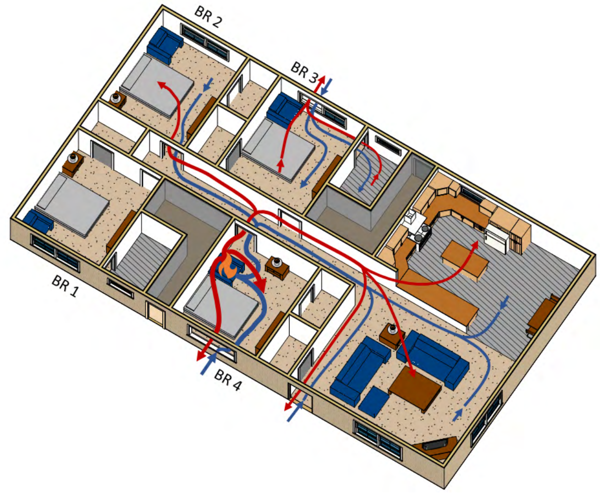
Figure 5.131: Changes in flow in structure following fire department interventions in Experiment 8b.

The search crew continued down the hallway to bedrooms 1 and 2. The crew split to enter each bedroom. The bedroom 1 door was then opened, which allowed higher-pressure combustion gases and lower-pressure air to exchange between the hallway and the bedroom, as seen in Figure 5.132a. Upon entering bedroom 1, the hallway door was closed to isolate the bedroom from the flow of combustion gases (Figure 5.132b).

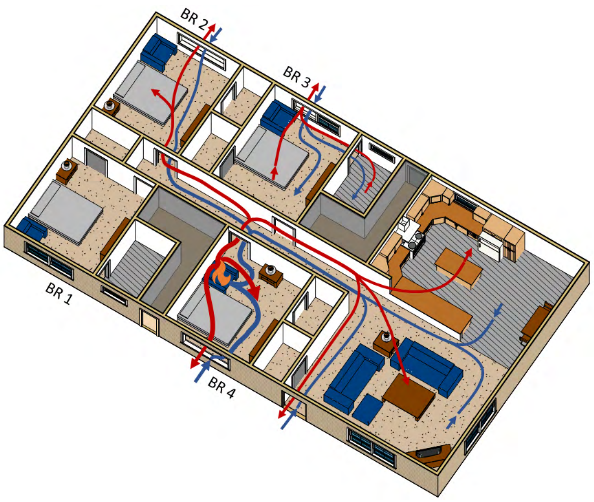
The second half of the search crew entered bedroom 2 and removed the window, which created an exterior vent in the bedroom. A flow path established between the higher-pressure fire room and the lower-pressure exterior (Figure 5.132c). This allowed combustion gases to flow through bedroom 2. The bedroom 1 window was also removed, which similarly created an exterior vent. In contrast to bedroom 2, bedroom 1 was isolated so the newly established flow path began and ended at the bedroom 1 window (Figure 5.132d).



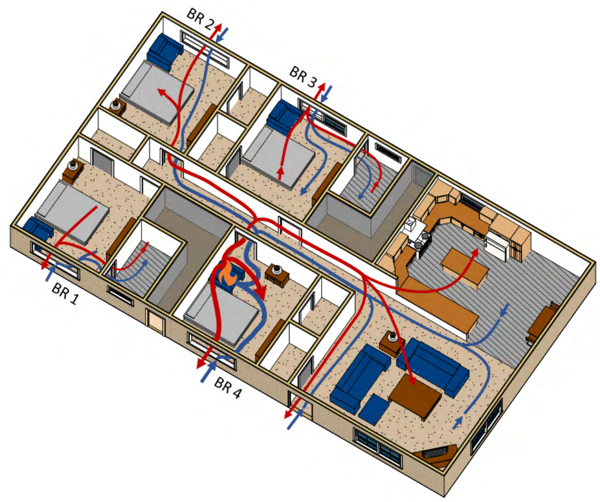
(a) Open BR1 Door



(b) Close BR1 Door



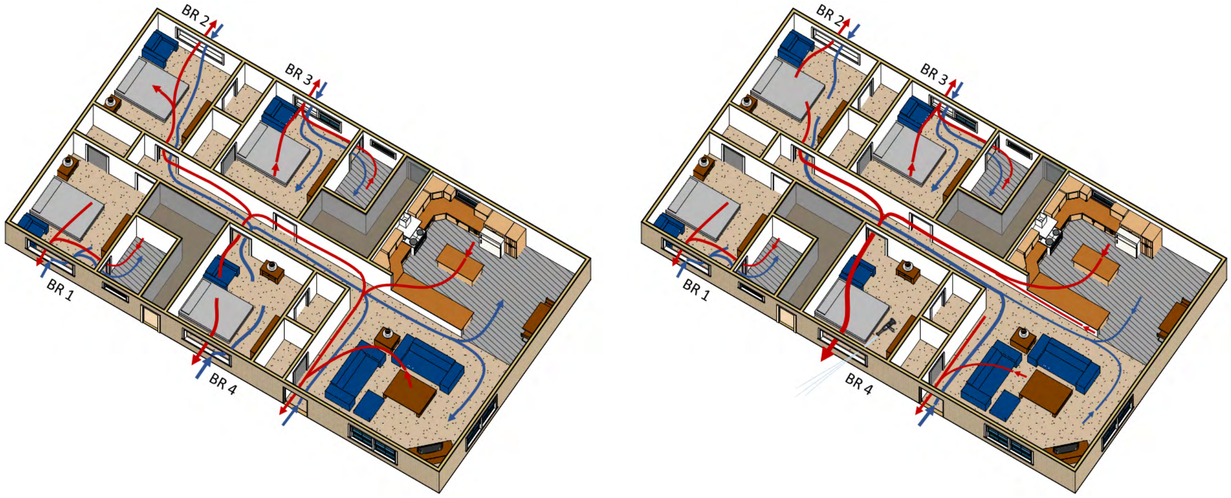
(c) Remove BR2 Window



(d) Remove BR1 Window

Figure 5.132: Changes in flow in structure following fire department interventions in Experiment 8b.

Interior suppression was conducted with a smooth bore nozzle with a 7/8 in. tip, set to flow 160 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline (Figure 5.133a). Suppression extinguished the bedroom 4 fire and reduced the production of higher-temperature, higher-pressure combustion gases, however accumulated combustion gases in the structure continued to drive existing gas flows. Hydraulic ventilation occurred out of the failed double-wide bedroom 4 window with the tip off, at half bale, and in an O-pattern (Figure 5.133b). An area of low pressure was created in the fire room, which drew gases from open volumes of the structure through the bedroom 4 vents to the exterior.



(a) Suppression

(b) Hydraulic Ventilation

Figure 5.133: Changes in flow in structure following fire department interventions in Experiment 8b.

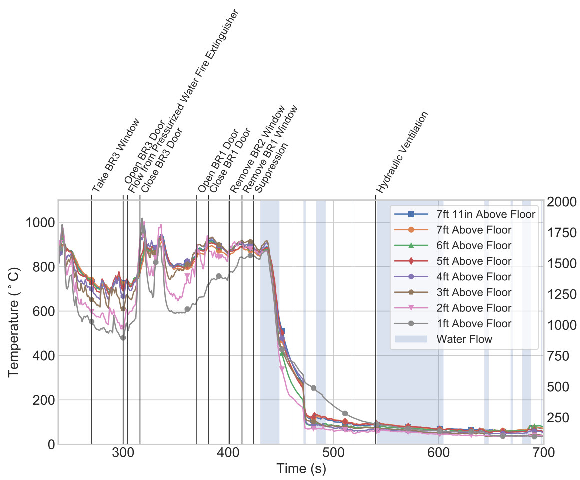
5.9.1 Bedroom 4

The bedroom 4 fire transitioned through flashover approximately 205 s post-ignition. Although temperatures were declining, fire room temperatures indicated a post-flashover state at the time of first intervention. Temperatures ranged from 745 °C (1373 °F) at the ceiling to 550 °C (1022 °F) 1 ft above the floor, as shown in Figure 5.134a.

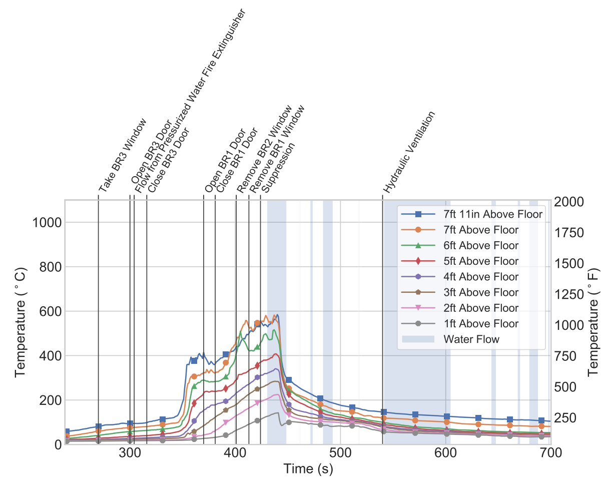
When the bedroom 3 door was opened, a flow path was created between the fire room and the exterior through the ventilated bedroom 3 window. Combustion gases exhausted from the bedroom and were replaced by air, which entrained toward the fire room. The O_2 available for combustion increased and the heat release rate of the hallway and bedroom 4 fire correspondingly increased. Temperatures in bedroom 4 exceeded 880 °C (1616 °F). Flaming combustion in the hallway was extinguished with the contents of a 2 1/2 gallon pressurized water fire extinguisher. The crew did not flow water directly into the fire compartment. As a result, temperatures remained above 800 °C (1472 °F) until suppression. Suppression reduced fire room temperatures below 530 °C (986 °F). Additional water flows in the fire room further decreased temperatures below 120 °C (248 °F). Following suppression, hydraulic ventilation through the failed bedroom 4 window created an area of low pressure in the fire room. Combustion gases and entrained air from open volumes of the structure flowed through bedroom 4 vents and exhausted to the exterior. Bedroom 4 temperatures further decreased to below 70 °C (158 °F).

The closet door in bedroom 4 was closed prior to ignition. The closed door isolated the closet from the bulk flow of combustion gases. However, higher-pressure gases in the fire room flowed through the leakage area around the closed door and gradually increased closet temperatures. Closet temperatures at the time of first intervention ranged from 130 °C (266 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor (Figure 5.134b).

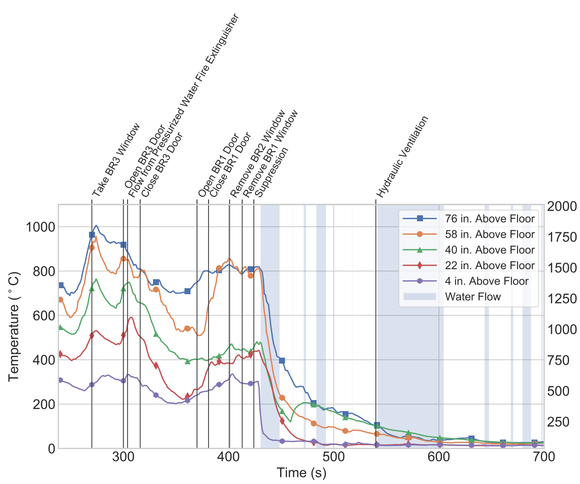
Approximately 345 s post-ignition, the top of the closet door burned through. Combustion gases flowed into the closet and temperatures increased to 585 °C (1085 °F) at the ceiling and 140 °C (284 °F) 1 ft above the floor. Initial suppression decreased closet temperatures below 300 °C (572 °F). Additional water flows in the fire room decreased closet temperatures below 160 °C (320 °F). The bedroom 4 closet was adjacent to the flows established through the bedroom 4 vents. Therefore, the impact of hydraulic ventilation on closet temperatures was negligible.



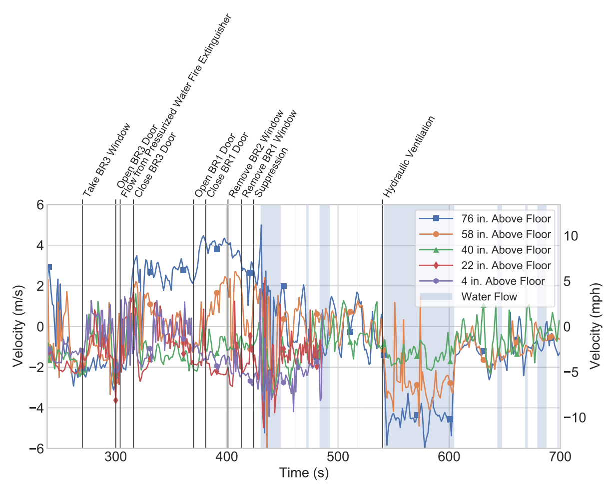
(a) Bedroom 4 Temperature



(b) Closet Temperature



(c) Bedroom 4 Doorway Temperature



(d) Bedroom 4 Doorway Velocity

Figure 5.134: Temperature and velocity time histories in bedroom 4 in post-intervention period during Experiment 8b.

Prior to intervention, bedroom 4 doorway temperatures ranged from 965 °C (1769 °F) 76 in. above the floor to 290 °C (554 °F) 4 in. above the floor (Figure 5.134c). Doorway temperatures followed the same decreasing trend as bedroom temperatures until the bedroom 3 door was opened. The open door led to increases in both heat release rate and temperature due to the additional O_2 available for combustion.

After the bedroom 3 door was opened, the crew used a pressurized water fire extinguisher to suppress the flaming combustion in the hallway. Flames on the door frame were also extinguished and doorway temperatures decreased, but no water flowed into the fire room. As a result, temperatures at the doorway began to recover. At this point the doorway flows were bidirectional. Combustion gases flowed out of the bedroom at 800 °C (1472 °F) between 2.0 m/s and 4.0 m/s (4.5 mph and 9.0 mph) at the top two measurement probes (Figure 5.134d). Gases were entrained into the fire room through the bottom three probes between -0.5 m/s and -1.8 m/s (-1.1 mph and -4.0 mph) at temperatures between 470 °C and 310 °C (878 °F and 590 °F) (Figure 5.134d).

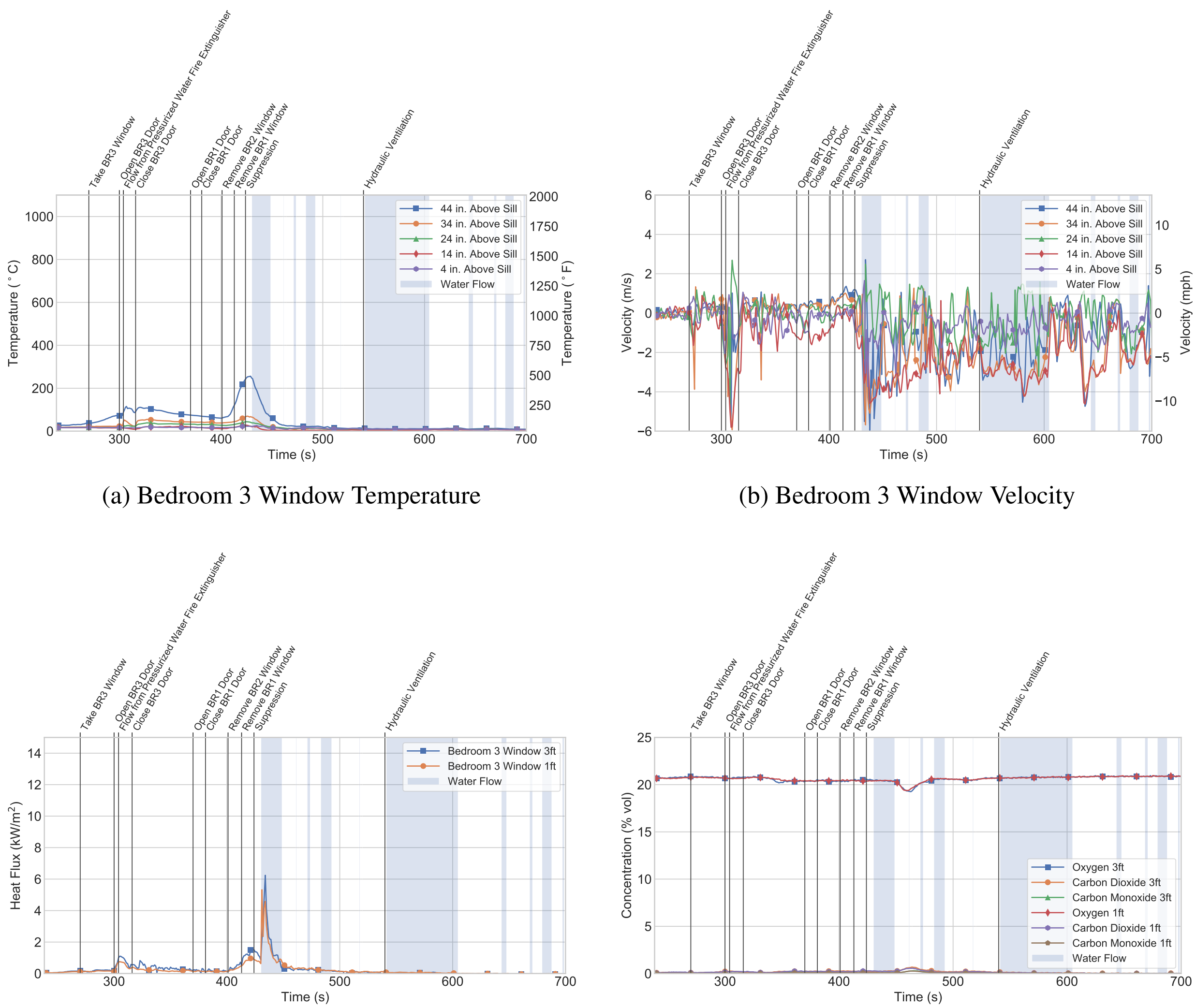
Suppression of the bedroom 4 fire decreased doorway temperatures to below 150 °C (302 °F) and door velocities fluctuated between $\pm$ 1.0 m/s ($\pm$ 2.2 mph). Hydraulic ventilation through the bedroom 4 window created an area of low pressure in the fire room, which resulted in unidirectional flow through the bedroom 4 vents toward the exterior. Door velocities ranged from -1.0 m/s to -4.0 m/s (-2.3 mph to -8.9 mph) and temperatures decreased below 45 °C (113 °F).

5.9.2 Bedroom 3

The bedroom 3 door was closed prior to ignition, which isolated the bedroom from the bulk flow of combustion gases. Higher-pressure combustion gases in the hallway still flowed through the leakage area around the closed door and through the HVAC vents. Combustion gases that flowed into the bedroom around the top corner of the closed door auto-ignited approximately 201 s post-ignition. Flaming combustion was sustained at the corner of the doorway (Figure 5.135). The smoke layer in the bedroom had descended approximately 1 ft to 2 ft from the ceiling, generally independent of the flaming combustion at the door.

Figure 5.135: Pre-intervention Bedroom 3 Door Combustion

At the time of window ventilation, the window temperatures ranged from 40 °C (104 °F) at the top probe to 20 °C (68 °F) at the bottom 4 probes (Figure 5.136a). The ventilated window created an exterior vent local to bedroom 3. A flow path was established that began and ended at the bedroom 3 window. Accumulated combustion gases exhausted through the top probe at 0.4 m/s (0.9 mph), which increased the temperature at the top of the window to 70 °C (158 °F), as seen in Figure 5.136a. Air was entrained through the bottom of the window at -1.6 m/s (-3.6 mph). Air entrainment decreased temperatures at the bottom probes to 15 °C (59 °F).



(a) Bedroom 3 Window Temperature

(b) Bedroom 3 Window Velocity

(c) Bedroom 3 Window Heat Flux

(d) Bedroom 3 Window Gas Concentration

Figure 5.136: Post-intervention window temperature, heat flux, and gas concentrations in bedroom 3 during Experiment 8b.

The bedroom 3 door was opened 30 s after the window was ventilated. There was an initial outflow of gases at the top two probes between 0.5 m/s and 1.0 m/s (1.1 mph at 2.2 mph), which increased temperatures 44 in. above the sill to 115 °C (239 °F) and 34 in. above the still to 52 °C (126 °F). Within 4 s, unidirectional inflow was established through the bedroom 3 window with peak velocities of -5.8 m/s (-13.0 mph) driven by the fire that had spread through hallway, as shown in Figure 5.137a. Due to the increased inflow, temperatures at the window decreased, until the bedroom 3 door was closed 12 seconds later.

(a) Open BR3 Door

(b) BR3 Door Failure

Figure 5.137: Post-intervention Bedroom 8b conditions.

There was a temporary increase in window temperatures after the bedroom was isolated. Combustion gases that had accumulated above the window soffit began to cool, sink in the space, and flow through the window. These gases continued to cool until the top of the bedroom 3 door burned through approximately 390 s post-ignition (Figure 5.137b). Combustion gases flowed into bedroom 3, which increased the temperature at the top of window to 255 °C (491 °F). Before entering the fire room, the suppression crew flowed water onto/through the bedroom 3 door to extinguish the flaming door. This water flow decreased the temperature of combustion gases flowing into bedroom 3. The decrease continued as the suppression crew extinguished the bedroom 4 fire. Suppression, combined with gas exchange to the environment, dropped window temperatures to 15 °C (59 °F). Hydraulic ventilation created an area of lower pressure in the fire room, which caused gases in bedroom 3 to flow through the burned door toward bedroom 4. Gas flow through the window became unidirectional inflow, which further decreased window temperatures to 10 °C (50 °F).

Heat flux at the bedroom 3 window was 0.2 kW/m^2 3 ft above the floor and 0.1 kW/m^2 1 ft above the floor (Figure 5.136c), due to the closed bedroom 3 door. Heat flux remained nominally constant until the bedroom 3 door was opened. Initially, combustion gases flowed through the bedroom, which increased heat flux to 1.1 kW/m^2 and 0.8 kW/m^2 3 ft and 1 ft above the floor, respectively. Water flow from the pressurized water fire extinguisher in the hallway decreased the heat release rate of the fire in the hallway and decreased the heat flux in the bedroom. Following water flow, the bedroom 3 door was closed. As combustion gases flowed out of the bedroom through the window, heat flux continued to decrease.

When the bedroom 3 door burned through 390 s post-ignition, combustion gases began to flow into bedroom 3. Heat flux peaked to 1.5 kW/m^2 and 1.0 kW/m^2 at the 3 ft and 1 ft elevations, respectively. The water flowed from the pressurized water fire extinguisher to suppress the burning bedroom 3 door fire caused additional combustion gas flow into bedroom 3. The increased flow velocity caused the window heat flux to temporarily peak to 6.2 kW/m^2 and 5.3 kW/m^2 at the 3 ft and 1 ft elevations, respectively. Suppression of the doorway fire and water flow in the fire room reduced the production of combustion gases and ultimately, the heat flux in bedroom 3 decreased. Bidirectional flow through the window lifted the smoke layer in the bedroom and heat flux at both elevations was negligible prior to hydraulic ventilation.

Similar to heat flux, gas concentrations below the window at the time of intervention indicated that the closed door limited the accumulation of combustion gases. Gas concentrations were approximately 20.9% O_2, 0.1% CO_2, and 0% CO at both locations, as shown in Figure 5.136d. Bidirectional flow through the open window, suppression of the hallway fire, and the limited duration of when the bedroom door was opened prevented the smoke layer from descending below the window. Therefore, gas concentrations were minimally impacted. Suppression of the door fire led to additional gas flow into bedroom 3. Similar to the spike in heat flux, gas concentrations temporarily increased to 19.3% O_2, 0.7% CO_2, and 0.3% CO post-suppression at both elevations. Air entrainment through the window improved gas concentrations, which recovered to pre-ignition levels prior to hydraulic ventilation.

Prior to intervention, temperatures at the top two measurement elevations in the center of the bedroom were increasing due to the accumulation of combustion gases (Figure 5.138). Recall from Figure 5.135, the smoke layer had descended approximately 1 ft from the ceiling and the corner of door had ignited. Bedroom 3 temperatures ranged from 230 °C (446 °F) at the ceiling to 15 °C (59 °F) 1 ft above the floor. Flow through the ventilated bedroom 3 window limited the temperature increase in the bedroom from flaming combustion around the door frame.

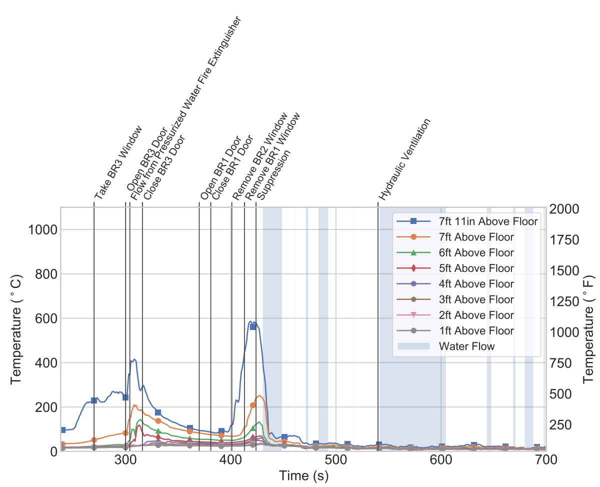


Figure 5.138: Post-intervention temperature in bedroom 3 during Experiment 8b.

Gas flow through bedroom 3 increased immediately following the opening of the bedroom 3 door. Temperatures in the room increased to 415 °C (779 °F) at the ceiling and 120 °C (248 °F) 5 ft above the floor. Temperatures below 5 ft remained near pre-ignition levels due to air entrainment from the window. Water flow from the pressurized water can cooled combustion gases flowing into bedroom 3; subsequently, bedroom 3 ceiling temperatures decreased to 275 °C (527 °F). Closing the bedroom 3 door stopped the flow into bedroom 3 and temperatures continued to decrease until the door burned through, at which point ceiling temperatures spiked to 585 °C (1085 °F).

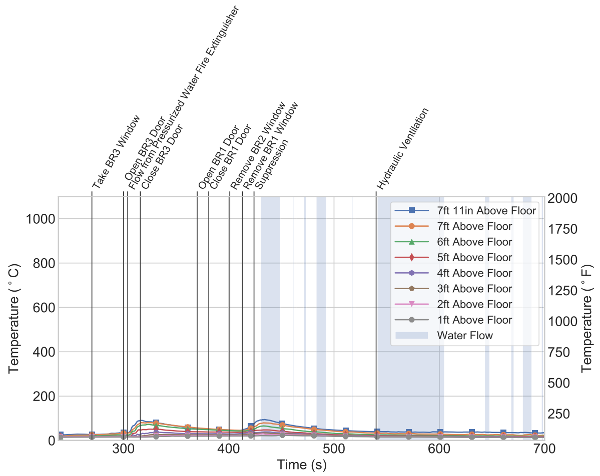
Suppression of the bedroom 3 door fire and subsequently the bedroom 4 fire decreased the temperature of combustion gases flowing into bedroom 3. Following extinguishment of the bedroom 4 fire, temperatures had dropped below 25 °C (77 °F).

The bathroom 3 door was open at the time of ignition, which allowed gas flow between the bedroom and bathroom. Additionally, gases flowed into the space through the HVAC supply vents. Bathroom 3 temperatures at the time of intervention ranged from 25 °C (77 °F) at the ceiling to 15 °C (59 °F) 1 ft above the floor (Figure 5.139a). Temperatures in the bathroom peaked to 90 °C (194 °F) after the bedroom 3 door was opened. The bathroom was adjacent to, but not part of the flow path established between the fire room and the bedroom 3 window, which minimized the temperature increase compared to similar heights in the bedroom. Following isolation of bedroom 3, bathroom temperatures began to decrease, but the lack of a local exterior vent resulted in a slower recovery compared to the bedroom.

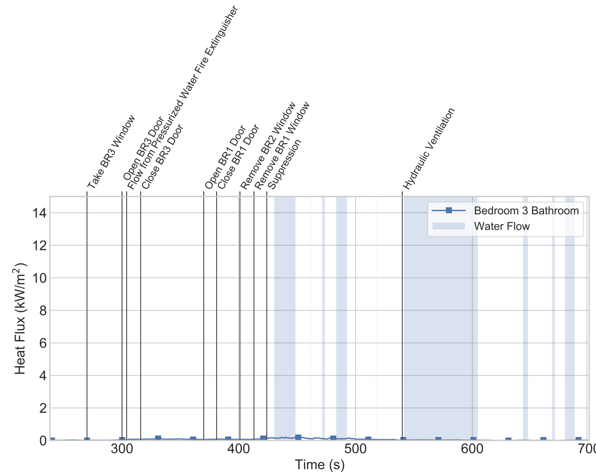
Bathroom temperatures increased to 95 °C (203 °F) following burn through of bedroom 3 door. Again, this temperature increase was not as severe as the increase in the adjacent bedroom. Temperatures began to decrease following suppression, dropping below 49 °C (120 °F). Additional water flow and gas exchange through the window further decreased bathroom temperatures below 40 °C (104 °F). The bathroom was adjacent to the flow path established through the bedroom 4 vents, which minimized the impact of hydraulic ventilation.

Similar to the 1 ft heat flux in the adjacent bedroom, at the time of intervention the heat flux 1 ft above the bathroom 3 floor was negligible (Figure 5.139b). The lack of gas flows and temperature rise resulted in minimal measured heat flux for the duration of the experiment.

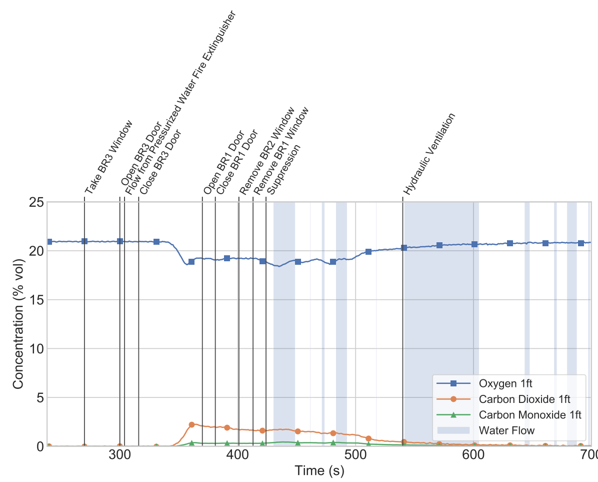
Gas concentrations at the time of intervention were 21.0% O_2, 0% CO_2, and 0% CO, which indicated that the smoke layer had not descended to the 1 ft elevation (Figure 5.139c). Approximately 30 s after bedroom 3 was isolated (346 s post-ignition), gas concentrations sharply decreased to 18.6% O_2, 2.2% CO_2, and 0.4% CO. This decrease coincided with the loss of visibility in the bathroom 3 camera as the smoke layer in the bathroom descended to the floor. Gas concentrations remained nominally constant until after suppression, when the smoke layer in the bathroom lifted as bidirectional flow through the bedroom 3 window exhausted combustion gases from bathroom 3.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux

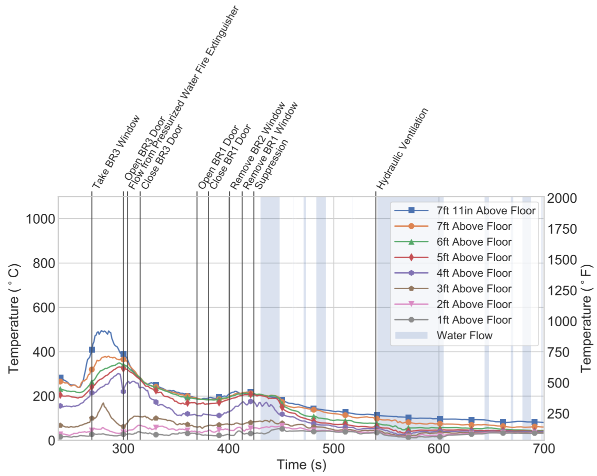


(c) Bathroom 3 Gas Concentration

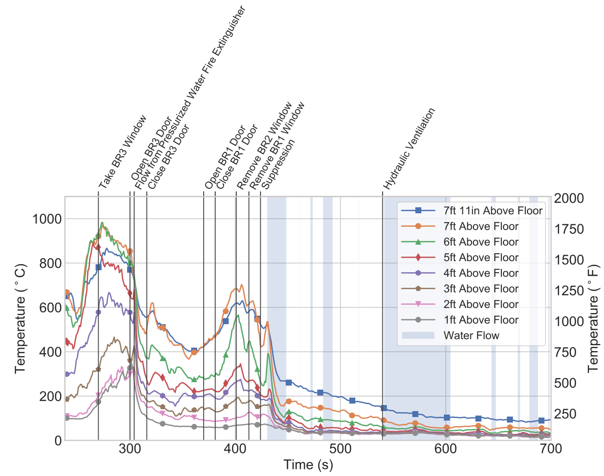
Figure 5.139: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 8b.

5.9.3 Hallway

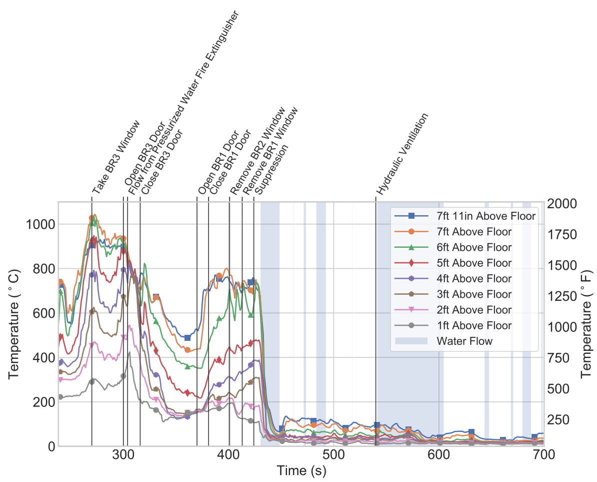
Figure 5.140 shows the temperature time histories for each hallway location. Hallway temperatures at the time of first intervention were dependent on proximity to the fire room (bedroom 4). Temperatures in the mid hallway were the highest at the time of fire department intervention, followed by the start hallway, end hallway, and living room entryway, respectively. The open front door combined with the large volume of the common space limited the accumulation of combustion gases. Additionally, inflow of air at the front door cooled gases through mixing. As a result, the temperatures at the living room entryway hallway were generally lower than the start hallway, mid hallway and end hallway locations.



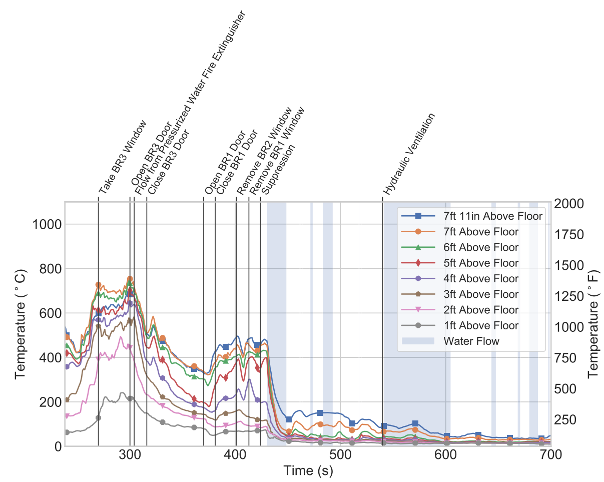
(a) Living Room Entryway Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.140: Temperature time histories in the hallway in the period following fire department intervention in Experiment 8b.

Prior to intervention, flames extended from bedroom 4 into the hallway and ignited the carpet. Flames spread along the carpet toward both the end hallway and start hallway locations. The lack of an exterior vent between the fire room and the end hallway limited flame spread in that direction. The open front door provided sufficient gas exchange to enable flame spread from the bedroom toward the start hallway location. The influence of ventilation can be seen in the temperature disparity between the start hallway and end hallway locations in Figures 5.140b and 5.140d, respectively.

Temperatures throughout the hallway locations remained elevated until flaming combustion between the start hallway and mid hallway locations was extinguished with a pressurized water fire extinguisher. As the production of combustion gases local to the hallway stopped, temperatures decreased at all hallway locations. Temperatures at the mid hallway and start hallway locations continued to decrease for approximately 60 s following water flow in the hallway, until exhaust flows from the bedroom 4 fire reignited the carpet. Temperatures at the end hallway began to increase 10 s later.

The removal of the window created an exterior vent in bedroom 2, which diverted some exhaust flow from the front door toward the window. As a result, temperatures at the start hallway location began to decrease and temperatures at the mid hallway and end hallway locations continued to increase, particularly at lower elevations. When the suppression crew made entry, they flowed water in the hallway and into bedroom 3 to extinguish flames beyond the room of origin before making entry into bedroom 4 to extinguish the main body of fire. Temperatures ahead of the hoseline (mid hallway and end hallway) decreased quicker than behind the hoseline (start hallway and living room entry). Following suppression, hydraulic ventilation was conducted through the failed bedroom 4 window. This created an area of low pressure in the bedroom. Air entrained through the bedroom 2 window along the flow paths in the structure, which maximized the impact of hydraulic ventilation.

Similar to temperature, heat flux at the time of intervention was a function of proximity to bedroom 3 and proximity to the flow path between the fire room and the front door (Figure 5.141). The large volume of the common space and air entrained through the front door limited the accumulation of combustion gases, and the heat flux to the floor at the living room entryway remained lower than the other three hallway locations.

Flow through the open bedroom 3 door increased the available oxygen for combustion in bedroom 4, which increased the heat release rate of the fire. Flames spread along the carpet through the hallway, which increased the heat flux at the end hallway, start hallway, and mid hallway locations. The start hallway heat flux increased to 18.3 kW/m^2 and the mid hallway heat flux peaked to 59.4 kW/m^2, an indication of flaming combustion near the heat flux gauge. Flaming combustion outside bedroom 4 was extinguished with a pressurized water fire extinguisher, which decreased the hallway heat fluxes. Water flow coated the heat flux gauges with water; as a result, the mid hallway heat flux remained elevated following water flow.

Even though the temperatures began to increase back toward the magnitudes prior to the hallway water flow, heat fluxes were slower to respond. At the start of interior suppression, the remaining heat flux locations remained below 2.5 kW/m^2. During suppression, the end hallway, start hallway, and living room entryway heat fluxes peaked to 8.9 kW/m^2, 3.3 kW/m^2, and 7.6 kW/m^2, respectively. The suppression crew flowed water in the hallway in an O-pattern, to both cool gases above and suppress the flame combustion along the floor. The suppression actions dropped heat fluxes to negligible magnitudes.

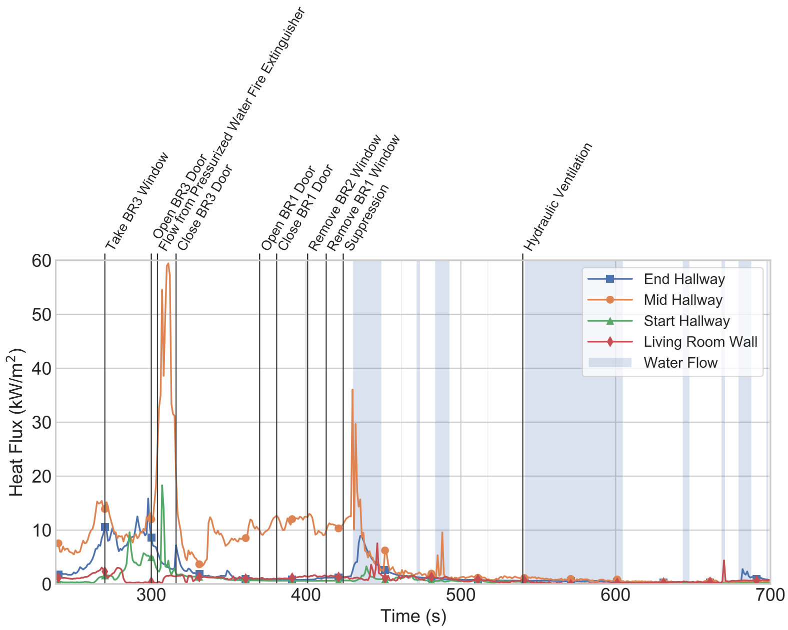


Figure 5.141: Heat flux time histories in the hallway in post-intervention period during Experiment 8b.

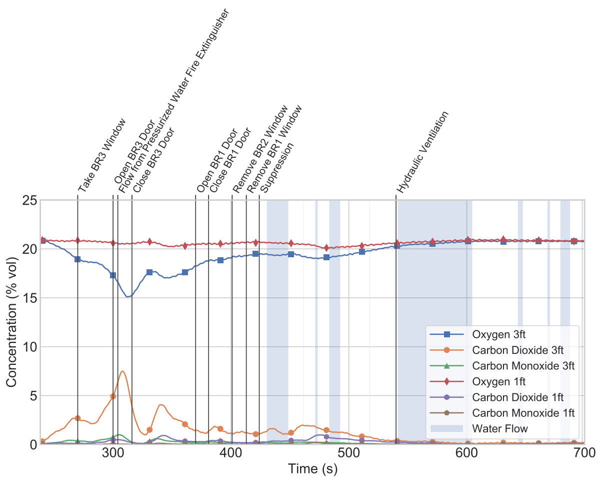
Table 5.18 shows the gas concentrations measured throughout the hallway and living room entryway locations at the time of intervention. Gas concentrations indicated that the smoke layer had descended to the 1 ft level at the mid hallway and end hallway locations. The large volume of the common space and bidirectional flow through the front door limited the smoke layer descent to the 3 ft level at the start hallway and living room entryway locations.

Table 5.18: Hallway Gas Concentrations at Intervention for Experiment 8b

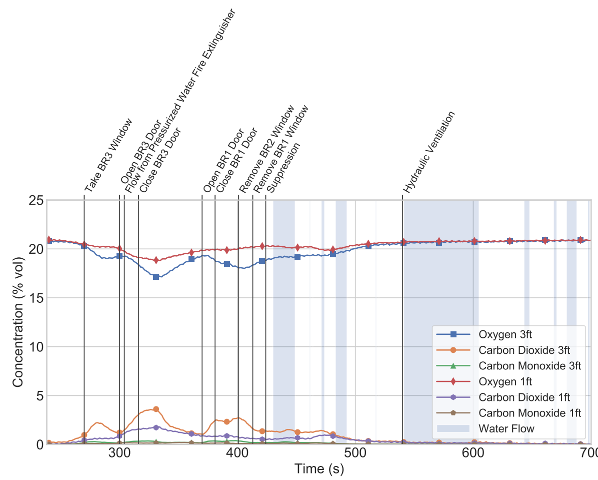
Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	18.9	2.7	0.4
	1 ft	20.8	0.1	0
Start Hallway	3 ft	20.2	0.8	0.2
	1 ft	20.5	0.4	0.1
Mid Hallway	3 ft	15.0	6.6	1.1
	1 ft	15.0	7.4	1.3
End Hallway	3 ft	8.6	10.2	1.0
	1 ft	17.7	4.4	0.8

Figure 5.142 shows the gas concentration time histories in the living room and hallway locations. With the exception of the 1 ft elevation at the living room entryway, which was aided by air inflow through the front door, O_2 concentrations were decreasing and CO_2 and CO concentrations were increasing at intervention. The additional air provided by opening the bedroom 3 door led to an

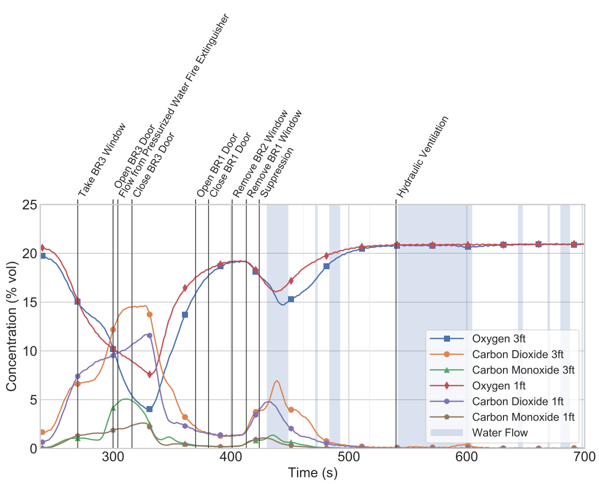
increase in flame spread from bedroom 4 to the hallway, which increased the production of combustion gases. Gas concentrations reflected this, particularly at the mid hallway and end hallway locations, where the impact of gas flow through open exterior vents was marginal. Following the opening of the bedroom 3 door, flaming combustion outside bedroom 3 was extinguished with a pressurized water fire extinguisher, which decreased the localized production of combustion gases. Hallway gas concentrations at all locations improved.



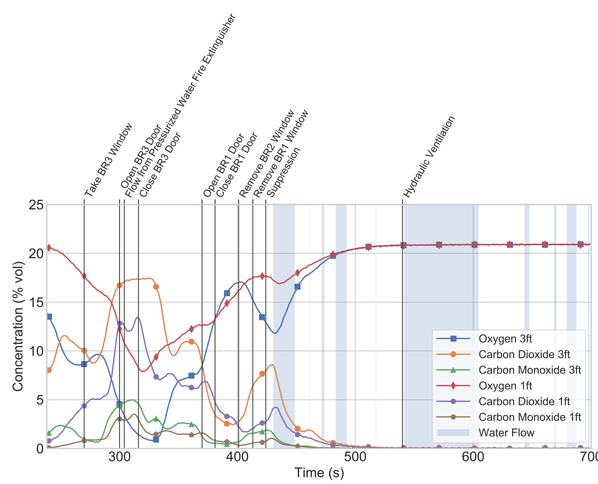
(a) Living Room Entryway Hall Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.142: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 8b.

Approximately 60 s after water flow in the hallway, flames spread back into the hallway from the bedroom 4 fire. This flame spread resulted in an increase of combustion gases in the hallway, most notably at the end hallway location, which was far from an exterior vent. Removal of the bedroom 2 window created an exterior vent, which increased gas flows toward the end hallway location and through bedroom 2. Combustion gases flowed down the hallway toward the vent, which worsened gas concentrations at the mid hallway and 3 ft above the floor at the end hallway. At the same time, entrained air through the window improved gas concentrations 1 ft above the floor at the end hallway. Increased inflow through the front door improved start hallway gas concentrations.

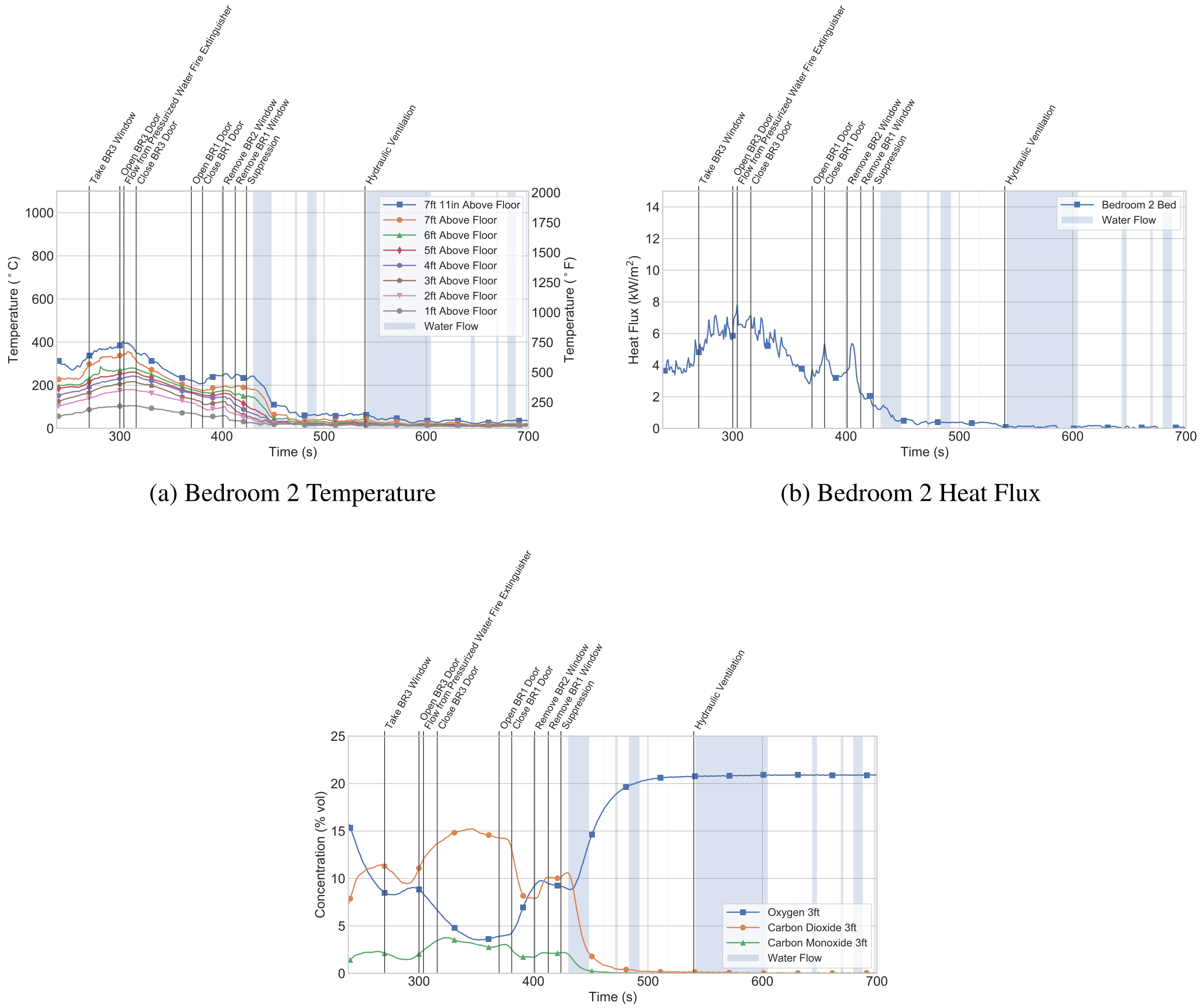
Suppression decreased the production of combustion gases in bedroom 4 and caused unidirectional air inflow through the bedroom 2 window. Hallway gas concentrations improved to pre-ignition conditions at the end hallway, mid hallway, and start hallway locations prior to hydraulic ventilation. Unidirectional inflow through the front door maximized the impact of hydraulic ventilation at the living room entryway location.

5.9.4 Bedroom 2

The bedroom 2 door was open at the time of ignition, which allowed combustion gases from the bedroom 4 fire to flow into the bedroom. Bedroom 2 temperatures at the time of initial intervention ranged from 340 °C (644 °F) at the ceiling to 85 °C (185 °F) 1 ft above the floor, as shown in Figure 5.143a. Temperatures in bedroom 2 continued to increase until water flow from the pressurized water fire extinguisher suppressed the hallway fire. There was a continued decrease in temperatures until 380 s, when bedroom 4 temperatures began to increase, most notably at the ceiling. The increase coincided with the recovery of mid hallway and end hallway temperatures as the bedroom 4 fire began to spread back into the hallway.

The bedroom 2 window was opened 131 s after the initial intervention (401 s post-ignition). The resulting bidirectional flow through the ventilated bedroom 2 window lifted the smoke layer in the bedroom and temperatures 6 ft and below decreased. Temperatures 7 ft and above remained nominally steady as those measurement elevations were above the window soffit.

Suppression of the bedroom 4 fire cooled combustion gases, which contracted and dropped in pressure. This resulted in a temporary unidirectional inflow through the window. Initial water flow decreased temperatures below 115 °C (239 °F). Additional water flows and bidirectional flow through the window decreased temperatures below 70 °C (158 °F). Unidirectional inflow through the window during hydraulic ventilation decreased temperatures below 30 °C (86 °F).



(a) Bedroom 2 Temperature

(b) Bedroom 2 Heat Flux

(c) Bedroom 2 Gas Concentration

Figure 5.143: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 8b.

Heat flux to the bed at the time of intervention was 4.8 kW/m^2 and was increasing, as combustion gases continued to flow into the bedroom (Figure 5.143b). The heat flux on the bed followed a similar trend as temperatures in the center of the room and peaked to 7.8 kW/m^2 prior to suppression. Water flow in the hallway suppressed flaming combustion and cooled combustion gases that flowed toward bedroom 2. As a result, heat flux correspondingly decreased.

Between 370 s and 381 s, the heat flux on the bed peaked to 5.4 kW/m^2, which coincided with the opening and closing of the bedroom 1 door. The opened bedroom 1 door increased gas flows in the hallway, as higher-pressure gases flowed into bedroom 1 and lower-pressure gases flowed into the hallway. This led to increased gas velocities into bedroom 2. Heat flux increased despite the decreasing temperatures. The closed bedroom 1 door reduced gas flows through the hallway and the heat flux to the bed decreased.

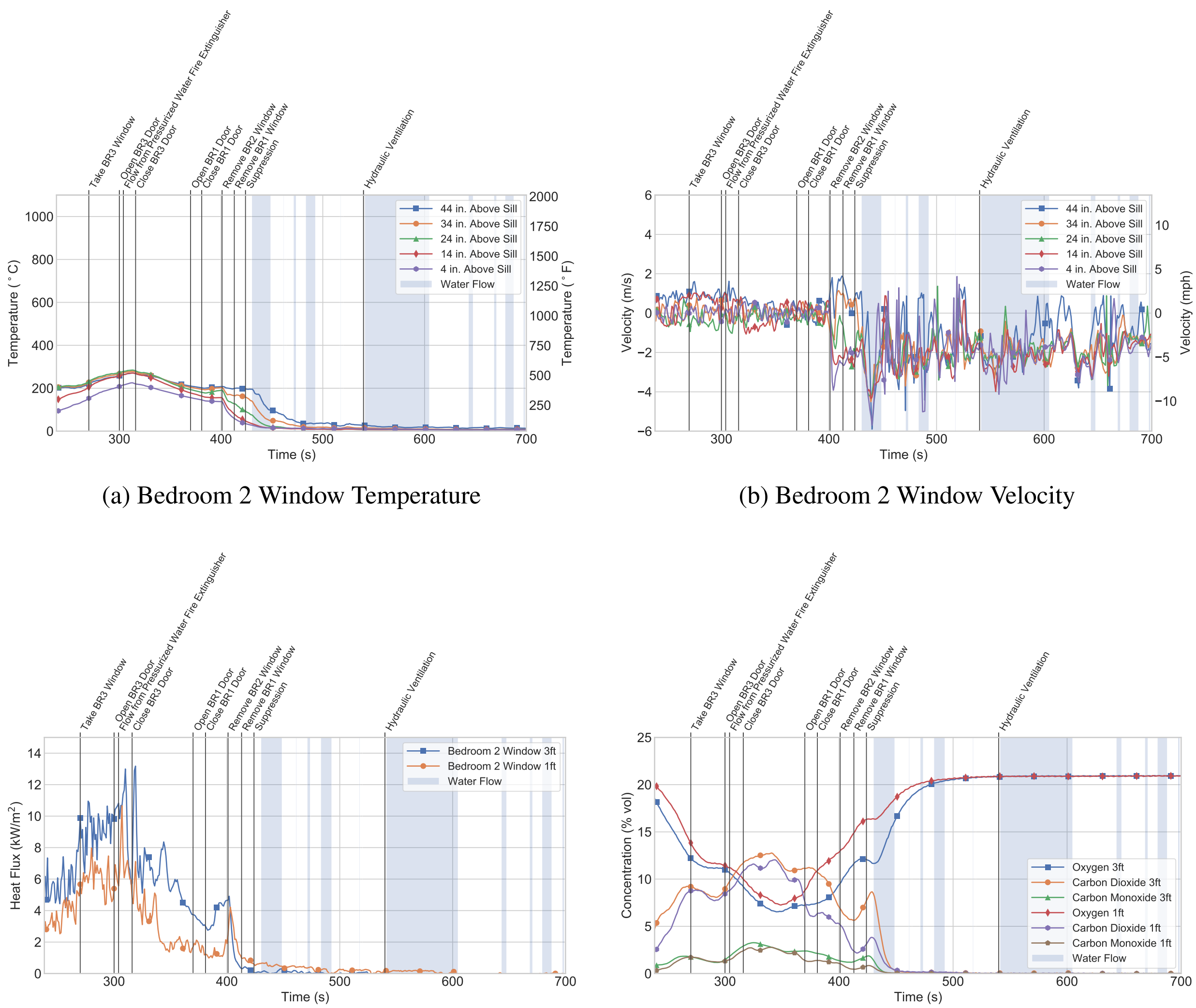
The removal of the bedroom 2 window created an area of low pressure in the bedroom. Higher-pressure combustion gases flowed toward the vent, which caused heat flux to temporarily increase to 5.4 kW/m^2. The heat flux dropped as bidirectional flow through the window lifted the smoke layer. Combustion gases exhausted through the vent and cooler air was entrained into the bedroom. Heat flux continued to decrease with suppression and dropped below 0.6 kW/m^2. Hydraulic ventilation exhausted accumulated combustion gases from bedroom 2, which further decreased heat flux to below 0.1 kW/m^2.

At the time of intervention, gas concentrations were 8.5% O_2, 11.3% CO_2, and 2.1% CO, which indicated that the smoke layer had descended to at least the top of the bed (Figure 5.143c). Following suppression of the hallway fire with the pressurized water fire extinguisher, temperatures throughout the hallway and bedroom 2 cooled. The combustion gases in bedroom 2 dropped in elevation within the space as they cooled, which led to an increase in measured gas concentrations. The gas concentrations at the bed level peaked at 3.5% O_2, 15.2% CO_2, and 3.8% CO. Gas concentrations began to improve as the production of combustion gases from the hallway decreased. Toggling the bedroom 1 door increased gas flow and mixing at the end hallway and in bedroom 2. The gas concentrations in bedroom 2 further recovered toward pre-ignition levels as these gases mixed in bedroom 2. Following the removal of the bedroom 2 window, the O_2 concentrations decreased and CO_2 and CO concentrations increased for approximately 10 s, due to the increased flow of combustion gases through the bedroom. As bidirectional flow was established through the window and suppression of the bedroom 4 fire resulted in a unidirectional intake, gas concentrations at the bed improved. Gas concentrations returned to pre-ignition conditions prior to hydraulic ventilation.

Similar to temperatures in the center of the room, bedroom 2 window temperatures were increasing prior to intervention and ranged from 230 °C to 155 °C (446 °F to 311 °F), as shown in Figure 5.144a. Window temperatures continued to increase and peaked at 285 °C (545 °F) at the top of window. Water flow in the hallway extinguished localized combustion and hallway temperatures cooled. As a result, the window temperatures decreased.

The removal of the bedroom 2 window created an exterior vent in the bedroom. A flow path between the fire room and the exterior of the structure established. Combustion gases exhausted from the top of the window at 1.8 m/s (4.0 mph), which caused temperatures at the top two locations to increase. Air was entrained through the bottom of the sill at -3.0 m/s (-6.7 mph), which decreased temperatures at the bottom three locations (Figure 5.144b).

Suppression created an area of low pressure in the hallway and fire room due to gas contraction. Flow through the window became unidirectional inflow at -5.9 m/s (-13.2 mph), which decreased window temperatures at all elevations. The initial water flow decreased window temperatures below 95 °C (203 °C) and continued to decrease to below 30 °C (85 °F) prior to hydraulic ventilation. The unidirectional inflow in excess of -4.1 m/s (-9.2 mph) established during hydraulic ventilation dropped window temperatures below 20 °C (68 °F).



(a) Bedroom 2 Window Temperature

(b) Bedroom 2 Window Velocity

(c) Bedroom 2 Window Heat Flux

(d) Bedroom 2 Window Gas Concentration

Figure 5.144: Post-intervention window temperature, heat flux, and gas concentration in bedroom 2 during Experiment 8b.

At the time of intervention, the smoke layer in bedroom 2 had descended below the 1 ft level. Heat flux below the bedroom 2 window was 9.9 kW/m^2 3 ft above the floor and 5.7 kW/m^2 1 ft above the floor (Figure 5.144c). The heat flux below the window continued to increase as combustion gases flowed into bedroom 2. Heat flux peaked to 13.0 kW/m^2 and 10.7 kW/m^2 at the 3 ft and 1 ft elevations, respectively. Water flow in the hallway cooled combustion gases that flowed into bedroom 2, which decreased the flow of gases and resulting heat flux. The heat flux at both elevations increased following the increased gas flows through the end hallway due to the toggling of bedroom 1 door, but immediately decreased upon removal of the bedroom 2 window. Bidirectional flow through the ventilated window lifted the smoke layer, which caused heat flux to decrease below 0.7 kW/m^2. Unidirectional inflow during suppression decreased heat flux to negligible levels prior to hydraulic ventilation.

Similar to the window heat flux measurements, gas concentrations at the time of intervention indicated that the smoke layer had descended below the 1 ft level. Gas concentrations below the bedroom 2 window were 12.2% O_2, 9.2% CO_2, and 1.8% CO 3 ft above the floor and 13.8% O_2, 8.8% CO_2, and 1.7% CO 1 ft above the floor (Figure 5.144d). Gas concentrations continued to increase following the use of the pressurized water fire extinguisher in the hallway as combustion gases cooled and dropped in elevation. Gas concentrations peaked at values above ambient to 6.5% O_2, 12.8% CO_2, and 3.3% CO 3 ft above the floor and 7.3% O_2, 12.0% CO_2, and 2.8% CO 1 ft above the floor. Concentrations improved as the production of gases from the hallway stopped.

Following the ventilation of the bedroom 2 window, the exhaust was primarily accumulated combustion gases, which caused CO_2 and CO to worsen. As air was entrained through the window following suppression, gas concentrations improved to 20.9% O_2, 0.1% CO_2, and 0% CO at both elevations above the floor.

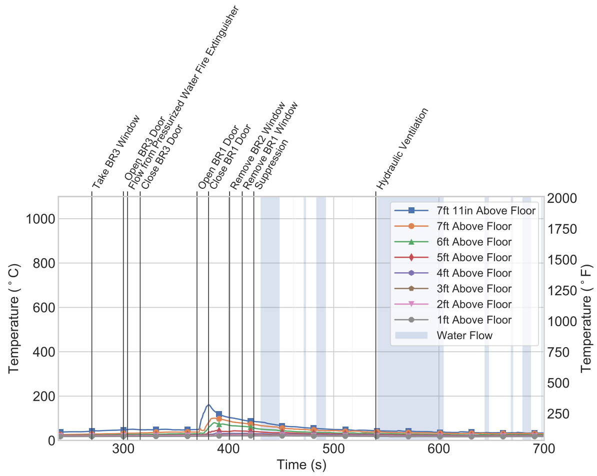
5.9.5 Bedroom 1

The bedroom 1 door was closed at the time of ignition, which limited bulk gas flow into the bedroom. Combustion gases flowed into bedroom 1 through the HVAC supply vent and through the leakage area around the closed door. At the time of intervention, bedroom 1 temperatures ranged from 40 °C (104 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor, as shown in Figure 5.145a.

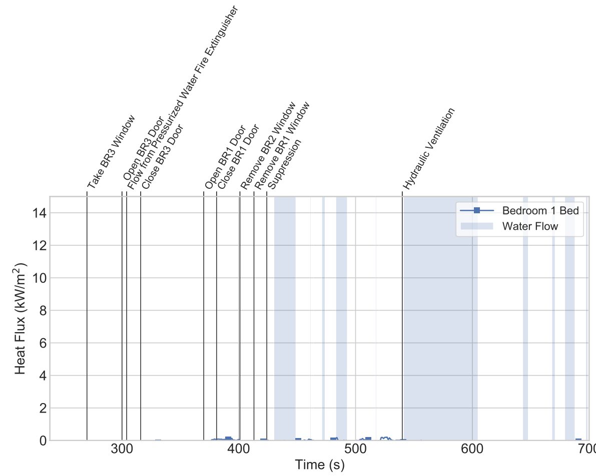
When the bedroom 1 door was opened, higher-pressure gases in the hallway flowed into the lower-pressure bedroom and lower-pressure gases flowed toward the fire room. The inflow of combustion gases increased temperatures to 160 °C (320 °F) at the ceiling and 20 °C (68 °F) 1 ft above the floor. The closure of the bedroom 1 door stopped the flow of combustion gases into the bedroom. Bedroom temperatures began to decrease. The removal of the bedroom 1 window created an exterior vent, and a flow path established the bedroom and the exterior. Accumulated combustion gases flowed out of the bedroom and cool air flowed into the bedroom, which further decreased temperatures.

At the time of intervention, heat flux to the bed was negligible due to the closed door, as shown in Figure 5.145b. The open bedroom 1 door allowed combustion gases to flow into the bedroom, but the minimal flow of combustion gases and low temperatures resulted in a nominal change in heat flux.

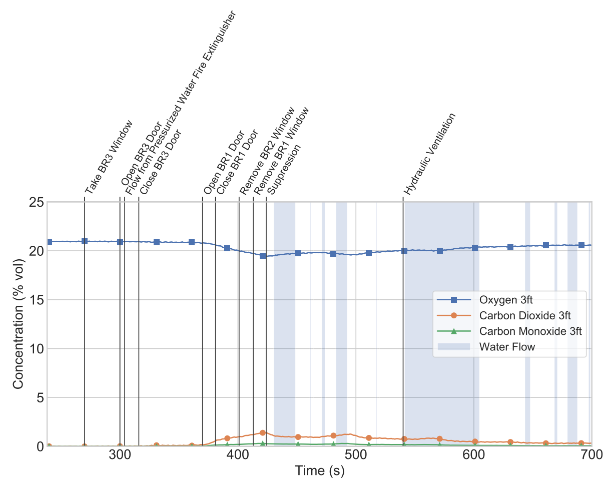
At the time of intervention, gas concentrations at the bed were 20.9% O_2, 0% CO_2, and 0% CO (Figure 5.145c). Gas concentrations increased to 19.5% O_2, 1.4% CO_2, and 0.3% CO following the opening of the bedroom door. The closed bedroom 1 door prevented further accumulation of combustion gases in the bedroom. Accumulated combustion gases exhausted to the exterior following the removal of the bedroom 1 window. The closed bedroom door minimized the effects of suppression and hydraulic ventilation. Gas concentrations were slow to completely recover as the lower temperatures resulted in a minimal pressure rise. The lack of pressure limited gas flows to the exterior.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



(c) Bedroom 1 Gas Concentration

Figure 5.145: Post-intervention bed level temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 8b.

The bathroom 1 door was open at the time of ignition, which allowed gas flow between bedroom 1 and bathroom 1. Additionally, gas flowed through the HVAC supply vent. At the time of intervention, bathroom temperatures ranged from 25 °C (77 °F) at the ceiling to 15 °C (59 °F) 1 ft above the floor (Figure 5.146). Flow through the open bedroom 1 door peaked bathroom temperatures between 55 °C to 25 °C (131 °F to 77 °F), which was less than the temperature increase in the adjacent bedroom. The closed bedroom 1 door stopped the flow of combustion gases into bedroom 1 and bathroom 1. The effect of the closed door was minimal in the bathroom, as it was one room removed from the bedroom door. Bathroom 1 was adjacent to, but not part of the flow path between bedroom 1 and the exterior, which minimized the impact of bidirectional flow through the window. Bathroom ceiling temperatures remained in excess of 50 °C (122 °F) for the duration of the experiment.

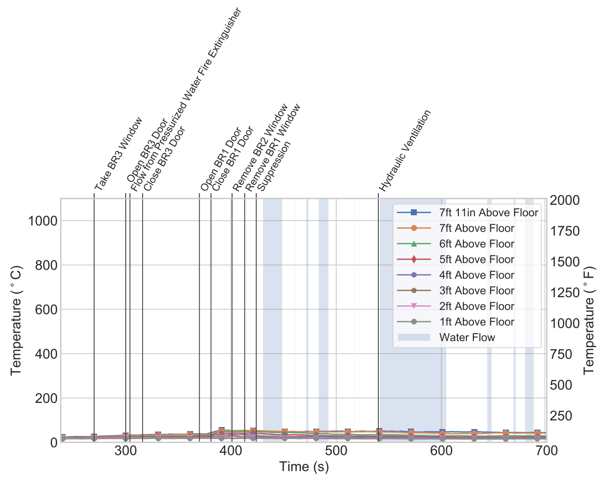


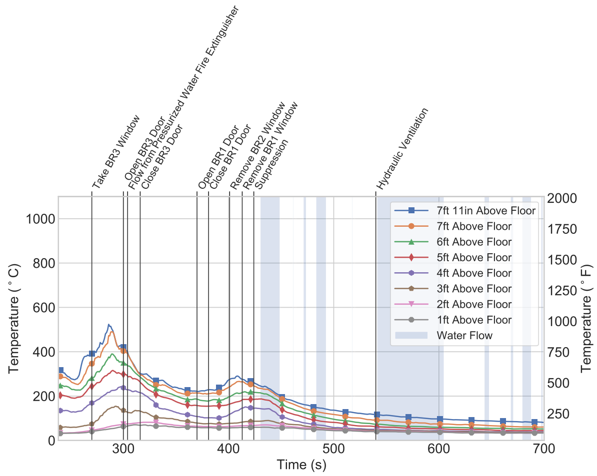
Figure 5.146: Post-intervention temperatures in bathroom 1 during Experiment 8b.

5.9.6 Common Space

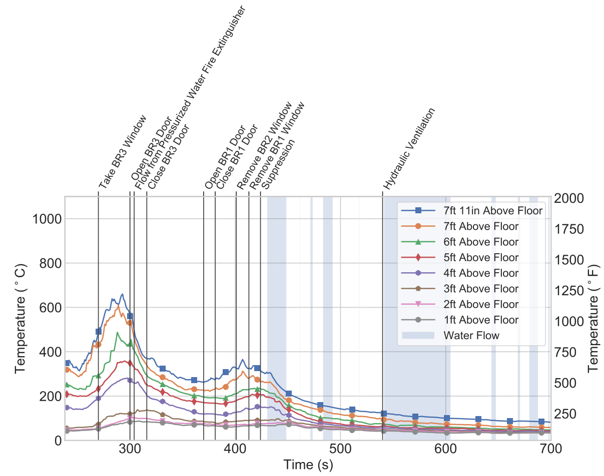
At the time intervention, the smoke layer in the common space had descended to approximately 3 ft. Kitchen temperatures ranged from 390 °C (734 °F) at the ceiling to 50 °C (122 °F) 1 ft above the floor, as shown in Figure 5.147a. The living room, which was along the flow path between bedroom 4 and the front door, had higher temperatures due to the increased flow of exhaust gases. Living room temperatures ranged from 490 °C (914 °F) at the ceiling to 50 °C (122 °F) 1 ft above the floor as shown in Figure 5.147b. Combustion gases continued to flow into the common space and peak ceiling temperatures exceeded 525 °C (977 °F) in the kitchen and 660 °C (1220 °F) in the living room.

Suppression of flaming combustion in the hallway with a pressurized water fire extinguisher reduced the production of combustion gases in the hallway, and temperatures within the common space correspondingly decreased. As flames spread back into the hallway, the kitchen and living room temperatures began to increase. Ceiling temperatures increased to 365 °C (689 °F) in the living room and 290 °C (554 °F) in the kitchen.

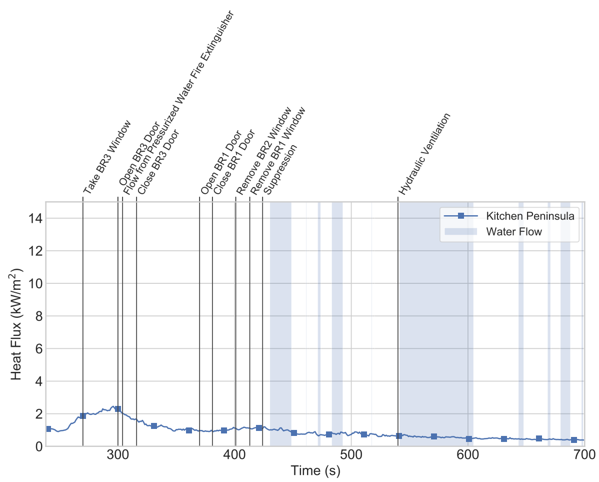
Removal of the bedroom 2 window increased the flow of gases through bedroom 1 due to the creation an exterior vent. This decreased the flow of gases toward the front door and temperatures in the common space began to decrease. Suppression decreased the heat release rate of the bedroom 4 fire, which decreased common space temperatures below 215 °C (419 °F). Additional water flow and entrainment through the front door decreased common space temperatures below 130 °C (266 °F). Flow through the bedroom 4 vents became unidirectional toward the exterior during hydraulic ventilation and flow through the front door became unidirectional inflow. Common space temperatures decreased below 100 °C (212 °F).



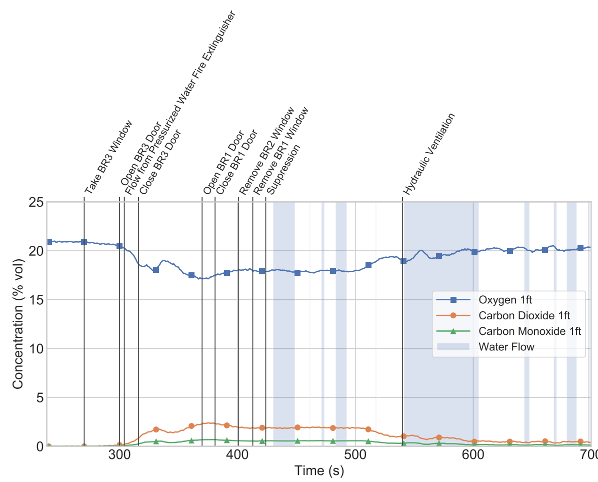
(a) Kitchen Temperature



(b) Living Room Temperature



(c) Kitchen Heat Flux



(d) Kitchen Gas Concentration

Figure 5.147: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 8b.

The kitchen was adjacent to the flow path between bedroom 4 and the front door. As a result, the influence of air entrainment in the kitchen was less than in the living room and the smoke layer eventually reached the floor. At the time of intervention, heat flux was 1.9 kW/m^2 1 ft above the kitchen floor, as shown in Figure 5.147c. Combustion gases flowed into the kitchen, and the heat flux peaked at 2.5 kW/m^2. Suppression of the hallway fire decreased the flow of combustion gases through the common space and the heat flux in the kitchen decreased, but the smoke layer remained near the floor. As a result, the kitchen heat flux remained nominally constant at approximately 1.0 kW/m^2. Suppression decreased the heat release rate of the bedroom 4 fire, which decreased the heat flux of combustion gases in the kitchen. Hydraulic ventilation through the bedroom 4 window and bidirectional flow through the front door lifted the smoke layer in the common space, which decreased the heat flux to below 0.5 kW/m^2.

At the time of intervention, gas concentrations 1 ft above the floor in the kitchen were 20.9% O_2, 0.1% CO_2, and 0% CO (Figure 5.147d). Similar to the kitchen heat flux, gas concentrations worsened to 17.1% O_2, 2.4% CO_2, and 0.7% CO following hallway suppression, as the smoke layer descended in the kitchen. They remained steady through suppression. Gas concentrations began to slowly improve following suppression as the production of combustion gases stopped. Hydraulic ventilation increased air inflow through the front door, which increased the rate that gas concentrations returned to pre-ignition values. The slower recovery time of the kitchen gases compared to other locations was a result of the location being adjacent to the flow path and the kitchen cabinets, which impeded gas flow.

5.10 Experiment 9

The search tactics in Experiment 9 were designed to evaluate door initiated operations conducted during interior suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide window in the bedroom 4 were removed and the door to bedroom 4 was opened. The front door, doors to bedrooms 2 and 3, and door to bathroom 3 were opened. The doors to bedroom 1 and bathroom 1 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

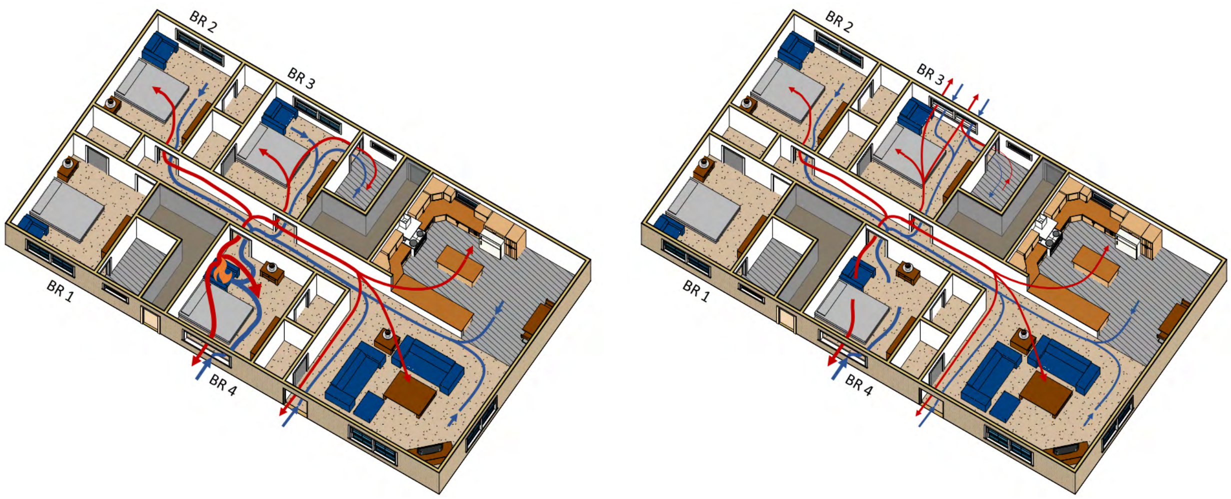
Post bedroom 4 flashover, the suppression crew entered through the front door and began interior operations. As the suppression crew reached the fire compartment and flowed water, the search crew proceeded to bedroom 3 and opened the lower panes of the double-wide bedroom 3 window. The crew then proceeded to bedroom 2. Simultaneously, the interior crew opened the lower panes of the double-wide bedroom 2 window and an exterior crew on side A opened the lower panes of the double-wide bedroom 1 window. The exterior crew entered bedroom 1 and opened the bedroom 1 door. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the bedroom 4 windows. 91 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 336 gallons.

Table 5.19: Experiment 9 Event Times

	Elapsed Time			
Event	From Ignition		From Intervention	
	(mm:ss)	(s)	(mm:ss)	(s)
Ignition	00:00	0	—	—
Suppression	04:47	287	00:00	0
Open BR3 Window	04:59	299	00:12	12
Open BR1 & BR2 Windows	05:22	322	00:35	35
Open BR1 Door	05:36	336	00:49	49
Hydraulic Ventilation	06:52	412	02:05	125

Figures 5.148 and 5.149 show the change in gas flows throughout the structure as a result of fire department interventions. Prior to intervention, the fire in bedroom 4 had transitioned through flashover. Flow paths were established between the bedroom 4 fire and the bedroom 4 window and between the bedroom 4 fire and the front door, as shown in Figure 5.148a. These flow paths provided a source of air to sustain combustion and allowed products of combustion to exhaust from the structure. The initial fire department intervention was the entry of the suppression crew through the front door. The crew advanced into the structure with an 1 3/4 in. handline equipped with a combination nozzle set to flow a straight stream at 150 gpm and a nozzle pressure of 50 psi. The suppression crew first flowed from the start hallway location and advanced toward the fire room using a flow and move approach while manipulating the nozzle in an O-pattern. As the suppression crew reached the fire room and applied water directly to burning surfaces, the search crew entered bedroom 3. The lower panes of the bedroom 3 windows were opened 12 s later. This action

created a new vent in bedroom 3, which acted as a unidirectional exhaust for the majority of the post-intervention period, as shown in Figure 5.148b.



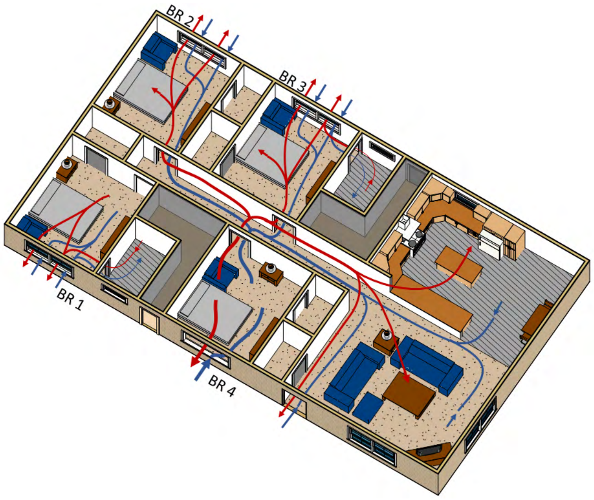
(a) Flows Prior to Intervention

(b) Open BR3 Window

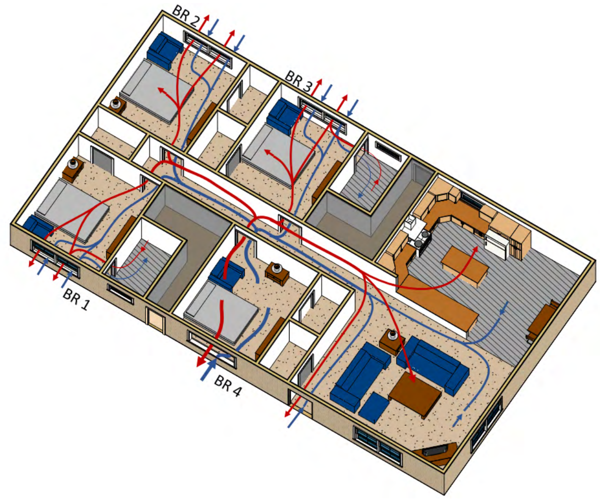
Figure 5.148: Changes in flow in structure following fire department interventions in Experiment 9.

The crew continued their search in bedroom 2. The bedroom 2 windows were opened 35 s after intervention, which established a new flow path between the fire room and the bedroom. Higher-temperature gases exhausted from the structure through the upper portion of the vent and cooler air flowed in through the lower portion, as shown in Figure 5.149a. Simultaneously, an exterior crew opened the lower panes of the bedroom 1 window (Figure 5.149a). Higher-temperature gases accumulated in bedroom 1 through the leakage area around the closed door and through the HVAC system, which drove bidirectional flow between the bedroom and the exterior. The exterior crew then entered bedroom 1 and opened the door 15 s later (Figure 5.149b).

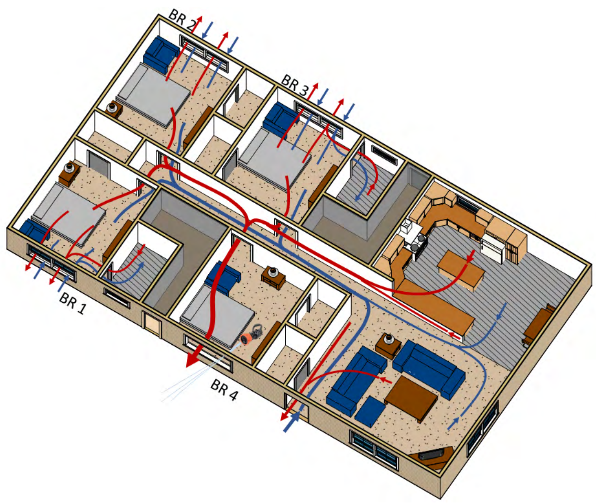
Products of combustion continued to exhaust through exterior vents at 125 s after initial intervention. Hydraulic ventilation with a stationary, wide-fog pattern decreased the pressure in the bedroom 4 window, which drew products of combustion from remote areas of the structure toward bedroom 4. Fresh air was drawn into the structure through other ventilation openings, particularly through the bedrooms 1, 2, and 3 windows and the front door (Figure 5.149c).



(a) Open BR1 & BR2 Windows



(b) Open BR1 Door

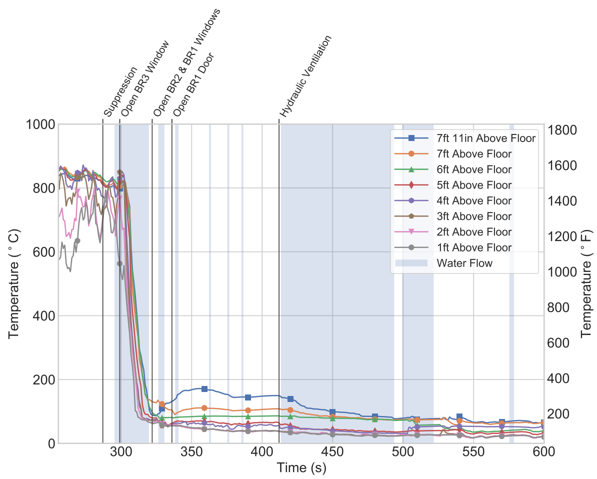


(c) Hydraulic Ventilation

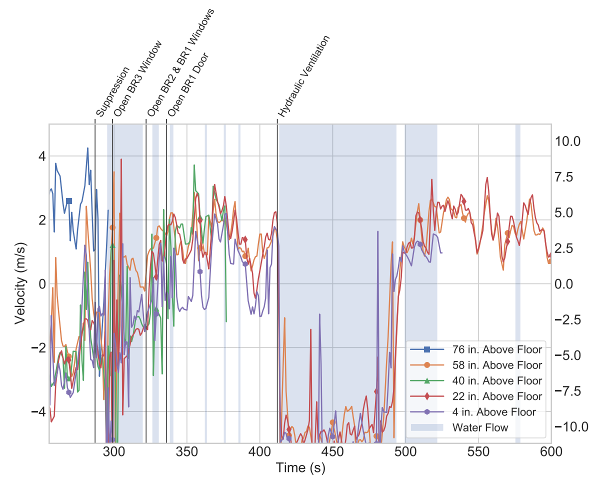
Figure 5.149: Changes in flow in structure following fire department interventions in Experiment 9.

5.10.1 Bedroom 4

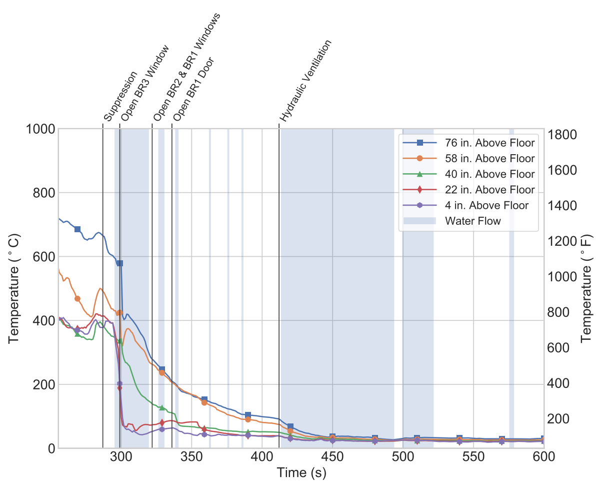
Temperatures in bedroom 4 immediately prior to the start of suppression were uniformly in excess of 600 °C (1112 °F), as shown in figure 5.150a. This indicated that the bedroom was in a steady, post-flashover state. Bidirectional flows were maintained in the bedroom 4 doorway and in the bedroom 4 window, with burning primarily occurring close to those vents. Figure 5.150b shows that the majority of the bedroom 4 doorway acted as an inlet at the time of intervention. Velocities at measurement locations below 58 in. ranged from -0.6 m/s to -1.9 m/s (-1.3 mph to -4.3 mph) immediately prior to the start of suppression. Air from the front door and remote portions of the structure was entrained into the fire room through the lower portion of the doorway. Corresponding inlet temperatures in the bedroom 4 doorway ranged from 490 °C to 378 °C (914 °F to 712 °F) (Figure 5.150c). Higher-temperature gases flowed through the upper portion of the door into the hallway (76 in. above the floor). Velocity and temperature measurements were 1.1 m/s (2.5 mph) and 690 °C (1274 °F) at the time of intervention, respectively.



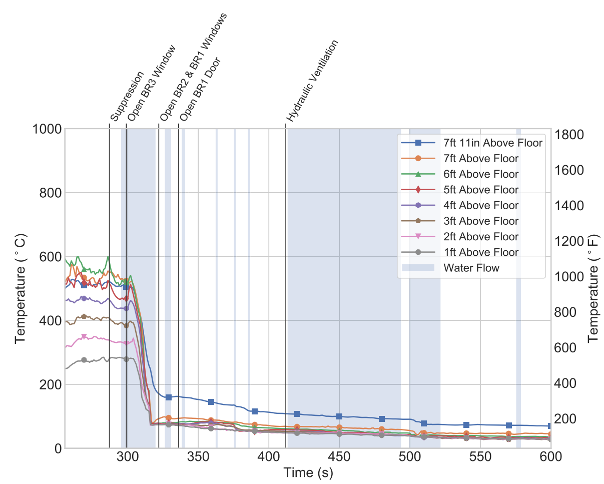
(a) Bedroom 4 Temperature



(b) Bedroom 4 Doorway Velocity



(c) Bedroom 4 Doorway Temperature



(d) Bedroom 4 Closet Temperature

Figure 5.150: Temperature time histories in the doorway and closet of bedroom 4 for the period following fire department intervention in Experiment 9.

Temperatures in bedroom 4 and the bedroom 4 doorway remained steady until 12 s after intervention, when the suppression crew was able to apply water directly into the fire room. This action caused temperatures to sharply decrease. The temperature decrease continued as the suppression crew advanced into bedroom 4 and extinguished the fire. After the bedroom fire was controlled, products of combustion exhausted through the open window until hydraulic ventilation was initiated. Although the 40 in. and 76 in. velocity probes were damaged during suppression, the remaining two velocity probes indicated that hydraulic ventilation created a unidirectional flow through the bedroom 4 doorway. Velocities were between -3.5 m/s to -6.5 m/s (-7.8 mph to -14.5 mph). This indicated that gases from remote areas of the structure flowed toward the exterior vent at the bedroom 4 window.

Temperatures in the bedroom 4 closet all increased at 218 s post-ignition, as the upper portion of the door burned through (Figure 5.150d). Temperatures remained steady, measuring 520 °C (968 °F) at the ceiling and 280 °C (536 °F) 1 ft above the floor until 302 s (14 s after intervention). Following water flow in bedroom 4, all temperatures below the ceiling decreased to under 100 °C (212 °F). These temperatures continued to decrease through hydraulic ventilation and had dropped below 45 °C (113 °F) when crew stopped flowing water. The top temperature measurement remained elevated as the thermocouple remained in physical contact with the ceiling versus measuring the gas temperature.

5.10.2 Bedroom 3

The door between bedroom 3 and the hallway was opened prior to ignition, which allowed the room to fill with combustion gases. Visibility in the bedroom 3 camera was lost as the smoke layer descended to the floor. At the time of intervention, temperatures in bedroom 3 (Figure 5.151) ranged from 215 °C (419 °F) at the ceiling to 56 °C (133 °F) 1 ft above the floor. Temperatures in bedroom 3 began to decrease immediately after the start of water flow in the hallway, 8 s after intervention (295 s after ignition). This decrease was accelerated after the lower panes of the bedroom 3 window were opened, which created a new exterior vent in bedroom 3. Products of combustion exhausted from the window, which lifted the smoke layer in bedroom 3 and temperature at elevations 3 ft and below decreased. Hydraulic ventilation decreased temperature below 70 °C (158 °F) at all elevations.

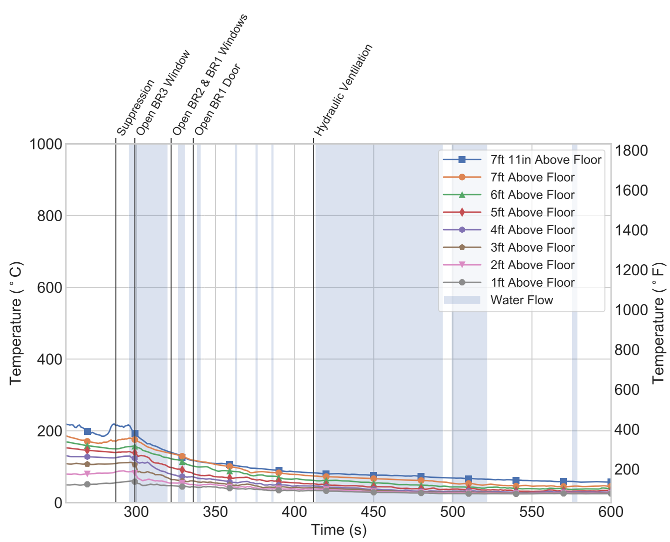
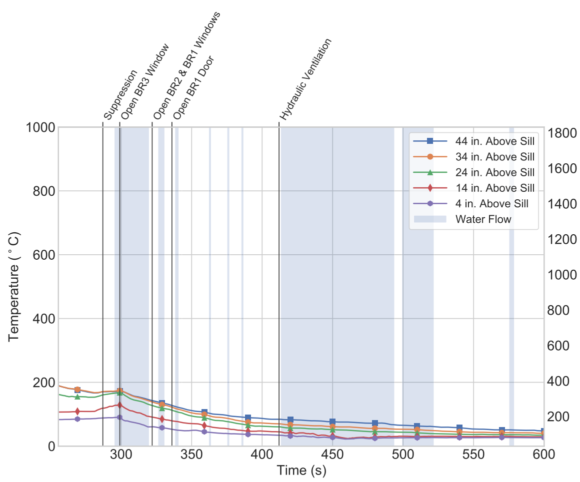


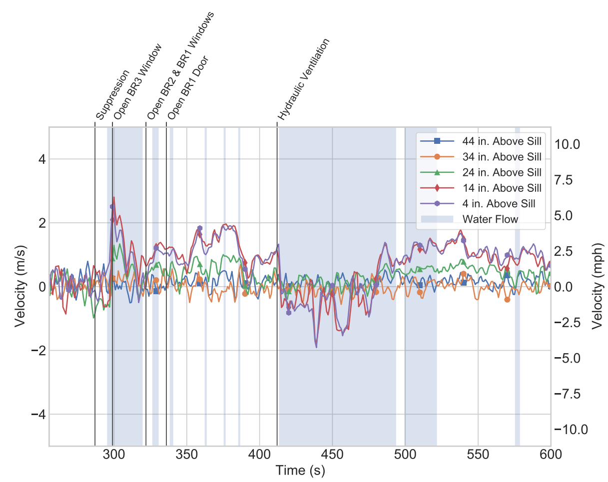
Figure 5.151: Post-intervention temperature in bedroom 3 during Experiment 9.

Temperatures in the bedroom 3 window (Figure 5.152a) were steady prior to the opening of the window. Immediately after the lower pane of the window was opened, temperatures began to continuously decrease and there was initially a unidirectional exhaust vent with velocities between

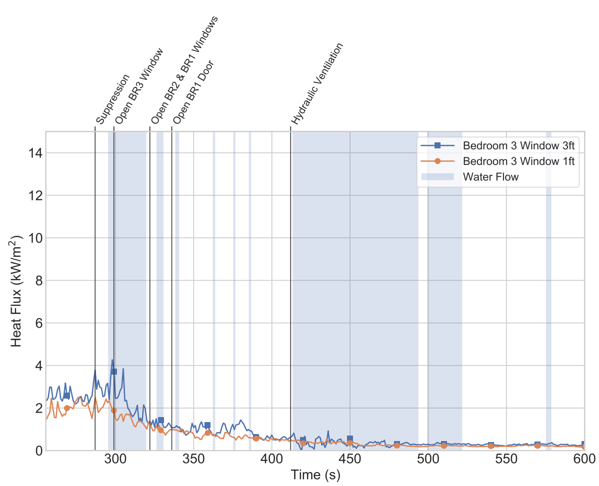
2.8 m/s and 3.8 m/s (6.3 mph to 8.5 mph). Note that because only the bottom pane was opened, the top two probes remained near zero. The magnitude of the exhaust flow velocities decreased as suppression actions extinguished the bedroom fire which reduced the production of combustion gases. In the period between the end of initial suppression actions and the start of hydraulic ventilation, the flow through the lower panes of the bedroom 3 windows continued to be primarily exhaust. The exhaust velocities ranged between approximately 1 m/s and 2 m/s (2.2 mph to 4.5 mph). When hydraulic ventilation was initiated through the bedroom 4 window, the flow in the bedroom 3 window changed such that the window acted as a unidirectional inlet for the duration of the action, with inlet velocities fluctuating between -0.4 m/s and -2.2 m/s (-0.9 mph to -4.9 mph).



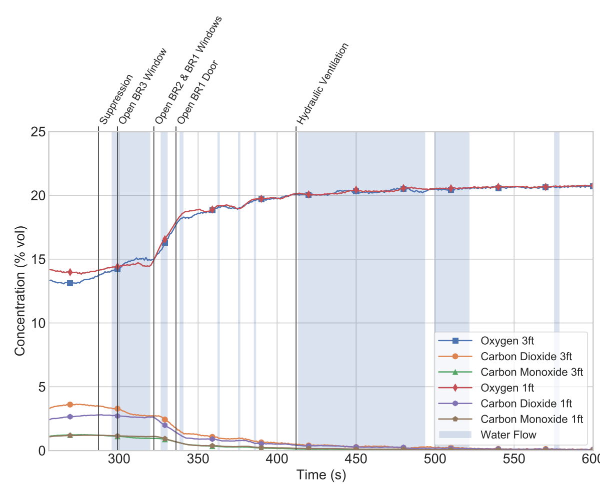
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



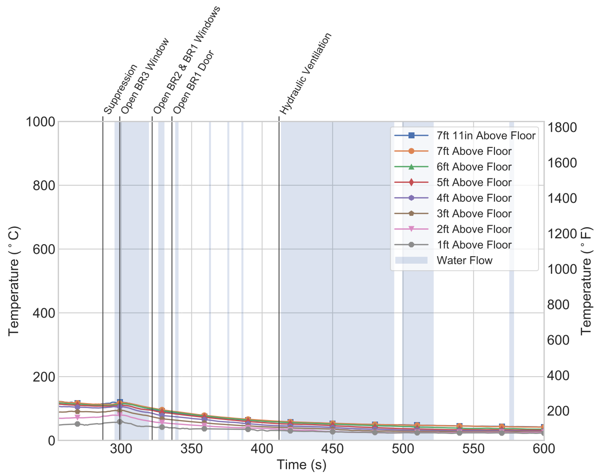
(d) Bedroom 3 Window Gas Concentration

Figure 5.152: Post-intervention window temperature, heat flux, gas concentration, and velocity in bedroom 3 during Experiment 9.

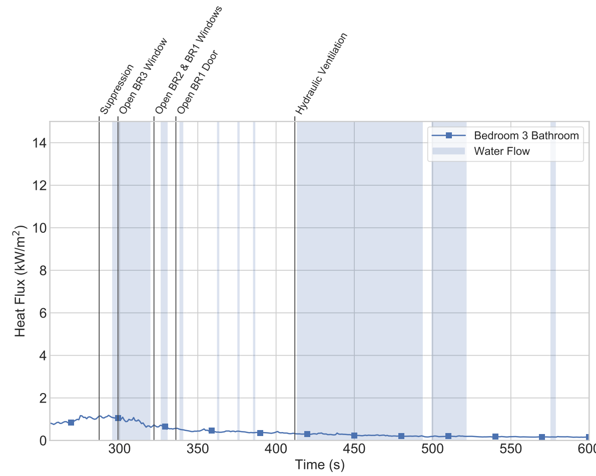
Heat fluxes below the bedroom 3 window are shown in Figure 5.152c. At the time of intervention, the heat flux was 3.8 kW/m^2 and 2.5 kW/m^2 at the 3 ft and 1 ft elevations, respectively. Heat flux at the 3 ft elevation remained elevated during the initial period of unidirectional exhaust. Even though temperatures were decreasing, the increased gas velocity resulted in the higher flux. Heat flux at both elevations in the window began to decrease within 12 s, as the gas temperature and velocity through bedroom 3 decreased. Heat flux decreased below 1.0 kW/m^2 prior to the start of hydraulic ventilation.

Prior to intervention, bedroom 3 had filled with products of combustion. As a result, gas concentrations at the time of intervention were characterized by elevated concentrations of CO and CO_2 and low concentrations of O_2. Gas concentrations at intervention were 13.6% O_2, 3.5% CO_2, and 1.2% CO 3 ft above the floor and 14.1% O_2, 2.8% CO_2, and 1.2% CO 1 ft above the floor, respectively. They remained steady following the entry of the suppression crew and the initial suppression actions. CO and CO_2 concentrations began to decrease and O_2 concentrations began to increase 32 s after intervention (319 s after ignition), as suppression actions reduced the production rate of combustion gases and combustion gases exhausted through ventilation openings in the structure. Gas concentrations returned to near pre-ignition levels prior to the start of hydraulic ventilation.

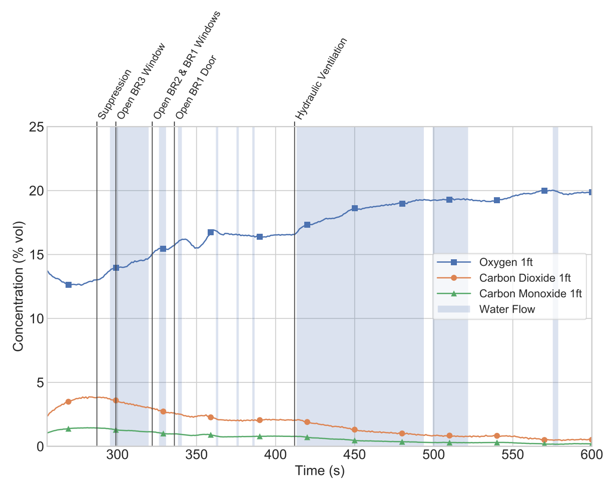
Temperatures (Figure 5.153a) and heat flux (Figure 5.153b) measured in bathroom 3 generally followed a similar trend to those in the adjacent bedroom. Temperatures in bathroom 3 ranged from 115 °C (239 °F) at the ceiling to 53 °C (127 °F) 1 ft above the floor at the time of intervention. The heat flux measured 1 ft above the floor was 1.2 kW/m^2. Heat flux and temperatures remained steady in the time period between suppression crew entry and the opening of the bedroom 3 window. Simultaneous with window opening, temperatures and heat flux in bathroom 3 began to decrease, as suppression cooled gases and the exhaust continued through the bedroom 3 window. The heat flux decreased to negligible values prior to the end of initial suppression actions. Temperatures gradually decreased below 60 °C (140 °F) in the period between suppression and hydraulic ventilation.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



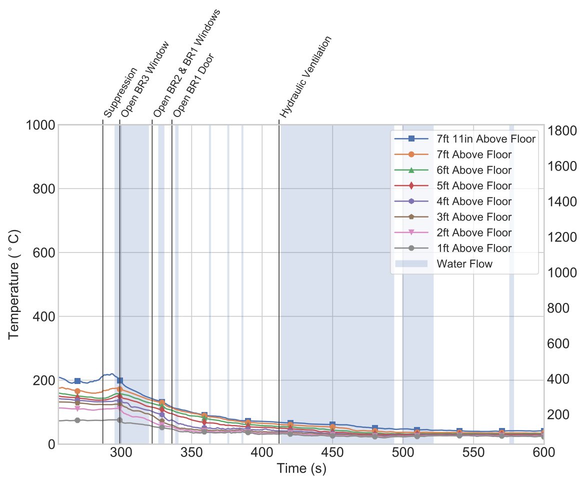
(c) Bathroom 3 Gas Concentration

Figure 5.153: Post-intervention temperature, heat flux, and gas concentration in bathroom 3 during Experiment 9.

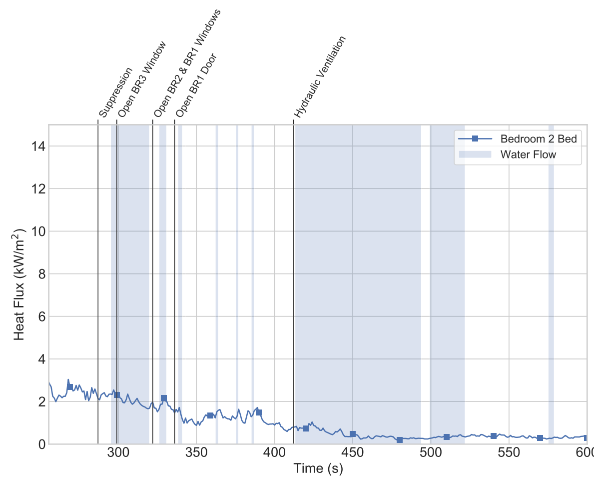
Figure 5.153c shows that O_2, CO_2, and CO concentrations at the time of intervention were 13.0%, 3.8%, and 1.4%, respectively. These values are comparable to those measured at the corresponding location in bedroom 3. CO and CO_2 concentrations decreased following initial intervention. The lack of an local exhaust vent in the bathroom caused these values to decrease at a considerably slower rate than in the adjacent bedroom. At the start of hydraulic ventilation, O_2, CO_2, and CO concentrations were 16.6%, 2.1%, 0.8%, respectively. Although CO and CO_2 concentrations continued to decrease during hydraulic ventilation, these values remained elevated for approximately 200 s following the end of hydraulic ventilation.

5.10.3 Bedroom 2

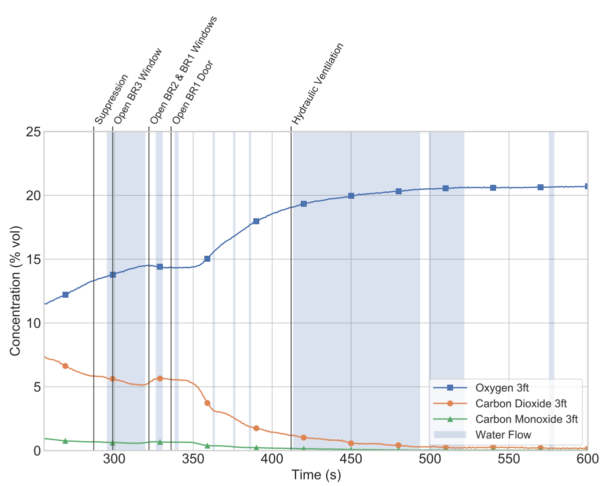
The door between bedroom 2 and the hallway was opened prior to ignition, which allowed the room to fill with products of combustion as the fire in bedroom 4 grew to a post-flashover state. At the time of intervention, temperatures in bedroom 2 (Figure 5.154a) ranged from 213 °C (415 °F) at the ceiling to 70 °C (158 °F) 1 ft above the floor. Temperatures in bedroom 2 trended similarly to those in bedroom 3 and decreased immediately after the start of water flow in the hallway, 8 s after intervention (295 s after ignition). This decrease continued through the opening of the lower panes of the bedroom 2 window. This action accelerated the rate that temperatures decreased, particularly at elevations near the floor. Temperatures continued to decrease through hydraulic ventilation, decreasing below 45°C (113 °F) at all elevations.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

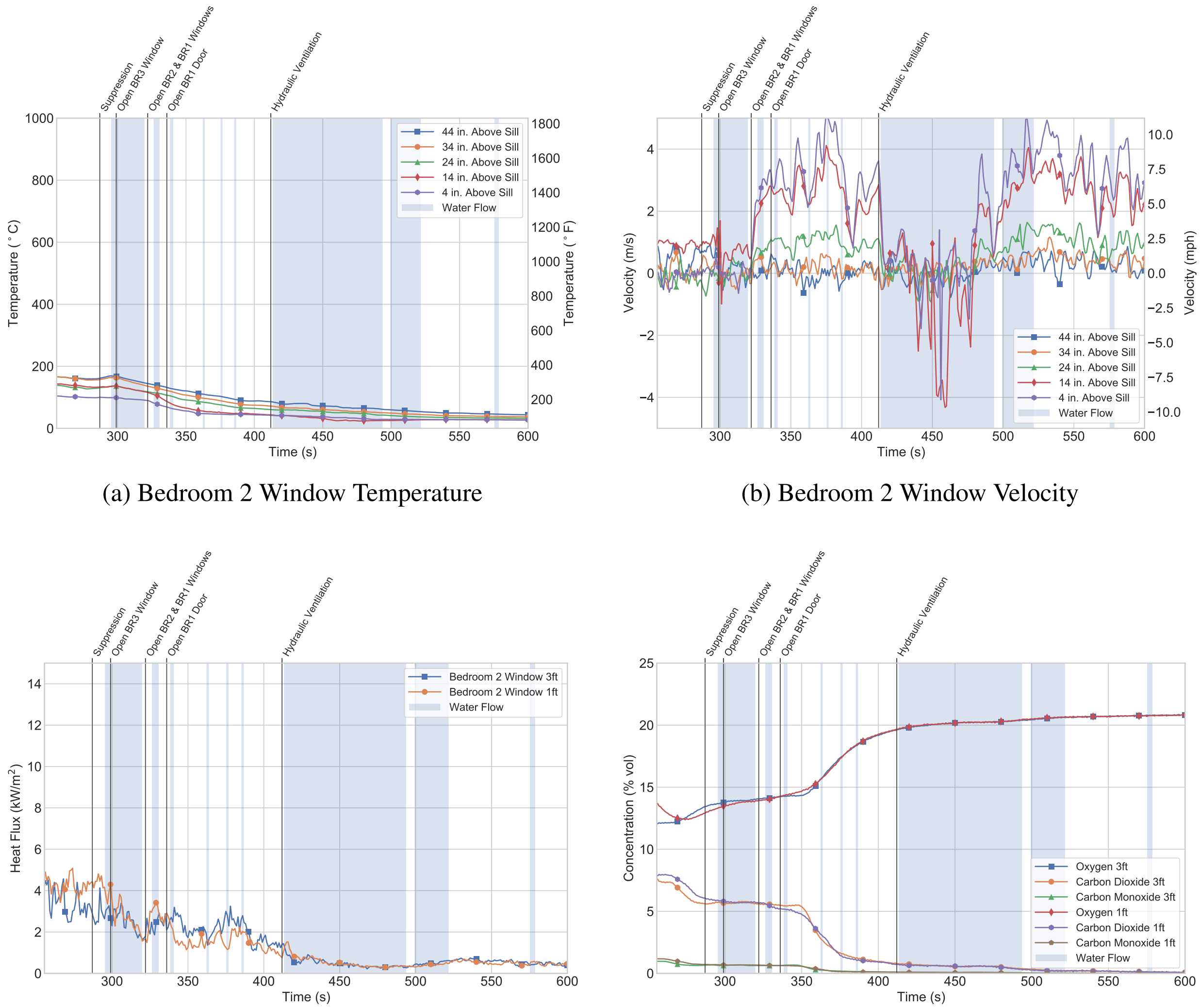
Figure 5.154: Post-intervention bed level temperature, heat flux, and gas concentration in bedroom 2 during Experiment 9.

The bedroom 2 heat flux, in the center of the bed measured 3 ft above the floor, followed a similar trend to the temperatures in center of the room. The heat flux was 2.1 kW/m^2 at the time of intervention, and stayed nominally steady following the entry of the suppression crew. The measured heat flux began to gradually decrease as the suppression crew started flowing water in the hallway. The rate of decrease continued through the opening of the lower panes of the bedroom 2 windows and the remainder of the suppression actions. Heat flux on the bed had decreased to a negligible value prior to the start of hydraulic ventilation.

Peak CO and CO_2 concentrations at the measurement location 3 ft above the floor on the bed in bedroom 2 were measured 240 s after ignition (47 s before fire department intervention). At the time of suppression crew entry, CO and CO_2 concentrations were decreasing from this peak and the O_2 concentration was increasing, as shown in Figure 5.154c. O_2, CO_2, and CO concentrations were 13.3%, 5.8%, and 0.7% at the time of intervention, respectively. During the ventilation sequence, gas concentrations leveled off to steady values until 58 s after intervention (345 s after ignition), when gas concentrations began to improve due to the combined effects of extinguishment of the bedroom fire and the exhaust of products of combustion through the bedroom 2 windows. CO and CO_2 concentrations remained elevated at the start of hydraulic ventilation, with O_2, CO_2, and CO concentrations of 19.0%, 1.2%, and 0.2%, respectively. Hydraulic ventilation caused CO and CO_2 concentrations to decrease to negligible values.

Temperatures in the bedroom 2 window (Figure 5.155a) decreased immediately after suppression. Velocities in the bedroom 2 window, shown in Figure 5.155b, were negligible prior to the opening of the lower panes of the bedroom 2 windows, 35 s after intervention.

Following the opening of the bedroom 2 window, unidirectional exhaust flow was established. Higher-temperature gases exhausted through the open window. Similar to bedroom 3, the top two probes remained blocked by the top window pane; thus, measured velocities were negligible. Exhaust velocities between the 4 in. and 24 in. probes ranged between 1.6 m/s and 5.3 m/s (3.6 mph and 11.9 mph), respectively. Hydraulic ventilation caused both window temperatures and velocities to decrease as the window acted as a unidirectional intake and fresh air was entrained into the bedroom.



(a) Bedroom 2 Window Temperature

(b) Bedroom 2 Window Velocity

(c) Bedroom 2 Window Heat Flux

(d) Bedroom 2 Window Gas Concentration

Figure 5.155: Post-intervention window temperature, heat flux, gas concentration, and velocity in bedroom 2 during Experiment 9.

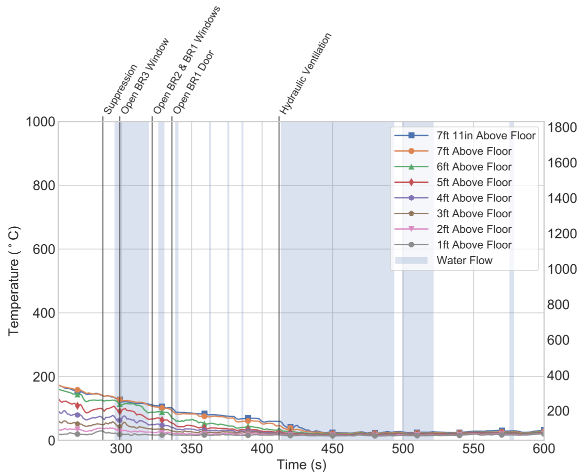
At the time of intervention, the heat fluxes measured below the bedroom window were 4.4 kW/m^2 and 2.9 kW/m^2 at 3 ft and 1 ft above the floor, respectively. Heat flux at both elevations remained steady immediately after intervention and decreased simultaneously with the start of suppression in the hallway. This decrease was punctuated by a brief peak that was observed coincident with the opening of the bedroom 2 window, as combustion gases began to exhaust through the upper portion of the vent. Heat flux at both elevations continued to decrease with magnitudes dropping below 1 kW/m^2 prior to the start of hydraulic ventilation.

Gas concentrations in the bedroom 2 window trended similarly to those in the center of bedroom 2, as shown in Figure 5.155d. At the time of intervention, gas concentrations were 13.4% O_2, 5.6% CO_2, and 0.7% CO at the 3 ft elevation and 12.9% O_2, 6.7% CO_2, and 0.7% CO at the 1 ft elevation. Gas concentrations remained steady until 80 s after intervention (347 s after ignition), when the combined effects of suppression and flow through the bedroom 2 window caused gas concentrations to begin to trend toward ambient. CO and CO_2 concentrations remained elevated at the start of hydraulic ventilation, but decreased to negligible values by the end of that action.

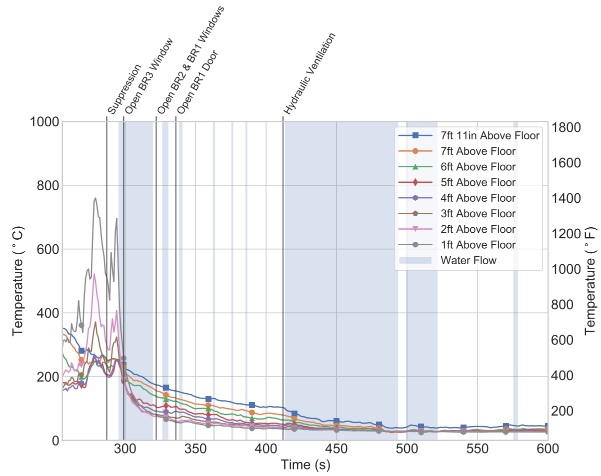
5.10.4 Hallway

Temperatures in the living room entryway were stratified and decreasing at the time of intervention (Figure 5.156a). Temperatures ranged from 141 °C (286 °F) at the ceiling to 30 °C (86 °F) 1 ft above the floor. This temperature distribution was reflective of the predominant intake flows that were maintained through the open front door in the time period prior to intervention. Temperatures in the living room entryway decreased following intervention, as suppression actions extinguished the fire and reduced the production of combustion gases. Living room entryway temperatures had uniformly dropped below 60 °C (140 °F) by the start of hydraulic ventilation. Hydraulic ventilation caused temperatures at all elevations in the living room entryway to further decrease, as cool air was entrained through the newly established uni-directional vent at the front door.

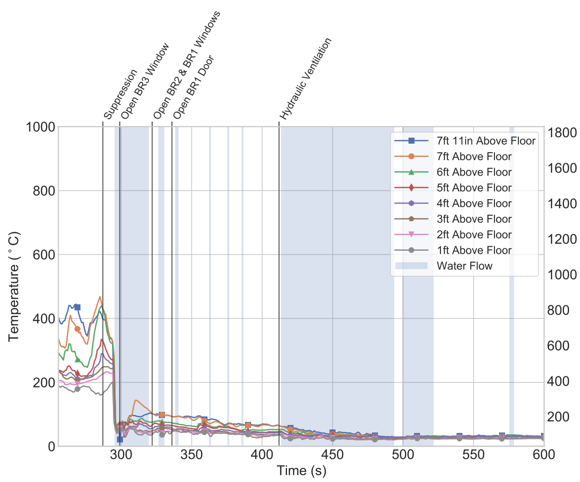
Unique to the start hallway location, temperatures were greatest close to the floor (Figure 5.156b). This was an indication of flaming combustion of the carpet due to the entrained air along the inlet portion of the flow path. Temperatures from 3 ft to 1 ft above the floor ranged from 394 °C to 696 °C (741 °F to 1285 °F), while the remainder of temperatures were approximately 250 °C (482 °F). Start hallway temperatures began to decrease immediately after the start of water flow in the hallway, as suppression actions extinguished visible burning and cooled surfaces.



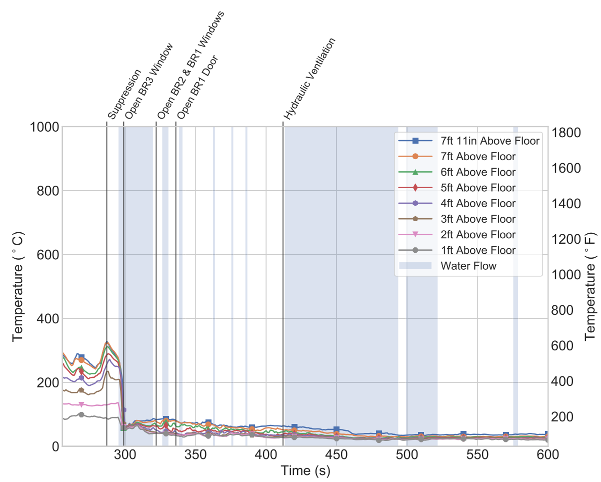
(a) Living Room Entryway Hallway Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.156: Temperature time histories in the hallway in the period following fire department intervention in Experiment 9.

Temperatures at the mid hallway and end hallway locations were stratified at the time of intervention, with the greatest temperatures close to the ceiling and the lowest temperatures close to the floor. The greatest bulk hallway temperatures occurred in closest proximity to the fire room. Temperatures ranged from 450 °C to 152 °C (842 °F to 306 °F) at the mid hallway location and from 330 °C to 90 °C (626 °F to 194 °F) at the end hallway location. Similar to the trend observed at the start hallway location, temperatures began to decrease immediately after the start of water flow in the hallway and continued to decrease as the suppression crew extinguished the fire. Temperatures had uniformly decreased below 100 °C (212 °F) at all hallway locations prior to the start of hydraulic ventilation. Hydraulic ventilation caused temperatures to further decrease, as cool air was drawn through the open front door toward the vent created in the bedroom 4 window.

Figure 5.157 shows that at the time of suppression crew entry, heat flux was highest at the start

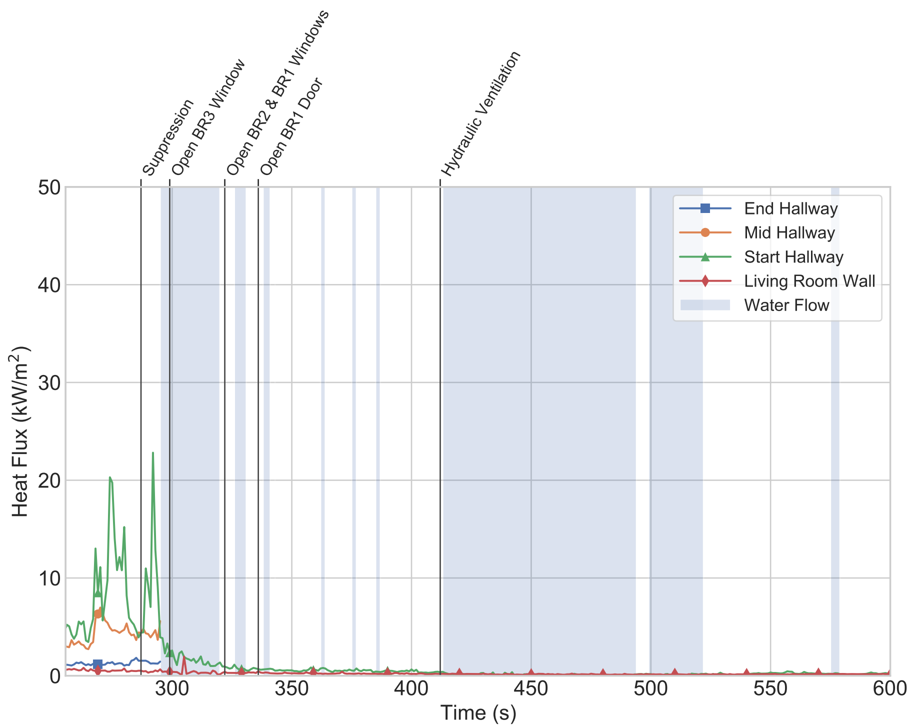


Figure 5.157: Heat flux time histories in the hallway in post-intervention period during Experiment 9.

hallway and mid hallway measurement locations. The start hallway location reached a peak heat flux of 23 kW/m^2, which coincided with the spike in temperatures at the 3 ft and 1 ft elevations. Heat flux at the mid hallway location measured 4.4 kW/m^2, which was driven by the flow of higher-temperature combustion gases from bedroom 4. As distance from the fire room increased, the magnitude of heat flux generally decreased. Heat flux at intervention was lower at the end hallway and living room entryway locations, measuring 1.5 kW/m^2 and 0.5 kW/m^2, respectively.

Initial suppression actions resulted in instantaneous peaks in heat flux at the mid hallway and end hallway locations. Water flowed across the heat flux gauges in the floor, which impacted the accuracy of the measurement. Heat flux at living room entryway and start hallway locations began to decrease simultaneously with the start of water flow in the hallway. Heat flux reached negligible values, as the suppression crew extinguished the fire.

Table 5.20 shows gas concentrations measured in the hallway at the time of intervention. The gas concentrations are further indication that prior to intervention the smoke layer had descended past the 1 ft measurement location at the start hallway, mid hallway, and end hallway locations and past the 3 ft measurement location at the living room entryway location.

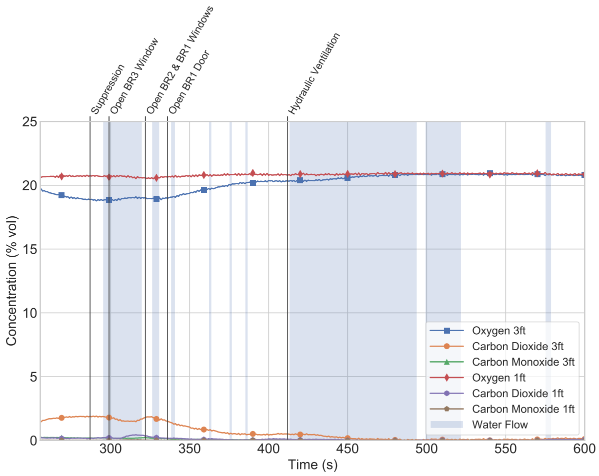
Table 5.20: Hallway Gas Concentrations at Intervention for Experiment 9

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	18.9	1.9	0.2
	1 ft	20.0	0.2	0
Start Hallway	3 ft	18.4	2.7	0.2
	1 ft	18.3	3.3	0.2
Mid Hallway	3 ft	16.3	3.5	0.3
	1 ft	14.2	4.7	0.5
End Hallway	3 ft	14.8	4.6	0.5
	1 ft	14.1	6.0	0.8

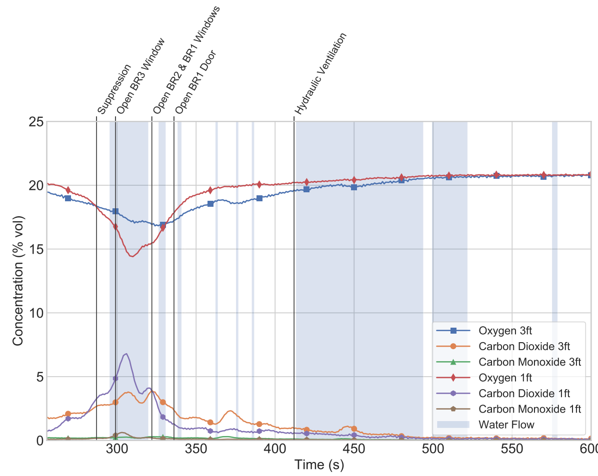
At the time of intervention, gas concentrations at the living room entryway location were approximately steady (Figure 5.158a). Peak CO and CO_2 concentrations were reached prior to the start of suppression. Water flow into the hallway and bedroom 4 halted the production of combustion gases. Gas concentrations recovered to pre-ignition levels by the completion of hydraulic ventilation, due to the close proximity of the open front door.

At the start hallway and mid hallway hallway locations, the 1 ft elevation had lower O_2 concentrations and higher CO and CO_2 concentrations compared to the 3 ft elevation. This counter-intuitive response was driven by burning along the hallway carpet between the two measurement locations, as flames flowed from bedroom 4 into the hallway. The mid hallway and end hallway locations had the lowest O_2 concentrations and highest CO_2 and CO concentrations of the four measurement locations within the hallway (Figures 5.158c and 5.158d), respectively.

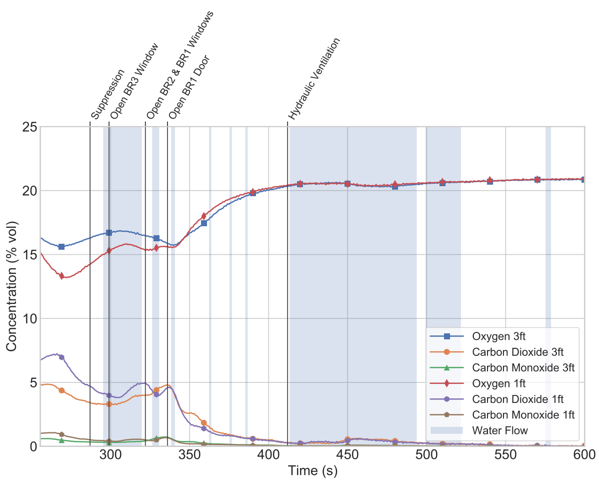
At the end hallway location, the 3 ft elevation measured higher concentrations of combustion gases compared to the 1 ft elevation, as the combustion gases filled the hallway from the top down. Flame spread along the hallway carpet did not extend past the mid hallway location toward the end hallway location, as there was no local exterior vent in bedroom 3. As a result, the 1 ft elevation at the end hallway did not measure as large of changes in gas concentrations as the mid hallway or start hallway locations. Suppression reduced the production of combustion gases and flow through the open vents continued to exchange gases, which led gas concentrations to return to pre-ignition levels by the start of hydraulic ventilation.



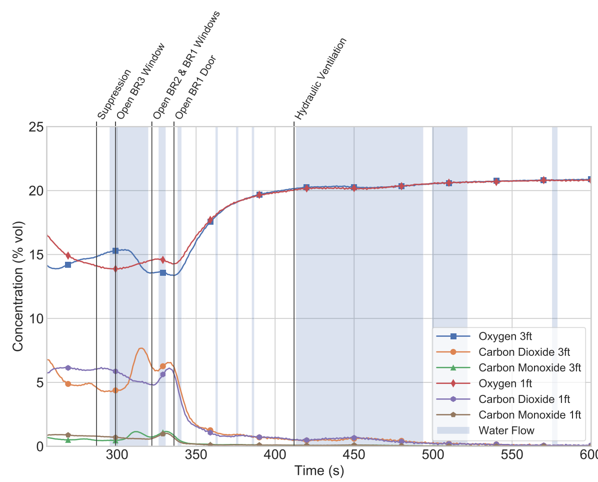
(a) Living Room Entryway Hallway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration

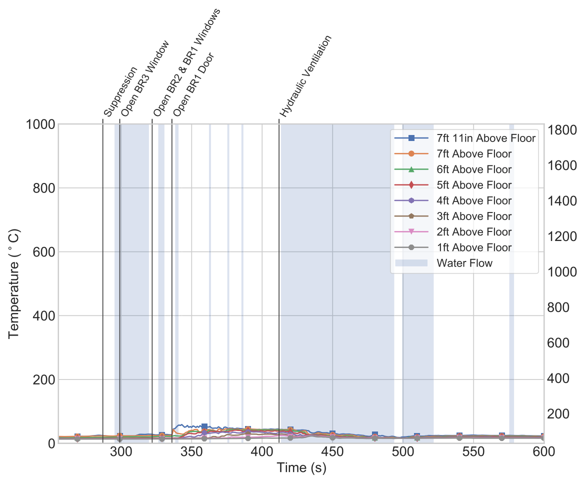


(d) End Hallway Gas Concentration

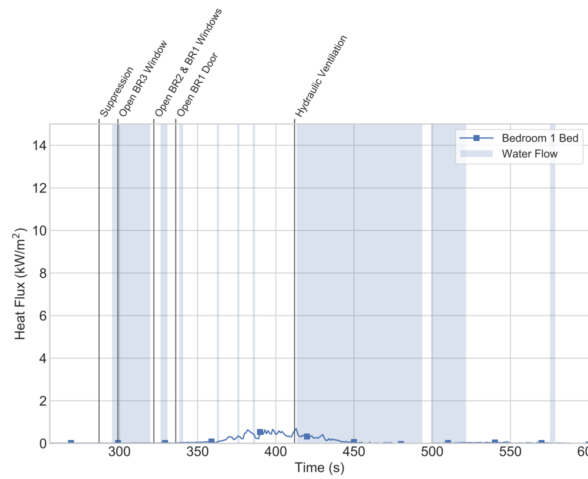
Figure 5.158: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 9.

5.10.5 Bedroom 1

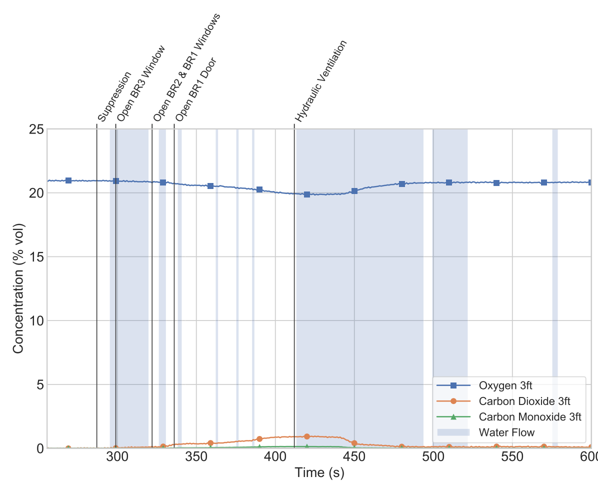
In contrast to bedrooms 2 and 3, the door between bedroom 1 and the hallway was closed prior to ignition. As a result, the temperatures and heat flux measured in bedroom 1 were considerably less than in open spaces of comparable volume within the structure. At the time of intervention, temperatures at all elevations were uniformly below 25 °C (77 °F) and the heat flux measured 3 ft above the floor in the center of the bed was negligible (Figures 5.159a and 5.159b, respectively). Temperatures and heat flux remained low until 49 s after intervention (336 s after ignition), when the bedroom 1 door was opened. This allowed products of combustion to flow into bedroom 1 from the hallway. Immediately following the opening of the bedroom 1 door, ceiling temperatures peaked to 59 °C (138 °F) and the bed heat flux peaked to 0.6 kW/m^2. Following these peaks, temperatures and heat flux decreased. Hydraulic ventilation accelerated the rate of heat flux decrease. Heat flux and temperatures reached approximately pre-ignition values prior to the end of hydraulic ventilation.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



(c) Bedroom 1 Gas Concentration

Figure 5.159: Post-intervention bed level temperature, heat flux, and gas concentrations in bedroom 1 during Experiment 9.

Gas concentrations first began to change following the opening of the bedroom 1 door. As combustion gases began to flow through the bedroom, due to the low pressure exhaust vent (open bedroom 1 window), O_2 concentrations began to decrease and CO and CO_2 concentrations began to increase. The O_2, CO_2, and CO concentrations reached peak values of 19.9%, 0.9%, and 0.1% approximately 30 s after the start of hydraulic ventilation, respectively. At this point, the change in gas flows within the structure, in particular the increased air flow through vents, led to a steady improvement of conditions. Concentrations returned to pre-ignition levels prior to the end of hydraulic ventilation.

Temperatures in bathroom 1 trended similarly to those in the adjacent bedroom, as shown in Figure 5.160. The door between bathroom 1 and bedroom 1 was closed prior to ignition, which restricted the gas exchange between the spaces to the leakage area around the closed door and through the HVAC supply duct. Temperatures at the time of intervention were uniformly below 25 °C (77 °F). Following the opening of the bedroom 1 door at 49 s after intervention (336 s after ignition), peak ceiling temperatures increased to 45 °C (113 °F) in the bathroom. Prior to hydraulic ventilation, temperatures remained steady due to the lack of gas exchange between the bathroom and the rest of the structure. This trend continued as the bathroom 1 door remained closed through hydraulic ventilation.

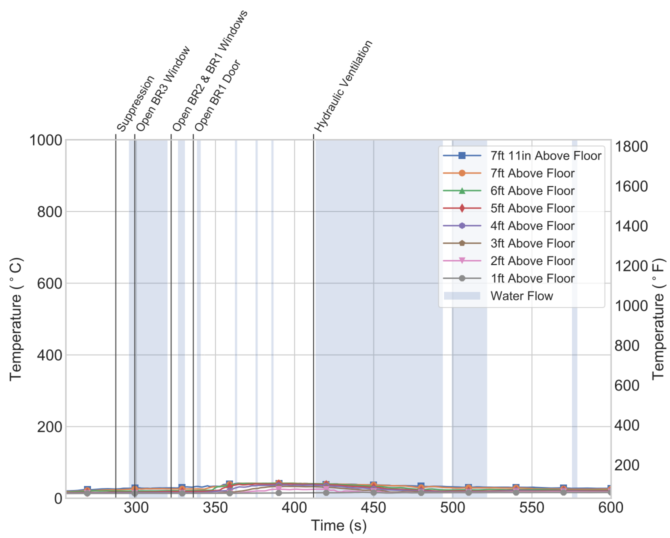


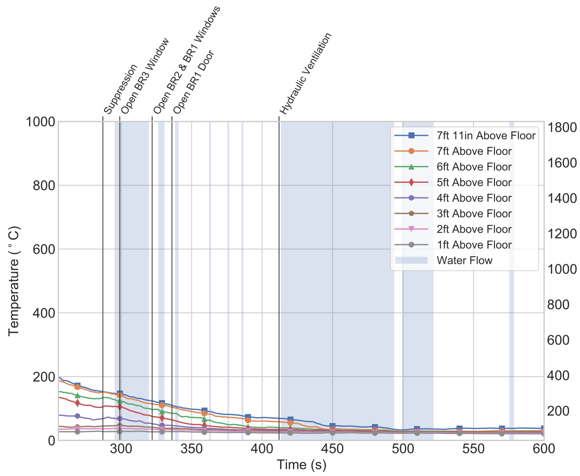
Figure 5.160: Post-intervention temperature in bathroom 1 during Experiment 9.

5.10.6 Common Space

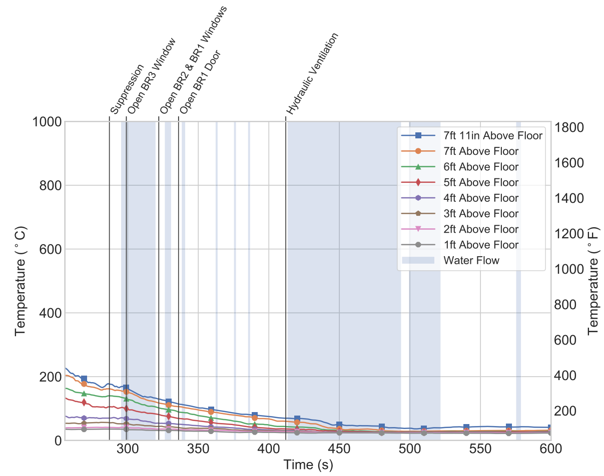
The peak temperatures at both common space measurement locations (living room and kitchen) were observed prior to the time of intervention, approximately simultaneous with flashover of bedroom 4. As a result, temperatures in both the kitchen and living room were decreasing at the time of intervention, as shown in Figures 5.161a and 5.161b, respectively. Temperatures were higher in the living room than in the kitchen, as the living room was along the flow path between the fire room and the front door. Living room temperatures ranged from 176 °C (349 °F) at the ceiling to 53 °C (127 °F) at the floor. Kitchen temperatures ranged from 153 °C (307 °F) at the ceiling to 35 °C (95 °F) 1 ft above the floor. Temperatures decreased throughout the suppression actions in the hallway and fire room. Hydraulic ventilation accelerated the rate at which temperatures decreased as fresh air was entrained through the front door. Temperatures decreased to approximately pre-ignition values by the end of that action.

Similar to temperature, the heat flux measured 1 ft above the floor in the kitchen peaked as bedroom 4 transitioned through flashover. Following the peak of 1.2 kW/m^2, the heat flux continued to decrease regardless of intervention (Figure 5.161c). By the completion of suppression, the heat flux had decreased below 0.2 kW/m^2, which minimized the impact of hydraulic ventilation.

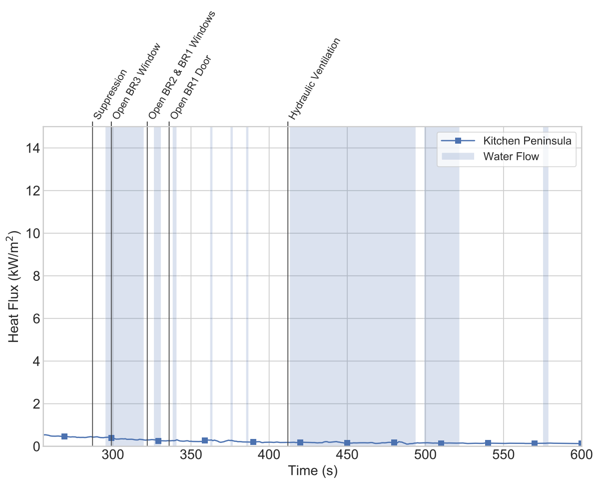
Gas concentrations at the 1 ft elevation in the kitchen first began to deteriorate at approximately 258 s as the O_2 concentration began to decrease (Figure 5.161d). The decrease in O_2 and corresponding increase in CO_2 and CO concentrations continued through suppression. Temperatures within the kitchen cooled as a result of suppression, which caused combustion gases to drop in elevation within the space and worsen gas concentrations. The O_2, CO_2, and CO concentrations reached peak values of 19.3%, 0.8%, and 0.3%, respectively. These concentrations were more representative of those found in an isolated bedroom compared to the open bedrooms because the kitchen was relatively further from bedroom 4 and not along a flow path. Gas concentrations began to fluctuate during hydraulic ventilation. The recovery to pre-ignition levels, which occurred approximately 500 s after initial intervention, was a result of the measurement location with respect to the kitchen obstructions (between the kitchen island and peninsula) and the lack of an open vent in the kitchen.



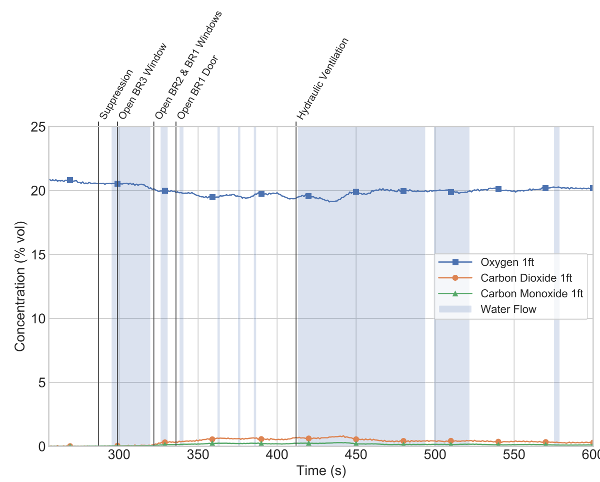
(a) Kitchen Temperature



(b) Living Room Temperature



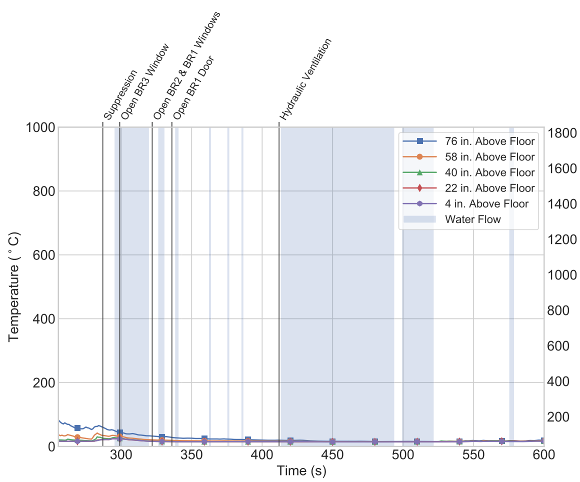
(c) Kitchen Heat Flux



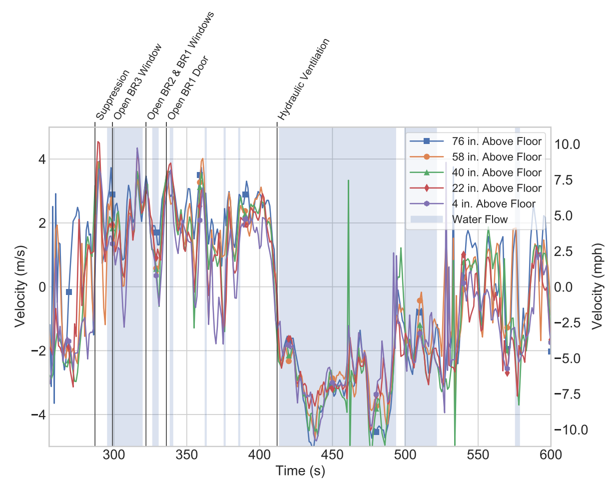
(d) Kitchen Gas Concentration

Figure 5.161: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 9.

Prior to intervention, bidirectional flow was maintained through the front door. Higher-temperature gases exhausted through the top of the doorway and cool air entrained through the lower portion of the doorway, as shown by the doorway temperature and velocity data in Figures 5.162a and 5.162b, respectively. After the suppression crew entered and began flowing water, doorway temperatures started to decrease. In the time period between suppression crew entry and the start of hydraulic ventilation, measured doorway velocities were predominantly positive (an indication of exhaust flow). There were intermittent periods of inflow due to gusts of wind across the front door. Hydraulic ventilation caused the doorway to transition to a unidirectional inlet.



(a) Front Doorway Temperature



(b) Front Doorway Velocity

Figure 5.162: Post-intervention temperatures and velocities in the front doorway during Experiment 9.

5.11 Experiment 10

Experiment 10 was designed to establish the baseline conditions for comparison to the other nine experiments with bedroom 4 ignitions. At the time of ignition, the lower panes of the double window in bedroom 4 were removed, the door to bedroom 4 was opened, and the front door was opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2 and 3 were opened. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4. The fire reached a post-flashover state, at which point interior suppression occurred. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the bedroom 4 windows. The experiment was considered to be complete at the end of hydraulic ventilation. 66 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 231 gallons. All interior doors and exterior windows remained in their initial positions for the duration of the experiment. Table 5.21 provides the timing of each event relative to ignition as well as relative to the first intervention, which in this experiment was suppression.

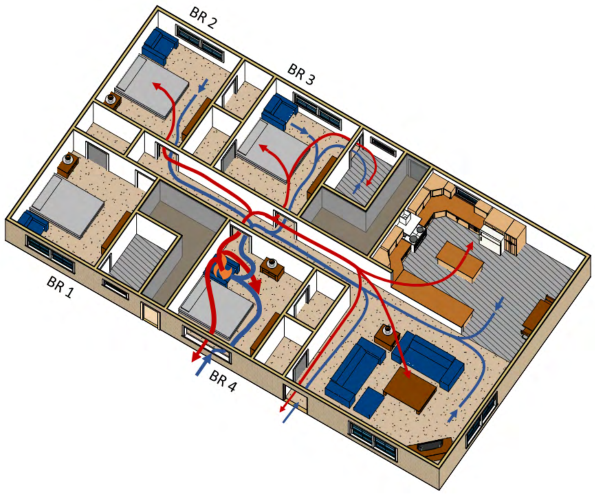
Table 5.21: Experiment 10 Event Times

Event	Elapsed Time			
	From Ignition		From Intervention	
	(mm:ss)	(s)	(mm:ss)	(s)
Ignition	00:00	0	—	—
Suppression	05:01	301	00:00	0
Hydraulic Ventilation	06:51	411	01:50	110

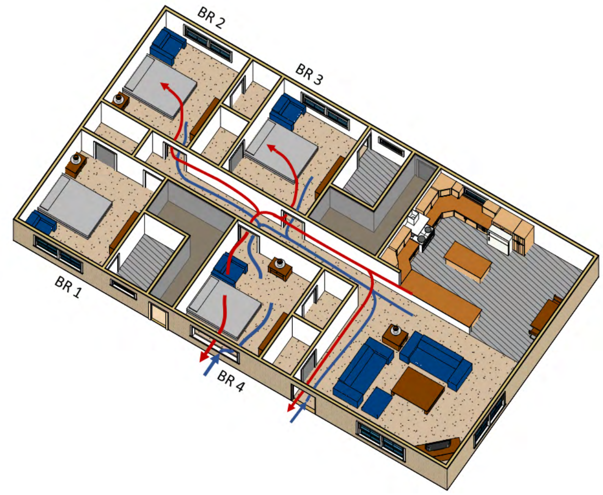
Figures 5.163a through 5.163c depict the flows within the structure pre- and post-fire department intervention during Experiment 10. At the time of fire department intervention, the bedroom 4 fire was entraining lower-pressure, lower-temperature air and exhausting higher-pressure, higher-temperature combustion gases, generating bidirectional flow through the bedroom 4 window vent (Figure 5.163a).

The suppression crew entered the structure through the front door and advanced to the bedroom 4 door with a combination nozzle set to flow a straight stream at 150 gpm with a nominal nozzle pressure of 50 psi, connected to an 1 3/4 in. hoseline. The bedroom 4 door was opened and water was flown immediately. Suppression reduced the heat release rate of the fire and reduced the production of higher-pressure, higher-temperature combustion gases, limiting the flow through the bedroom 4 door to open volumes of the structure (Figure 5.163b).

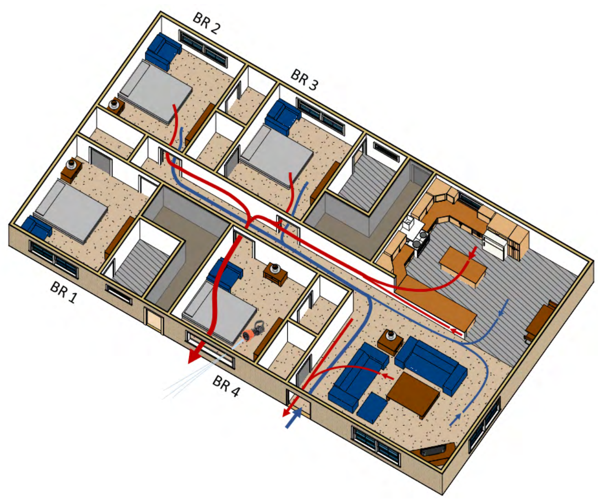
Hydraulic ventilation occurred out of the failed double-wide bedroom 4 window with a narrow fog in an O-pattern. As water flowing from the room created an area of low pressure, the bedroom 4 vents became unidirectional, exhausting combustion gases from open volumes of the structure (Figure 5.163c).



(a) Flows Prior to Intervention



(b) Suppression



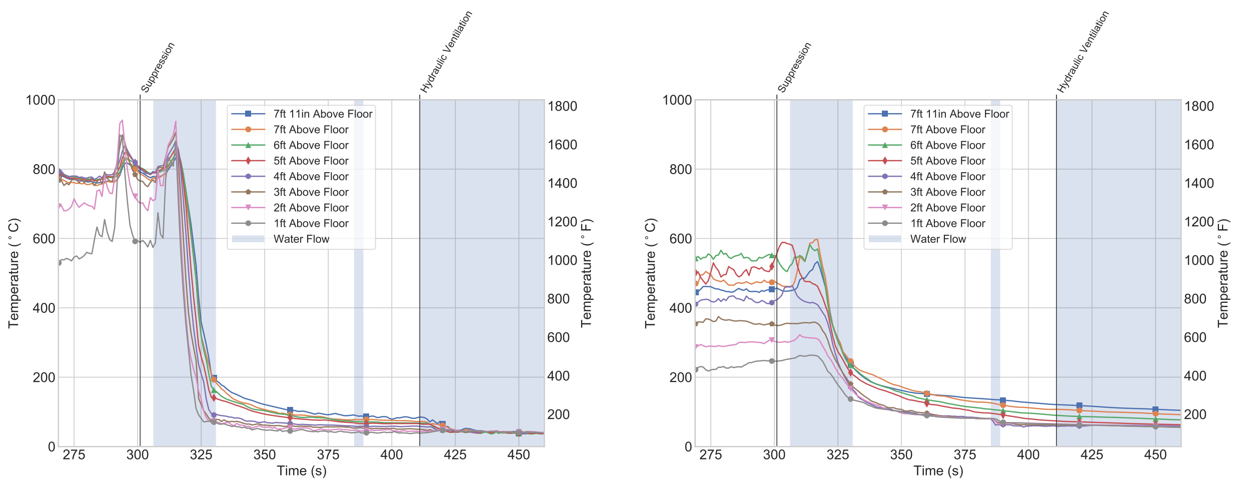
(c) Hydraulic Ventilation

Figure 5.163: Changes in flow in structure following fire department interventions in Experiment 10.

5.11.1 Bedroom 4

Prior to suppression, bedroom 4 temperatures were in a post-flashover state, with floor to ceiling temperatures in excess of 600 °C (1112 °F) as shown in Figure 5.164a. Temperatures within the room remained at those levels until 14 s after the start of suppression (315 s post ignition) when temperatures all dropped below 200 °C (392 °F) over the next 15 s. This drop coincided with the suppression crew getting water directly into the bedroom after initially suppressing the flaming carpet and cooling gases in the hallway on their approach. Temperatures within the closet, which sharply increased following the failure of the door at 251 s post-ignition, were steady prior to intervention ranging from 554 °C (1029 °F) at the ceiling to 246 °C (493 °F) 1 ft above the floor. Following suppression, the bedroom 4 temperatures cooled to two differently ranged groups: at

5 ft and above temperatures were between 180 °C and 135 °C (356 °F and 275 °F) and below 5 ft temperatures were between 90 °C and 65 °C (194 °F and 150 °F). The split was driven by the presence of residual combustion gases high in the space combined with heat transfer from the walls to those gases compared to the entrainment of cooler gases low in the space through the open vents. Following hydraulic ventilation through the bedroom 4 window, temperatures at all elevations had dropped to 39 °C (102 °F). The closet temperatures decreased to similar magnitudes after suppression and continued to decrease through hydraulic ventilation, though the impact was less in the closet compared to the bedroom as the closet was offset of the flow path.

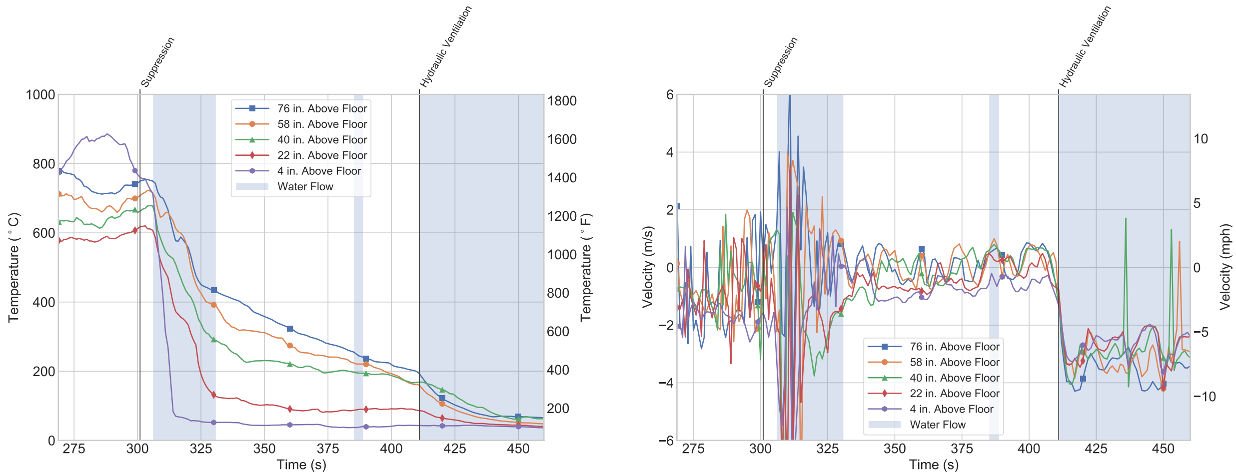


(a) Bedroom 4 Temperature

(b) Bedroom 4 Closet Temperature

Figure 5.164: Post-intervention room and closet temperature in bedroom 4 during Experiment 10.

Temperatures and velocities measured at the bedroom 4 door show that prior to suppression, when the room was in a post-flashover state, temperatures were in excess of 600 °C (1112 °F) (Figure 5.165a) and there was a mix of intake and exhaust flows through the doorway (Figure 5.165b) as air was entrained/consumed and combustion gases were exhausted. Following suppression, doorway temperatures showed a similar split as those within the room. Temperatures at 22 in. and 4 in. above the floor remained nominally steady at 90 °C (194 °F) and 45 °C (113 °F), respectively. Temperatures at the upper three measurement locations continued to cool in the time period between suppression and hydraulic ventilation, but had noticeably higher magnitudes that ranged between 192 °C and 164 °C (378 °F and 327 °F) as combustion gases flowed into the hallway. Although the velocity measurements fluctuated during the time period following suppression and prior to hydraulic ventilation, on average the lowest two probes showed gases flowing into the bedroom and the top three probes showed gases flowing out of the bedroom. During hydraulic ventilation, entrainment from the flowing water created a unidirectional intake at the bedroom 4 door (-3 m/s (-6.7 mph)) and further decreased bedroom doorway temperatures.



(a) Doorway Temperature

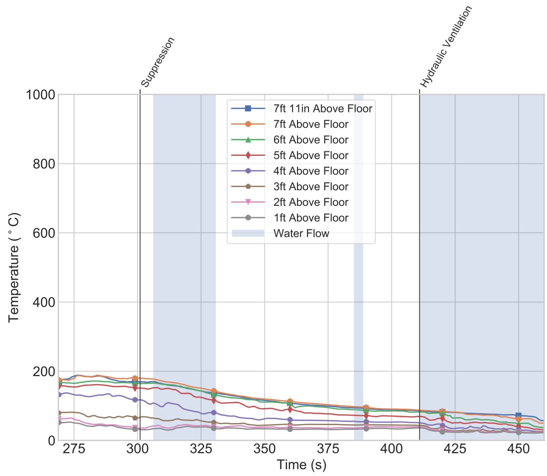
(b) Doorway Velocity (+ Indicates Flow Out of Room)

Figure 5.165: Post-intervention doorway temperature and velocity in bedroom 4 during Experiment 10.

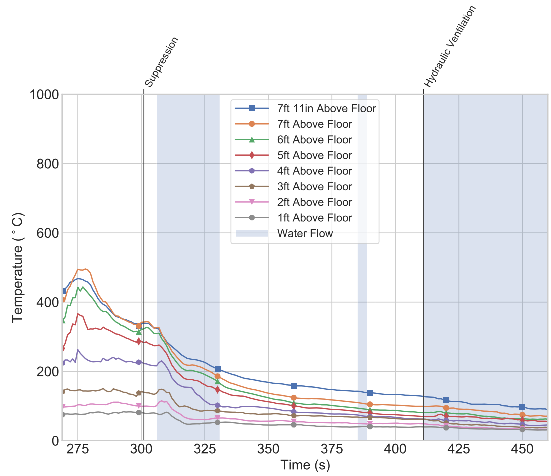
5.11.2 Hallway

At the time of intervention, temperatures throughout the egress pathway from the bedrooms to the front door remained stratified, with the highest magnitudes at the mid hallway location which was the closest location to the fire room (Figure 5.166). Prior to suppression, the mid hallway temperatures ranged from 660 °C (1220 °F) at the ceiling to 260 °C (500 °F), lower than temperature range measured at the bedroom doorway (Figure 5.166c). This difference was a result of exhaust gases mixing with the cooler gases in the hallway.

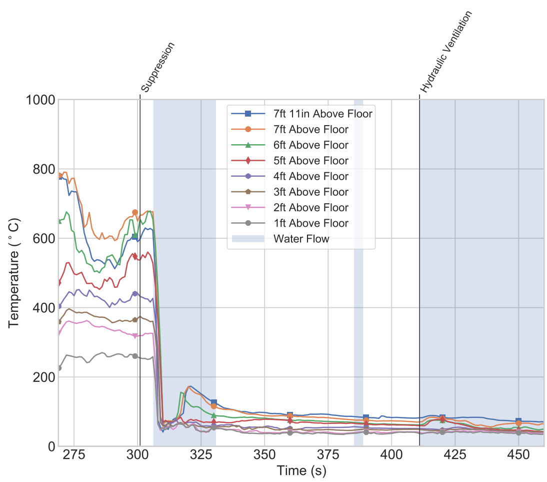
At the end hallway location, lack of an exhaust vent led to an increase in pressure due to the accumulation of higher temperature combustion gases (Figure 5.166d). At the 1 ft elevation, cooler gases from bedroom 2 flowed toward the fire past the end hallway location due to the lower pressure area created by the fire plume in bedroom 4. This flow of air kept the lower elevations cooler. Temperatures at the end hallway location remained nominally lower than the mid hallway location due to distance from fire room.



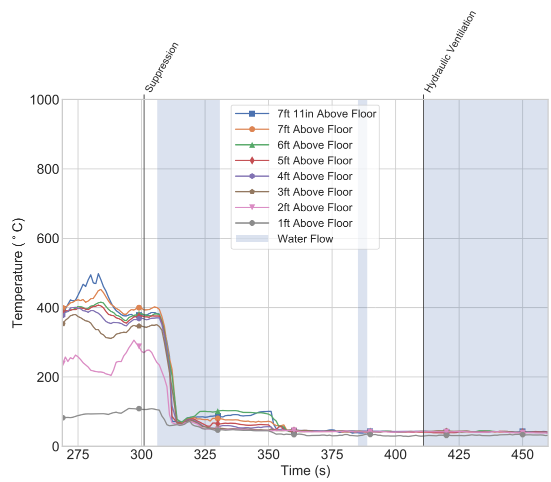
(a) Living Room Entryway Hallway Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature

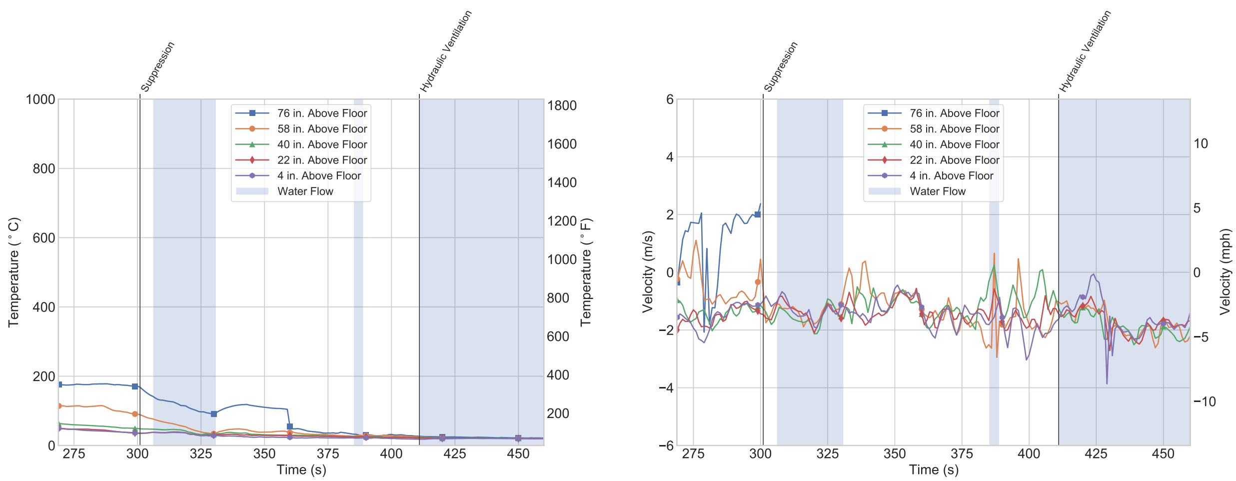


(d) End Hallway Temperature

Figure 5.166: Temperature time histories in the hallway in the period following fire department intervention in Experiment 10.

Temperatures at the start hallway and living room entryway locations were the lowest based on their respective proximity to the open front door, as shown in Figures 5.166b and 5.166a. The open front door, combined with the open volume of the common space, limited the accumulation of combustion gases which kept the smoke layer above 6 ft in this space. Additionally, inflow of air at the front door cooled gases through mixing. Following suppression, the mid hallway and end hallway locations showed the sharpest temperature decline in part because those locations had the highest magnitudes but also because water flow occurred past the start hallway location. The temporary spike in temperature at the mid hallway location was a result of residual combustion gases from bedroom 4. Temperatures continued to decrease through hydraulic ventilation.

The front doorway temperatures and velocities show the fire development in bedroom 4 created a predominate intake vent at the front door, as measured locations at 40 in. and below recorded negative velocities (Figure 5.167). The 58 in. elevation fluctuated between intake and exhaust prior to suppression while the 76 in. elevation was mostly exhaust flow. The elevated temperatures at the 58 in. and 76 in. elevations compared to the lower three locations show the impact of combustion gas exhaust versus fresh air intake. During hydraulic ventilation, the front door vent was unidirectional intake and temperatures returned to pre-ignition values.



(a) Front Doorway Temperature

(b) Front Doorway Velocity (+ values indicate flow out of structure)

Figure 5.167: Temperature and velocity time histories at the front door fire department intervention in Experiment 10.

The heat fluxes measured in the living room entryway and hallway, shown in Figure 5.168, generally followed a similar trend to the corresponding thermocouple arrays. Heat flux values peaked when the bedroom 4 fire transitioned through flashover and dropped to nominally steady values prior to suppression. The mid hallway location, which was closest to the fire room, had the highest heat flux values at approximately 6 kW/m^2 compared to the living room entryway, which was furthest from the fire room, and had the lowest heat flux values at approximately 1 kW/m^2.

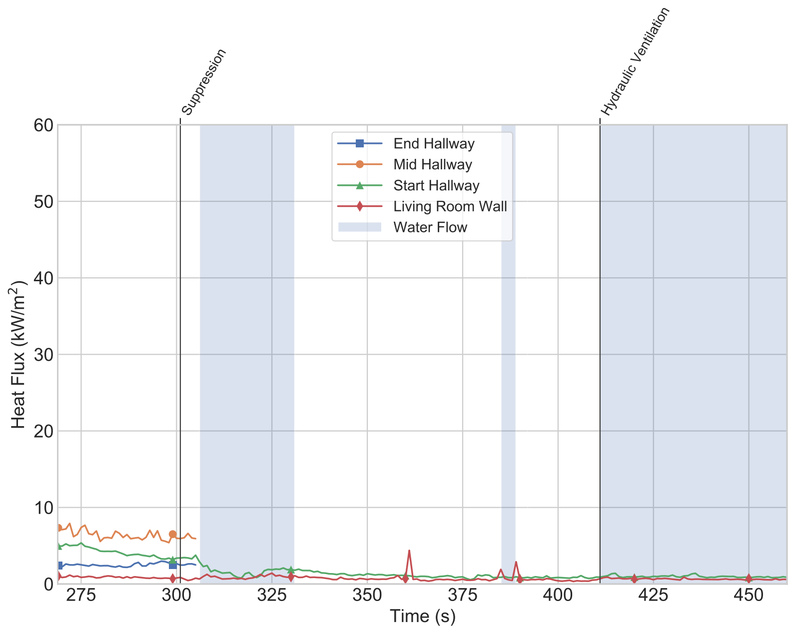


Figure 5.168: Heat flux time histories in the hallway in post-intervention period during Experiment 10.

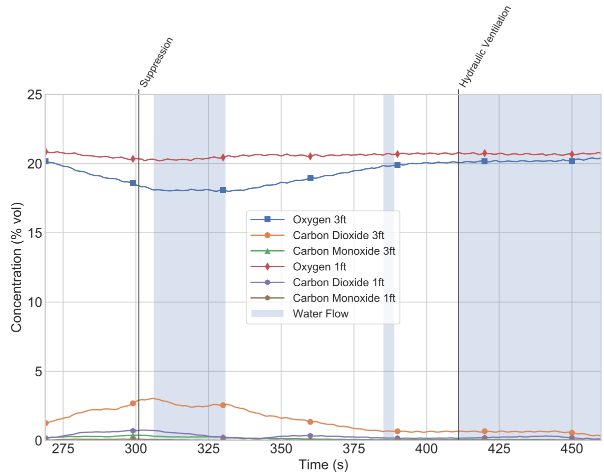
Table 5.22 shows gas concentrations measured at the hallway locations at the time of intervention. The gas concentrations are further indication that prior to intervention, the smoke layer had descended past the 1 ft measurement location at the mid hallway and end hallway locations and likely only down to the 3 ft measurement location at the start hallway and living room entryway locations.

Table 5.22: Hallway Gas Concentrations at Intervention for Experiment 10

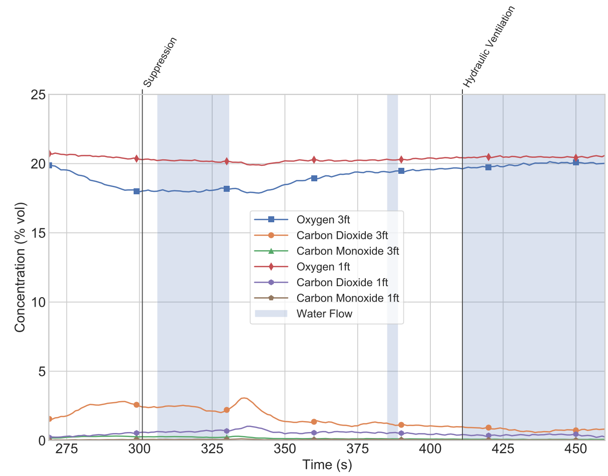
Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	18.4	2.9	0.4
	1 ft	20.3	0.7	0.1
Start Hallway	3 ft	18.0	2.4	0.3
	1 ft	20.3	0.6	0.1
Mid Hallway	3 ft	14.7	6.3	0.4
	1 ft	12.9	6.9	0.7
End Hallway	3 ft	10.5	9.3	0.6
	1 ft	16.2	4.1	0.5

Suppression of the bedroom 4 fire improved gas concentrations at all hallway locations as minimum O_2 concentrations and maximum CO_2 and CO concentrations occurred prior to water flow (Figure 5.169). The large volume of the common space combined with the open front door limited the accumulation of combustion gases at these locations to the extent that there was nominal impact in gas concentrations at the 1 ft elevation (Figures 5.169a and 5.169b). Combustion gases continued to exhaust through the open front door as the remaining higher-temperature, higher-pressure gases within the structure flowed toward the lower-pressure environment. As a result, concentrations returned to near pre-ignition values at the 3 ft elevations. Hydraulic ventilation had minimal impact as gas concentrations had recovered to pre-ignition levels prior to the start of the water flow.

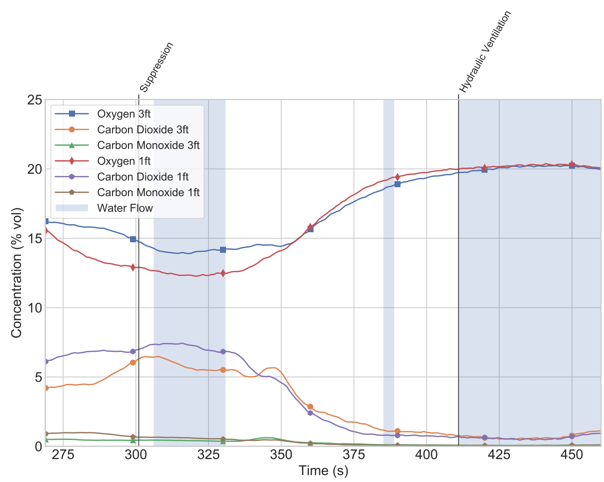
The mid hallway and end hallway locations had the lowest O_2 concentrations and highest CO_2 and CO concentrations of the four measurement locations within the hallway (Figures 5.169c and 5.169d). At the mid hallway location, concentrations at the 1 ft elevation showed lower O_2 concentrations and higher CO and CO_2 concentrations compared to the 3 ft elevation. This counter-intuitive response was driven by burning along the hallway carpet near the mid hallway location due to flame spread from bedroom 4. At the end hallway location, the 3 ft elevation measured higher concentrations of toxic gases compared to the 1 ft elevation as the combustion gases filled the hallway from the top down. Flame spread along the hallway carpet did not extend past the mid hallway location. As a result, the 1 ft elevation at the end hallway location did not measure as large of changes in gas concentrations as the mid hallway despite a lack of open vent between the fire room and end hallway. Following suppression, the end of combustion gas production combined with the exchange of gases at the open vents led to return of pre-ignition gas concentrations by the start of hydraulic ventilation.



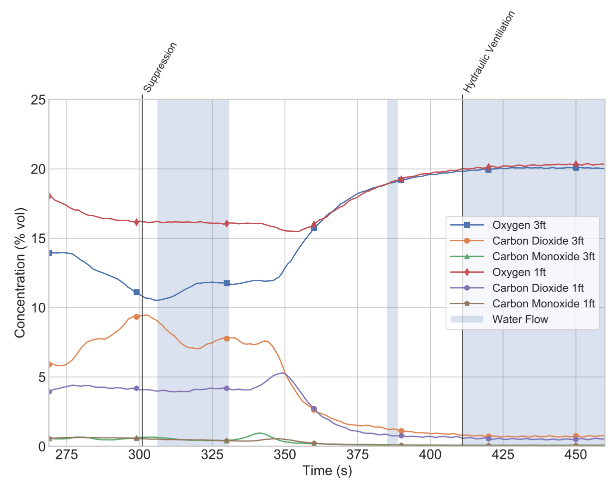
(a) Living Room Entryway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration

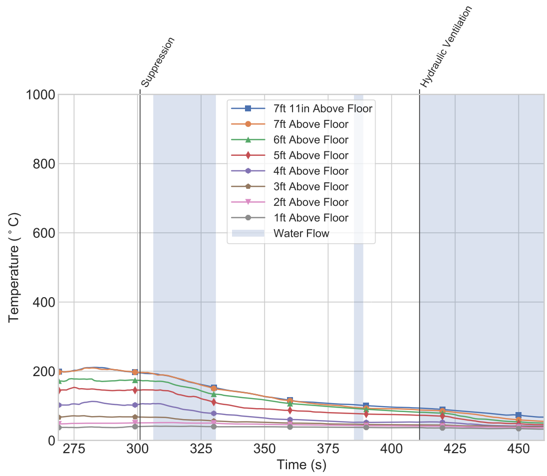


(d) End Hallway Gas Concentration

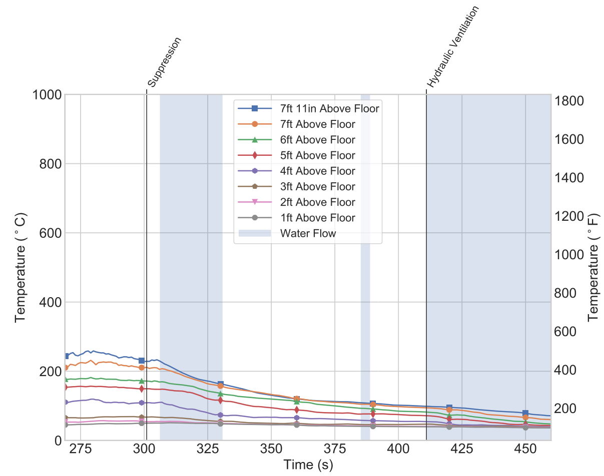
Figure 5.169: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 10.

5.11.3 Common Space

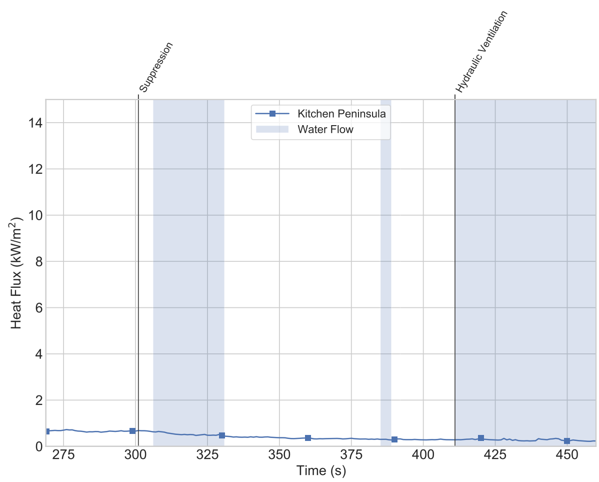
The peak temperatures and overall temperature ranges in the living room and kitchen (Figures 5.170b and 5.170a) were similar to the living room entryway (Figure 5.166a), despite being offset from the flow path between the fire room and open front door. Combustion gases from the fire room either exhausted through the low pressure front door or mixed with the air that initially filled the volume of the common space. Exhaust flow through the front door limited the accumulation of gases. Mixing limited the temperature rise from the gases that did accumulate. Temperatures dropped following suppression and continue to decrease through hydraulic ventilation. However, the rate of temperature decline was not as high as the other locations; for example, in the hallway, the measurement locations were not in the flow path between the front door through the fire room.



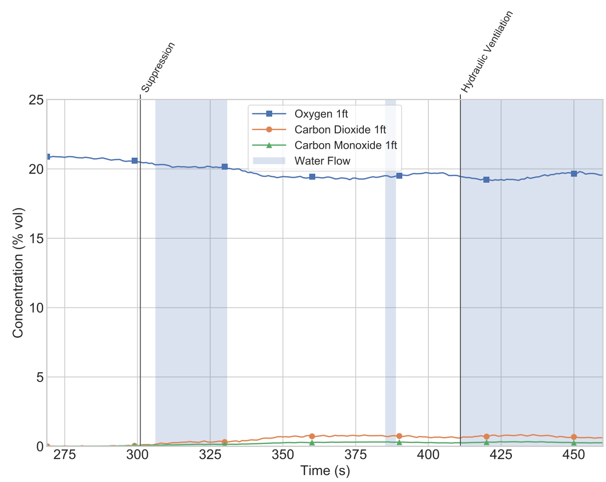
(a) Kitchen Temperature



(b) Living Room Temperature



(c) Kitchen Heat Flux



(d) Kitchen Gas Concentration

Figure 5.170: Post-intervention temperature, heat flux, and gas concentrations in the common space (kitchen and living room) during Experiment 10.

At the 1 ft elevation in the kitchen, between the kitchen island and the peninsula of cabinets that delineate the kitchen from the living room, was a measurement location for gas concentration and heat flux. Prior to suppression, the total heat flux was 0.7 kW/m^2 (Figure 5.170c), noticeably lower than the hallway values (Figure 5.168) because of the lack gas flow. Similar to the temperature magnitudes, the measured heat flux dropped following suppression and continued to decrease through hydraulic ventilation, falling below 0.2 kW/m^2.

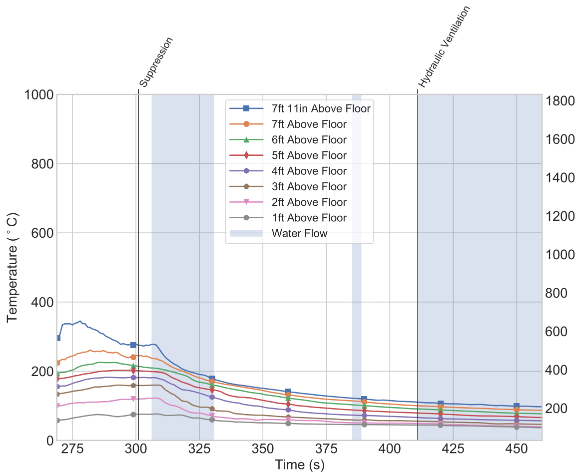
The behavior of the gas concentrations was slightly different. At the time of suppression the O_2 concentration was 20.5% and the CO_2 and CO concentrations were both 0.1%. Following suppression, the accumulated combustion gases within the space cooled. The cooler gases dropped within the space and remained in the kitchen as that area was off of the flow path. This resulted in a decrease in O_2 concentration to 19.2% and increase in CO_2 and CO concentrations to 0.8% and

0.3%, respectively. These values were nominally steady through hydraulic ventilation.

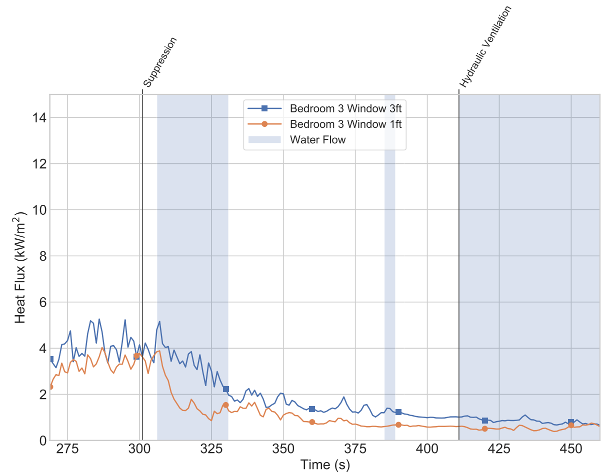
At the time of intervention, front doorway temperatures ranged from 171 °C (340 °F) 76 in. above the floor to 35 °C (95 °F) 4 in. above the floor. Front door velocities indicated bidirectional flow through the doorway. Combustion gases exhausted at approximately 2.0 m/s (4.5 mph) and cool air entrained at approximately -1.4 m/s (-3.1 mph). Upon suppression crew entry into the structure, the bidirectional probes were removed from the doorway. Data recorded after this time period are not reflective of flow through the doorway.

5.11.4 Bedroom 3

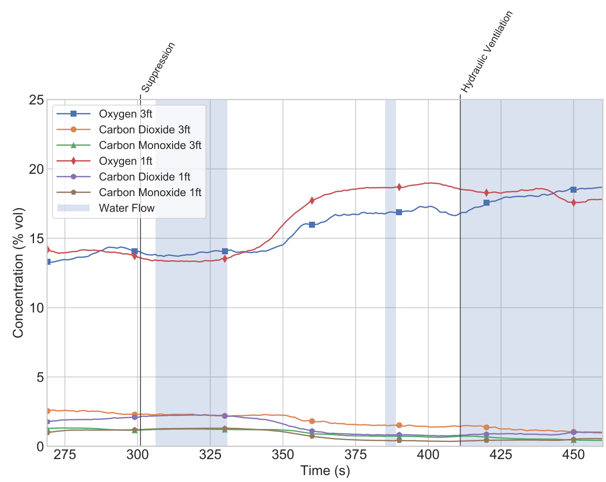
The bedroom 3 door was open prior to ignition, and remained open through the duration of the experiment. Combustion gases flowed into the space and temperatures generally rose within space until suppression, as shown in Figure 5.171a. Temperatures ranged from 277 °C (531 °F) at the ceiling to 76 °C (169 °F) 1 ft above the floor prior to suppression. An exception was the ceiling temperature, which peaked following flashover in bedroom 4. Although the ceiling temperature at intervention was below its peak, temperatures were still the highest at the ceiling and lowest 1 ft above the floor as gases filled the room from the top down. Temperatures at all elevations dropped at the onset of suppression due to a drop in production of combustion gases. Without a source of higher temperature combustion gases to continue to fill the bedroom, the bedroom became the source of those gases. The exchange of gases with the hallway as well as heat loss to the structure is reflected in the steady drop in temperatures. Temperatures continued to decrease through hydraulic ventilation. Heat fluxes measured at the 3 ft and 1 ft elevation below the bedroom 3 window followed a similar trend to the temperatures. The heat flux at both elevations steadily dropped from 4 kW/m^2 to under 2 kW/m^2 through suppression (Figure 5.171b). The heat flux magnitudes continued to decrease through hydraulic ventilation as temperatures within the space cooled, which reduced the convective heat transfer. The gas concentrations at the 3 ft and 1 ft elevations responded slower compared to the other measurements, showing improvement following suppression. For the gas concentrations to improve, the combustion gases within the bedroom needed to be exhausted from space and be replaced by less toxic gases. The lack of exterior local bedroom, slowed this recovery (Figure 5.171c). The effect of hydraulic ventilation on temperature, heat flux, and gas concentrations was not as pronounced as in the bedroom 4 or the hallway due to the lack of vent in bedroom 3; the doorway was therefore the intake and exhaust.



(a) Bedroom 3 Temperature



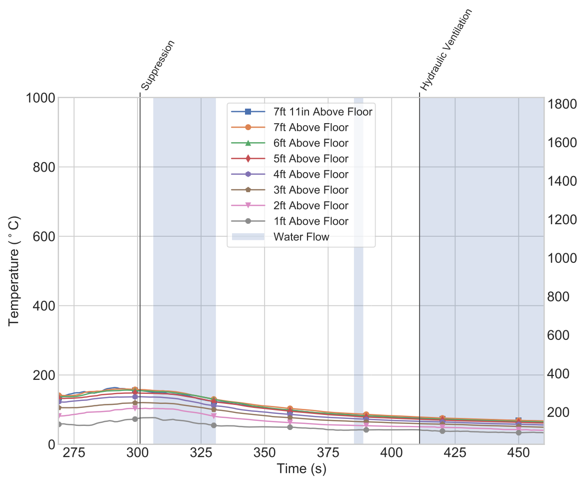
(b) Bedroom 3 Window Heat Flux



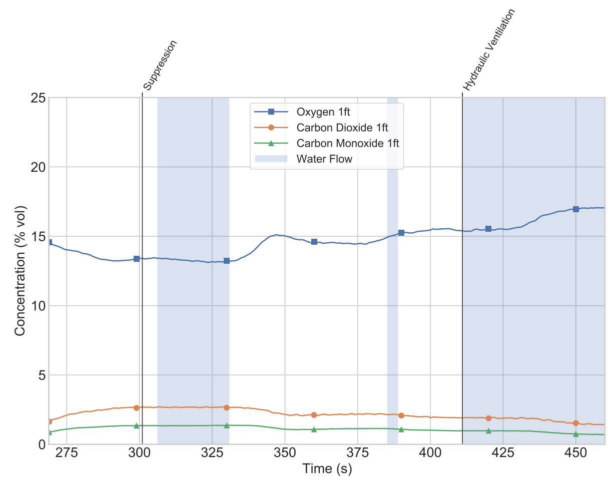
(c) Bedroom 3 Window Gas Concentration

Figure 5.171: Post-intervention temperature, window heat flux, and window gas concentrations in bedroom 3 during Experiment 10.

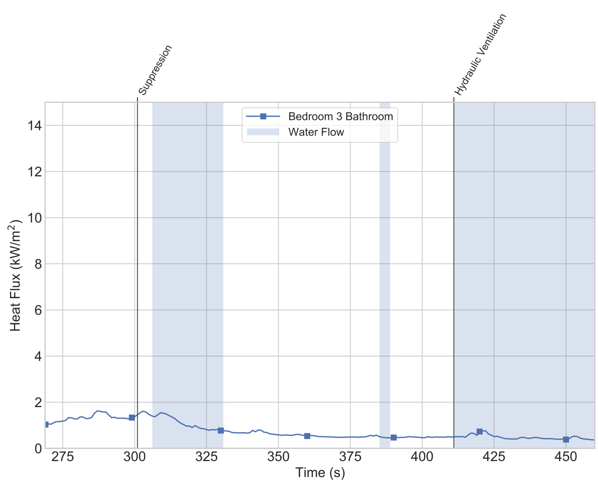
The door from bathroom 3 to bedroom 3 was also open for the duration of the experiment. The resulting temperature, heat flux, and gas concentrations in bathroom 3 are shown in Figure 5.172. The magnitudes in bathroom 3 compared to bedroom 3 were lower, mainly due to distance from the fire room. The additional distance increased heat losses from the gases to the structure and allowed for additional mixing. Although the respective temperature and heat flux magnitudes were lower, their responses to suppression were similar. The gas concentrations in the bathroom had a more muted response to suppression and subsequently hydraulic ventilation. The O_2 concentration was 13.2% at the completion of suppression but only recovered to 17.7% following hydraulic ventilation. The CO_2 and CO concentrations were steady through suppression at 2.7% and 1.4%, respectively, but only recovered to 1.4% and 0.6%, respectively. The impact of the lack of an exterior vent local to bedroom 3 was more evident in bathroom 3. Without an exterior vent, the low pressure area created by flowing hoseline could not efficiently exchange gases through the space without trying to draw a vacuum within the space. As a result, areas within the structure with less resistance (i.e., along the hallway to the front door) were able to recover to pre-ignition values sooner.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Gas Concentration



(c) Bathroom 3 Heat Flux

Figure 5.172: Post-intervention bathroom 3 temperatures, gas concentrations, and heat flux time histories during Experiment 10.

5.11.5 Bedroom 2

The door to bedroom 2 was open for the duration of the experiment. The open bedroom door allowed combustion gases to fill the space, which resulted in continued temperature rise until suppression. Temperatures ranged from 271 °C (520 °F) at the ceiling to 89 °C (192 °F) 1 ft above the floor prior to suppression, similar to temperatures in bedroom 3 which also had an open door (Figure 5.173). Temperatures at all elevations decreased 7 s after the start of suppression of the bedroom 4 fire. Production of higher temperature combustion gases had stopped. Heat losses to the structure combined with the exhaust flow of gases in bedroom to the hallway (which were at higher relative temperatures and pressures) led to the decrease. Temperatures continued to decrease through hydraulic ventilation, however similar to bedroom 3, the lack of an exterior vent in bedroom 2 limited the impact relative to locations within the flow path.

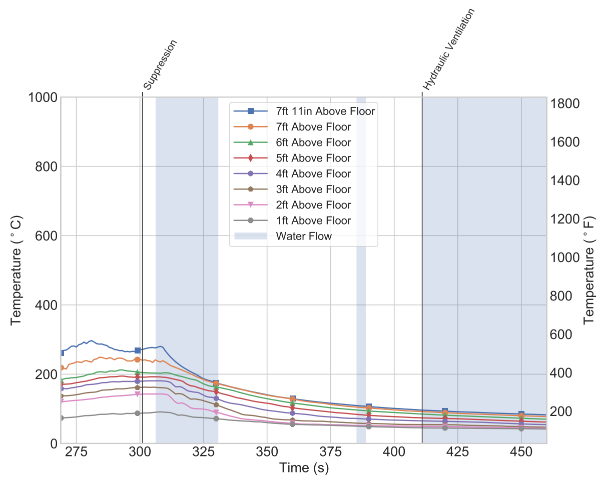
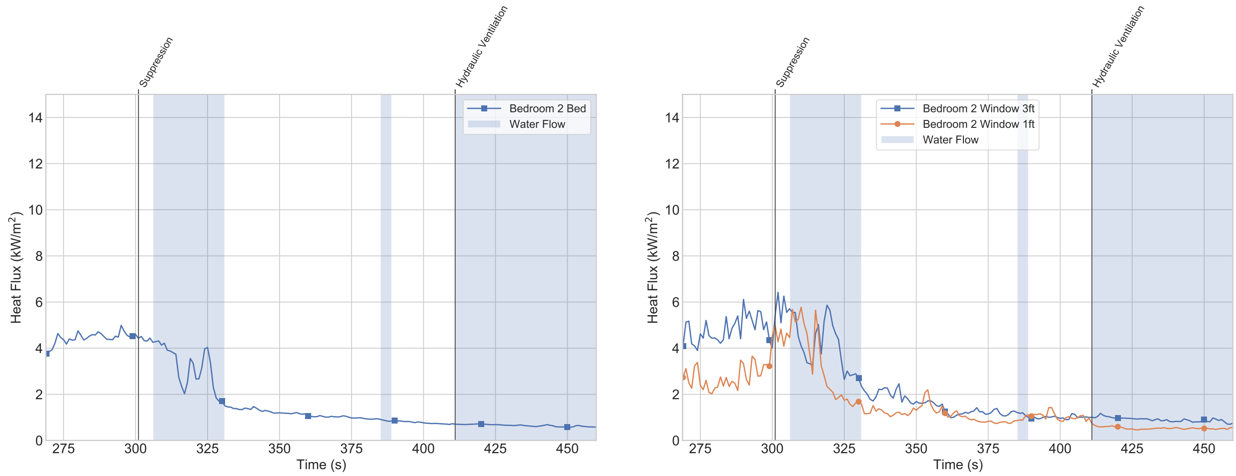


Figure 5.173: Post-intervention temperature in bedroom 2 during Experiment 10.

The measured heat flux responses at 3 ft above the floor at the bed and at the 3 ft and 1 ft elevations at the window were similar to the measured temperatures. Following the onset of suppression, the measured heat fluxes began to decrease, dropping from a range of 4 kW/m^2—5 kW/m^2 to below 2 kW/m^2. At approximately 315 s, the heat flux values fluctuated (first dropping, recovering, and dropping a second time) due to circulating gas flows which impacted the convective heat transfer. This was likely a result of gas contraction in the hallway associated with suppression. Following the fluctuation, the heat flux values continued to decrease through hydraulic ventilation, dropping below 0.7 kW/m^2. The magnitudes remained above pre-ignition values as the temperature in bedroom 2 remained slightly elevated.

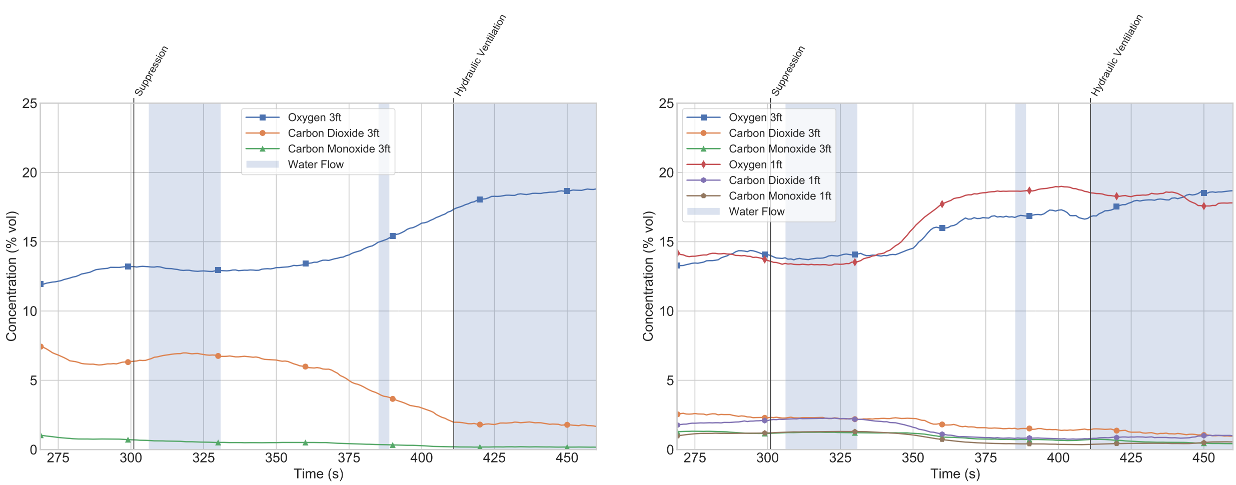


(a) Bedroom 2 Heat Flux

(b) Bedroom 2 Window Heat Flux

Figure 5.174: Post-intervention heat flux in bedroom 2 during Experiment 10.

Gas concentrations were measured at the same locations as the heat flux. Prior to suppression, the O_2 concentration at all three locations was below 15%, an indication that the smoke layer had descended to the 1 ft elevation and that there was insufficient oxygen to support combustion (Figure 5.175). The gas concentrations remained steady through suppression and began to recover upon completion of suppression as bedroom 2 became an area of higher relative pressure compared to the hallway. This resulted in a rise in the smoke layer and an improvement in gas concentrations. The values plateaued during hydraulic ventilation prior to reaching their pre-ignition levels, as the lack of a local exterior vent in bedroom 2 ultimately limited the exchange of gases.



(a) Bedroom 2 Gas Concentration

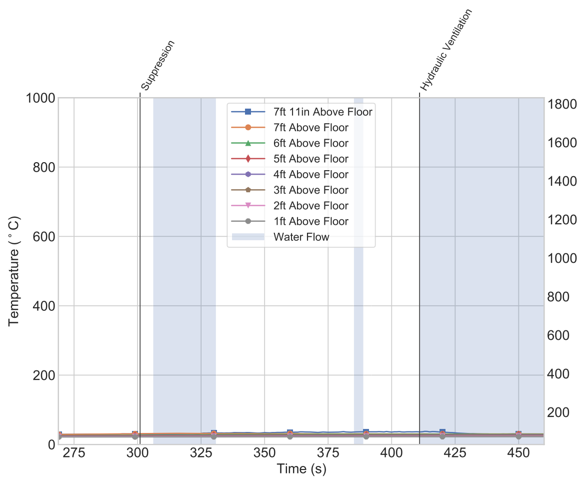
(b) Bedroom 2 Window Gas Concentration

Figure 5.175: Bedroom 2 temperature and heat flux time histories after fire department intervention for Experiment 10.

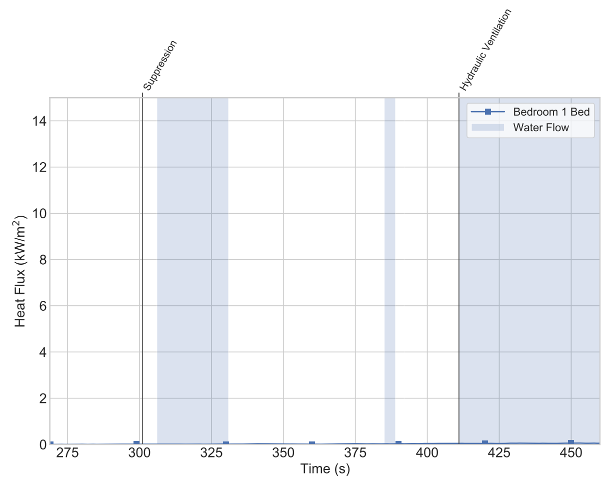
5.11.6 Bedroom 1

The doors to bedroom 1 and bathroom 1 were closed for the duration of the experiment. The closed doors limited the transport of combustion gases into bedroom 1 and bathroom 1, with the exception of what passed through gaps between the doors and door frames and through the HVAC duct network. Figure 5.176 shows the temperatures, heat flux, and gas concentrations within bedroom 1 and bathroom 1. In both bedroom 1 and bathroom 1, the ceiling temperature peaked just prior to hydraulic ventilation at 37 °C (99 °F) and 40 °F (104 °F), respectively (Figures 5.176a and 5.176d). After suppression, even though the doors to bedroom 1 and bathroom 1 were closed, accumulated combustion gases in the HVAC system flowed into both rooms causing temperatures to rise for a short period of time. The bathroom reached a higher peak ceiling temperature because of the smaller volume compared to the bedroom. Hydraulic ventilation dropped the pressure in the fire room, which drove gas flows within the HVAC toward bedroom 4, dropping ceiling temperatures within these spaces. At elevations 7 ft and below in both rooms, temperatures remained below 30 °C (86 °F). The lack of higher temperature gas accumulation and gas flow resulted in negligible changes in heat flux. The heat flux located on the bed, 3 ft above the floor, peaked at less than 0.1 kW/m^2.

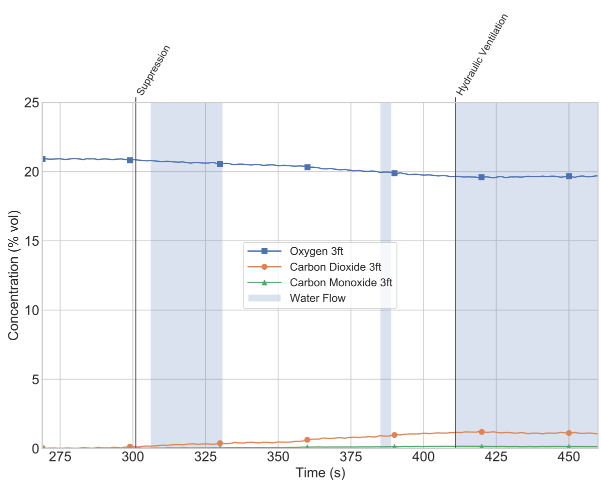
As a result of isolation provided by the bedroom 1 door, CO and CO_2 concentrations in bedroom 1 were lower at the time of intervention compared to the open bedrooms (bedrooms 2 and 3) (Figure 5.176c). Following intervention, the CO and CO_2 concentrations at the bedroom 1 measurement location increased while the O_2 concentrations decreased, with no substantial impact from the hydraulic ventilation. Although the isolation limited the recovery of gas concentrations, the peak values were less severe than those observed in non-isolated areas, with peak O_2, CO, and CO_2 concentrations of 19.6%, 1.2%, and 0.1%, respectively.



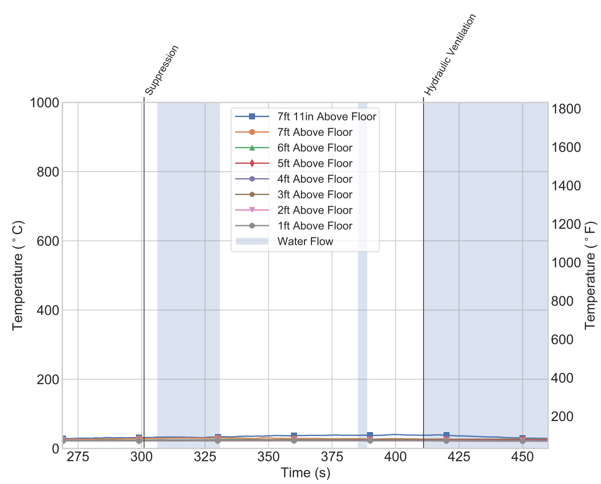
(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



(c) Bedroom 1 Gas Concentration



(d) Bathroom 1 Temperature

Figure 5.176: Post-intervention temperatures, heat flux, and gas concentrations for bedroom 1 and bathroom 1 for Experiment 10.

6 Discussion

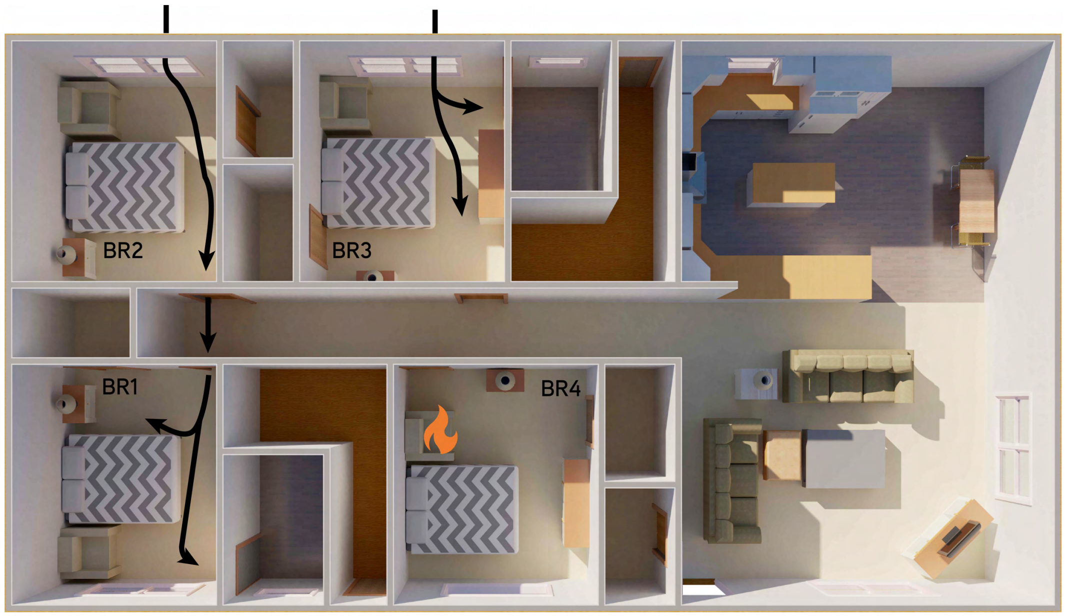
In this section, changes in fire dynamics as a function of search and rescue tactics and their timing relative to suppression are analyzed with respect to toxic gas and thermal exposures to firefighters and potentially trapped occupants. Experiments are analyzed based on the individual scenario examined as well as across scenarios to provide quantification to the experimental variables studied. The following itemized list is included to provide additional context to the experiments conducted.

- Interior operations of search crews were simulated by controlling the opening and closing of interior doors by exterior crews and a series of purpose built cable systems. Specific to each experiments, windows were ventilated and doors were opened or closed to simulate search crews moving through the structure.
- Window ventilation occurred via one of three actions: take (ventilate with a hook), open (slide the bottom sashes up), or remove (physically remove the entire window from the structure). See Appendix A for a description of the different window ventilation tactics.
- The suppression crew staged on the deck outside of the structure. The event marker for suppression in these experiments was the go to work indicator for the crew to deploy and begin either interior or exterior water application. The start of water flow was at the discretion of the suppression crew. The timing depended on the experimental scenario taking into account the time needed for crew members to move into position and can lag the event marker by several seconds.
- Exposures to potential occupants and searching firefighters were estimated by using a combination of gas concentration, heat flux, and temperature measurements at discrete locations throughout the structure.

6.1 Pathways for Search Crews

For the 10 bedroom 4 fires that included search operations (excluding the baseline experiment, Experiment 10), there were three general pathways that the simulated crews used as part of the interior search operations. In these experiments, the movement of search crews was simulated. In some experiments, thermal exposures to firefighters would have limited the ability for firefighters to safely occupy some spaces. A discussion on thermal exposures to firefighters is included in Section 6.3.

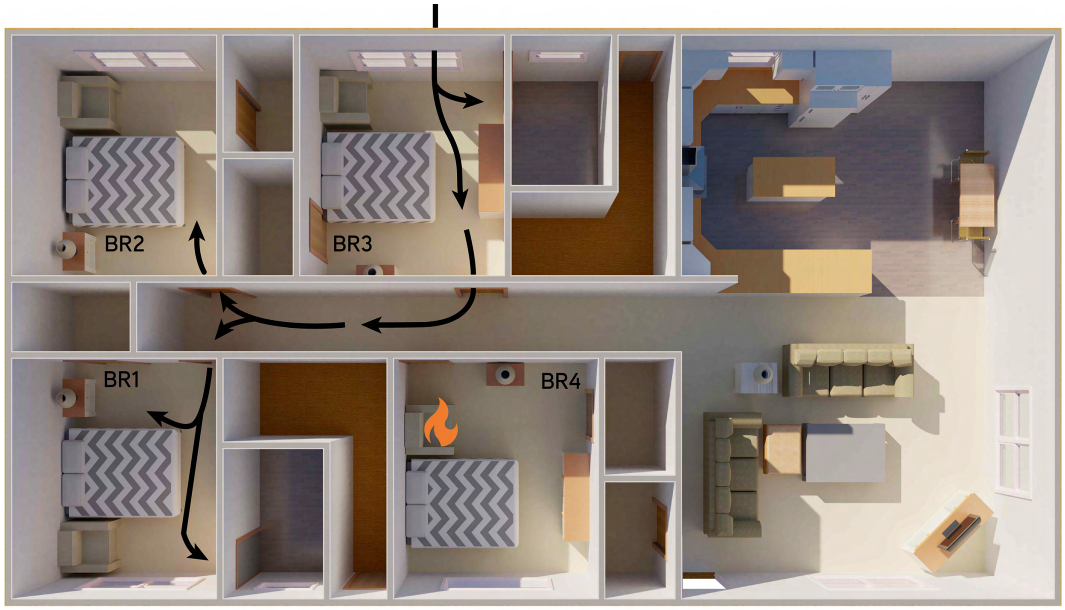
In Figures 6.1 – 6.3, the arrows represent the overall path of travel for the search crew(s) within the structure and are not intended to be representative of the physical footsteps taken within each compartment. The first pathway was simultaneous window initiated search into bedrooms 2 and 3. Crews entered the structure by taking the bedroom windows, and the firefighters that entered into bedroom 2 proceeded to search beyond the room of entry by entering a previously isolated bedroom 1. Experiments 1–5 utilized this approach. The key variables that changed were if the bedroom of entry was isolated after entry and the timing of suppression relative to the start of search operations. Figure 6.1 shows the routes taken for the crews for these 5 experiments.



Experiment	Details
1, 2, 3	Isolation of bedroom 3 post entry, varied suppression timing
4, 5	Isolation of bedroom 2 post entry, varied suppression timing

Figure 6.1: Window initiated search pathways that originated simultaneously from bedrooms 2 and 3 for a bedroom 4 fire. Black lines represent pathways the search crews took.

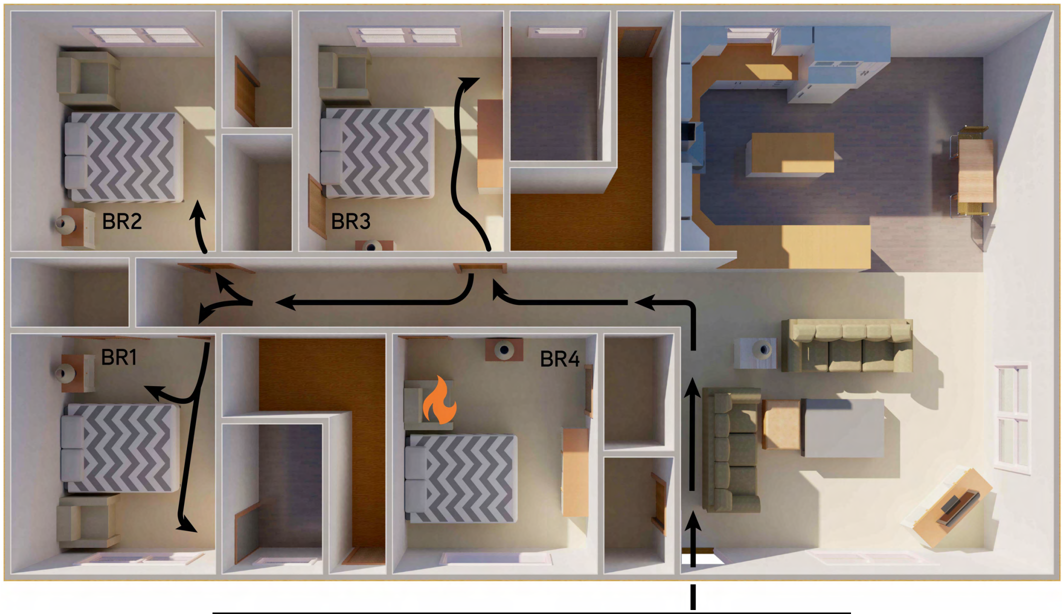
Two window initiated search experiments examined exterior entry only into bedroom 3. In Experiment 8, the crew entered bedroom 3 through the window, proceeded across the hallway to isolate bedroom 4 before moving down the hallway to search bedroom 1 and 2. For Experiment 8b, the bedroom 3 door was closed prior to the window initiated search. Following a search of bedroom 3, a pressurized water fire extinguisher was used in the hallway as the search crew moved down the hallway, past the fire compartment which could not be isolated, to search bedrooms 1 and 2. Figure 6.2 shows the routes taken for the crews for these 2 experiments.



Experiment	Details
8	Isolation of bedroom 4 post entry
8b	Isolation of bedroom 3 prior to entry

Figure 6.2: Window initiated search pathways that originated from bedroom 3 for a bedroom 4 fire. Black lines represent pathways the search crews took.

Three bedroom experiments included door initiated search. In these experiments, the crews entered the open front and traveled down the hallway to search bedroom 3, then re-entered the hallway to travel past the fire room to search bedrooms 1 and 2. The variables changed were isolation of the front door (Experiment 6), isolation of the fire compartment (Experiment 7), and search during suppression (Experiment 9). Figure 6.3 shows the routes taken for the crews for these 3 experiments.



Experiment	Details
6	Isolation of front door post entry
7	Isolation of bedroom 4 post entry
9	During suppression

Figure 6.3: Door initiated search pathways for a bedroom 4 fire. Black lines represent pathways the search crews took.

6.2 Estimated Toxic Gas and Thermal Exposure Conditions Prior to Intervention

To assess the impact of tactics, particularly how the search tactics change exposures for occupants and firefighters, it is important to quantify the conditions prior to the initial fire service intervention across similar experimental groups. Here, that discussion focuses on both the toxic gas exposure to occupants (Section 6.2.1) and the thermal exposure to occupants (Section 6.2.2).

6.2.1 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 throughout the structure to generate a time-dependent exposure of toxic gases to a potential occupant. 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 escape 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, toxic FED values can be used to assess the effects of firefighting interventions, but should not necessarily be employed as a predictor of lethality.

Although the mathematical relationship is beyond the scope of this report, toxic FED is related to the probability of the conditions being non-tenable for a certain percentage of the population through a lognormal distribution. A toxic FED value of 1.0 is defined as the toxic exposure at which the median (50%) population would be incapacitated. Here, incapacitation is defined to be when an individual can no longer impact his/her own egress. The detailed probabilistic relationship between toxic FED and the percentage of people incapacitated is unknown. However, a toxic FED value of 0.3 can be related qualitatively to a level that affects vulnerable members of the population (i.e., young children, elderly, and/or unhealthy occupants), while a toxic FED of 3.0 will likely incapacitate all but the least sensitive people. The toxic 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 from burning hydrocarbon-based fuels. In this case, the general N-gas equation can be simplified to [85]:

$$FED_{toxic} = (FED_{CO} * HV_{CO_2}) + FED_{O_2} \tag{6.1}$$

In Equation 6.1, FED$_{CO}$ and FED$_{O_2}$ account for 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 as a function of time. The expression for FED$_{CO}$ is:

$$FED_{CO}(t) = \int_0^t 3.317 * 10^{-5} [CO]^{1.036} (V/D) dt \tag{6.2}$$

where $[CO]$ 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 depend 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 V = 25 L/min. The exposure dose, D, is taken as 30% COHb. 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 6.1 by the hyperventilation factor, HV_{CO_2}:

$$HV_{CO_2}(t) = exp\left(\frac{0.1903(exp(\chi_{CO_2})) + 2.0004}{7.1}\right) \tag{6.3}$$

where χ_{CO_2} is the volume percent of CO_2. Lastly, the fraction of an incapacitating dose due to low oxygen hypoxia, FED$_{O_2}$:

$$FED_{O_2}(t) = \int_0^t \frac{dt}{exp[8.13 - 0.54(20.9 - \chi_{O_2}(t))]} \tag{6.4}$$

where dt is the time step and χ_{O_2} is the volume percent of O_2.

Again, it is important to note that the threshold criteria for untenability 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% [86]. It is important to recognize that incapacitating levels of COHb have been found in surviving fire victims [85]. Active subjects are typically more severely affected by COHb concentrations than sleeping subjects.

Gas concentrations and the resultant toxic FEDs can vary considerably prior to fire department intervention, due to differences in ignition location, initial fire growth, and time of intervention. To control for the time of intervention, the analysis will focus on the cumulative toxic FED at the time of earliest intervention across the bedroom experiments, which occurred during Experiment 4 at 270 s post-ignition of the upholstered chair in bedroom 4. At this point, for all bedroom experiments, bedroom 4 was in post-flashover state. Figure 6.4 shows the locations for exposure measurements of potentially trapped occupants and Table 6.1 presents the median and range of cumulative toxic FED at the gas measurement locations within the structure for the 11 bedroom experiments.

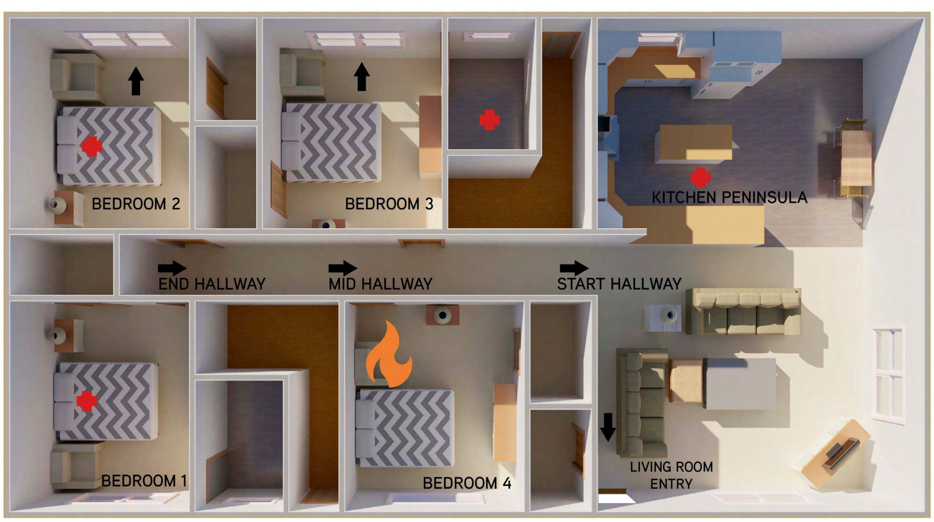


Figure 6.4: Toxic gas exposure measurement locations. The red plus signs are locations of potentially trapped occupants and the black arrows are measurement locations along potential egress pathways.

Examination of the data in Table 6.1 shows that at 3 ft and below throughout the structure and at 270 s post ignition, the minimum toxic FED values were below 0.12 and maximum values reached approximately 4. Recall from earlier discussion, that a toxic FED of 0.3 represents the criterion for incapacitation for vulnerable individuals or about 11% of the population and a value of 1.0 represents the same criterion for approximately 50% of the population. It is also important to recognize that for experiments with later intervention times, the toxic FED magnitudes continued to rise at all measurement locations within structure.

Table 6.1: Toxic Exposures at Time of Earliest Intervention (270 s Post Ignition) for All Bedroom Fires

Elevation	Room	Fractional Effective Dose Median	Fractional Effective Dose Range
3 ft	Bedroom 1	0.008	0.006 — 0.012
	Bedroom 2	1.59	0.028 — 3.99
	Bedroom 2 Window	1.35	0.037 — 2.61
	Bedroom 3 Window	0.345	0.013 — 0.897
	Living Room Entry	0.045	0.013 — 0.133
	Start Hallway	0.016	0.008 — 0.069
	Mid Hallway	0.301	0.011 — 0.729
	End Hallway	0.807	0.120 — 3.84
1 ft	Bedroom 2 Window	0.451	0.015 — 1.20
	Bedroom 3 Window	0.121	0.007 — 0.373
	Bathroom 3	0.045	0.008 — 0.381
	Kitchen Peninsula	0.011	0.008 — 0.016
	Living Room Entry	0.015	0.011 — 0.023
	Start Hallway	0.015	0.008 — 0.035
	Mid Hallway	0.173	0.012 — 0.803
	End Hallway	0.119	0.011 — 0.516

The median toxic FED values in Table 6.1 indicate higher values at the 3 ft elevations for all of the locations where there were both 3 ft and 1 ft measurements (bedroom 2 and 3 windows, living room entry, start hallway, mid hallway, and end hallway). To assess if the 3 ft elevation is statistically different than 1 ft elevation the data set was paired down to include the experiments which contained nominally the same initial conditions. Compared to the full set of bedroom experiments, Experiment 8b was the only experiment where the state of one of the bedroom doors was different prior to ignition. In this case, the bedroom 3 door was closed. Therefore, Experiment 8b was excluded from the statistical assessment. In Experiments 6 — 9, the door to bathroom 1 was open. To determine if the state of the bathroom 1 door impacted the gas concentrations in bedroom 1, the bedroom 1 data for the remaining 10 experiments was examined using a chi squared analysis. The analysis returned a p-value of 0.437, greater than 0.05, which indicated that there weren't statistical differences in bedroom 1 prior to firefighter intervention based on whether the bathroom 1 door was opened or closed. As a result, the set of 10 experiments can be used to assess if there are other statistical differences within the structure.

The data at the 1 ft and 3 ft elevations was assessed using Wilcoxon signed-rank statistical test. This is a non-parametric method for testing whether two samples originate from the same distribution. The analysis returned a p-value of 1E-05, less than 0.05, which indicated that the differences between the 3 ft toxic FEDs and 1 ft toxic FEDs are statistically significant. Combustion gases filled the structure from the top down, which resulted in the formation of a smoke layer and significantly higher toxic FED exposures.

In addition to an assessment as a function of elevation, the data in Table 6.1 also suggests that some locations could be different as a function of position (i.e., is bedroom 1 behind a closed door different than bedrooms 2 or 3 which had open doors?). Data from the 10 experiments were analyzed using a Friedman test; a non-parametric statistical test for quantifying if any differences between more than two groups are significant. Two subsets of the measurement locations in Table 6.1 were examined: all 3 ft measurements and all 1 ft measurements. In both groups, a p-value less than 0.05 was returned from the Friedman test, which indicated that there were statistically significant differences within the respective groups. To determine which locations had different toxic FEDs, a Nemenyi post-hoc analysis was conducted. A Nemenyi test finds the groups of data that differ as long as a global statistical test, such as the Friedman test, shows that the data among the full set of groups were not statistically similar. In other words, toxic gas exposures increase with elevation.

Analysis of the relationships between each of the eight 3 ft gas locations revealed several pairs where the difference in toxic FED values were statistical significant:

- Start hallway and living room entry toxic FEDs are lower than the toxic FEDs at the bedroom 2 bed and the bedroom 2 and 3 windows (i.e., position along intake of flow path versus end point of flow path).
- Bedroom 1 toxic FED is lower than the toxic FEDs at the bedroom 2 bed, the bedroom 2 and 3 windows, and the end hallway (i.e., position behind a closed bedroom door).
- Bedroom 2 toxic FED is higher than the toxic FED at the mid hallway (i.e., position at end of intake portion of flow path versus position at end point of flow path).

The cumulative toxic FEDs nearest the open front door (start hallway and living room entry) were lower than both of the non-isolated bedrooms. The open front door limited the accumulation of combustion gases at both the start hallway and living room entryway, but also served as an intake for air which aided the flame spread from the bedroom fire to the hallway.

Combustion gases flowed out of bedroom 4 through the interior doorway and traveled to areas of lower pressure: down the hallway toward the open bedroom 2, across the hallway toward bedroom 3, and down the hallway toward the kitchen and living room and ultimately the open front door. During the growth phase of the fire, the pressure difference between the fire room and the bedrooms was still sufficient to drive gas flow toward those rooms. As a result, a key takeaway from this analysis is that the 3 ft elevation cumulative toxic FED at the earliest average intervention time was lower in the isolated bedroom (bedroom 1) compared to both the non-isolated bedrooms (bedrooms 2 and 3) and the end hallway location.

The furthest measurement location along the flow path that began and ended at the bedroom 4 door was in bedroom 2. Consequently, the combustion gases that flowed into bedroom 2, banked down the walls toward the floor. This led to an accumulation of toxic gases and subsequent increase in toxic FEDs across the 10 experiments. Ultimately these values were statistically different than the mid hallway location despite the mid hallway being closer to the fire room because of air entrainment through the front door toward the fire room. This highlights the impact of gas travel along flow paths within a structure even when there is no exterior vent along that path.

An assessment of the relation between each of the eight measurements at the 1 ft elevation, similarly resulted in several differences in FED values that were statistically significant:

- Start hallway and living room entry toxic FEDs are lower than the toxic FEDs at the bedroom 2 window and mid hallway (i.e., position along intake of flow path versus end point of flow path).
- Kitchen peninsula toxic FED is lower than the toxic FED at the bedroom 2 and bedroom 3 windows, the end hallway, and the mid hallway (i.e., position adjacent to flow path versus along exhaust portions of flow path).
- Bathroom 3 toxic FED is lower than the toxic FED at the bedroom 2 window (i.e., position adjacent to flow path versus end point of flow path).

Like the 3 ft elevation, the cumulative toxic FEDs at the living room entry and start hallway which were close to the open exterior vent (i.e., near open front door) were lower than the 1 ft elevation at bedroom 2 window, the further location from the open vent. Although the open front door limited the accumulation of combustion gases at both the living room entryway and start hallway, the air intake along the flow path to fire room aided the flame spread into to the hallway. As a result, both the 1 ft elevations at the start hallway and living room entry were lower than mid hallway despite being statistically similar at the 3 ft elevation.

The kitchen peninsula was chosen to represent a shielded but non-isolated potential occupant location off of the flow path between the fire room and the open front door. The combination of the open front door and being flow path adjacent limited the accumulation of combustion within the kitchen. As a result the toxic toxic FED at the kitchen peninsula was lower than both open bedrooms as well as the mid hallway and end hallway locations.

The measurement location of 1 ft elevation in bathroom 3 was chosen to assess the impact of being in an open space adjacent to open space (bedroom 3). The toxic FEDs prior to intervention in bathroom 3 did not vary enough from bedroom 3 window to be statistically different, however when compared to 1 ft elevation at the bedroom 2 window where there was additional gas accumulation, the differences were significant. Similar to the 3 ft elevation in bedroom 2, these differences show the how gas accumulations changes based on position within or adjacent to a flow path.

6.2.2 Estimated Occupant Thermal Exposure

Similar to the computations for exposure to toxic gases, FED can also be computed for hazards associated with heat exposure. Heat exposure has three primary pathways that may result in life threats: hyperthermia, body surface burns, and respiratory tract burns.

Hyperthemia (heat stroke) can result if an occupant is exposed to a heat flux for a prolonged period of time such that the body temperature rises above a critical threshold. This rise in temperature, however, depends on various parameters including, but not limited to the activity level of the occupant, the humidity of the air, and the type of clothing [87]. It is estimated for a well hydrated person, exposure to air over 15 minutes at temperatures over 120 °C (248 °F) for dry still air and 85 °C (185 °F) for saturated still air can result in gradual increase of body temperature without skin burns. The increase of body temperature above 42.5 °C (108.5 °F) is fatal unless treated within minutes [88].

Pain threshold is reached when the temperature at 0.1 mm depth of the skin reaches 44.8 °C (112 °F) [88]. These effects on the skin are independent of the mode of heat transfer [89]. If the human skin is in contact with a brass block having a temperature of 60 °C (140 °F), it is estimated to take 1 s for noticeable pain, 10 s for partial thickness skin burn (i.e., second-degree burn), and 100 s for a full thickness skin burn (i.e., third-degree burn) [89].

Moreover, an occupant escaping a fire is exposed to heat from the fire by either convection or radiation modes of heat transfer. The convective heat transfer for air temperatures above 120 °C (248 °F) (pain and hyperthermia threshold) is dependent on the humidity, ventilation rate, and protective clothing. A total heat flux value of 2.5 kW/m^2 is accepted as a tenability limit, above which the subsequent skin burn hazard increases. Below this threshold, the exposure can be tolerated for minutes. Appendix B provides a table of heat flux ranges for several reference thresholds.

Respiratory tract burns do not occur in absence of skin burns. Respiratory tract burns are more dependent on the amount of water vapor in air than the skin burns. At 100 °C (212 °F) steam caused burns at all levels [90]. The maximum breathable saturated air is 60 °C (140 °F) [91].

The thermal FED is therefore a combination of radiative and convective effects, expressed as by Equation 6.5 [87]:

$$FED_{thermal}(t) = \int_{t_1}^{t_2} \left(\frac{1}{t_{rad}(t)} + \frac{1}{t_{conv}(t)} \right) dt \tag{6.5}$$

It is important to note that because of the nature of radiation, the air temperature and humidity may be below the incapacitation level when the radiant heat fluxes are above the tenability limit (2.5 kW/m^2). Therefore, rapid heating of the skin may occur and result in localized skin burns above this radiative threshold. Equation 6.6 predicts the time (min.) to incapacitation due to radiant heat:

$$t_{rad}(t) = \frac{q_c}{q(t)^{4/3}} \text{ for } q(t) > 2.5\ kW/m^2 \quad (6.6)$$

where, q_c denotes critical threshold for burns:

- 1.33–1.67 $(kW/m^2)^{4/3}$·min for first degree burns
- 4–12 $(kW/m^2)^{4/3}$·min for second degree burns
- 16.67 $(kW/m^2)^{4/3}$·min for third degree burns.

It is recommended that a value of 10 $(kW/m^2)^{4/3}$·min be used for q_c for the threshold for incapacitation and serious injury [87] due to radiant heat. For these experiments, measurements of $q(t)$ were made of total heat flux (combined convective and radiative). Therefore, the estimates of the radiative component of the thermal FED should be considered to be conservative.

Time to incapacitation for convection dominated heat transfer for air with water vapor content less than 10% is calculated using Equation 6.7 [92]

$$t_{conv}(t) = C_q T(t)^{-n} \quad (6.7)$$

In this equation, C_q and the index n are empirical constants derived from experimental data obtained for a subject wearing specific clothes. Purser [87] provided a set of values for this equation: $C_q = 5 \times 10^7$ and n = -3.4. However, parameter values provided by Purser were based on a temperature versus time curve derived from the data when unclothed subjects were exposed to humid and dry air by Blockley [91].

A practical set of parameters were provided by Crane [93]: $C_q = 4.1 \times 10^8$ and n = -3.61, which were for a healthy adult wearing clothing. The C_q value provided by Crane was a statistically-derived proportionality constant that considered the amount of heat absorbed by the body before incapacitation. Therefore, the C_q value may be different for other body types, ages, health, and clothing, and thus may not apply directly to a firefighter. Ultimately, the set of parameters provided by Crane were used here to calculate time to incapacitation of an occupant.

Temperatures and heat fluxes and the combined resultant FEDs can vary considerably prior to fire department intervention, due to differences in ignition location, initial fire growth, and time of intervention. To control for the time of intervention, the analysis will focus on the cumulative FED at the time of earliest intervention across the bedroom experiments, which occurred during Experiment 4 at 270 s post-ignition of the upholstered chair in bedroom 4. At this point, for all bedroom experiments, bedroom 4 was in post-flashover state. Figure 6.5 shows the locations for exposure measurements of potentially trapped occupants and Table 6.1 presents the median and range of cumulative thermal FED at all temperature and heat flux measurement locations within the structure for the 11 bedroom experiments.

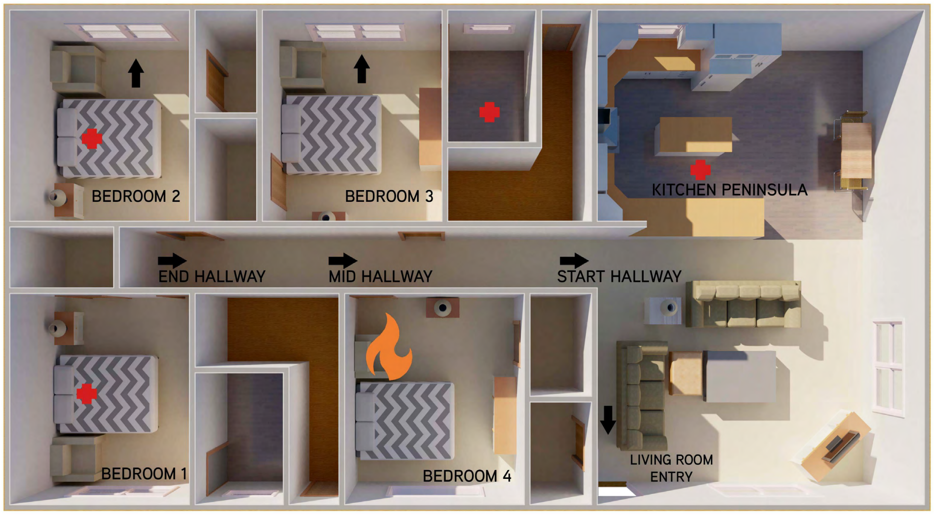


Figure 6.5: Thermal exposure measurement locations. The red plus signs are locations of potentially trapped occupants and the black arrows are measurement locations along potential egress pathways.

Examination of the median data in Table 6.2 shows that the peak thermal FEDs occurred in the spaces (the start, mid, and end hallway locations) closest to the fire room. The three hallway locations were connected to the fire room via the open fire room door. The thermal FEDs at these locations were driven by both flame spread along the carpet and the accumulation of combustion gases that began to descend to the floor level.

The median thermal FED values in Table 6.2 indicate higher values at the 3 ft elevations for all of the locations where there were both 3 ft and 1 ft measurements (bedroom 2 and 3 windows, living room entry, start hallway, mid hallway, and end hallway). To assess if the 3 ft elevation is statistically different than 1 ft elevation the data set was paired down to include the experiments which contained nominally the same initial conditions. Compared to the full set of bedroom experiments, Experiment 8b was the only experiment where the state of one of the bedroom doors was different prior to ignition. In this case, the bedroom 3 door was closed. Therefore, Experiment 8b was excluded from the statistical assessment. A similar analysis to the toxic gas exposure data was conducted to determine if the state of the bathroom 1 door impacted the thermal exposures which similarly indicated that there weren't statistical differences in bedroom 1 prior to firefighter intervention based on whether the bathroom 1 door was opened or closed. As a result, the remaining set of 10 experiments was used to assess if there are other statistical differences within the structure.

Table 6.2: Thermal Exposures at Time of Earliest Intervention (270 s Post Burner Ignition) for All Bedroom Fires

Elevation	Room	Thermal Fractional Effective Dose Median	Range
3 ft	Bedroom 1	5.2e-4	1.1e-4 — 9.3e-4
	Bedroom 2	0.42	0.02 — 0.82
	Bedroom 2 Window	0.93	0.24 — 1.44
	Bedroom 3 Window	0.26	2.6e-4 — 0.54
	Living Room Entry	0.008	0.002 — 0.16
	Start Hallway	3.33	1.18 — 13.9
	Mid Hallway	8.20	4.16 — 27.6
	End Hallway	1.32	0.08 — 3.22
1 ft	Bedroom 2 Window	0.19	0.002 — 0.68
	Bedroom 3 Window	0.003	1.7e-4 — 0.17
	Bathroom 3	9.1e-4	1.6e-4 — 0.004
	Kitchen Peninsula	7.7e-4	2.2e-4 — 0.001
	Living Room Entry	0.001	1.6e-4 — 0.078
	Start Hallway	2.99	1.16 — 13.9
	Mid Hallway	5.97	3.75 — 2.65
	End Hallway	0.06	0.003 — 0.40

The data at the 1 ft and 3 ft elevations was assessed using Wilcoxon signed-rank statistical test. This is a non-parametric method for testing whether two samples originate from the same distribution. The analysis returned a p-value of 7E-11, less than 0.05, which indicated that the differences between the 3 ft thermal FEDs and 1 ft thermal FEDs are statistically significant. Combustion gases filled the structure from the top down, which resulted in the formation of a smoke layer and significantly higher thermal FED exposures at higher elevations. Similar to the toxic gas exposures, thermal exposures increase with elevation.

In addition to an assessment as a function of elevation, the data in Table 6.2 also suggests that some locations could be different as a function of position. Data from the 10 experiments were analyzed using a Friedman test; a non-parametric statistical test for quantifying if any differences between more than two groups are significant. Within the 3 ft and 1 ft groups, a p-value less than 0.05 was returned from the Friedman test, which indicated that there were statistically significant differences within the respective groups. To determine which locations had different thermal FEDs, a Nemenyi post-hoc analysis was conducted. A Nemenyi test finds the groups of data that differ as long as a global statistical test, such as the Friedman test, shows that the data among the full set of groups were not statistically similar.

At the 3 ft elevation, there were both similarities and differences in thermal FED with respect to areas of highest hazard when compared to the toxic gas FED. The similarities include lower thermal FEDs in the spaces behind closed doors and near open vents (e.g. open front door). More specifically:

- Bedroom 1 thermal FED was lower than the start hallway, mid hallway, end hallway, and bedroom 2 window locations (i.e., position behind a closed bedroom door).
- Living room entry thermal FED was lower than the start hallway, mid hallway, end hallway, and bedroom 2 window locations (i.e., position along intake of flow path versus end point of flow path).

The statistical comparison differences between thermal and toxic FEDs were that:

- Start hallway and mid hallway thermal FEDs were both higher than the bedroom 2 bed and bedroom 3 window locations (i.e., proximity to fire room).

Although the open front door limited combustion gas accumulation at the start hallway location (see Table 6.1 prior to intervention, there was still flow of combustion gases and flame spread in the hallway toward the source of oxygen (open front door). The combination of radiative heat transfer from the flame spread and convective heat transfer through the flow of combustion gases led to higher thermal FEDs at both the mid hallway and start hallway locations.

An assessment of the relation between each of the eight measurements at the 1 ft elevation, similarly resulted in several differences in FED values that were statistically significant:

- Living room entry thermal FED is lower than the start hallway, mid hallway, and bedroom 2 window locations (i.e., position along intake of flow path versus end point of flow path).
- Kitchen peninsula thermal FED was lower than the start hallway, mid hallway, end hallway, and bedroom 2 window locations (i.e., position both adjacent to flow path and proximity of location to fire compartment).
- Bathroom 3 thermal FED was lower than the start hallway, mid hallway, and bedroom 2 window locations (i.e., position adjacent to flow path versus along exhaust portions of flow path).
- Bedroom 3 window thermal FED was lower than the mid hallway location (i.e., proximity of location to fire compartment).

Like the 3 ft elevation, the cumulative FEDs at the living room entry, which was close to the open exterior vent (i.e., near open front door), were lower than the 1 ft elevation at bedroom 2 window, the start hallway, and mid hallway locations. Unlike the toxic gas FEDs, the thermal FED at the start hallway was statistically different, in these cases higher than living room entry due to the flame spread along the carpet and heat transfer from the flow of combustion gases.

The kitchen peninsula was a shielded but non-isolated occupant location off of the flow path between the fire room and the open front door. The combination of the open front door and being flow path adjacent limited the accumulation of combustion within the kitchen. As a result the thermal FED at the kitchen peninsula was lower than the open bedroom 2 as well as the start hallway, mid hallway and end hallway locations.

The thermal FEDs prior to intervention in bathroom 3 were statistically different than the 1 ft elevations in the mid hallway and start hallway. The differences show the impact of a location being two rooms removed a from areas of high hazard (hallway locations) and that remote space lacking an exterior vent. These factors combined to limit the flow of combustion gases and flame spread into the space, when there was a pathway of lower resistance for flame spread and gas flow through the open front door.

6.3 Estimated Thermal Exposure to Firefighters During Search

Temperature and heat flux measurements in different locations in the structure can be used to approximate the thermal exposure to firefighters during search and rescue operations. This analysis is independent of the toxic or thermal exposure to occupants, as it gives an approximation of the time that the areas of the structure would fall into ranges of relative hazard for firefighters conducting a search.

The thermal insult to firefighters can be approximated using a modified version of Utech's thermal operating classes. 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 [94]. According to Utech, routine conditions are those with a surrounding temperature between 20 °C (70 °F) and 72 °C (162 °F) 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 72 °C (162 °F) and 200 °C (392 °F) 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. Emergency operating conditions are present when heat flux exceeds 12 kW/m^2 and temperature is in excess of 200 °C (392 °F). 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 firefighter's PPE is only be able to withstand an exposure on the order of a few seconds. The thresholds for the thermal operating classes are illustrated in Figure 6.6.

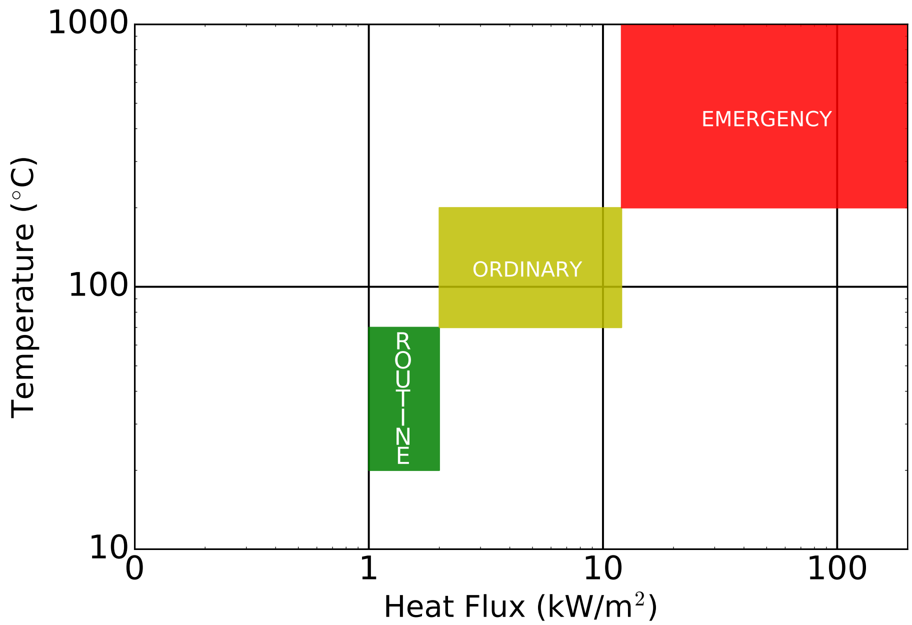


Figure 6.6: Thermal Operating Classes [94, 95]

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 have the performance standards for firefighter PPE [96, 97]. Research conducted on SCBA facepieces, which have been identified as one of the weak points of the firefighter PPE ensemble, has quantified the heat flux thresholds at which various forms of damage can manifest [98–100]. These thresholds are illustrated in Figure 6.7. The figure shows that while the most severe damage in a short period of time can be expected for heat flux exposures in the emergency operating class; hole formation, bubbling, and microcracking were observed for heat fluxes consistent with the ordinary operating class.

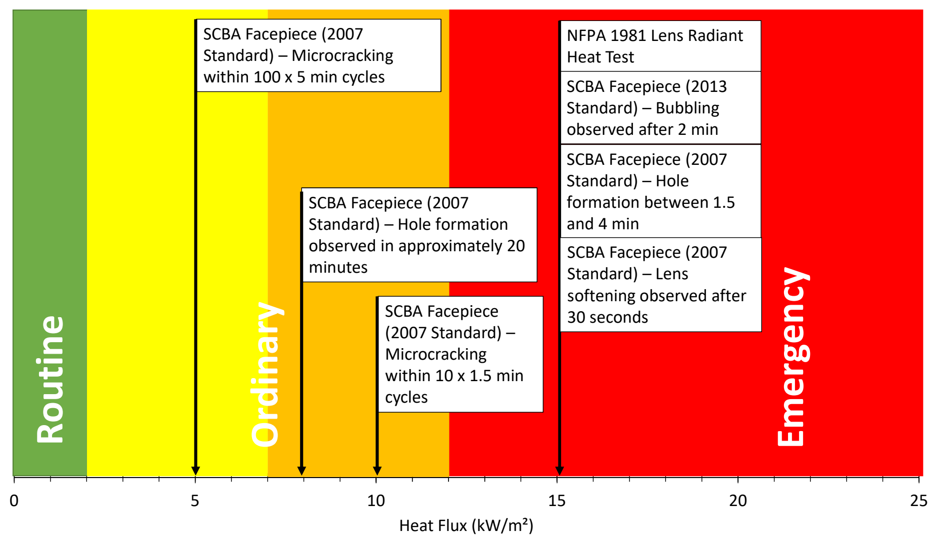
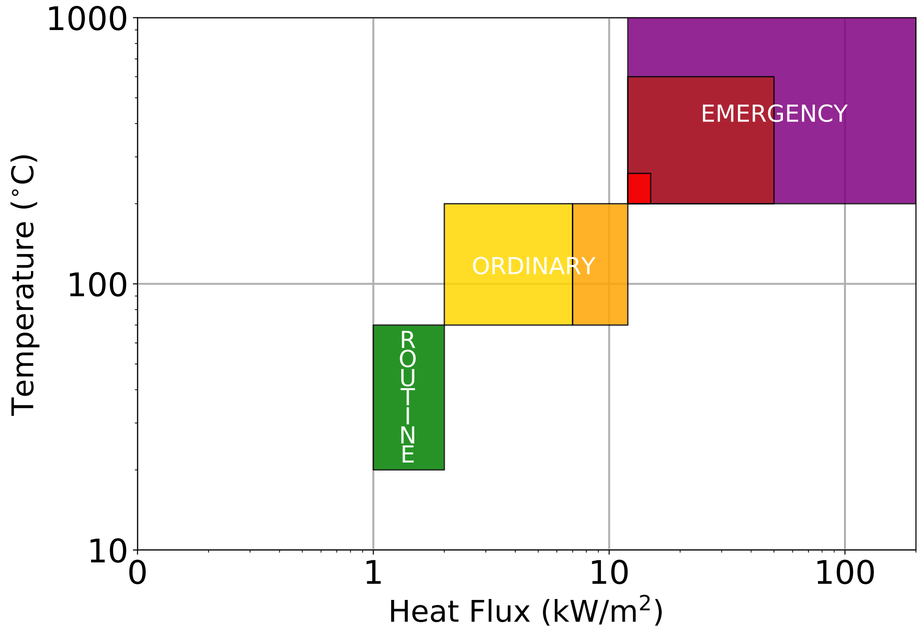


Figure 6.7: Comparison of thermal operating classes with modern PPE performance limits from [97–100]

Madrzykowski [95] compiled previous research efforts to characterize the thermal operating environment of firefighters. Recent literature 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.

Leveraging recent fire environment and PPE research, Utech's original operating classes can be modified to better describe the thermal hazards to which firefighters may be exposed. To reflect the data highlighted in Figure 6.7, the ordinary operating class is split into two levels based on heat flux exposures. Provided firefighters were not operating under higher thermal exposure conditions, they are still likely able to function under ordinary operating conditions from 10 min. to 20 min. at a time. To better characterize the upper limits of exposure, the emergency operating class is split into three regions. The top bound of emergency I is set to be at the thermal conditions for which many firefighter personal protective equipment components are evaluated [96]. Emergency II is defined as the region where the thermal conditions are representative of localized burning/flaming combustion, and emergency III would be equivalent to a post-flashover exposure. The emergency classes represent exposures at which a firefighter may be able to safely operate on the order of tens of seconds (emergency I) to beyond the limits of personal protective equipment (emergency II and III). The modified thermal classes and corresponding temperature and heat flux ranges are presented in Figure 6.8.



Operating Class	Temperature Range [°C]	Heat Flux Range [kW/m^2]
Routine	20 – 72	1 – 2
Ordinary I	72 – 200	2 – 7
Ordinary II	72 – 200	7 – 12
Emergency I	200 – 260	12 – 15
Emergency II	260 – 600	15 – 50
Emergency III	> 600	> 50

Figure 6.8: Modified Thermal Operating Classes

Consider the baseline bedroom 4 ignition experiment, Experiment 10. The fire was ignited in the upholstered chair next to the bed in bedroom 4. At the time of ignition, the exterior vents included the bedroom 4 window and front door. The door to bedroom 1 was closed, while the doors to bedroom 2, bedroom 3, and bedroom 4 were open. The fire spread from the chair to the bed and flashover occurred following the failure of the bedroom 4 windows. Following flashover, the suppression crew conducted interior suppression operations. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the bedroom 4 windows. All interior doors and exterior windows remained in their initial positions for the duration of the experiment. The development of thermal classes at the 3 ft elevation during the baseline experiment show the how the relative hazard of areas within the structure change a function of time. Figure 6.9 shows the shows the thermal conditions expressed in terms of thermal operating classes corresponding to the 3 ft temperature and heat flux in the period following intervention for Experiment 10.

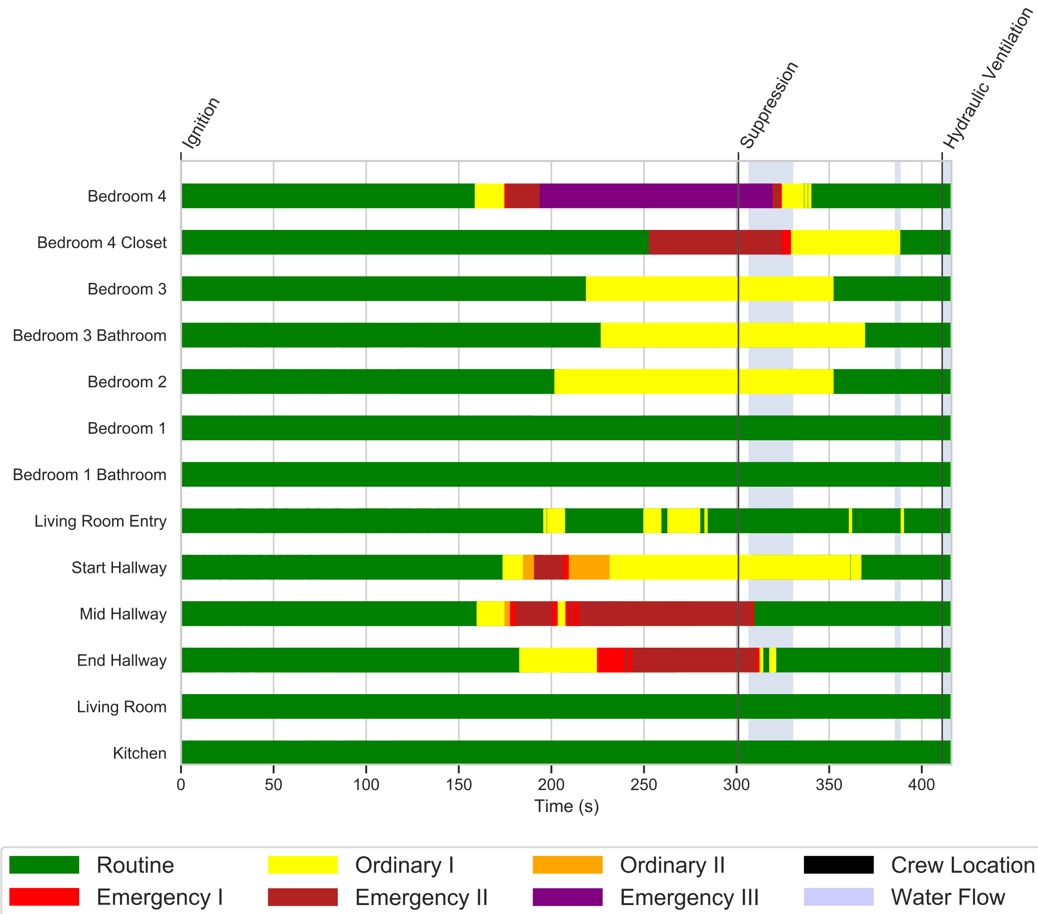


Figure 6.9: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes for baseline bedroom ignition experiment without intervention (Experiment 10).

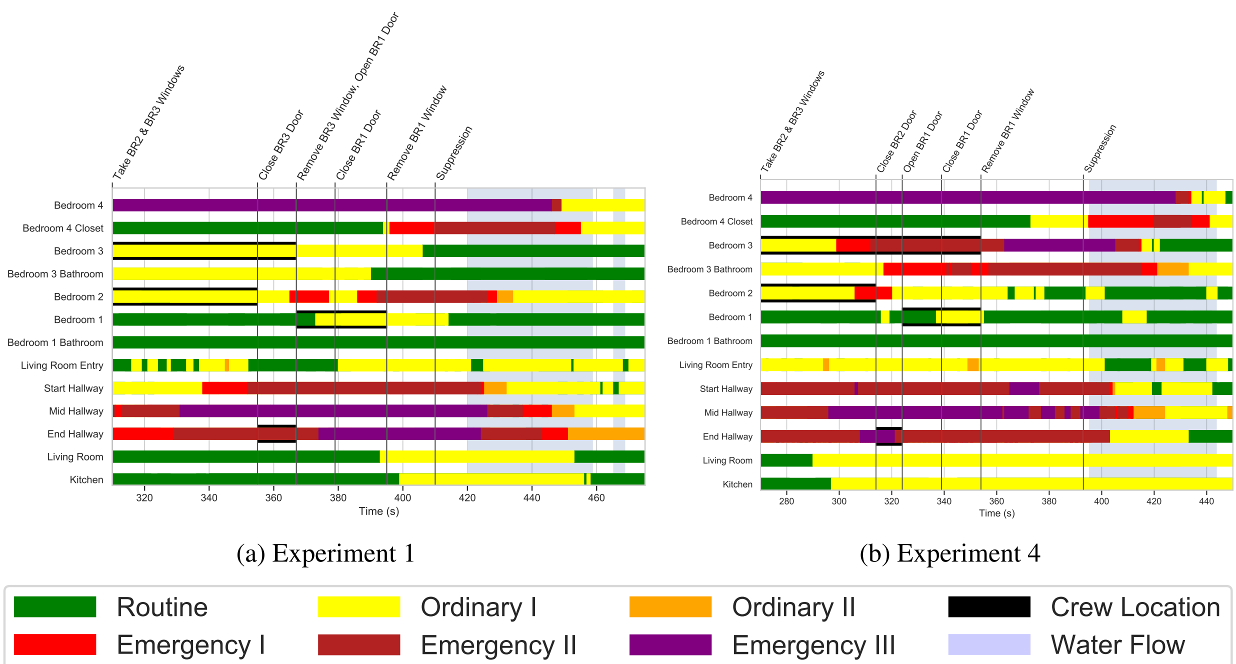
The operating class in bedroom 4 increased from routine to ordinary, 160 s after ignition. Temperatures exceeded 72 °C (162 °F) at the 3 ft as flames spread to the bed and there was rollover across the bedroom 4 ceiling level and into the hallway. Flames in the hallway increased the mid hallway heat flux to over 2 kW/m^2 which increased the thermal exposure to an ordinary operating class. Further flame spread across the bed and into the hallway over the next 15 s, led to emergency operating classes in both bedroom 4 (3 ft temperature in excess of 300 °C (572 °F)) and the mid hallway (floor heat flux in excess of 12 kW/m^2). As bedroom 4 reached a steady post-flashover state at approximately 250 s post ignition, the end hallway location also increased to an emergency operating class due to the flame spread along the hallway carpet and accumulation of combustion gases. At the same time, the start hallway increased to an ordinary exposure class while the living room entry fluctuated between ordinary and routine levels as the open front door limited the accumulation of combustion gases.

For bedrooms 2 and 3 where the hallway door was open through the duration of the experiment, the operating level reached ordinary levels and 3 ft temperatures peaked at approximately 160 °C (320 °F). In contrast, the operating level in bedroom 1, which was isolated from the start of the experiment remained at the routine level with the 3 ft temperature remaining below 25 °C (77 °F).

6.3.1 Impact of Isolation

Bedroom Isolation from Window Initiated Search Pre-Suppression

Experiments 1 and 4 examined window initiated search that occurred prior to suppression. The primary difference between the two experiments was which bedroom was isolated following initial entry — bedroom 3 in Experiment 1 compared to bedroom 2 in Experiment 4. To assess the impact of isolation of the space of entry for a window initiated search prior to suppression, Figure 6.10 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiments 1 and 4. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.



(a) Experiment 1

(b) Experiment 4

Figure 6.10: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics.

In both Experiments 1 and 4, the doors between the hallway and bedrooms 2 and 3 were open from the time of ignition, which resulted in temperatures consistent with ordinary operating conditions at the time that the bedroom windows were ventilated. Window ventilation established bi-directional flows local to the vents in both experiments.

In Experiment 1, where bedroom 2 was not isolated, 3 ft temperatures steadily rose and reached a intermediate peak of 226 °C (439 °F) 58 s post intervention, values consistent with an emergency operating class. Temperatures temporarily decreased following gas exchange across the hallway while the bedroom 1 door was opened and closed, but within 20 s of bedroom 1 door closure (80 s post window ventilation), the 3 ft temperatures had risen from 130 °C (266 °F) to 300 °C (572 °F) and heat flux had risen from 4.0 kW/m^2 to 12.3 kW/m^2 moving bedroom 2 from the ordinary operating class back to the emergency operating class. Temperature and heat flux remained elevated and the room remained in the emergency operating class until suppression of the bedroom 4 fire.

In Experiment 4, where bedroom 3 was not isolated, 3 ft temperatures in bedroom 3 steadily rose from 146 °C (295 °F) to 200 °C (392 °F) in the 30 s following window ventilation, which increased the operating class from ordinary to emergency. Over the next 30 s, the lack of isolation, presence of an exterior vent, and close proximity to the fire compartment resulted in flame spread across the hallway and into bedroom 3. Within 90 s of window ventilation, the 3 ft temperatures crossed 800 °C (1472 °F) and the room transitioned through flashover as shown in Figure 6.11. Bedroom 3 remained in the emergency operating class until suppression, with 3 ft temperatures peaking at 935 °C (1715 °F). Additionally, bathroom 3, which was also not isolated, reached the emergency operating class 98 s after initial intervention. The 3 ft temperatures peaked at 330 °C (626 °F) and 10 kW/m^2. Bathroom 3 was adjacent to, but not part of the flow path created between the fire room and the bedroom 3 window, which both delayed and dampened the temperature and heat flux rise in the space relative to the bedroom.

Figure 6.11: Photograph of side C exterior fire conditions at bedroom 3 window 90 s after window ventilation during Experiment 4.

In both Experiments 1 and 4, the bedrooms which were isolated after ventilation transitioned back to the routine operating class prior to suppression due to the combination of the closed door and local exterior vent. In Experiment 1, 3 ft bedroom 3 temperatures peaked at 145 °C (293 °F) and in Experiment 4, 3 ft bedroom 2 temperatures peaked at 256 °C (493 °F). In both experiments, the peak temperatures in these rooms occurred immediately prior to closure of the respective bedroom doors, further quantifying the thermal protection provided by a closed door due to the isolation from the flow path. Figure 6.12 shows post-experiments photographs of both bedrooms for the respective experiments. Note the distinct differences in thermal damage between Figures 6.12a and 6.12b where the rooms were isolated and Figures 6.12c and 6.12d where the rooms were not isolated.

(a) Experiment 1 Bedroom 3 (Isolated)

(b) Experiment 4 Bedroom 2 (Isolated)

(c) Experiment 1 Bedroom 2 (Not Isolated)

(d) Experiment 4 Bedroom 3 (Not Isolated)

Figure 6.12: Post experiment photographs of bedrooms 2 and 3 for Experiments 1 and 4.

In both experiments, the crew that entered through the bedroom 2 window crossed the hallway to open the bedroom 1 door and subsequently close the bedroom 1 door behind them. The operating class at the end hallway was at the emergency level with 3 ft temperatures between 500 °C and 600 °C (932 °F and 1112 °F) and heat fluxes between 10 kW/m^2 and 20 kW/m^2. Flaming combustion at the end hallway location led to thermal conditions (emergency class II and III) that were beyond the testing limits of PPE and limit the residence time of firefighters attempting to traverse the hallway.

In Experiment 8b a window initiated search ahead of suppression was performed into a room, in this case bedroom 3, that was isolated prior to ignition. Figure 6.13 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 8b. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

Figure 6.13: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics into an isolated room (Experiment 8b).

As shown in Figure 6.13, bedroom 3 remained in the routine operating class for the duration experiment. Prior to the window ventilation, there was intermittent flaming combustion at the top of the door frame due to the 1000 °C (1832 °F) temperatures at the ceiling in the hallway (Figure 6.14a). Although sustained combustion on the bedroom 3 side of the door did not occur (Figure 6.14b, the intermittent burning is an indication that a closed door may not provide infinite protection. The 3 ft temperature in the bedroom was at 20 °C (68 °F) prior to the ventilation of the window and remained nominally steady in the 30 s until the door was opened. Despite the exterior vent created in bedroom 3, the closed door provide sufficient flow resistance to prevent the higher temperature, higher pressure fire gases from filling the bedroom as shown by the hallway conditions following the door being opened in Figure 6.14c. Additionally, because the door was only opened for 16 s and there was water flow from a pressurized water fire extinguisher immediately following the bedroom door being opened, flaming combustion local to the mid hallway location was temporarily controlled and the 3 ft temperatures in bedroom 3 peaked at 38 °C (100 °F) shortly after the door was closed.

(a) 10 s Prior to Window Ventilation

(b) Immediately Prior to Hallway Door Open (30 s Post Window Ventilation)

(c) Immediately Following Hallway Door Open

Figure 6.14: Images of bedroom 3 from Experiment 8b prior to window ventilation and before and after opening the interior hallway door.

To proceed to search bedrooms 1 and 2, the search crews needed to proceed past the fire room where doorway temperatures at the 3 ft elevation were in excess of 600 °C (1112 °F). It it important to recognize that although the pressurized water fire extinguisher was able to suppress a portion of the flaming combustion in the hallway which reduced the operating class from emergency to ordinary, the bedroom 4 fire remained unaffected and in a post-flashover state. While the crews searched the remaining two bedrooms, bedrooms 1 and 2, fire from bedroom 4 began to spread back into the hallway as shown in Figure 6.13 with the mid hallway location increasing back to an emergency operating class (3 ft temperatures in excess of 300 °C (572 °F) and heat flux at 13 kW/m^2). These thermal conditions would limit the duration for which firefighters could safely operate in this space. Temperature and heat flux continued to increase in the hallway until suppression began to return conditions throughout the structure to routine operating levels.

Fire Room Isolation from Door Initiated Search Pre-Suppression

In Experiment 7, the search crews performed a door initiated search ahead of suppression that included isolation of the fire room door. It is important to recognize that for this experiment the bedroom 4 door was hardened to ensure that it could be closed to quantify the effects of the door closure. There is no guarantee that the fire room door will be present at the time of fire department arrival due to fire growth. Figure 6.15 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 7. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

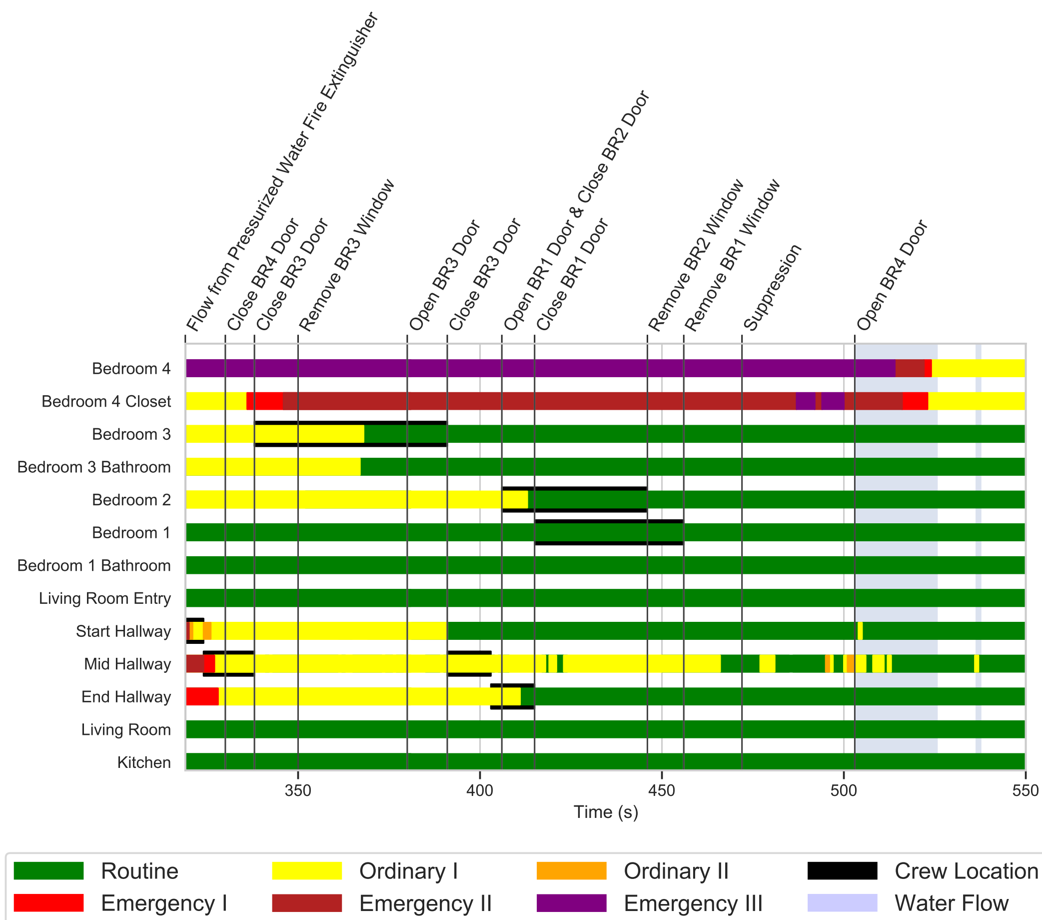


Figure 6.15: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression door initiated search tactics with fire room isolation (Experiment 7).

Prior to flow from the pressurized water fire extinguisher, the start hallway was in the emergency operating class due to the 35 kW/m^2 measured at the start hallway heat flux gauge. Figure 6.16 shows the flaming combustion along the carpet between bedroom 4 and the start hallway location. Following water flow to the carpet, the heat flux dropped to below 6 kW/m^2 and the operating class dropped to the ordinary level. This also allowed the search crew reach bedroom 4 and close the door, which isolated the rest of the structure from the fire compartment.

Start Hallway	
3 ft Temperature	177 °C (350 °F)
Heat Flux	35 kW/m^2

Mid Hallway	
3 ft Temperature	273 °C (523 °F)
Heat Flux	3.8 kW/m^2

Figure 6.16: Photograph of start hallway and thermal conditions at start hallway and mid hallway prior to flow from pressurized water fire extinguisher in Experiment 7.

Although the failed windows in bedroom 4 were sufficient ventilation to maintain a post-flashover state in bedroom 4 (temperatures in excess of 800 °C (1472 °F)), an effect of the isolation was that the remaining parts of the structure did not increase to operating classes above ordinary. As the crews searched the remaining bedrooms, the respective rooms were still isolated from hallway. The 3 ft temperature at the mid hallway and end hallway locations ranged between 100 °C (212 °F) at the time of isolation to 75 °C (167 °F) at the time of suppression, and it could be assumed the bedroom 4 door would remain intact for duration of time between isolation and suppression.

In both cases where the bedroom door was opened from ignition (bedrooms 2 and 3), the closure of those doors combined with the removal of the window dropped the operating class to the routine level prior to suppression. Bedroom 1, which was isolated prior to ignition, remained in the routine class for the duration of the experiment, which 3 ft temperatures remaining below 21 °C (70 °F) and negligible measured heat flux.

Fire Room Isolation from Window Initiated Search Pre-Suppression

Experiment 8 was designed to replicate a search crew conducting a window initiated search into the bedroom on the opposite side of the hallway from the fire room and then proceeding to isolate the fire room after searching the room of entry. It is important to recognize that for this experiment the bedroom 4 door was hardened to ensure that it could be closed to quantify the effects of the door closure. There is no guarantee that the fire room door will be present at the time of fire department arrival due to fire growth. Figure 6.17 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 8. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

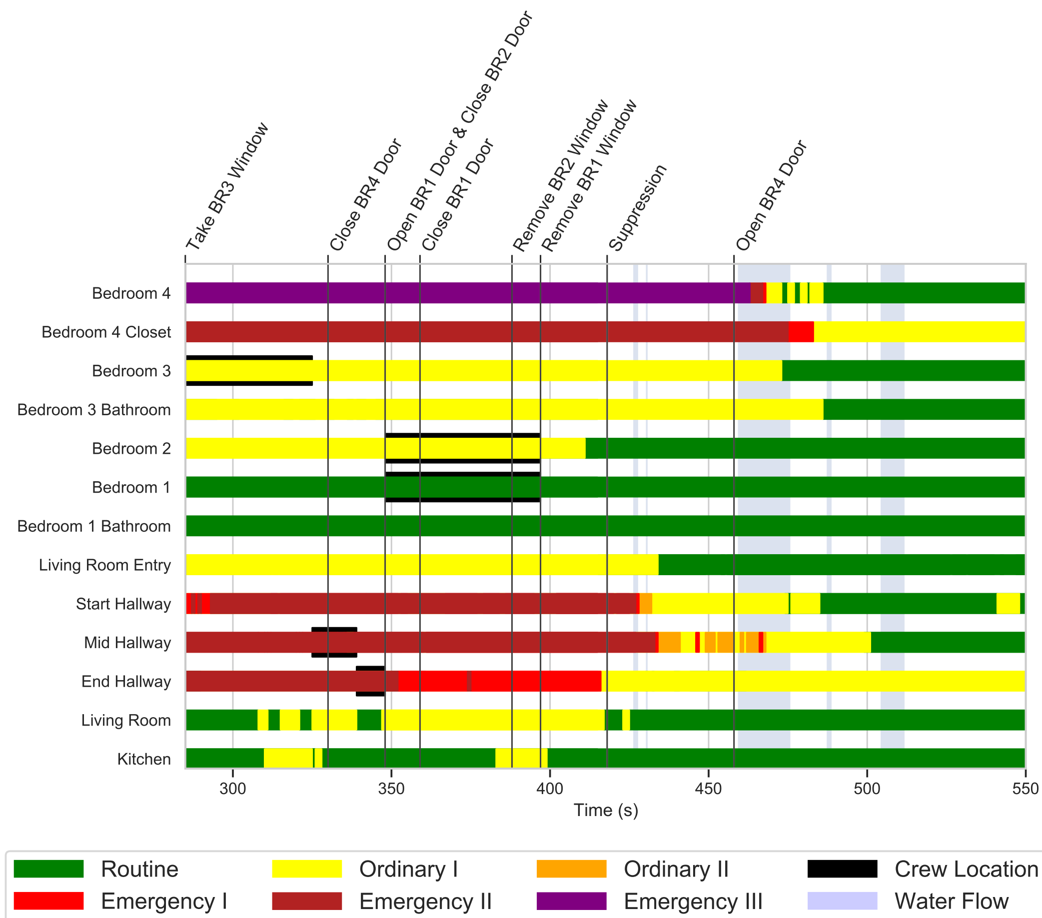


Figure 6.17: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics with fire room isolation (Experiment 8).

Ventilation of the bedroom 3 window created a new exterior vent in the structure. Initially uni-directional exhaust flow was established at the window. The 3 ft temperature in the center of the room was 140 °C (284 °F) prior to ventilation and increased to 180 °C (356 °F) over the 45 s that the crew searched bedroom 3 and then crossed the hallway to close the bedroom 4 door. Temperatures returned to approximately 140 °C (284 °F) as bidirectional flow was established at the window, and remained steady as the higher temperature combustion gases that had accumulated in the structure flowed toward the vented window. As a result, bedroom 3 remained in the ordinary operating class.

The mid hallway location was in the emergency operating class (emergency II) at the time the crew crossed the hallway to close the bedroom 4 door due to the accumulation of combustion gases and flaming combustion along the carpet. This resulted in 3 ft temperatures of 400 °C (752 °F)) and heat fluxes to the floor of 14 kW/m^2. Firefighters remained in the emergency operating class as they moved to the end hallway before entering bedrooms 1 and 2, due to 330 °C (626 °F) 3 ft temperatures. At these thermal conditions, the time period for which firefighters can safely operate is limited. The closure of the bedroom 4 door resulted in a reduction of gas temperatures in hallway locations (the end hallway location dropped to an ordinary level after entry into the bedrooms), but the mid hallway and start hallway locations remained in the emergency operating class due to flame spread along the carpet (similar to Figure 6.16).

The isolation and subsequent removal of the bedroom 2 window reduced the operating level within bedroom 2 from ordinary to routine. The 3 ft temperatures dropped from 185 °C (365 °F) to 130 °C (266 °C) in the 18 s between isolation and window removal and then to below 72 °C (160 °F) over the next 23 s. The bedroom heat flux similarly dropped from 5 kW/m^2 prior to isolation to below 1 kW/m^2 following window ventilation. Similar to Experiment 7, bedroom 1, which was isolated prior to ignition, remained in the routine class for the duration of the experiment, which 3 ft temperatures remaining below 30 °C (86 °F) and negligible measured heat flux.

Front Door Isolation Pre-Suppression

Experiment 6 examined door initiated search prior to suppression where the front door was closed by the search crew after they entered the structure. To assess the impact of front door closure, Figure 6.18 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 6. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

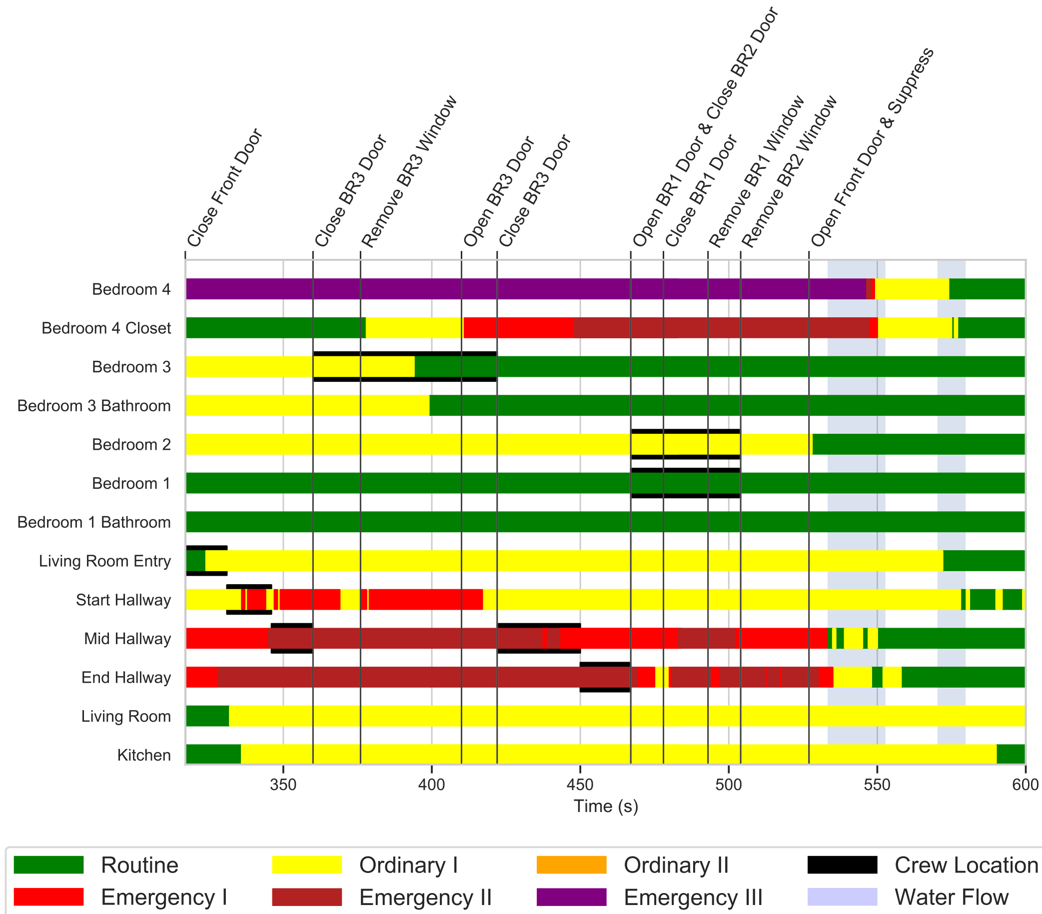


Figure 6.18: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression door initiated search tactics with front door closure (Experiment 6).

Similar to fire room conditions in Experiment 7 and Experiment 8, where the bedroom door was closed, floor to ceiling temperature remained above 800 °C (1472 °F) in bedroom 4 until suppression, as the bedroom 4 windows supplied sufficient oxygen for combustion despite the closed front door. The closure of the front door did remove a bi-directional vent as a pathway for air supply to the ventilation-limited bedroom 4 fire. It also cutoff an pathway for combustion gases to exhaust from the structure. The combined effect was that there was less oxygen available for combustion in the hallway due to accumulation of combustion gases which limited flame spread from bedroom 4 to the hallway. The effects of smoke layer descent were noticeable in the living room and kitchen where 3 ft temperatures increased from approximately 60 °C (140 °F) to peak values over 140 °C (284 °F) within 100 s of front door closure.

At the start hallway and mid hallway locations, the 3 ft temperatures at the start hallway increased from 145 °C to over 200 °C (293 °F to 392 °F) and the mid hallway increased from 220 °C to 280 °C (428 °F to 536 °F) in the 40 s following closure of the front door from which point 3 ft temperatures remained nominally steady. This thermal exposure represented an emergency operating class. The end hallway location entered the emergency level 25 s after the front door was closed as the hot gas layer reached the 3 ft level at the dead end of the hallway. The 3 ft temperatures at the end hallway peaked at 370 °C (698 °F) 73 s after the front door was closed (30 s after bedroom 3 was first isolated). Following the opening of the bedroom 1 door, 3 ft temperatures temporarily dropped below 200 °C (392 °F) due to mixing with the cooler gases behind the initially closed door. Following closure of the bedroom 1 door, an increase in temperature returned the thermal class back to the emergency level until suppression.

For both bedrooms 2 and 3, which reached the ordinary operating level due to the open bedroom doors prior to ignition, the operating classes returned to routine levels following isolation and ventilation. Bedroom 1, which was isolated prior to ignition, remained in the routine class for the duration of the experiment, with 3 ft temperatures remaining below 28 °C (82 °F) and negligible measured heat flux.

6.3.2 Impact of Search Timing Relative to Suppression

Experiments 4 and 5 examined window initiated search that occurred prior to and during suppression. To assess the impact of suppression timing relative to search, Figure 6.19 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiments 4 and 5. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

Figure 6.19: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during pre-suppression (Experiment 4) and during suppression (Experiment 5) search tactics.

In both Experiments 4 and 5, the doors between the hallway and bedrooms 2 and 3 were open from the time of ignition, which resulted in temperatures consistent with ordinary operating conditions at the time that the bedroom windows were ventilated. Window ventilation established bi-directional flows local to the vents in both experiments and a temporary period (approximately 10 s) of steady values at the 3 ft measurement locations in the center of the room immediately following the intervention.

In Experiment 4, where search occurred ahead of suppression, the 3 ft temperatures in the non-isolated bedroom 3 steadily rose from 146 °C (295 °F) to 800 °C (1472 °F) within 90 s of window ventilation as flames spread across the hallway and the room transitioned through flashover. Bedroom 3 remained in the emergency operating class (emergency III) until suppression, with 3 ft temperatures peaking at 935 °C (1715 °F). Additionally, bathroom 3, which was not isolated, reached the emergency operating class (emergency II) 98 s after initial intervention. The 3 ft temperatures peaked at 330 °C (626 °F) and 10 kW/m^2. Bathroom 3 was adjacent to, but not part of the flow path created between the fire room and the bedroom 3 window, which both delayed and dampened the temperature and heat flux rise in the space.

Bedroom 2 which was isolated after ventilation in Experiment 4 peaked to the emergency operating class prior to isolation, transitioned back to routine prior to suppression due to the combination of the closed door and local exterior vent. The 3 ft bedroom 2 temperature peaked at 256 °C (493 °F). The crew that entered through the bedroom 2 window crossed the hallway to open the bedroom 1 door and subsequently closed the door behind them. The operating class at the end hallway was at the emergency III level with 3 ft temperatures of approximately 500 °C (932 °F) and heat fluxes of approximately 10 kW/m^2. Flaming combustion at the end hallway location led to thermal conditions (emergency class II and III) that were beyond the testing limits of PPE and limit the residence time of firefighters attempting to traverse the hallway.

In Experiment 5, suppression was coordinated with the window initiation search operations as water flow began 8 s after the windows were ventilated. The peak 3 ft temperature in both bedrooms 2 and 3 was 130 °C (266 °F) which occurred immediately prior to ventilation of the respective bedroom windows. The combination of suppression and ventilation of the bedrooms returned them to the routine operating level (6 s in bedroom 3 and 18 s in bedroom 3) while the crews were still in the bedrooms. As the crew crossed the hallway from bedroom 2 to bedroom 1, the end hallway location had also returned to a routine operating class with 3 ft temperatures of approximately 43 °C (110 °F). Bedroom 1, which was isolated prior to ignition, remained in the routine class for the duration of the experiment, which 3 ft temperatures remaining below 21 °C (70 °F) and negligible measured heat flux.

A comparison of these experiments show the beneficial effect of coordinated search and suppression for reducing the thermal operating class for firefighters in the structure. In the experiment where search occurred prior to suppression, the combination of isolation and ventilation was effective at reducing the local thermal operating class for searching firefighters.

6.4 Estimated Toxic Gas and Thermal Exposures to Occupants During Search

To assess the impact of search tactics and the timing of tactics relative to suppression on occupants both the thermal FED and toxic FED are considered. To control for variances in fire growth and timing across experiments in order to best compare results across experiments, the average rate of change of the respective FED values (FER) over the time window of interest will be compared. Since, by mathematical definition, FED always increases, the FER can be used to assess the rate at which the exposure to a potential occupant is increasing. Essentially, when comparing a set of actions, the lower FER in comparison is an indication that the corresponding action was more effective at reducing the hazard.

6.4.1 Impact of Isolation

Bedroom Isolation from Window Initiated Search Pre-Suppression

Experiments 1 and 4 examined window initiated search that occurred prior to suppression. The primary difference between the two experiments was which open bedroom was isolated following initial entry — bedroom 3 in Experiment 1 and bedroom 2 in Experiment 4. To remove potential bias due to the distance from the fire room to the respective isolated space and because measurements were in different locations within the respective rooms (3 ft on the bed and 1 ft in the bathroom), Table 6.3 includes the average toxic and thermal FER from the time of isolation to primary suppression for the bedroom 2 bed, bedroom 2 window, bathroom 3 and bedroom 3 window.

Table 6.3: Impact of Bedroom Isolation on Occupant Tenability for Pre-Suppression Window Initiated Search

	Average Toxic FER		Average Thermal FER	
Location	Isolated	Not Isolated	Isolated	Not Isolated
Bedroom 2 Bed (3 ft)	0.0065 (Exp 4)	0.037 (Exp 1)	0.0020 (Exp 4)	0.054 (Exp 1)
Bedroom 2 Window (1 ft)	0.0012 (Exp 4)	0.034 (Exp 1)	0.0008 (Exp 4)	0.033 (Exp 1)
Bedroom 2 Window (3 ft)	0.0025 (Exp 4)	0.088 (Exp 1)	0.016 (Exp 4)	0.060 (Exp 1)
Bathroom 3 (1 ft)	0.010 (Exp 1)	0.34 (Exp 4)	4.5e-5 (Exp 1)	0.015 (Exp 4)
Bedroom 3 Window (1 ft)	0.0029 (Exp 1)	0.25 (Exp 4)	5.3e-5 (Exp 1)	0.16 (Exp 4)
Bedroom 3 Window (3 ft)	0.0041 (Exp 1)	0.90 (Exp 4)	0.0017 (Exp 1)	0.59 (Exp 4)

The rate of exposure increase data in Table 6.3 show the impact of isolation after entry on both the toxic gas and thermal exposure to potential occupants. At all locations, the average rate of FED increase (both toxic and thermal) was lower at the locations which were isolated. The differences between isolated and non-isolated are most pronounced in bedroom 3 due to the closer proximity to the fire room (bedroom 3 is across the hallway from bedroom 4). Recall from Sections 5.4 and 6.3.1, that prior to suppression in Experiment 4, fire extended out of bedroom 4 and across the hallway into bedroom 3. Bedroom 3, which was not isolated in this experiment, transitioned through flashover. In Experiment 1, the closure of the bedroom 3 door following entry through the ventilated window prevented the spread of fire into the space. As a result the rate of increase for both toxic FED and thermal FED was generally 2 orders of magnitude lower in the isolated space compared to the non-isolated space. The exception was the 1 ft elevation in the bathroom, which was still 1 order of magnitude lower for the toxic FER.

In Experiment 8b a window initiated search prior to suppression was performed into a room (bedroom 3) that was isolated prior to ignition. Table 6.4 shows the average rate of change of toxic and thermal FED for bedrooms 1, 2, and 3 from the time at which the bedroom 3 window was vented until 30 s after the bedroom 3 door was opened and closed following the crew leaving the room to search beyond point of entry. During this period of time, the bedroom 1 door and window remained closed and the bedroom 2 door remained opened and bedroom 2 window remained closed.

Table 6.4: Impact of Isolation on Occupant Tenability for Window Initiated Search Pre-Suppression into Isolated Room

Location	Isolated	
	Average Toxic FER	Average Thermal FER
Bedroom 1 Bed (3 ft)	2.2e-5 (Exp 8b)	2.9e-6 (Exp 8b)
Bathroom 3 (1 ft)	2.2e-5 (Exp 8b)	8.6e-7 (Exp 8b)
Bedroom 3 Window (1 ft)	2.3e-4 (Exp 8b)	3.5e-6 (Exp 8b)
Bedroom 3 Window (3 ft)	1.63-4 (Exp 8b)	6.7e-6 (Exp 8b)

Location	Not Isolated	
	Average Toxic FER	Average Thermal FER
Bedroom 2 Bed (3 ft)	0.24 (Exp 8b)	0.027 (Exp 8b)
Bedroom 2 Window (1 ft)	0.095 (Exp 8b)	0.017 (Exp 8b)
Bedroom 2 Window (3 ft)	0.12 (Exp 8b)	0.038 (Exp 8b)

Recall Figure 6.13 from Section 6.3.1, the closed door prior to the window initiated search kept bedroom 3 in the routine operating class for firefighters for the duration of the experiment. This was similar to bedroom 1, which was also isolated but did not have a vented window. In contrast, bedroom 2 which had an open interior door reached the ordinary operating class. The FER data shows similar results for the toxic and thermal exposures to potentially trapped occupants. The rate of toxic and thermal FED increase in bedroom 3 was of similar magnitude to bedroom 1 compared to bedroom 2. In particular the rate of toxic FED increase was between 2 to 3 orders of magnitude higher in the open bedroom. This further shows the impact of the closed door in reducing exposure and that ventilation into an isolated space does not drastically change the conditions of the space.

Fire Room Isolation from Door/Window Initiated Search Pre-Suppression

Two experiments were conducted to quantify the impact to conditions within the structure where the fire compartment was isolated for search operations conducted prior to suppression. In Experiment 7, the door to bedroom 4 was isolated following search originating through the open front door and in Experiment 8 the door to bedroom 4 was isolated following a window initiated search originating in bedroom 3.

To assess the effectiveness of this tactic, Experiment 7 is compared to Experiment 10, the baseline experiment for which ventilation/isolation did not vary from the same initial conditions that were set in Experiments 7. Table 6.5 presents average toxic and thermal FERs for over the time period following isolation of the fire room (bedroom 4) door until just prior to isolation of bedroom 2 in Experiment 7 compared to the 60 s time period following flashover in bedroom 4 until the start of suppression in Experiment 10. The locations in bedroom 2, start hallway, and end hallway are included table because they represent the best direct comparison of locations between the two experiments. The locations in bedroom 3 were not included because the bedroom 3 door was closed

8 s after the bedroom 4 door in Experiment 7 which deviated from Experiment 10 and there was an insufficient time window between the respective door closures to present a representative FER average. Lastly, the mid hallway location was omitted because in Experiment 7 was pressurized water fire extinguisher was used at mid hallway location to put out the carpet fire to allow for door closure. This did not occur in Experiment 10, which limits the ability to assess the effect of the bedroom 4 door closure at that measurement location.

Table 6.5: Impact of Fire Room Isolation on Occupant Tenability for Pre-Suppression Door Initiated Search: From Bedroom 4 Isolation Until Prior to Bedroom 2 Isolation

	Average Toxic FER		Average Thermal FER	
Location	Experiment 7	Experiment 10	Experiment 7	Experiment 10
Bedroom 2 Bed (3 ft)	0.055	0.032	0.0032	0.014
Bedroom 2 Window (1 ft)	0.018	0.021	6.3e-4	0.0038
Bedroom 2 Window (3 ft)	0.053	0.031	0.0040	0.014
Start Hallway (1 ft)	6.4e-4	2.1e-4	0.0029	0.011
Start Hallway (3 ft)	0.0023	0.0017	0.0037	0.013
End Hallway (1 ft)	0.0062	0.0062	1.6e-4	0.0018
End Hallway (3 ft)	0.025	0.014	0.0011	0.050

The data in Table 6.5 reveal two key takeaways from the fire room isolation. The first is that in Experiment 7, the rate of increase of FED due to the thermal conditions are an order of magnitude less in the case where the fire room was isolated from the remainder of the structure. The isolation limited the flow of combustion gases into the hallway. This resulted in lower velocity which in turn decreased the convection heat flux. Additionally, the accumulated combustion gases dropped in temperature due to mixing, gas exchange through the open front door, and heat loss to the structure. These factors combined to lower the thermal FED. The toxic FERs did not have the same response. Although the closure of the fire room door reduced the heat exposure, the composition of the accumulated gases did not change. As a result, the toxic FERs were of similar magnitude to the non-isolated experiment and generally slightly higher. Some of these differences could be attributed to experimental variability and that as the gases cooled, they lost some of their buoyancy and began to descend within the space.

Table 6.6 presents the rates to show the change if there was a corresponding change in ventilation to increase the gas exchange. The time window for the Experiment 7 ranges from when the bedroom 2 door was closed up until the bedroom 4 door was re-opened for suppression. The time range in Experiment 10 is the same as was used in Table 6.5. Over the 100 s following the time period shown in Table 6.5, the average thermal FERs in Experiment 7 dropped another order of magnitude, down to two orders of magnitude compared to Experiment 10. The toxic FERs also decreased to be an order of magnitude less than Experiment 10. The drop in toxic FER highlights the impact of ventilation and isolation at improving gas concentrations within space. Over this 100 s time period, the bedroom 2 door was closed and the window was removed. The window removal allowed for air to enter the room and combustion gases to exhaust and the isolation acted a barrier for that air to reach the fire. The closure of the bedroom 2 door also resulted in more efficient gas exchange through the open front door as all four bedrooms were closed which reduced the volume of space that exchanged air through the door.

Table 6.6: Impact of Fire Room Isolation on Occupant Tenability for Pre-Suppression Door Initiated Search: From Bedroom 2 Isolation Until Prior to Bedroom 4 Open for Suppression

	Average Toxic FER		Average Thermal FER	
Location	Experiment 7	Experiment 10	Experiment 7	Experiment 10
Bedroom 2 Bed (3 ft)	0.0066	0.032	1.0e-4	0.014
Bedroom 2 Window (1 ft)	0.0032	0.021	2.5e-5	0.0038
Bedroom 2 Window (3 ft)	0.0029	0.031	1.0e-4	0.014
Start Hall (1 ft)	4.2e-4	2.1e-4	4.4e-5	0.011
Start Hall (3 ft)	6.2e-4	0.0017	1.4e-4	0.013
End Hall (1 ft)	9.1e-4	0.0062	6.4e-5	0.0018
End Hall (3 ft)	9.0e-4	0.014	1.6e-4	0.050

To assess the impact of fire room isolation during a window initiated search pre-suppression, consider Experiment 8. Similar to Experiment 4, ventilation of the bedroom 3 window ahead of suppression created an exterior vent which initially resulted in unidirectional exhaust flow of combustion gases through the window. Within approximately 10 s the flow became bi-directional and the inflow of air began to flow across the hallway toward the fire room. Unlike Experiment 4, where these conditions eventually resulted in flame spread across the hallway and flashover of bedroom 3; in Experiment 8, the search crew crossed the hallway and closed the bedroom 4 door isolating the fire room from the rest of the structure. Table 6.7 shows the average toxic and thermal FERs in bedroom in the 45 s period following the start of window ventilation until the bedroom 4 door was closed and a similar 45 s period following the closure of the fire room (bedroom 4) door. The data show that isolation of the fire room door was effective at reducing both the toxic and thermal FER in the bedroom where a window was vented for search.

Table 6.7: Impact of Fire Room Isolation on Occupant Tenability for Window Initiated Search Pre-Suppression

Location	Post Window Ventilation, Pre Fire Room Isolation	
	Average Toxic FER	Average Thermal FER
Bathroom 3 (1 ft)	0.022 (Exp 8)	0.0011 (Exp 8)
Bedroom 3 Window (1 ft)	0.018 (Exp 8)	0.0099 (Exp 8)
Bedroom 3 Window (3 ft)	0.019 (Exp 8)	0.020 (Exp 8)
	Post Fire Room Isolation	
Location	Average Toxic FER	Average Thermal FER
Bathroom 3 (1 ft)	0.021 (Exp 8)	1.8e-4 (Exp 8)
Bedroom 3 Window (1 ft)	0.0083 (Exp 8)	0.0068 (Exp 8)
Bedroom 3 Window (3 ft)	0.0041 (Exp 8)	0.0097 (Exp 8)

6.4.2 Impact of Search Timing Relative to Suppression

Two pairs of experiments were designed to examine the impact of suppression relative to window initiated search operations: Experiments 1/2 and Experiments 4/5. Experiments 1 and 2 featured window initiated search that occurred prior to suppression and during suppression, respectively. Following ventilation of the bedroom windows, bedroom 3, which was nearest the fire room (bedroom 4), was isolated. Table 6.8 shows the average toxic and thermal FED rate of change from the time of isolation to primary suppression for bedrooms 2 and 3.

Table 6.8: Impact of Suppression Timing on Occupant Tenability for During Suppression Window Initiated Search and Bedroom 3 Isolation

Location	Not Isolated			
	Average Toxic FER		Average Thermal FER	
Bedroom 2 Bed (3 ft)	0.037 (Exp 1)	0.0055 (Exp 2)	0.054 (Exp 1)	5.7e-5 (Exp 2)
Bedroom 2 Window (1 ft)	0.034 (Exp 1)	0.0038 (Exp 2)	0.033 (Exp 1)	1.3e-5 (Exp 2)
Bedroom 2 Window (3 ft)	0.088 (Exp 1)	0.0053 (Exp 2)	0.060 (Exp 1)	5.7e-5 (Exp 2)
	Isolated			
Location	Average Toxic FER		Average Thermal FER	
Bathroom 3 (1 ft)	0.010 (Exp 1)	0.0088 (Exp 2)	4.5e-5 (Exp 1)	1.7e-5 (Exp 2)
Bedroom 3 Window (1 ft)	0.0029 (Exp 1)	0.0019 (Exp 2)	5.3e-5 (Exp 1)	1.8e-5 (Exp 2)
Bedroom 3 Window (3 ft)	0.0041 (Exp 1)	0.0018 (Exp 2)	0.0017 (Exp 1)	6.1e-5 (Exp 2)

The data show that for Experiment 2 the toxic and thermal FER in the non-isolated bedroom (bedroom 2) were at least an order of magnitude less compared to open bedroom in Experiment 1. In the isolated bedroom (bedroom 3), even though the FER differences were not as large, the toxic and thermal FERs were still less at each location for search during suppression compared to search ahead of suppression.

Experiments 4 and 5 also examined window initiated search that occurred prior to suppression and during suppression, respectively. The primary difference between these two experiments and Experiments 1 and 2 was which open bedroom was isolated following initial entry; for these experiments bedroom 2 was isolated. Table 6.9 shows the average toxic and thermal FER from the time of isolation until primary suppression for bedrooms 2 and 3. During Experiment 4, as discussed earlier, the exterior vent created by venting the window combined with the close proximity to the fire room and lack of isolation resulted in flame spread in bedroom 3 and eventual flashover of the space. In Experiment 5, where search occurred during suppression, flame spread into bedroom 3 was prevented and the both the toxic and thermal FERs were between 2-3 orders of magnitude lower. Similar to the Experiments 1 and 2, the magnitudes of the differences in FER were less for the isolated room, but the during suppression experiment had lower rates of FED increase.

Table 6.9: Impact of Suppression Timing on Occupant Tenability for During Suppression Window Initiated Search and Bedroom 2 Isolation

	Isolated			
Location	Average Toxic FER		Average Thermal FER	
Bedroom 2 Bed (3 ft)	0.0065 (Exp 4)	0.0033 (Exp 5)	0.0020 (Exp 4)	8.4e-6 (Exp 5)
Bedroom 2 Window (1 ft)	0.0012 (Exp 4)	0.0015 (Exp 5)	0.0008 (Exp 4)	3.2e-6 (Exp 5)
Bedroom 2 Window (3 ft)	0.0025 (Exp 4)	0.0014 (Exp 5)	0.0016 (Exp 4)	8.4e-6 (Exp 5)
	Not Isolated			
Location	Average Toxic FER		Average Thermal FER	
Bathroom 3 (1 ft)	0.34 (Exp 4)	0.0046 (Exp 5)	0.015 (Exp 4)	4.0e-6 (Exp 5)
Bedroom 3 Window (1 ft)	0.25 (Exp 4)	7.7e-4 (Exp 5)	0.16 (Exp 4)	2.9e-6 (Exp 5)
Bedroom 3 Window (3 ft)	0.90 (Exp 4)	7.2e-4 (Exp 5)	0.59 (Exp 4)	5.3e-6 (Exp 5)

These experiments highlight the impact of both suppression and isolation at reducing the rate of FED increase to potentially trapped occupants. The large drop in FERs in both during suppression experiments, in particular in the non isolated rooms, shows the value of early suppression on hazard reduction. Further, the extent of the impact of both of these tactics (suppression and isolation) is magnified for entry points in close proximity to the fire room.

6.5 Estimated Toxic Gas and Thermal Exposures During Rescue

In lieu of using an instrumented manikin that would have limited the rescue timing to the single speed at which it were removed and would have limited the egress pathways, the removal of occupants was simulated by performing a piecewise analysis of the discrete measurement locations within the house. Assessment of occupant rescue was performed by combining the appropriate subset of the 16 locations of temperature, heat flux, and gas concentrations to determine a cumulative exposure during rescue. The time period and duration at each relevant measurement location along the egress pathway were combined with data generated by members of the project technical panel.

To determine the rate at which a potential occupant could be moved between measurement locations, technical panel members conducted a series of time-to-task experiments designed to capture the speed at which firefighters could remove a potential occupant from a structure. In total, 12 members of the technical panel worked with members from their departments to conduct 360 individual victim removal time-to-task experiments.

The firefighters that participated in the experiments included career and volunteer members that ranged from 19 years old to 70 years old with a range of less than 1 year experience to over 37 years of experience. The drags were performed with both dummies (220 instances) that ranged between 44 lbs to 180 lbs and people (140 instances) that ranged between 120 lbs to 215 lbs. The drag distances ranged from as short as 4 ft, to as long as 100 ft, with a median distance of 15 ft. Occupants were dragged along floor types that included carpet, wood, tile, and concrete. Although these time-to-task experiments did not occur under the same conditions expected during a fire call, for 350 of the 360 instances, the firefighters had their vision impaired either through smoke from a training fire, theatrical smoke, or coverings on face pieces. The histogram and cumulative distribution of the time-to-task drag data can be found in Figure 6.20.

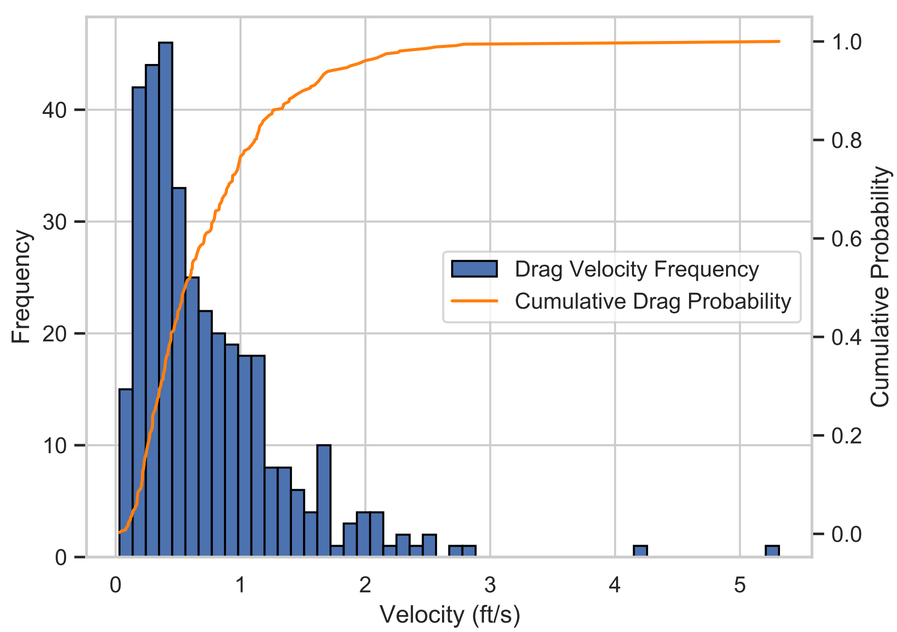


Figure 6.20: Histogram of victim removal velocity and cumulative distribution probability based on project technical panel time to task data for 360 individual time-to-task experiments.

As the range of data in Figure 6.20 shows, using a single value to represent drag velocity would provide an incomplete assessment. Therefore to better capture the rate at which potentially trapped occupants could be removed from the structure, the 25th and 75th quartile values are used to provide the middle 50% of speeds. These quartiles correspond to 0.32 ft/s (25th) and 1.0 ft/s (75th) and are used to show the range of exposures associated with the range of rescue velocities.

To assess the impact of removal of a potentially trapped occupant, both the toxic and thermal FEDs were calculated by summing the respective contributions from the different locations within the structure based on the different movement speeds. The toxic and thermal FEDs at the rescue point of origin were subtracted from the removal FEDs to determine a relative FED. Essentially, if the relative FED is positive, the occupant would have received additional exposure compared to being left in place. If the relative FED is negative, the occupant would have received a lower exposure compared to being left in place.

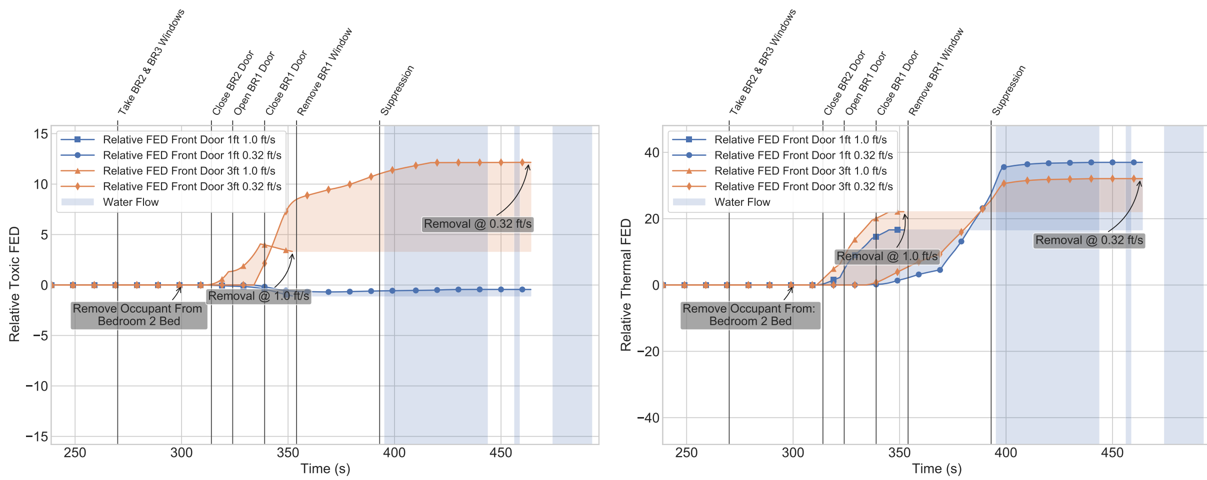
6.5.1 Impact of Isolation

Window Initiated Search Pre-Suppression

Experiment 4 examined window initiated search that occurred prior to suppression for a bedroom fire. In this experiment, the doors to bedrooms 2 and 3 were open prior to ignition. Following ventilation of those two windows, the door bedroom 2 was closed and the door to bedroom 3 remained opened. Figure 6.21 shows the relative toxic gas and thermal FEDs from Experiment 4 for a potential occupant on bedroom 2 being removed through the hallway to the front door. Recall from Section 6.5, that to calculate a relative FED, the toxic gas and thermal FEDs at the point of origin were subtracted from respective toxic gas and thermal FEDs calculated along the removal pathway. Essentially, if the relative FED is positive, the occupant would have received additional exposure compared to being left in place. If the relative FED is negative, the occupant would have received a lower exposure compared to being left in place.

The relative toxic FED (Figure 6.21a) shows that removal of the occupant through the front door at the 1 ft elevation through the range of velocities was effective at reducing the toxic exposure compared to leaving the occupant on the bed in an isolated bedroom. Removal at the 3 ft elevation however, would have resulted in an increased FED compared to remaining in the isolated space as the smoke layer as the smoke layer descended to approximately 3 ft above the floor.

The relative thermal FED shown in Figure 6.21b highlights the increased hazard associated with when the rescue path is past a non-isolated fire room and occurs prior to suppression. Prior to suppression, the end hallway, mid hallway, and start hallway locations had all reached the emergency operating class I and above (recall Figure 6.10b). At 314 s, just as the bedroom 2 door was closed, the mid hallway flux increased to more than 60 kW/m^2 due to flame spread from bedroom 4 into the hallway. This eventually led to flashover of the non-isolated bedroom, bedroom 3. This resulted in relative thermal FEDs at 1 ft/s and 3 ft above the floor to exceed 20. Although the measurement instrumentation allowed for a computation of the relative thermal FED in the hallway, flaming combustion throughout the mid hallway location would have made removal of an unprotected occupant along this pathway intractable.



(a) Toxic FED Relative to Bedroom 2 Bed

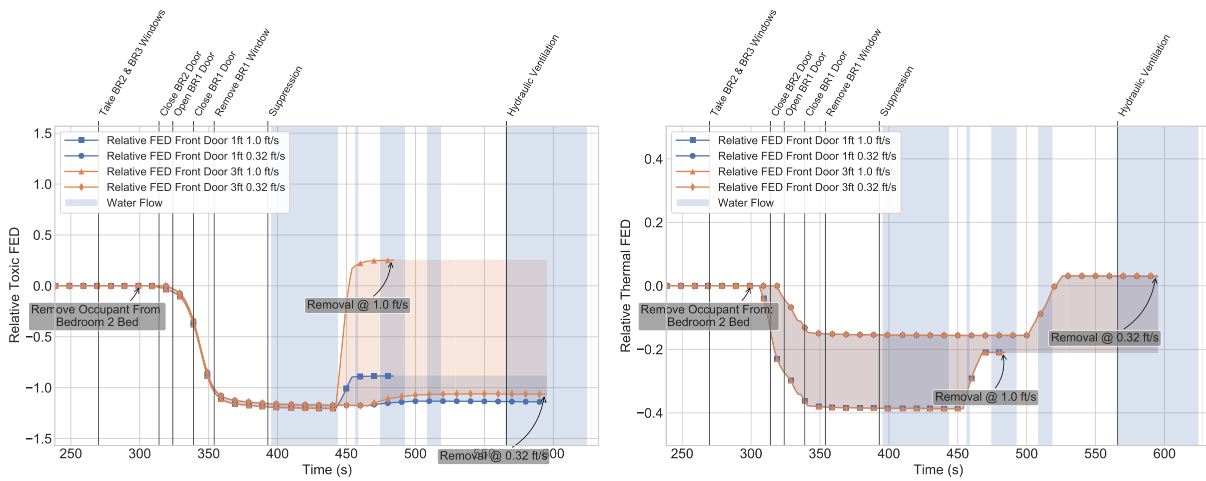
(b) Thermal FED Relative Bedroom 2 Bed

Figure 6.21: Cumulative toxic and thermal FED relative to an isolated location on bedroom 2 bed for window initiated search ahead of suppression (Experiment 4). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

In Experiment 4, bedroom 2 was isolated as the crew entered the space. Consider the scenario, where the occupant was moved from the bed (at 3 ft) to the 1 ft elevation below the vented bedroom 2 window and remained at that location until the suppression crew completed an initial knock down of the fire in bedrooms 3 and 4. Figure 6.22 shows the relative toxic and thermal FED during removal that occurred 40 s after the start of the suppression.

Movement from the bed to the 1 ft elevation at the window following isolation of bedroom from the flow of combustion gases resulted in a reduction in both relative toxic gas and thermal FEDs. The closed bedroom door resulted in bi-directional flow being established at the bedroom 2 window – effectively a new flow path was created that began and ended at the window. Air inflow at the window resulted in improved gas concentrations compared the higher elevation bed location which was offset from the window which was vented for entry, and thus a reduction in relative toxic gas FED (Figure 6.22a). After the occupant was moved into the hallway for removal, the relative toxic gas began to increase, particularly for removal at the higher elevation as there was still residual combustion gases that accumulated pre-suppression. Additionally, the slower removal velocity had a smaller increase as the smoke layer continued to lift following suppression.

Similar to the relative toxic gas FED, the lower elevation and air intake through the window resulted in lower temperatures and heat fluxes and therefore lower relative thermal FEDs compared to remaining on the bed. The relative thermal FEDs also increased as the occupant was moved into the hallway due to heat transfer from the walls, floor, and ceiling that had been heated over the duration of the experiment. In contrast to the relative toxic gas FEDs, the slower removal speed resulted in higher relative thermal FEDs as the compartment remained at above ambient temperatures longer than it took for the smoke layer to rise above 3 ft. Ultimately, though, the delayed removal from bedroom 2 until suppression resulted in lower toxic gas and thermal exposures for a potentially trapped occupant.



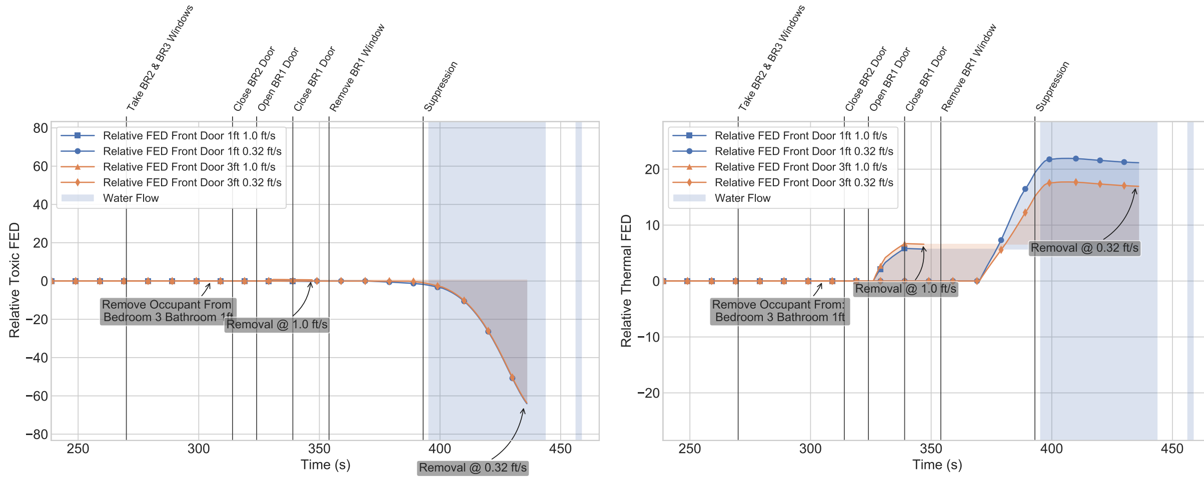
(a) Toxic FED Relative to Bedroom 2 Bed

(b) Thermal FED Relative Bedroom 2 Bed

Figure 6.22: Cumulative toxic and thermal FED relative to an isolated location on bedroom 2 bed for post-suppression removal following window initiated search ahead of suppression (Experiment 4). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

Figure 6.23 shows the relative toxic and thermal FED from bathroom 3 for Experiment 4. Compared to bedroom 2, the relative toxic and thermal FEDs during occupant removal are lower for bathroom 3. There are two factors that contribute to this difference. The first is that because the bedroom 3 door remained opened, the comparison FED for the relative difference increased at rate higher than the isolated bedroom (recall Table 6.3). The second is position within the structure. In the case of bedroom 2, the fire room is along the pathway to the front door. An egress from bathroom 3 to the front door did not have to pass the fire room, but was still exposed to heat and combustion gases that spread into the hallway. This resulted in the increased thermal FED for the bedroom 2 occupant.

It important to note, that in Experiment 4, flashover occurred in bedroom 3 at 375 s after ignition. The fire in bedroom 3 consumed the oxygen in bathroom 3 and resulted an eventual peak FED of 78. The deterioration of bathroom 3 resulted in the misleading large negative relative toxic FED for occupant removal in Figure 6.23a.



(a) Toxic FED Relative to Bathroom 3

(b) Thermal FED Relative to Bathroom 3

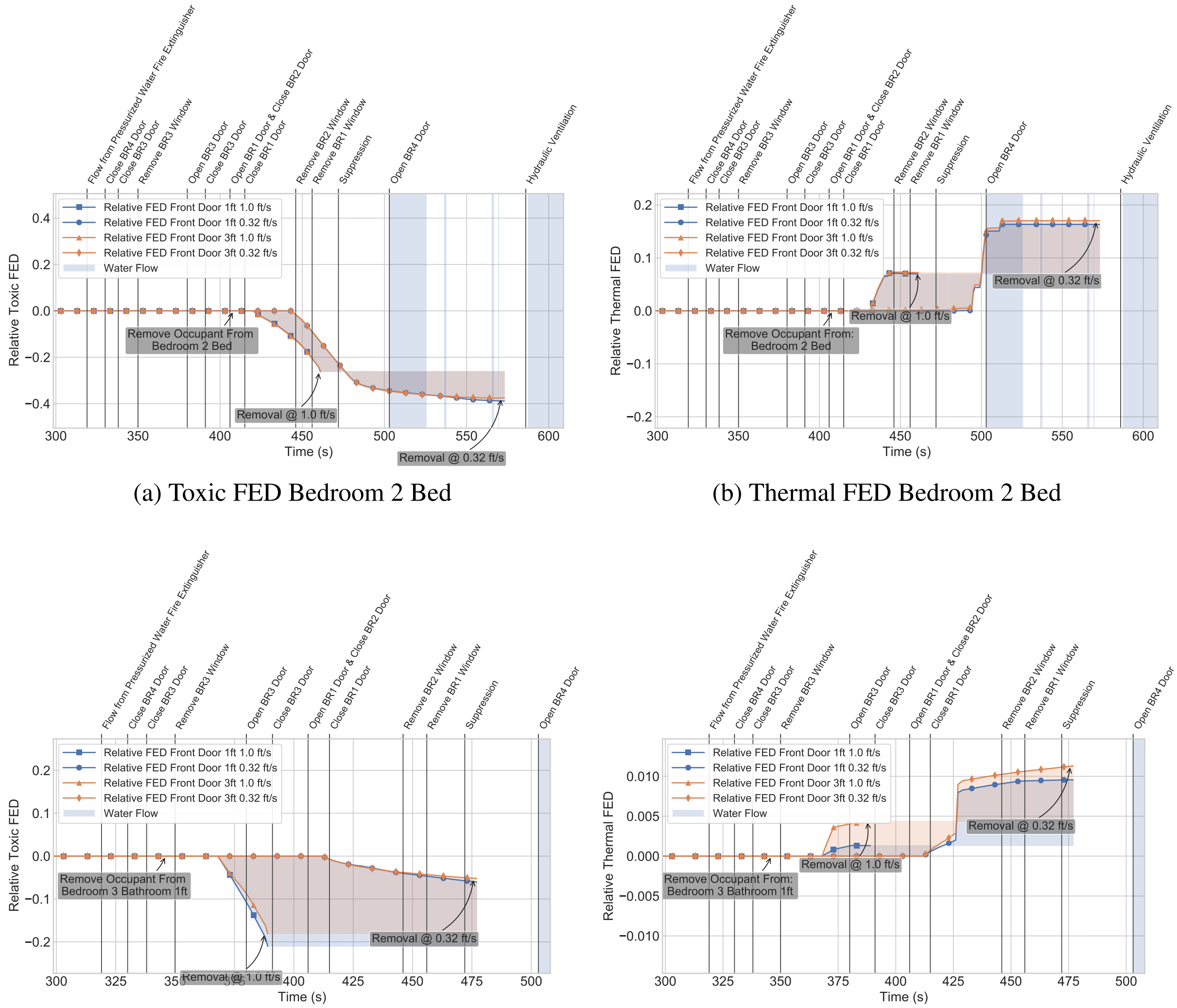
Figure 6.23: Toxic and thermal FED relative to a non isolated bathroom 3 occupant for window initiated search ahead of suppression (Experiment 4). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

Fire Room Isolation from Door/Window Initiated Search Pre-Suppression

In Experiment 7, the search crews performed an interior search ahead of suppression that included isolation of the fire room door. All bedrooms were open from ignition. It is important to recognize that for this experiment the bedroom 4 door was hardened to ensure that it could be closed to quantify the effects of the door closure. There is no guarantee that the fire room door would always be present and with sufficient remaining integrity to be closed.

Figure 6.24 shows the relative toxic and thermal FEDs for removal of an occupant through the front door. Ahead of isolation of bedroom 4, a pressurized water fire extinguisher was used to put out the portions of the hallway carpet that had caught fire. Isolation of the fire room, limited the spread of higher temperature combustion gases into the rest of the structure. Suppression of the flaming combustion removed the acute thermal exposure of the hallway. Note: This series of experiments did not assess the suppression capabilities and limitations of a pressurized water fire extinguisher. The results from this experiment, however, do include the effects of suppression of the flaming combustion in the hallway.

As a result, the relative toxic FED for occupant removal for both locations, at both elevations, and across the range of velocities resulted in lower exposure compared occupants remaining in place. Although the thermal FED increased in both cases due to residual heat in the hallway, the cumulative increase was approximately 2 orders of magnitude lower when compared to removal pre-suppression without isolation (Experiment 4 – Figures 6.21b and 6.23b). Removal at the lower elevation and faster velocity was shown to have the most impact, though the differences in elevation for removal at the same velocity was not as large due the isolation of the hazard from the path of egress.



(a) Toxic FED Bedroom 2 Bed

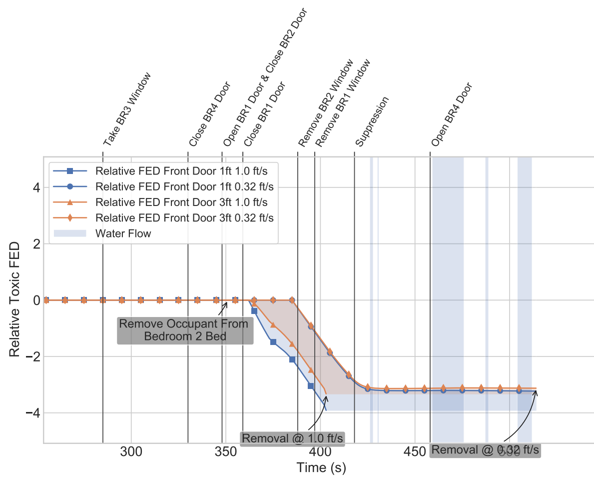
(b) Thermal FED Bedroom 2 Bed

(c) Toxic FED Bathroom 3

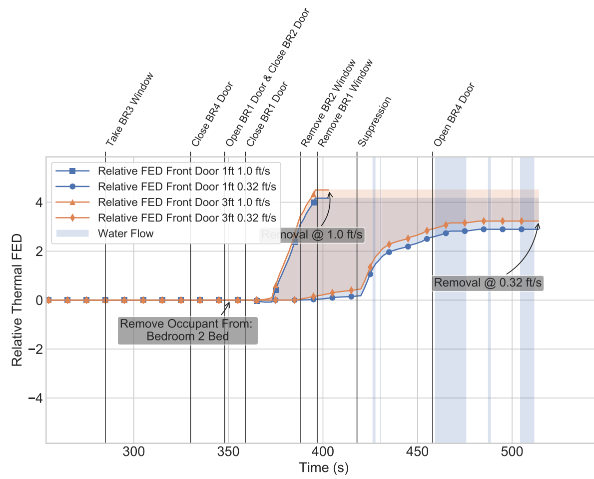
(d) Thermal FED Bathroom 3

Figure 6.24: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for door initiated search ahead of suppression with isolation of the fire room (Experiment 7). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

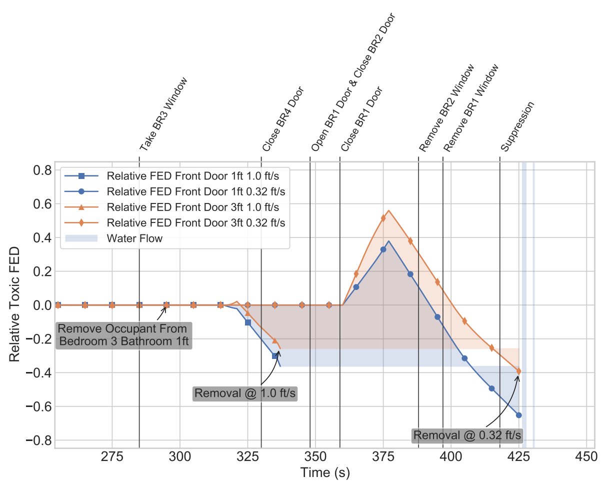
To assess the impact of fire room isolation during a window initiated search pre-suppression, consider Experiment 8. Similar to Experiment 4, ventilation of the bedroom 3 window ahead of suppression created an exterior vent which initially resulted in unidirectional exhaust flow of combustion gases through the window. Unlike Experiment 4, where these conditions eventually resulted in flame spread across the hallway and flashover of bedroom 3, in Experiment 8, the search crew crossed the hallway and closed the bedroom 4 door. Figure 6.25 shows the relative toxic and thermal FEDs for removal of an occupant through the front door from an occupant originating in bedroom 2 and bathroom 3.



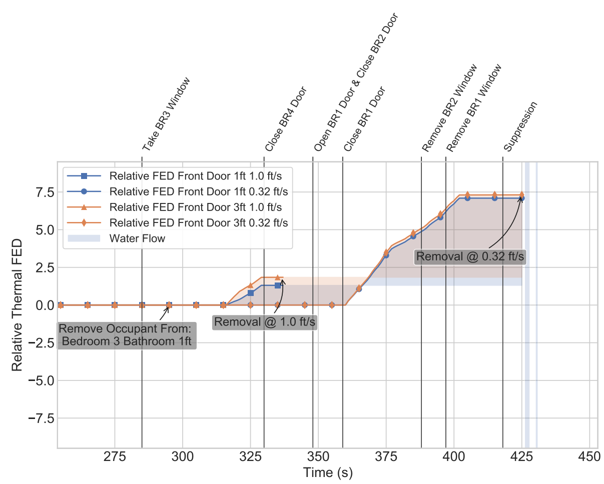
(a) Toxic FED Bedroom 2 Bed



(b) Thermal FED Bedroom 2 Bed



(c) Toxic FED Bathroom 3



(d) Thermal FED Bathroom 3

Figure 6.25: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for window initiated search ahead of suppression with isolation of the fire room (Experiment 8). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

Similar to Experiment 7, the relative toxic FED was less for occupants that were removed from bedroom 2 at either elevation and for the range of velocities as the source of combustion gases was isolated from the egress path with the closure of the fire room door. Additionally, the bedroom 2 window lacked a local exterior vent until later in the experiment so the accumulated combustion gases prior to bedroom 4 isolation resulted in a steady rise of cumulative toxic exposure. For the thermal FED, both elevations resulted in higher relative FEDs. In Experiment 8, suppression of the carpet fire did not occur as part of the isolation of the bedroom 4 door. It only occurred once the suppression crew entered the structure, as a potential occupant being removed at the slower velocity would have crossed between the mid hallway and start hallway locations. As a result, in this case, the occupant that was removed at a slower velocity was exposed to a lower relative thermal FED because the carpet fire was already suppressed. The relative thermal FED data highlights the value of coordinated suppression and removal.

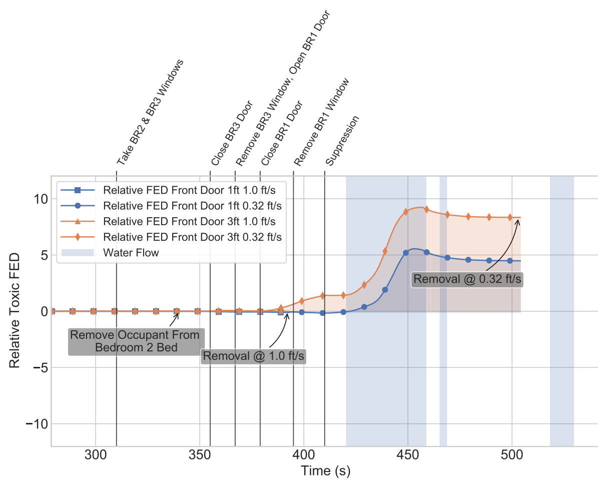
For bathroom 3, the faster range of velocities resulted in a relative decrease in toxic FED at both elevations. For the slower range of removal velocities, there was temporary period of increase, before an ultimate net decrease by the time of removal. The peak occurred while the potential occupant was between the mid hallway and start hallway locations where there there were accumulated combustion gases and coincided with lift in the smoke layer in bathroom 3 due to the open bedroom 3 window. Once the occupant moved into the living room (i.e., further from the fire room and near a large exterior vent in the open front door) the relative FEDs decreased. Similar to bedroom 2, the relative thermal FEDs for removal from bathroom 3 increased due to the acute exposure from flaming combustion along the carpet. The lower relative values at the slower velocities were not seen here because the removal occurred prior to suppression crew extinguishing the carpet fire.

6.5.2 Impact of Suppression Timing

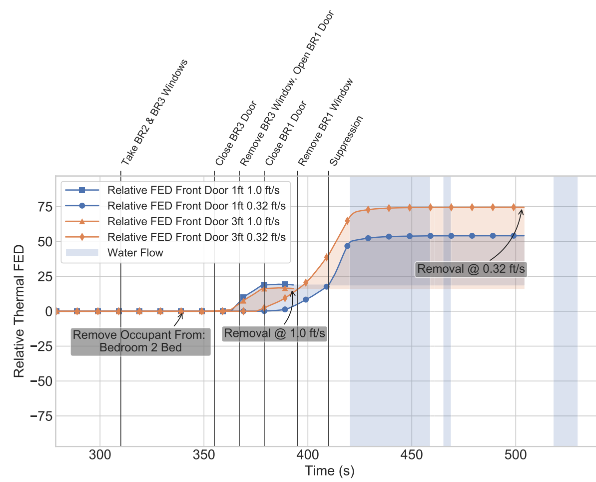
Window Initiated Search During Suppression

Experiments 1 and 2 were designed to compare the impact of search and rescue operations relative to suppression for a window initiated search. In Experiment 1, tactics began prior to suppression, and in Experiment 2, tactics coincided with the start of suppression. Figure 6.26 shows the toxic and thermal FEDs during removal relative to a potentially trapped occupant on the bedroom 2 bed remaining in place. The relative toxic FED for removal pre-suppression (Figure 6.26a) shows the importance of elevation and removal time/velocity. The 1 ft elevation pathway at 1.0 ft/s resulted in less toxic FED increase compared to leaving the occupant in place (relative toxic FED of approximately -0.1 at removal). The 3 ft elevation removal at 1.0 ft/s resulted in a negligible change in toxic FED compared to the bedroom 2 bed. Figure 6.26a also shows that as the removal velocity slowed prior to suppression, there was continued increase to relative toxic FED. Despite the potential reduction in toxic FED, Figure 6.26b, shows that removing an occupant past the fire room resulted in large increase in relative thermal FED. During this time period in Experiment 1, the carpet outside of the fire room had ignited and flames extended out of the top of the bedroom 4 doorway, conditions equivalent to an emergency operating class for a fully protected firefighter. Therefore, without action taken to control these hazards, this was likely not a viable egress path for an occupant being rescued.

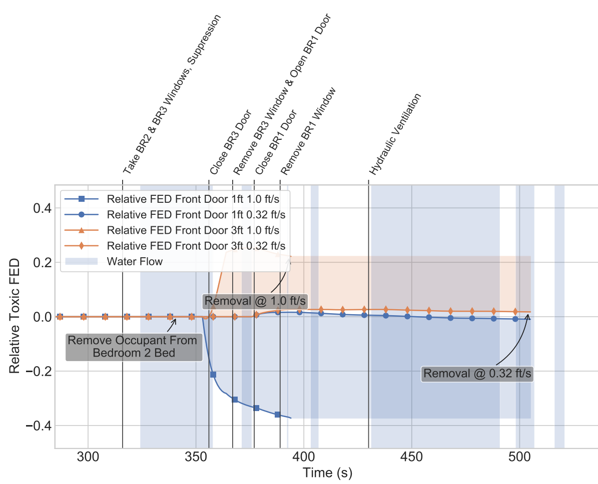
In Experiment 2 where suppression coincided with search and rescue, changes in relative thermal FED were negative, but generally negligible (Figure 6.26d). This is an indication that the thermal threat from passing the fire room did not pose the same hazard as in Experiment 1. The relative toxic FED however still indicated the value in keeping the potential occupant low in the space. At the 1 ft elevation there was a decrease in cumulative toxic FED compared to an increase for an occupant removed at 3 ft relative to leaving the occupant in bedroom 2. Although suppression removed the thermal hazard from the fire and reduced the smoke production, combustion gases still remained in the hallway. This highlights the need for post-suppression ventilation to reduce the toxic hazard due to accumulated combustion gases.



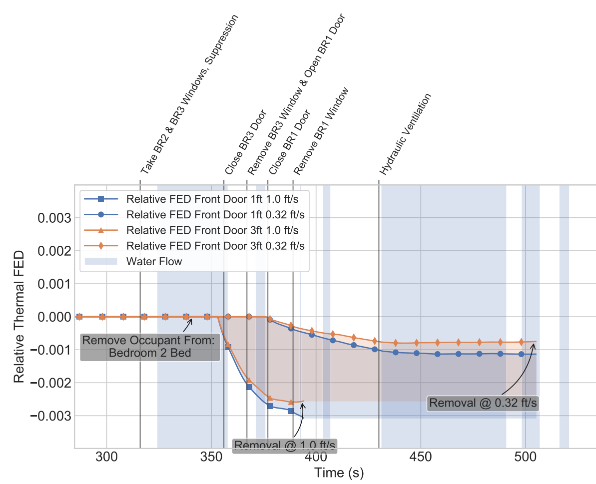
(a) Toxic FED Bedroom 2 Bed Pre-Suppression



(b) Thermal FED Bedroom 2 Bed Pre-Suppression



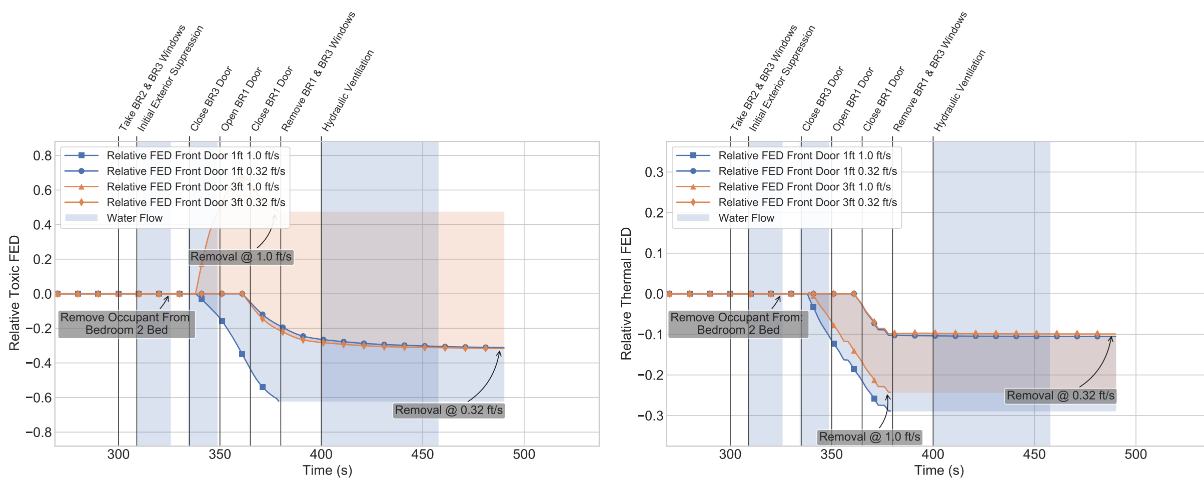
(c) Toxic FED Bedroom 2 Bed During Suppression



(d) Thermal FED Bedroom 2 Bed During Suppression

Figure 6.26: Toxic and thermal FED relative to bedroom 2 bed for window initiated search prior to suppression (Experiment 1) suppression and for window initiated search during suppression (Experiment 2). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

Experiment 3 examined window initiated search during suppression, similar to Experiment 2, except that in Experiment 3 the initial suppression action occurred from the exterior. Following an initial knock-back, the crew moved inside to complete extinguishment of the bedroom 4 fire. Figure 6.27 shows the toxic and thermal FEDs relative to a potentially trapped occupant on the bed in bedroom 2. The initial exterior water showed a similar result to the initial interior water. The thermal hazard in the hallway from the bedroom 4 fire was reduced, and thus removing the occupant from the bedroom 2 bed resulted in a positive impact at either elevation in the hallway. At both elevations, the faster removal time resulted in a larger relative reduction. Experiment 3 also showed the importance of occupant removal at lower elevations due to the accumulation of combustion gases.

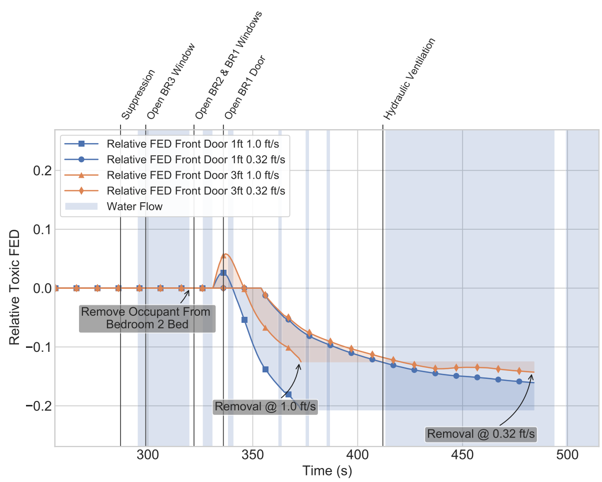


(a) Toxic FED Bedroom 2 Bed During Suppression (b) Thermal FED Bedroom 2 Bed During Suppression

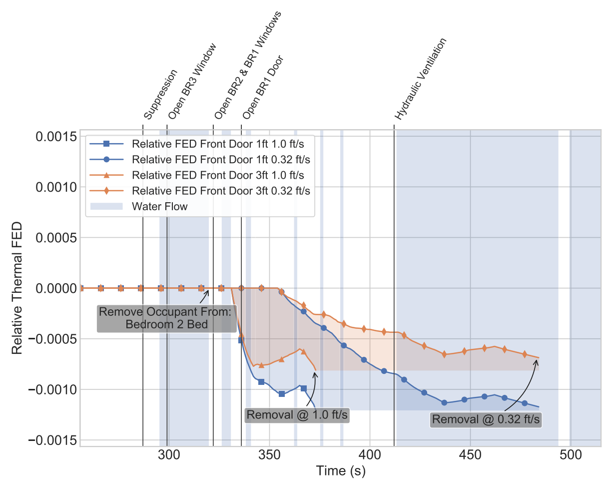
Figure 6.27: Toxic and thermal FED relative to bedroom 2 bed for window initiated search during initial exterior suppression (Experiment 3). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

Door Initiated Search During Suppression

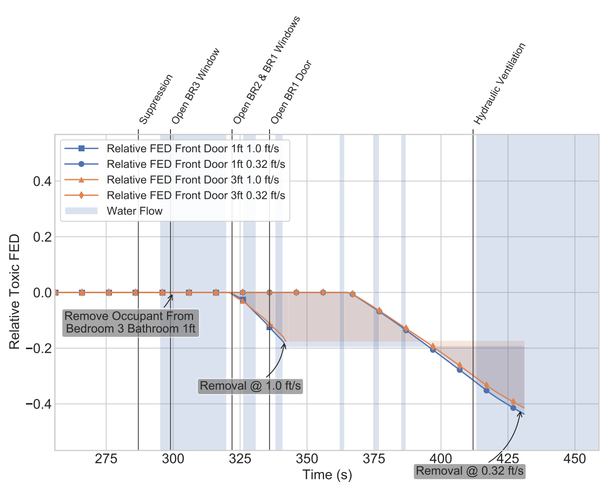
Experiment 9 examined door initiated search operations that occurred during suppression (Figure 6.28). The doors to bedroom 2 and bedroom 3 were open prior to intervention. The search crew followed the suppression crew into the structure and opened the windows (see Appendix A.2) as the respective rooms were searched. For both the bedroom 2 and bathroom 3 location, the removal of the occupant through the hallway at either elevation resulted in lower accumulated toxic gas FED compared to leaving the occupant in place. This appears to be in contrast to the removal results during suppression. In Experiment 9, the bottom panes of the window were opened compared to the window being taken (see Appendix A.1) for the window initiated search operations. The opened windows resulted in less efficient gas exchange compared to the full panes being ventilated. The less efficient gas exchange resulted in higher point of origin toxic gas FEDs, which translated to a larger relative impact of removal. The combination of data across these experiments shows the importance of expedient removal if an occupant's point of origin lacks sufficient ventilation post suppression. Additionally, this data highlights the importance of local ventilation if external factors delay occupant removal post suppression. For both locations, the removal of the occupants resulted in negligible increases in relative thermal FED (≈ 0.001) as suppression effectively removed the thermal hazard.



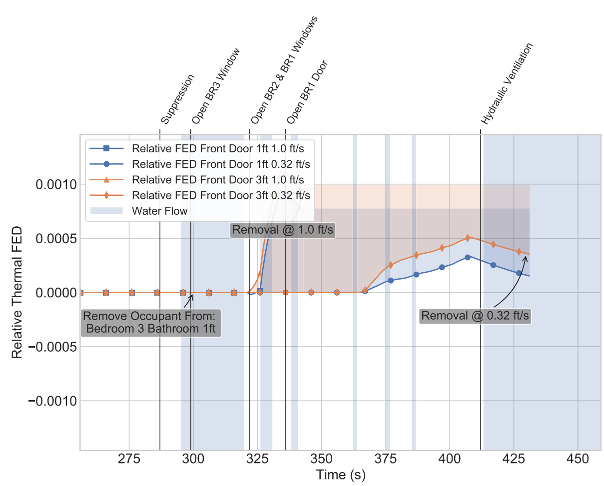
(a) Toxic FED Bedroom 2 Bed During Suppression



(b) Thermal FED Bedroom 2 Bed During Suppression



(c) Toxic FED Bathroom 3 During Suppression



(d) Thermal FED Bathroom 3 During Suppression

Figure 6.28: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for door initiated search during suppression (Experiment 9). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

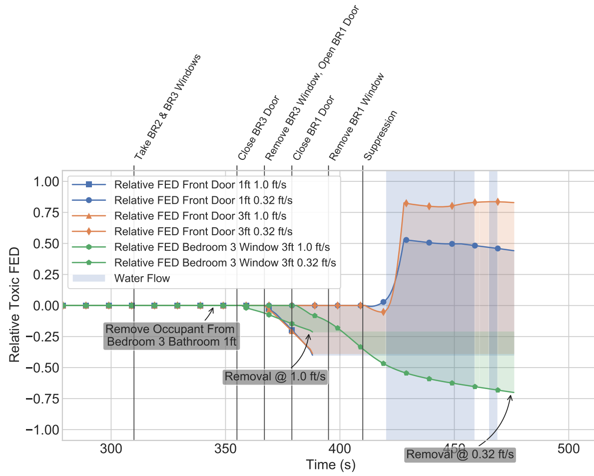
6.5.3 Impact of Egress Pathway

In experiments where search occurred prior to suppression, in the absence of fire room isolation, flame spread from bedroom 4 into the hallway created thermal conditions equivalent to the emergency operating class, which would limit the duration for firefighters to safely occupy the space. These conditions would have also been untenable for an unprotected occupant. For fires where suppression is delayed, an alternate path of egress may present the best option for minimizing the cumulative exposure to the potential occupant. A limitation of the analysis in this section is that the time-to-task data for occupant removal through a window is not as clearly defined as a drag or carry velocity. Many factors can influence this timing including but not limited to: occupant size (height, weight) and clothing, crew size (number of firefighters, firefighter height and weight) and experience, obstructions in the room, area of window opening, window sill height, and exterior conditions (sill height above ground, removal to ground or ladder, etc). Therefore, this analysis focused on moving the occupant from the point of origin to the window sill, 3 ft above the floor. The occupant then "remained" at the window for the time duration it would take for an occupant to be removed through the front door over the median 50% range of velocities generated from the project technical panel. This is a conservative assessment of the window egress pathway as the occupant remained in the structure for this range of times.

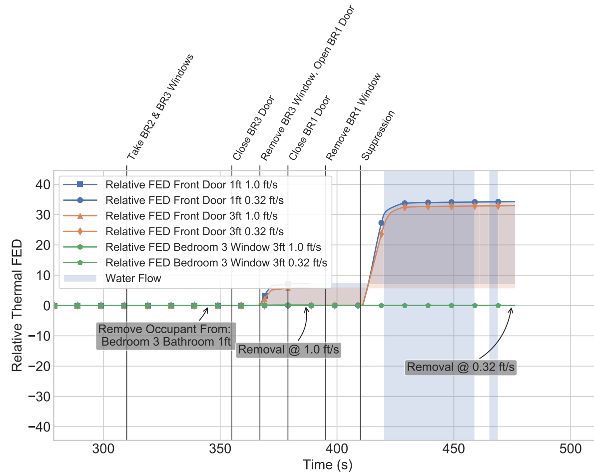
In Experiment 1, window initiated search occurred in bedrooms 2 and 3 with isolation of bedroom 3 following entry. Figure 6.29 shows the relative toxic and thermal FEDs for Experiment 1 for an occupant in both bedrooms removed through the front door (at 3 ft and 1 ft above the floor) and moved to 3 ft above the floor at the open window. In the isolated bedroom 3, moving the occupant from 1 ft above the floor to 3 ft above the floor at the window sill resulted in a decrease in relative toxic FED (Figure 6.29a). The combination of ventilation and isolation established a different flow path – one that that began and ended at the bedroom 3 window. Here, firefighters could leverage the bidirectional flow through the window (high exhaust of combustion gases and low entertainment of air) to reduce to toxic exposure. The change in elevation (3 ft vs. 1 ft) combined with the exhaust of combustion gases resulted in a slight increase in thermal FED due to convective heat transfer associated with the increased flow of higher temperature gases. Although the relative thermal FED increase at the window peaked at 0.18, this was nearly two orders of magnitude lower compared to removing the occupant through the hallway (Figure 6.29b).

In the non-isolated bedroom prior to suppression, moving the occupant to the window at the 75th percentile speed resulted in a negligible increase in relative toxic FED and a decrease in relative thermal FED of 0.5. The flow path established between the fire room and the bedroom 2 window resulted in bi-directional flow at the window. Intake of air through the lower portion of the window reduced thermal exposure compared to the bed which was adjacent to, but not part of the flow path. It is important to note, that relative to the isolated bedroom 3, both the toxic and thermal FEDs in the non-isolated bedroom 2 increased at higher relative rates (recall Table 6.3).

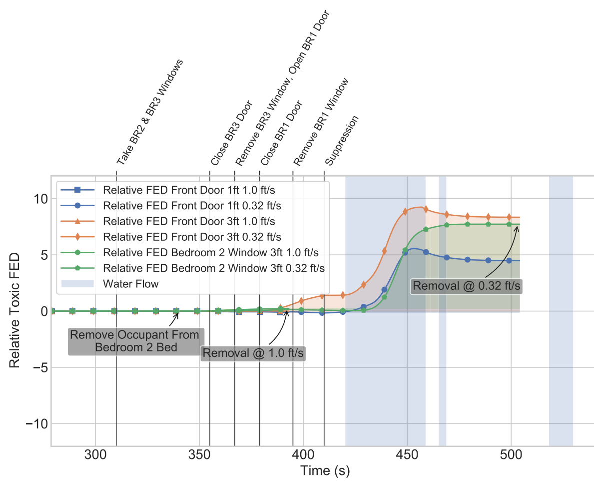
For the 25th percentile velocity, at the onset of suppression, there was an increase in the relative toxic gas and thermal FED at the non-isolated bedroom 2 window. At first glance this may appear counter-intuitive, but recognition of flow paths and hose stream mechanics explain this result. The crew utilized a flow and move tactic from a 7/8 in. smooth bore nozzle. As the suppression team proceeded toward bedroom 4, water flow was needed in the hallway to cool gases and extinguish the flaming combustion. The higher pressure gases generated ahead of the hose stream from the flowing water moved toward an area of lower pressure. Since bedroom 4 was pressurized from the fire and the doors to bedrooms 1 and 3 were closed, the only path toward an area of lower pressure was through bedroom 2 to the vented window. Gas velocities at the bedroom 2 window became unidirectional exhaust for approximately 20 s as higher-pressure combustion gases flowed through the open bedroom. Despite a uniform drop in temperature, the increase gas velocity temporarily increased the heat flux at the window which resulted in a relative thermal FED from -0.5 to 0.75. The increased flow of combustion gases resulted an increase in the relative thermal FED of 7.5 at the bedroom 2 window. Although relative FEDs increased at the window, it is important to remember that within the same time window and removal speed, an egress path through the front door at 1 ft would have resulted in a relative toxic gas FED increase of approximately 5 and a relative thermal FED increase of over 50. The change in exposure during suppression highlights the value of pre-suppression isolation and knowledge of gas transport along flow paths. For a more detailed description see the fire dynamics discussion in Section 5.1.



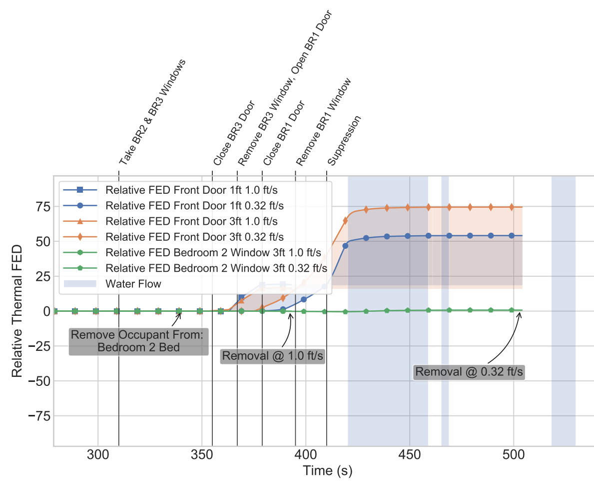
(a) Toxic FED Bathroom 3 Pre-Suppression



(b) Thermal FED Bathroom 3 Pre-Suppression



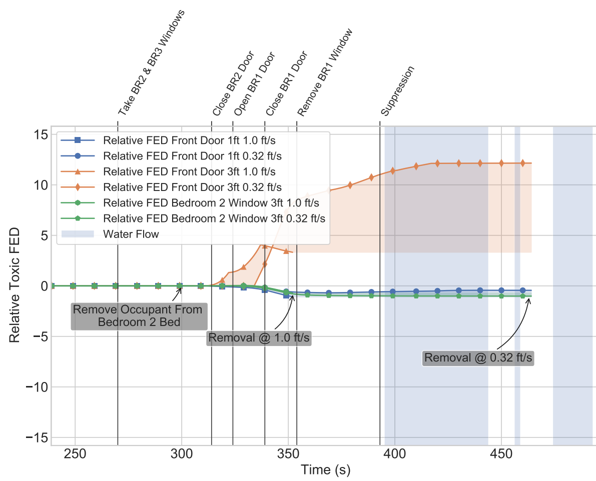
(c) Toxic FED Bedroom 2 Bed Pre-Suppression



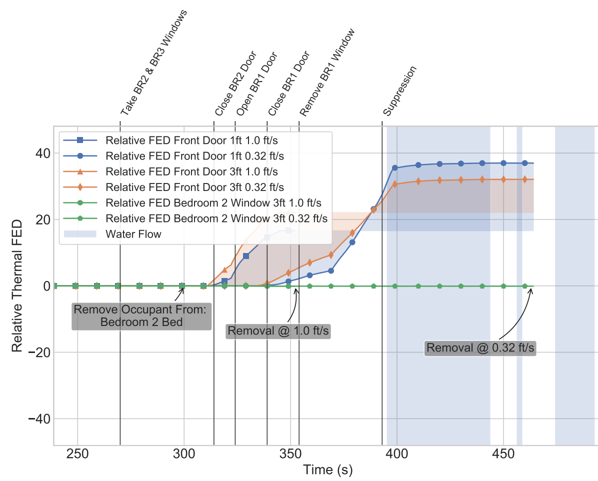
(d) Thermal FED Bedroom 2 Bed Pre-Suppression

Figure 6.29: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for window initiated search prior to suppression (Experiment 1). The comparisons include removing the occupant through the front door and moving to the respective bedroom window at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

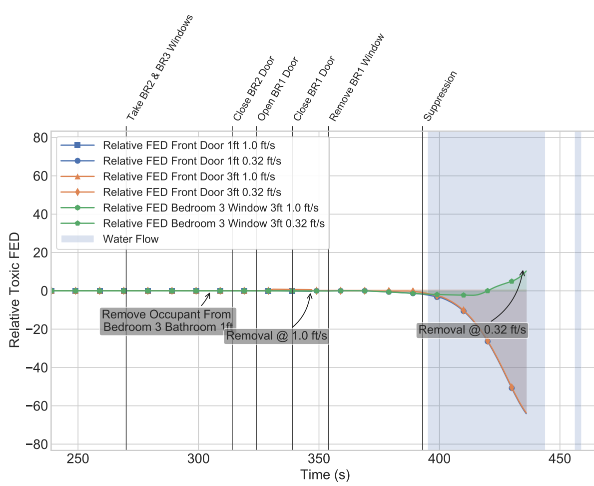
Similar to Experiment 1, Experiment 4 examined window initiated search, except that in this experiment bedroom 2 was isolated and bedroom 3 was not. Figure 6.30 shows the relative toxic and thermal FEDs for Experiment 4 for an occupant in both bedrooms removed through the front door (at 3 ft and 1 ft above the floor) and moved to 3 ft above the floor at the open window. In the isolated bedroom 2, moving the occupant from the bed to the window sill resulted in a decrease in relative toxic FED (Figure 6.30a). The combination of ventilation and isolation established a different flow path – one that that began and ended at the bedroom 2 window. Firefighters could leverage the bidirectional flow through the window (high exhaust of combustion gases and low entertainment of air) to reduce to toxic exposure. In contrast to the isolated bathroom 3 in Experiment 1, movement from the bed to the window sill did not result in a change in elevation. Ultimately, air intake through the window resulted in a decrease of relative thermal FED due to larger decrease in temperature and heat flux compared to bed location (Figure 6.30b).



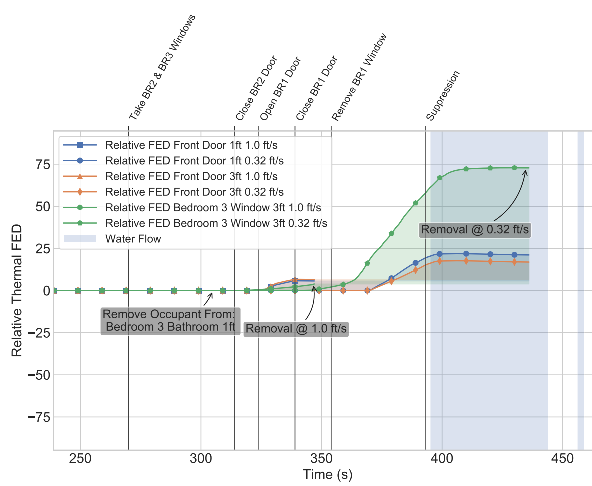
(a) Toxic FED Bedroom 2 Bed Pre-Suppression



(b) Thermal FED Bedroom 2 Bed Pre-Suppression



(c) Toxic FED Bathroom 3 Pre-Suppression



(d) Thermal FED Bathroom 3 Pre-Suppression

Figure 6.30: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for window initiated search prior to suppression (Experiment 4). The comparisons include removing the occupant through the front door and moving to the respective bedroom window at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

In Experiment 4, flame spread across the hallway into the non-isolated bedroom 3 resulted in eventual flashover of the space and large increases to both the relative and toxic relative FEDs for an occupant moved the window (Figures 6.30c and 6.30d). In the absence of isolation, the close proximity of bedroom 3 to the fire room resulted in a shorter period of time for potential removal through the window.

7 Future Research

The 11 bedroom experiments and 10 kitchen experiments combine to provide a foundation for understanding the impact of coordinating isolation, ventilation, and suppression on firefighter safety and occupant tenability during search and rescue operations. This research explored the origin and timing of search and rescue tactics relative to suppression and how these variables affect toxic gas and thermal exposures to occupants and fire service personnel. These 21 experiments were conducted in purpose-built, fully-furnished, single-story single-family dwellings.

Across the series of experiments, the front door was open at ignition to simulate an occupant leaving the door open upon egress and to ensure sufficient ventilation to support a post-flashover fire. The effects of a closed front door were shown to limit fire growth during the kitchen fires, but there was sufficient ventilation to sustain a post-flashover fire for the bedroom fires. Bedroom experiments with the front door closed could provide more insight into toxic gas hazard development in the kitchen and living room.

Future research on search and rescue tactics should expand into additional single-family residential structure types (e.g., size, compartmentation, number of stories) as as well as into larger multi-family and high-rise dwellings. In particular, multi-story single family structures, such a colonial, townhouse, or ranch with basement should be examined to study the effects of search initiated points (doors or windows) both above and below the fire. There is a need to quantify how the rates of fractional effective dose may change across the variables of ventilation, isolation, and suppression in these scenarios. Moreover, how firefighter time-to-task data overlays with the larger structure types.

Research is also needed to quantify the capabilities and limitations of pressurized water fire extinguishers. In particular, there is a need understand how pressurized water fire extinguishers can be used to control spaces and/or enable isolation the fire compartment(s) in support of both search and rescue operations.

Further development work is needed to correlate cumulative heat flux to an assessment of skin burns, particularly to account for blood flow, sweating, etc. effects as well as impact of clothing. There is also a need for an improved understanding of heat transfer to firefighters. This requires more research on heat transfer into and through personal protective equipment, more specifically the impact of how compression points (e.g., knees and elbows of searching firefighters) can impact the rate of heat transfer through gear.

8 Summary

Twenty-one experiments were conducted in two purpose-built single-story single-family dwellings to analyze search and rescue tactics. Eleven of the experiments examined bedroom fires, eight examined kitchen fires, and two examined living room fires. This manuscript examined the bedroom fires. In 6 of the 11 bedroom fires search operations occurred prior to suppression, in 4 of the 11 bedroom fires search operations occurred during suppression, and one bedroom fire was the baseline experiment where the initial conditions remained fixed for the duration of the experiment. Further, the series of bedroom experiments examined search operations that originated via window (x7) and via front door (x3). In all experiments, hydraulic ventilation was performed following suppression. Temperature, velocity, and pressure were measured throughout each structure to assess the fire dynamics. Heat flux and gas concentrations were employed to assess the impact of tactics on occupant tenability.

The relatively small number of experiments and a single structure type limit the ability to make universal, definitive assessments of tactical performance; however, several trends were identified that could influence tactical decisions on the fireground:

1. Prior to intervention, there were statistically significant differences in toxic and thermal exposures to occupants as a function of elevation. The higher the elevation, the higher the exposure to the potentially trapped occupant.
2. Prior to intervention, it was shown that spaces isolated prior to ignition had statistically lower measured exposures compared to non-isolated spaces.
3. Prior to intervention, positions at increased distances from the fire along established flow paths (intake versus exhaust/end point) were shown to have lower exposures; however, the intake portion was a supply of oxygen which facilitated fire growth, so this was a temporary factor.
4. A closed fire room door for a bedroom fire was effective at reducing flame spread as well as reducing the operating class for searching firefighters and toxic and thermal exposure rates for potentially trapped occupants.
5. For scenarios where ventilation preceded suppression as part of search operations, isolation of spaces was shown to be effective at reducing the thermal operating class for firefighters and the toxic and thermal exposure rates compared to spaces that were not isolated.
6. Prior to suppression, removal of an isolated occupant along a pathway that required passing the fire compartment was shown to increase the exposure to the occupant compared to remaining isolated.
7. Removal of an occupant lower in the space (1 ft above the floor) was shown to result in a lower accumulated exposure compared to higher elevations (3 ft above the floor) even if the higher elevation egress occurred at a rate that was 3 times as fast.

8. Suppression, both interior and exterior, was effective at reducing the thermal operating class for searching firefighters and the rate of thermal exposure increase to occupants, however for scenarios without corresponding ventilation, the toxic exposure rate remained elevated when compared to scenarios where ventilation was coordinated with suppression.

9. Less than 160 gallons (89 gallons $\pm$ 30 gallons) was used during the initial suppression period and less than 360 gal including hydraulic ventilation was used in total for suppression for each of the bedroom fire experiments.

It is important to note that the appropriateness of search and rescue tactics and the corresponding ventilation and suppression tactics ultimately depend on local resources, response model, and the circumstances of the specific incident.

References

[1] U.S. Fire Administration. U.S. Fire Statistics. 2019. URL: https://www.usfa.fema.gov/data/statistics/#trends.

[2] S. Ahrens and R. Maheshwari. Home Structure Fires. Technical report, National Fire Protection Association, Quincy, Massachusetts, 2020.

[3] *American Housing Survey 2019*. Washington, DC, 2021.

[4] Trulia's Guide To The Most Popular Home Styles In America. https://www.trulia.com/blog/guide-to-most-popular-home-styles, 2017. Accessed: 2021-09-15.

[5] IAFC Safety-Health and Survival Section. Rules of Engagement for Structural Firefighting. Technical report, February 2012.

[6] National Fire Protection Association, Quincy, Massachusetts. *NFPA 1006, Standard for Technical Rescue Personnel Professional Qualifications*, 2021.

[7] National Fire Protection Association, Quincy, Massachusetts. *NFPA 1700, Guide for Structural Fire Fighting*, 2021.

[8] J. Norman. *Fire Officer's Handbook of Tactics*. PennWell Corporation, Tulsa, Oklahoma, 5th edition, 2019.

[9] J. Mittendorf. *Truck Company Operations 2nd Edition*. PennWell Corporation, Tulsa, Oklahoma, 2011.

[10] M. Dugan. Conducting A Proper Size-Up. *Firehouse*, August 1998.

[11] D. Stratton. The Basics of Enhancing Your Size-Up. *Fire Engineering*, 171(6), June 2018.

[12] D. Dodson. The Art of Reading Smoke - FDIC. https://www.fdic.com/articles/2014/06/david-dodson-the-art-of-reading-smoke.html, June 2014.

[13] Mabas Division 11. IFSI Cornerstone Reading Smoke Program. https://www.youtube.com/watch?v=EGudslcPE3M, February 2015.

[14] 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.

[15] K. Stakes, J. Bryant, N. Dow, J. Regan, and C. Weinschenk. Analysis of the Coordination of Suppression and Ventilation in Multi-Family Dwellings. UL Firefighter Safety Research Institute, Columbia, Maryland, June 2020.

[16] C. Clausing and J. Fortney. *Essentials of Fire Fighting Seventh Edition*. Fire Protection Publications, Stillwater, Oklahoma, 2018.

[17] 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.

[18] B. Brush, B. Bryant Jr., D. Doornick, Marshall J. Ledin, N., J. McWilliams, M. Morrison, B. Olsen, S. Thomas, and L. Zahourek. Firefighter Rescue Survey. 2021.

[19] G. Graham. High-risk, low-frequency events in public safety. https://www.lexipol.com/resources/blog/high-risk-low-frequency-events-in-public-safety/?p=14791.

[20] B. Carey. Deaths During Search, 2010 to Present. *Backstep Firefighter*, October 2015.

[21] J. Coleman. *Searching Smarter*. PennWell Corporation, Tulsa, Oklahoma, 2011.

[22] P. Mastronardi. Secondary Search Techniques. *Firehouse*, Septmeber 2017.

[23] Clackamas Fire District #1. *Rescue & Search*. Clackamas Fire District #1, Milwaukie, OR, 2019.

[24] J. Smith. *Stategic and Tactical Considerations on the Fireground, Third Edition*. Pearson, Upper Saddle River, New Jersey, 2012.

[25] M. Mason. Residential Search: Applying the Principles. *Fire Engineering*, 170(9), September 2017.

[26] S. Marsar. Survivability Profiling: Are the Victims Savable? *Fire Engineering*, 162(12):69, December 2009.

[27] S. Corrigan. Beyond the Door, The Risk Analysis. https://community.fireengineering.com/m/blogpost?id=1219672%3ABlogPost%3A621909.

[28] B. Brush. VES: Victims Expecting Search. https://www.firefighternation.com/rescue/ves-victims-expecting-search.

[29] G. Schwalbe. Civilian Victim Removal. *Fire Engineering*, 171(9), September 2018.

[30] J. Riker. Removals from Fire Buildings. *Fire Engineering*, 162(2), February 2009.

[31] 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.

[32] M. Bowyer, M. Loflin, and T. Merinar. Arson fire kills three fire fighters and injures four fire fighters following a floor collapse in a row house – Delaware. NIOSH F2016-18, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2018.

[33] M. Bowyer and T. Merinar. Volunteer fire fighter dies in a floor collapse while working above a residential basement fire – South Dakota. NIOSH F2015-21, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2017.

[34] T. Hales and M. Loflin. Fire fighter falls through floor and dies at residential structure fire – Ohio. NIOSH F2015-19, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2017.

[35] M. Bowyer, S. Miles, and P. Moore. Career Female Fire Fighter Dies After Becoming Lost and Running Out of Air in a Residential Structure Fire – Pennsylvania. NIOSH F2014-25, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2017.

[36] 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.

[37] 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.

[38] M. Bowyer and M. Loflin. Volunteer fire fighter found unresponsive with his facepiece off dies eight days later – Maryland. NIOSH F2013-13, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2014.

[39] J. Tarley, S.T.. Miles, and M. Bowyer. Volunteer Captain Dies After Floor Collapse Traps Him in Basement – New York. NIOSH F2013-02, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2014.

[40] 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.

[41] M. Bowyer, M. Loflin, T. Merinar, and J. Tarley. Career fire fighter dies and another is injured following structure collapse at a triple decker residential fire – Massachusetts. NIOSH F2011-30, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2012.

[42] 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.

[43] 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.

[44] S. Wertman. One career fire fighter/paramedic dies and a part-time fire fighter/paramedic is injured when caught in a residential structure flashover – Illinois. NIOSH F2010-10, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2010.

[45] 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.

[46] S. Miles and S. Wertman. Volunteer fire fighter dies while lost in residential structure fire – Alabama. NIOSH F2008-34, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2009.

[47] M. Bowyer. A volunteer mutual aid fire fighter dies in a floor collapse in a residential basement fire – Illinois. NIOSH F2008-26, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2009.

[48] T. Baldwin and M. Bowyer. A career captain and a part-time fire fighter die in a residential floor collapse – Ohio. NIOSH F2008-09, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2009.

[49] R. Braddee. Volunteer fire lieutenant killed while fighting a basement fire – Pennsylvania. NIOSH F2008-08, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2009.

[50] S. Berardinelli and S. Wertman. Volunteer fire fighter and trapped resident die and a volunteer lieutenant is injured following a duplex fire – Pennsylvania. NIOSH F2008-06, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2008.

[51] S. Berardinelli and M. Bowyer. A volunteer mutual aid captain and fire fighter die in a remodeled residential structure fire – Texas. NIOSH F2007-29, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2008.

[52] J. Tarley and S. Miles. A career captain and an engineer die while conducting a primary search at a residential structure fire – California. NIOSH F2007-28, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2009.

[53] V. Lutz. Career fire fighter dies and captain is injured during a civilian rescue attempt at a residential structure fire – Georgia. NIOSH F2007-16, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2008.

[54] M. Bowyer and V. Lutz. Career fire fighter dies in wind driven residential structure fire – Virginia. NIOSH F2007-12, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2008.

[55] M. Bowyer, T. Merinar, and J Tarley. Volunteer fire fighter dies after falling through floor supported by engineered wooden-I beams at residential structure fire – Tennessee. NIOSH F2007-07, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2007.

[56] S. Berardinelli, M. Bowyer, and J. Tarley. Career fire fighter injured during rapid fire progression in an abandoned structure dies six days later – Georgia. NIOSH F2007-02, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2009.

[57] S. Berardinelli and M. Bowyer. Career Fire Fighter Dies in Residential Row House Structure Fire – Maryland. Niosh f2006-28, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2007.

[58] R. Braddee and J. Tarley. Career engineer dies and fire fighter injured after falling through floor while conducting a primary search at a residential structure fire – Wisconsin. Niosh f2006-26, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2007.

[59] R. Koedam. Volunteer deputy fire chief dies after falling through floor hole in residential structure during fire attack – Indiana. Niosh f2006-24, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2007.

[60] R.E. Koedam, T. Merinar, and M. Bowyer. One Probationary Career Firefighter Dies and Four Career Firefighters are Injured at a Two-Alarm Residential Structure Fire – Texas. NIOSH F2005-02, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2007.

[61] S. Berardinelli and M. McFall. Career fire fighter dies and two career fire fighters injured in a flashover during a house fire – Ohio. NIOSH F2003-12, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2005.

[62] R. Braddee and L. Frederick. Volunteer fire fighter killed and career chief injured during residential house fire – Tennessee. NIOSH F2002-12, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2002.

[63] L. Frederick and N. Romano. One career fire fighter dies and a captain is hospitalized after floor collapses in residential fire – North Carolina. NIOSH F2002-11, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2003.

[64] M. McFall and J. Tarley. First-floor collapse during residential basement fire claims the life of two fire fighters (career and volunteer) and injures a career fire fighter captain – New York. NIOSH F2002-06, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2003.

[65] 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.

[66] R. Braddee and J. Tarley. Residential fire claims the lives of two volunteer fire fighters and seriously injures an assistant chief – Missouri. NIOSH F2001-15, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2001.

[67] K. Cortez and J. Tarley. Two volunteer fire fighters die fighting a basement fire – Illinois. NIOSH F2001-08, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2002.

[68] T. Mezzanotte and F. Washenitz. Residential house fire claims the life of one career fire fighter – Florida. NIOSH F2000-44, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2001.

[69] M. McFall and E. Schmidt. Arson Fire Claims the Life of One Volunteer Fire Fighter and One Civilian and Severely Injures Another Volunteer Fire Fighter – Michigan. NIOSH F2000-16, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2001.

[70] M. McFall, R. Braddee, and T. Mezzanotte. Career Fire Fighter Dies and Three Are Injured In a Residential Garage Fire – Utah. NIOSH F2000-23, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2000.

[71] T.P Mezzanotte, E. Schmidt, T.A. Pettit, and D. Castillo. Structure Fire Claims the Lives of Three Career Fire Fighters and Three Children – Iowa. NIOSH F2000-04, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2001.

[72] F. Washenitz, R. Braddee, T.A. Pettit, and E. Schmidt. Two Fire Fighters Die and Two Are Injured in Townhouse Fire – District of Columbia. NIOSH 99-F21, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 1999.

[73] T. Baldwin and K. Cortez. Single-family dwelling fire claims the life of a volunteer fire fighter – Indiana. NIOSH 99-F02, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 1999.

[74] ThermalZone, Philadelphia, PA. *Air Handlers TZHSLT/TZHDLT-High Efficiency*, 2019. URL: http://www.thermalzone.com/Commercial-Air-Handlers/TZHSLTST%20air%20handler%20HI%20EFF.pdf.

[75] American Society for Testing and Materials, West Conshohocken, PA. *Standard E 779: Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, 2010.

[76] International Code Council. *2018 International Energy Conservation Code*. Washington, DC, 2018.

[77] L.G. Blevins. Behavior of bare and aspirated thermocouples in compartment fires. In *National Heat Transfer Conference, 33rd Proceedings*, pages 15–17, 1999.

[78] 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.

[79] R.A. Bryant. A comparison of gas velocity measurements in a full-scale enclosure fire. *Fire Safety Journal*, 44:793–800, 2009.

[80] 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, MD, 2008.

[81] W.M. Pitts, A.V. Murthy, J.L. de Ris, J. Filtz, K. Nygård, D. Smith, and I. Wetterlund. Round robin study of total heat flux gauge calibration at fire laboratories. *Fire Safety Journal*, 41(6):459–475, 2006.

[82] 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.

[83] 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.

[84] C. Weinschenk and J. Regan. Analysis of Search and Rescue Tactics in Single-Story Single-Family Homes Part II: Kitchen and Living Room Fires. Technical report, UL Fire Safety Research Institute, Columbia, Maryland, December 2021.

[85] 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, MA, 5th edition, 2016.

[86] D.A. Purser. *Fire Toxicity*, chapter Asphyxiant components of fire effluents. Woodhead Publishing, Cambridge, UK, 2010.

[87] D.A. Purser. Toxicity Assessment of Combustion Products. *The SFPE Handbook of Fire Protection Engineering*, 2:83–171, 2002.

[88] K. Buettner. Effects of Extreme Heat and Cold on Human Skin: II. Surface temperature, pain and heat conductivity in experiments with radiant heat. *Journal of Applied Physiology*, 3(12):703–713, 1951.

[89] J. P. Bull and J. C. Lawrence. Thermal conditions to produce skin burns. *Fire and Materials*, 3(2):100–105.

[90] A. R. Moritz and FC Henriques Jr. Studies of Thermal Injury: II. The relative importance of time and surface temperature in the causation of cutaneous burns. *The American journal of pathology*, 23(5):695, 1947.

[91] W. V. Blockley. Biology data book. *Federation of American Societies for Experimental Biology, Bethesda, MD*, 1973.

[92] L. Speitel. Toxicity Assessment of Combustion Gases and Development of a Survival Model. Technical report, Federal Aviation Administration, Washington, D.C., Office of Aviation Research, 1995.

[93] C.R. Crane. Human tolerance limit to elevated temperature: an empirical approach to the dynamics of acute thermal collapse. In *Memorandum Report AAC-114-78-2*. US Department of Transportation, Federal Aviation Administration, Washington, D.C., 1978.

[94] H. Utech. Status report on research programs for firefighters protective clothing. In *Proceedings of the Fire Department Instructor's Conference*, Indianapolis, IN, 1973.

[95] D. Madrzykowski. Fire Fighter Equipment Operational Environment: Evaluation of Thermal Conditions. NFPA Fire Protection Research Foundation, Quincy, Massachussets, August 2017.

[96] National Fire Protection Association, Quincy, Massachusetts. *NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*, 2018.

[97] National Fire Protection Association, Quincy, Massachusetts. *NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services*, 2013.

[98] A. Putorti, A. Mensch, N. Bryner, and G. Braga. Thermal Performance of Self-Contained Breathing Apparatus Facepiece Lenses Exposed to Radiant Heat Flux. Technical Report NIST TN 1785, National Institute of Standards and Technology, Gaithersburg, MD, 2013.

[99] R. Kesler, C. Mitsingas, A. Quiat, T. Lee, D. Madrzykowski, and G. Horn. Mechanical properties and off-gassing characteristics of new and legacy facepieces. NISTGCR 18-019, 2018.

[100] G. Horn, R. Kesler, J. Regan, and D. Madrzykowski. A Study on the Effect of Repeat Moderate Intensity Radiant Exposures on SCBA Facepiece Properties. NISTGCR 17-014, 2017.

[101] G. Stickler. Solar radiation and the earth system, relating solar radiation physics to earth space science concept. Education brief, NASA, 2009.

[102] D.I. Lawson and D.L. Simms. The ignition of wood by radiation. *British Journal of Applied Physics*, (3):288–292, 1952.

[103] J.B. Fang and J.N. Breese. Fire Development in Residential Basement Rooms. NBSIR 80-2120, National Bureau of Standards (currently NIST), Gaithersburg, MD, 1980.

Appendix A Window Interventions

Within this series of experiments, window ventilation occurred via one of three sets of actions: take, open, or remove. The following sections describe these actions in detail.

A.1 Take Window

To begin window initiated search operations, exterior crews used pike poles to break one of two double-hung, dual-pane bedroom windows. The area of the opening created was 3 ft x 4 ft. This action was designed to replicate the action that search crews would take to make an exterior entry point to search the interior of the structure. Figure A.1 shows a series of images of firefighters taking one-half of the bedroom 2 and bedroom 3 windows during Experiment 1. After this was completed, one side of the window remained intact (Figure A.1c).

(a) Take Window (Before)

(b) Take Window (During)

(c) Take Window (After)

Figure A.1: Firefighters taking a window during Experiment 1.

A.2 Open Window

For some experiments where search operations were initiated through the front door, bedroom windows were opened to simulate the search crew venting the space while leaving the windows intact. Two 31.75 in. x 17.75 in. openings were created. To execute the actions of the crew, hardware was designed to allow firefighters to open the bottom panes of windows from the outside by pulling on a cable (Figure A.2a). Figure A.2 shows firefighters opening a window during Experiment 9. As Figure A.2d shows, once the window was opened, the upper panes remained untouched.

(a) Open Window Hardware

(b) Open Window (Before)

(c) Open Window (During)

(d) Open Window (After)

Figure A.2: Firefighters opening a window during Experiment 9.

A.3 Remove Window

The removal of the two double-hung, dual-pane windows from bedrooms occurred during window initiated search and door initiated search experiments. The window install was designed as a plug. Once the shims, that were installed to ensure an air tight seal, were pulled, the entire two-window assembly could be removed. This action was designed to simulate the search crew breaking all of the glass and clearing the window frame to maximize the area of the vent (6 ft by 4 ft). This occurred either after isolation of the space or after suppression. For the window initiated search experiments that included isolation, the window removal reflected the crew taking the second of the two windows.

Firefighters removed a window by pulling the entire window assembly out of the structure. This action is shown in Figure A.3, where firefighters are seen removing a window during Experiment 4.

(a) Remove Window (Before)

(b) Remove Window (During)

(c) Remove Window (After)

Figure A.3: Firefighters removing a window during Experiment 4.

Appendix B Heat Flux Exposure References

To provide additional context to the heat flux values measured during the experiments discussed in this report, Table B.1 provides the heat flux ranges for several reference points.

Table B.1: Heat Flux Ranges of Common Reference Points

Reference	Heat Flux Range
Sunny day	1 kW/m^2 [101]
Tenability threshold for burns	2.5 kW/m^2 [89]
Pain to skin within seconds	3-5 kW/m^2 [89]
Threshold to floor for flashover	20 kW/m^2 [102]
TPP test	84 kW/m^2 [96]
Flames over surface	60-200 kW/m^2 [103]