Analysis of Search and Rescue Tactics in Single-Story Single-Family Homes Part II: Kitchen and Living Room Fires

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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 ten 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.

Eight experiments examined kitchen fires, and two experiments examined living room fires. 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.

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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
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 10 of the 20 experiments which were conducted where the fire was ignited in the kitchen or the living room.

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.

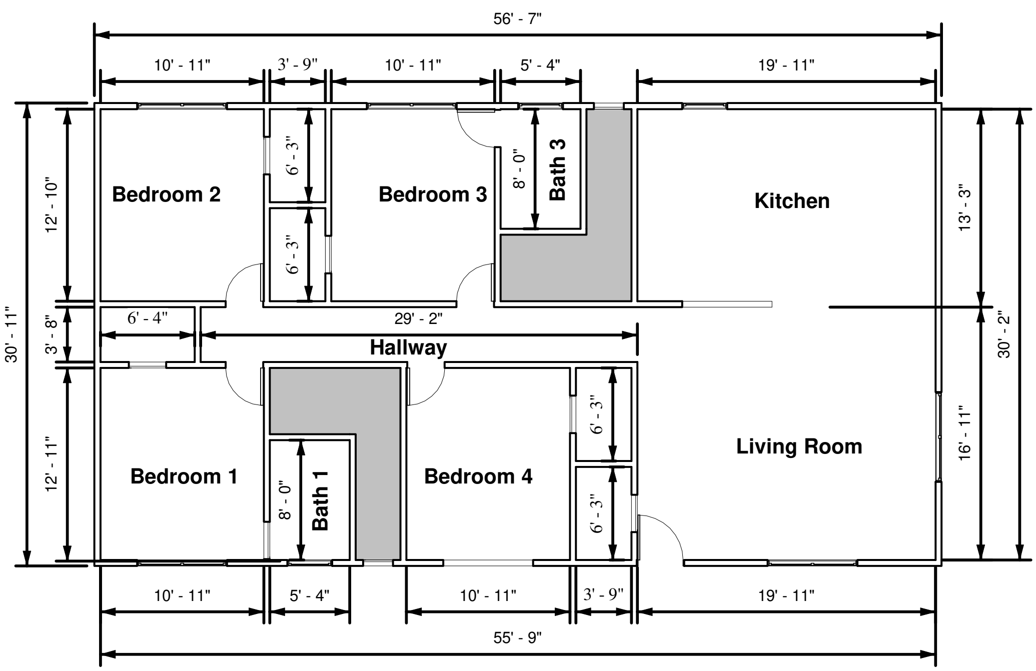
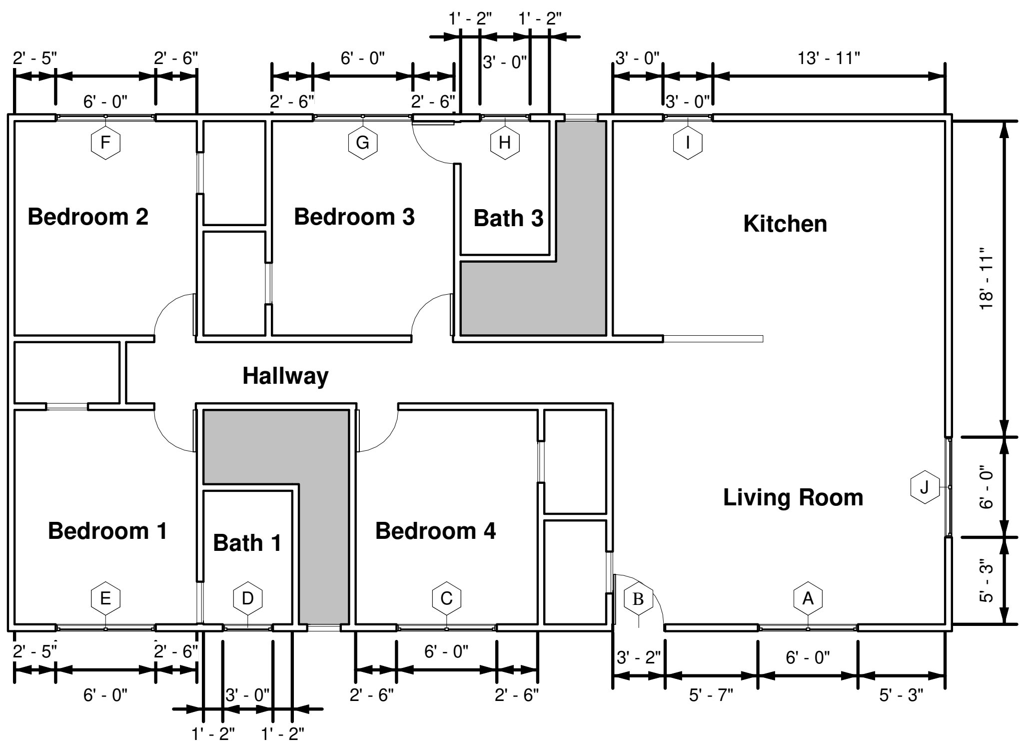


Figure 3.3: Dimensioned layout of structure.

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 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 ± 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.

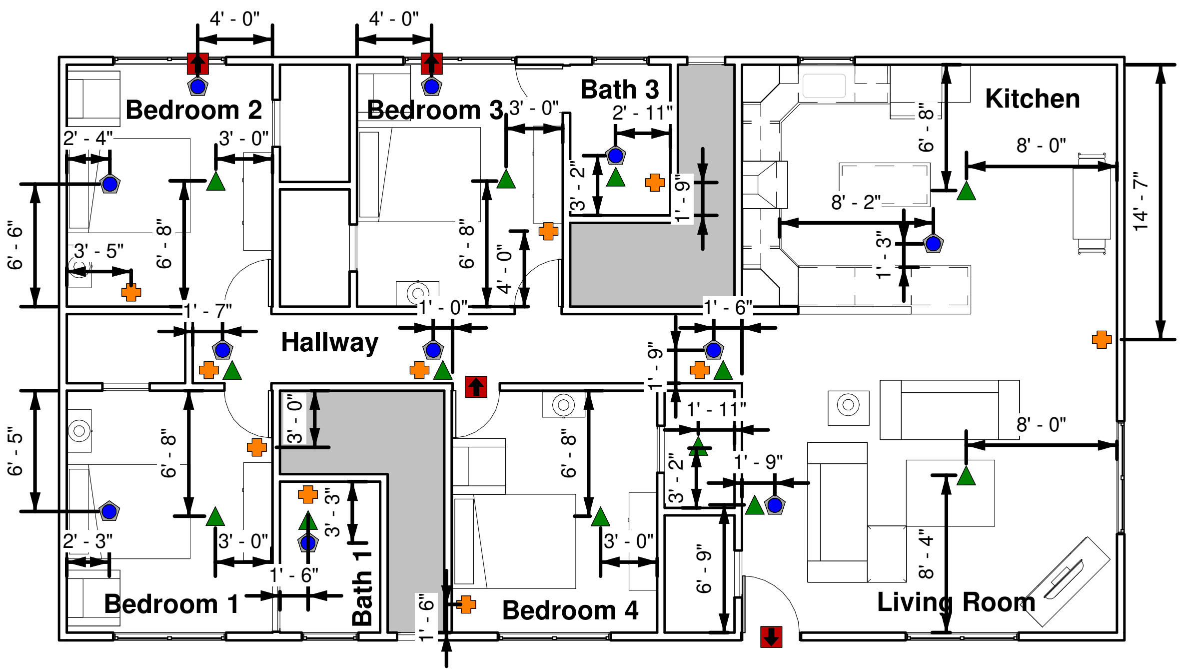
At a minimum, a single crew of three personnel was utilized for suppression, and two crews of two personnel were utilized for exterior horizontal ventilation and interior door manipulation via pre-rigged cables, and/or secondary suppression actions. A standby crew for rapid intervention was present in 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 with a nominal pressure of 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 load conditions 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.

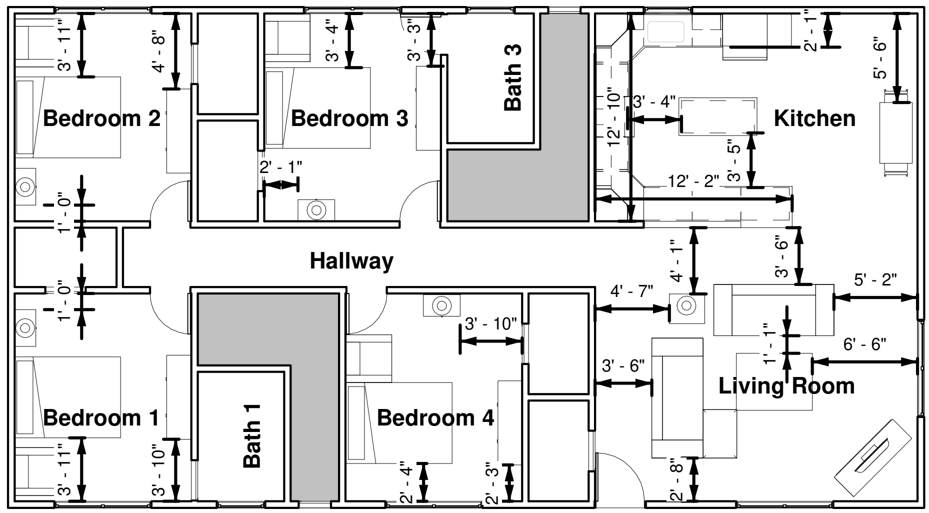


Figure 3.6: Dimensioned layout of bedroom, kitchen, and living room fuels.

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

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 3.8.

Figure 3.8: Photograph of bathroom fuel layout.

3.4.2 Kitchen

The open floor-plan kitchen featured both upper and lower cabinets, a range, a range hood, a refrigerator, and an island as well as a small table and two chairs along the wall opposite the cabinets. Figure 3.9 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 3.9: 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.

The kitchen ignition was initiated from propane burner with 2.5 L/min flow rate that produced an approximate 4 kW pilot flame. The propane burner was lit by firefighters in full PPE who then placed a 7.5 in. diameter (at the bottom of the tray) aluminum cooking tray with 3/4 cup of canola oil on a stand 5 in. above the burner. After placing the canola oil, the firefighters left the structure. The pilot burner remained fixed at 4 kW until the oil reached its auto-ignition temperature. At this point the burner was shut down, and the flame produced by the oil spread to adjacent fuels on the counter and kitchen cabinets. A total of 111 paper cups were place in the kitchen cabinets directly above the burner to help facilitate flame spread from the oil fire to the cabinets. Figure 3.10 shows the kitchen ignition configuration, but note however the cabinets were closed prior to ignition.

Figure 3.10: Photograph of ignition setup for kitchen fire. Prior to ignition of the pilot burner, the cabinet doors were closed. The pan of oil was placed on top of the stand above the burner after the burner is ignited.

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	144.5
		electronic circuits, metal components	
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

Living room fires were ignited with an electric match located in the corner of the upholstered sofa furthest from the front door where the seat cushion met the armrest. A slit was made in the fabric and a small amount of the polyester batting was pulled out. Figure 3.12 shows the ignition setup with the matchbook tucked into the corner underneath the batting.

Figure 3.12: Photograph of ignition setup for a living room fire.

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 10 of the 20 experiments which were conducted with kitchen and living room 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, Part II, includes the kitchen and living room experiments, numbered 11-20. The bedroom fire experiments can be found in Part I [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, Sections 4.1 and 4.2 present a representative example of the fire dynamics from ignition until intervention for both a kitchen fire and a living room fire, respectively. Sections 5.1—5.10 examine the fire dynamics of each kitchen and living room 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.

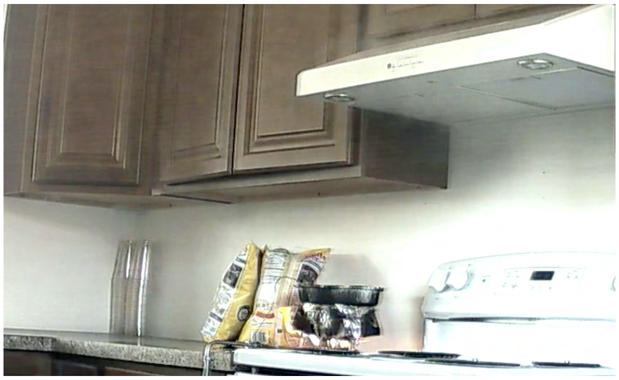
4 Experimental Results from Ignition to Intervention

For the eight kitchen ignitions and two living room 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, 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 sections 4.1, and 4.2 present a discussion on the fire dynamics from ignition until first intervention through analysis of a representative kitchen (Experiment 18) and living room (Experiment 19) experiment, respectively.

4.1 Kitchen Ignition

All kitchen experiments (Experiments 11–18) were ignited on the kitchen counter via an aluminum pan of cooking (canola) oil heated to its ignition temperature from a propane burner. This ignition configuration, intended to simulate a stovetop cooking fire, is described in more detail in Section 3.4.2. For all of the kitchen ignition experiments, the kitchen window was removed and the front door to the structure was open prior to ignition. Consider Experiment 18, discussed in this section, as a representative example of a kitchen ignition experiment prior to any fire department interventions.

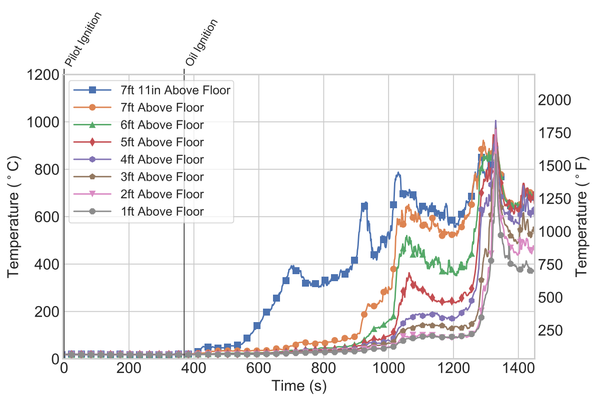
Upon ignition of the propane burner (t = 0 s, Figure 4.1), the temperature of the oil in the pan began to increase, and it ignited after crossing its ignition temperature 370 s after pilot ignition of the burner. Across the eight kitchen experiments, the oil ignition occurred 355 (5:55) $\pm$ 32 s after pilot ignition of the gas burner. Figure 4.2 shows the kitchen and living room temperatures for Experiment 18. Prior to the ignition of the oil, no temperature increase was observed at the kitchen (Figure 4.2a) or living room (Figure 4.2b) measurement locations.



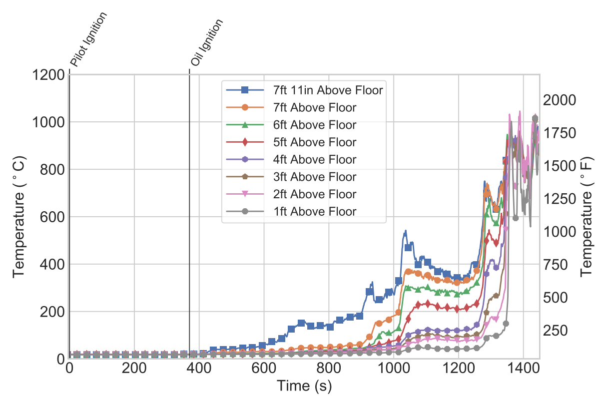
(a) Prior to Oil Ignition

(b) At Oil Ignition

Figure 4.1: Still images from kitchen ignition video prior to and at ignition of cooking oil on kitchen counter.



(a) Kitchen Temperature



(b) Living Room Temperature

Figure 4.2: Temperature time histories in common space (kitchen and living room) from ignition (t = 0 s) until firefighter intervention for Experiment 18.

The ceiling temperature in the kitchen first began to increase 405 s after ignition, shortly after the oil ignition, and it continued to climb as flames began to extend to the cabinets, as shown in Figure 4.3. The temperature at other elevations in the kitchen increased more slowly, not rising until the hot gas layer in the kitchen began to develop. As the fire continued to spread to the cabinets, fire was observed out of the side C window 975 s after ignition.

Figure 4.3: Camera view of fire beginning to spread from oil pan to kitchen cabinets at t = 406 s.

At 1000 s after ignition, temperatures 5 ft and above began to increase more rapidly, which corresponded to the time at which the kitchen counter was heated to the point of ignition, as shown in Figure 4.4. Following this increase, temperatures in the kitchen remained relatively steady until a final increase, which preceded the transition through flashover 1325 s after pilot ignition. The kitchen remained in a post-flashover state until suppression.

(a) Pre-Kitchen Counter Ignition (t = 975 s)

(b) Post-Kitchen Counter Ignition (t = 1015 s)

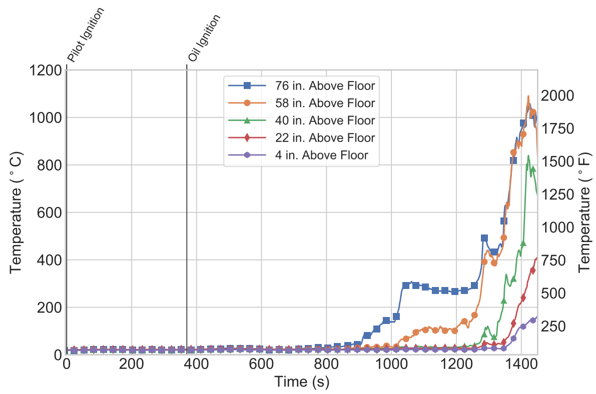
Figure 4.4: Camera view from side D living room wall toward kitchen before and after kitchen counter ignited during Experiment 18.

The living room temperatures, shown in Figure 4.2b, generally followed a similar trend to the kitchen temperatures because the two spaces composed a single volume, separated only by the counter-height kitchen peninsula. Ceiling temperatures first exhibited an increase approximately 450 s after pilot ignition as the ceiling jet from the kitchen began to extend into the living room. Temperatures at all elevations in the living room increased at a slower rate than those in the kitchen due to further distance from the ignition source and closer proximity to the open front door. Ignition of the peninsula countertop between the kitchen and living room (approximately 1015 s after ignition) led to temperature increases at a more rapid rate, which matched similar kitchen

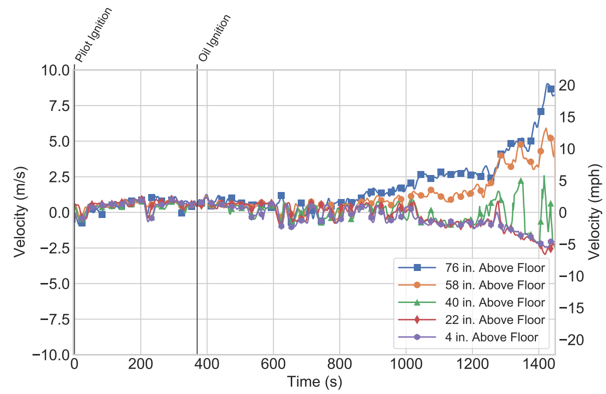
Figure 4.5: Camera view of rollover from kitchen to living room during Experiment 18.

temperature increases. Living room temperatures remained relatively steady until rollover was observed from the kitchen into the living room (Figure 4.5), 1240 s after pilot ignition. This rollover increased temperatures close to the ceiling and heated fuel surfaces, causing the living room to transition through flashover 1355 s after ignition. Fire was first observed out the side A living room windows 1300 s after ignition, and was observed out of both windows and the front door following flashover of the common space.

Front doorway temperature and velocity measurements show that bidirectional flow was established as the kitchen fire began to spread to the cabinets approximately 900 s after pilot ignition when products of combustion began to exhaust through the upper portion of the front door. As the kitchen fire continued to grow and the hot gas layer descended, temperature increases were also measured at the 58 in. and 40 in. probes. The corresponding velocity measurements indicated positive flow (flow out of the structure) at the 58 in and 76 in. probes. Entrainment into the structure, shown via the negative velocities at 40 in. and below, began approximately 100 s after ignition. As the living room fire transitioned through flashover, the exhaust from the doorway changed from smoke to fire (Figure 4.7b), resulting in an increase in the magnitude of positive and negative doorway velocities as fire vented from the upper portion of the doorway and air was entrained through the lower portion.



(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 kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

(a) Pre-Kitchen Counter Ignition (t = 295 s)

(b) Post-Kitchen Counter Ignition (t = 1315 s)

Figure 4.7: Camera view from side A exterior showing change from smoke exhaust to fire exhaust during Experiment 18.

As the kitchen fire began to grow in size (Figure 4.8), the 7 ft pressure began to increase, while the 4 ft and 1 ft pressures began to decrease. This reflected the development of a higher-pressure, higher-temperature gas layer close to the ceiling and the entrainment of cool air through the front door and through kitchen window. The 7 ft pressure first began to increase approximately 900 s after ignition. The 7 ft pressure reached a local peak 1030 s after ignition, coincident with the increase in living room and kitchen temperature observed after ignition of the kitchen counter. The 7 ft pressure increase was mirrored by a decrease in 4 ft and 1 ft pressures. Following the local peak at 1030 s, the pressure at all three elevations decreased below 0 Pa. The negative measured pressure in the living room was driven by the gases flowing past the measurement probes, which created areas of lower pressure.

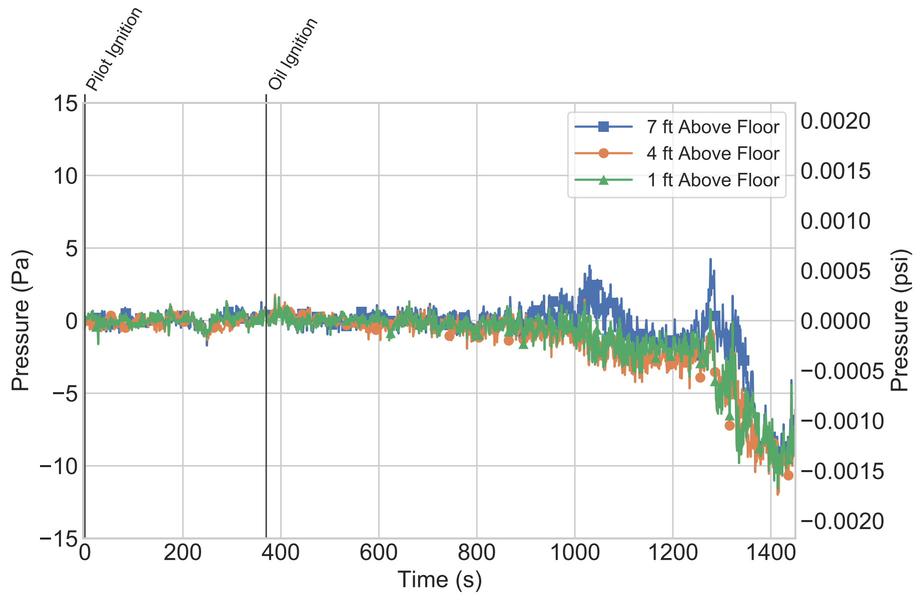
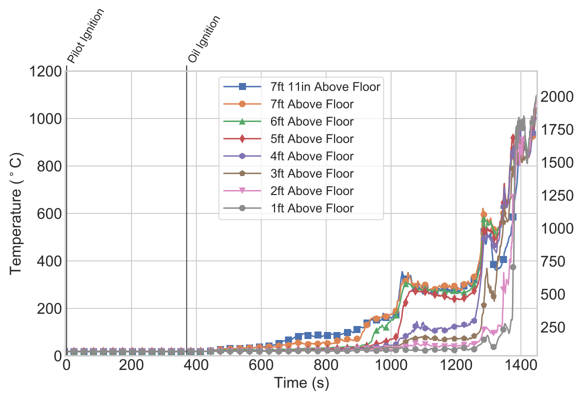


Figure 4.8: Pressure time histories in the living room due to a fire in kitchen from pilot ignition (t = 0 s) until firefighter intervention for Experiment 18.

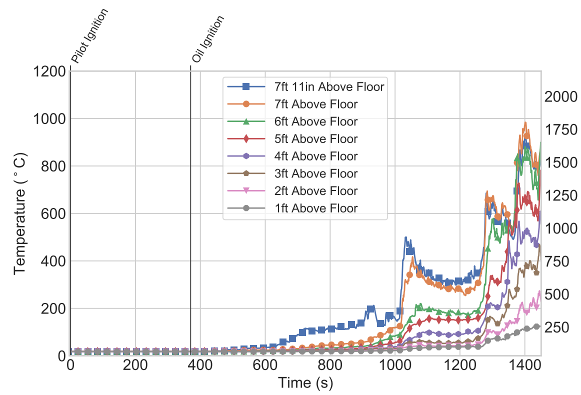
Hallway

As the kitchen fire spread, air in the hallway and open bedrooms was entrained by the area of low pressure generated by the smoke plume and was replaced by products of combustion. Figure 4.9 shows the temperatures in the living room entryway and at the three hallway measurement locations. Temperatures at the living room entryway location were similar to the temperatures in the center of the living room. Figure 4.9a shows that living room entryway temperatures first began to increase after the ignition of the cooking oil, followed by a more rapid increase approximately 270 s after ignition that corresponded with ignition of the kitchen counter. Prior to flashover of the kitchen and living room, temperatures at the living room entryway location reached a steady state, ranging between 295 °C (563 °F) at the ceiling and 95 °C (203 °F) 1 ft above the floor. Temperatures then increased at 1240 s as rollover was observed in the living room. Temperatures at all elevations in the living room entryway exceeded 600 °C (1112 °F) as the living room fire transitioned through flashover, 1380 s after pilot ignition.

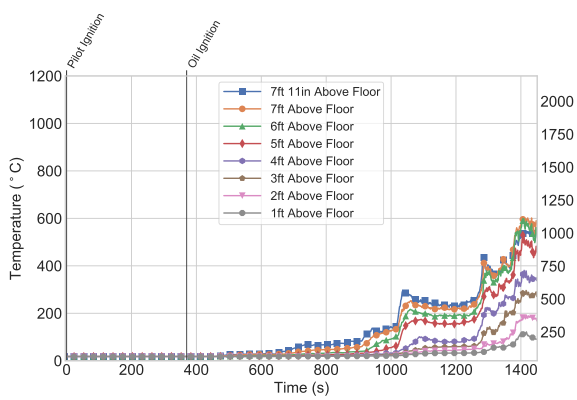
Temperatures close to the ceiling at the start hallway location exhibited temperature increases at similar times as the living room and kitchen temperatures (Figure 4.9b), coincident with ignition of the kitchen counter, rollover into the living room, and flashover of the common space. Unlike the temperatures in the living room entryway, the temperatures at the start hallway location were not consistent with post-flashover conditions. Temperatures remained stratified at the time of fire department intervention, ranging from 930 °C (1760 °F) at the ceiling to 120 °C (248 °F) 1 ft above the floor. Temperatures at the mid hallway (Figure 4.9c) and end hallway locations (Figure 4.9d) followed similar trends to the start hallway temperatures except with lower magnitudes due to distance from the fire and lack of flow once the open bedrooms and hallway began to fill with combustion gases. At the time of intervention, peak temperatures ranged from 635 °C to to 95 °C (1175 °F to 203 °F) at the mid hallway location and 450 °C to 100 °C (842 °F to 212 °F) at the end hallway location.



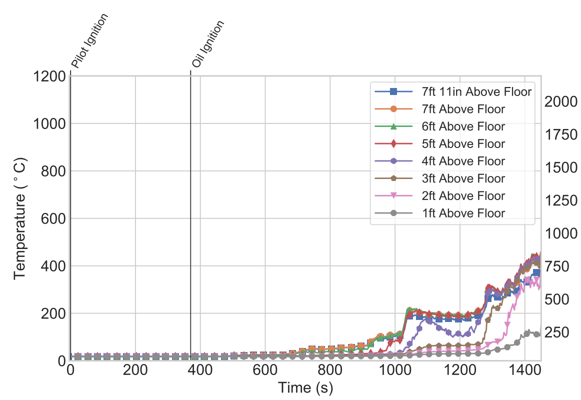
(a) Living Room Entry Hallway Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 4.9: Temperature time histories in the hallway due to a fire in the kitchen from pilot ignition (t = 0 s) until firefighter intervention for Experiment 18.

The heat flux to the floor, measured in the living room entryway, start hallway, mid hallway, and end hallway locations, increased in concert with the development of a hot gas layer in those locations (Figure 4.10). The living room entryway heat flux was the first to exhibit a substantial increase, which began simultaneous with rollover in the living room, approximately 1240 s after pilot ignition. As the living room fire transitioned through flashover, the heat flux measured in the living room entryway increased above 20 kW/m^2 at 1350 s, the magnitude typically associated with flashover. This heat flux ultimately peaked at 228 kW/m^2, consistent with direct flame impingement likely associated with padding and carpet burning over-top the gauge. Heat flux at the start hallway location increased at approximately the same time, although the magnitude of the peak was lower than in the living room at 14 kW/m^2. Heat flux at the remaining two hallway locations remained less than 5 kW/m^2 until the time of intervention. The comparatively higher heat flux observed at the start hallway location was a result of the increased convective flow and flaming combustion. The combustion gases flowing past the gauge via the descending smoke layer,

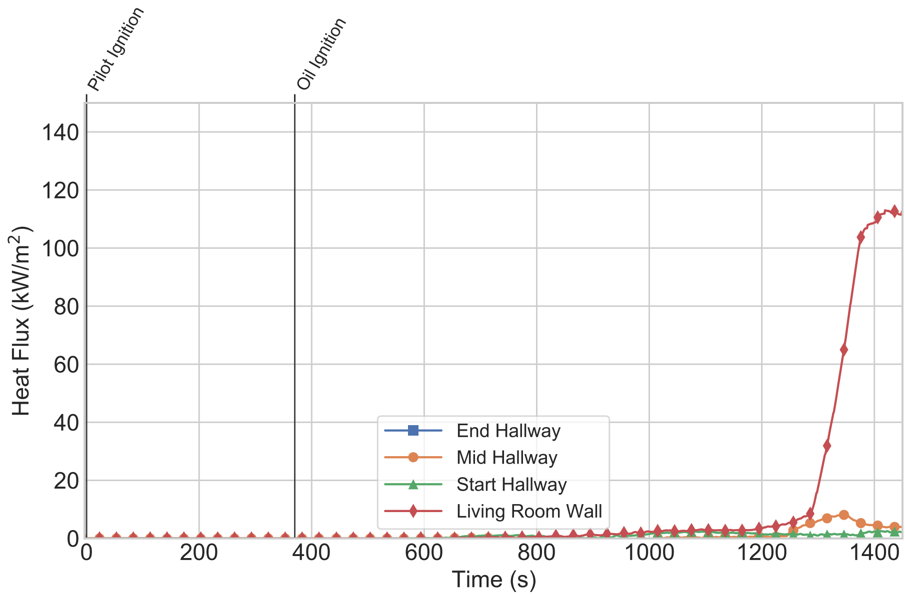
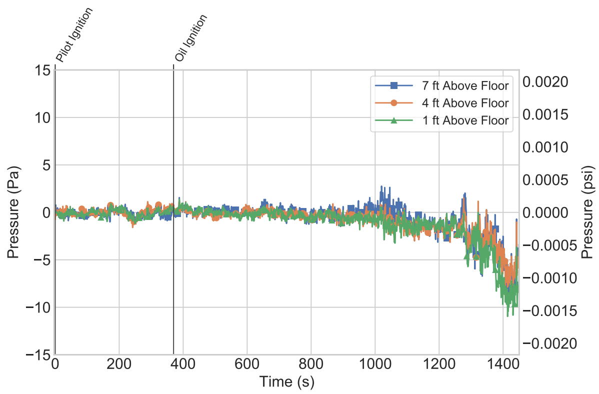


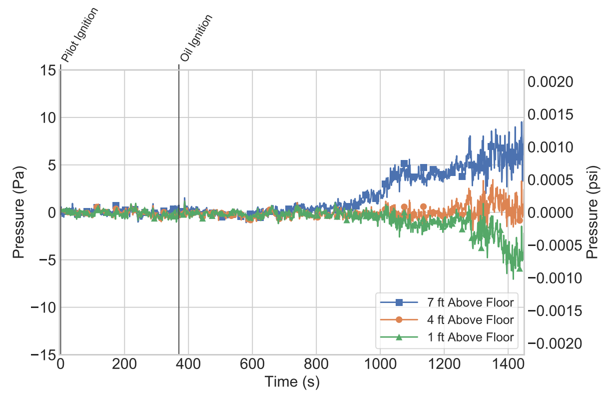
Figure 4.10: Heat flux time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

combined with rollover prior to the onset of flashover, resulted in the elevated heat flux measurements.

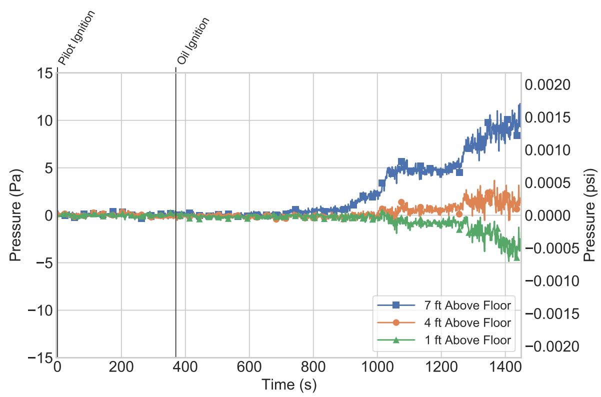
Pressures in the hallway (shown in Figure 4.11) reflect the flow of combustion products from the common space through the hallway and the corresponding entrainment of air from the bedrooms and hallway to the common space fire. Pressures at the start hallway location (Figure 4.11a) were similar to living room pressure, with values decreasing below 0 Pa approximately 1100 s after ignition to the flow of combustion gases and entrainment. Due to the accumulation of higher temperature combustion gases, pressures at the mid and end hallway locations (Figures 4.11b and 4.11c, respectively) increased at the 7 ft elevation starting approximately 900 s after ignition. This increase in 7 ft pressures was followed by an increase in 4 ft pressures, which started approximately 960 s after ignition as the smoke layer began to descend within the hallway. Simultaneous with the increase in 4 ft pressures, the 1 ft pressure decreased below 0 Pa, an indication that air from the open bedrooms and hallway was being drawn toward the fire in the common space. This bidirectional flow in the hallway was maintained until the time of intervention.



(a) Start Hallway Pressure



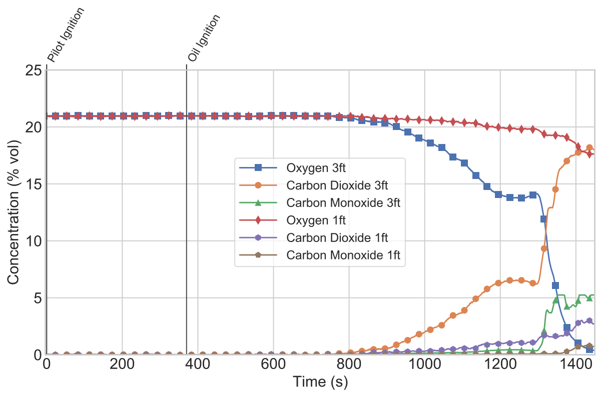
(b) Mid Hallway Pressure



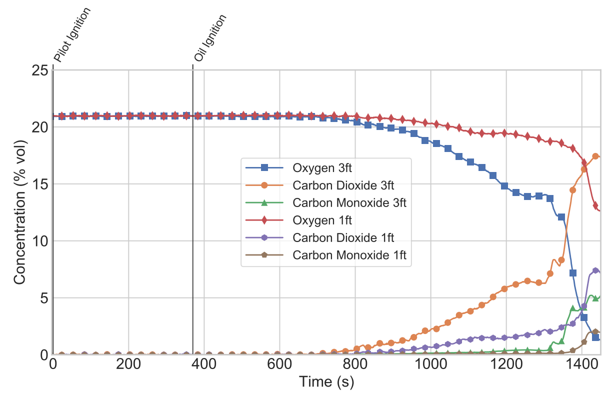
(c) End Hallway Pressure

Figure 4.11: Pressure time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

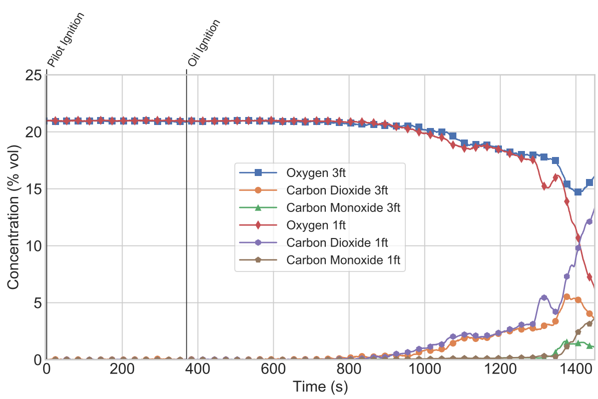
The gas concentrations measured in the hallway further reflected the exchange of air and products of combustion at remote locations in the structure. O_2, CO_2, and CO concentrations at 1 ft and 3 ft measurement elevations in the hallway maintained pre-ignition conditions until between 775 s and 800 s after pilot ignition, as shown in Figure 4.12. As the kitchen fire developed and began to involve additional fuel, air from the hallway and remote bedrooms was entrained toward the kitchen and was replaced with products of combustion. As the smoke layer in the hallway descended, the concentrations of products of combustion began to increase at the 1 ft and 3 ft measurement locations. The first hallway gas measurement location to indicate a change in gas concentrations was the end hallway location as the gases banked down after hitting the wall at the end of the hallway. The O_2 concentration began to decrease and CO and CO_2 began to increase 775 s after pilot ignition. This change was measured at both the 1 ft and 3 ft elevations, although the rate of change was greater at the 3 ft measurement location than at the 1 ft measurement location. CO and CO_2 concentrations increased and O_2 concentration decreased at a more rapid rate beginning 1300 s after pilot ignition, coincident with the onset of flashover in the kitchen.



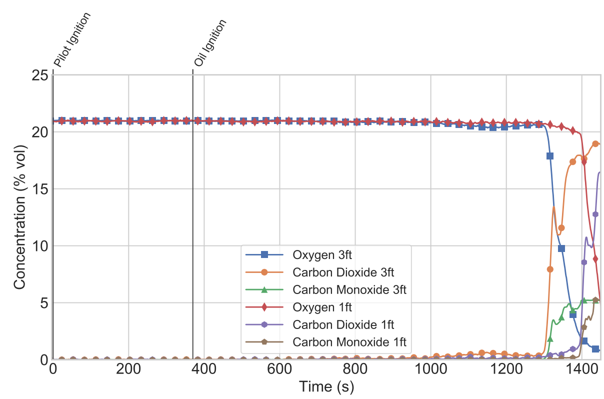
(a) End Hallway Gas Concentration



(b) Mid Hallway Gas Concentration



(c) Start Hallway Gas Concentration

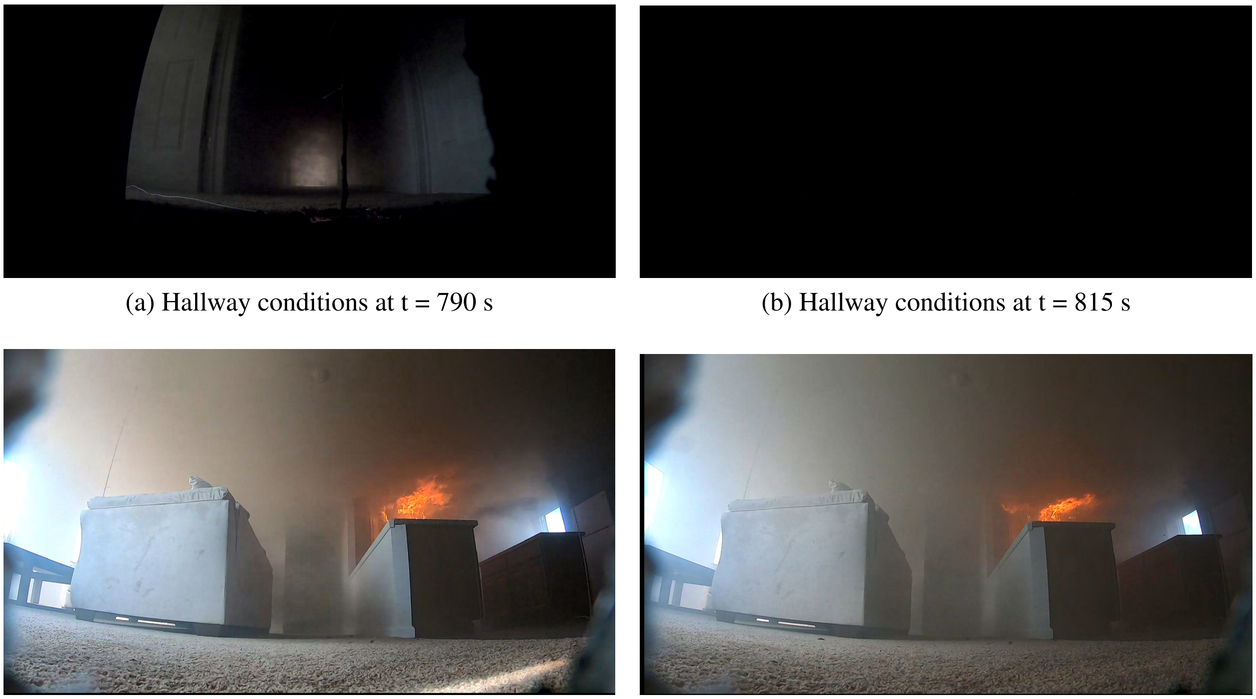


(d) Living Room Entry Hallway Gas Concentration

Figure 4.12: Gas concentration time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

The gas concentrations at the mid hallway and end hallway locations generally followed a similar trend to the end hallway location: As the smoke layer in the hallway descended to the floor, CO and CO_2 concentrations at the three hallway measurement locations began to increase while O_2 began to decrease (Figures 4.12b and 4.12a). Initially, the increase in CO and CO_2 and decrease in O_2 was gradual, but the rate at which these concentrations changed increased simultaneous with flashover in the common space. Gas concentrations at the mid hallway location first indicated a change from ambient approximately 720 s after pilot ignition. Prior to any firefighter intervention, concentrations were comparable to the end hallway location, although the CO concentration measured at the time of intervention was higher at the mid hallway location.

The timing of the initial change in gas concentration at the mid hallway and end hallway locations approximately matched the time at which visibility was lost in the hallway camera. Figure 4.13 shows the camera located at the end of the hallway began to lose visibility at floor level approximately 790 s after pilot ignition as the smoke layer descended to the floor, and lost visibility completely by 815 s after ignition. This loss of visibility was not observed at the living room camera location, as Figure 4.13 shows. The reason for this discrepancy was the continued exchange of air in the common space up until the time of flashover. The hallway and remote bedrooms began to fill with products of combustion and optically dense smoke, which obscured visibility and increased toxic gas concentrations.



(a) Hallway conditions at t = 790 s

(b) Hallway conditions at t = 815 s

(c) Living Room conditions at t = 790 s

(d) Living Room conditions at t = 815 s

Figure 4.13: Loss of visibility at hallway camera location compared to living room camera location during Experiment 18.

Gas concentrations at the start hallway location (Figure 4.12c) first indicated a change from ambient later in the experiment than the mid hallway and end hall locations because it was closer to the open front door where gases were exchanged with the environment. Both the 1 ft and 3 ft gas concentrations began to change approximately 900 s after pilot ignition. The decrease in O_2 and increase in CO and CO_2 concentrations was gradual until the time of flashover, at which point O_2 sharply decreased and CO and CO_2 sharply increased until the time of fire department intervention.

Air exchange in the common space was further supported by the gas concentrations in the living room entryway, shown in Figure 4.12d. Unlike the gas concentrations in the hallway, where CO and CO_2 began to increase and O_2 began to decrease as the hallway became charged with smoke, the bidirectional flow through the front door maintained visibility and higher oxygen concentrations (and limited CO and CO_2 accumulation) in the living room entryway. Gas concentrations in the living room entryway did not begin to change until approximately 1300 s after ignition, coincident with the onset of flashover in the kitchen. Figure 4.12d shows that 3 ft O_2 concentrations sharply decreased and CO and CO_2 concentrations sharply increased at this time, followed shortly afterward (at 1395 s) by the 1 ft gas concentrations as the entire common space fire transitioned through flashover. At the time of fire department intervention in Experiment 18, gas concentrations were 0.8% O_2, 18.8% CO_2, and 5.2% CO 3 ft above the floor and 3.8% O_2, 15.8% CO_2, and 5.2%

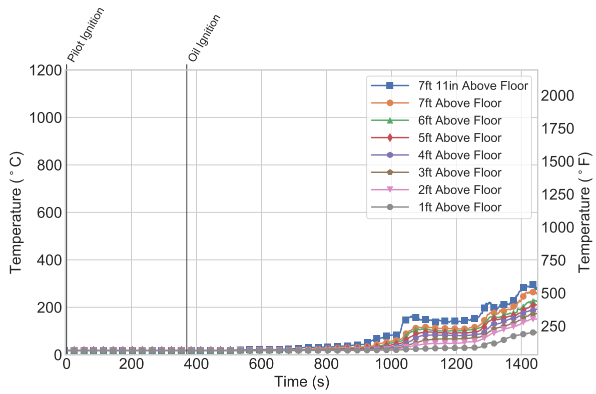
CO 1 ft above the floor.

Bedrooms

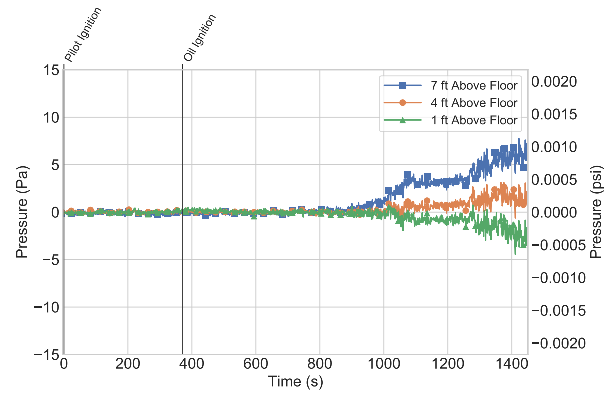
Across the series of kitchen ignition experiments, the initial door position varied based on the specific objective of each experiment. The state of the initial door of position impacted the transport of gases to and from that space, but did not directly impact the fire growth in the kitchen. The following examination of the corresponding changes to conditions within the respective bedrooms is based on the initial door positions of Experiment 18. 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 position of the bedroom door (i.e., open versus closed) was the largest factor for differences between the bedroom experiments.

Open Bedrooms

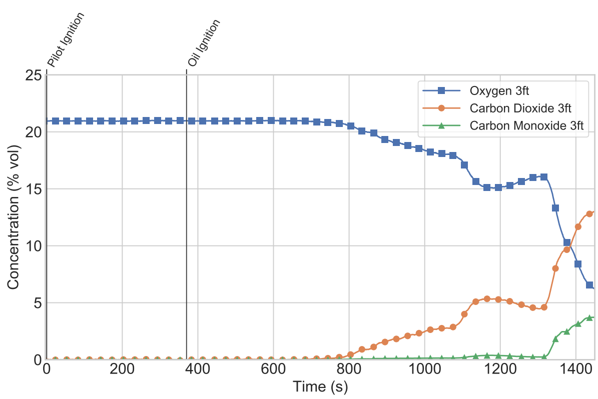
In Experiment 18, the doors to bedrooms 2 and 3 were left open from the start of the experiment, allowing for exchange of gases with the rest of the house. The temperature, pressure, gas concentrations, and heat flux in bedroom 2 maintained pre-test conditions until approximately 500 s after ignition. At that point, the smoke layer in the hallway began to bank down past the top of the bedroom 2 doorway, allowing products of combustion to flow into the bedroom, which increased the ceiling temperature (Figure 4.14a). Temperatures at all elevations in the room began to increase 1030 s after ignition, simultaneous with the increase in temperatures observed elsewhere in the structure. Initially, this temperature increase was gradual due to the distance of bedroom 2 from the origin of the fire. Temperatures in bedroom 2 further increased as the common space fire transitioned through flashover. At the time of fire department intervention in Experiment 18, temperatures in bedroom 2 were still increasing, ranging from 280 °C (536 °F) at the ceiling to 94 °C (201 °F) 1 ft above the floor.



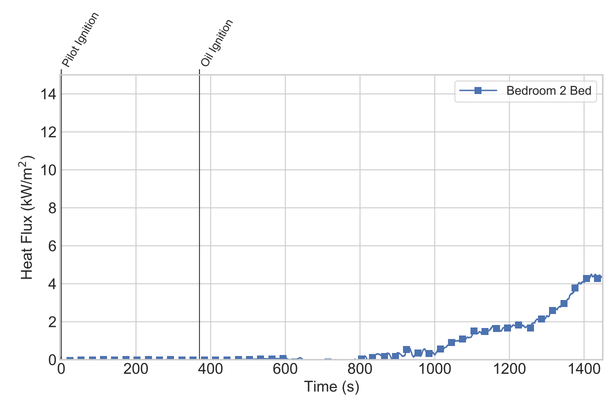
(a) Bedroom 2 Temperature



(b) Bedroom 2 Pressure



(c) Bedroom 2 Gas Concentration



(d) Bedroom 2 Heat Flux

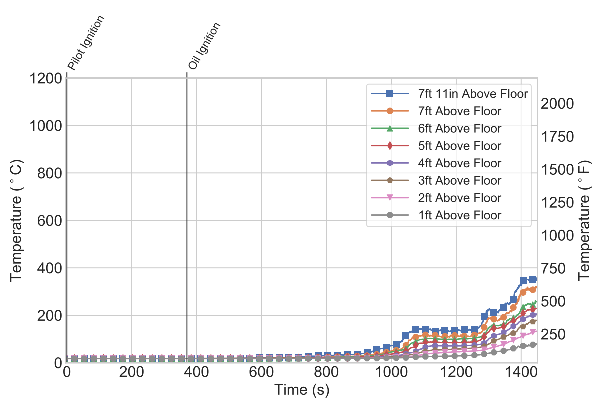
Figure 4.14: Bedroom 2 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

The pressures measured in bedroom 2 during Experiment 18 (Figure 4.14b) reflected the temperature behavior described above. The 7 ft pressure first began to increase approximately 900 s after pilot ignition, as a smoke layer began to develop in the bedroom. The 4 ft and 1 ft pressures remained at 0 Pa until approximately 1030 s after pilot ignition, when the smoke layer began to descend. This resulted in an increase in the 4 ft pressure while the 1 ft pressure became negative as air flowed into the hallway, which was at a lower pressure. The magnitude of the pressure at all elevations increased sharply in the period preceding flashover of the common space.

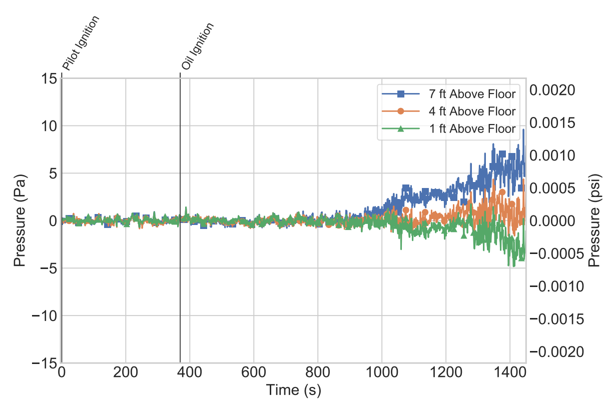
The gas concentrations measured 3 ft above the floor at the center of the bed (Figure 4.14c) similarly reflected the development of a smoke layer in bedroom 2. Gas concentrations first began to change approximately 840 s after pilot ignition as the smoke layer began to descend past the 3 ft level in the bedroom. As pressure data indicated, CO and CO_2 concentrations increased as smoke traveled from the hallway to the bedroom, while the O_2 concentration decreased as air flowed toward the kitchen fire. Gas concentrations began to change more sharply 1300 s after ignition, as the common space began to transition through flashover. At the time of intervention, O_2, CO_2, and

CO concentrations at the 3 ft bed location in Experiment 18 were 6.1%, 13.0%, and 3.9%, respectively. Heat flux (Figure 4.14d), measured 3 ft above the floor in the center of the bed (next to the gas probe), followed a similar trend to temperatures and gas concentrations, beginning to increase at the same time that temperatures began to uniformly increase, approximately 1030 s after pilot ignition. Heat flux steadily increased until the time of intervention, reaching a peak of 3.3 kW/m^2.

The conditions in bedroom 3 closely resembled those in bedroom 2, as shown by the temperature and pressure data in Figure 4.15. The ceiling temperature in bedroom 3 first began to increase approximately 500 s after pilot ignition, as smoke in the hallway banked down past the top of the doorway and began to flow into bedroom 3. Shortly afterward, the 7 ft pressure (Figure 4.15b) began to increase, reflecting the flow of combustion products from the hallway to bedroom 3. As the smoke layer in bedroom 3 continued to descend, temperatures at all elevations began to gradually increase approximately 1000 s after ignition. Simultaneously, the 4 ft pressure began to increase and the 1 ft pressure began to decrease as the hot products of combustion accumulated in the room, resulting in a loss of visibility in the bedroom 3 camera as gases close to the floor were drawn into the lower-pressure hallway. Temperatures began to increase at a more rapid rate approximately 1300 s after ignition as the common space began to transition to flashover. The closer proximity of bedroom 3 to the common space resulted in higher temperatures at the time of intervention compared to bedroom 2, with temperatures ranging from 365 °C (689 °F) at the ceiling to 96 °C (205) 1 ft above the floor.



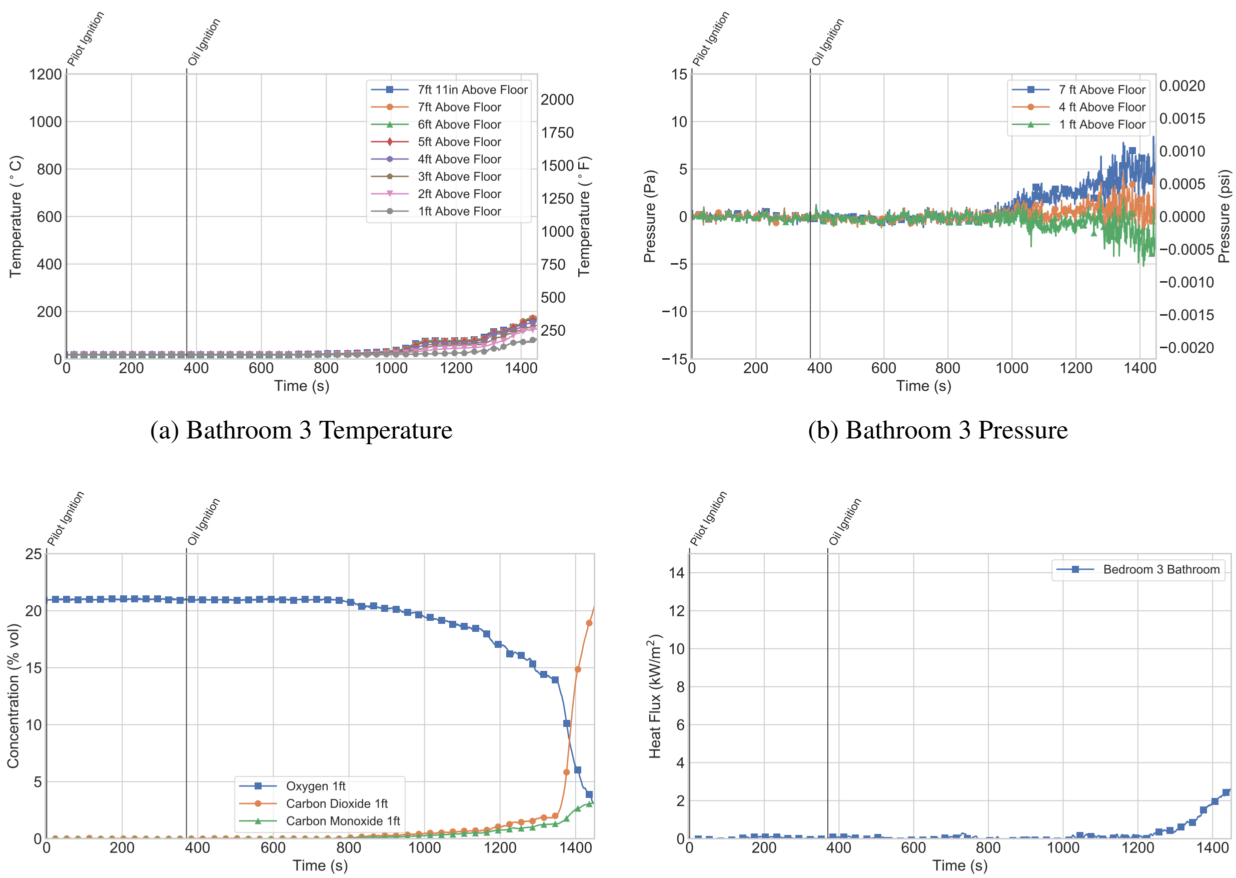
(a) Bedroom 3 Temperature



(b) Bedroom 3 Pressure

Figure 4.15: Bedroom 3 temperature and pressure time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

Temperatures in the bathroom adjacent to bedroom 3 began to increase later in the experiment than those in bedroom 3 because the gas layer in bedroom 3 had to first descend to the height of the bathroom 3 door in order for products of combustion to flow into the bathroom. This occurred approximately 100 s after ignition and resulted in an increase first in ceiling temperature at 830 s, followed by an increase in 7 ft pressure at 950 s. Visibility was lost in the bathroom 3 camera between 1040 and 1065 s, which corresponded to an increase in temperature at all elevations, an increase in the 4 ft pressure, and a decrease in the 1 ft pressure. In the 30 s preceding flashover of the common space, a sharp increase was observed in temperature and the magnitude of pressures in the bathroom. The temperatures in bathroom 3 at the time of intervention were lower than those measured in both bedrooms 2 and 3, ranging from 178 °C to 77 °C (352 °F to 171 °F).



(a) Bathroom 3 Temperature

(b) Bathroom 3 Pressure

(c) Bathroom 3 Gas Concentration

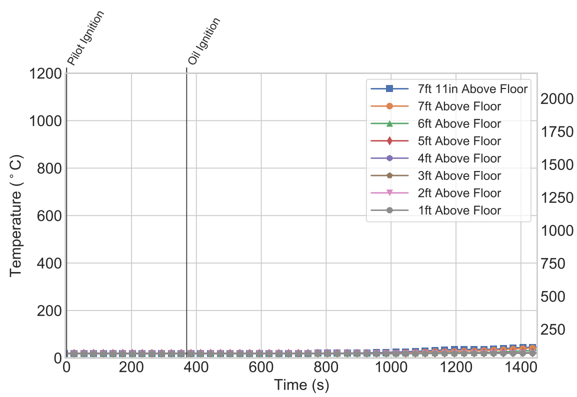
(d) Bathroom 3 Heat Flux

Figure 4.16: Bathroom 3 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

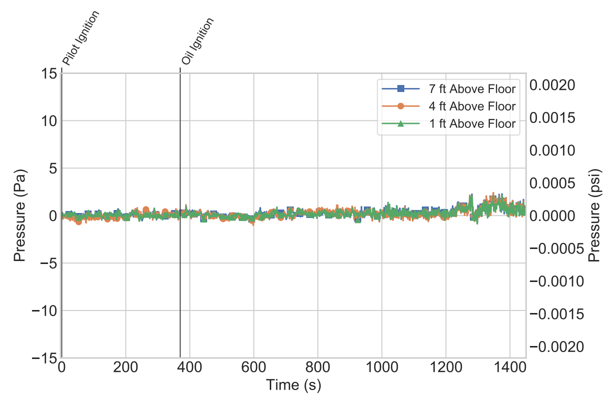
Visible smoke conditions in the bathroom began to increase at 810 s as gas concentrations began to change (Figure 4.16c). As CO and CO_2 concentrations increased as a result of the bathroom filling with smoke, O_2 decreased as fresh air was drawn through the bedroom toward the kitchen fire. The initial increase in CO and CO_2 was gradual, but concentrations increased substantially as the common space fire transitioned through flashover. Gas concentrations were increasing at the time of intervention, with O_2, CO_2, and CO concentrations of 2.7%, 20.9%, and 3.2%, respectively. Similar to bedroom 2, the oxygen concentration was below the threshold of 15% needed to support combustion. Heat flux (Figure 4.16d), measured 1 ft above the floor in the center of the bathroom, followed a similar trend to temperatures, beginning to increase at the same time that temperatures began to uniformly increase, approximately 1030 s after pilot ignition. Heat flux steadily increased until the time of intervention, reaching a peak of 2.9 kW/m^2.

Closed Bedrooms

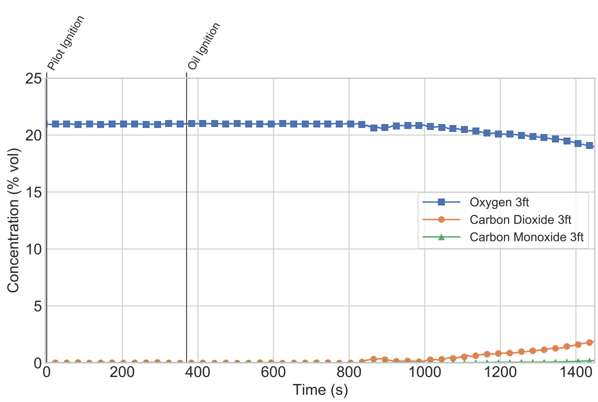
The doors to bedroom 1 and bedroom 4 remained closed from the beginning of the experiment through fire department intervention in Experiment 18. As a result, temperatures and gas concentrations remained substantially lower than the corresponding bedrooms where the doors were left open. Figure 4.17 shows the temperature, pressure, gas concentration, and heat flux measured in bedroom 1. The pressures recorded over the duration of Experiment 18 were negligible, as shown in Figure 4.17b, which reflected the lack of flow into the room because of the closed door. Temperatures in the bedroom only began to increase approximately 1000 s after ignition as products of combustion leaked around the closed door and through the HVAC ducts. The timing of this increase mirrored the temperature observed in the common space, hallway, and open bedrooms at approximately the same time, although the magnitude of the temperature increase was negligible compared to other areas of the structure.



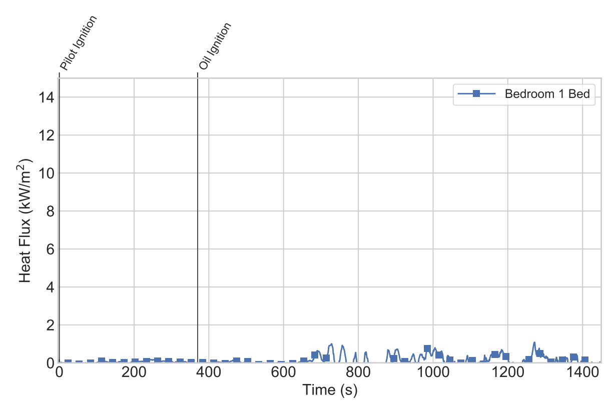
(a) Bedroom 1 Temperature



(b) Bedroom 1 Pressure



(c) Bedroom 1 Gas Concentration

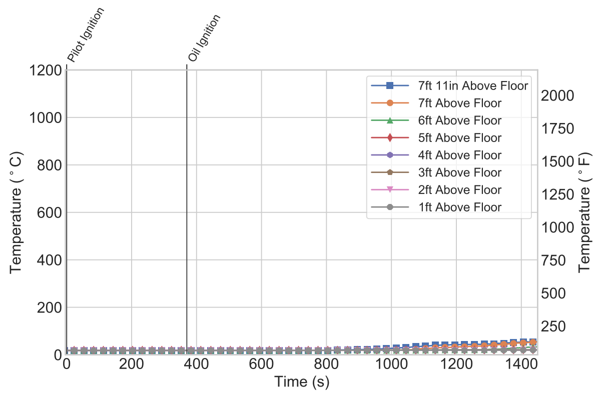


(d) Bedroom 1 Heat Flux

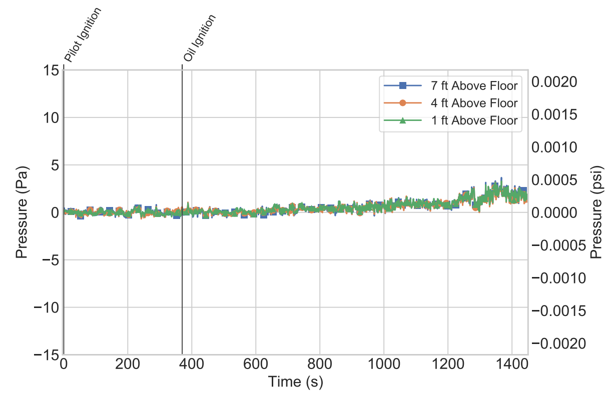
Figure 4.17: Bedroom 1 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

Gas concentrations were measured 3 ft above the floor in the center of the bed in bedroom 1. As smoke leaked into bedroom 1 through the closed door, increasing temperatures, O_2 concentrations first began to decrease and CO and CO_2 concentrations began to increase, as shown in Figure 4.17c. Note that the rate at which these values changed was markedly lower than in bedroom 2, which was located immediately across the hallway with an open door. In contrast to the sharp increases that were observed in the open bedrooms coincident with flashover, the increase in CO and CO_2 and decrease in O_2 was gradual. As a result, the O_2, CO_2, and CO values were 19%, 2.9%, and 0.2%, respectively, at the time of intervention—considerably lower than the corresponding values in either open bedroom. As result of the comparatively low temperatures and minimal relative changes in gas concentrations within bedroom 1, the heat flux on the bed (Figure 4.17d) was negligible prior to intervention.

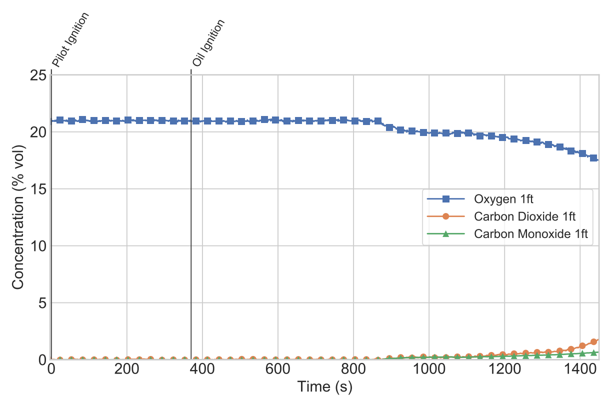
Bathroom 1 was immediately adjacent to bedroom 1, and was isolated from the bedroom by a closed door. The two closed doors between bathroom 1 and the hallway provided sufficient isolation, so the primary pathway for transport was through the HVAC supply in the ceiling. Only the temperatures from 6 ft above the floor to the ceiling exhibited any noticeable temperature increase (Figure 4.18a). This temperature increase started 830 s after ignition, and at the time of intervention, temperatures ranged from 55 °C (131 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor. The bathroom 1 pressure gradually increased at all three elevations, coinciding with the rise in temperature (Figure 4.18b). The uniform pressure behavior was driven by the absence of local vent either in the form of an open door or window or HVAC return.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Pressure

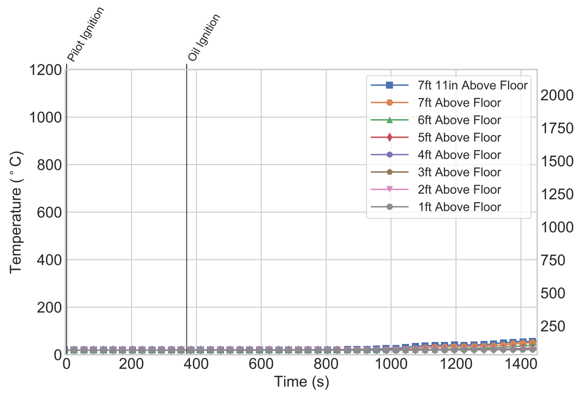


(c) Bathroom 1 Gas Concentration

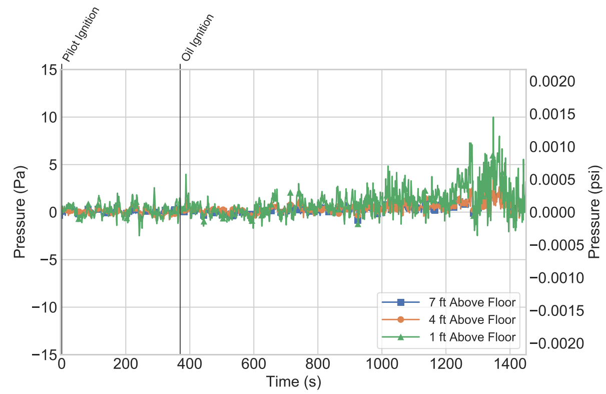
Figure 4.18: Bedroom 1 temperatures and pressure time histories in the hallway due to a fire in bedroom 4 from ignition (t = 0 s) until firefighter intervention for Experiment 18.

Gas concentrations at the 1 ft elevation in bathroom 1 first began to change shortly after the initial temperature increase was noted, 865 s after pilot ignition (Figure 4.18c). Similar to the behavior observed in bedroom 1, CO and CO_2 concentrations gradually increased as smoke slowly flowed into bathroom 1 through leakage points around the bedroom 1 and bathroom 1 doors. At the time of intervention, the O_2, CO_2, and CO concentrations were 17.5%, 1.9%, 0.7%, respectively. These concentrations were also considerably lower than the corresponding values in either open bedroom.

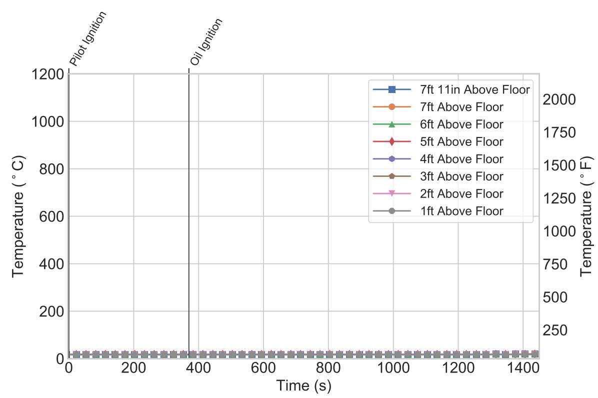
The temperature and pressure measured in bedroom 4 and the attached closet, shown in Figure 4.19, trended similarly to the values measured in bedroom 1. Temperatures in bedroom 4 initially began to gradually increase at 830 s, reaching values ranging from 57 °C (135 °F) at the ceiling to 22 °C (72 °F) 1 ft above the floor. The bedroom 4 closet temperature (Figure 4.19c) did not exhibit any appreciable temperature rise in the period prior to intervention. Note: Although the location of this room with respect to the hallway was comparable to bathroom 1, the magnitude of temperature increase observed was lower. This was attributable to an HVAC supply vent being located in bathroom 1, compared to no HVAC vent in the bedroom 4 closet. The transport of smoke into closed bedrooms via the supply vents accounted for the positive pressure increase measured in these closed spaces (Figures 4.17b, 4.18b, and 4.19b).



(a) Bedroom 4 Temperature



(b) Bedroom 4 Pressure



(c) Bedroom 4 Closet Temperature

Figure 4.19: Bedroom 4 temperatures, pressure, and closet temperature time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 18.

4.2 Living Room Ignition

Two experiments, Experiments 19 and 20, were conducted with the ignition in a living room sofa. Although these limited experiments could not be compared to the same depth as the bedroom or kitchen ignitions, the fire dynamics of this ignition location were important as it pertained to the fire development in the common space. Of particular interest was the change in timeline of fire growth compared to kitchen ignition.

Here, Experiment 19 will be the representative experiment. Prior to ignition, the front door and the kitchen window were open. The door to bedroom 1 was closed while the doors to bedrooms 2, 3, and 4 were open.

The fire was ignited in the side B corner of the upholstered sofa that was parallel to side A of the living room. Gas temperatures at the living room ceiling first began to rise 40 s after ignition (Figure 4.20a), and 10 s later temperatures rose in the kitchen. By 145 s, temperatures at all elevations within the living room had risen above pre-ignition values; at this point ceiling temperatures exceeded 170 °C (338 °F) (Figure 4.20b). At the time of Figure 4.20b, the smoke layer had filled the living room and kitchen to approximately 6 ft above the floor. At this point, the temperature rise below the smoke layer was driven by a combination of radiative heat transfer from the smoke layer and flames on the sofa.

(a) Initial Ceiling Temperature Rise (40 s)

(b) Initial Floor to Ceiling Temperature Rise (145 s)

Figure 4.20: Interior views of fire growth at the time of initial temperature rise at the ceiling (40 s post ignition) and floor to ceiling temperature rise (145 s post ignition).

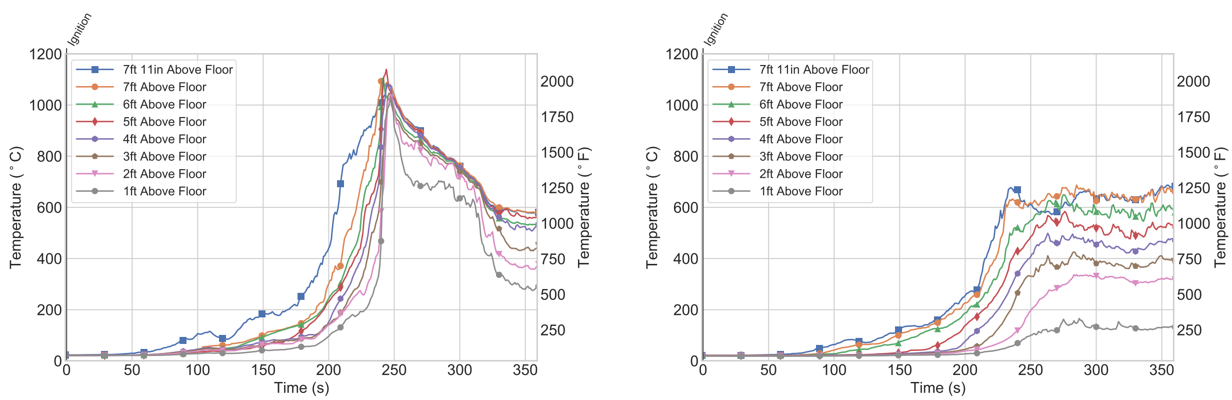
Flames were first visible from the front door 238 s (3:58) post ignition as the 1 ft elevation crossed 330 °C (626 °F). Figure 4.21 correspondingly shows the interior and exterior conditions. By 241 s, all temperatures exceeded 600 °C (1112 °F), an indication the living room had reached flashover. At 248 s, the living room temperatures reached their peak floor to ceiling magnitudes between 1000 °C and 1100 °C (1832 °F and 2012 °F).

(a) Living Room At First Visible Exterior Flames (238 s)

(b) Side A Exterior At First Visible Exterior Flames (238 s)

Figure 4.21: Interior and exterior view at time (238 s post ignition) when flames were first visible on the exterior.

Flames remained present out the front door until suppression occurred. Additionally, flames remained visible out the living room windows which, failed shortly after flashover. Temperatures in the living room remained in a post flashover state until suppression. Figure 4.22 shows the time history of the measured temperatures in both the living room and kitchen. Air entrained by the fire through the open front door and through the failed living room windows was consumed at the interface of those vents, which limited the combustion in the living room. The small area and high sill of the open kitchen window also limited the inflow of air into the kitchen. Even though the kitchen temperatures had a similar initial temperature rise at 50 s and a sharp increase when the living room fire transitioned through flashover, the values then remained stratified, ranging between 130 °C (266 °F) 1 ft above the floor to 650 °C (1202 °F) at the ceiling. There was insufficient oxygen to support a transition through flashover in the kitchen.



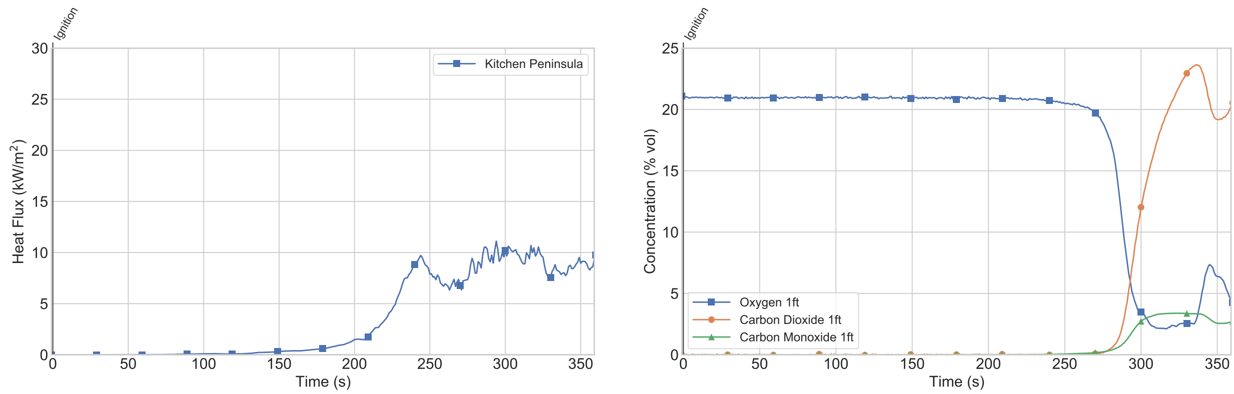
(a) Living Room Temperature

(b) Kitchen Temperature

Figure 4.22: Temperature time histories in common space (kitchen and living room) from ignition (t = 0 s) until firefighter intervention for Experiment 19.

Recall the fire dynamics from a kitchen ignition, (Figure 4.2) in which both the kitchen and living fires transitioned to flashover. In the kitchen experiments, the ignition location was at the opposite end of the common space from the primary vent, which allowed the fire to spread across the additional fuel toward fresh air. In contrast to the kitchen, ignition was in the middle of the common space, and the primary direction of flame spread toward the open door limited spread toward the kitchen. Also note that the timeline to flashover in the living room ignition experiments was over 1000 s sooner, driven by the synthetic fuel composition of the sofas.

At the 1 ft elevation in the kitchen, between the the island and peninsula, the heat flux first began to increase at 138 s while the gas concentrations responded more slowly, first measuring a change at 238 s (Figure 4.23). The heat flux responded first because of the heat transfer from the hot gas layer that developed within the common space. The gas layer needed to descend to the 1 ft elevation for a change in gas concentration to be measured. Despite being shielded from the main body of fire by the kitchen peninsula, the heat flux ranged between 8 kW/m^2 and 10 kW/m^2 285 s prior to intervention (Figure 4.23a). The heat flux remained below 15 kW/m^2, a value typically associated with rollover. This was another indication of the lack of flaming combustion in the kitchen. This heat flux response was also different than during a bedroom ignition where the closed kitchen window limited gas flow and thus heat transfer (Figure 4.23a).



(a) Kitchen Heat Flux (b) Kitchen Gas Concentration

Figure 4.23: Kitchen heat flux and gas concentration time histories for a living room fire from ignition (t = 0 s) until firefighter intervention for Experiment 19.

For the Experiment 19 living room ignition, the O_2, CO_2, and CO concentrations in the kitchen were 2.5%, 23.5%, and 3.4%, respectively, at 335 s post-ignition which represented the peak measured concentrations prior to intervention (Figure 4.23b). These values were below the 15% O_2 concentration needed to support combustion.

Pressure in the living room, shown in Figure 4.24, remained at pre-test conditions through the initial growth phase of the fire because the open door and kitchen window were of sufficient size to limit pressure increases in the living room. As the living room fire continued to spread and flames were visible out the front door (238 s post-ignition), the 7 ft and 4 ft pressures reached their peak values of 5.5 Pa (0.0008 psi) and 4.5 Pa (0.0006 psi), respectively. The 1 ft pressure fluctuated around 0 Pa. This reflected the development of a higher-pressure, higher-temperature gas layer close to the ceiling, and the entrainment of cool air through the front door at lower elevations in common space. Following the local peak at 238 s, the pressure at all three elevations decreased below 0 Pa by 280 s. The negative measured pressure in the living room was driven by the flowing gases past the measurement probes, which created areas of lower pressure—gases flowing toward the front door at 4 ft and above, and gases flowing toward the fire below 4 ft. This flow behavior was also shown at the front doorway velocity probes.

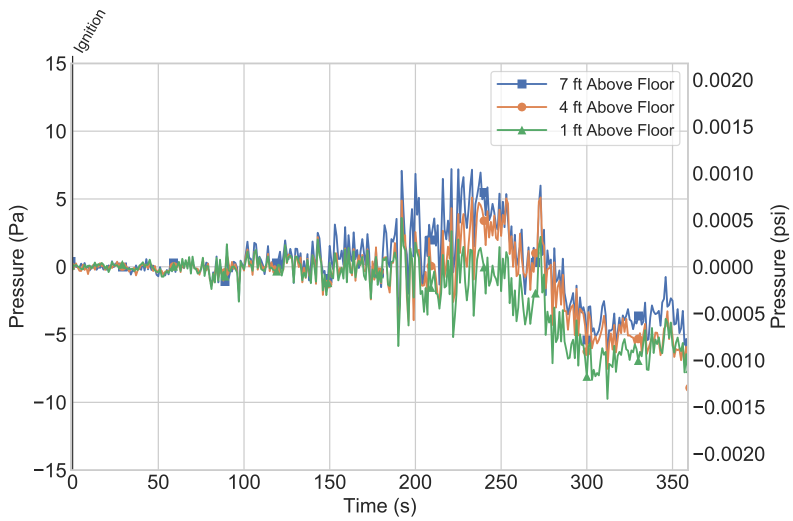
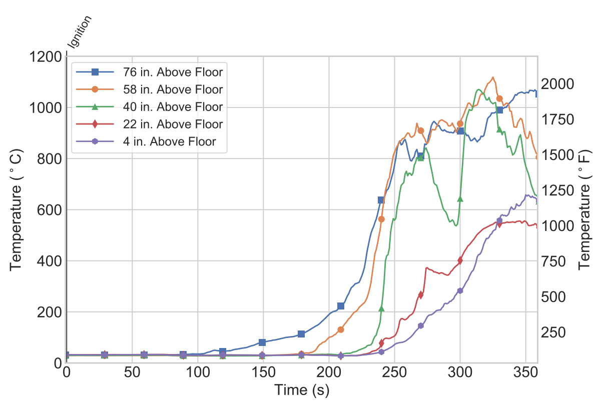
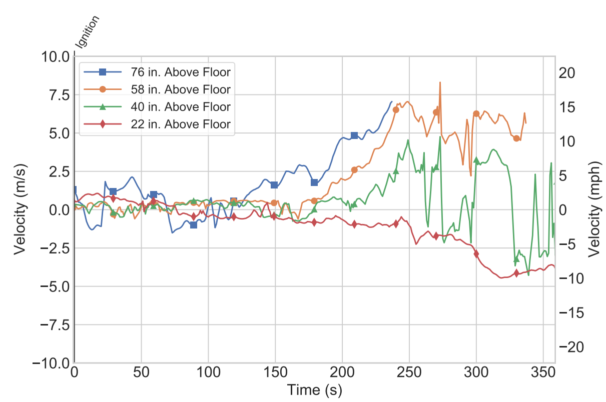


Figure 4.24: Pressure time histories in the living room due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

Temperature and velocity measurements taken in the front door show that as living room fire began to spread to the adjacent the sofa, bidirectional flow was established in the front door, as shown in Figure 4.25. As the living room fire transitioned through flashover at 241 s, front temperatures at the 76 in. elevation to the 40 in. elevation ranged from 605 °C to 260 °C (1185 °F to 500 °F) with exhaust velocities that ranged between 7 m/s to 4 m/s (15.5 mph to 9 mph). Temperatures at the 22 in. and 4 in. were noticeably lower, at 86 °C (187 °F) and 45 °C (113 °F), respectively. Although the 4 in. velocity probe malfunctioned, the 22 in. probe measured an inflow of 1 m/s (2.2 mph). The lower two doorway thermocouples still measured temperature increases, though not as much as the higher elevations because the heat transfer at those locations was balanced by radiation from the exhausting flames and convective cooling due to inflow of air.



(a) Front Doorway Temperature



(b) Front Doorway Velocity

Figure 4.25: Front doorway temperature and velocity time histories for a living room fire from ignition (t = 0 s) until firefighter intervention for Experiment 19.

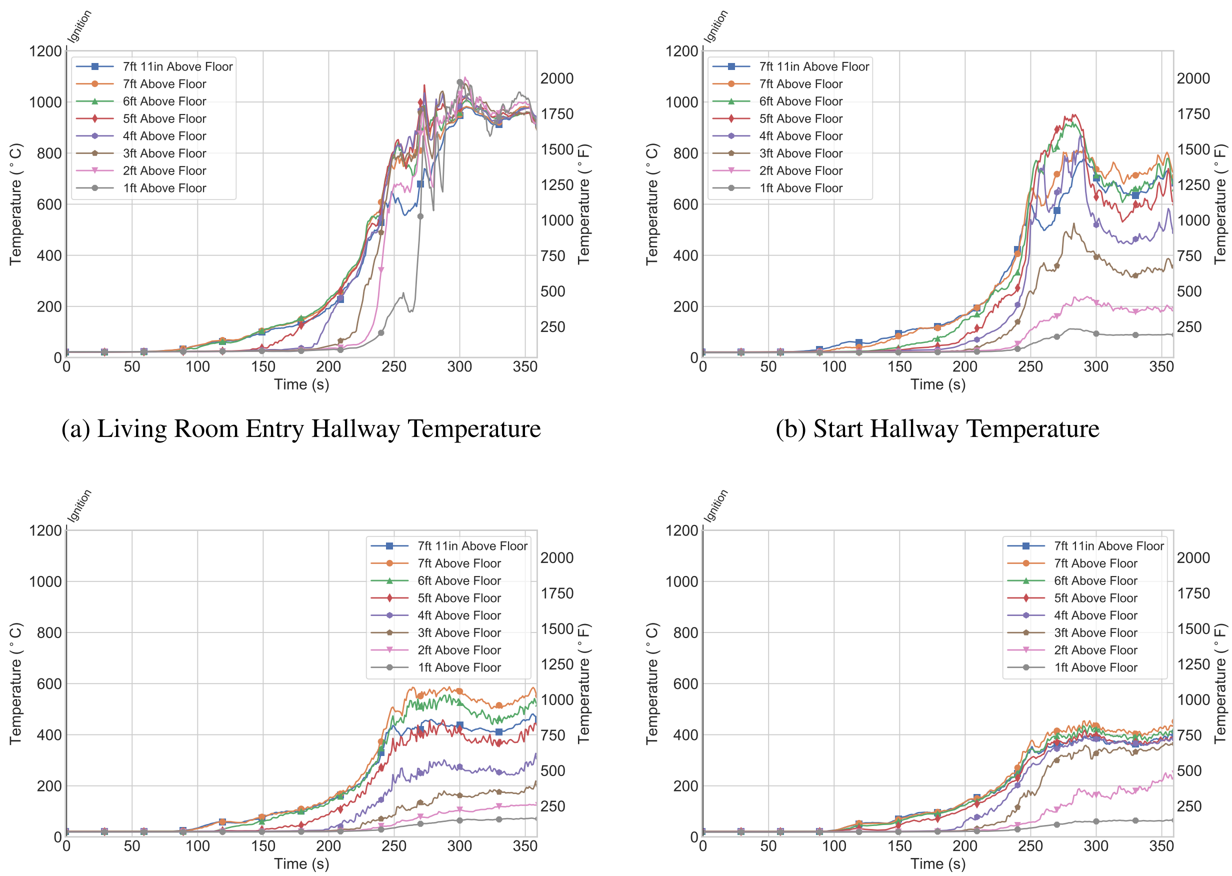
Measured temperatures at the 76 in. and 58 in. elevations in the doorway continued to rise until suppression, with peak values that exceeded 1000 °C (1832 °F). There were noticeable fluctuations at the 40 in. elevation temperature, which was tied to the gas velocity shifting between inlet and outlet conditions. Between 250 s and 300 s and again at 325 s to 350 s, inflow was recorded at the 40 in. probe, which corresponded to drops in measured temperature. The rise in inflow height was tied to living room window failure (approximately 275 s), which increased the exhaust vent area. At 22 in. and below there was consistent inflow in the living room. Figure 4.26 shows the exterior conditions on side A prior to first firefighter intervention.

Figure 4.26: Side A exterior image of conditions at the front door and living room windows prior to first firefighter intervention for a living room fire (Experiment 19).

Hallway

As the heat release rate of the living room fire increased, air from remote locations in the structure flowed toward the low pressure area generated by the fire plume and was replaced by products of combustion. Figure 4.27 shows the temperatures in the living room entryway and at the three hallway measurement locations. Temperatures at the living room entryway location were similar to the temperatures in the center of the living room (Figure 4.22a). Figure 4.27a shows that ceiling temperatures in living room entryway temperatures first began to slowly increase at 76 s, before a more rapid increase approximately 238 s after ignition, corresponding to the flames out the front door. Temperatures at the living room entryway location reached a post-flashover steady state at 271 s, 30 s after the living room reached flashover, ranging between 1050 °C (1922 °F) at the ceiling 950 °C (1742 °F) 1 ft above the floor. The living room entryway temperatures remained elevated and steady because of proximity to the front door where the inflow of oxygen supported continued combustion.

Temperatures close to the ceiling at the start hallway (Figure 4.27b) exhibited increases at similar times to the living room and kitchen temperatures, coincident with flame spread across the ignition sofa. As time progressed, the start hallway location temperatures were more reflective of the kitchen than the living room. Temperatures at elevations above 4 ft all rose above 600 °C (1112 °F) by 251 s, 10 s after flashover in the living room. At 285 s, these temperatures peaked, ranging from 940 °C to 745 °C (1724 °F to 1373 °F) before decreasing to approximately steady values ranging between 725 °C to 485 °C (1337 °F to 905 °F). Temperatures at 3 ft and below also peaked at 285 s, but remained below 500 °C (932 °F) with the 1 ft level peaking at 111 °C (232 °F). In similar fashion to the kitchen, the lack of oxygen prevented flame spread down the hallway. Temperatures at the mid hallway (Figure 4.27c) and end hallway (Figure 4.27d) locations followed similar trends to the start hallway temperatures except with lower magnitudes due to distance from the fire and lack of flow once the open bedrooms and hallway began to fill with combustion gases. At the time of intervention, peak temperatures ranged from 580 °C to 70 °C (1076 °F to 158 °F) at the mid hallway location and 450 °C to 65 °C (842 °F to 149 °F) at the end hallway location.



(a) Living Room Entry Hallway Temperature

(b) Start Hallway Temperature

(c) Mid Hallway Temperature

(d) End Hallway Temperature

Figure 4.27: Temperature time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

The heat flux to the floor, measured in the living room entryway, start hallway, mid hallway, and end hallway locations, increased in concert with the development of a hot gas layer in those locations, as shown in Figure 4.28. The living room entryway heat flux was the first to exhibit a substantial increase, which coincided with temperature rises throughout the space due the development of a smoke layer. As the living room fire transitioned through flashover, the heat flux measured in the living room entryway experienced a peak at 44 kW/m^2 at 250 s. The heat flux dropped to 10 kW/m^2 over the next 10 s driven by convective cooling due to the increased inflow at the front door before exceeding 200 kW/m^2 20 s later, a magnitude consistent with direct flame impingement. This was likely associated with padding and carpet burning overtop the gauge. The inlet provided by the open front door supplied sufficient air to sustain combustion at this location. Heat flux at the start hallway location increased at approximately the same time, although the magnitude of the peak was lower than in the living room (12 kW/m^2). Heat flux at the remaining two hallway locations generally remained less than 2.5 kW/m^2 until the time of intervention. Note the spike at the mid hallway location was due to a picture from the wall falling on top of the gauge impacting the measurement. The comparatively high heat flux observed at the start hallway location was a result of combustion gases flowing past the gauge via the descending smoke layer combined with rollover prior to the onset of flashover.

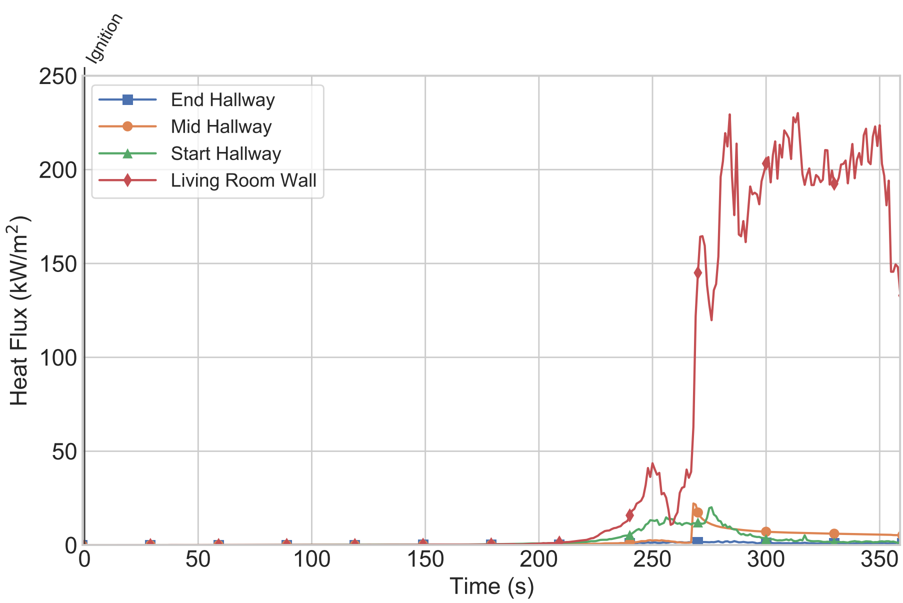
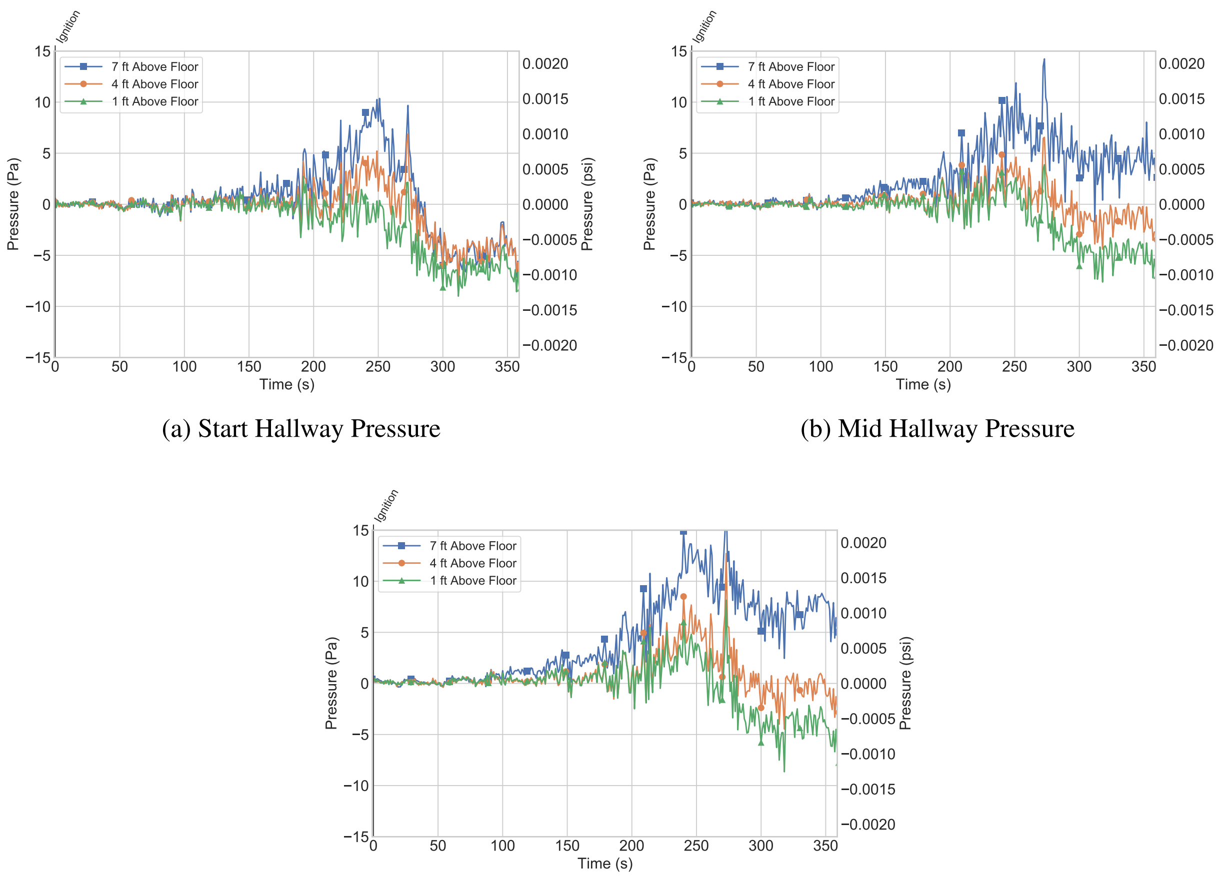


Figure 4.28: Heat flux time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

Pressures in the hallway (Figure 4.29) reflect the flow of combustion products from the common space through the hallway and corresponding air flow from the bedrooms and hallway toward the living room fire. Pressures at the start hallway (Figure 4.29a) were similar to living room pressures, with the 7 ft and 4 ft values reaching peaks as the living room fire transitioned through flashover, at 8 Pa (0.001 psi) and 3 Pa (0.0004 psi), respectively. The 1 ft elevation fluctuated between 0 Pa and -2 Pa (-0.0003 psi). Following the peak, the start hallway pressure decreased, and all three elevations measured negative values by 283 s. By 300 s, the pressures ranged between -4 Pa (-0.0006 psi) at the 7 ft elevation to -7 Pa (0.001 psi) at the 1 ft elevation. The negative measured pressure at the start hallway was similar to that in the living room. The measurements were driven by the gases flowing past the measurement probes, which created areas of lower pressure: gases flowing toward the living room at 4 ft and above, and gases flowing toward the fire below 4 ft. Recall from Figure 4.27b the stratification in temperature above and below the 4 ft elevation.

Pressures at the end hallway location (Figure 4.29c) reached peak values at 241 s, ranging from 15 Pa (0.002 psi) 7 ft above the floor to 4 Pa (0.0006 psi) 1 ft above the floor, as the living room fire transitioned through flashover. The higher pressures were a result of combustion gases flowing down the hallway and hitting the end hallway wall and banking down toward the floor. Peak pressures at the mid hallway location occurred 10 s later than the end hallway location, once the hallway began to fill with smoke (Figure 4.29b). The magnitudes at the mid hallway location were slightly lower, ranging from 12 Pa (0.0017 psi) 7 ft above the floor to 1.5 Pa (0.0002 psi) 1 ft above the floor.

At the mid and end hallway locations, the 7 ft pressures remained above 0 Pa, an indication the upper portion of the hallway continued to be filled with higher temperature, higher pressure gases. The lack of an exterior vent led to this accumulation. The 4 ft and 1 ft pressures decreased below 0 Pa, an indication that gases from the open bedrooms and hallway were being drawn toward the fire in the living room. This bidirectional flow in the hallway was maintained until the an intervention was made.



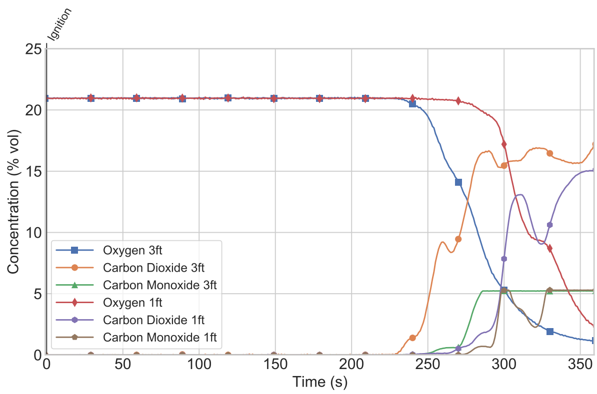
(a) Start Hallway Pressure

(b) Mid Hallway Pressure

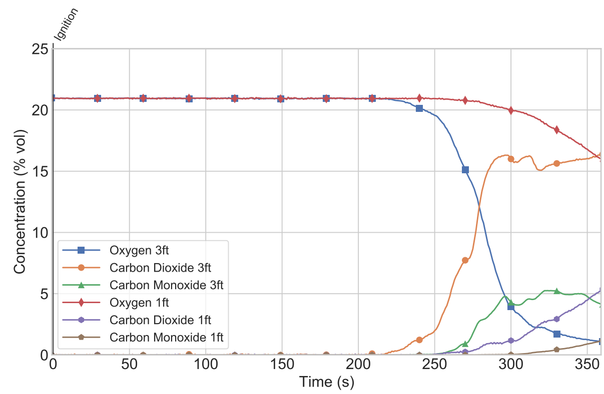
(c) End Hallway Pressure

Figure 4.29: Pressure time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

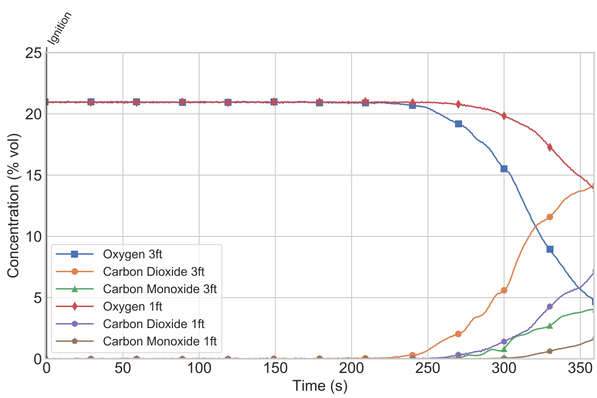
The gas concentrations measured 3 ft above the floor at the start, mid, and end hallway locations further reflected the exchange of air and products of combustion at remote locations in the structure. O_2, CO_2, and CO concentrations at 1 ft and 3 ft measurement elevations in the hallway maintained pre-ignition conditions until 223 s after ignition (Figure 4.30), which coincided with temperature rises at the 3 ft elevation at the respective locations (Figure 4.27). The living room entryway 3 ft location responded approximately 10 s later as exhaust through the open front door slowed the smoke layer development.



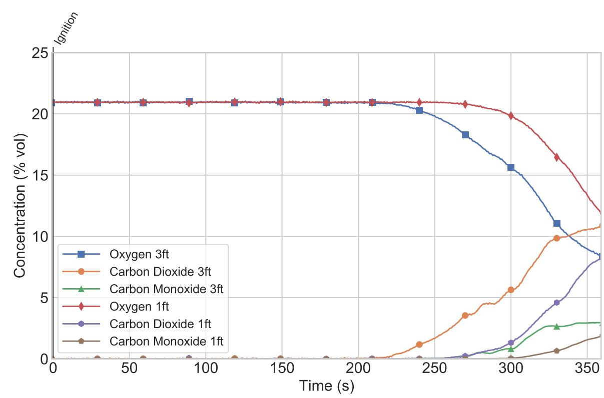
(a) Living Room Entry Hallway Gas Concentration



(b) End Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) Start Hallway Gas Concentration

Figure 4.30: Gas concentration time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

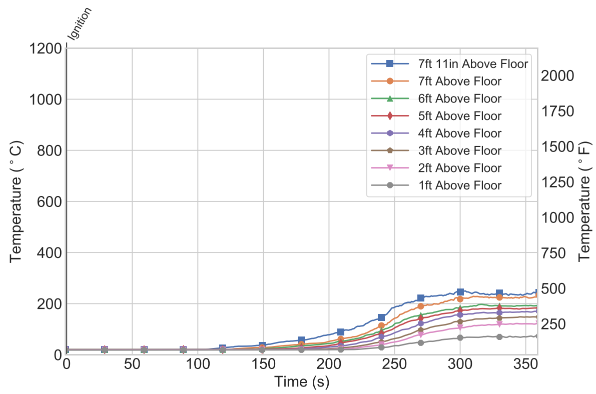
At the 1 ft elevation, the living room entry hallway location gas concentrations began to increase 20 s after the 3 ft elevation and 25 s at the start, mid, and end hallway locations. Post flashover of the living room, the close distance to flaming combustion was responsible for both the faster response at the 1 ft elevation and the more severe gas concentrations at both elevations for the living room entry hallway location. The end hallway location, despite being further from ignition, had the next most acute response because gases that flowed down the hallway, hit the end hallway wall, and banked down to the floor. This was also reflected in the pressure plots (Figure 4.29). Prior to intervention, the oxygen concentration at the 3 ft elevation dropped below 15%, the threshold associated with the ability to sustain combustion. Gas concentrations throughout the interior spaces open to the living room were indicative of ventilation-limited conditions.

Bedrooms

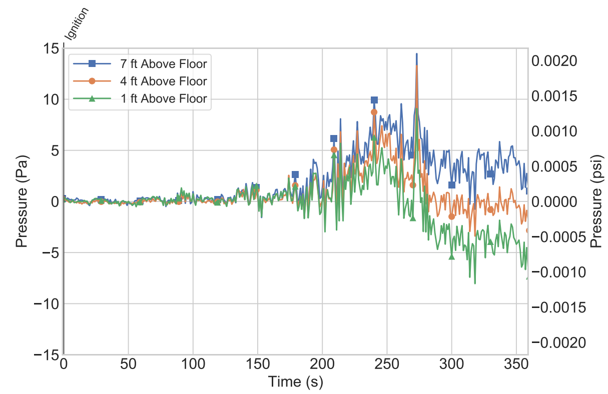
For the two living room experiments, the initial door positions were the same. The doors to bedrooms 2, 3, and 4 were open from the start of the experiment, allowing for an exchange of gases with the rest of the house. The closed bedroom 1 door limited the transfer of gases from the hallway.

Open Bedrooms

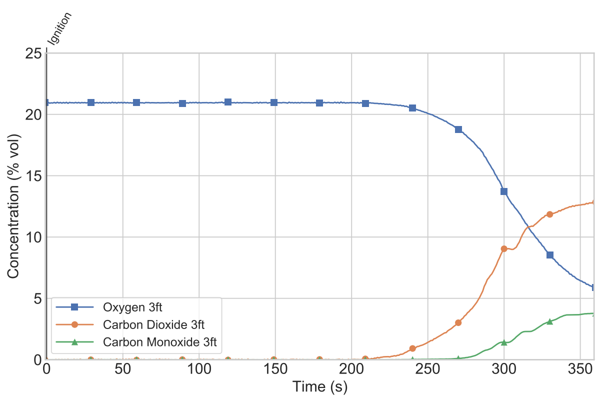
In bedroom 2, the ceiling temperature first began to increase at 110 s after ignition, approximately 15 s after the ceiling temperature at the end hallway location and nominally around the same time as the 6 ft elevation. At this point, the smoke layer in the hallway began to bank down past the top of the bedroom 2 doorway, allowing products of combustion to flow into the bedroom. Temperatures steadily rose in the bedroom as the space filled with combustion gases, and reached a nominal plateau around 320 s until suppression. The pressures measured in bedroom 2 (Figure 4.31b) initially reflected the temperature behavior. All three pressures rose as the bedroom filled with combustion gases. As the living room fire transitioned to flashover, the pressures decreased toward steady values similar to that of the end hallway. The 7 ft elevation remained positive, an indication of the accumulation of combustion gases, while the 1 ft elevation became negative as gas flowed into the hallway, which was at a lower pressure.



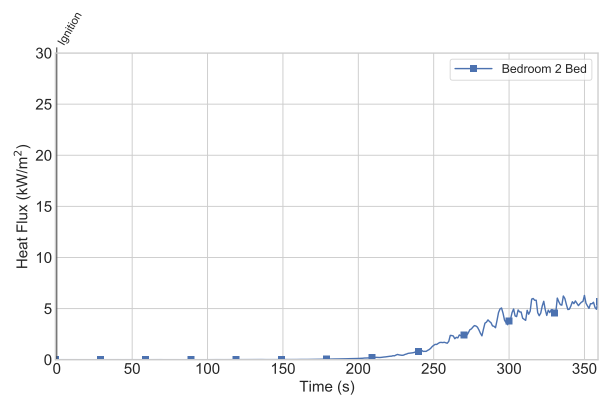
(a) Bedroom 2 Temperature



(b) Bedroom 2 Pressure



(c) Bedroom 2 Gas Concentration

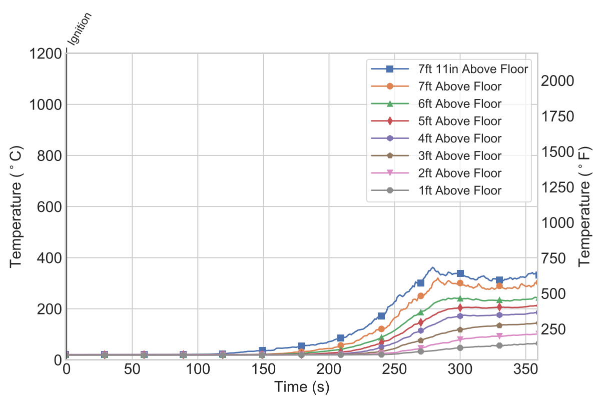


(d) Bedroom 2 Heat Flux

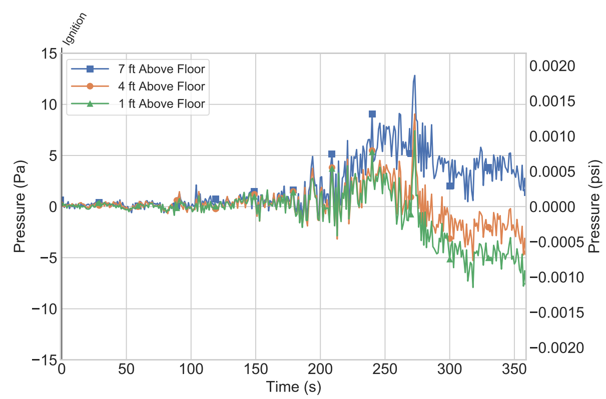
Figure 4.31: Bedroom 2 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

The gas concentrations measured 3 ft above the floor at the center of the bed (Figure 4.31c) similarly reflect the development of a smoke layer in bedroom 2. Gas concentrations first began to change approximately 220 s after pilot ignition as the smoke layer began to descend past the 3 ft level in the bedroom. As gas data indicated, CO and CO_2 concentrations increased as smoke traveled from the hallway to the bedroom while the O_2 concentration decreased as air flowed toward the kitchen fire. Gas concentrations steadily changed as combustion gases continued to accumulate in the space. Heat flux (Figure 4.31d), measured 3 ft above the floor in the center of the bed (next to the gas probe), followed a similar trend to temperatures and gas concentrations, beginning to increase as the smoke layer descended in the space. Heat flux steadily increased due to heat transfer from the higher temperature gases in the space until the time of intervention, reaching a peak of 6 kW/m^2.

The conditions in bedroom 3 resembled those in bedroom 2, as shown by the temperature and pressure data in Figure 4.32. The ceiling temperature in bedroom 3 first began to increase approximately 120 s after pilot ignition as smoke in the hallway banked down past the top of the doorway and began to flow into bedroom 3. Shortly after, the 7 ft pressure (Figure 4.32b) began to increase, reflecting the flow of combustion products from the hallway to bedroom 3. As the smoke layer in bedroom 3 continued to descend, temperatures at all elevations began to gradually increase. Simultaneously, the 4 ft pressure began to increase and the 1 ft pressure began to decrease as the hot products of combustion accumulated in the room and gases close to the floor were drawn into the lower-pressure hallway. The closer proximity of bedroom 3 to the common space resulted in higher temperatures at the time of intervention compared to bedroom 2, with a peak temperature 340 °C (644 °F) at the ceiling compared to 240 °C (464 °F) at the ceiling in bedroom 2.



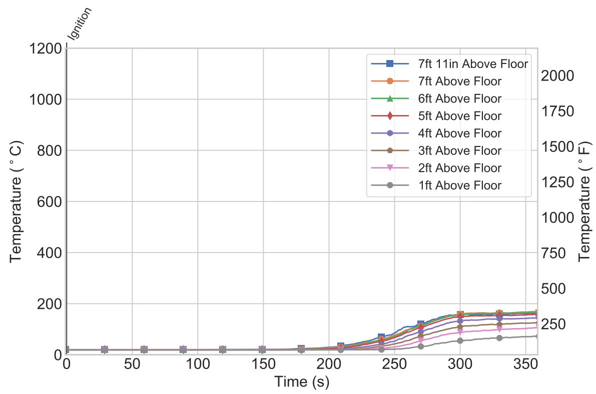
(a) Bedroom 3 Temperature



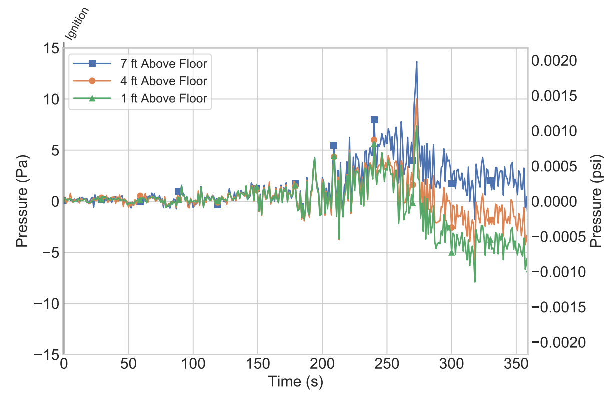
(b) Bedroom 3 Pressure

Figure 4.32: Bedroom 3 temperature and pressure time histories in the hallway due to a fire in the kitchen from ignition (t = 0 s) until firefighter intervention for Experiment 19.

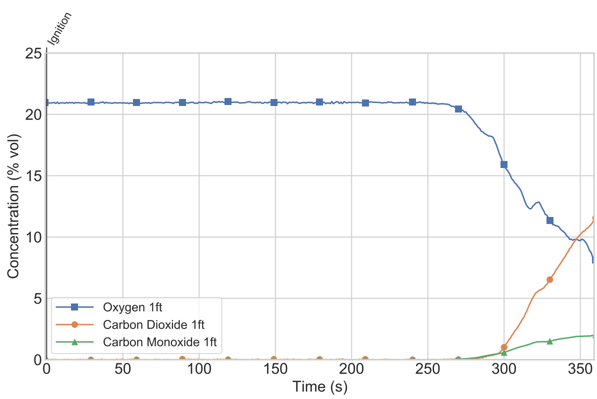
Temperatures in the bathroom adjacent to bedroom 3 began to increase later in the experiment than those in bedroom 3, because the gas layer in bedroom 3 had to first descend to the height of the bathroom 3 door in order for products of combustion to flow into the bathroom. This occurred approximately 150 s after ignition, or 30 s after ceiling temperatures began to rise in bedroom 3. The temperature rise was lower in magnitude in the bathroom and the adjoining bedroom due to heat loses to the room and through mixing with gases originally in the space. Pressure behaved similar to the bedroom as the 4 ft and 1 ft elevation pressures dropped below 0 Pa, an indication that gases flowed out of the bathroom.



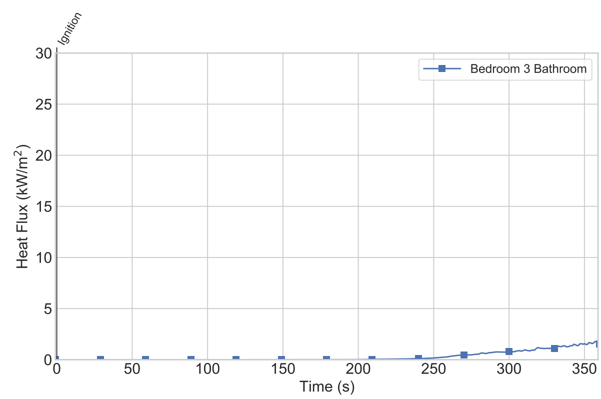
(a) Bathroom 3 Temperature



(b) Bathroom 3 Pressure



(c) Bathroom 3 Gas Concentration



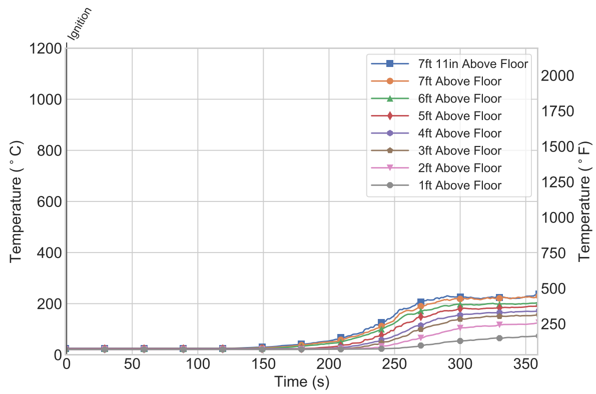
(d) Bathroom 3 Heat Flux

Figure 4.33: Bathroom 3 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

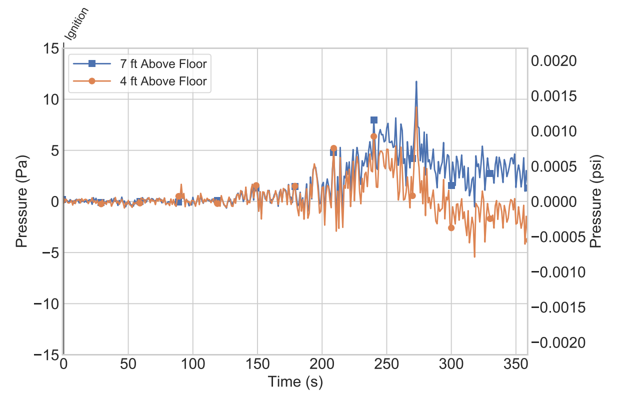
CO and CO_2 concentrations increased as a result of the bathroom filling with smoke, and O_2 decreased as fresh air was drawn through the bedroom toward the kitchen fire 80 s after temperatures first began to rise because the smoke layer needed to descend to the 1 ft elevation. Gas concentrations were increasing at the time of intervention as the bathroom continued to fill with combustion products. Similar to bedroom 2, the oxygen concentration was below the threshold of 15% needed to support combustion. Heat flux (Figure 4.33d), measured 1 ft above the floor in the center of the bathroom, followed a similar trend to temperatures, beginning to increase as higher temperature gas temperatures flowed into the bathroom. Heat flux steadily increased until the time of intervention, reaching a peak of 2 kW/m^2.

Bedroom 4 temperatures (measured in the center of the room, doorway, and closet), pressures, and door velocities are shown in Figure 4.34. The temperature and pressure trended similarly to the values measured in bedrooms 2 and 3. Both quantities began to increase at 130 s due to the accumulation of gases in room. Temperature and velocity measurements indicate gas first began to enter the bedroom 4 doorway 15 s earlier. The higher temperature at the door compared to the room occurred because the gases in the bedroom lost heat to the walls and ceiling, as well as through mixing with initial ambient gases. The above ambient 7 ft pressure measurements also aligned with the negative velocity measurement at the door because a negative velocity was an indication of flow into the bedroom.

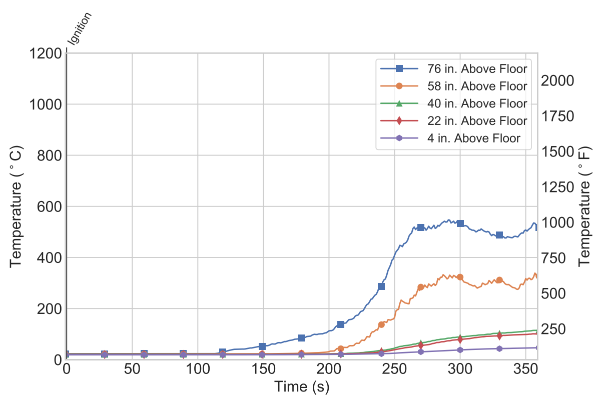
The bedroom 4 closet temperature (Figure 4.34e) did not exhibit any appreciable temperature rise in the period prior to intervention. Gas flow into the closet was limited by the closed door and the lack of an HVAC supply vent.



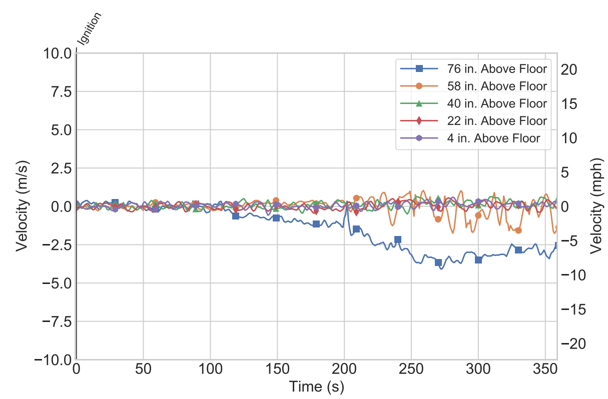
(a) Bedroom 4 Temperature



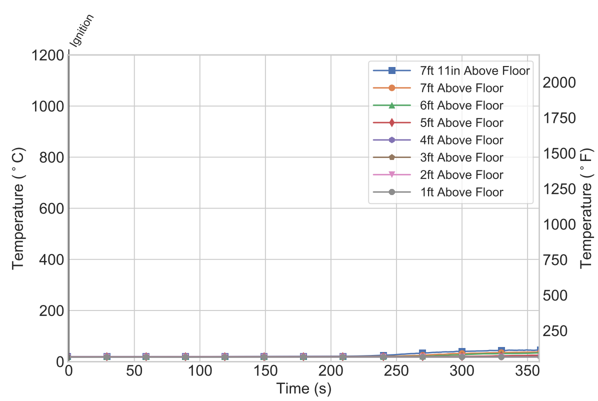
(b) Bedroom 4 Pressure



(c) Bedroom 4 Doorway Temperature



(d) Bedroom 4 Doorway Velocity

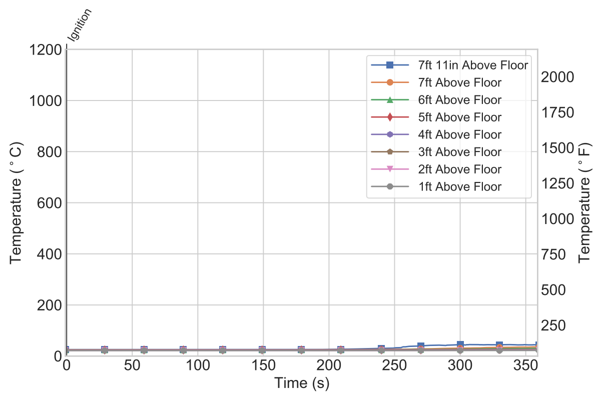


(e) Bedroom 4 Closet

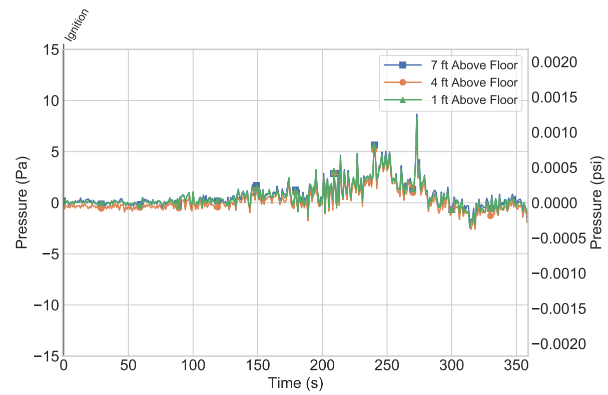
Figure 4.34: Bedroom 4 temperatures, pressure, and velocity time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

Closed Bedroom

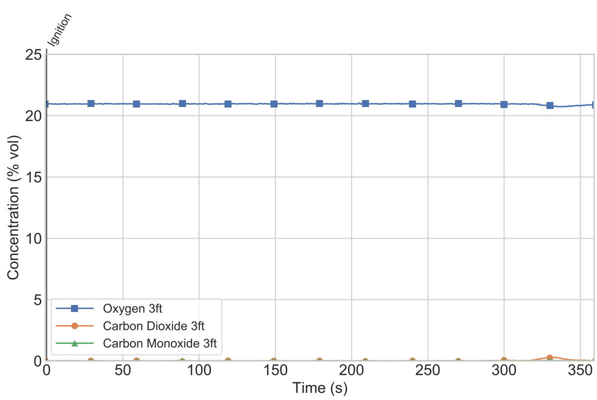
The door to bedroom 1 remained closed from the beginning of the experiment through fire department intervention. As a result, temperatures and gas concentrations remained lower than the corresponding bedrooms where the doors were left open. Figure 4.35 shows the temperature, pressure, gas concentration, and heat flux measured in bedroom 1. The pressures rose uniformly as there was low pressure exhaust vent, as shown in Figure 4.35b, and the lower peaks compared to other spaces reflects the lack of flow into the room because of the closed door. Temperatures in the bedroom only began to increase approximately 200 s after ignition as products of combustion leaked around the closed door and through the HVAC ducts. The ceiling temperature peaked at 45 °C (113 °F) and remained at ambient levels at 5 ft and below.



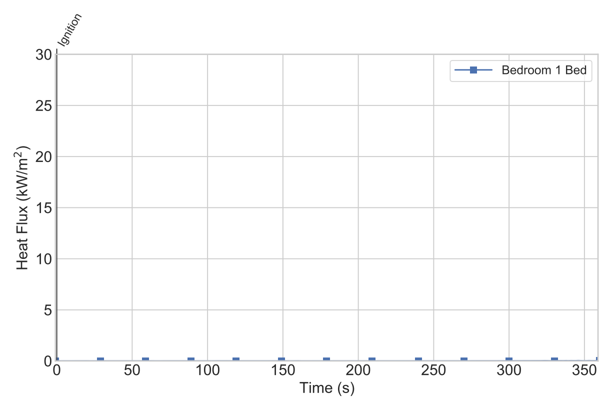
(a) Bedroom 1 Temperature



(b) Bedroom 1 Pressure



(c) Bedroom 1 Gas Concentration

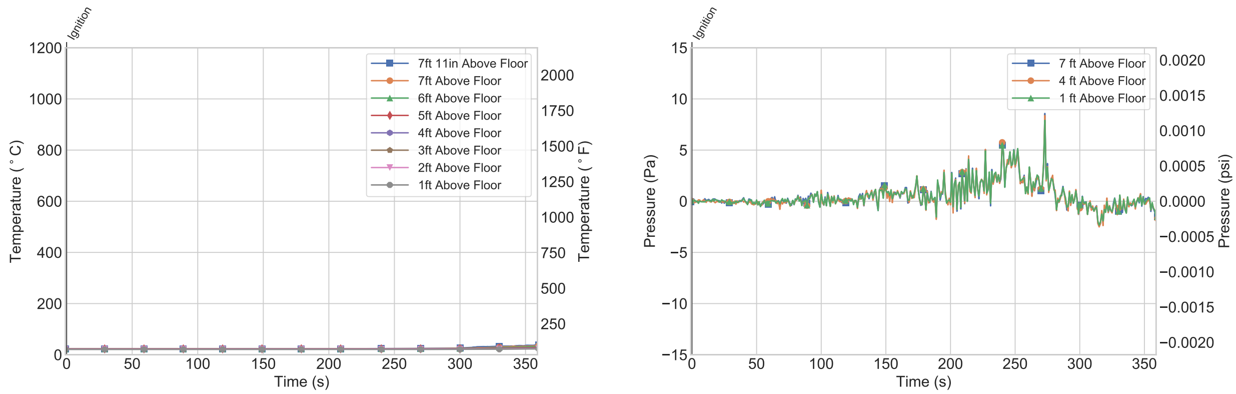


(d) Bedroom 1 Heat Flux

Figure 4.35: Bedroom 1 temperatures, pressure, gas concentrations, and heat flux time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

Gas concentrations were measured 3 ft above the floor in the center of the bed in bedroom 1. Although smoke leaked into bedroom 1, the accumulation of combustion gases did not descend to the 3 ft level to have a measurable change, as shown in Figure 4.35c. As a result of the comparatively low temperatures and minimal relative changes in gas concentrations within bedroom 1, the heat flux on the bed (Figure 4.35d) was negligible prior to intervention.

Bathroom 1 was immediately adjacent to bedroom 1 and was isolated from the bedroom by a closed door. The two closed doors between bathroom 1 and the hallway provided sufficient isolation, so the primary pathway for transport was through the HVAC supply in the ceiling. There was no noticeable temperature increase (Figure 4.36a). The bathroom 1 pressure gradually increased at all three elevations (Figure 4.36b). The uniform pressure behavior was driven by the absence of a local vent either in the form of an open door or window or HVAC return.



(a) Bathroom 1 Temperature

(b) Bathroom 1 Pressure

Figure 4.36: Bathroom 1 temperatures and pressure time histories in the hallway due to a fire in the living room from ignition (t = 0 s) until firefighter intervention for Experiment 19.

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 11

The search tactics in Experiment 11 were designed to evaluate a comparison of window initiated operations conducted prior to interior suppression of a common space (living room and kitchen) fire. At the time of ignition, both the kitchen window and front door were opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2 and 3 were opened. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets which led to flashover of the kitchen. The fire then spread to the living room, where flashover occurred following the failure of the side A and side D windows. Post-flashover of the common space, crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. The crew in bedroom 3 entered the bedroom and proceeded toward the door to the hallway and closed the door. This action isolated bedroom 3 from the fire gases produced by the common space fire. At the same time, the crew in bedroom 2 entered the bedroom and proceeded toward the hallway. This crew was unable to isolate bedroom 2 and continued across the hallway searching beyond the room of entry. After isolation of bedroom 3, the crew in in that room removed the remainder of the double-wide window in the compartment. Simultaneously, the crew that entered bedroom 2 crossed the hall to bedroom 1. The closed bedroom 1 door was opened to allow for crew entry. The crew closed the door behind them. Once isolated in bedroom 1, the crew proceeded to remove the bedroom 1 window. At this point the search tactic comparison was complete and suppression began with interior suppression by entry to the structure through the front door. 228 gallons of water were flowed during suppression. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side A living room windows. The total amount of water flowed during suppression and hydraulic ventilation was 445 gallons. Table 5.1 provides the timing of each event relative to ignition of the pilot burner as well as relative to the first intervention, which in this experiment was the venting of half of the double-wide bedroom 2 and bedroom 3 windows.

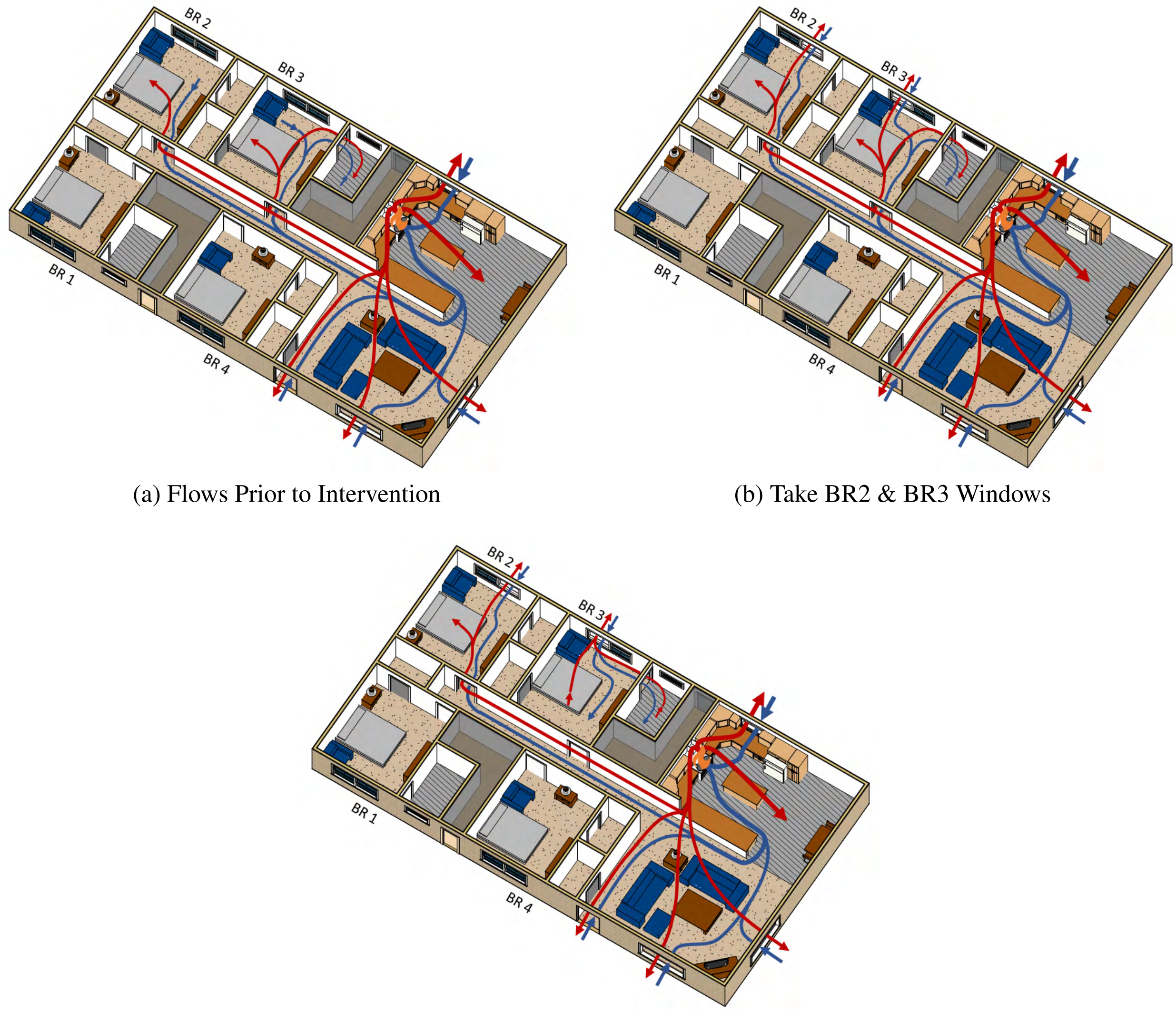
At the time of fire department intervention, the common space was in a steady post-flashover state.

Table 5.1: Experiment 11 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	05:50	350	—	—
Take BR2 & BR3 Windows	22:00	1320	00:00	0
Close BR3 Door	22:47	1367	00:47	47
Open BR1 Door, Remove BR3 Window	23:00	1380	01:00	60
Close BR1 Door	23:14	1394	01:14	74
Remove BR1 Window	23:26	1406	01:26	86
Suppression	23:55	1435	01:55	115
Hydraulic Ventilation	28:17	1694	06:17	377

Figure 5.1a shows that bidirectional flows were established at the front door, side A/side D living room windows and at the kitchen window. Fresh air was entrained through the lower portion of these vents and flames and smoke were exhausted through the upper portion. The primary flow path within the volume of structure was established between these vents. Initial fire department intervention was breaking half of the bedroom 2 and 3 windows, which created new exterior vents at these locations and established additional flow paths. Since the bedroom 2 and 3 doors were open at the time of intervention, this action created a bidirectional flow through both bedrooms, as shown in Figure 5.1b, allowing fresh air to flow into the bedrooms through the lower portion of the window, while hot gases exhausted through the upper portion. This flow continued in both bedrooms until the bedroom 3 door was closed. As Figure 5.1c shows, the closed bedroom 3 door isolated the room from the products of combustion in the hallway. A new flow path was established with the open bedroom 3 window serving as the intake and exhaust. This allowed for the exchange of smoke that was already trapped in the room with fresh air from the exterior of the structure. In contrast, the bedroom 2 door was not closed, simulating a firefighter that was unable to find the door or a room that did not have a door. The lack of isolation to bedroom 2 resulted in a sustained bidirectional flow through bedroom 2 for the duration of Experiment 11.

After the bedroom 3 door was isolated, the bedroom 1 door was opened, simulating a firefighter moving across the hallway from bedroom 2 to bedroom 1. This briefly established a bidirectional flow into bedroom 1 (Figure 5.2a), as products of combustion flowed into bedroom 1, which had been previously isolated behind the closed door. Simultaneous with the opening of bedroom 1, the second half of the window was removed in bedroom 3, providing a larger surface area for ventilation. The bedroom 1 door was closed after 14 s, re-isolating that room from the products of combustion in the hallway (Figure 5.2b). The bedroom 1 window was removed 12 s after the door was closed (Figure 5.2c). These actions created a similar scenario to the one in bedroom 3. At the time of suppression, bedrooms 1 and 3 were isolated from the hallway via a closed door. Trapped smoke exhausted through the respective open windows. Bedroom 2 was not isolated from the hallway, and had a sustained bidirectional flow through the open window. Bedroom 4 was isolated behind a closed door and the bedroom window remained closed for the duration of the



(a) Flows Prior to Intervention

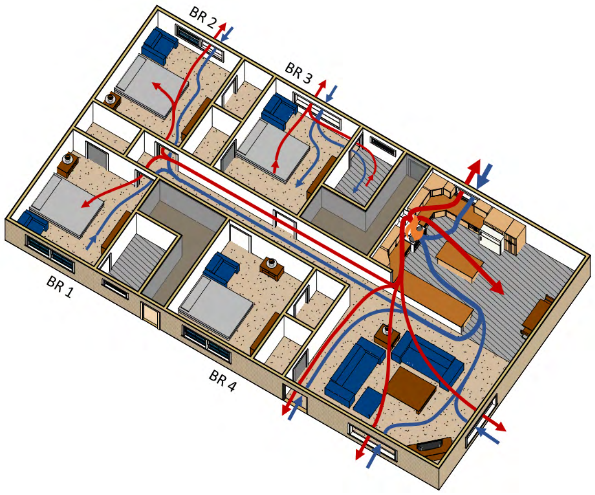
(b) Take BR2 & BR3 Windows

(c) Close BR3 Door

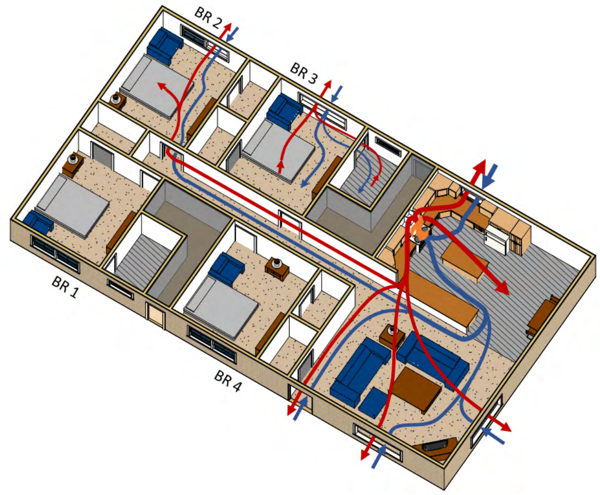
Figure 5.1: Changes in gas flows within the structure following fire department interventions in Experiment 11.

experiment.

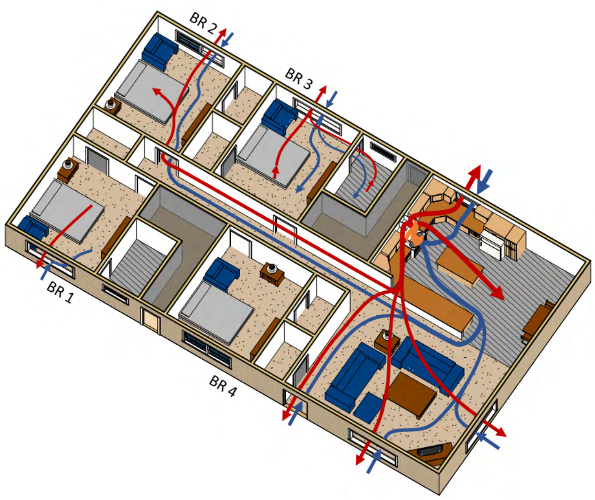
Suppression was initiated on side A of the structure by firefighters who used a 7/8 in. smooth bore nozzle nominally flowing 165 gpm from a 1 3/4 in. hoseline. Firefighters utilized a flow-and-move technique that started on the deck due to flames venting through the front door and side A living room window and continued to the interior as the flames were knocked down. Following the suppression and the completion of search sequence, the suppression crew initiated hydraulic ventilation through the side A living room window with the tip on and fully opened nozzle rotated in an O-pattern (Figure 5.2d). This action reduced the pressure at the living room window and drew products of combustion from remote locations along the flow path in the structure toward the living room.



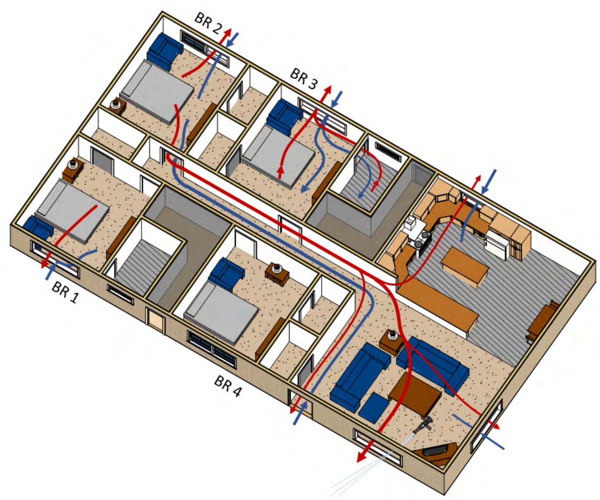
(a) Open BR1 Door, Remove BR3 Window



(b) Close BR1 Door



(c) Remove BR1 Window

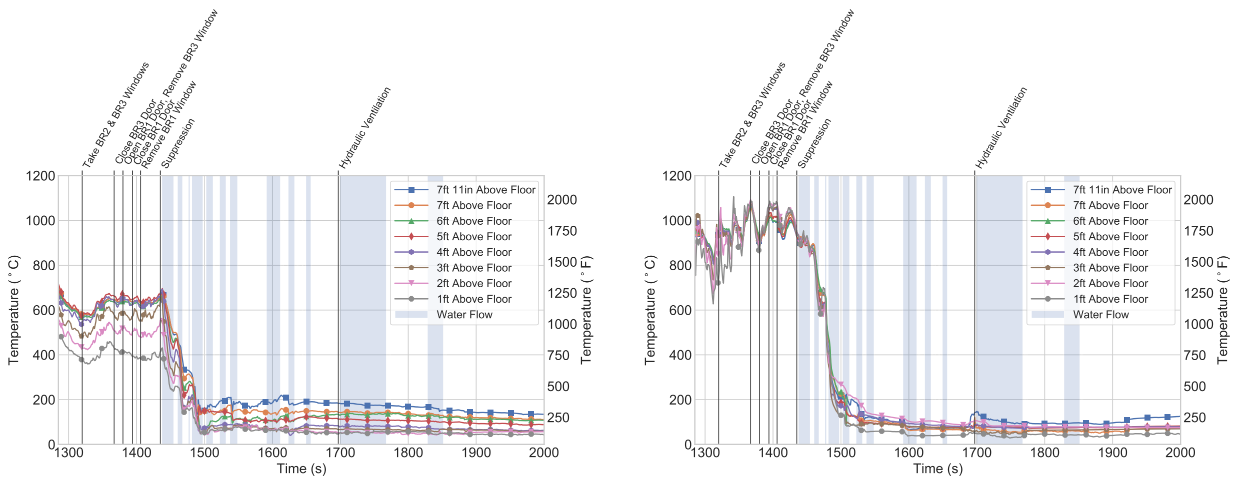


(d) Hydraulic Ventilation

Figure 5.2: Changes in gas flows within the structure following fire department interventions in Experiment 11.

5.1.1 Common Space

Temperatures in the living room began to decrease from floor-to-ceiling 1000 °C (1832 °F) 20 s after the initial suppression action, and continued to decrease as the suppression crew advanced into the space (Figure 5.3a). Kitchen temperatures, which ranged from 580 °C (1076 °F) at the ceiling to 380 °C (716 °F) 1 ft above the floor, were lower than the living room at the time of intervention despite visible flames out of the kitchen window due to a lack of oxygen needed to support combustion in the kitchen (Figure 5.3b). These temperatures, however, began to decrease within 5 s of the initial suppression action. The high incident heat flux to the nozzle firefighter as suppression was initiated on the deck led to an initial shallow angled stream, which initially resulted in more efficient water application to the kitchen compared to the living room. Prior to hydraulic ventilation, firefighters flowed a total of 228 gallons.



(a) Kitchen Temperature

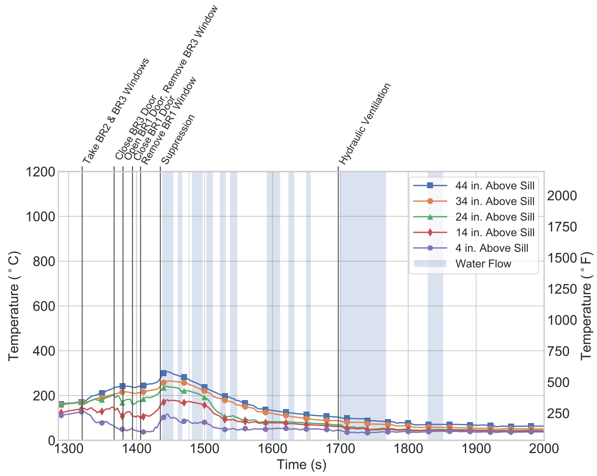
(b) Living Room Temperature

Figure 5.3: Temperature time histories in the common space for the period following fire department intervention in Experiment 11.

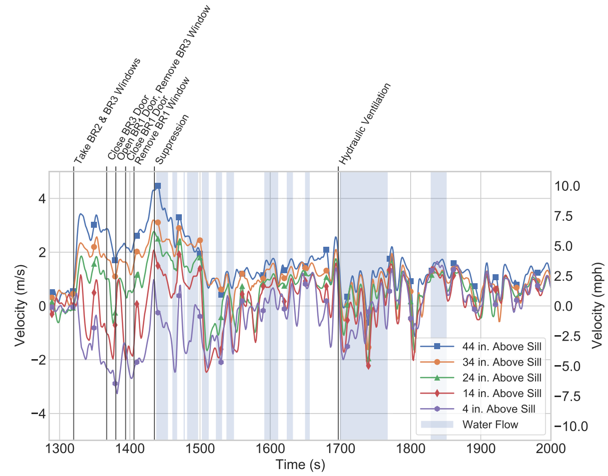
5.1.2 Bedroom 2

The initial fire department intervention was the breaking of half of the bedroom 2 and bedroom 3 windows. Figure 5.4 shows the window temperature, gas velocity, heat flux and gas concentration measured in bedroom 2. Following ventilation, temperatures increased in the upper portion of the window and decreased in the lower portion as bidirectional flow was established (Figure 5.4b). Due to bedroom 2 door remaining open, these flows ranged between 1 m/s to 4 m/s exhaust (2.2 mph to 9 mph) at 24 in. and above the window sill and 0 m/s to -2 m/s (0 mph to -4.5 mph) intake below 24 in. above the sill until 1400 s. An increase in heat release of the fire combined with the exterior vent in bedroom 2 resulted in increased flow of combustion gases within this flow path. As a result, flows through the bedroom 2 window transitioned to unidirectional exhaust until suppression removed the source of the higher pressure combustion gases. When hydraulic ventilation was conducted in the living room, the flowing hose stream created an area of lower pressure in the living room, which entrained air within the flow path resulting in negative velocities at the window.

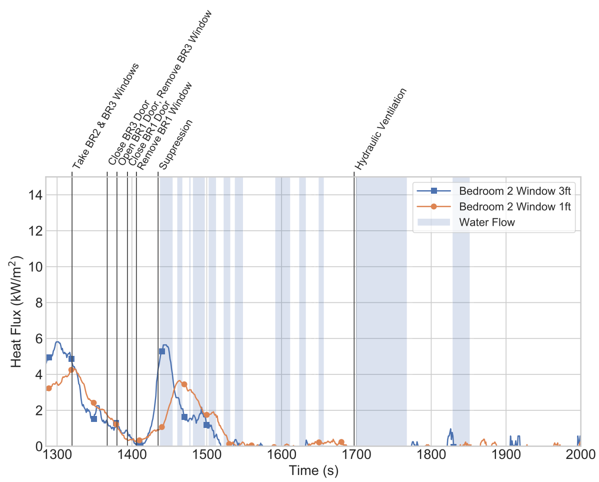
Figure 5.4c shows that 3 ft and 1 ft window heat fluxes initially began to decrease with the ventilation of the bedroom 2 window. The air entrainment through the bottom of the open window had a cooling effect on both the 3 ft and 1 ft gauges, resulting in a decrease in heat flux. The heat flux dropped from values of 6.0 kW/m^2 and 5.2 kW/m^2 at the 3 ft and 1 ft elevations, respectively, to 1.2 kW/m^2. Similar to the temperatures in the window, at 1400 s post-ignition the hot gas flow from the hallway through the low pressure window vent resulted in an increase in convective heat transfer particularly at the higher elevation gauge, which rose to 6.8 kW/m^2 prior to suppression. Following suppression, the window heat flux at both elevations decreased until the end of the experiment.



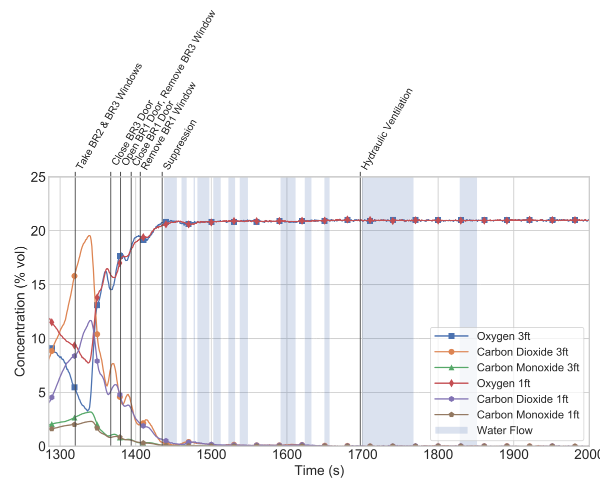
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



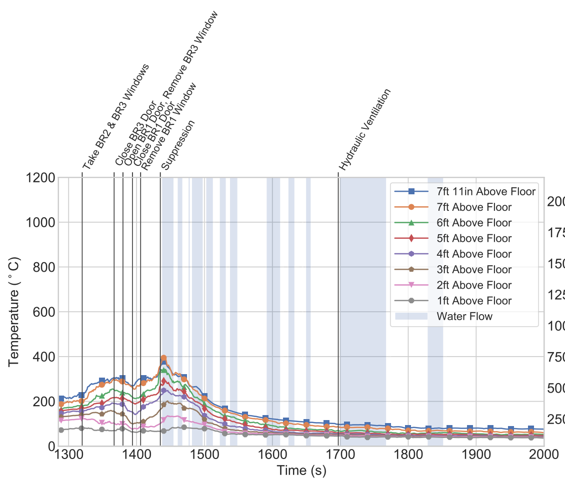
(d) Bedroom 2 Window Gas Concentration

Figure 5.4: Post-intervention window temperature, velocity, heat flux and gas concentrations in bedroom 2 during Experiment 11.

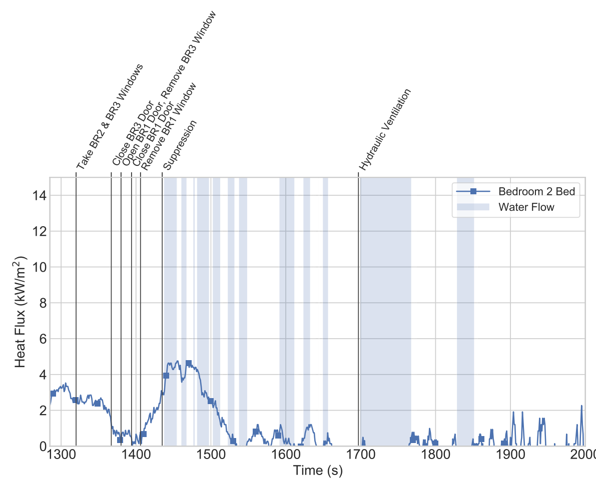
At the time of window ventilation, the smoke layer had banked down to the floor in the bedroom, resulting in elevated concentrations of CO and CO_2 and low concentrations of O_2. The gas concentrations measured 3 ft and 1 ft above the floor in the window (Figure 5.4d) show that approximately 50 s after the window was ventilated, CO and CO_2 concentrations decreased and O_2 concentrations increased as the entrained air replaced products of combustion that had previously filled the bedroom. This decrease in toxic gas concentrations and increase in oxygen continued through the remainder of the ventilation sequence and through suppression.

Figure 5.5a shows that temperatures within the room at the time of intervention ranged from 230 °C (446 °F) at the ceiling to 80 °C (176 °F) 1 ft above the floor. Temperatures increased over the next

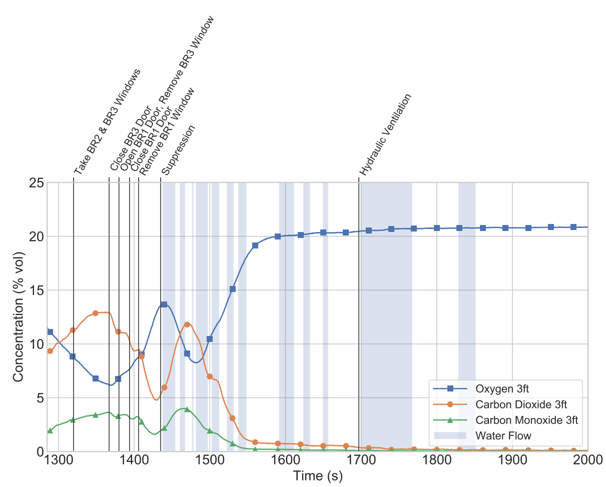
120 s as ventilation actions were performed, before reaching a peak simultaneous with the start of suppression, when the bedroom 2 temperatures ranged from 295 °C (563 °F) at the ceiling to 70 °C (158 °F) 1 ft above the floor. As the suppression crew flowed water into the living room and kitchen, the production of high-temperature combustion gases stopped, and temperatures in the space decreased for the remainder of the experiment. A similar trend was observed at the bed heat flux location, shown in Figure 5.5b. At the time of intervention, the heat flux in the center of the bed was increasing, peaking at 4.6 kW/m^2. Air entrainment resulting from the window ventilation temporarily caused heat flux to decrease, but the heat flux began to increase again 81 s after the window was opened, as the location on the bed had increased convective heat transfer due to the hot gases that flowed through bedroom 2. As suppression occurred, the heat flux in the center of the bed decreased for the remainder of the experiment.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

Figure 5.5: Bedroom 2 temperature and heat flux time histories after fire department intervention for Experiment 11.

The gas sample location on the bed (Figure 5.5c) exhibited a similar initial increase in CO and CO_2 and decrease in O_2 to the window locations. Unlike the window locations, however, CO and CO_2 reached a local minimum and began to increase again at the same time as suppression, while the O_2 concentrations exhibited opposite behavior. This response approximately matches the timing of the heat flux increase observed at the same location, which suggests that the rebound in gas concentrations was a result of the flow of products of combustion into bedroom 2 as a result of the lack of isolation. As suppression began to take effect, reducing the production rate of smoke, CO and CO_2 began to decrease again and O_2 concentrations began to trend toward ambient starting approximately 160 s after the bedroom 2 window ventilation.

5.1.3 Bedroom 3

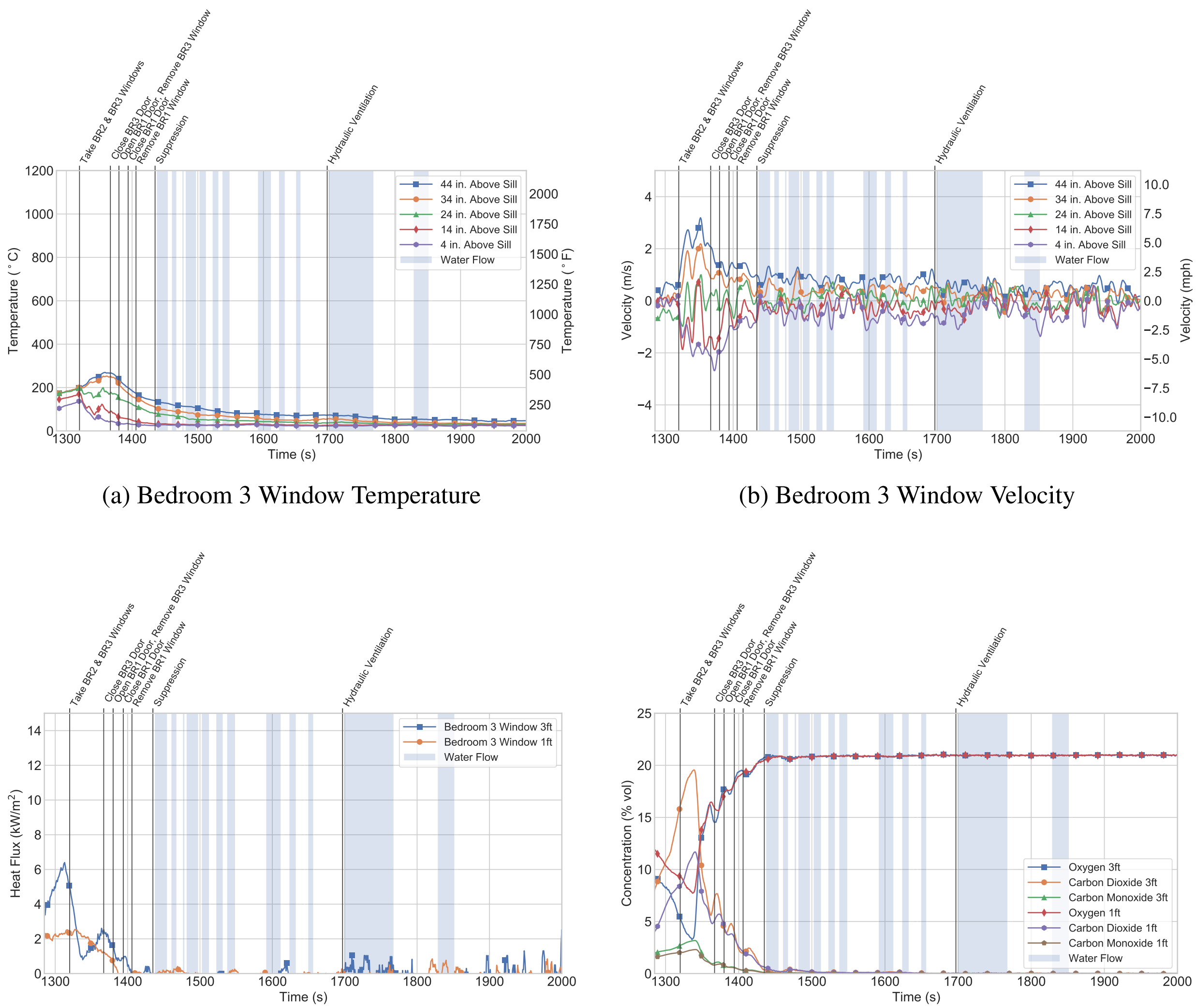
Prior to the initial intervention of venting the bedroom 2 and bedroom 3 windows, the conditions in bedroom 3 were similar to bedroom 2. The window temperature, velocity, heat flux, and gas concentrations prior to intervention and throughout the remainder of the experiment are shown in Figure 5.6.

After window ventilation, a bidirectional flow was established through bedroom 3. Temperatures increased at 44 in. and 34 in. above the sill elevations and decreased at 14 in. and 4 in. above the sill elevations (Figure 5.6a). This aligns with the flow velocities at the window; the upper two locations measured exhaust flow of combustion gases of approximately 2 m/s (4.5 mph) and the lower two elevations measured air intake of -2 m/s (-4.5 mph) (Figure 5.6b). The bedroom door was closed 47 s after the window was vented. The magnitude of the window velocities decreased, ranging between $\pm$ 1 m/s (2 mph). The closed bedroom door isolated bedroom 3 from the pressure driven flow of hot gases from the hallway, while the open window allowed hot gases in the room to exhaust to the exterior.

Similar to the behavior observed in bedroom 2, the air entrainment following ventilation of the bedroom 3 window resulted in a decrease in the window heat flux measurements at both the 3 ft and 1 ft elevations, as shown in Figure 5.6c. At the time of intervention, the heat flux was 7.0 kW/m^2 and 2.9 kW/m^2 at the 3 ft and 1 ft window measurement locations, respectively. While the 3 ft window heat flux exhibited a slight increase after the initial drop as a result of the hot gases exhausting through the window, the 1 ft window heat flux decreased continuously after window ventilation. After the bedroom 3 door was closed, the heat flux continued to drop at both elevations, decreasing to negligible values prior to the onset of suppression.

At the time of fire department intervention in bedroom 3, gas concentrations were 5.3% O_2, 16.7% CO_2, and 2.7% CO 3 ft above the floor in the window and 9.3% O_2, 8.4% CO_2, and 2.0% CO 1 ft above the floor (Figure 5.6d). At the time that the window was ventilated, O_2 concentration was decreasing and the CO and CO_2 concentrations were increasing at both elevations. After the window was ventilated, CO and CO_2 concentrations continued to increase and O_2 concentrations continued to decrease until 20 s after window ventilation. At this point the intake through the window led an improvement in toxic gas concentrations as CO and CO_2 began to decrease and

O_2 began to increase. This trend continued as the bedroom 3 door was closed, allowing smoke in the bedroom to vent through the open window. By the time that suppression was initiated 68 s after isolation of bedroom 3, gas concentrations below the window had recovered to approximately pre-test conditions.



(a) Bedroom 3 Window Temperature

(b) Bedroom 3 Window Velocity

(c) Bedroom 3 Window Heat Flux

(d) Bedroom 3 Window Gas Concentration

Figure 5.6: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 2 during Experiment 11.

Following window ventilation, the closed bedroom door isolated bedroom 3 from the flow of hot gases from the hallway and the open window allowed hot gases in the room to exhaust to the exterior. In contrast to the open bedroom 2 where temperatures increased prior to suppression, the compartment isolation during bedroom 3 resulted in a decrease in temperatures in the window and at the center of the room, as shown in Figures 5.6a and 5.7, respectively. Temperatures at all elevations in bedroom 3 had decreased below 140 °C (284 °F) prior to the start of suppression, and continued to decrease for the remainder of the experiment.

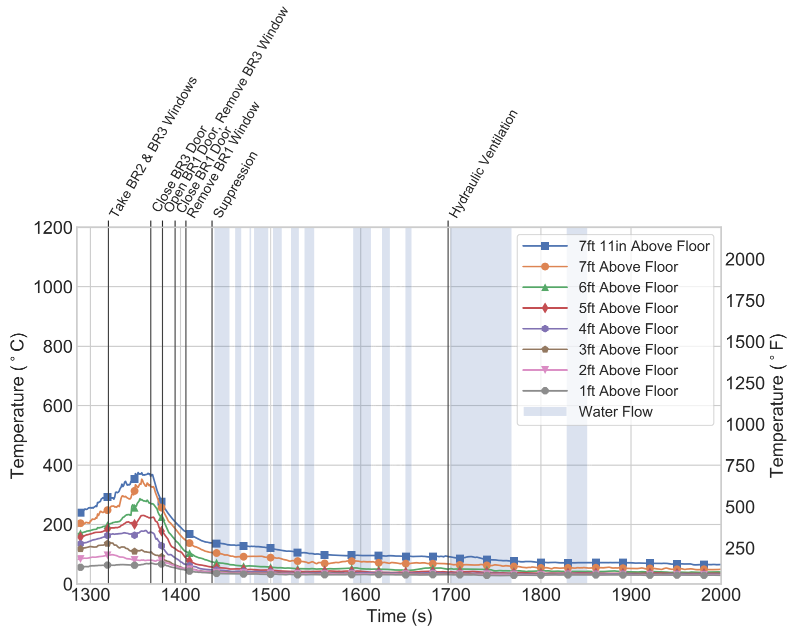
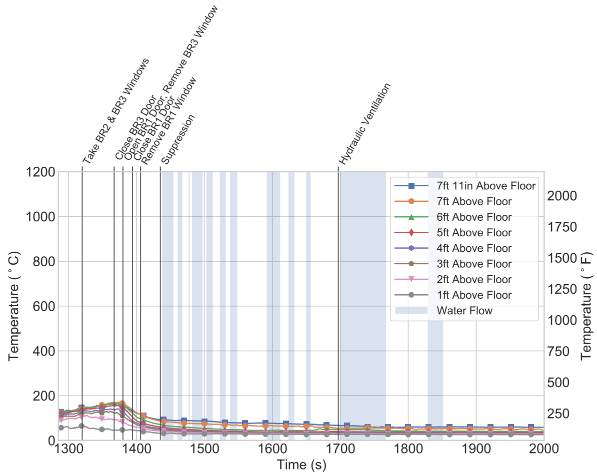


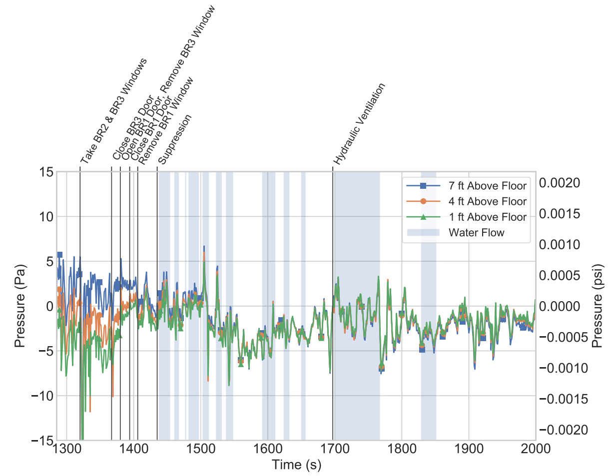
Figure 5.7: Post-intervention bedroom 3 temperature during Experiment 11.

Figure 5.8a shows that temperatures in bathroom 3 were generally lower than in the adjoining bedroom, ranging from 145 °C (293 °F) at the ceiling to 65 °C (149 °F) 1 ft above the floor at the time of intervention. After the bedroom 3 window was broken the bathroom 3 temperatures closest to the ceiling continued to increase as a result of the hot gases flowing through the adjacent bedroom, while the 1 ft and 2 ft temperatures exhibited a gradual decrease as a result of air entrainment through the window. After the bedroom 3 door was closed, the bathroom temperatures all began to decrease as smoke was exhausted from the space through the open bedroom 3 window. The entrained air similarly reduced the heat flux measured in the bathroom (Figure 5.8d). At the time of intervention, the heat flux measured 1 ft above the floor in the bathroom was 1.7 kW/m^2, less than the corresponding elevation at the bedroom 3 window. The lack of combustion gases flowing into this space and decreasing temperatures led to a continued drop in heat flux, reaching a negligible value prior to suppression.

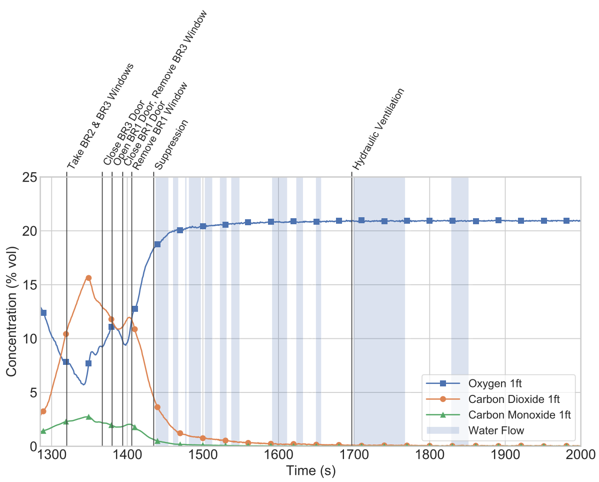
At the time the bedroom 3 window was ventilated, O_2, CO_2, and CO concentrations in bathroom 3 were 7.8%, 10.4%, and 2.3%, respectively. After the window was broken, CO and CO_2 concentrations continued to increase and O_2 continued to decrease until 27 s after the window was broken. This trend was similar to that observed in bedroom 3. Initially following the peak, the CO and CO_2 decrease and O_2 increase was gradual until 85 s after the window was broken, when concentrations began to trend sharply toward ambient concentrations. This more gradual return to pre-test conditions compared to the bedroom 3 gas sample locations was likely a result of this room not being directly in the flow path established with intake and exhaust at the bedroom 3 window.



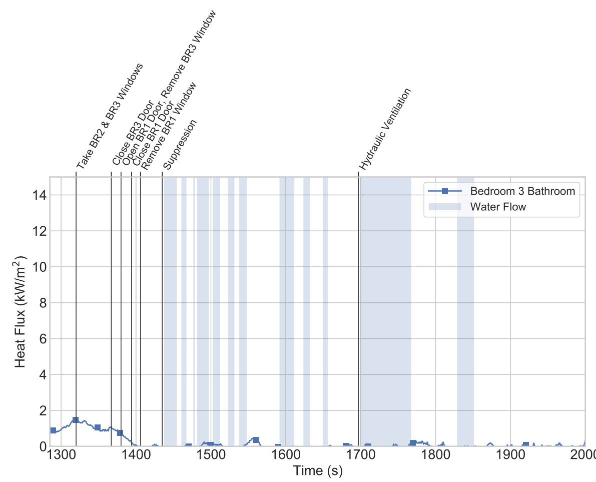
(a) Bathroom 3 Temperature



(b) Bathroom 3 Pressure



(c) Bathroom 3 Gas Concentration



(d) Bathroom 3 Heat Flux

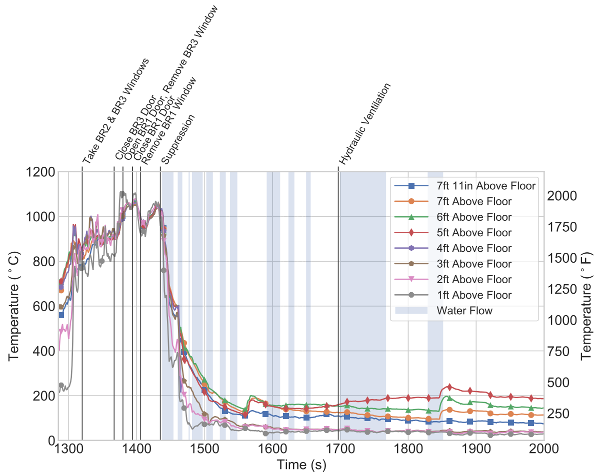
Figure 5.8: Post-intervention bathroom 3 temperatures, pressure, gas concentrations, and heat flux time histories during Experiment 11.

5.1.4 Hallway

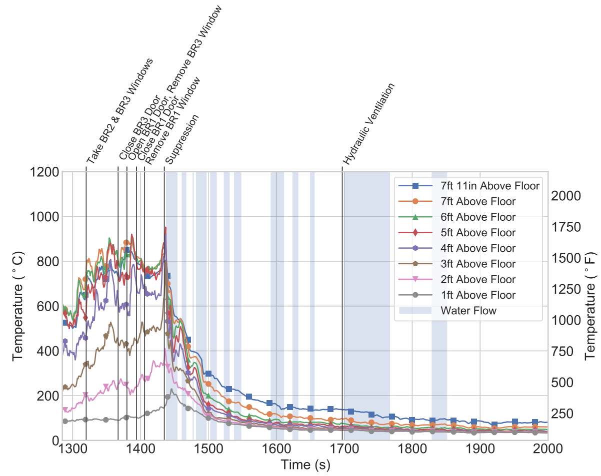
At the time of intervention, temperatures in the egress pathway from the bedrooms to the front door were highest in the living room entryway. Temperatures decreased with distance from the common space; the end hallway temperatures registered the lowest values at the time of intervention. The living room entryway temperatures (Figure 5.9a) followed a similar trend to the living room and kitchen due to proximity to the source fire, remaining in a post-flashover state (i.e., all elevations greater than 600 °C (1112 °F) from the time of fire department intervention until the onset of suppression. At the start hallway location (Figure 5.9b), temperatures above 4 ft exceeded 600 °C (1112 °F) while temperatures 3 ft and below remained under 500 °C (932 °F) during the period between initial fire department intervention and suppression. The gap in temperature was an indication of hot gas layer height height. Immediately prior to suppression, temperatures 6 ft and above increased sharply above 600 °C, an indication of rollover down the hallway.

At the mid hallway measurement location (Figure 5.9c), temperatures were similar to the start hallway location, except lower in magnitude. Temperatures at the time of window ventilation ranged from 458 °C to 100 °C (856 °F to 212 °F), and increased over the next 115 s to 642 °C at the ceiling and 168 °C 1 ft above the floor at the time of suppression due to the increase in flow of combustion gases to the low pressure window vents opened in the bedrooms. Temperatures remained stratified as the lower elevation thermocouples were cooled by gases flowing toward the fire because of entrainment.

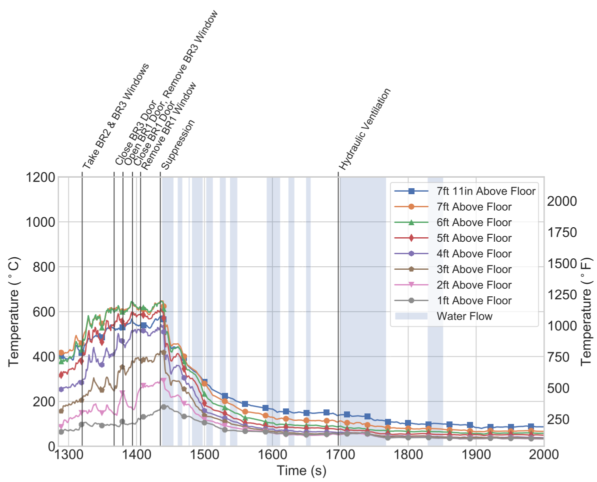
At the end hallway location (Figure 5.9d), temperatures 3 ft and above increased in a similar manner to those at the mid hallway location. At the 2 and 1 ft elevations, the temperature increased until 35 s after the window ventilation, before briefly decreasing as a result of the entrained air through fire through the vented bedroom 2 window and then following the opening of the bedroom 1 door. The temperatures at these elevations again began to increase after the bedroom 1 door was closed. Temperatures at the living room entryway and all three hallway locations began to decrease simultaneous with the start of suppression, and continued to decrease as the suppression crew advanced into the common space.



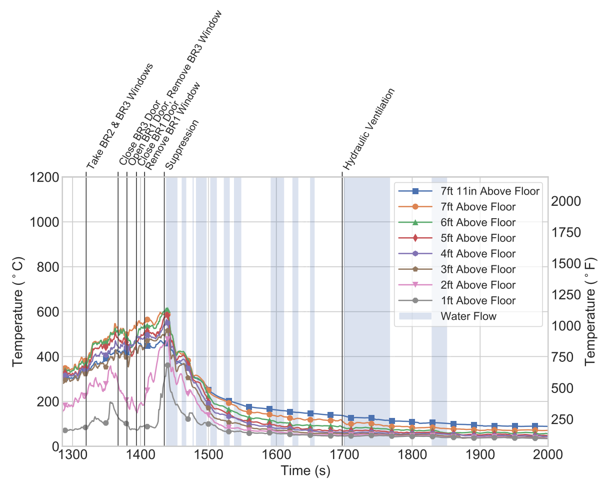
(a) Living Room Entry Hallway Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.9: Temperature time histories in the hallway in the period following fire department intervention in Experiment 11.

The heat fluxes measured in the living room entryway and hallway, shown in Figure 5.10, generally followed a similar trend to the corresponding thermocouple arrays. In the period between the initial fire department intervention and suppression, the heat flux to the floor in the living room entryway ranged between 45–65 kW/m^2 during the period between intervention and suppression, consistent with post-flashover conditions. The heat fluxes measured at the start hallway and mid hallway locations were considerably lower, maintaining a steady value of approximately 5 kW/m^2 in the period between intervention and suppression. A brief peak was observed immediately prior to suppression, with peaks at the start and mid hallway locations of 20 kW/m^2 and 12 kW/m^2, respectively, which coincided with flame spread along the hallway carpet. Following suppression, these values dropped below 1 kW/m^2

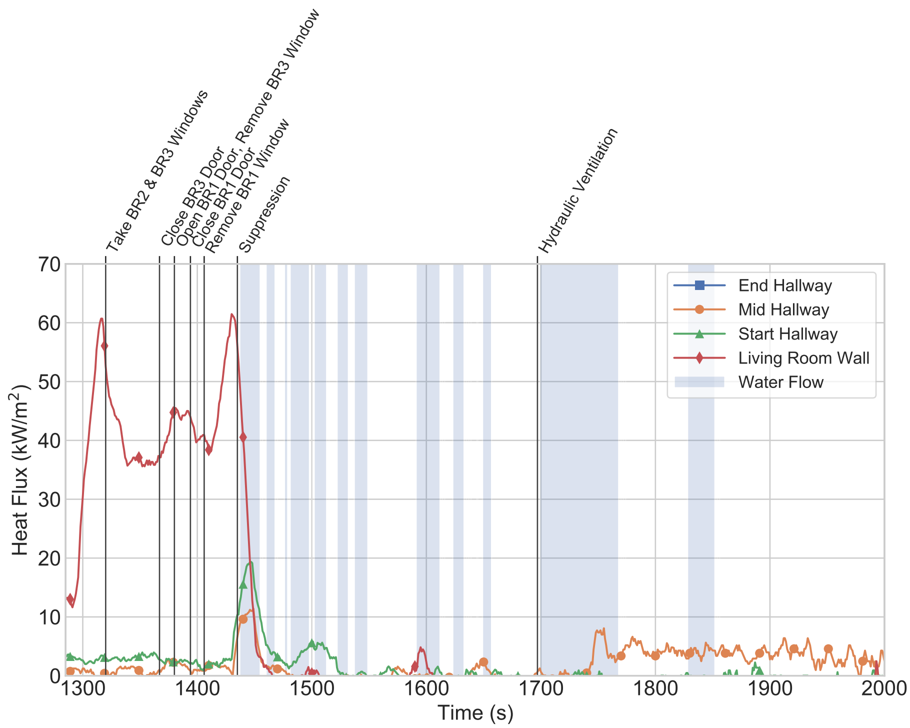


Figure 5.10: Heat flux time histories in the hallway in post-intervention period during Experiment 11.

Figure 5.11 shows the gas concentrations at the living room entryway and the three hallway locations in Experiment 11. Gas concentrations at the living room entryway at the time of intervention reflected the post-flashover conditions observed at that location (Figure 5.11a). At the 3 ft elevation, O_2 concentrations remained below 5%, CO_2 concentrations remained above 15%, and CO concentrations reached the upper measurement threshold of the analyzer, 5%. Gas concentrations 3 ft above the floor at the living room entryway did not begin to recover until approximately 45 s post-suppression. Following suppression, the 3 ft living room gas concentrations began to return to ambient levels.

Table 5.2 lists hallway gas concentrations at intervention. At the time of first intervention, compared to the 3 ft elevation, the 1 ft O_2 concentration was higher and CO_2 and CO concentrations were lower, with concentrations of 18.2%, 4.5%, and 0.8%, respectively. This difference was driven by air intake through the front door. This intake eventually led to flame spread past the measurement location as the 1 ft CO and CO_2 continued to increase until the concentrations were comparable in magnitude to those measured 3 ft above the door. The 1 ft O_2 concentration did not decrease as low as the 3 ft O_2, reaching a minimum value of 7.4%. The 1 ft gas concentrations did not recover until after hydraulic ventilation was complete (> 300 s), suggesting that fuel materials may have been smoldering in the direct vicinity of the gas sample probe or obstructed the sample probe.

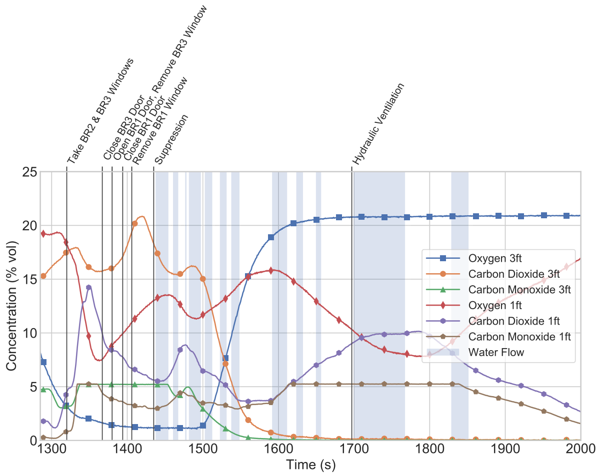
Table 5.2: Hallway Gas Concentrations at Intervention for Experiment 11

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	3.1	17.5	3.2
	1 ft	18.2	4.5	0.8
Start Hallway	3 ft	14.5	6.3	0.9
	1 ft	12.5	8.3	1.7
Mid Hallway	3 ft	5.3	15.2	3.8
	1 ft	15.5	5.7	1.2
End Hallway	3 ft	1.3	17.7	4.3
	1 ft	15.5	5.2	1.1

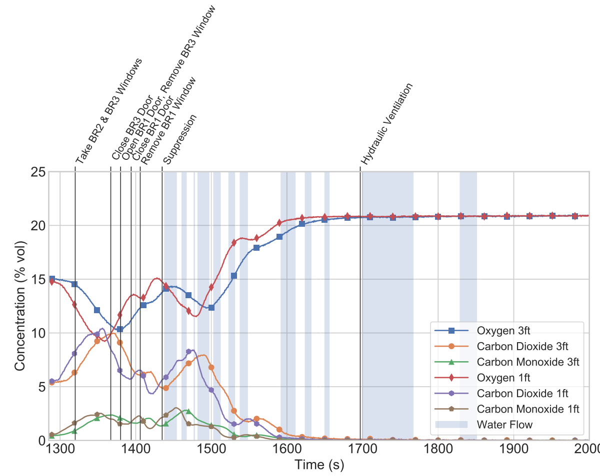
The 3 ft and 1 ft gas concentrations at the start hallway location trended similarly to each other. CO and CO_2 concentrations increased and O_2 concentrations decreased from the time that the windows were broken until peak was reached 61 s and 37 s at the 3 ft and 1 ft elevations, respectively. Gas concentrations observed at the peak were 9.3% O_2, 10.3% CO_2, and 2.5% CO 3 ft above the floor and 10.4% O_2, 9.7% CO_2, and 2.2% CO 1 ft above the floor. At this time, gas concentrations at the start hallway location began to return toward ambient conditions as the fresh air entrained through the bedroom windows and open bedroom 1 door established a flow of fresh air through the hallway toward the living room. This recovery continued until just prior to onset of suppression as flame rollover occurred at the start hallway location (see Figure 5.9b). Gas concentrations at the start hallway location began to return to ambient as suppression began. Gas concentrations at both elevation in the start hallway location had returned to ambient prior to the initiation of hydraulic ventilation (370 s post-intervention).

A similar trend was observed at the mid hallway measurement location (Figure 5.11c). O_2 concentrations at 3 ft and 1 ft were decreasing at intervention while CO and CO_2 concentrations were increasing. Post-intervention, CO and CO_2 concentrations generally followed the trend observed at the start hallway location, with concentrations increasing through the time of intervention until the entrained air from the bedroom window ventilation caused concentrations to start to decrease 30 s after intervention. This decrease was temporary, as gas CO and CO_2 concentrations began to increase again as the additional air caused fire growth prior to suppression. The result was an increase in CO and CO_2 concentrations until a final peak 140 s after intervention, when suppression caused these gas concentrations to decrease to a negligible value prior to hydraulic ventilation. O_2 concentrations changed in the opposite direction to the toxic gases, decreasing during periods of fire growth and increasing as additional air was entrained from window ventilation. The decrease in CO and CO_2 and increase in O_2 at the mid hallway location following window ventilation was less pronounced at the 3 ft elevation than at the 1 ft elevation — at 3 ft, CO and CO_2 concentrations only decreased for 35 s before increasing to a peak, whereas at 1 ft, they decreased for 70 s after the peak value. The peak gas concentrations measured at the 3 ft elevation were 1.6% O_2, 17.3% CO_2, and 5.0% CO, observed immediately prior to a sharp decrease preceding suppression, 140 s after intervention (1460 s after ignition). The peak gas concentrations measured at the 1 ft elevation were 10.3% O_2, 10.5% CO_2, and 2.6% CO, observed 40 s after intervention (1360 s after ignition).

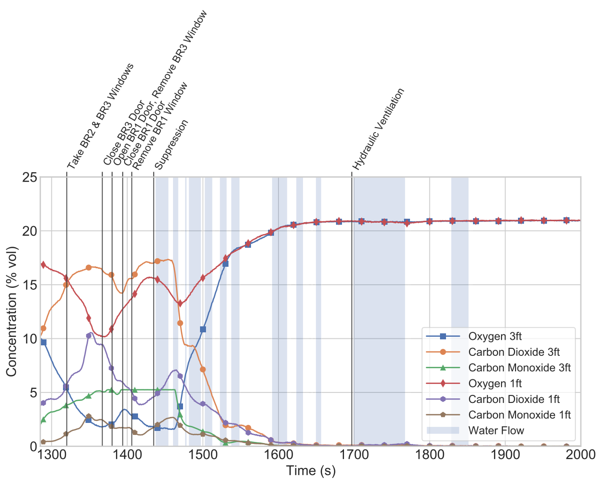
At time of intervention, the O_2, CO_2, and CO concentrations 3 ft above the floor at the end hallway location (Figure 5.11d) were 1.2%, 17.7%, and 4.2%, respectively. Gas concentrations at the 3 ft level remained unchanged by the window ventilation and subsequent door control, and only began to trend toward ambient conditions 140 s after intervention (1460 s after ignition), following the start of suppression. The 1 ft gas concentrations at the end hallway location trended similarly to the corresponding locations at the start and mid-hall locations. Following intervention, CO and CO_2 concentrations continued to increase and O_2 concentrations continued to decrease until the entrained air from the bedroom 2 window began flow through the measurement location, resulting in a local peak in CO and CO_2 concentrations 35 s after intervention. This decrease continued until approximately 120 s after intervention, when toxic gas concentrations again began to increase and O_2 began to decrease as a result of the continued flow of hot gases through the end hallway location because of the lack of isolation between bedroom 2 and the hallway. This increase in CO and CO_2 occurred simultaneous with the increase in temperature at the 1 ft elevation shown in Figure 5.9d. CO and CO_2 increased to peak values of 2.8% and 9.0% 143 s after intervention, while the O_2 decreased to a minimum value of 13.2%. After the peak, gas concentrations began to return to ambient as suppression took effect in the common space, returning to pre-test conditions prior to the start of hydraulic ventilation.



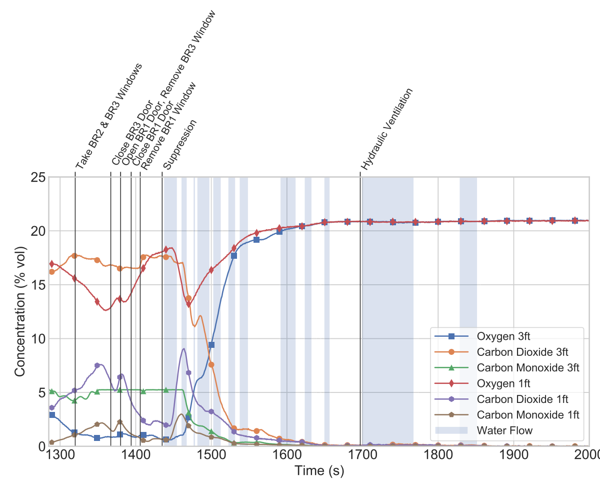
(a) Living Room Entry Hallway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration

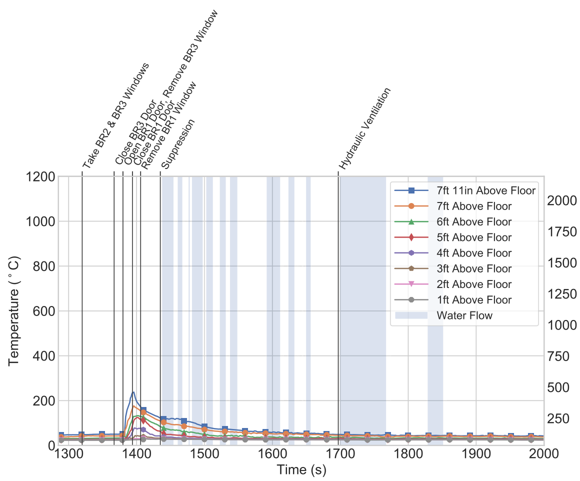


(d) End Hallway Gas Concentration

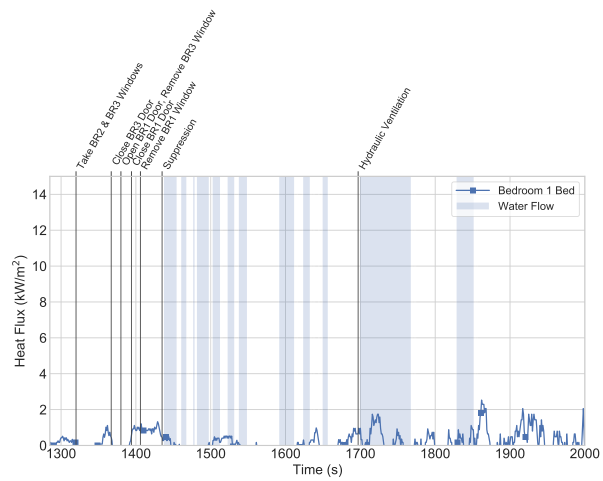
Figure 5.11: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 11.

5.1.5 Bedroom 1

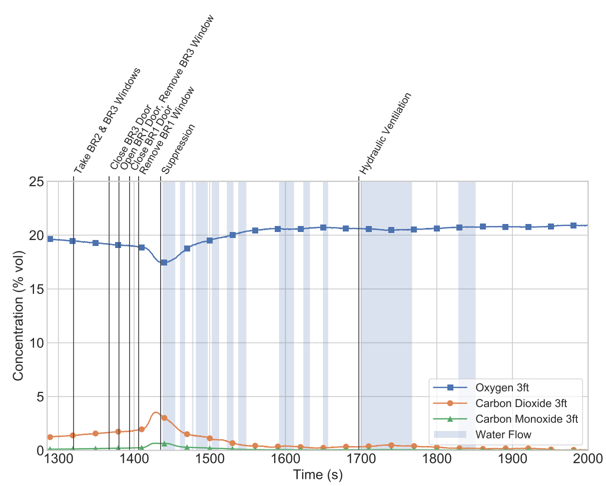
Prior to the opening of the bedroom 1 door 60 s after fire department intervention (1624 s after ignition), the bedroom was isolated from the hallway and adjoining common space. As such, temperatures at the time of intervention were substantially lower than temperatures in bedrooms 2 and 3, ranging from 50 °C (122 °F) at the ceiling to 23 °C (73 °F) 1 ft above the floor immediately prior to the bedroom door opening. After the bedroom door was opened, hot gases from the hallway flowed into bedroom 1, resulting in a sharp increase in temperatures at elevations between 3 ft above the floor and the ceiling. Temperatures peaked when the bedroom door was closed 14 s later, with temperatures in the room ranging from 238 °C (460 °F) at the ceiling to 25 °C 1 ft above the floor (77 °F) . The re-isolation of bedroom 1 and subsequent ventilation of the bedroom 1 window resulted in a decrease in temperatures for the remainder of the experiment as products of combustion that had flowed into the room exhausted to the exterior. As a result of the lower temperatures in bedroom 1, heat flux measured 3 ft above the floor in the center of the bed remained low for the duration of the experiment (Figure 5.12b).



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux

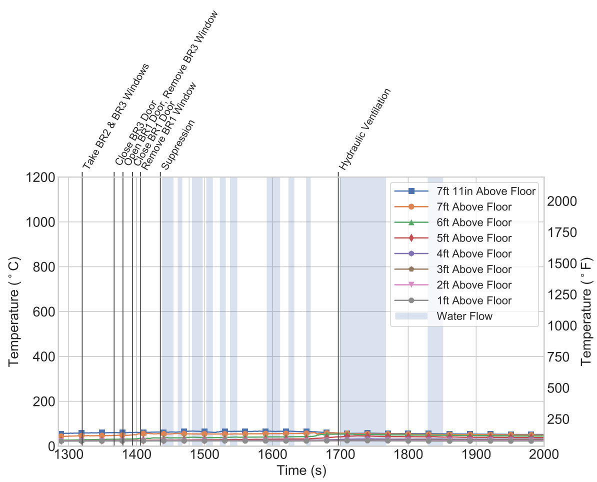


(c) Bedroom 1 Gas Concentration

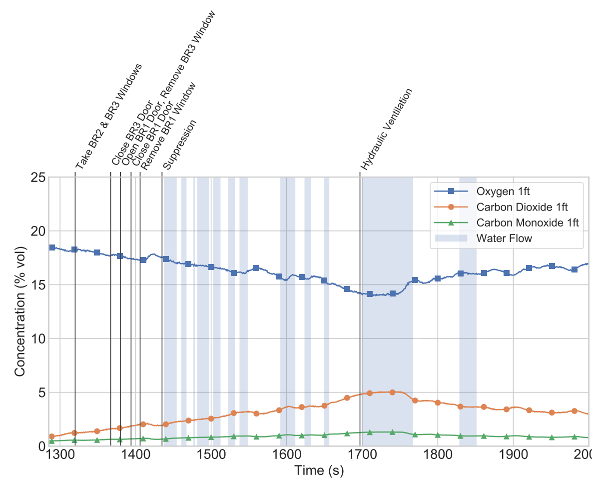
Figure 5.12: Temperature, heat flux, and gas concentrations in bedroom 1 in period following fire department intervention during Experiment 11.

At the sample location on the bed, 3 ft above the floor, gas concentrations in bedroom 1 similarly remained low prior to the opening of the door, with O_2, CO_2 and CO concentrations of 19.1%, 1.8%, and 0.2%, respectively. Gas concentrations did not immediately respond to the flow of gases in the room, with CO and CO_2 concentrations instead beginning to increase at a more rapid rate once the smoke layer descended to the 3 ft level. Peak values occurred 40 s after the bedroom 1 door was first opened. The re-isolation of bedroom 1 and subsequent ventilation of the bedroom 1 window caused peak O_2, CO_2, and CO concentrations in bedroom 1 to be considerably lower than across the hallway in bedroom 2, with peak concentrations of 17.4%, 3.2%, and 0.6%, respectively, occurring simultaneous with the start of suppression.

The door between bathroom 1 and bedroom 1 remained closed for the duration of the experiment, keeping temperatures in bathroom 1 below 70 °C (158 °F) (Figure 5.13a). Although temperatures remained low, peak gas concentrations were high compared to the adjacent bedroom, as shown in Figure 5.13b. Immediately prior to opening the bedroom 1 door, O_2, CO_2, and CO concentrations 1 ft above the floor in the bathroom were 17.8%, 1.6%, and 0.6%, respectively – lower than the corresponding values 3 ft above the floor in bedroom 1. Gas concentrations in the bathroom were not significantly affected by the manipulation of the bedroom 1 door and subsequent ventilation actions. Instead, the HVAC supply provided a route for products of combustion to fill the bathroom via the HVAC supply duct, but the lack of a return and the closed bedroom door precluded any exhaust of these products of combustion from the room. As a result, CO and CO_2 concentrations in bathroom 1 continued to increase as other areas of the structure had already returned to ambient conditions. CO and CO_2 concentrations continued to increase and O_2 values continued to decrease until the start of suppression, with O_2, CO_2 and CO values of 14.0%, 5.0%, and 1.4%, respectively. Following this peak, gas concentrations gradually began to trend toward ambient as the production of combustion products began to stop.



(a) Bathroom 1 Temperature

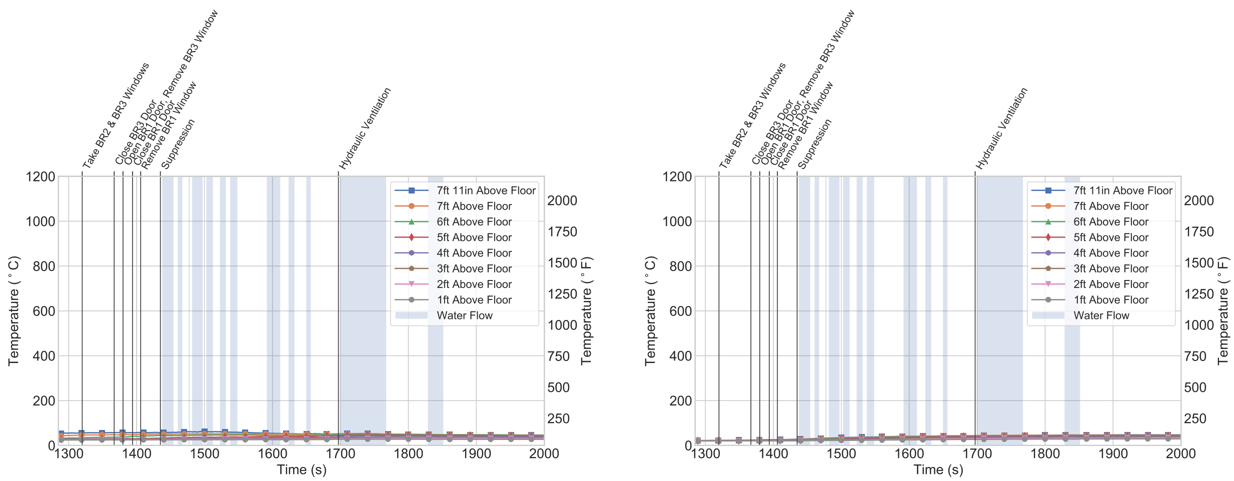


(b) Bathroom 1 Gas Concentration

Figure 5.13: Temperature and gas concentrations in bathroom 1 in period following fire department intervention during Experiment 11.

5.1.6 Bedroom 4

The door between bedroom 4 and the hallway remained closed for the duration of the experiment, resulting in lower peak temperatures than the other three bedrooms in the structure. Temperatures in bedroom 4 remained below 65 °C (150 °F) for the duration of the experiment, as shown in Figure 5.14. The peak temperatures measured in the closet, which did not have an HVAC supply and was two closed doors removed from the hallway, (Figure 5.14b) were lower – remaining below 45 °C (113 °F) for the duration of the experiment. The temperature in both bedroom 4 measurement locations gradually decreased throughout hydraulic ventilation.



(a) Bedroom 4 Temperature

(b) Bedroom 4 Closet

Figure 5.14: Temperatures in bedroom 4 in period following fire department intervention during Experiment 11.

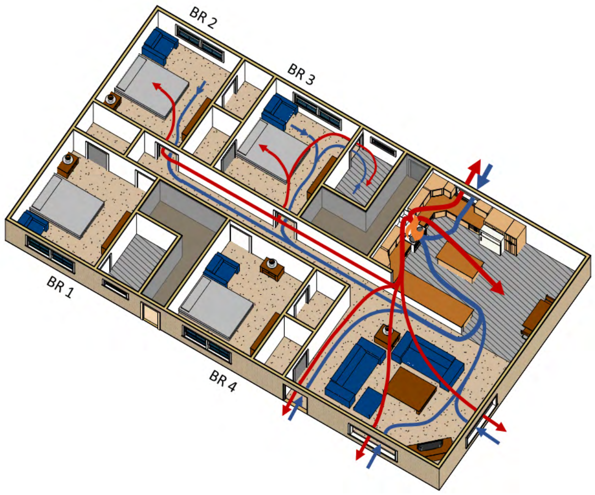
5.2 Experiment 12

The search tactics in Experiment 12 were designed to evaluate a comparison of window initiated operations conducted during interior suppression of a common space (living room and kitchen) fire. At the time of ignition, both the kitchen window and front door were opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2 and 3 were opened. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets which led to flashover of the kitchen. The fire then spread to the living room, where flashover occurred following the failure of the side A and side D windows. Post-flashover of the common space, suppression occurred via interior operations. At the onset of suppression, crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. The crew in bedroom 3 entered the bedroom and proceeded toward the door to the hallway and closed the door. This action isolated bedroom 3 from the fire gases produced by the common space fire. At the same time, the crew in bedroom 2 entered the bedroom and proceeded toward the hallway. This crew was unable to isolate bedroom 2 and continued across the hallway searching beyond the room of entry. After isolation of bedroom 3, the crew in in that room removed the remainder of the double-wide window in the compartment. Simultaneously, the crew that entered bedroom 2 crossed the hall to bedroom 1. The closed bedroom 1 door was opened to allow for crew entry. The crew closed the door behind them. Once isolated in bedroom 1, the crew proceeded to remove the bedroom 1 window. At this point the search tactic comparison was complete and suppression began with interior suppression with entry to the structure through the front door. 153 gallons were flowed during suppression. Upon the suppression crew announcement of fire under control, hydraulic ventilation first occurred out of the side A living room window and then out of the side D living room window. The total amount of water flowed during suppression and hydraulic ventilation was 509 gallons. Table 5.3 lists the times at which events occurred during Experiment 12.

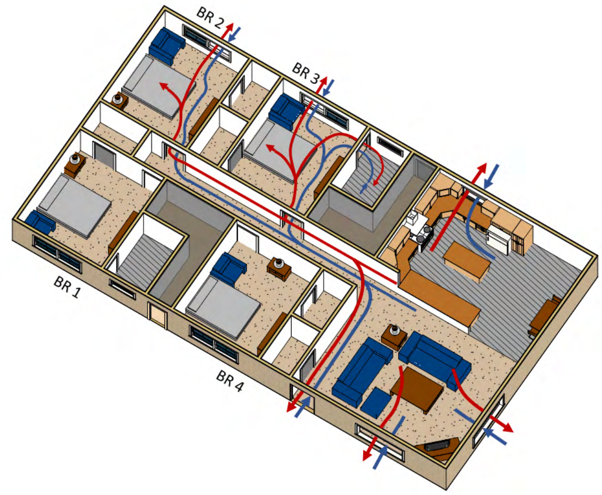
Table 5.3: Experiment 12 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	05:27	327	—	—
Take BR2 & BR3 Windows, Suppression	22:28	1348	00:00	0
Close BR3 Door	23:10	1390	00:42	42
Open BR1 Door, Remove BR3 Window	23:22	1402	00:54	54
Close BR1 Door	23:32	1412	01:04	64
Remove BR1 Window	23:44	1424	01:16	76
Hydraulic Ventilation	25:49	1549	03:21	201

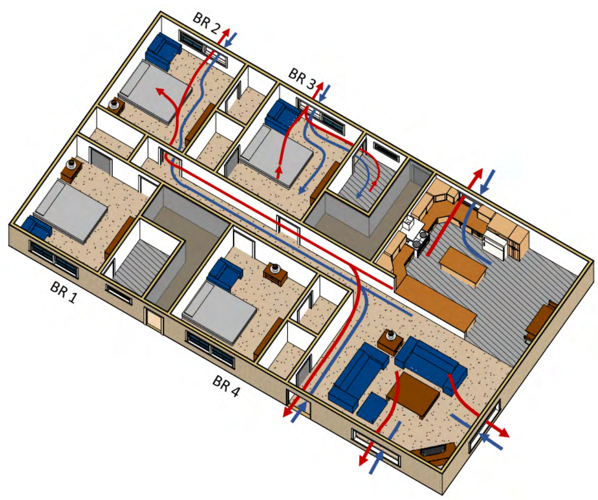
At the time of fire department intervention, the common space was in a steady, post-flashover state, with bidirectional flows from the front door, kitchen window, and the side A and side D living room windows, as shown in Figure 5.15a. Smoke and flames were exhausted out of the structure through the top portion of these vents while fresh air was entrained through the lower portion. The initial fire department intervention was suppression, initiated from side A, conducted simultaneous with ventilation of half of the bedroom 2 and bedroom 3 windows. Suppression was initiated from the deck with a 1 3/4 in. handline equipped with a combination nozzle set to flow a straight stream with a flow rate of 150 gpm. The suppression crew flowed from their initial position into the doorway and side A living room window for 12 s before advancing to the doorway, where they flowed for 5 s before advancing into the living room using a flow-and-move technique. The ventilation action created new exterior vents at these locations and established additional flow paths. Since the doors between bedrooms 2 and 3 and the hallway were open at the time of ignition, this action created a bidirectional flow through both bedrooms, allowing fresh air to be entrained into both bedrooms through the lower portion of the windows, while hot gases exhausted through the upper portion, as shown in Figure 5.15b. As suppression actions reduced temperatures and brought the fire under control, the magnitude of the flow velocities that originated from the common space decreased. Closing the door to bedroom 3 isolated the bedroom from the products of combustion in the hallway and changed the flow path that included the bedroom 3 window as flow to/from the hallway was stopped (Figure 5.15c). Accumulated smoke in bedroom 3 exhausted to the exterior of the structure through the open window. In contrast, bedroom 2 was not isolated. Bidirectional flow through the doorway persisted.



(a) Flows Prior to Intervention



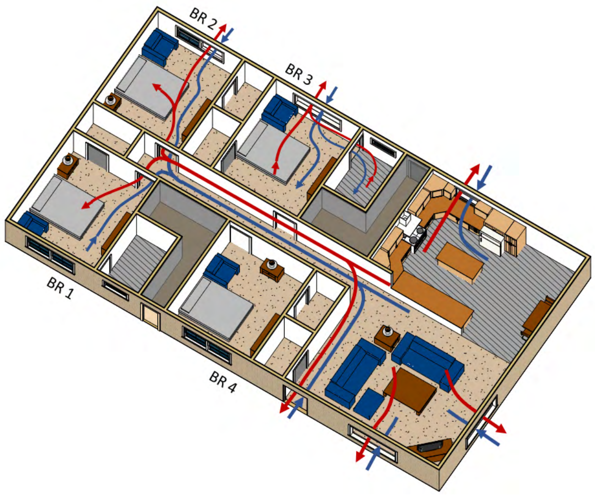
(b) Take BR2 & BR3 Windows, Suppression



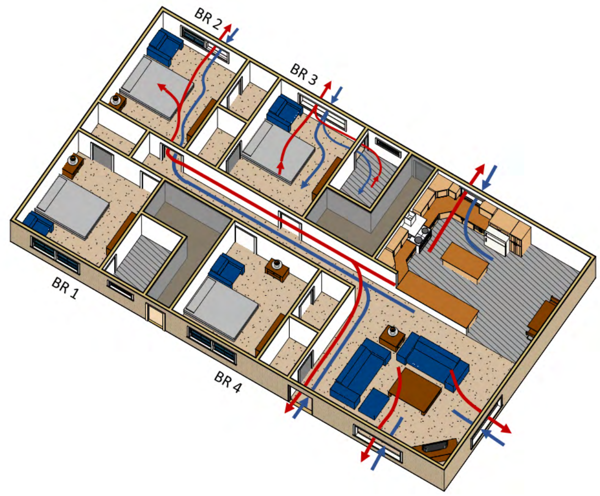
(c) Close BR3 Door

Figure 5.15: Changes in gas flows within the structure following fire department interventions in Experiment 12.

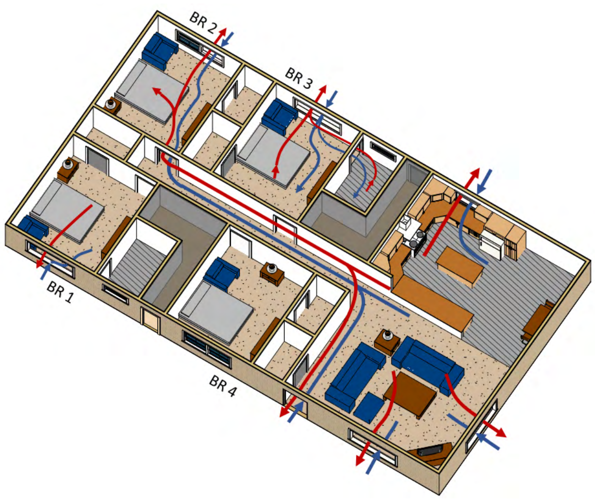
Simultaneous with the closing of the bedroom 3 door, the bedroom 1 door was opened, simulating a firefighter searching across the hallway from bedroom 2. This briefly established a bidirectional flow into bedroom 1. As shown in Figure 5.16a, products of combustion from the hallway flowed into bedroom 1 and replaced the fresh air that had previously occupied the space. The bedroom 1 door was closed again 10 s later, isolating the room from this flow, as shown in Figure 5.16b. Combustion gases, which had flowed into bedroom 1 while the door was opened, remained in the space until 12 s later, when the bedroom 1 window was removed. This created a new flow path which allowed trapped smoke to exhaust through the upper portion and fresh air to flow through the lower portion, as shown in Figure 5.16c. After the search sequence was completed, the suppression crew first initiated hydraulic ventilation through the side A window with a narrow-fog stream rotated in an O-pattern (Figure 5.16d). This action reduced the pressure at the living room window and drew products of combustion from remote locations along the flow path in the structure toward the living room.



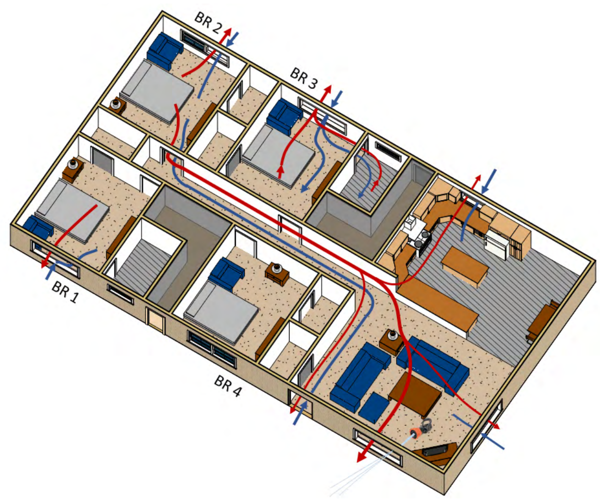
(a) Open BR1 Door, Remove BR3 Window



(b) Close BR1 Door



(c) Remove BR1 Window

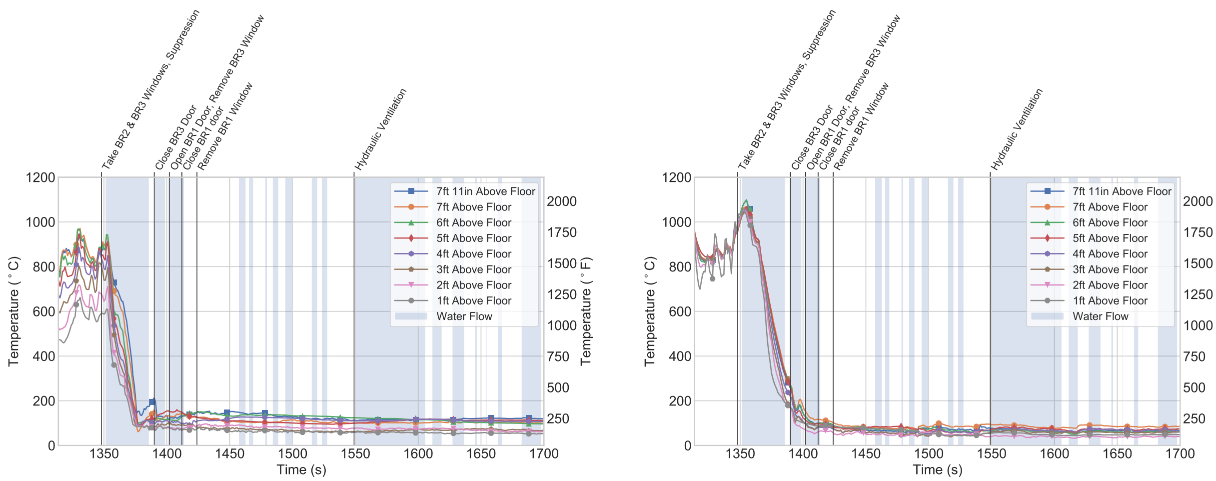


(d) Hydraulic Ventilation

Figure 5.16: Changes in gas flows within the structure following fire department interventions in Experiment 12.

5.2.1 Common Space

Kitchen and living room temperatures at the time of intervention were uniformly in excess of 600 °C (1112 °F), consistent with post-flashover conditions (Figure 5.17). Living room and kitchen temperatures began to decrease immediately after the initial exterior suppression action, and continued to decrease as the suppression crew flowed water into the space. The suppression actions extinguished the common space fire, decreasing kitchen temperatures below 200 °C (392 °F) and living room temperatures below 300 °C (572 °F) within 40 s of the initial water application. Primary suppression was completed within 64 s, just after the search crew that entered through the bedroom 3 window had crossed the hallway to search the bedroom 1. A total of 153 gallons were flowed from the start of suppression to the start of hydraulic ventilation.



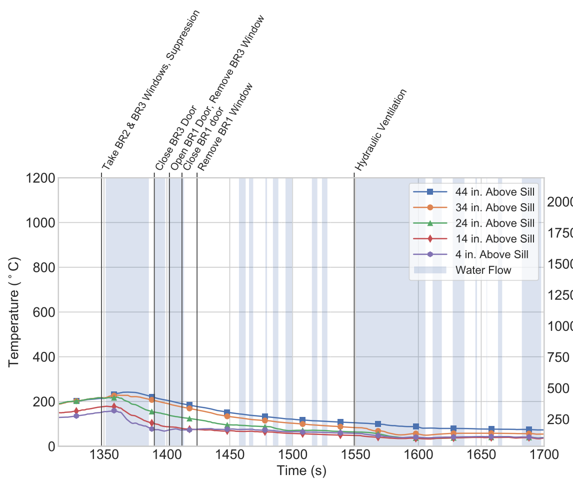
(a) Kitchen Temperature

(b) Living Room Temperature

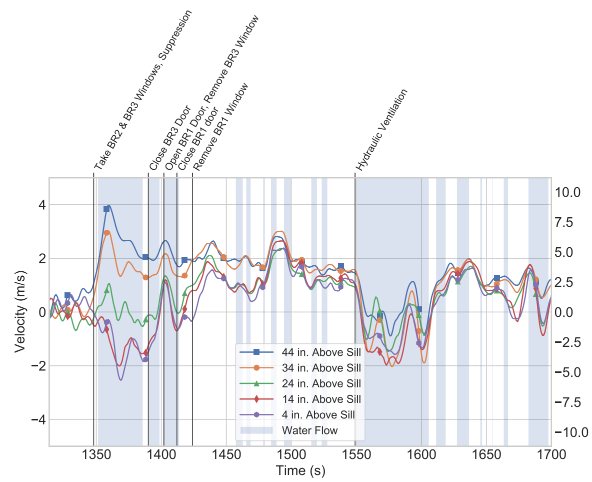
Figure 5.17: Temperature time histories in the common space for the period following fire department intervention in Experiment 12.

5.2.2 Bedroom 2

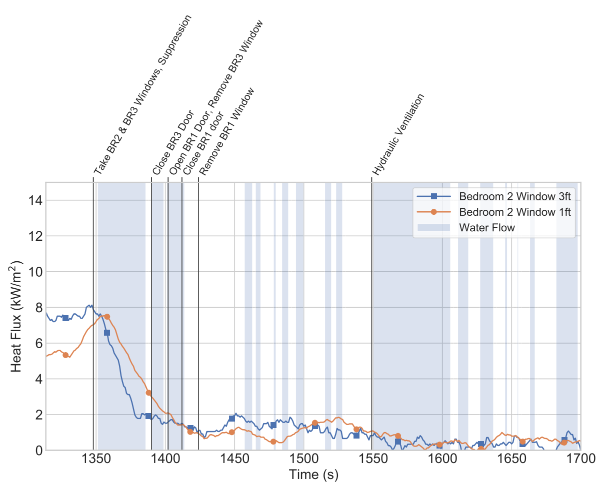
Simultaneous with the start of suppression, half of the bedroom 2 and 3 windows were ventilated. Figure 5.18 shows the temperature, velocity, heat flux, and gas concentrations measured in the window in the period following intervention. Figures 5.18b and 5.18a show that immediately after the bedroom 2 window was ventilated, a bidirectional flow was established through the vent, with high temperature gases exhausting through the upper portion of the window while the lower portion of the window acts as an inlet, with air flowing into bedroom 2. The magnitude of the bedroom 2 window velocities briefly increased during the initial portion of the suppression actions, but began to decrease as the common space fire was extinguished and gas contraction was observed. At their peak, exhaust velocities ranged between 4.5 m/s and 2.5 m/s (10 mph and 5.6 mph), with corresponding temperatures between 245 °C and 210 °C (473 °F and 410 °F). Entrainment velocities ranged between -2.7 m/s and -2.3 m/s (6.0 mph and 5.1 mph), with corresponding temperatures between 160 °C and 175 °C (320 °F and 347 °F). After the primary suppression actions were completed, a bidirectional flow was maintained with continuously decreasing exhaust temperatures in the bedroom 2 window. This bidirectional flow was maintained through the end of the ventilation sequence, when a period of unidirectional exhaust was observed which lasted approximately from the time the bedroom 1 window was opened until the beginning of hydraulic ventilation. Wind velocity data indicated that this unidirectional exhaust was a result of sustained wind on side A in the period preceding hydraulic ventilation. After hydraulic ventilation was initiated, the bedroom window acted as a unidirectional inlet, allowing air to be entrained into the structure as gases flowed toward the area of lower pressure created by hydraulic ventilation in the common space.



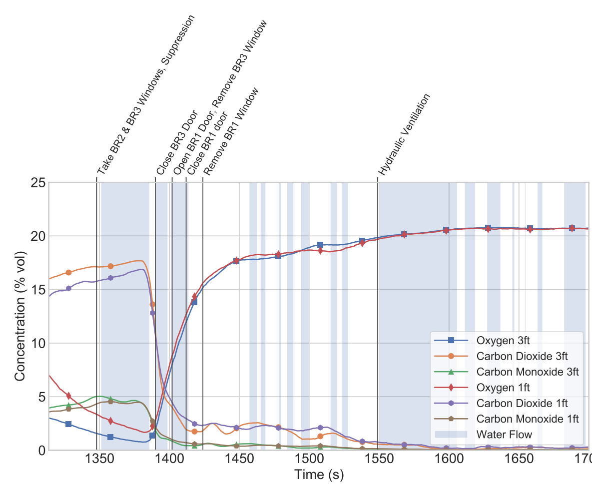
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



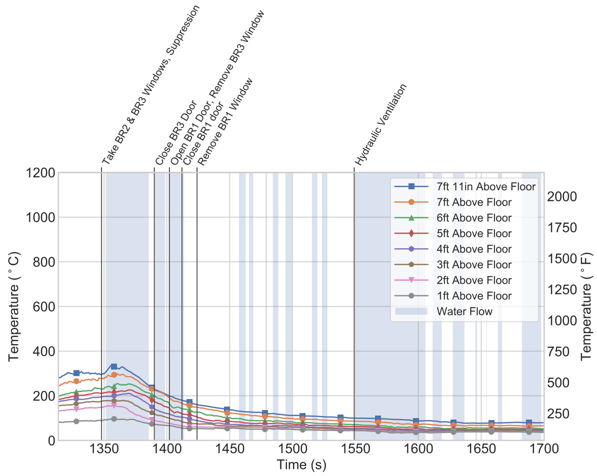
(d) Bedroom 2 Window Gas Concentration

Figure 5.18: Post-intervention window temperature, velocity, heat flux and gas concentrations in bedroom 2 during Experiment 12.

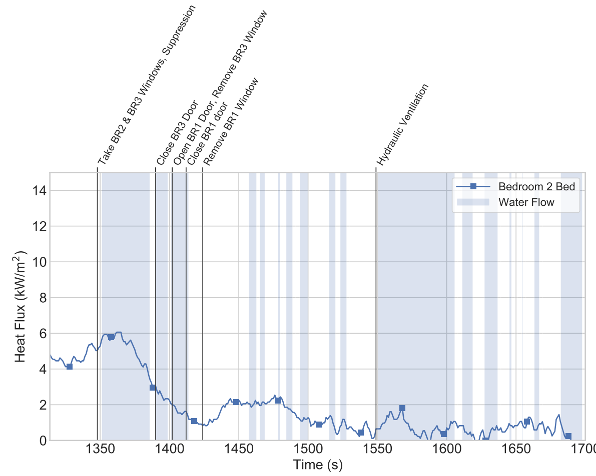
At the time of intervention, the heat flux values measured at the gauges 3 ft and 1 ft elevations above the floor under the window were 8.1 kW/m^2 and 7.1 kW/m^2, respectively. Immediately following intervention, the combination of suppression and air entrainment through the lower portion of the window caused the heat flux at both elevations to sharply decrease. This decrease continued through the remainder of the suppression and ventilation actions. Prior to the start of hydraulic ventilation, heat flux at both elevations had dropped to 1.0 kW/m^2 at both the 3 ft and 1 ft elevations, respectively. Hydraulic ventilation caused heat flux to further decrease to negligible values.

The time histories of gas concentrations at the bedroom 2 window location are shown in Figure 5.18. At the time of intervention, gas concentrations were 1.6% O_2, 17.1% CO_2, and 5.0% CO at the 3 ft elevation and 3.4% O_2, 15.7% CO_2, and 4.4% CO at the 1 ft elevation. The high CO and CO_2 concentrations and low O_2 concentration at this location indicate that the smoke layer had descended past the 1 ft measurement location in bedroom 2. Immediately after intervention, CO and CO_2 concentrations continued to increase for 35 s after intervention, when toxic gas concentrations peaked at above ambient values and began to decrease due to suppression. This decrease continued until gas concentrations reached a steady state at approximately the same time that the bedroom 1 window was opened. Gas concentrations at both bedroom 2 window locations remained elevated at the start of hydraulic ventilation, which caused gas concentrations to further trend toward ambient. At the end of hydraulic ventilation, CO and CO concentrations remained above zero, but less than 0.2% and 0.4%, respectively.

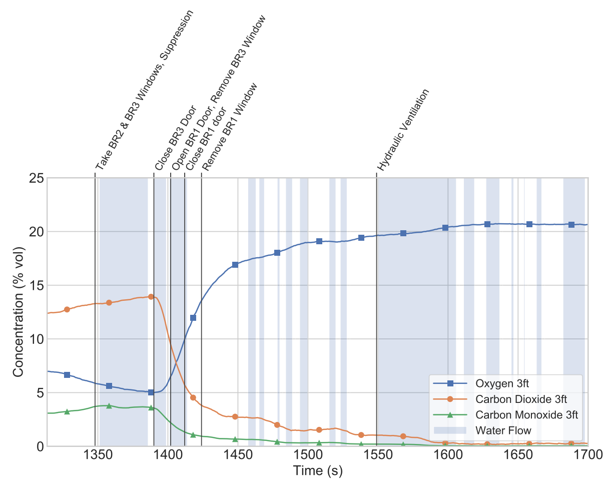
Figure 5.19 shows the time histories of temperature in the center of bedroom 2 and gas concentration and heat flux on the bedroom 2 bed, 3 ft above the floor. Temperatures in the center of the room ranged from 295 °C to 90 °C (563 °F to 194 °F). Immediately following intervention, temperatures in bedroom 2 continued to increase, as the relative higher temperature, higher pressure gases from the hallway flowed through the the room. This increase continued for approximately 20 s after intervention, when the combination of suppression and air entrainment through the bedroom 2 window resulted in a decrease in temperature at all elevations. The heat flux measured in the center of the bed (Figure 5.19b) followed a similar trend. Heat flux increased from 5.0 kW/m^2 at the time of intervention to a peak of 6.0 kW/m^2 approximately 30 s later before decreasing through the remainder of the vent sequence. Prior to the start of hydraulic ventilation, temperatures and heat flux decreased below 100 °C (212 °F) and 1 kW/m^2, respectively. Hydraulic ventilation caused these values to further decrease to pre-ignition conditions.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



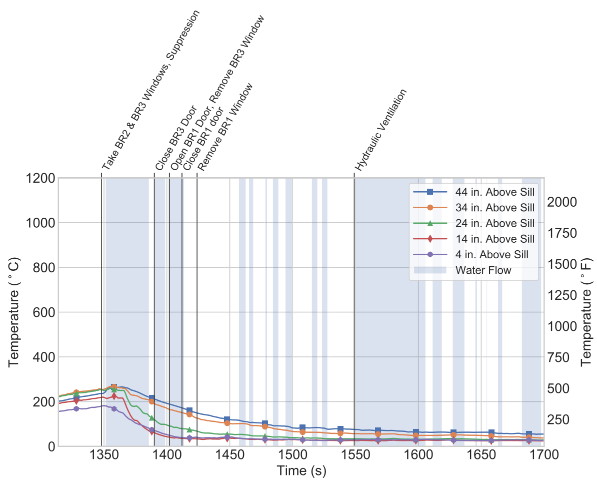
(c) Bedroom 2 Gas Concentration

Figure 5.19: Bedroom 2 temperature and heat flux time histories after fire department intervention for Experiment 12.

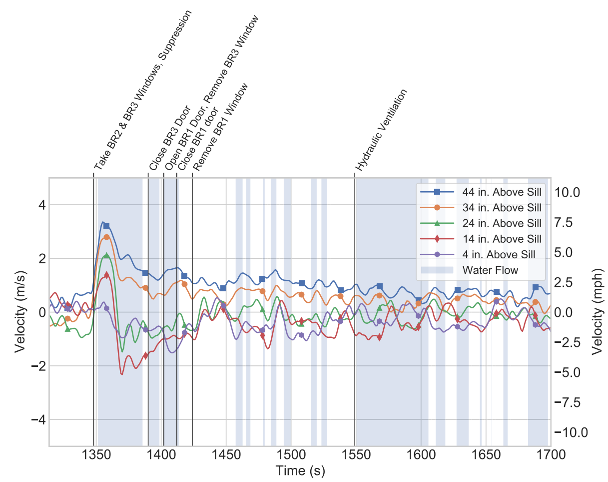
Figure 5.19c shows the time histories of gas concentration on the bedroom 2 bed. At the time of intervention, O_2, CO_2, and CO concentrations on the bed were 6.0%, 13.3%, and 3.6%, respectively. The high concentrations of CO and CO_2 and low concentration of O_2 suggests that the smoke layer had descended past the measurement location prior to intervention, which is consistent with the similar measurement locations in bedrooms 2 and 3. Immediately following intervention, CO and CO_2 concentrations continued to increase while the O_2 concentration continued to decrease until 40 s after intervention. At this point, suppression began to reduce the rate of production of toxic gases and fresh air began to flow through bedroom 2 from the inlet flow path created at the window. The rate of decrease in CO and CO_2 and increase in O_2 concentration was initially high and decreased after the ventilation sequence was completed. Immediately prior to hydraulic ventilation, O_2, CO_2, and CO concentrations were 19.6%, 1.1%, and 0.2%, respectively. Hydraulic ventilation caused these concentrations to further decrease, but they remained slightly above their pre-ignition values until the end of the experiment.

5.2.3 Bedroom 3

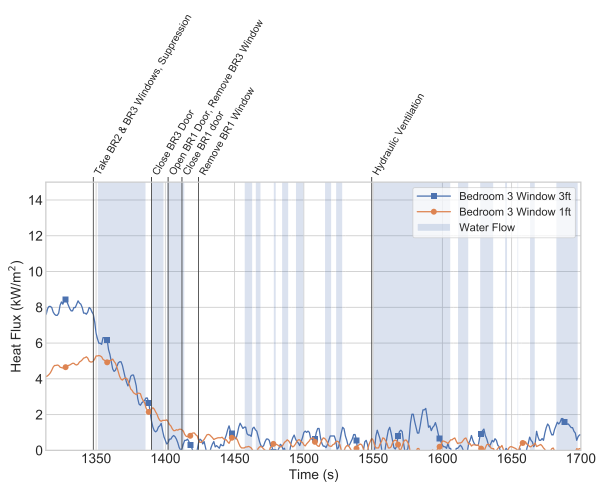
Simultaneous with the beginning of suppression, half of the bedroom 3 window was ventilated. Figure 5.20 shows the time histories of temperature, velocity, heat flux, and gas concentration in the bedroom 3 window. Immediately following window ventilation, a unidirectional exhaust was briefly established as the bedroom was full of higher temperature, higher pressure gases and the vent was created between the fire in the common space and the exterior. After the pressure dropped due to exhaust and suppression actions, bidirectional flow was established through the vent, with high temperature gases exhausting through the upper portion of the window. The lower portion of the window acted as an inlet, with air flowing into bedroom 3 (Figure 5.20b). At their peak, exhaust velocities ranged between 3.9 m/s and 1.5 m/s (8.7 mph and 3.3 mph), with corresponding temperatures between 266 °C and 225 °C (511 °F and 437 °F). After an inlet was established at the lower three probes, the peak inlet velocities ranged between -2.1 m/s and -1.0 m/s (-4.7 mph to -2.2 mph), with corresponding temperatures between 225 °C and 180 °C (437 °F to 356 °F). After the bedroom 3 door was closed, the flow path was changed; the bedroom 3 window acted as the sole vent. The velocity data in Figure 5.20b shows that peak exhaust and entrainment velocities remained relatively steady during this period, with peaks between 1 m/s to 2 m/s (2.2 mph to 4.4 mph) in magnitude. Because of the closed bedroom 3 door, hydraulic ventilation had no noticeable effect on the rate of change of window temperature of velocity.



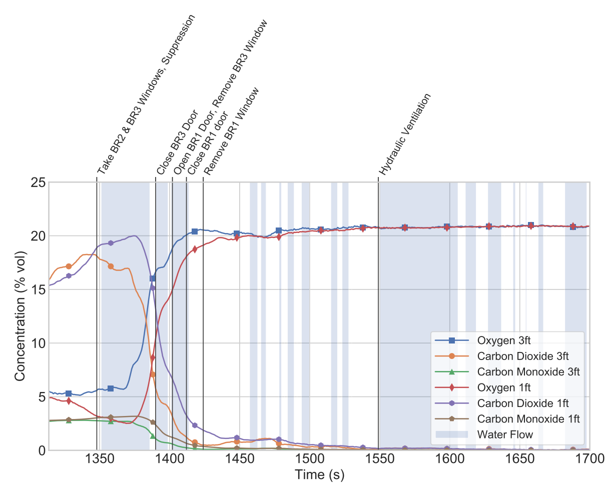
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.20: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 12.

At the time of intervention, heat flux 3 ft and 1 ft above the floor in the bedroom 3 window was 8.0 kW/m^2 and 5.4 kW/m^2, respectively (Figure 5.20c). Immediately after intervention, the combined cooling action of suppression and the entrained air through the lower portion of the bedroom 3 window caused a decrease in heat flux at both elevations. The heat flux continued to decrease after the bedroom 3 door was closed, and dropped to negligible values within 90 s of the bedroom 3 door being closed.

Gas concentrations at the time of intervention in 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 time histories of gas concentrations at the 3 ft and 1 ft measurement locations in the bedroom 3 window are shown in Figure 5.20d. CO and CO_2 concentrations began to decrease and O_2 concentrations began to increase approximately

20 s after the onset of suppression, which approximately matches the timing of the suppression crew's advancement into the living room to conduct interior suppression actions. The combination of gas contraction secondary to suppression and the air entrainment through the bedroom 3 window caused gas concentrations in bedroom 3 to continue to trend toward ambient through the closing of the bedroom 3 door. At this time, a new flow path was established in the room, with trapped smoke exhausting through the upper portion of the window and fresh air flowing into the space through the lower portion of the window. When the remainder of the bedroom 3 window was ventilated 54 s after intervention (1402 s after ignition), the larger vent size allowed products of combustion to exhaust at a more rapid rate, which resulted in gas concentrations trending toward ambient at a faster rate, as shown in Figure 5.20d. The continued exhaust through the bedroom 3 window caused CO and CO_2 concentrations to decrease to approximately negligible values prior to the start of hydraulic ventilation.

Gas concentrations at the time of intervention in 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 time histories of gas concentrations at the 3 ft and 1 ft measurement locations in the bedroom 3 window are shown in Figure 5.20d. CO and CO_2 concentrations began to decrease and O_2 concentrations began to increase approximately 20 s after the onset of suppression, which aligns with the timing of the suppression crew's advancement into the living room to conduct interior suppression actions. Gas exchange through the bedroom 3 window combined with isolation from the common space due to the closed door resulted in a continued trend toward pre-ignition levels. When the remainder of the bedroom 3 window was ventilated 54 s after intervention (1402 s after ignition), the larger vent size allowed products of combustion to exhaust at a more rapid rate, which resulted in gas concentrations trending toward ambient at a faster rate, as shown in Figure 5.20d. The continued exhaust through the bedroom 3 window caused CO and CO_2 concentrations to decrease to approximately negligible values prior to the start of hydraulic ventilation.

The temperatures measured in the center of bedroom 3, shown in Figure 5.21, ranged from 400 °C to 75 °C (752 °F to 167 °F) at the time of intervention. Bedroom 3 temperatures responded to interventions in a consistent manner to the instruments in the window. Immediately following intervention, temperatures close to the ceiling in bedroom 3 began to increase, as hot gases from the common space fire flowed through the center of bedroom 3 toward the vented window. This increase which corresponded to the unidirectional exhaust through the vented window, was brief, as temperatures reached a peak 15 s after the beginning of suppression and subsequently started to decrease. This decrease continued after the bedroom 3 door was closed. Similar to the trend observed with gas concentrations, temperatures began to decrease at a more rapid rate after the remainder of the bedroom 3 window was removed. Prior to the start of hydraulic ventilation, temperatures in bedroom 3 had decreased uniformly below 100 °C (212 °F). Because of the closed bedroom door between bedroom 3 and the common space, hydraulic ventilation did not have a noticeable impact on temperatures.

Figure 5.22 shows the time histories of temperature, gas concentration, and heat flux in bathroom 3. Temperatures in the bathroom were increasing at the time of intervention and ranged from 175 °C to 80 °C (347 °F to 176 °F). The temperatures continued to increase for approximately 20 s after

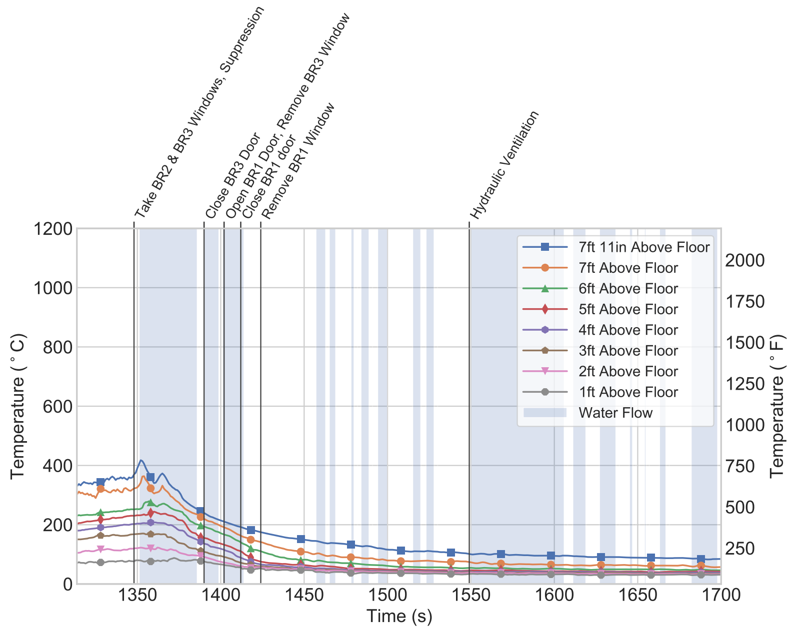
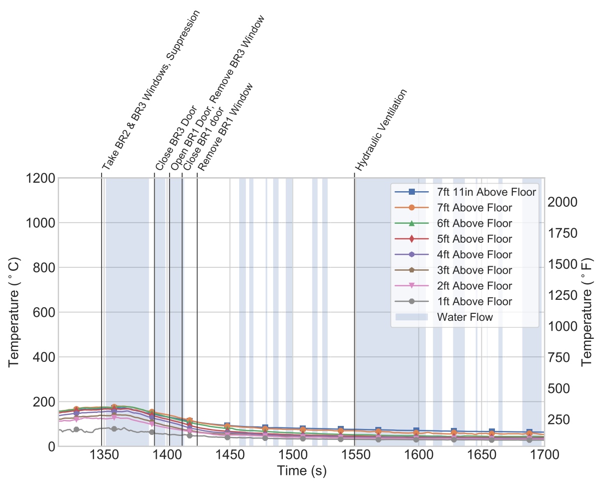


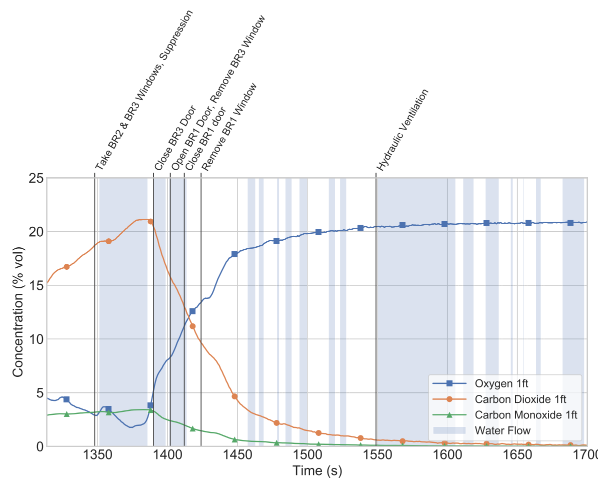
Figure 5.21: Post-intervention bedroom 3 temperature during Experiment 12.

intervention, before beginning to decrease as the cooling effects of suppression and air entrainment into bedroom 3 were observed. Heat flux measured 1 ft above the floor in bathroom 3 trended similarly to temperature. Figure 5.22c shows that the bathroom 3 heat flux was 2.6 kW/m^2 at the time of intervention and continued to increase to a peak of 3.0 kW/m^2 that was simultaneous with the peak in temperature at that location. After peaking, heat flux continuously decreased until reaching a negligible value 120 s after intervention (1497 s after ignition).

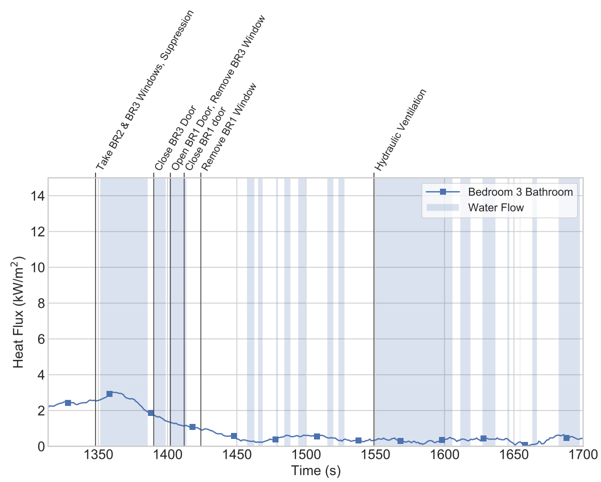
The gas concentration time histories in bathroom 3 are shown in Figure 5.22b. Immediately after intervention, CO and CO_2 concentrations continued to increase and the O_2 concentration continued to decrease until approximately 40 s after intervention. This recovery occurred slightly later in the experimental timeline than at the corresponding measurement location in the adjacent bedroom, which was due the location of the bathroom from the flow path established at the bedroom 3 window. CO and CO_2 continued to decrease and O_2 continued to increase as the bedroom 3 door was closed and the second half of the window was removed. Bathroom concentrations returned to pre-ignition conditions by 1600 s, approximately 60 s longer than the same elevation in the bedroom in the flow path.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Gas Concentration



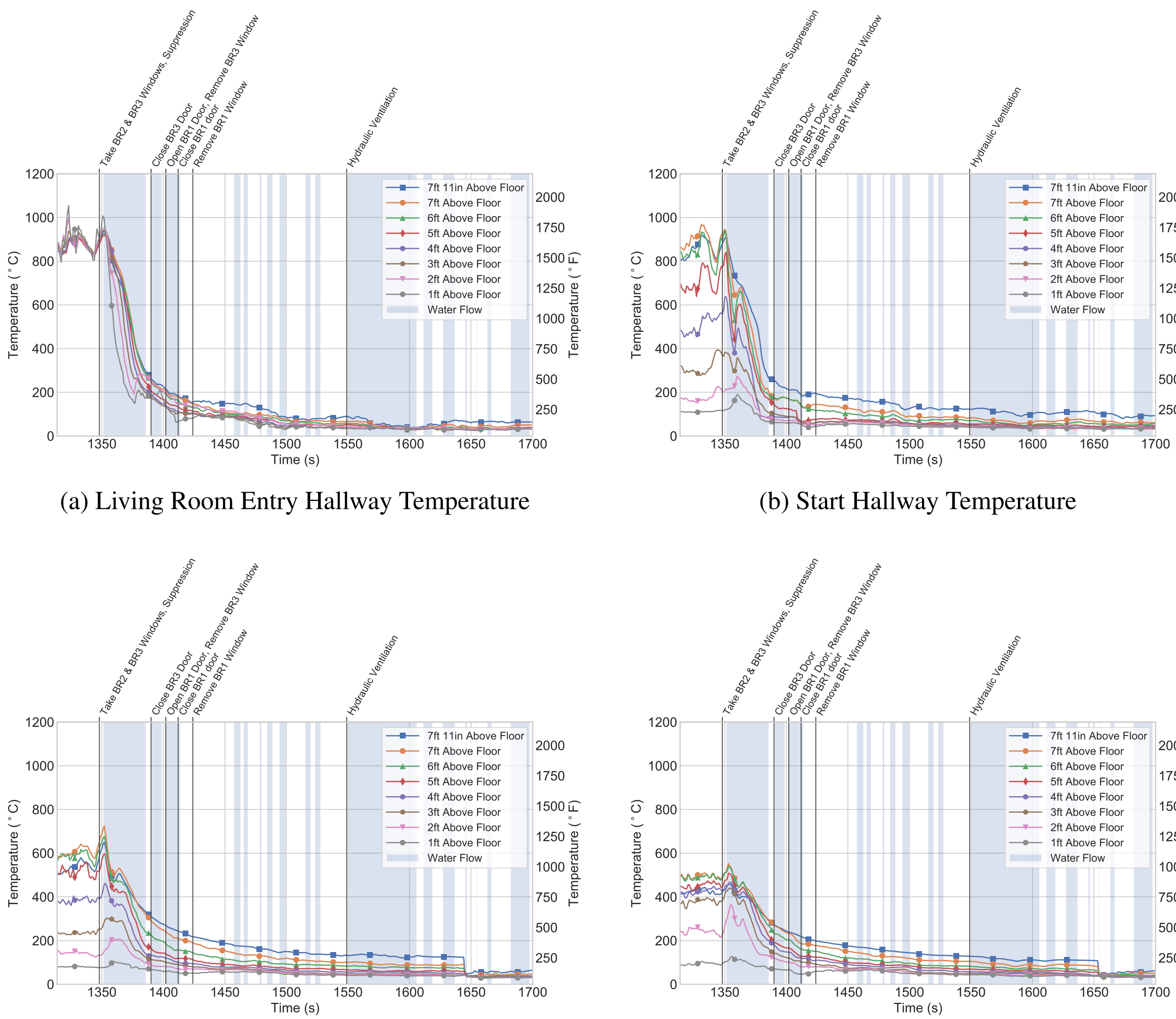
(c) Bathroom 3 Heat Flux

Figure 5.22: Post-intervention bathroom 3 measurements during Experiment 12.

5.2.4 Hallway

Figure 5.23 shows the time histories of temperature in the living room entryway and three hallway measurement locations during Experiment 12. Temperatures in the living room entryway, shown in Figure 5.23a, were uniformly in excess of 600 °C (1112 °F) at the time of intervention, consistent with post-flashover conditions. Temperatures at this location began to decrease coincident with the start of suppression, and continued to decrease at a consistent rate through the remainder of the suppression and ventilation actions.

The temperatures profiles at the three hallway locations were stratified at the time of intervention as the combustion gases filled the hallway and open bedrooms from the top down. The finite amount of oxygen due to a lack of exterior vent at ignition limited flame spread. These temperatures ranged from 925 °C to 115 °C (1697 °F to 239 °F), 635 °C to 75 °C (1175 °F to 167 °F), and 490 °C to 90 °C (914 °F to 194 °F) at the start hallway, mid-hallway, and end hallway ceiling and 1 ft above the floor locations, respectively. Temperatures at all elevations in the hallway increased as additional hot gases flowed through the hallway toward the exterior vents created by ventilation of the bedroom 2 and 3 windows. This temperature increase was temporary, between 25 and 30 s at the hallway locations, as suppression actions extinguished the common space fire. As a result, temperatures continuously decreased in magnitude for the remainder of the experiment.



(a) Living Room Entry Hallway Temperature

(b) Start Hallway Temperature

(c) Mid Hallway Temperature

(d) End Hallway Temperature

Figure 5.23: Temperature time histories in the hallway in the period following fire department intervention in Experiment 12.

Heat flux measurements at the living room entryway and hallway locations, shown in Figure 5.24, were consistent with the temperature measurements at those locations. Heat flux in the living room entryway was 37.5 kW/m^2 at the time of intervention, consistent with the post-flashover conditions present in the common space. Heat flux at this location began to decrease immedi-

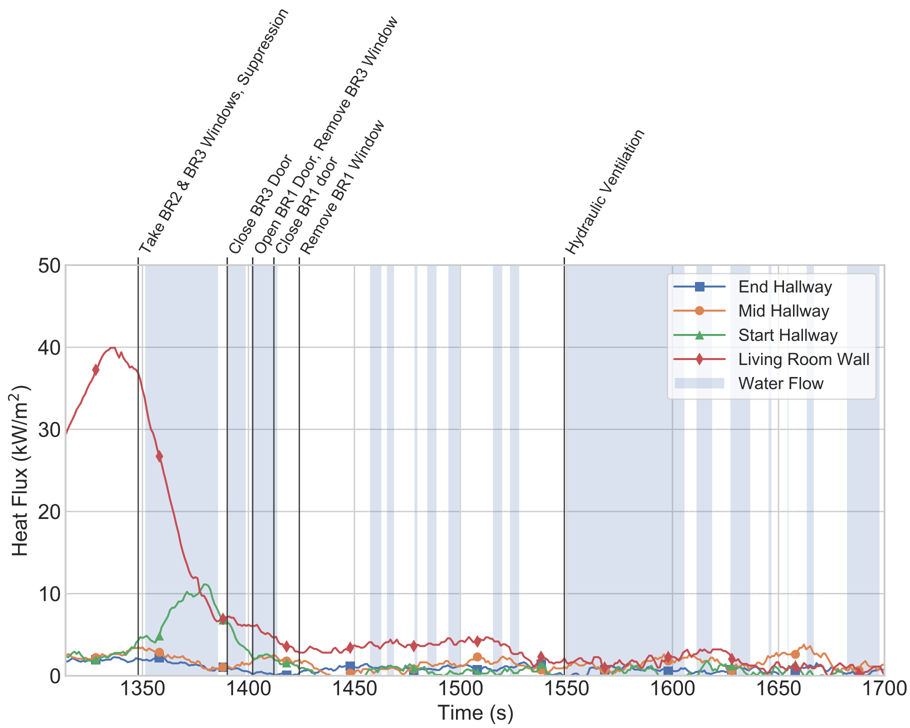


Figure 5.24: Heat flux time histories in the hallway in post-intervention period during Experiment 12.

ately after suppression began, and continued to decrease through the remainder of the suppression actions. Heat flux measured at the start hall location was considerably lower at the time of intervention, 4.3 kW/m^2, but began to increase as ventilation of the bedroom 2 and 3 windows established new flow paths through those locations and the hallway, causing additional flame spread along the carpet and hot gases from the post-flashover living room to flow over the start hall location, resulting in a peak heat flux of 13.3 kW/m^2 30 s after intervention. As suppression actions resulted in extinguishment of the common space fire, heat flux at the start hall location began to decrease. Furthermore, the increase that was observed at the start hall location after intervention was not observed at the mid-hallway and end hallway locations, where heat flux generally decreased in the period following intervention.

Gas concentrations at the time of intervention are shown in Table 5.4 and time histories at the living room entryway location are shown in Figure 5.25. At the time of intervention, the gas concentrations measured at each location were generally consistent with elevated concentrations of CO and CO_2 and a low concentration of O_2.

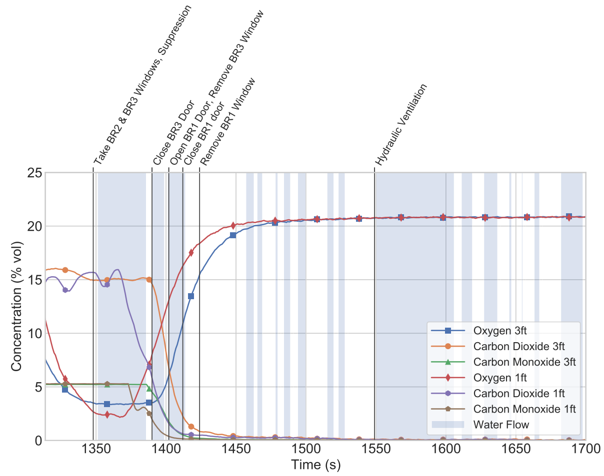
Table 5.4: Hallway Gas Concentrations at Intervention for Experiment 12

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	3.6	15.0	5.0
	1 ft	2.9	15.7	5.0
Start Hall	3 ft	7.9	10.9	3.3
	1 ft	6.6	12.1	3.0
Mid-Hall	3 ft	1.2	17.0	5.0
	1 ft	11.1	8.7	2.2
End Hall	3 ft	0.3	17.3	4.6
	1 ft	17.3	2.9	0.8

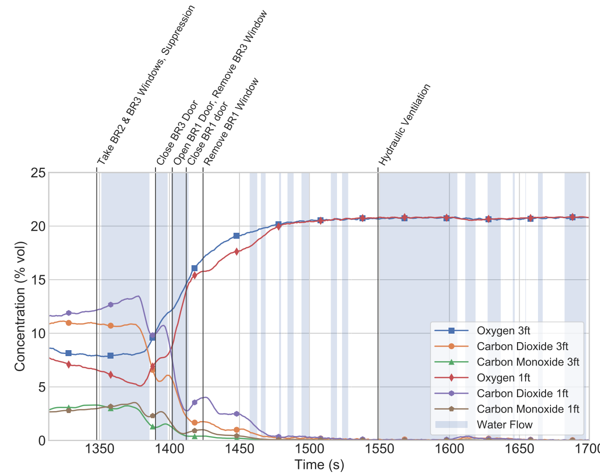
At the living room entryway location (Figure 5.25a), CO and CO_2 concentrations at the living room entryway were above 5% and 15%, respectively, which is consistent with the post-flashover conditions that were observed in the common space at the time. Immediately following the start of suppression, gas concentrations remained steady until 30 s after intervention, when CO and CO_2 at the 1 ft elevation began to indicate a decrease while O_2 increased. The 3 ft elevation followed a similar trend 10 s later. The timing of the improvement in gas concentrations in the living room approximately matches the time at which the suppression crew had advanced to the interior of the common space and had extinguished the bulk of the fire and the smoke layer proximal to the front door lifted. CO and CO_2 concentrations continued to decrease while the O_2 concentration increased at the 3 ft and 1 ft living room locations following this peak, with gas concentrations returning to pre-test conditions prior to the start of hydraulic ventilation.

Gas concentrations at the start hallway location were lower than those observed at the living room location, but still consistent with the smoke layer that had descended past the 1 ft elevation. The gas concentrations at the time of intervention are listed in Table 5.4 and the time history of start hallway gas concentration is shown in Figure 5.25b. Following the onset of suppression and window ventilation, CO and CO_2 concentrations continued to increase and the O_2 concentration continued to decrease at both elevations until 30 s after intervention, when suppression actions began to take effect, causing CO and CO_2 to begin to decrease and O_2 to begin to increase. This trend was briefly interrupted 40 s after intervention (1387 s after ignition), when the closure of the bedroom 3 door disrupted the exhaust flow in the hallway and resulted in a momentary increase in CO and CO_2 and decrease in O_2. Following this local peak, gas concentrations continued to trend toward ambient for the remainder of the experiment, with gas concentrations returning to approximately ambient conditions prior to the initiation of hydraulic ventilation.

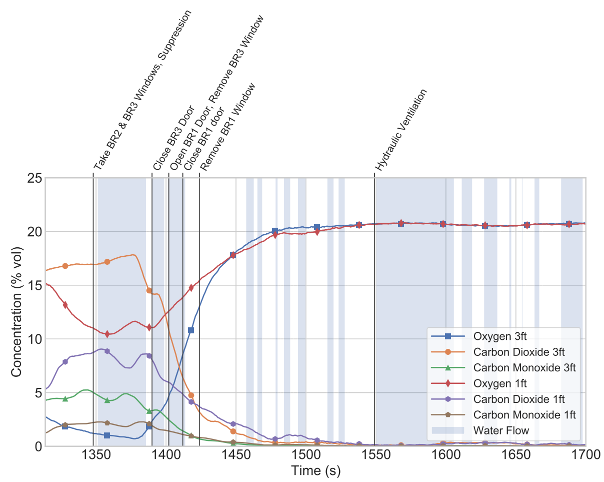
Gas concentrations at the mid hallway location, shown in Figure 5.25c, were comparable in magnitude to those observed at the start hallway location at the time of intervention. The 3 ft gas concentrations at the mid hallway behaved comparably to those at the start hall location, with CO and CO_2 increasing immediately following intervention to a peak 30 s after the start of suppression, followed by a continuous decrease. In contrast to the start hallway gas concentrations, gas measurements at the 1 ft mid hallway location indicated a decrease in CO and CO_2 concentration and



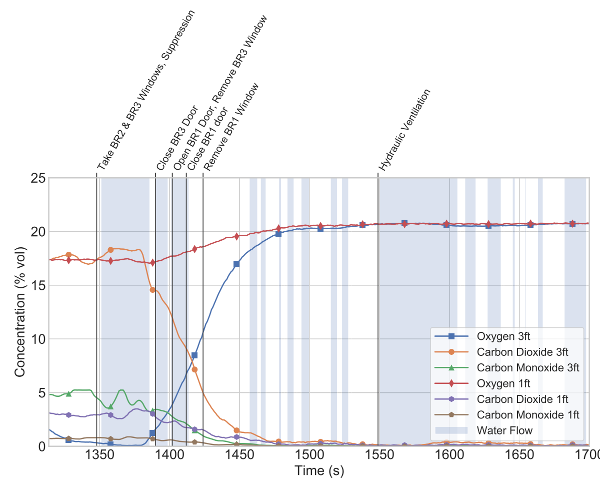
(a) Living Room Entry Hallway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

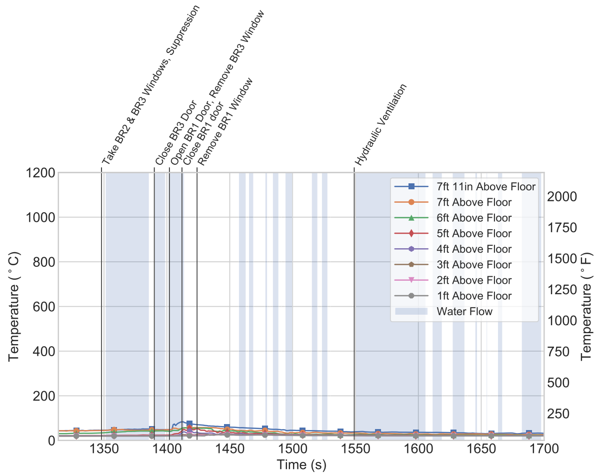
Figure 5.25: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 12

increase in O_2 immediately following the start of suppression and window ventilation, as fresh air entrained through the bedroom 3 window flowed through the mid hallway location. Following this initial decrease, CO and CO_2 briefly increased to a local peak 40 s after intervention, followed by a final decrease toward ambient concentrations. Gas concentrations at both mid hallway elevations had reached approximately ambient conditions prior to the start of hydraulic ventilation.

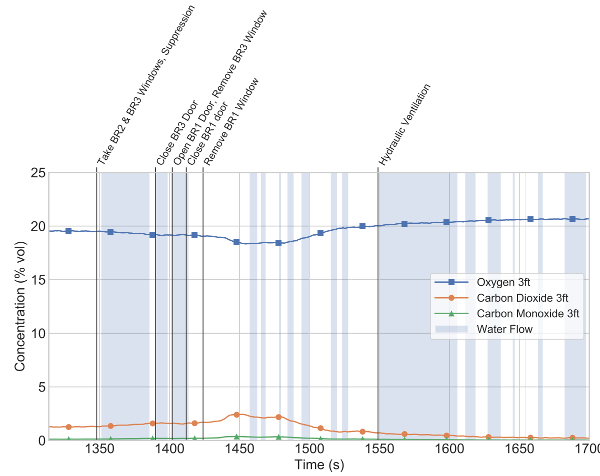
Figure 5.25d shows the time history of gas concentrations at the end hallway location. Although 3 ft gas concentrations at the end-hall location were comparable in magnitude to those observed at the other three measurement locations listed in Table 5.4, the 1 ft CO and CO_2 concentrations were considerably lower and O_2 concentration was considerably higher. This likely indicates that the fresh air that had been in bedroom 2 at the beginning of the experiment was still flowing toward the common space fire at the time of intervention, which resulting in comparatively lower toxic gas concentrations at intervention. Immediately following the start of suppression and window ventilation, 3 ft gas concentrations behaved comparably to the corresponding locations at the start and mid hallway locations, with values remaining steady for 30 s following intervention, and CO and CO_2 beginning to decrease and O_2 beginning to increase as the suppression crew extinguished the common space fire. Although the O_2 concentration was higher and the toxic gas concentrations were lower at the time of intervention, the 1 ft gas concentrations generally followed a similar trend, maintaining steady values until 40 s after intervention before beginning to trend toward pre-ignition levels. Similar to the other hallway locations, end hallway gas concentrations at both elevations had returned to approximately ambient concentrations prior to the start of hydraulic ventilation.

5.2.5 Bedroom 1

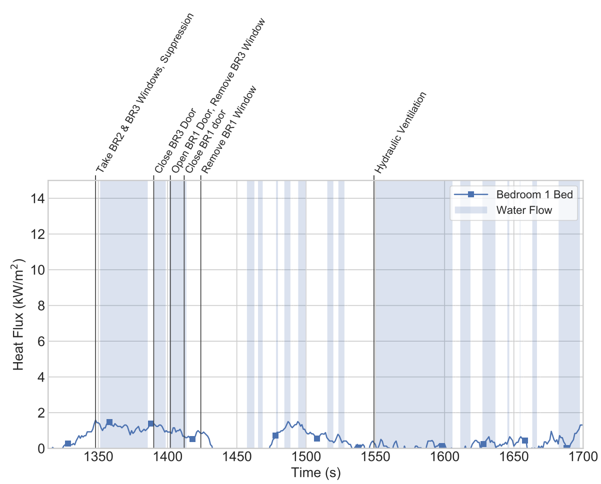
The door between bedroom 1 and the hallway was closed from the start of the experiment, which isolated bedroom 1 from combustion gases that filled the hallway. Figure 5.26 shows the time histories of temperature, heat flux, and gas concentration in bedroom 1 during Experiment 12. Figure 5.26a shows that at the time of intervention, temperatures 6 ft and above had increased to values ranging from 33 °C to 45 °C (91 °F to 113 °F) as a result of smoke leakage around the door and through the HVAC system, while temperatures close to the floor remained relatively unchanged. Immediately after the bedroom 1 door was opened, temperatures above 4 ft began to increase, as hot gases from the hallway flowed through the open bedroom door. Bedroom 1 ceiling temperatures peaked at 85 °C (185 °F) and 4 ft temperatures peaked at 48 °C (118 °F) just as the bedroom door was closed cutting off the flow of gases into the bedroom. Following this peak, temperatures decreased continuously for the remainder of the experiment, with no noticeable impact from hydraulic ventilation. As a result of the comparatively low temperatures and lack of gas flow in bedroom 1 during Experiment 12, the heat flux measured on the bed (Figure 5.26c) was approximately 1 kW/m^2 at the time of intervention and increased to approximately 1.5 kW/m^2 after the bedroom 1 door was opened. Following this peak, the heat flux in bedroom 1 decreased for the remainder of the experiment.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Gas Concentration

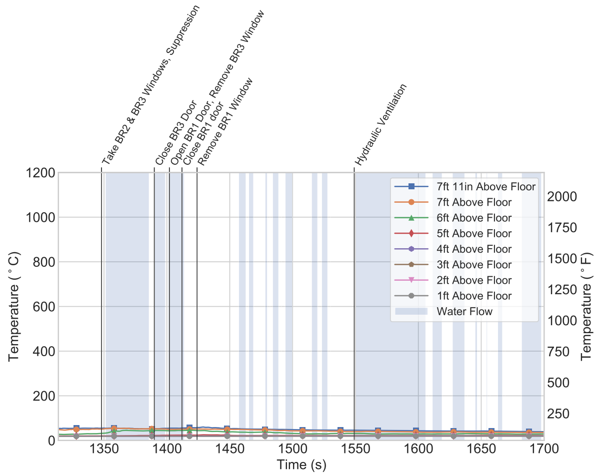


(c) Bedroom 1 Heat Flux

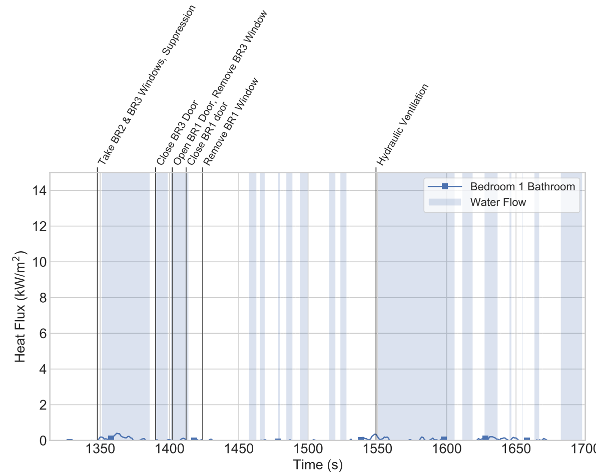
Figure 5.26: Temperature, heat flux, and gas concentrations in bedroom 1 in period following fire department intervention during Experiment 12.

At the time of intervention, O_2, CO_2, and CO concentrations 3 ft above the floor on the bed in bedroom 1 were 19.5%, 1.3%, and 0.1%, respectively, as shown in Figure 5.26b. These CO and CO_2 concentrations are considerably lower than the values measured at the corresponding bed location in bedroom 2, which was not isolated. Following initial intervention actions, gas concentrations continued to change gradually as products of combustion leaked through the doorway, with CO and CO_2 increasing and O_2 decreasing. The rate of change of gas concentrations did not noticeably change after the bedroom 1 door was opened as the smoke layer did not descend to the 3 ft elevation during the time window at which the door was open. Gas concentrations in bedroom 1 peaked approximately 100 s after intervention, which was after the ventilation sequence had been completed and the bedroom 1 window had been removed. This was a result of residual gases cooling and descending in the space. CO and CO_2 concentrations remained elevated at the start of hydraulic ventilation, at values of 0.1% and 0.7%, respectively as the closed bedroom 1 door limited flow toward the area of low pressure created by the flowing water.

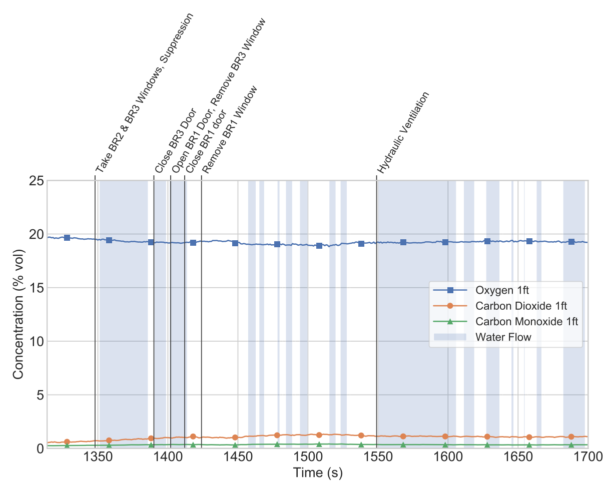
The door between bedroom 1 and bathroom 1 was closed from the beginning of the experiment. Figure 5.27 shows the time histories of temperature, heat flux, and gas concentration in the period following intervention in bathroom 1. Although the bathroom was isolated from the hallway by two closed doors, the temperatures closest to the ceiling were comparable at the time of intervention, a result of products of combustion transported into bathroom 1 via the HVAC system. Temperatures in bathroom 1 remained relatively steady from the start of suppression through the end of the ventilation sequence, with the ceiling temperature peaking at approximately 60 °C (140 °F) shortly after the bedroom 1 window was opened. Temperatures close to the floor remained approximately ambient. Following this peak, temperatures gradually decreased for the remainder of the experiment, with no noticeable effect from hydraulic ventilation. As a result of the comparatively low temperatures and minimal gas flow in bathroom 1, heat flux 1 ft above the floor, shown in Figure 5.27b, was negligible.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Heat Flux



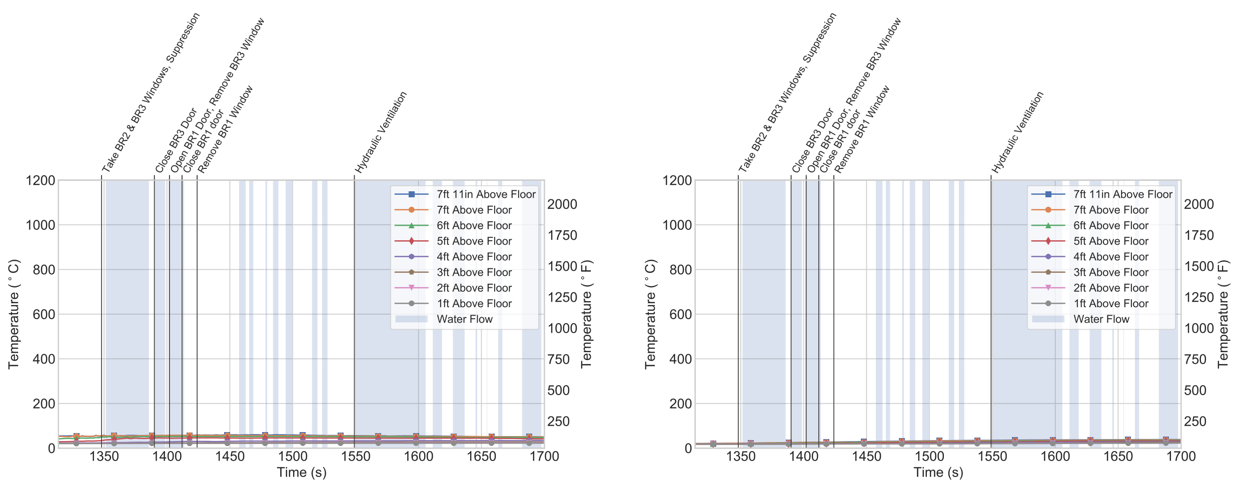
(c) Bathroom 1 Gas Concentration

Figure 5.27: Temperature, heat flux, and gas concentrations in bathroom 1 in period following fire department intervention during Experiment 12.

Gas concentrations in bathroom 1, shown in Figure 5.27c, were comparable to those measured in the adjacent bedroom at the time of intervention, with O_2, CO_2, and CO concentrations of 19.5%, 0.7%, and 0.3%, respectively. The gas concentrations gradually increased until approximately 140 s after intervention, when O_2, CO_2, and CO maintained steady peak values of 19.0%, 1.3%, and 0.4%, respectively, for approximately 40 s before beginning to gradually decrease for the remainder of the experiment. Although the magnitude of these CO and CO_2 concentrations were substantially lower than the peak concentrations measured elsewhere in the structure, they remained elevated for several hundred seconds after intervention as a result of the lack of air exchange between bathroom 1 and the rest of the structure.

5.2.6 Bedroom 4

Figure 5.28 shows the time histories of temperature in bedroom 4 and the bedroom 4 closet during Experiment 12. Similar to bedroom 1, the doorway between bedroom 4 and the hallway was closed from the beginning of the experiment. At the time of intervention, temperatures at all elevations in bedroom 4 had started to increase as a result of smoke leakage into bedroom 4. Temperatures at the time of intervention ranged from 55 °C (131 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor, and remained relatively steady throughout the ventilation sequence. As a result of the isolation provided by the closed bedroom door, hydraulic ventilation had little impact on the rate of change of temperatures in bedroom 4. Temperatures in bedroom 4 gradually decreased following suppression through heat transfer to the walls and leakage through the door.



(a) Bedroom 4 Temperature

(b) Bedroom 4 Closet

Figure 5.28: Temperature, heat flux, and gas concentrations in bedroom 4 in period following fire department intervention during Experiment 12.

Figure 5.28b shows that temperatures in the bedroom 4 closet were approximately ambient at the time of intervention, but increased following the start of suppression and ventilation actions. Temperatures in the closet were lower than in the adjacent bedroom, remaining below 40 °C for the duration of the experiment. Similar to the bedroom 4 temperatures, closet temperatures were unaffected by hydraulic ventilation and continued to gradually decrease to pre-ignition values due to heat transfer to the structure.

5.3 Experiment 13

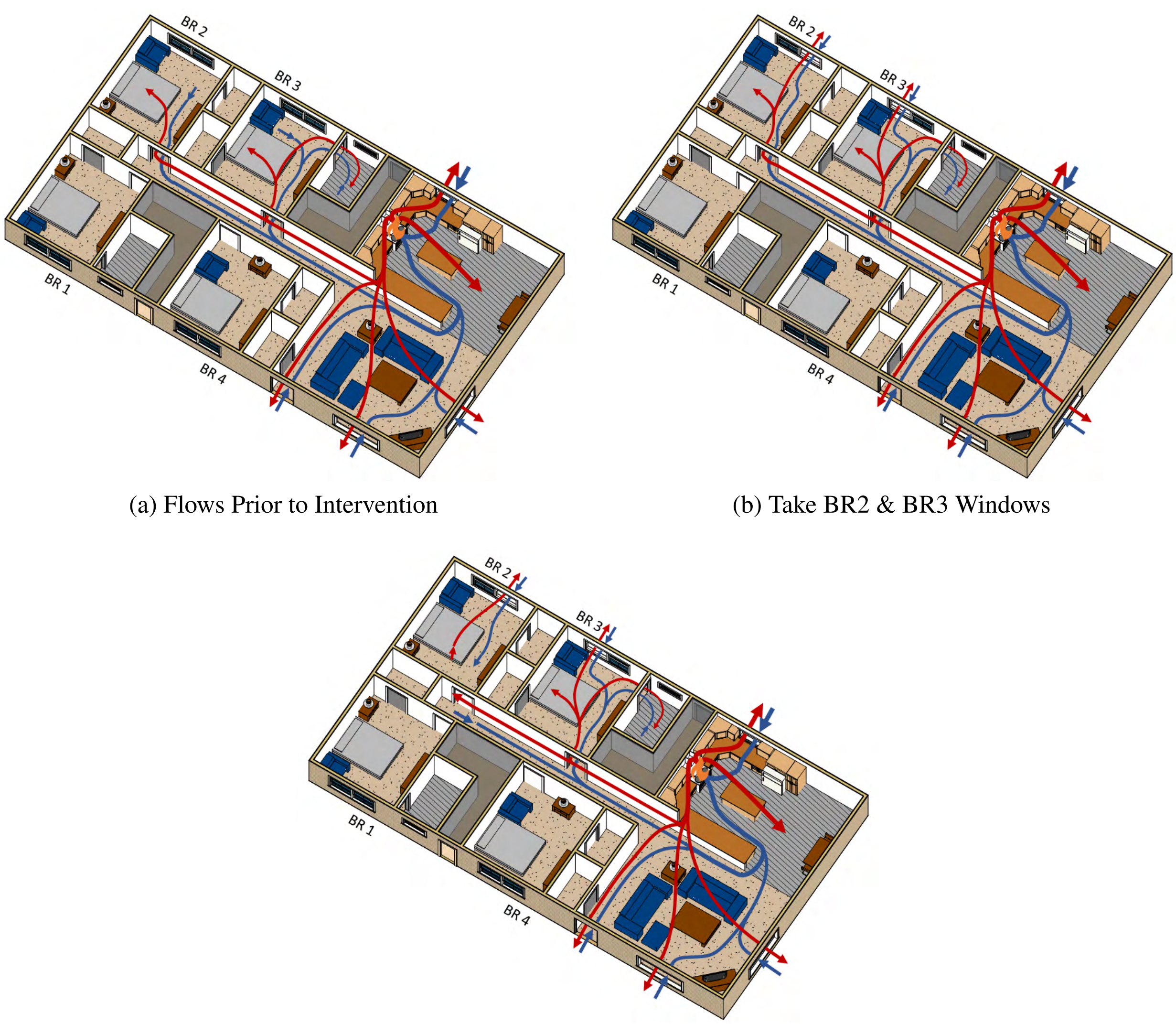
The search tactics in Experiment 13 were designed to evaluate a comparison of window initiated operations conducted prior to interior suppression of a common space (living room and kitchen) fire. At the time of ignition, the kitchen window and front door were opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2 and 3 were opened. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets, which led to flashover of the kitchen. The fire then spread to the living room, where flashover occurred following the failure of the side A and side D windows. Post-flashover of the common space, crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. The crew in bedroom 2 entered the bedroom and proceeded toward the door to the hallway and closed the door. This action isolated bedroom 2 from the fire gases produced by the common space fire. At the same time, the crew in bedroom 3 entered the bedroom and proceeded toward the hallway. This crew was unable to isolate bedroom 3. After isolation of bedroom 2, the crew crossed the hall to bedroom 1. The closed bedroom 1 door was opened to allow for crew entry. The crew closed the door behind them. Once isolated in bedroom 1, the crew proceeded to remove the bedroom 1 window. At this point the search tactic comparison was complete and suppression began with interior suppression with entry to the structure through the front door. 156 gallons were flowed during suppression. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side D living room windows. The total amount of water flowed during suppression and hydraulic ventilation was 312 gallons. The time at which tasks were initiated are listed in Table 5.5.

Table 5.5: Experiment 13 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	05:46	346	—	—
Take BR2 & BR3 Windows	21:50	1310	00:00	0
Close BR2 Door	22:32	1352	00:42	42
Open BR1 Door, Remove BR2 Window	22:45	1362	00:55	55
Close BR1 Door	22:55	1372	01:05	65
Remove BR1 Window	23:09	1386	01:19	79
Suppression	23:26	1406	01:36	96
Hydraulic Ventilation	28:24	1704	06:34	394

Figures 5.29 and 5.30 show the changes in flow in the period immediately preceding and following fire department intervention over the course of Experiment 13. At the time of intervention in Experiment 13, the living room and kitchen were in a post-flashover state. Bidirectional flows had been established through the kitchen window, the front door, and the side A and D living room windows; fire and smoke exhausted through the top of the vents while fresh air was entrained through

the lower portion (Figure 5.29a). The initial fire department intervention was the ventilation of the bedrooms 2 and 3 windows, creating two new exterior vents and establishing a bidirectional flow through both bedrooms, as shown in Figure 5.29b. Hot gases at the ceiling flowed from the hallway into the bedroom and exhausted through the upper portion of the bedroom window while fresh air was entrained through the lower portion of the bedroom window and flowed along the floor through the bedroom toward the common space fire. In bedroom 3, this bidirectional flow was maintained for the duration of the experiment. Conversely, in bedroom 2, the door between the hallway and the room was closed 42 s after intervention. This action isolated bedroom 2 from the products of combustion in the hallway and established a new flow path, with the bedroom 2 window acting as both the intake and exhaust, as shown in Figure 5.29c. This allowed smoke that was trapped in bedroom 2 to exhaust to the exterior of the structure.



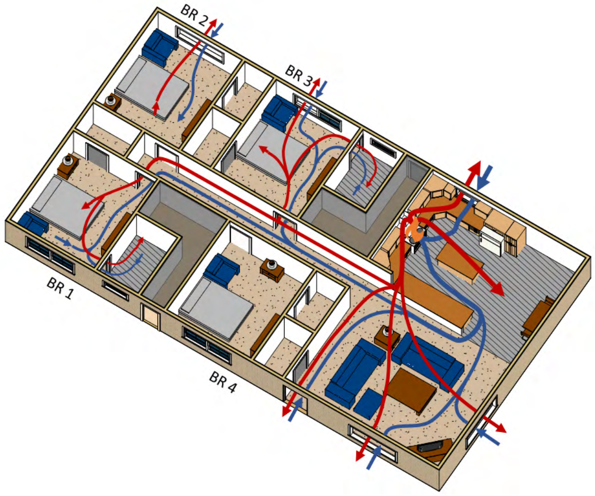
(a) Flows Prior to Intervention

(b) Take BR2 & BR3 Windows

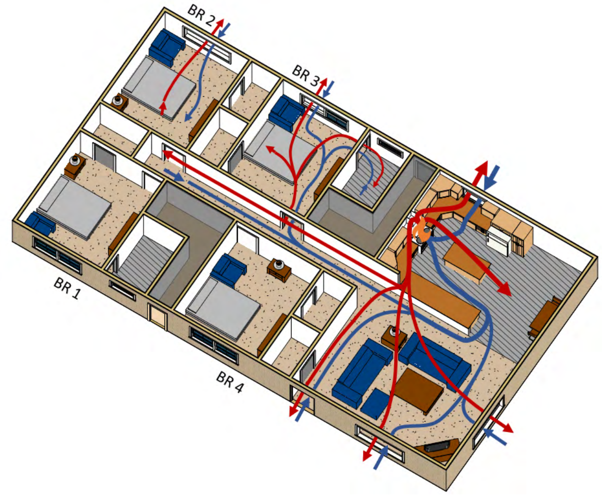
(c) Close BR2 Door

Figure 5.29: Changes in flow in structure following fire department interventions in Experiment 13.

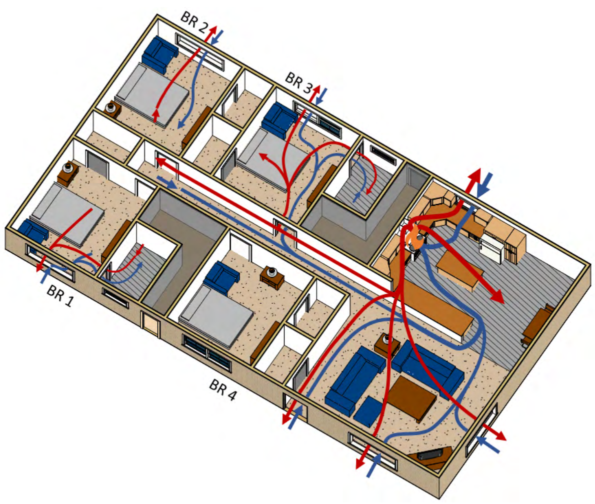
Shortly after the bedroom 2 door was closed, the bedroom 1 door was opened, simulating a firefighter searching across the hallway from bedroom 2. This briefly established bidirectional flow into bedroom 1, as shown in Figure 5.30a. Products of combustion from the hallway flowed into bedroom 1 and air in bedroom 1 flowed into the hallway. The bedroom 1 door was closed again 10 s later, which stopped gas exchange to the hallway to as shown in Figure 5.30b. The products of combustion which had flowed into bedroom 1 in the period between opening and closing the door were trapped in the space until 14 s later, when the bedroom 1 window was removed. This created a new flow path which allowed trapped smoke to exhaust through the upper portion and fresh air to flow through the lower portion (Figure 5.16c). After the search sequence was completed, suppression was initiated from the deck with a 1 3/4 in. handline equipped with a 7/8 in. smooth bore nozzle and nominal flow rate of 160 gpm. The suppression crew flowed water through the front door and living room window for 7 s to control the fire to the point where they could advance to the front door. They flowed water from the front door for 4 s before advancing to the interior while flowing. The majority of the common space had been extinguished within 30 s of the start of suppression. A total of 156 gallons were flowed from the start of suppression to the start of hydraulic ventilation. After the the living room fire had been brought under control, the suppression crew began hydraulic ventilation through the side D window with the tip off and fully opened nozzle rotated in an O-pattern. This action reduced the pressure at the living room window and drew products of combustion from remote locations in the structure toward the living room (Figure 5.30d).



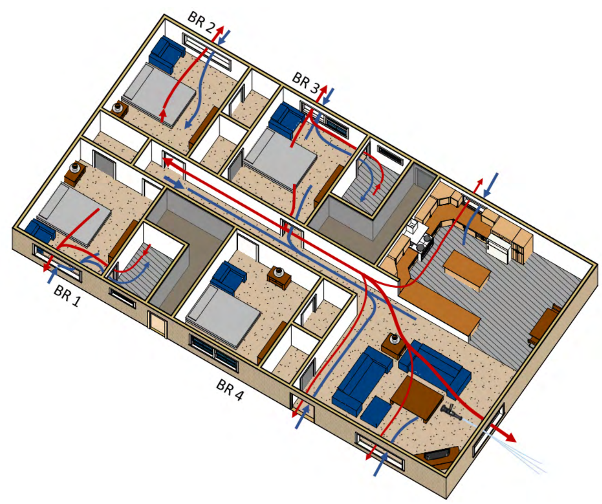
(a) Open BR1 Door, Remove BR2 Window



(b) Close BR1 Door



(c) Remove BR1 Window

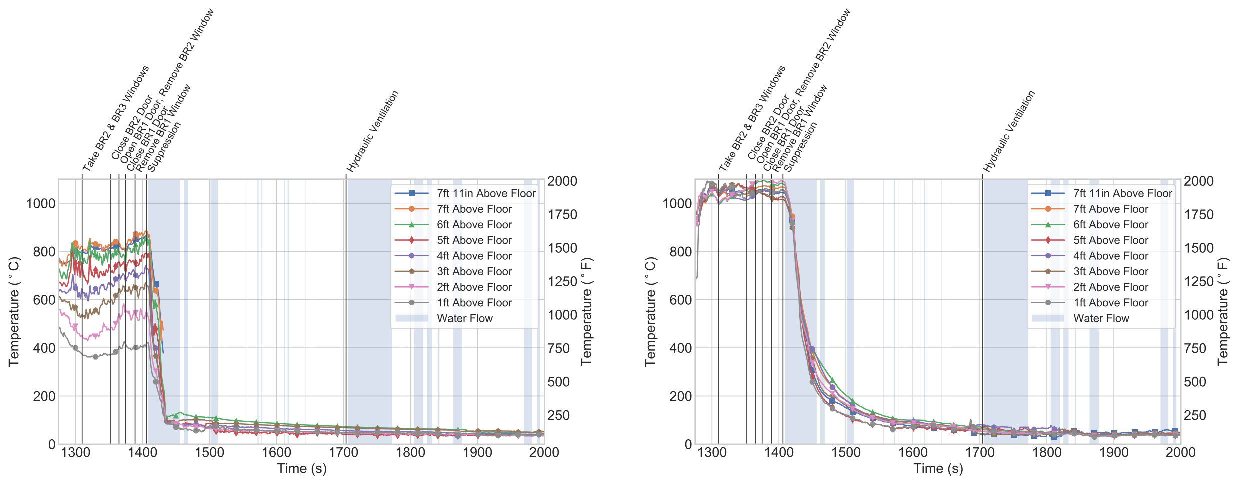


(d) Hydraulic Ventilation

Figure 5.30: Changes in flow in structure following fire department interventions in Experiment 13.

5.3.1 Common Space

Figure 5.31 shows the temperature in the kitchen and the living room in the period following intervention. Immediately prior to ventilation of the bedroom 2 and 3 windows, temperatures in the living room were uniformly in excess of 1000 °C (1832 °F), while temperatures in the kitchen were stratified from 820 °C to 380 °C (1508 °F to 716 °F). The living room temperatures were consistent with post-flashover conditions in the common space. The kitchen temperatures were lower, an indication that the lack of ventilation in the kitchen inhibited further flaming combustion. Temperatures in both the kitchen and living room were not noticeably affected by any of the actions of the ventilation sequence. Temperatures at both common space locations began to decrease immediately after the start of suppression.



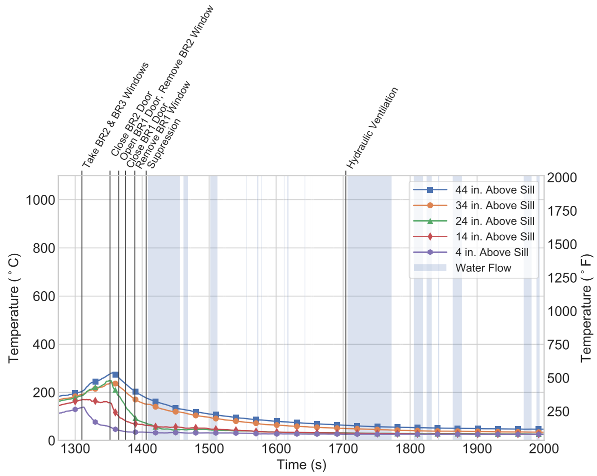
(a) Kitchen Temperature

(b) Living Room Temperature

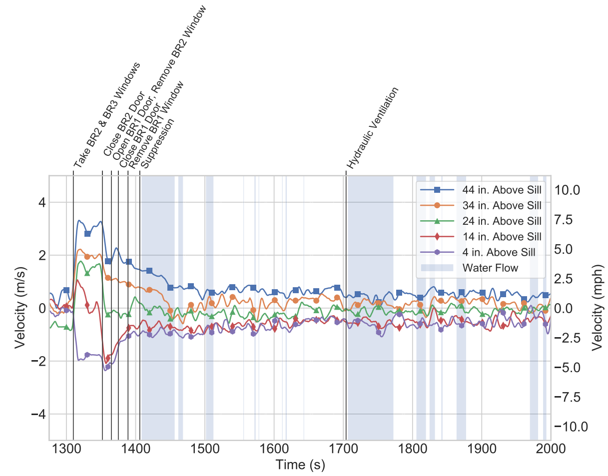
Figure 5.31: Temperature time histories in the common space for the period following fire department intervention in Experiment 13.

5.3.2 Bedroom 2

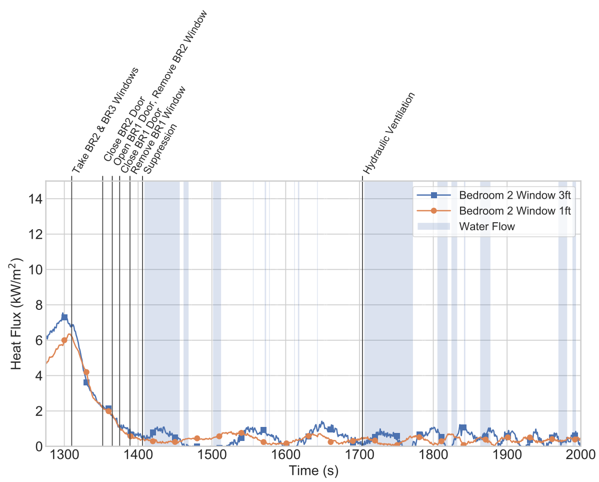
The initial fire department intervention in Experiment 13 was the ventilation of the bedroom 2 and 3 windows. The temperature, heat flux, velocity, and gas concentration measured at the bedroom 2 window are shown in Figure 5.32. Figure 5.32a shows that immediately following ventilation of the bedroom 2 window, temperatures at the upper three measurement locations (44 in., 34in., and 24 in. above the sill) increased, while the lower two measurement locations (4 in. and 14 in.) decreased. This was a result of the bidirectional flows established in the window; hot gases exhausted through the upper portion of the window and air was entrained through the lower portion. Figure 5.32b shows that peak exhaust velocities ranged from 3.5 m/s to 2.1 m/s (7.8 mph to 4.7 mph), while entrainment velocities ranged from -2.4 m/s to -1.2 m/s (-5.4 mph to -2.7 mph). Window velocities remained relatively steady in the period after the bedroom 2 window was vented while exhaust temperatures steadily increased to peaks ranging from 275 °C to 240 °C (527 °F to 464 °F), which occurred when the bedroom 2 door was closed. This action isolated bedroom 2 from the flow of hot gases from the hallway, and resulted in a decrease in exhaust temperatures and exhaust velocities. After the bedroom 2 door was closed, a bidirectional flow path was maintained in bedroom 2. Exhaust velocities and temperatures continuously decreased as trapped smoke vented through the open window and was replaced with air. No substantial change in window velocity was observed during hydraulic ventilation in bedroom 2 as a result of the closed door.



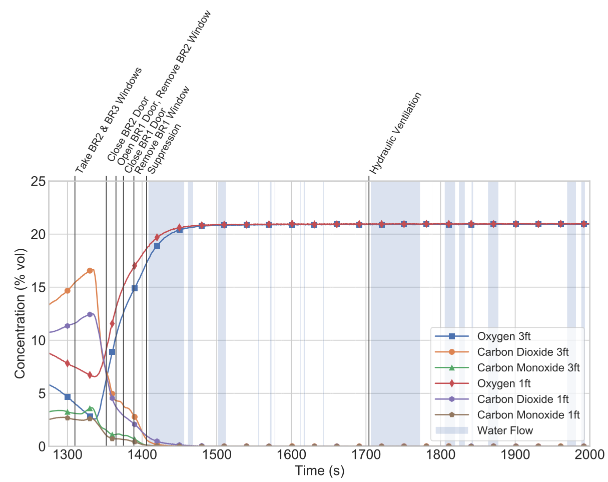
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

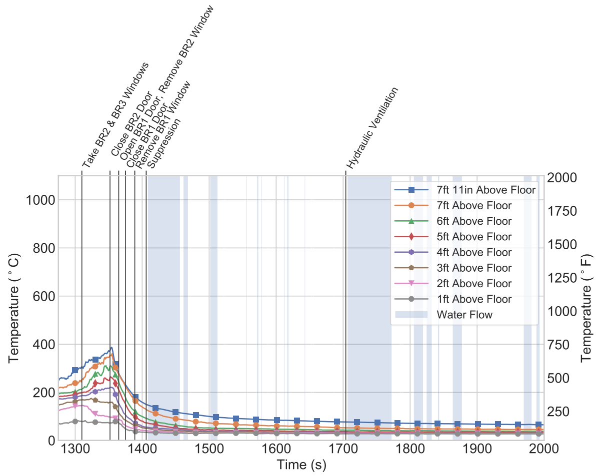
Figure 5.32: Post-intervention window temperature, velocity, heat flux and gas concentrations in bedroom 2 during Experiment 13.

Figure 5.32c shows the heat flux measured 3 ft and 1 ft above the floor in the bedroom 2 window at the time of intervention was 6.9 kW/m^2 and 6.3 kW/m^2, respectively. Immediately following window ventilation, the air entrainment through the lower portion of the window caused the heat flux at both elevations to decrease. This decrease continued as the bedroom 2 door was closed and the ventilation sequence continued, with the heat flux at both elevations decreasing below 0.5 kW/m^2 prior to the start of suppression.

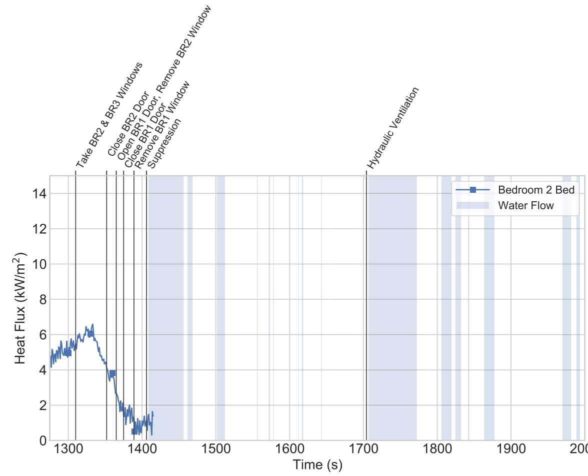
At the time of intervention, gas concentrations in the bedroom 2 window were characterized by high CO and CO_2 concentrations and low O_2 concentrations, consistent with a smoke layer that had descended below the 1 ft measurement location, as shown in Figure 5.32d. CO and CO_2 concentrations were higher at the 3 ft elevation than at the 1 ft elevation. Gas concentrations were 4.0% O_2, 15.4% CO_2, and 3.1% CO 3 ft above the floor and 7.5% O_2, 11.6% CO_2, and

2.5% CO 1 ft above the floor. Following window ventilation, CO and CO_2 increased and O_2 decreased for 25 s after the windows were ventilated. At this time, the fresh air entrained through the inlet portion of the window combined with the exhaust of combustion gases caused CO and CO_2 concentrations to begin to decrease and O_2 concentrations to return to pre-ignition levels. This trend continued as the bedroom 2 door was isolated, with gas concentrations at both elevations returning to approximate initial conditions prior to the end of the initial suppression actions.

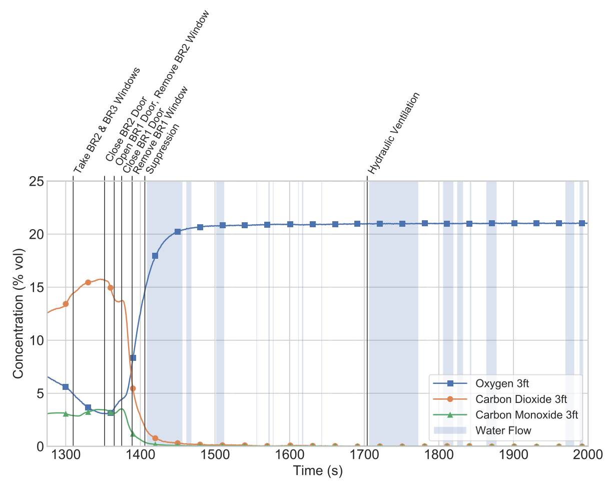
Figure 5.33 shows the time histories of temperature, gas concentration, and heat flux in the center of bedroom 2 in the post-intervention period of Experiment 13. Temperatures at all elevations were increasing immediately prior to intervention, as shown in Figure 5.33a. Immediately after the bedroom 2 window was vented, temperatures 4 ft and above continued to increase, while temperatures 3 ft and below began to decrease, reflecting the bidirectional flow that was established following window ventilation. Temperatures close to the ceiling continued to increase until the bedroom door was closed, isolating bedroom 2 from the flow of hot gases from the hallway. This resulted in a sharp decrease in temperature at all elevations, which continued for the duration of the experiment as products of combustion exhausted through the window. Temperatures had decreased below 150 °C (302 °F) prior to the start of suppression and below 75 °C (167 °F) prior to the start of hydraulic ventilation.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

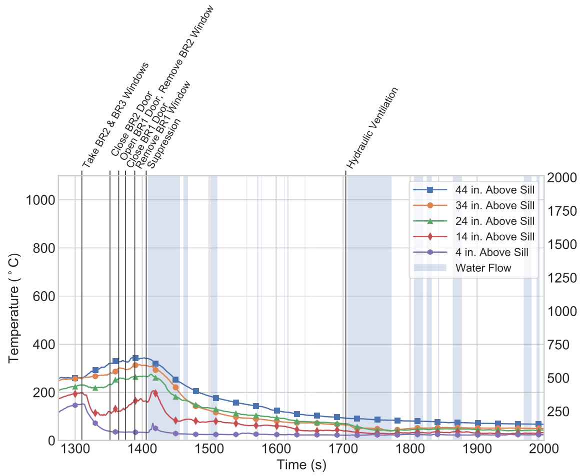
Figure 5.33: Bedroom 2 temperature and heat flux time histories after fire department intervention for Experiment 13.

Heat flux measured 3 ft above the floor on the center of the bed (Figure 5.33b) trended similarly to the room temperatures. At the time of intervention, the heat flux had been generally increasing from ignition, despite some fluctuations in the measurement. Following the ventilation of the bedroom window, the heat flux increased from 4.6 kW/m^2 to 6.0 kW/m^2 due to the flow of hot gases through the hallway door, across the bed, and out the upper portion of the window. Simultaneous with the bedroom 2 door closing, heat flux in the room began to decrease, as the supply of high temperature gases was cut off and the velocity of exhaust gases decreased. As a result, the heat flux dropped to below 1 kW/m^2 prior to suppression before there was instrument failure during suppression.

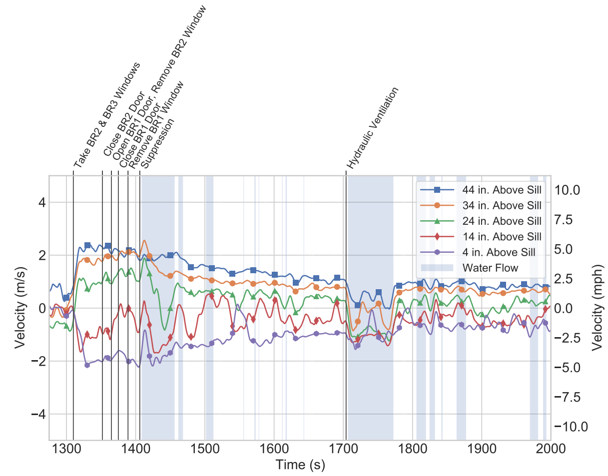
Figure 5.33c shows the time history of gas concentration 3 ft above the floor on the bed in bedroom 2. At the time of intervention, O_2, CO_2, and CO concentrations in bedroom 2 were 5.0%, 14.4%, and 2.9%, respectively, which were comparable to the values measured at the corresponding window location and were consistent with a smoke layer which had descended below the 3 ft measurement location. CO and CO_2 concentrations were increasing, while the O_2 concentration was decreasing, at the time that the bedroom 2 window was ventilated, in a manner similar to that observed at the window gas measurement locations. In contrast to the bedroom 2 window measurement locations, this increase in CO and CO_2 continued for 45 s after the window was opened. A decrease in CO and CO_2 and increase in O_2 was observed following the closure of the bedroom 2 door. The delayed improvement in gas concentrations on the bedroom 2 bed relative to the window can be attributed to the longer distance between the measurement location and the window. Gas concentrations returned to approximately ambient conditions shortly after initial fire control were completed.

5.3.3 Bedroom 3

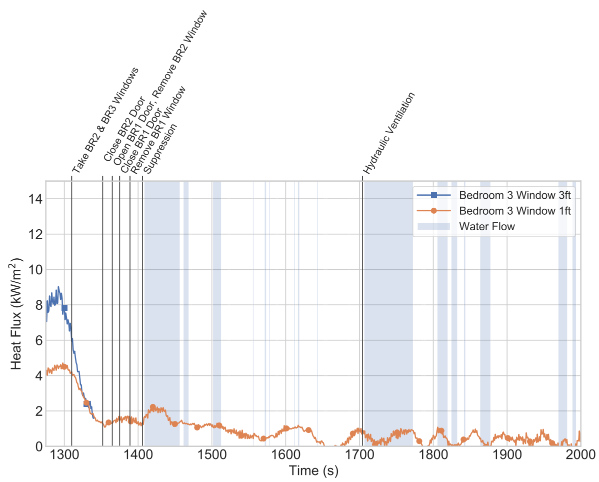
The bedroom 3 window was vented simultaneous with the bedroom 2 window as part of the initial fire department intervention. Figure 5.34 shows the time histories of temperature, velocity, heat flux, and gas concentration in the bedroom 3 window during Experiment 13. At the time of intervention, the temperatures measured at the bedroom 3 window were increasing, ranging from 250 °C to 150 °C (482 °F to 302 °F) from top to bottom at the window. Figure 5.34a shows that immediately following ventilation of the bedroom 2 window, temperatures at the upper three measurement locations (44 in., 34 in., and 24 in. above the sill) recorded a temperature increase, while the lower two measurement locations (14 in. and 4 in. above the still) recorded a temperature decrease. Bidirectional flow was established in the window. Hot gases exhausted through the upper portion of the window and air was entrained through the lower portion. Peak exhaust velocities ranged from 2.7 m/s to 1.0 m/s (6.0 mph to 2.2 mph), while entrainment velocities ranged from -2.0 m/s to -1.7 m/s (-4.5 mph to -3.8 mph), as shown in Figure 5.34b. In contrast to the window temperatures and velocities in bedroom 2, the lack of door control resulted in bidirectional flow with higher sustained magnitudes through the bedroom 3 window until the onset of suppression. Exhaust and entrainment velocities remained relatively constant at their post-ventilation values, while exhaust temperatures continuously increased until the start of suppression.



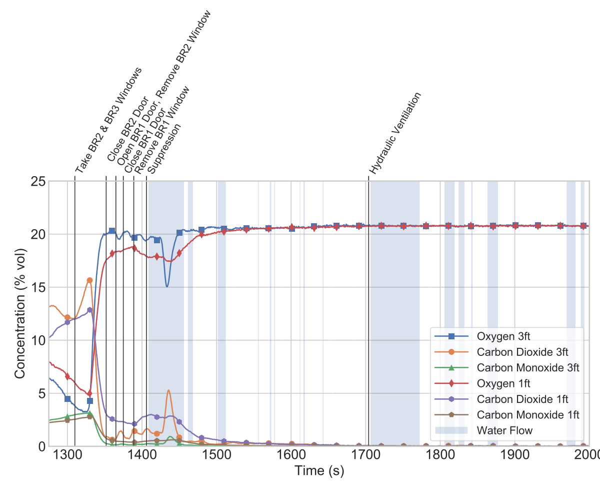
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.34: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 13.

Suppression was initiated 96 s after intervention (1406 s after ignition). Figure 5.34b shows a brief period of increased exhaust velocity at all five measurement locations 5 s after the start of suppression. This period of increased exhaust was accompanied by an increase in exhaust temperature, shown in Figure 5.34a. This was a result of air entrainment from the hoseline which was being manipulated in an O-pattern. The air entrainment resulted in an increased pressure in the common space, driving gas flow to the exterior vents — in this case, the non-isolated bedroom 3 window. This increase lasted approximately 5 s. Suppression actions brought the common space fire under control. Gas temperatures dropped and subsequently through gas contraction, the pressure dropped. This decrease in exhaust flow at the window continued until hydraulic ventilation was initiated, which caused velocities to uniformly decrease as fresh air was entrained through the bedroom 3 window toward the exterior vent in the living room.

Following ventilation of the bedroom 3 window, the flow of fresh air through the lower portion of the bedroom 3 window caused heat flux at both measurement elevations to decrease, as shown in Figure 5.34c. At the 3 ft elevation, the heat flux decreased continuously from 6.5 kW/m^2 to 1.8 kW/m^2 before there was signal failure from the instrument. The heat flux at the 1 ft elevation exhibited a similar decrease immediately following suppression, from 4.1 kW/m^2 to 1.2 kW/m^2. As suppression actions controlled the common space fire, heat flux at 1 ft elevation decreased to negligible values.

Figure 5.34d shows the time history of gas concentrations at the bedroom 3 window location. At the time of intervention, gas concentrations at the bedroom 3 measurement location were characterized by high concentrations of CO and CO_2 and low concentrations of O_2, indicating that the smoke layer had descended past the 1 ft measurement location. Gas concentrations were 3.8% O_2, 12.0% CO_2, and 3.0% CO 3 ft above the floor and 6.0% O_2, 11.9% CO_2, and 2.5% CO 1 ft above the floor. Immediately after ventilation, CO and CO_2 concentrations continued to increase for approximately 15 s before air entrainment through the lower portion of the window resulted in a sharp decrease in CO and CO_2 and increase in the O_2 concentration. Following this improvement in conditions, gas concentrations remained relatively steady until 5 s after the beginning of suppression, when a local peak in CO and CO_2 concentrations and sharp decrease in O_2 concentration was observed at the 3 ft measurement location simultaneous with the period of increased exhaust from the bedroom 3 window. A similar increase in toxic gas concentrations was not observed at the 1 ft measurement elevation. Following this local peak, CO and CO_2 concentrations continued to decrease while O_2 increased, with gas concentrations returning to ambient conditions prior to the start of hydraulic ventilation.

Temperatures measured in the center of bedroom 3, shown in Figure 5.35, followed a comparable trend to those observed at the window. At the time of intervention, temperatures were stratified from 370 °C (698 °F) at the ceiling to 75 °C (137 °F) 1 ft above the floor. Immediately following ventilation of the bedroom 3 window, temperatures began to change according to the bidirectional flow that was established in the room. Temperatures 5 ft and above increased and temperatures 4 ft and below decreased. The increase in temperatures close to the ceiling continued until the beginning of suppression. Although the 3 ft and 4 ft temperatures were initially cooled by inflow through the window, these temperatures began to increase again approximately 40 s after intervention as the flow of hot gases from the hallway increased. Immediately prior to suppression, temperatures in bedroom 3 ranged from 485 °C (905 °F) at the ceiling to 68 °C (154 °F) 1 ft above the floor. Suppression caused temperatures to decrease continuously with the exception of a brief increase in the temperatures above 4 ft, which occurred 5 s after the start of suppression. This was simultaneous with the period of increased exhaust shown in Figure 5.34b.

Figure 5.36 shows the time history of temperature, heat flux, and gas concentration measured in bathroom 3. Figures 5.36a and 5.36b show that temperatures and heat flux in the bathroom generally followed a similar trend to those in the adjacent bedroom. Temperatures at all elevations and heat flux 1 ft above the floor were increasing at the time of intervention, with temperatures ranging from 177 °C to 85 °C (351 °F to 185 °F) and a heat flux value of 2.9 kW/m^2. Immediately following ventilation of the bedroom 3 window, temperatures 5 ft above began to gradually increase, while temperatures 4 ft and below initially decreased as a result of fresh air entrainment through the

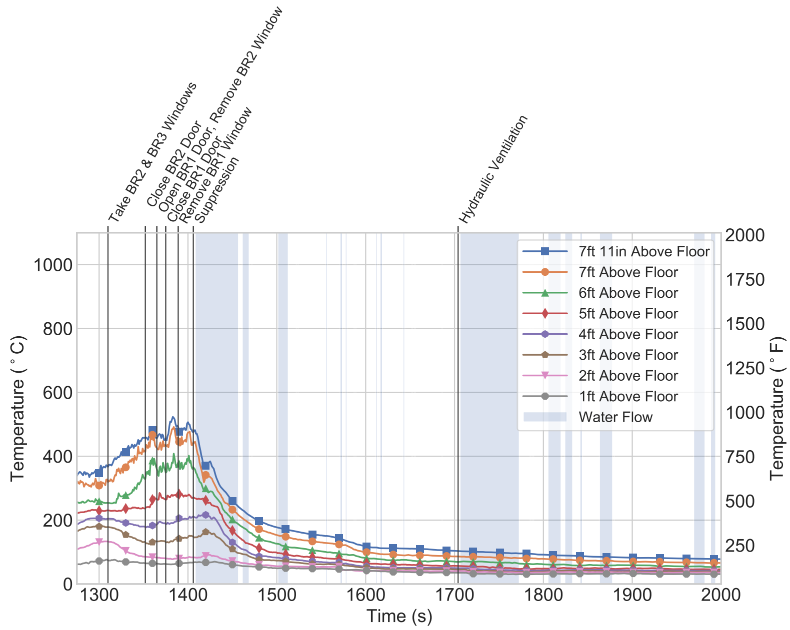
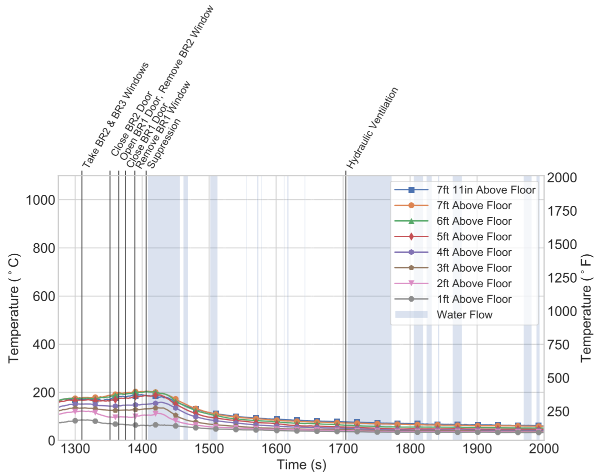


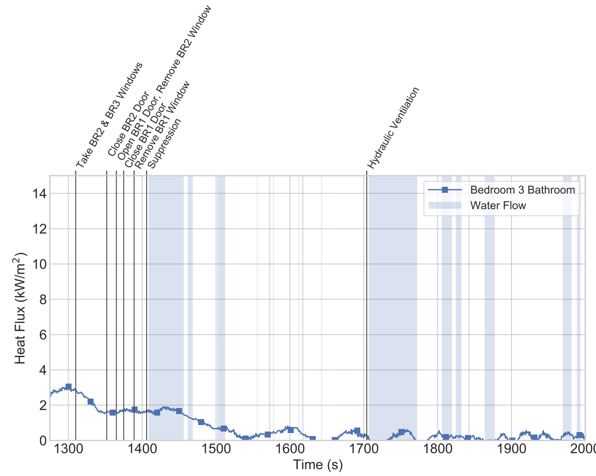
Figure 5.35: Post-intervention bedroom 3 temperature during Experiment 13.

bedroom 3 window. The initial decrease in temperatures was temporary at the 2 ft-4 ft elevations, where temperatures began to increase approximately 40 s after intervention as a result of the higher temperature gas flow through bedroom 3. The heat flux data exhibited a similar trend. Following intervention, heat flux decreased to 1.8 kW/m^2 at 40 s after intervention and plateaued prior to suppression. Suppression actions caused temperatures to decrease continuously with the exception of a brief increase in the temperatures 4 ft above the floor and below, which occurred 5 s after the start of suppression, simultaneous with the period of increased exhaust shown in Figure 5.34b.

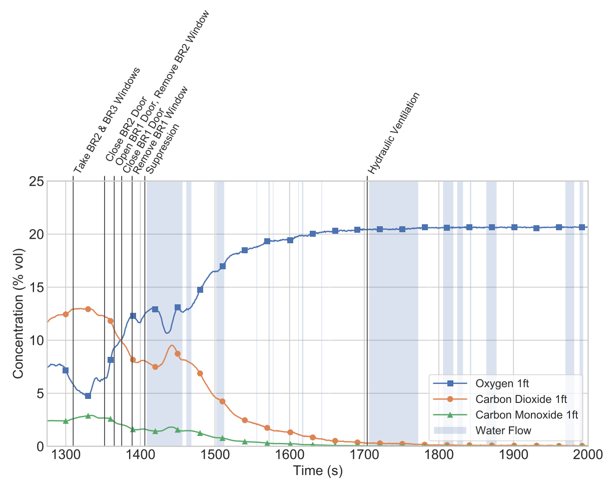
Figure 5.36c shows the time history of gas concentration in bathroom 3. At the time of intervention, O_2, CO_2, and CO concentrations were 5.9%, 12.9%, and 2.6%, respectively, which is comparable to the gas concentrations measured at the corresponding locations in bedroom 3. Immediately after ventilation, CO and CO_2 concentrations continued to increase for approximately 25 s, before air entrainment through the lower portion of the window resulted in a decrease in CO and CO_2 and increase in the O_2 concentration. Gas concentrations continued to improve until 5 s after the beginning of suppression, when a local peak in CO and CO_2 concentrations and sharp decrease in O_2 concentration was observed. This local peak corresponds with the peak in temperature, gas concentration, and heat flux observed at the bedroom 3 window measurement locations at the same time. Following this local peak, CO and CO_2 concentrations continued to decrease while O_2 increased, with gas concentrations returning to ambient conditions prior to the start of hydraulic ventilation.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux

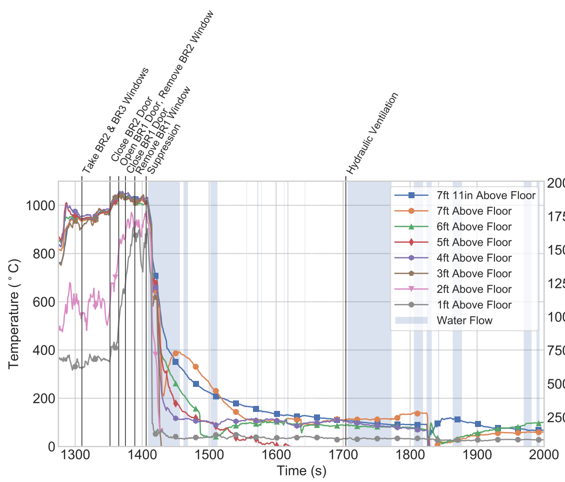


(c) Bathroom 3 Gas Concentration

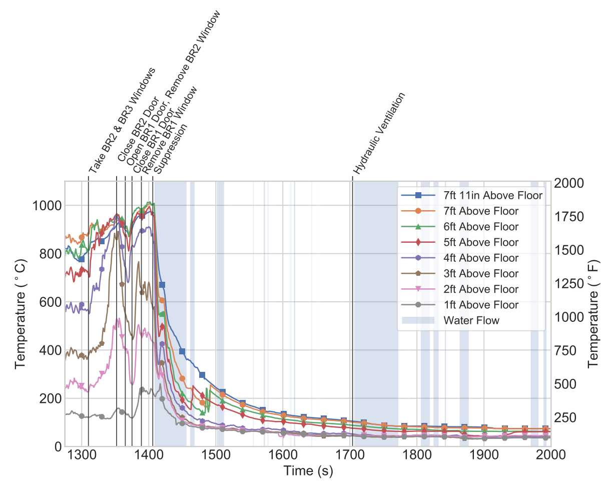
Figure 5.36: Post-intervention bathroom 3 temperature, heat flux, and gas concentration during Experiment 13.

5.3.4 Hallway

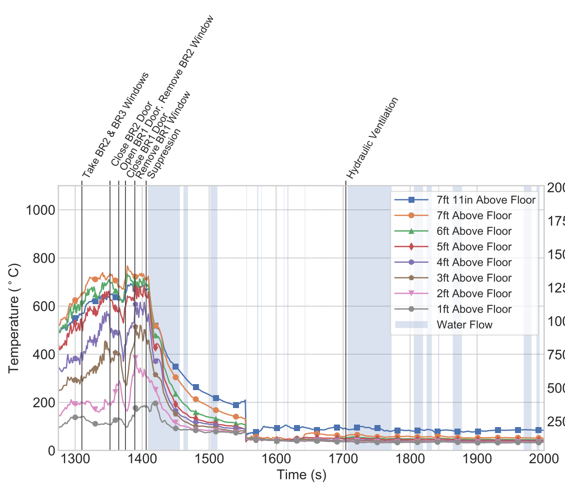
Figure 5.37 shows the time histories of temperature in the living room entryway and at the start, mid, and end hallway measurement locations. At the time of intervention, temperatures 3 ft and above at the living room entryway measurement were in excess of 800 °C (1472 °F). This is consistent with the post-flashover state of the living room at that time. Temperatures 1 ft and 2 ft above the floor were 325 °C and 530 °C (617 °F and 986 °F), respectively. The temperatures at these lower elevations were impacted by the exterior panel of the front door failing and folding over (Figure 5.38). The presence of the obstruction impacted local air flow and delayed the temperature rise. The living room fire remained in a post-flashover state, as the bedroom 2 and 3 windows were vented. The 1 ft and 2 ft temperatures increased above 900 °C (1652 °F) as the additional structure ventilation increased the inflow at the front door. Immediately after the start of suppression, temperatures in the living room entryway began to decrease. This decrease was punctuated by a brief period starting 5 s after the start of suppression, when temperatures between 3 ft and 5 ft plateaued. This plateau corresponds to the period in which increased exhaust was observed from bedroom 3. After this brief plateau, temperatures at all elevations decreased for the remainder of the experiment.



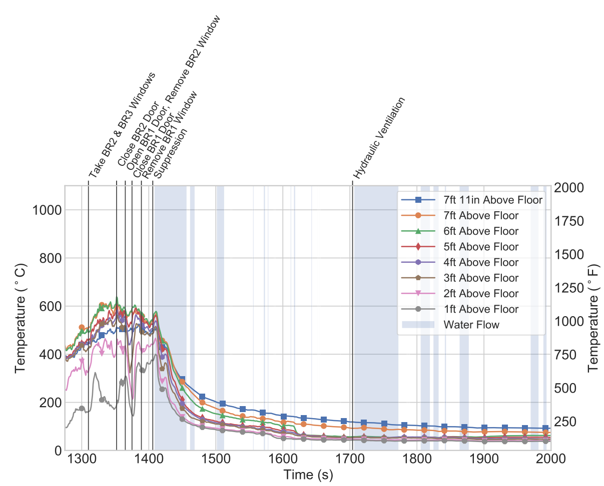
(a) Living Room Entry Hallway Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.37: Temperature time histories in the hallway in the period following fire department intervention in Experiment 13.

Figure 5.38: Photograph of front door panel fold over prior to suppression.

Temperatures at the three hallway measurement locations were stratified at the time of intervention. A lack of oxygen available for combustion prevented flame spread down the hallway. Temperatures were steady at the start hallway location but still increasing at the mid- and end hallway locations due to gas flow within the hallway. Temperatures were highest at the start hallway location, 883 °C (1621 °F) at the ceiling and 122 °C (252 °F) 1 ft above floor due the proximity to the common space fire. The mid hallway and end hallway locations had lower temperature ranges based on distance from the common space, with ceiling and floor temperature ranging from 643 °C to 136 °C (1189 °F to 277 °F) at the mid-hallway location, and from 510 °C to 160 °C (950 °F to 320 °F) at the end hallway location. Following ventilation of the windows in bedrooms 2 and 3, temperatures began to increase at all three locations. New flow paths were established between the common space and the exterior vents at the bedroom windows, which led to increased higher temperature gas flow through the hallway.

The distance between the hallway measurement locations and the inlet flow paths at the bedroom windows negated the cooling effect from entrained air that was observed at the bedroom measurement locations. In other words, the inlet air was mixed with higher temperature before flowing into the hallway. The temperature increase was most notable at the start hallway location, where the 3 ft and 4 ft temperatures increased in excess of 600 °C (1112 °F) in the period between ventilation of the bedroom windows and the closing of the bedroom 2 door.

When the bedroom 2 door was closed 42 s after intervention, the flow path through bedroom 2 was cut off. This restricted the flow of combustion gases through the hallway, as evidenced by the decrease in temperatures. This decrease continued until the bedroom 1 door opened, which allowed the lower-pressure volume of air that had been trapped behind the closed door to exchange with the hallway. The additional volume of air that flowed toward the common space resulted in an increase in both the heat release of the fire and temperature at all three hallway locations approximately 65 s after intervention (1375 s after ignition).

Following the fluctuations in temperatures caused by manipulation of the bedroom 2 door and bedroom 1 door, hallway temperatures maintained a steady state until the beginning of suppression. Hallway temperatures began to uniformly decrease immediately after the beginning of suppression. This decrease was punctuated by a brief temperature increase at all three measurement locations, which started approximately 5 s after the start of suppression. This temperature increase was most pronounced at measurement elevations lower than 5 ft above the floor. Further, the timing of this increase matched the increase in temperature, heat flux, CO and CO_2 concentration, and exhaust velocity observed in bedroom 3. Air entrainment from the hoseline increased the pressure in the common space. The increased pressure supplemented the gas flow along the flow path between the common space and the bedroom 3 window. This increased the flow of higher temperature gases through the hallway. As the suppression crew continued to flow water, temperatures dropped and gases contracted. Gas contraction led to a drop in pressure which decreased the flow of combustion gases through the space.

Figure 5.39 shows the time histories of heat flux in the living room entryway and at the three hallway locations during Experiment 13. Heat flux at the living room entryway fluctuated between 18 kW/m^2 and 22 kW/m^2 for the duration of the period between intervention and the start of suppression. Similar to the 1 ft and 2 ft temperatures at this location, the heat flux was also impacted by the front door panel failure. Heat flux measurements at the start, mid, and end hallway locations at the time of intervention were considerably lower than in the living room entryway, with values of 5.0 kW/m^2, 5.3 kW/m^2, 2.3 kW/m^2, respectively. Lower temperatures at these locations combined with lower velocity gas flows and no flaming combustion reduced the heat transfer. In the period between window ventilation and suppression, the hallway heat flux values remained relatively constant. Following the opening of the bedroom 1 door and subsequent increase in heat release rate of the fire, the start hall heat flux increased from 3.9 kW/m^2 to a peak of 25.6 kW/m^2. This indicates that there was an increase in flaming combustion near the start hallway location. The start hallway heat flux decreased from the peak value prior to suppression as the oxygen which was supplied from bedroom 1 was consumed. Suppression caused heat flux to decrease at all locations. Note, signal issues resulted in additional noise in data following suppression.

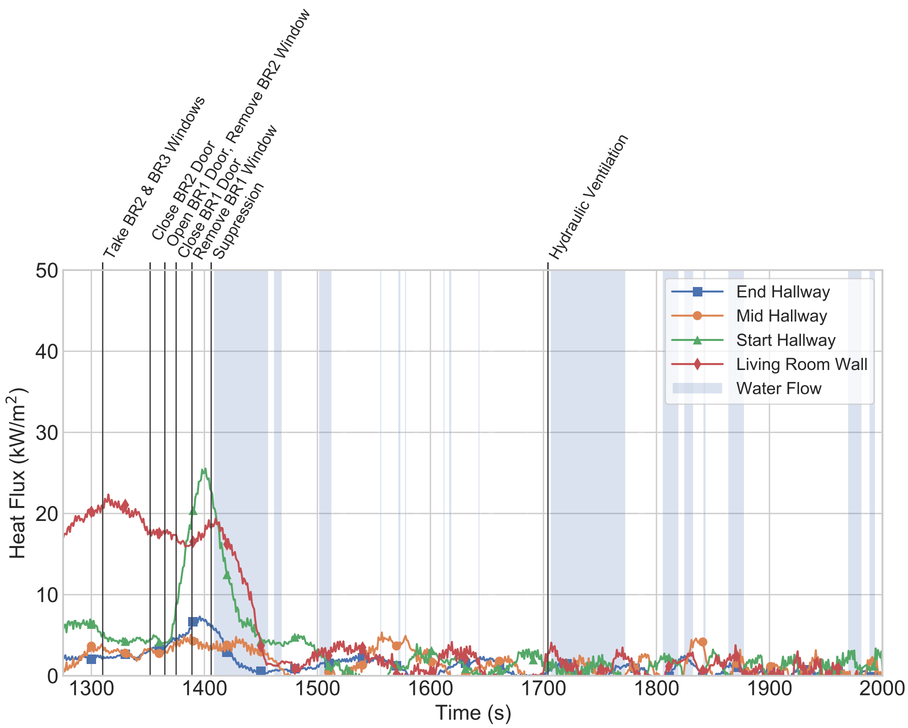


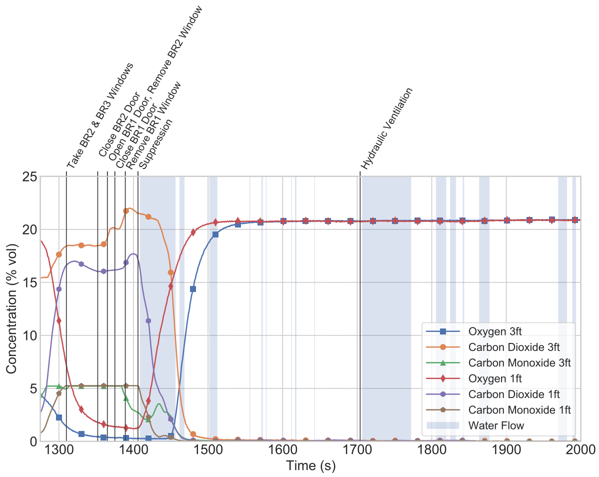
Figure 5.39: Heat flux time histories in the hallway in post-intervention period during Experiment 13.

Figure 5.40 shows the time histories of gas concentration at the living room entryway and hallway locations during Experiment 13. At the time of intervention, the distribtion of hallway gases was characterized by high concentrations of CO and CO_2 and a low O_2 concentration, as listed in Table 5.6.

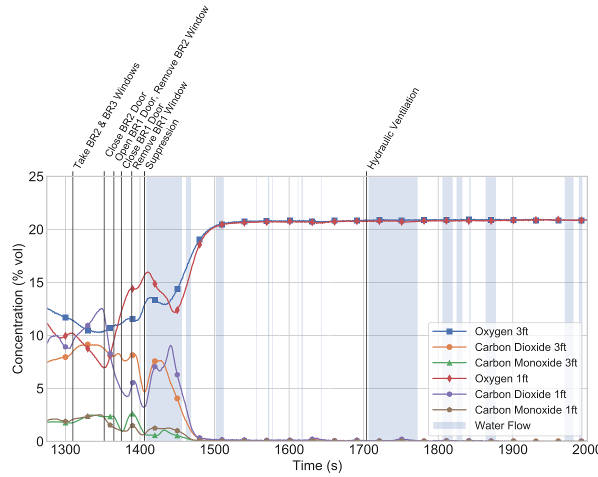
Table 5.6: Hallway Gas Concentrations at Intervention for Experiment 13

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	1.4	18.4	5.0
	1 ft	7.5	16.5	5.0
Start Hall	3 ft	11.4	8.4	1.7
	1 ft	10.2	9.2	2.1
Mid-Hall	3 ft	3.5	16.1	2.8
	1 ft	10.8	11.4	2.7
End Hall	3 ft	1.2	18.0	3.0
	1 ft	17.2	3.7	0.7

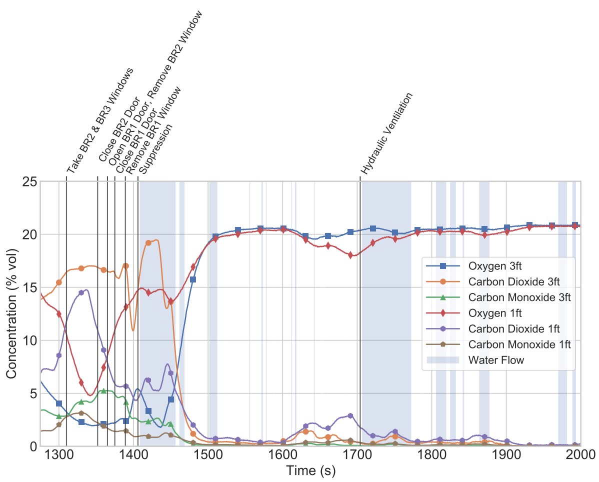
At the living room entryway, concentrations remained steady through the ventilation sequence. At the start of suppression, CO and CO_2 concentrations decreased and the O_2 concentration increased. This decrease was punctuated by a brief increase in CO and CO_2 and decrease in O_2, which started approximately 5 s and lasted approximately 15 s. This was most pronounced at the 3 ft elevation, where CO increased from 2.1% to 3.3%. Following this local peak, gas concentrations continued to trend toward ambient, returning to approximately ambient values prior to the start of hydraulic ventilation. This response was similar to the temporary temperature, heat flux, and velocity increases along the flow path that terminated at the bedroom 3 window.



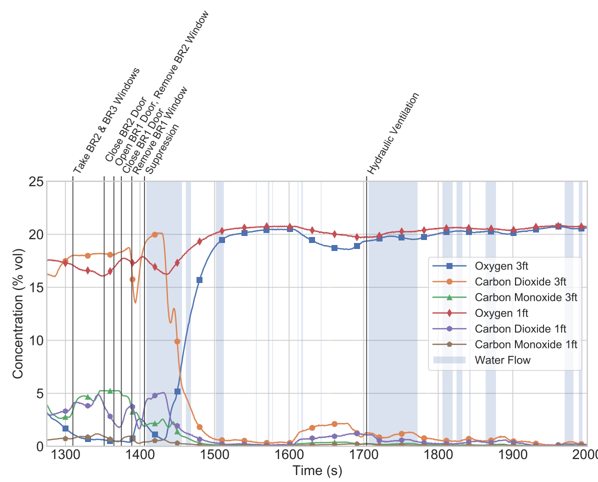
(a) Living Room Entryway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.40: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 13.

The magnitude of O_2, CO_2, and CO concentrations at the time of intervention varied among the three hallway locations, those of which are shown in Table 5.6. At all three hallway locations, CO and CO_2 concentrations at both elevations were increasing and the O_2 was correspondingly decreasing at the time of intervention.

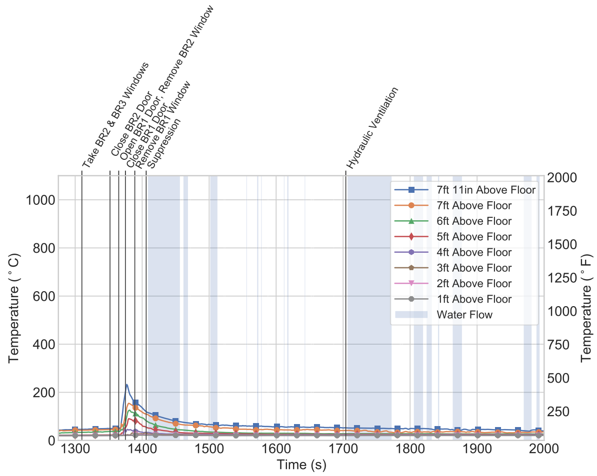
Following ventilation of the bedrooms 2 and 3 windows, air began to flow through the lower portion of windows and mix with the gases in the respective bedrooms. As the lower pressure gases flowed into the hallway toward the common space fire, further mixing resulted in a decrease in CO and CO_2 and increase in O_2 at all three hallway measurement locations. This improvement in gas concentrations was most pronounced at the start and mid hallway locations, which were located along the flow path between bedroom 3 to the common space. The bedroom 3 door remained open for the duration of the experiment compared to bedroom 2 which was closed following the window ventilation. At the mid and start hallway locations, CO and CO_2 continued to decrease while O_2 increased until suppression. At the end hallway location, the decrease in CO and CO_2 as a result of air entrainment through the bedroom 2 window was only observed at the 1 ft elevation and was limited compared to the benefit seen at the mid and start hallway locations.

After the bedroom 1 door was opened, air that had previously been trapped in that room was drawn toward the common space fire, resulting in a further decrease in CO and CO_2 and increase in O_2 at each hallway measurement location. In contrast to the benefit following window ventilation, the benefit following cycling of the bedroom 1 door was temporary, since the volume of air in bedroom 1 was fixed, the door was only open for a fixed amount of time, and that air led to increased burning near the start hallway location.

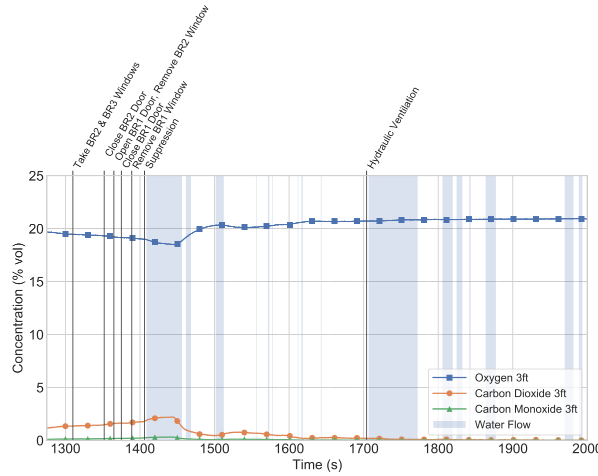
Gas concentrations at all three hallway measurement locations began to trend toward ambient approximately 20 s after suppression began. Similar to the trend observed with temperature and heat flux, this decrease was interrupted by a brief increase in CO and CO_2 as a result of the flow of products through the hallway due to increased pressure associated with air entrainment from hoseline. At the start hall location, gas concentrations had returned to pre-ignition levels prior to the start of hydraulic ventilation. At the mid and end hall locations, a local increase in gas concentration was measured starting approximately 300 s after intervention (1610 s after ignition). This increase was a result of smoldering debris during mop-up by the suppression crew. Hydraulic ventilation increased the rate of return to pre-ignition concentrations. This was more effective at the mid hallway location as there was a local exterior (bedroom 3 window) that served as a supply of air. The end hallway location return was not as pronounced due to not being in a flow path.

5.3.5 Bedroom 1

Figure 5.41 shows the time histories of temperature and gas concentration in bedroom 1 during Experiment 13. The door between bedroom 1 and the hallway was closed from the time of ignition. Figure 5.41a shows that at the time of intervention, temperatures in bedroom 1 were uniformly less than 50 °C (122 °F), which is considerably less than the temperatures measured at the same time in the open bedrooms. Temperatures remained steady until the bedroom 1 door was opened. The new flow path established through the doorway caused temperatures close to the ceiling to increase, as higher temperature, higher pressure products of combustion flowed from the hallway into the room. When the bedroom door was closed 10 s later, the flow from the hallway was cut off. Temperatures subsequently began to decrease. Temperatures in bedroom 1 further decreased as the bedroom 1 window was removed. Temperatures uniformly dropped below 50 °C (122 °F) prior to the start of hydraulic ventilation. As a result of the closed door between the bedroom and the hallway, hydraulic ventilation had no noticeable impact on temperatures in bedroom 1.



(a) Bedroom 1 Temperature

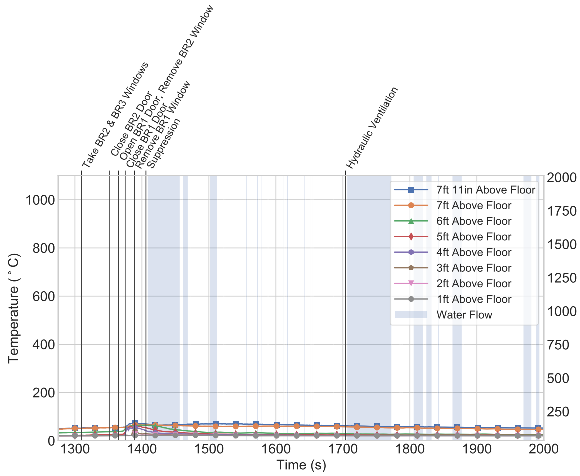


(b) Bedroom 1 Gas Concentration

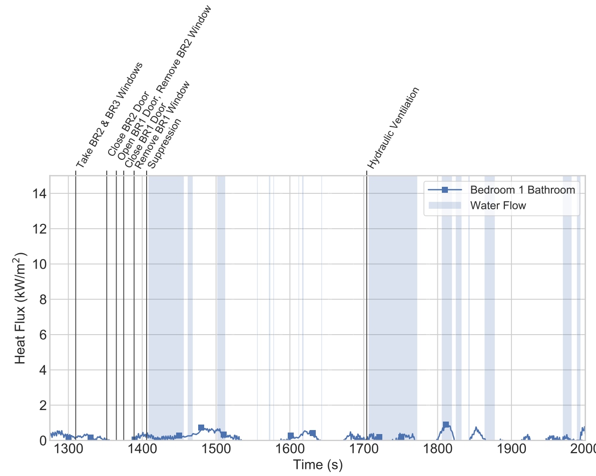
Figure 5.41: Bedroom 1 temperatures and gas concentrations following fire department intervention during Experiment 13.

Figure 5.41b shows the time history of gas concentration at the measurement location 3 ft above the floor on the bed in bedroom 1. At the time of intervention, O_2, CO_2, and CO concentrations were 19.5%, 1.4%, and 0.1%, respectively. Similar to the temperatures, these gas concentrations were considerably less severe than those measured in open bedrooms at the time of intervention. Independent of the initial ventilation actions, CO and CO_2 concentrations continued to steadily increase and the O_2 concentration continued to steadily decrease. These changes were driven by higher pressure gases pushing in from around the door and through transport through the HVAC system. The opening of the door to the hallway did not have as noticeable of an impact on gas concentrations as compared to temperatures as the smoke layer in the bedroom did not descend below the 3 ft level. The peak gas concentrations were observed 1446 s after intervention as the gases within the bedroom cooled and dropped within the space. Peak O_2, CO_2, and CO concentrations of 18.5%, 2.2%, and 0.2%, respectively, were observed. Gas concentrations began to return toward pre-ignition levels as the gases exhausted through the open bedroom window and as the suppression crew continued to bring the fire under control.

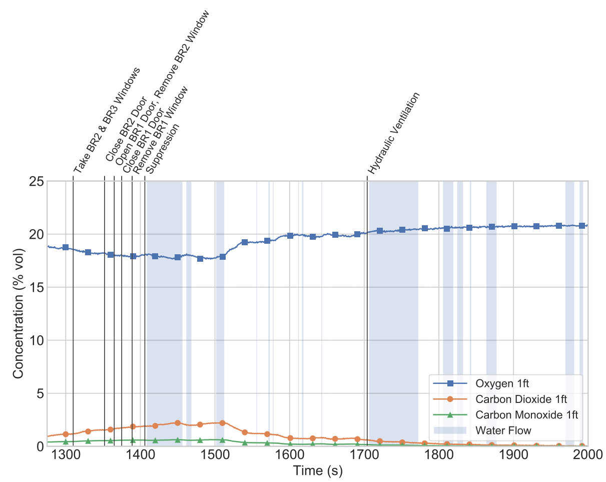
Figure 5.42 shows the time histories of temperature, heat flux, and gas concentration in the bathroom adjacent to bedroom 1. The door between bedroom 1 and bathroom 1 remained closed for the duration of the experiment. At the time of intervention, temperatures in bathroom 1 were uniformly below 50 °C (122 °F), comparable to those in the adjacent bedroom. Immediately following the bedroom 1 door being opened, temperatures close to the ceiling increased as products of combustion leaked through the bathroom door. Peak temperatures at the ceiling in bathroom 1 remained below 75 °C (167 °F) and temperatures 1 ft above the floor remained below 25 °C (77 °F) for the duration of the experiment. Bathroom temperatures were not substantially impacted by hydraulic ventilation due to the two closed doors between the bathroom and hallway. As a result of the low temperatures and lack of gas flow in bathroom 1 during Experiment 13, the heat flux values measured 1 ft above the floor were negligible, as shown in Figure 5.42b.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Heat Flux



(c) Bathroom 1 Gas Concentration

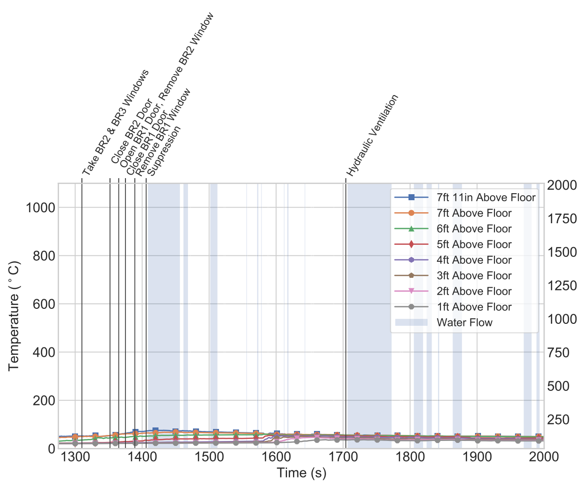
Figure 5.42: Bathroom 1 temperatures, heat flux, and gas concentrations following fire department intervention during Experiment 13.

Figure 5.42c shows that O_2, CO_2, and CO concentrations in bathroom 1 at the time of intervention were 18.6%, 1.2%, and 0.4%, respectively as a result of transport through the HVAC system. In the period following intervention, CO and CO_2 concentrations gradually increased while the O_2 concentration gradually decreased, with no noticeable change following the opening and closing of the bedroom 1 door. The peak O_2, CO_2, and CO values were measured approximately 180 s after intervention (1490 s after ignition), and were 17.9%, 2.2%, 0.6%. Note that this peak was observed later in the experiment than at other locations within the structure, including the adjacent bedroom, due to the lack of air exchange between bathroom 1 and the rest of the structure. Gas concentrations in bathroom 1 were unaffected by hydraulic ventilation, and returned to approximately ambient conditions approximately 225 s after the conclusion of hydraulic ventilation.

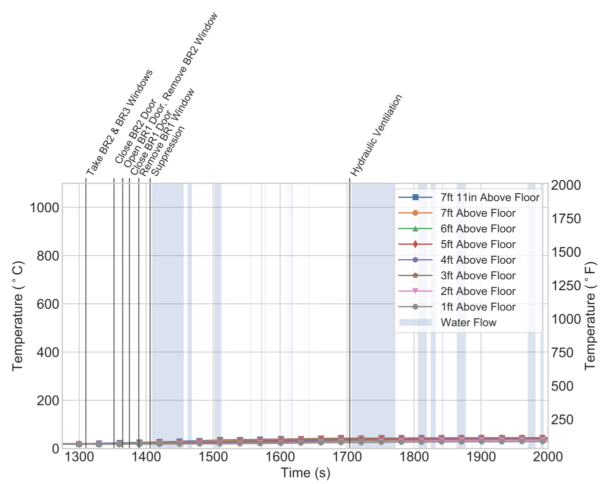
5.3.6 Bedroom 4

Similar to bedroom 1, the door between bedroom 4 and the hallway remained closed for the duration of the experiment. Figure 5.43a shows that temperatures in bedroom 4 at the time of intervention were uniformly below 50 °C (122 °F), comparable to the temperatures in bedroom 1 at the same time. Following intervention, temperatures gradually increased as a result of smoke leakage through the doorway. Suppression caused temperatures to gradually decrease. In the period between the start of suppression and the start of hydraulic ventilation, the suppression crew extinguished a portion of the burning door, which created a hole in the door and resulted in an increase in temperature between 2 ft and 5 ft. This temperature increase was minor compared to other locations in the structure, with temperatures remaining below 55 °C (131 °F).

Temperatures measured in the bedroom 4 closet, shown in Figure 5.43b were negligible at the time of intervention. The closet was behind two closed doors but in contrast to bathroom 1 there was no local HVAC vent. Temperatures remained below 45 °C (113 °F) at all elevations for the duration of Experiment 13.



(a) Bedroom 4 Temperature



(b) Bedroom 4 Closet

Figure 5.43: Bedroom 4 temperatures following fire department intervention during Experiment 13.

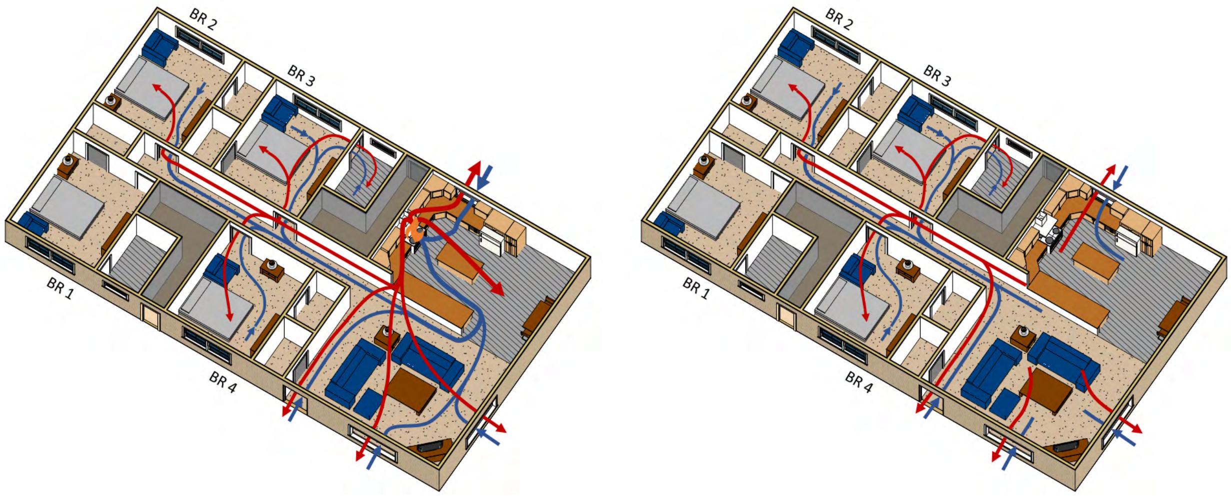
5.4 Experiment 14

The search tactics in Experiment 14 were designed to evaluate door initiated operations following suppression of a common space (living room and kitchen) fire. At the time of ignition, the kitchen window and front door were opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2, 3, and 4 were opened. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets which led to flashover of the kitchen. The fire then spread to the living room, where flashover occurred following the failure of the side A and side D windows. Post-flashover of the common space, interior suppression occurred. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side D living room windows as the search crew entered bedrooms 3 and 4 and opened the respective windows. The crew remained split and proceeded to bedroom 1 and bedroom 2. One-half of the crew opened the door to bedroom 1, while the second-half of the crew proceeded to bedroom 2. The respective bedroom windows were subsequently opened. The time at which interventions occurred in Experiment 14 are listed in Table 5.7.

Table 5.7: Experiment 14 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	05:53	353	—	—
Suppression	22:57	1377	00:00	0
Open BR3 & BR4 Windows, Hydraulic Ventilation	25:33	1533	02:36	156
Open BR1 Door	25:51	1551	02:54	174
Open BR1 & BR2 Windows	26:03	1563	03:06	186

At the time of fire department intervention, the common space was in a steady post-flashover state. At this time bedrooms 2, 3, and 4 were charged with smoke, while bedroom 1 remained isolated. Figure 5.44a shows that bidirectional flows developed through the open front door and side-A windows, the side-D living room windows, and the kitchen window. Fresh air was entrained through the lower portion of these vents and flames and smoke exhausted through the upper portion. The initial fire department intervention was suppression, which was conducted through the front door of the structure using 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 suppression crew first applied water to the interior from a position on the deck, flowing for 15 second through the front door and A side living room window in an O-pattern. Once the fire had been controlled to the point where the suppression crew could advance to the interior, the suppression crew crossed the threshold of the doorway and continued suppression operations. 134 gallons were flowed during suppression. Following suppression, the higher pressures gases in the open bedrooms began to flow toward the common space and the lower pressure exhaust vents: the front door and kitchen window (Figure 5.44b).



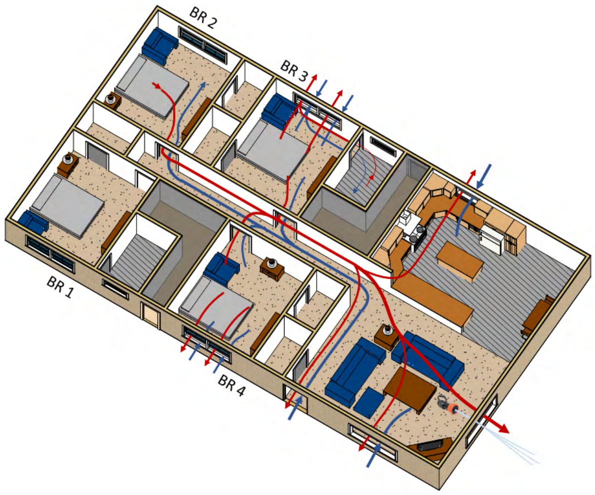
(a) Flows Prior to Intervention

(b) Suppression

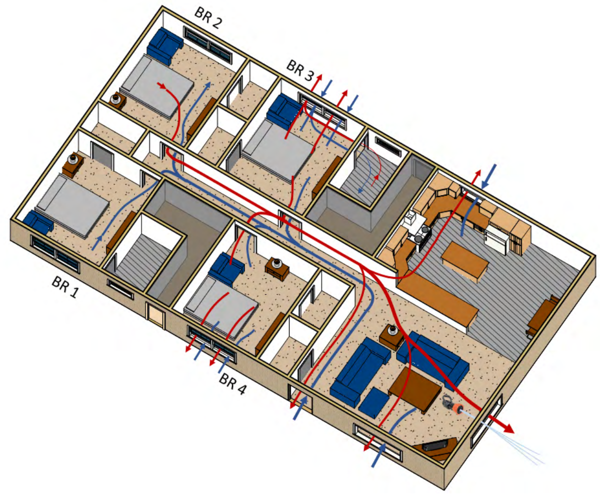
Figure 5.44: Changes in flow in structure before and after suppression in Experiment 14.

Once the fire had been extinguished, the suppression crew initiated hydraulic ventilation through the side D living room window with a wide-fog stream and fixed pattern. Hydraulic ventilation created an area of low pressure due to the flow of water through the side-D living room window, which drew products of combustion from remote points in the structure through the vent (Figure 5.45a). Prior to bedroom windows being opened, accumulation of combustion gases led to an increase in pressure at the 7 ft elevation in the bedrooms with the largest increases occurring in the open bedrooms. Simultaneous with the start of hydraulic ventilation, the lower panes of the bedroom 3 and 4 windows were opened. Due to the open bedroom 3 and 4 doors, unidirectional flow was established at the bedroom windows (intake of air) and through the bedroom doorways (mixture of air and combustion gases) because of the lower pressure area developed by hydraulic ventilation. The total amount of water flowed during suppression and hydraulic ventilation was 375 gallons.

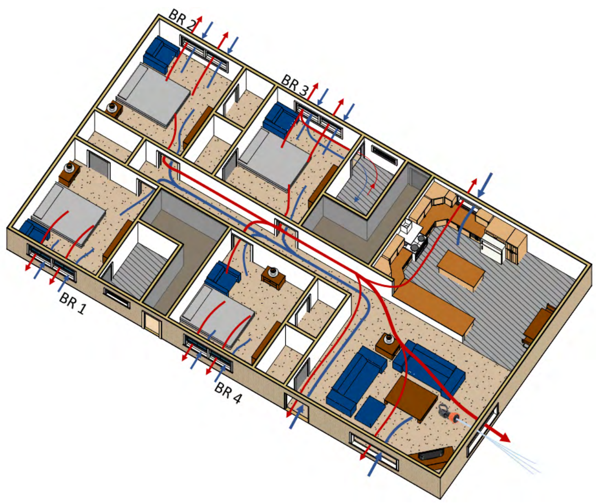
Prior to the opening of the bedroom 1 windows 186 s after intervention, the bedroom 1 door was opened, and products of combustion flowed from the bedroom into the hallway due to the low pressure created by the hydraulic ventilation (Figure 5.45b). The bedroom 1 windows were opened 12 s later, which created a second exhaust path for combustion gases. As additional vents were created, the draw through each vent was weakened. As a result, there was intermittent exhaust flow through the bedroom 1 windows. Simultaneous with the opening of the bedroom 1 windows, the bedroom 2 windows were opened. Similar to bedroom 3, the door between bedroom 2 and the hallway remained open from the time of ignition. When the bedroom 2 windows were opened, the velocity data from the bedroom 2 window showed that the predominant flow was fresh air intake, although similar to bedroom 1, there were intermittent exhaust flows (Figure 5.45c).



(a) Open BR3 & BR4 Windows, Hydraulic Ventilation



(b) Open BR1 Door

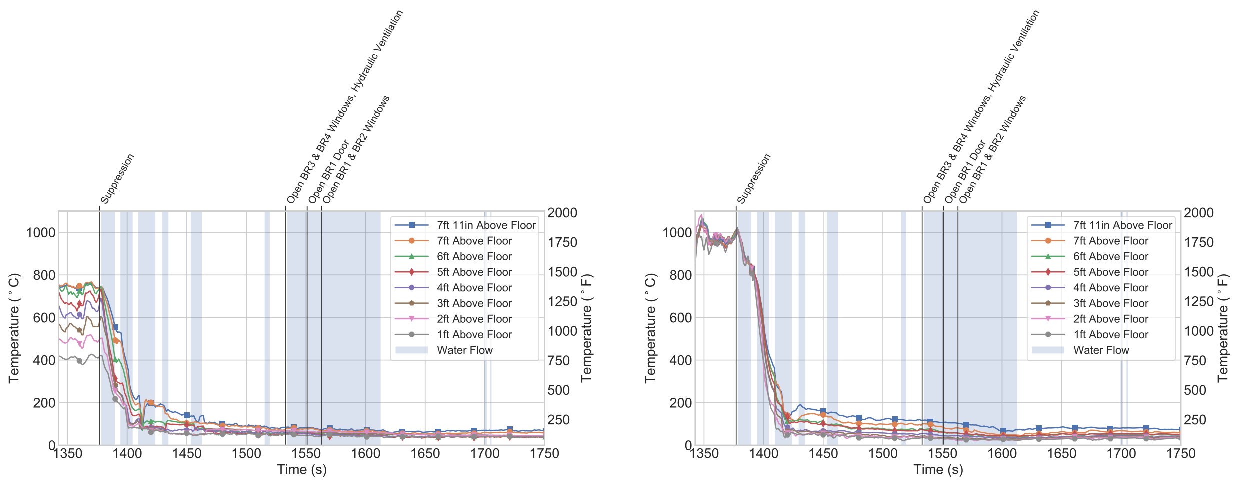


(c) Open BR1 & BR2 Windows

Figure 5.45: Changes in flow in structure following fire department interventions in Experiment 14.

5.4.1 Common Space

Figure 5.46 shows the temperatures in the kitchen and living room. Immediately prior to suppression, living room temperatures were uniformly in excess of 900 °C (1652 °F), consistent with post-flashover conditions, as shown in Figure 5.46b. Although the kitchen fire had transitioned through flashover prior to intervention, temperatures had stratified prior to suppression, ranging from 750 °C (1382 °F) at the ceiling 410 °C (700 °F) 1 ft above the floor. The comparatively lower temperatures in the kitchen were caused by the limited air entrainment in that area as a result of the lack of ventilation. Temperatures in both the living room and the kitchen began to decrease sharply following the onset of exterior suppression. The suppression crew flowed for 15 s from a position on the deck stairs before moving to the threshold of the front door, where the crew flowed into the common space for an additional 10 s. The suppression crew then advanced into the living room to complete primary suppression, flowing for an additional 17 s. The common space fire was extinguished approximately 50 s after the initial suppression action, with temperatures in the living room and kitchen were uniformly below 200 °C (392 °F).



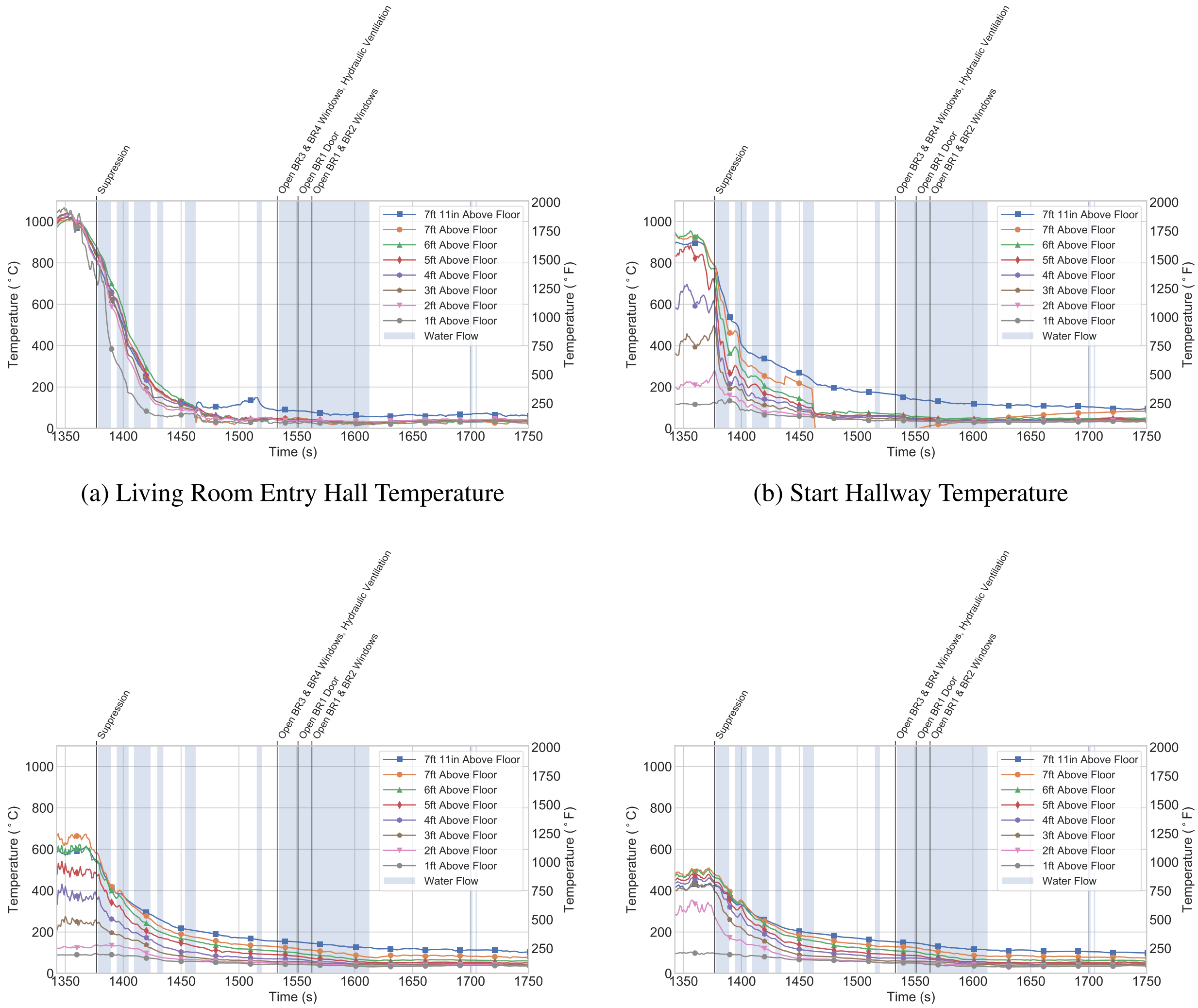
(a) Kitchen Temperature

(b) Living Room Temperature

Figure 5.46: Temperature time histories in the common space for the period following fire department intervention in Experiment 14.

5.4.2 Hallway

Similar to the temperatures in the common space, the temperatures in the living room entryway and hallway, shown in Figure 5.47 uniformly decreased starting immediately after the onset of suppression. At the time of intervention, the temperatures in the living room entryway were in excess of 1000 °C (1832 °F) at all elevations, above the threshold of 600 °C (1112 °F) consistent with post-flashover conditions. The temperatures at the start hallway, mid hallway, and end hallway locations were all stratified, with the magnitude of the temperatures decreasing with increasing distance from the common space ranging from 795 °C to 125 °C (1463 °F to 257 °F), 585 °C to 95 °C (1085 °F to 203 °F), and 485 °C to 95 °C (905 °F to 203 °F), at the start hallway, mid hallway, and end hallway locations, respectively. Temperatures at all hallway measurement locations dropped following the start of suppression with the largest impact occurring at the living room entryway and start hallway due to the proximity of the water flow and exhaust vents. In both locations, temperatures at 7 ft and below dropped below 75 °C (167 °F) by the end of primary suppression. The mid hallway and end hallway locations only dropped under 75 °C (167 °F) at 3 ft and below. Hallway temperatures continued to decrease as hydraulic ventilation was conducted with the majority of measurements below 38 °C (100 °F) at the conclusion of hydraulic ventilation.



(a) Living Room Entry Hall Temperature

(b) Start Hallway Temperature

(c) Mid Hallway Temperature

(d) End Hallway Temperature

Figure 5.47: Temperature time histories in the hallway in the period following fire department intervention in Experiment 14.

Heat flux values measured in the living room entryway and at the three hallway locations, shown in Figure 5.48, were consistent with the trend in temperatures measured in those locations. At the time of intervention, the heat flux measured in the living room entryway was 25 kW/m^2, consistent with post-flashover conditions, while hallway heat flux values were all below 3 kW/m^2. Following the initial suppression action, the living room entryway heat flux briefly increased to a momentary peak of 75 kW/m^2, before beginning to decrease. As suppression began to take effect, the living room heat flux continued to decrease to a value less than 2.5 kW/m^2 within 60 s of the beginning of suppression. At the start hall location, heat flux fluctuated in the period following suppression, increasing to peaks as high as 30 kW/m^2. The heat flux at this location decreased more slowly than the living room heat flux following suppression, remaining above 5 kW/m^2 for approximately 70 s after the start of suppression. This increase in heat flux contrasts with the temperature data at

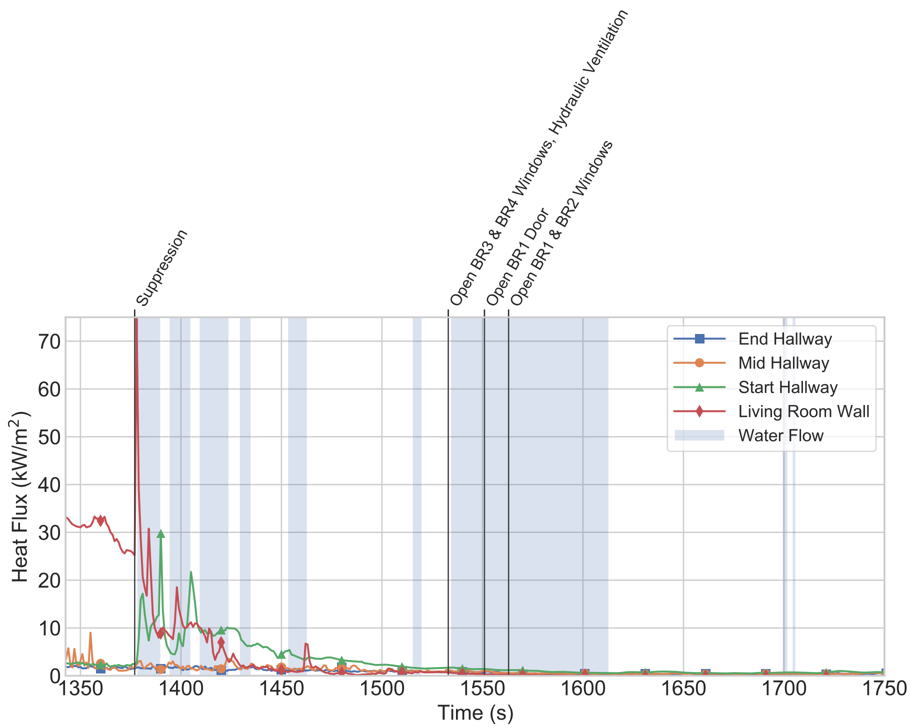


Figure 5.48: Heat flux time histories in the hallway in post-intervention period during Experiment 14.

this location, indicating that the elevated heat flux values are likely the result of the carpet burning around the heat flux gauge. Heat flux at the mid-hall and end hall locations began to decrease in the period following suppression, and had dropped to values less than 1.0 kW/m^2 prior to the start of hydraulic ventilation.

Table 5.8 shows that gas concentrations measured in the living room entryway prior to suppression were below the threshold needed to support combustion and were consistent with the post-flashover conditions that were observed at the time of intervention. The table also shows that gas concentrations measured in the hallway were similarly characterized by low O_2 concentrations and elevated CO and CO_2 concentrations, an indication that prior to intervention the smoke layer had descended past the 1 ft measurement location in the hallway.

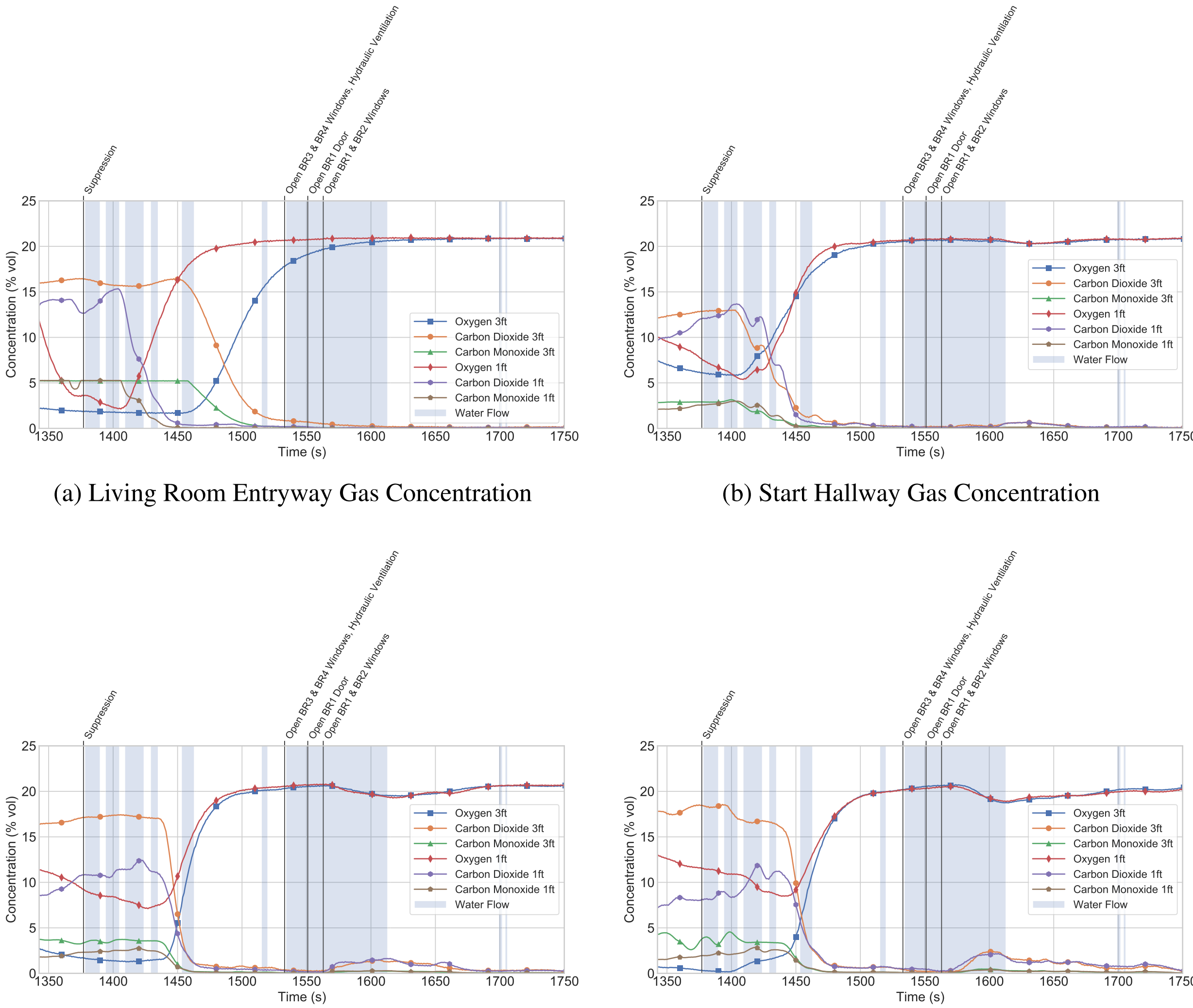
Figure 5.49 shows the time histories of gas concentrations at the living room and hall measurement locations. Following suppression, O_2 concentrations increased and CO and CO_2 concentrations decreased at all locations and elevations. At the living room entryway measurement location, this change was first observed at the 1 ft elevation, where gas concentrations began to trend toward ambient approximately 30 s after the beginning of suppression as fresh air was still entrained low in the space. Gas concentrations at the 3 ft elevation returned toward ambient shortly afterwards, 82 s after intervention as the smoke layer lifted at the front door.

In the hallway, O_2 began to increase and CO and CO_2 began to decrease between 30 and 60 s after the beginning of suppression. The improvement in conditions at the 3ft elevation mark in the

Table 5.8: Hallway Gas Concentrations at Intervention for Experiment 14

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	3.5	12.7	5.0
	1 ft	1.9	16.4	5.0
Start Hallway	3 ft	6.2	12.9	2.9
	1 ft	7.8	12.0	2.6
Mid Hallway	3 ft	1.7	17.1	3.3
	1 ft	9.4	10.7	2.3
End Hallway	3 ft	0.3	18.5	3.4
	1 ft	11.6	8.0	1.9

living room entry corresponds to the flows shown in Figure 5.44b. The higher pressure, higher temperature gases that accumulated in the open bedrooms and hallway reversed direction and flowed toward the open vents (front door and kitchen window) past the living room entryway.



(a) Living Room Entryway Gas Concentration

(b) Start Hallway Gas Concentration

(c) Mid Hallway Gas Concentration

(d) End Hallway Gas Concentration

Figure 5.49: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 14.

CO and CO_2 concentrations at all four measurement locations had decreased to comparatively negligible values prior to the start of hydraulic ventilation. After the bedroom 1 door and bedroom 1 and 2 windows were opened, a brief increase in CO and CO_2 and decrease in O_2 was observed due to mixing with the combustion gases that had accumulated in bedroom 2. The gases were drawn into the hallway by the area of lower-pressure created during hydraulic ventilation. This increase was most pronounced at the end hall location, nearest bedroom 2, where the CO concentration increased from less than 0.1% to 0.4% and 0.5% at the 3 ft and 1 ft elevations, respectively.

5.4.3 Bedroom 3

The bedroom 3 door was open for the duration of the experiment, which initially led to the accumulation of combustion gases within the space prior to suppression as there was no local exhaust vent. As a result, temperatures in bedroom 3 rose, but remained stratified between 385 °C (725 °F) at the ceiling to 78 °C (172 °F) 1 ft above the floor (Figure 5.50). These values were below the hallway temperatures as gases that flowed into the bedroom mixed with air and cooled slightly. Temperatures at all elevations began to decrease during the initial suppression action, and continued to decrease as the suppression crew brought the living room fire under control. Temperatures in the bedroom had decreased below 150 °C (302 °F) at all elevations prior to the bedroom 3 window opening and the start of hydraulic ventilation. The higher temperature and higher pressure combustion gases began to flow toward the lower pressure open vents following suppression. The prior natural flow of gases combined with only the bottom window panes being opened limited the impact of hydraulic ventilation in bedroom 3.

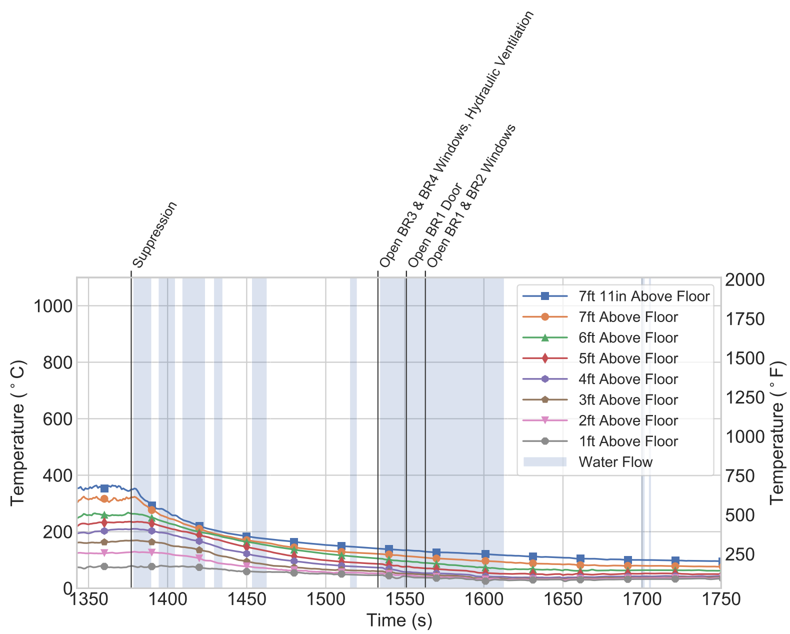
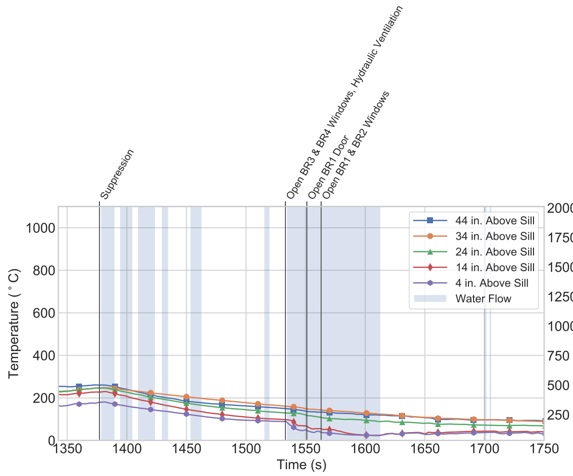


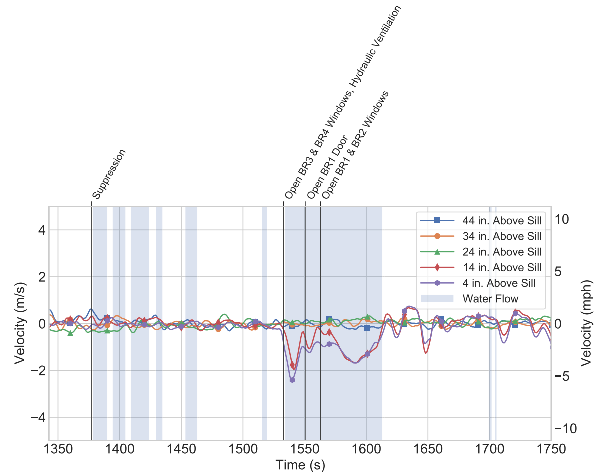
Figure 5.50: Post-intervention bedroom 3 temperature during Experiment 14.

The lower pane of the bedroom 3 windows were opened simultaneous with the start of hydraulic ventilation, which resulted in a noticeable decrease in temperature at the velocity probes 4 in. and 14 in. above the sill compared to the top 3 probes which where not exposed to air (Figure 5.51a). This flow pattern was driven by the entrainment of fresh air through the lower pane of the window as the window velocities in Figure 5.51b indicate.

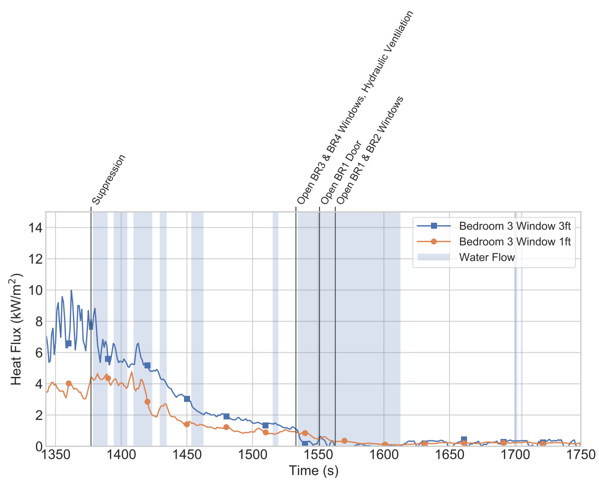
Figure 5.51c shows that immediately prior to intervention, the heat flux at the 3 ft and 1 ft window measurements were moderately steady at approximately 8 kW/m^2 and 4 kW/m^2, respectively. Heat flux at both elevations began to decrease 36 s after the start of suppression and reached values of approximately 1 kW/m^2 prior to the start of hydraulic ventilation. Air entrainment through the



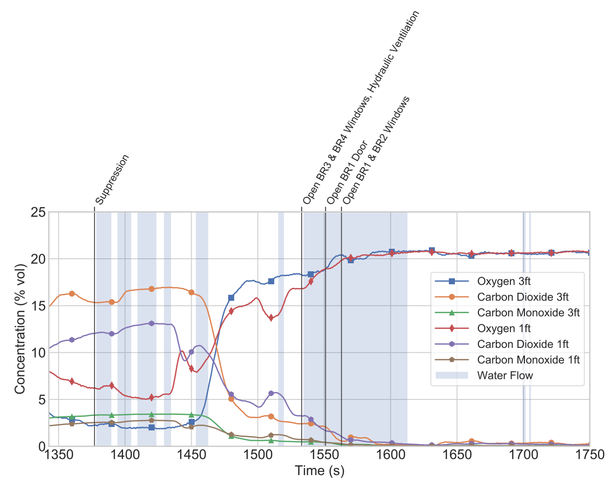
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



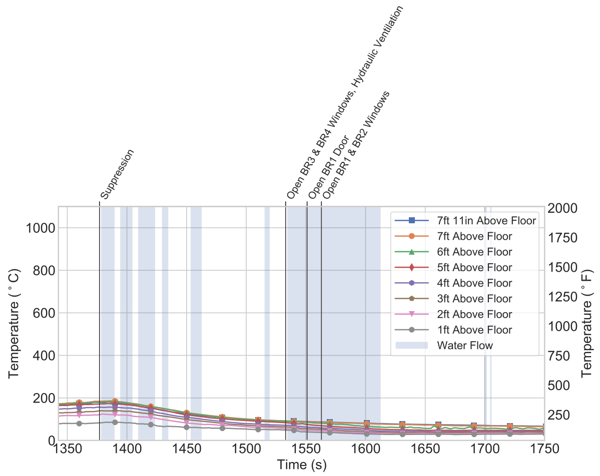
(d) Bedroom 3 Window Gas Concentration

Figure 5.51: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 14.

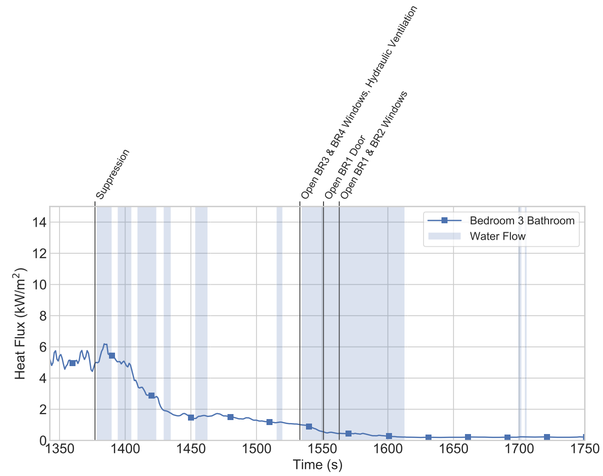
open bedroom windows driven by the hydraulic ventilation further dropped the heat flux at both elevations to negligible values before the end of hydraulic ventilation.

Gas concentrations at the time of intervention in bedroom 3, shown in Figure 5.51d, were comparable in magnitude to those observed at the corresponding elevation at the mid hallway location. The low O_2 concentrations and high CO and CO_2 concentrations suggested that the smoke layer had descended below the 1 ft gas measurement probe in bedroom 3. The 1 ft CO and CO_2 concentrations first began to decrease approximately 58 s after intervention, while the 3 ft concentrations lagged behind, beginning to trend toward ambient 88 s after intervention. Similar to the gas concentrations in the hallway, the timing of this increase in O_2 and decrease in CO and CO_2 roughly corresponded with completion of the interior suppression actions. The recovery to pre-ignition concentrations was slower than the hallway as the efficiency gas flows toward the common space exhaust vents was impacted by the furniture, particularly the bed, within the space. Hydraulic ventilation improved this efficiency and gases returned to pre-ignition values prior to the end of hydraulic ventilation.

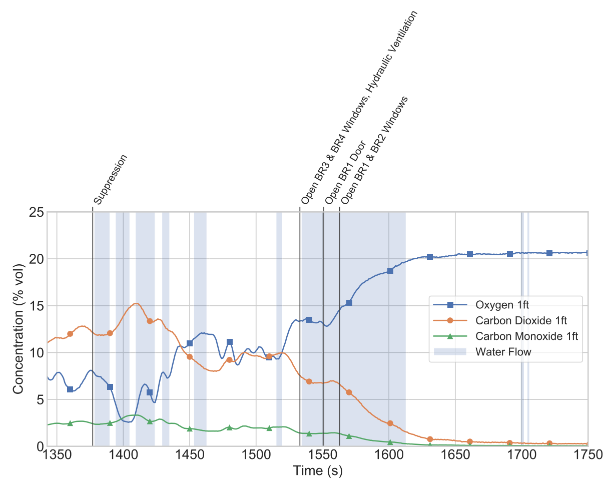
Temperatures in bathroom 3 (Figure 5.52a) were lower than those measured in the adjacent bedroom at the time of intervention, ranging from 185 °C (365 °F) at the ceiling to 85 °C (185 °F) 1 ft above the floor. Following suppression, the temperatures followed a similar trend to those in bedroom 3, beginning to decrease during the initial suppression action. By the time hydraulic ventilation was started and the bedroom 3 window was opened, temperatures in the bathroom ranged from 92 °C (198 °F) at the ceiling to 50 °C (122 °F) 1 ft above the floor. The combination of hydraulic ventilation and the bedroom 3 lower window panes being opened led to an increased exchange of gases and for temperatures below 6 ft to decrease toward pre-ignition magnitudes. The lack of vent local to the bathroom resulted gas temperatures in elevation above the door header to remained relative elevated at 47 °C (117 °F).



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

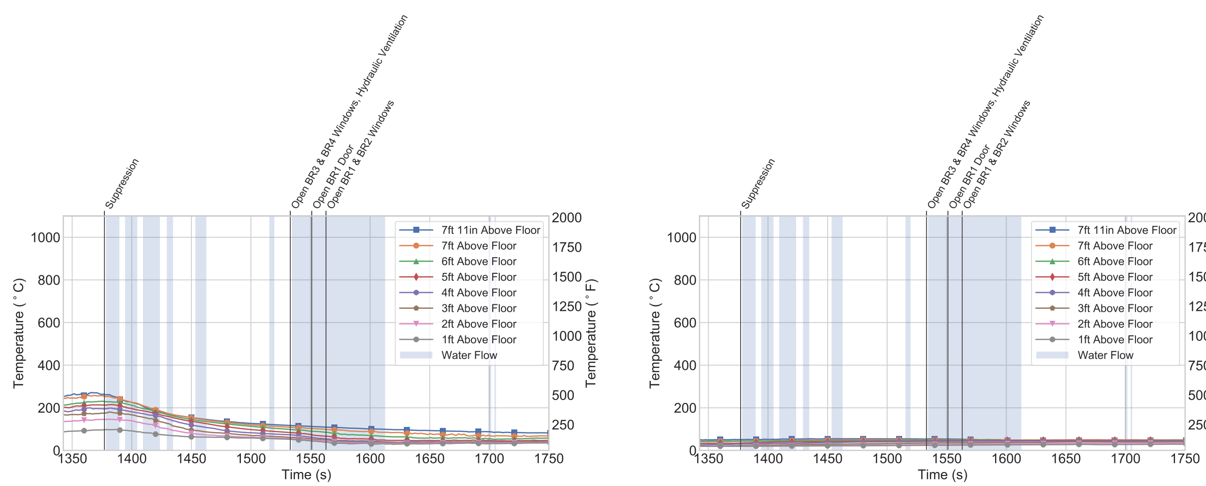
Figure 5.52: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 14.

The heat flux measured 1 ft above the floor in bathroom at the time of intervention was 5.0 kW/m^2, which is comparable to the value measured at the same elevation in the bedroom 3 window. Similar to the behavior observed in the adjacent bedroom, the bathroom 3 heat flux decreased 27 s after suppression was initiated, and continued to decrease as the common space fire was extinguished and the flow of combustion gases correspondingly decreased. Immediately prior to hydraulic ventilation and bedroom 3 window opening, the heat flux in the bathroom was approximately steady at 1 kW/m^2. Hydraulic ventilation caused the bathroom heat flux to drop at a faster rate than the natural cooling following suppression. Heat flux in the bathroom was negligible by the completion of hydraulic ventilation.

Figure 5.52c shows the time history of gas concentrations 1 ft above the floor in bathroom 3. Immediately prior to intervention, the distribution of bathroom gases was characterized by elevated levels of CO and CO_2 and low levels of oxygen; an indication that the smoke layer in the bathroom had descended past the 1 ft measurement height. These gas concentrations were comparable to those measured 1 ft above the floor in bedroom 3. CO and CO_2 concentrations in the bathroom increased through the initial suppression actions, reaching a peak 33 s after intervention with O_2, CO_2, and CO values of 2.7%, 15.2%, and 3.3%, respectively. Unlike in bedroom 3, where CO and CO_2 concentrations constantly decreased following suppression, gas concentrations in bathroom 3 leveled off in the period between suppression and hydraulic ventilation, with O_2, CO_2, and CO values of 9.3%, 9.8%, and 2.1%, respectively. Following the start of hydraulic ventilation, the decrease in CO and CO_2 concentrations and increase in O_2 concentration continued, although slightly elevated CO concentrations were still measured at the end of hydraulic ventilation.

5.4.4 Bedroom 4

Temperatures in bedroom 4, shown in Figure 5.53a trended similarly to those in bedroom 3, located across the hallway. At the time of intervention, temperatures in bedroom 4 ranged from 295 °C (563 °F) at the ceiling to 95 °C (203 °F) 1 ft above the floor. Temperatures at all elevations began to decrease during the initial suppression action, and continued to decrease below 120 °C (248 °F) prior to the start of hydraulic ventilation. Following the start of hydraulic ventilation and removal of the bedroom 4 window, temperatures close to the floor began to decrease more rapidly.



(a) Bedroom 4 Temperature

(b) Bedroom 4 Closet

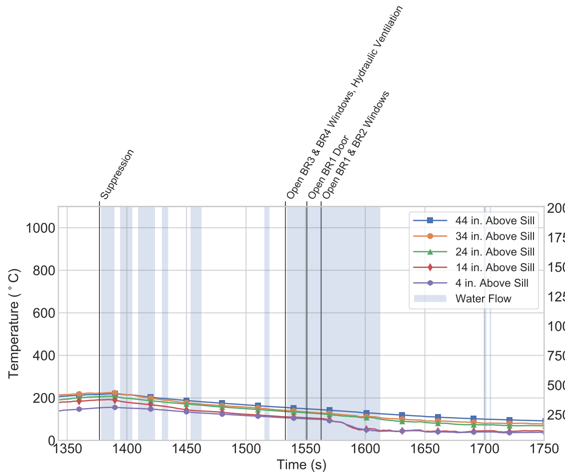
Figure 5.53: Bedroom 4 and bedroom 4 closet temperature time histories during Experiment 14.

The door between the bedroom 4 closet and bedroom 4 itself remained closed for the duration of the experiment, resulting in considerably lower peak temperatures than in the bedroom itself. Figure 5.53b shows that peak temperatures in the closet remained below 55 °C (131 °F) at all elevations. Similar to the observation in the isolated bedroom 1 and bathroom 1, temperatures in the bedroom 4 closet continued to gradually increase through suppression actions before reaching a peak and then gradually decreasing due to heat transfer to the closet walls.

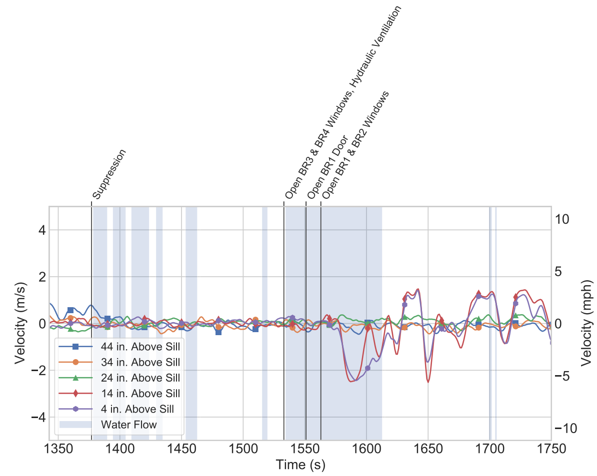
5.4.5 Bedroom 2

The window temperatures and velocities shown in Figures 5.54a and 5.54b indicate that the opening of the lower pane of the bedroom 2 window 186 s after the onset of the suppression (30 s after the start of hydraulic ventilation) created an inlet vent, allowing cool air to be entrained through the lower portion (i.e., 14 in. above the sill and lower) of the window for the remainder of the hydraulic ventilation tactic. The heat flux values measured immediately prior to suppression 3 ft and 1 ft above the floor below the window were 7.3 kW/m^2, and 6.1 kW/m^2, respectively, and began to decrease during the initial suppression action (Figure 5.54c). The measured heat flux at both window elevations reached steady values in the period between suppression and hydraulic ventilation as the gas flows within the space slowed and gases cooled. Figure 5.54c shows that it was not until the the combination of opening the lower panes of the bedroom 2 window and hydraulic ventilation that the heat flux values returned to pre-ignition magnitudes.

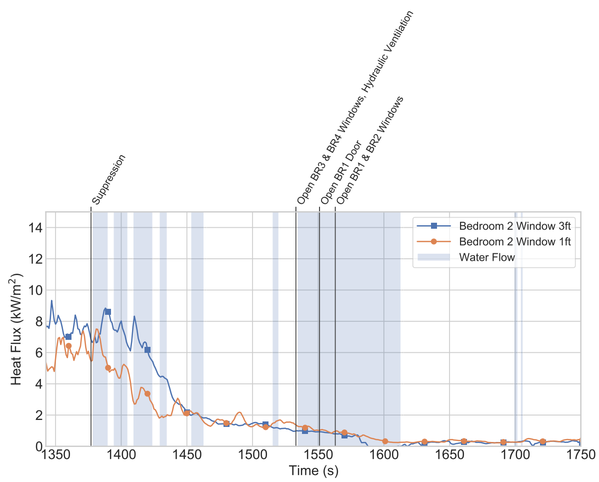
Prior to suppression, gas concentrations were 1.1% O_2, 17.6% CO_2, and 3.5% CO at the 3 ft elevation and 2.2% O_2, 16.7% CO_2, and 3.5% CO at the 1 ft elevation (Figure 5.54d). Concentrations remained nominally steady until 49 s after suppression started when the 1 ft gas concentration began to recover toward pre-ignition levels. The 3 ft elevation had measurable improvements 27 s later as the smoke layer rose due to exhaust through the open front door and kitchen window. Gas concentrations continued to recover through hydraulic ventilation, with their steepest rates in the 45 s following suppression as the production of combustion gases had stopped.



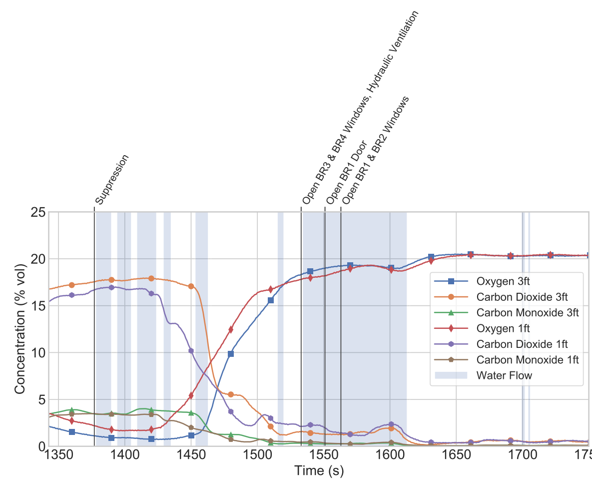
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



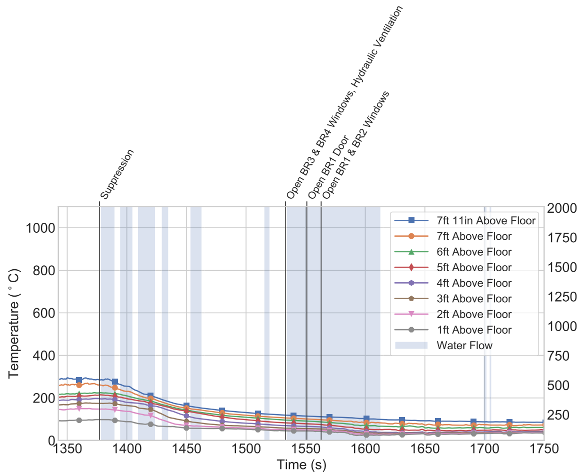
(c) Bedroom 2 Window Heat Flux



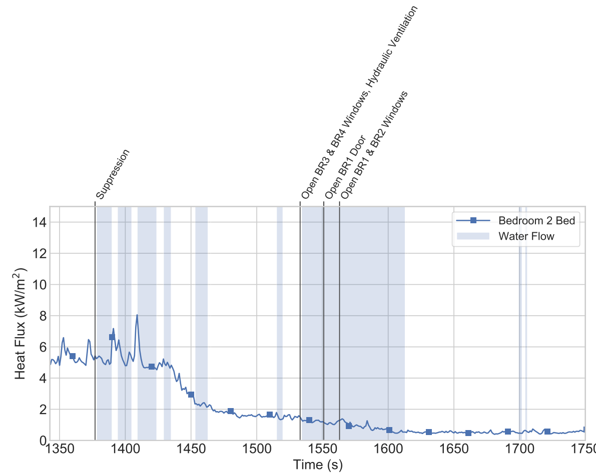
(d) Bedroom 2 Window Gas Concentration

Figure 5.54: Post-intervention temperature, velocity, heat flux measurements at bedroom 2 window during Experiment 14.

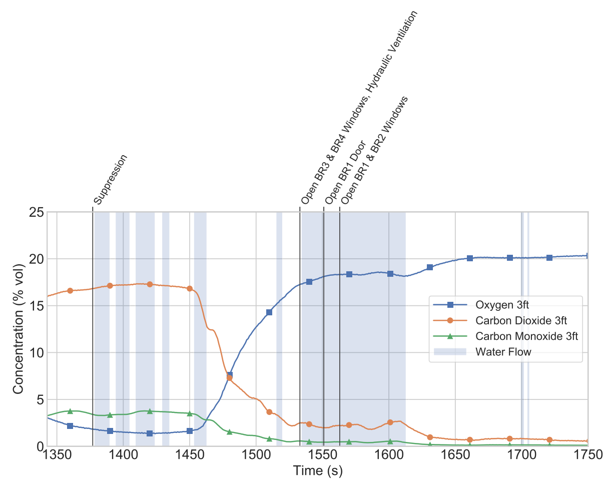
Prior to suppression, temperatures in the bedroom ranged from 285 °C (545 °F) at the ceiling to 98 °C (209 °F) 1 ft above the floor (Figure 5.55a). Temperatures at all elevations began to decrease during the initial suppression action. The start of hydraulic ventilation did not noticeably affect the rate at which these temperatures decreased. Following the opening of the bedroom window panes, temperatures at 5 ft and below decreased at a faster rate, which was aided by air entrainment through the open window. The bedroom 2 heat flux sensor 3 ft above the floor on the bed began to measure a decrease 58 s after intervention, roughly corresponding to the time at which the suppression crew had completed interior suppression actions (Figure 5.55b). This decrease continued until hydraulic ventilation was initiated, at which point the bed heat flux was steady at approximately 1.5 kW/m^2. Hydraulic ventilation accelerated the rate at which the bed heat flux decreased.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



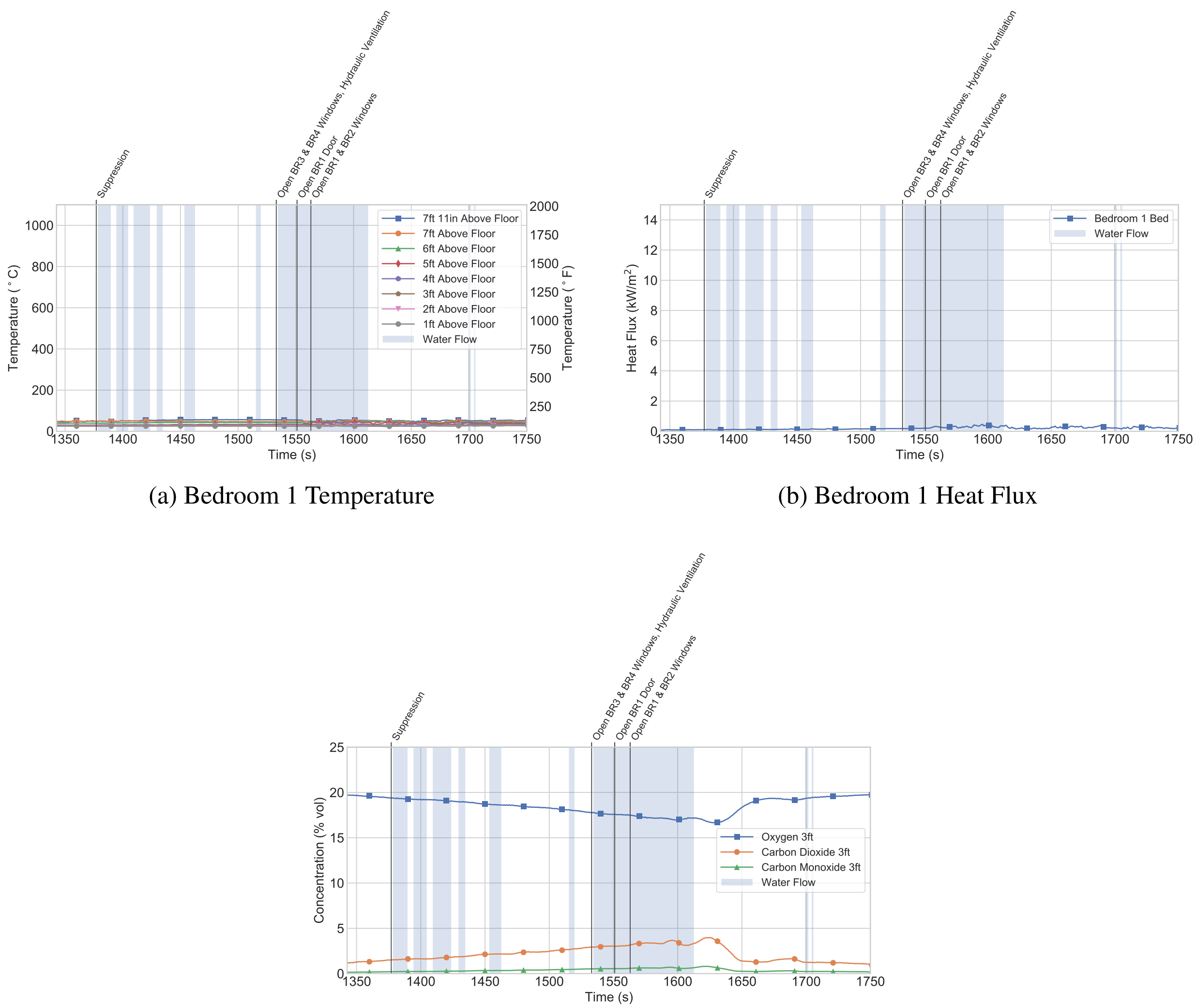
(c) Bedroom 2 Gas Concentration

Figure 5.55: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 2 during Experiment 14.

The gas sample location on the bed (Figure 5.55c) exhibited pre-suppression O_2, CO_2, and CO concentrations of 2.0%, 17.0%, and 3.5%, respectively. These values were similar to the pre-suppression concentrations measured at the 3 ft elevation at the window. As suppression began to take effect, CO and CO_2 began to decrease again and O_2 concentrations began to trend toward ambient through hydraulic ventilation.

5.4.6 Bedroom 1

In contrast to bedrooms 2 and 3, the door between bedroom 1 and the hallway was closed from the start of the experiment until 174 s after the beginning of suppression (1694 s after ignition). At the time of intervention, temperatures in bedroom 1 were below 50 °C (122 °F) at all elevations (Figure 5.56a), and the heat flux measured 3 ft above the floor at the center of the bed was negligible at 0.1 kW/m^2 (Figure 5.56b). After the bedroom door was opened during hydraulic ventilation, the bed heat flux and ceiling temperature increased to 0.4 kW/m^2 and 55 °C (131 °F) respectively and dropped shortly after. The magnitude of these increases was negligible, as temperatures in the hallway and common space had decreased substantially as a result of suppression.



(a) Bedroom 1 Temperature

(b) Bedroom 1 Heat Flux

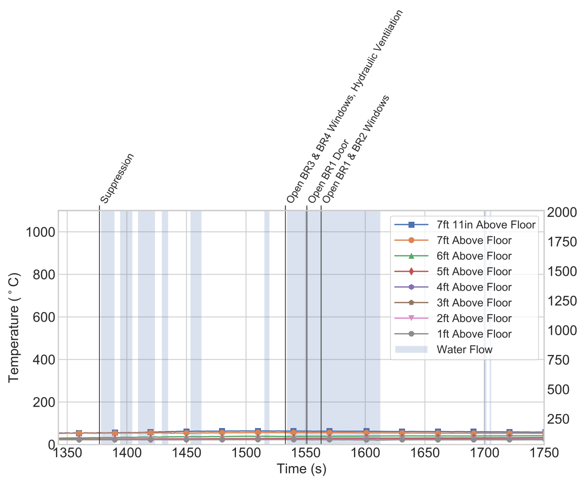
(c) Bedroom 1 Gas Concentration

Figure 5.56: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 14.

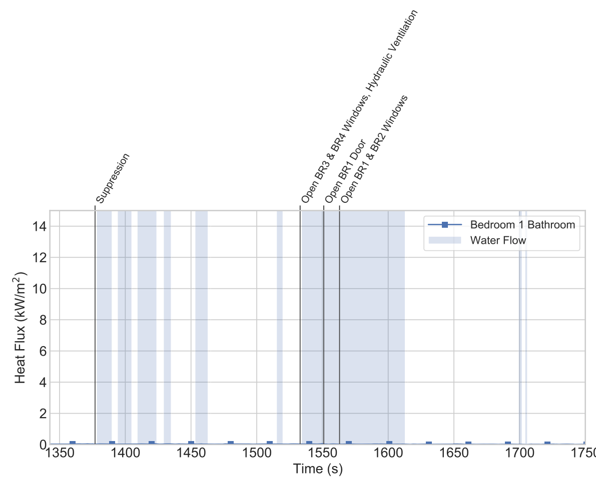
As a result of isolation provided by the bedroom 1 door, CO and CO_2 concentrations in bedroom 1 were lower at the time of intervention compared to the open bedrooms (bedroom 2 and bedroom 3). Following intervention, the CO and CO_2 concentrations at the bedroom 1 measurement location continued to increase while the O_2 concentrations continued to decrease, with no substantial impact from the hydraulic ventilation, doorway manipulation, or window ventilation, as shown in

Figure 5.56c. CO and CO_2 peaked 147 s post intervention (1624 s beyond ignition), after the completion of the hydraulic ventilation. Although the peak gas concentrations were observed later in the experiment than other bedrooms, the peak gas concentrations were less severe than those observed in non-isolated areas, with peak O_2, CO_2, and CO concentrations of 16.8%, 4.0%, and 0.8%, respectively.

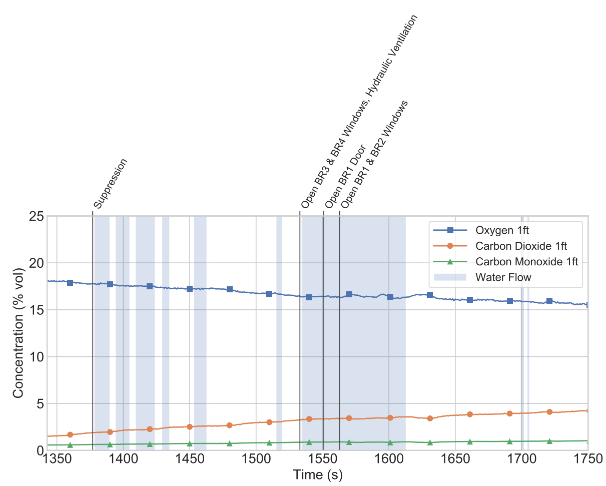
At the time of intervention, ceiling temperatures in bathroom 1 were 55 °C (131 °F), as shown in Figure 5.57, approximately the same as in the adjoining bedroom, despite the closed door between the two spaces. Similarly to bedroom 1, temperatures in bathroom 1 began to decrease following the start of hydraulic ventilation and continued to decrease for the remainder of the experiment. Consistent with the comparatively low temperatures, heat flux in bathroom 1, shown in Figure 5.57b remained below 0.1 kW/m^2 for the duration of the experiment.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Heat Flux



(c) Bathroom 1 Gas Concentration

Figure 5.57: Post-intervention temperature, heat flux and gas concentration measurements in bathroom 1 during Experiment 14.

Gas concentrations in bathroom 1 at the time of intervention were higher than those in bedroom 1 (Figure 5.57c). The higher toxic gas concentrations at the time of intervention were a result of the lack of an HVAC return duct in the bathroom. The HVAC supply provided a route for products of combustion to fill the bathroom, but the lack of a return and the closed bedroom door precluded efficient exhaust of these products of combustion from the room. The hydraulic ventilation and subsequent door and window opening did not substantially impact the rate of change of the gas concentrations in bedroom 1. CO and CO_2 concentrations continued to increase and O_2 concentrations continued to decrease until approximately 425 s after intervention (1800 s after ignition), after which they gradually trended to ambient. Peak O_2, CO_2, and CO concentrations in bathroom 1 were 15.3%, 4.4%, and 1.1%, respectively.

5.5 Experiment 15

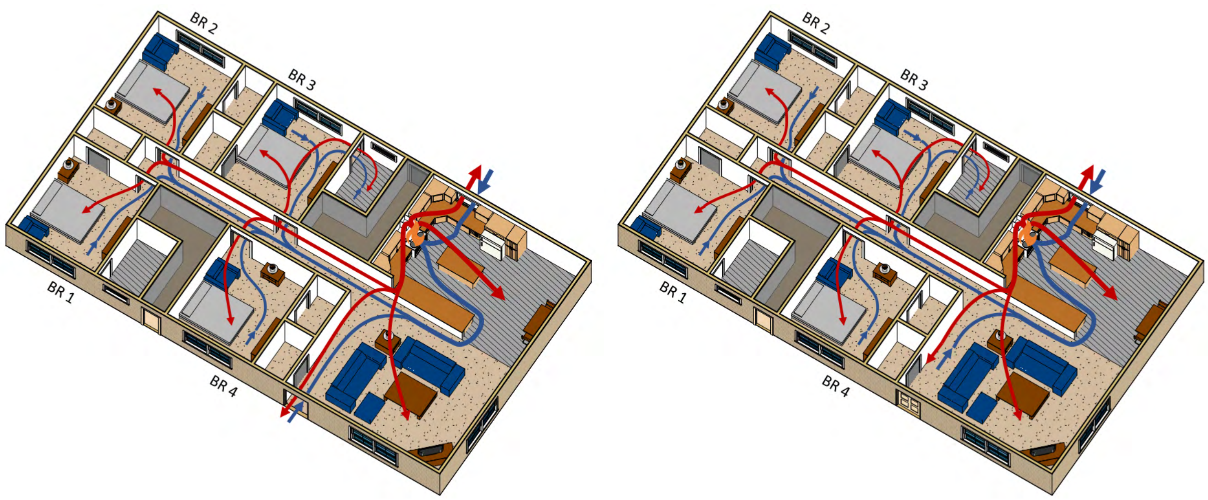
The search tactics in Experiment 15 were designed to evaluate door initiated operations with control of the front door prior to suppression. At the time of ignition, the kitchen window and front door were opened. The interior doors to all four bedrooms were opened. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets and at this point, crews entered the structure through the front door and closed it behind them. The crews traveled to bedroom 3 and bedroom 4, split to enter each bedroom, and isolated (closed the doors after entry). The crews proceeded to remove the bedroom 3 and bedroom 4 windows, respectively. After searching bedroom 3 and bedroom 4, the crews left the respective rooms, and closed the doors upon exiting. The crews then proceeded down the hallway toward bedroom 1 and bedroom 2. The crews split again, entered bedroom 1 and bedroom 2, and isolated both bedrooms. The windows in the respective rooms were then removed. At this point the search tactic comparison was complete and suppression began by opening the front door and proceeding with interior operations. 13 gallons of water were flowed during suppression. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the kitchen window. The total amount of water flowed during suppression and hydraulic ventilation was 362 gallons. The sequence of events and the times at which they occurred are listed in Table 5.9.

Table 5.9: Experiment 15 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	06:45	353	—	—
Close Front Door	22:22	1342	00:00	0
Close BR3 & BR4 Doors	23:05	1385	00:43	43
Remove BR3 & BR4 Windows	23:36	1416	01:14	74
Open BR3 & BR4 Doors	23:48	1428	01:26	86
Close BR3 & BR4 Doors	23:58	1438	01:36	96
Close BR1 & BR2 Doors	24:26	1466	02:04	124
Remove BR1 & BR2 Windows	24:56	1496	02:34	154
Open Front Door, Suppression	25:23	1523	03:01	181
Open BR3 & BR4 Doors	27:23	1643	05:01	301
Open BR1 & BR2 Doors	27:38	1658	05:16	316
Hydraulic Ventilation	28:09	1689	05:47	347

Figures 5.58 – 5.61 show the changes in flow over the course of the fire department interventions in Experiment 15. Prior to fire department intervention, bidirectional flows were sustained at the front door and the kitchen window. Hot gases exhausted through the upper portion of these vents and fresh air was entrained through the lower portion of these vents (Figure 5.58a). The

fire in Experiment 15 was in the growth stage at the time of intervention. Remote areas of the structure, particularly the open bedrooms and hallway, were still filling with smoke and could be characterized as two distinct zones, with a hot gas layer close to the ceiling and a cooler layer of air close to the floor. The initial fire department intervention was the closing of the front door. This simulated a search crew that arrived prior to a suppression crew, entered the structure, and controlled the door behind them. This action changed the flow such that the flow path between the front door and the kitchen was eliminated, leaving the only flow path (both intake and exhaust) at the kitchen window. As shown in Figure 5.58b, this was the only exterior source of air. Controlling the front door restricted the amount of air that was available for the fire for combustion. As the heat release dropped, the rate at which products of combustion were exhausted from the kitchen toward remote areas of the structure also dropped. As a result, the fire remained confined to the kitchen area in a pre-flashover state until suppression.

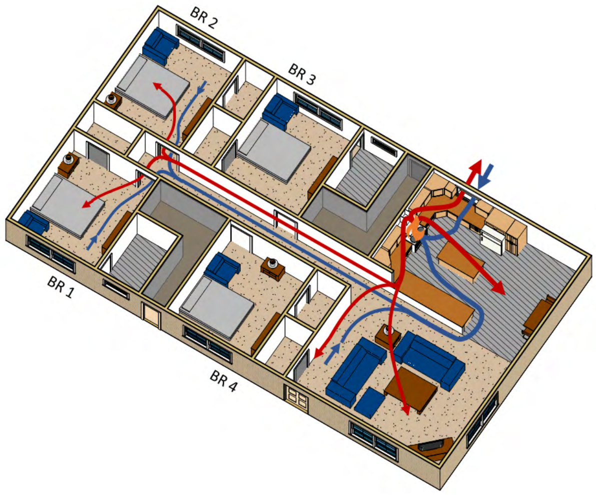


(a) Flows Prior to Intervention

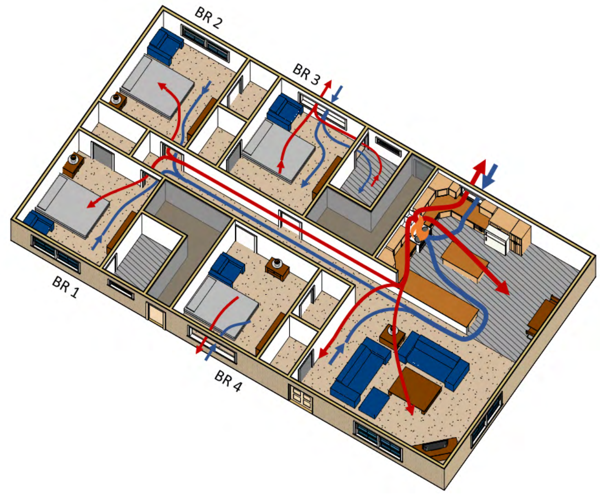
(b) Close Front Door

Figure 5.58: Changes in gas flows in the structure following fire department interventions in Experiment 15.

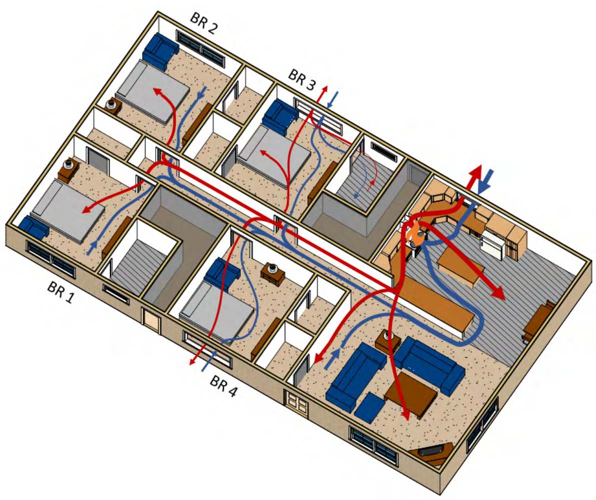
The bedroom 3 and 4 doors were closed 43 s after the front door was closed, simulating a search crew entering both bedrooms simultaneously, closing the respective door behind them, and beginning to search those spaces. This action isolated these rooms from the flow of products of combustion from the hallway, eliminating the bidirectional flows in the doorways (Figure 5.59a). The windows to bedrooms 3 and 4 were removed 11 s after the doors were closed, simulating a search crew ventilating the windows as they searched. This created new bidirectional vents: the bedrooms 3 and 4 windows. Products of combustion that were trapped behind the closed door exhausted through the upper portion of the window while air flowed through the lower portion of the window (Figure 5.59b). The bedrooms 3 and 4 doors were reopened 12 s later, simulating the search crew exiting the room after completing the search. This briefly allowed products of combustion to flow into bedrooms 3 and 4 before the door was closed again, once again eliminating the bidirectional flow through the door (Figures 5.59c and 5.59d). The smoke trapped in bedrooms 3 and 4 was able to continuously exhaust through the open windows.



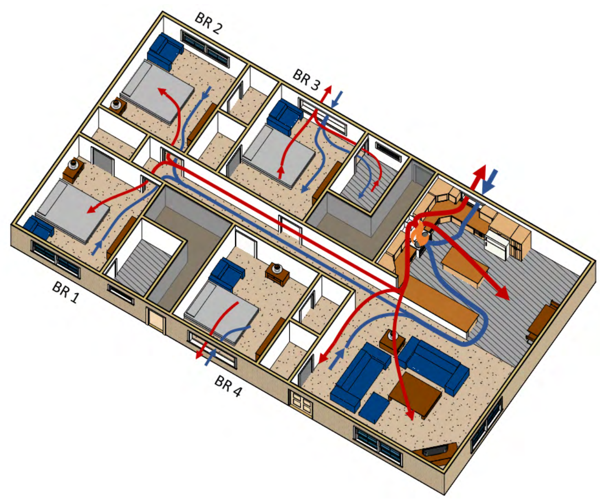
(a) Close BR3 & BR4 Doors



(b) Remove BR3 & BR4 Windows



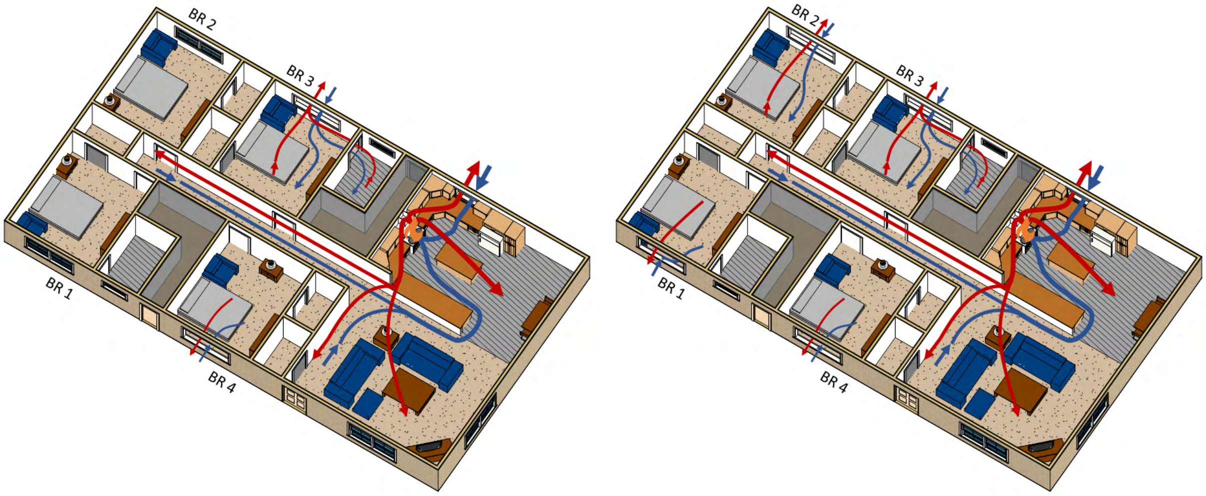
(c) Open BR3 & BR4 Doors



(d) Close BR3 & BR4 Doors

Figure 5.59: Changes in gas flows in the structure following fire department interventions in Experiment 15.

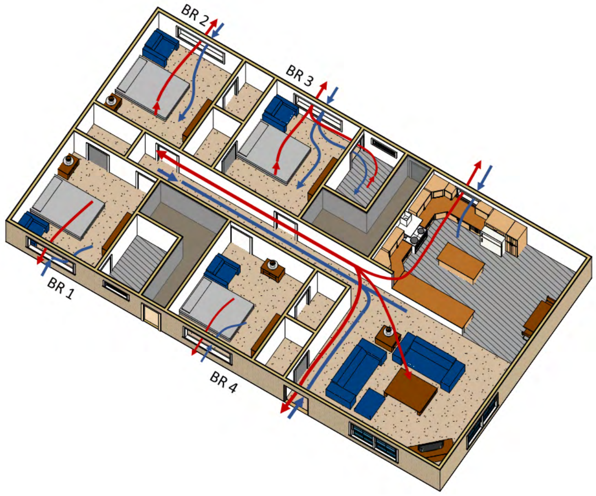
Bedroom 1 and 2 doors were closed 28 s after the bedroom 3 and 4 doors were closed for a second time. The search crew continued down the hallway, entered bedrooms 1 and 2, and closed the door behind them as they searched both rooms simultaneously (Figure 5.60a). The removal of the bedrooms 1 and 2 windows created new flow paths. The flow paths began and terminated at the windows of these rooms. Products of combustion that were trapped behind the closed door exhausted through the upper portion of the window while air flowed through the lower portion of the window (Figure 5.60b).



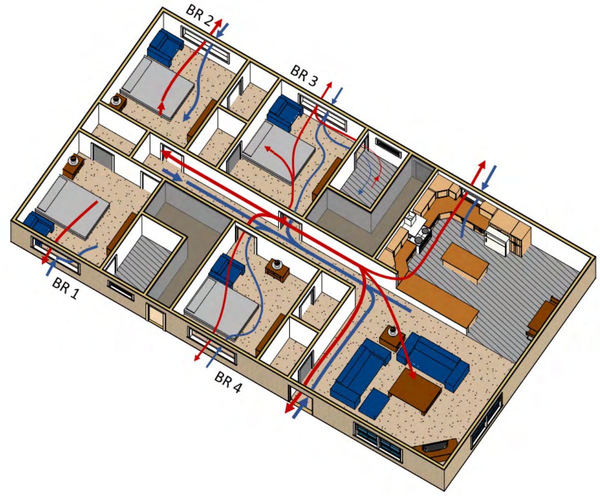
(a) Close BR1 & BR2 Doors (b) Remove BR1 & BR2 Windows

Figure 5.60: Changes in gas flows in the structure following fire department interventions in Experiment 15.

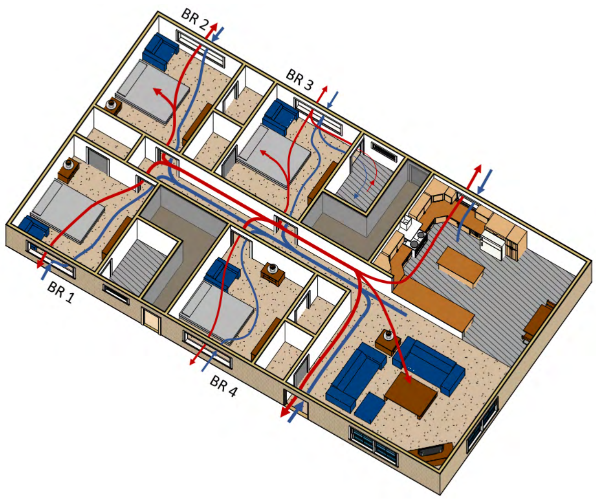
To initiate suppression, the front door was reopened 181 s after it was initially closed. Suppression was initiated from the deck with a 1 3/4 in. handline equipped with a combination nozzle set to flow a straight stream at 150 gpm. The suppression crew advanced into the living room using a flow-and-move technique. Bidirectional flow through the front door was re-established as the suppression crew advanced toward the kitchen fire (Figure 5.61a). Following fire control, the suppression crew made their way down the hallway, opening the bedrooms 3 and 4 doors first (Figure 5.61b), followed by the bedrooms 1 and 2 doors (Figure 5.61c). These actions allowed gases to flow between these rooms and the hallway. Hydraulic ventilation was initiated with a narrow-fog stream and fixed pattern through the side C kitchen window 347 s after intervention. The flowing water created a local area of lower pressure. This caused the four bedroom windows to act as inlets, drawing gases from remote areas of the structure toward the kitchen window, which acted as an exhaust, as shown in Figure 5.61d.



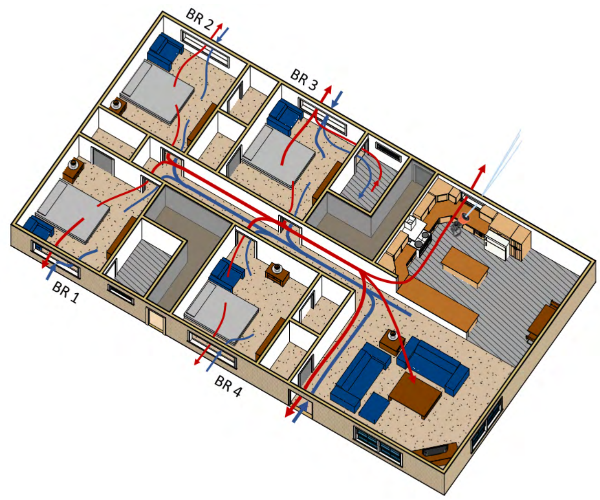
(a) Open Front Door, Suppression



(b) Open BR3 & BR4 Doors



(c) Open BR1 & BR2 Doors

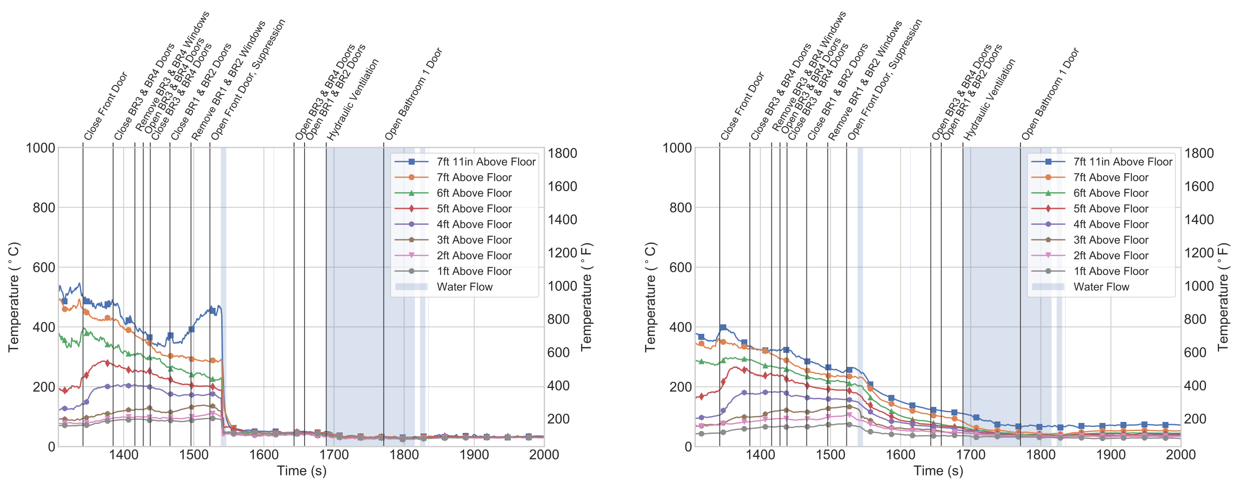


(d) Hydraulic Ventilation

Figure 5.61: Changes in gas flows in the structure following fire department interventions in Experiment 15.

5.5.1 Common Space

At the time of intervention, the common space fire had not transitioned through flashover, as shown by the kitchen and living room temperature time histories shown in Figure 5.62. Prior to closure of the front door, the camera view from a suppression crew firefighter indicated that the fire was mostly confined to the kitchen (the countertop cabinets above the ignition location), as shown by the image in Figure 5.63. Immediately prior to the closing of the door, temperatures ranged from 510 °C (950 °F) to 71 °C (160 °F) in the kitchen and from 380 °C (716 °F) to 45 °C (113 °F) in the living room. Following the front door closure, the 4 ft and 5 ft temperatures in both spaces exhibited a short increase, as the smoke layer descended at the two measurement locations following the change in flow path. The closed front door eliminated the bidirectional vent at that location, changing the flow path so that the only source of air for the kitchen fire was the bidirectional vent in the kitchen window. The smaller vent resulted in less efficient combustion, which resulted in a gradual decrease in all common space temperatures within 25 s of the door closing and continued until an abrupt drop occurred following suppression. One exception to this was the kitchen ceiling temperature which showed a rise from 1458 s until suppression. This rise was likely a result of burn through of a cabinet door that exposed some additional air and led to localized area of burning near the ceiling.



(a) Kitchen Temperature

(b) Living Room Temperature

Figure 5.62: Temperature time histories in the common space for the period following fire department intervention in Experiment 15.

Figure 5.63: Fire conditions immediately prior to front door closing during Experiment 15.

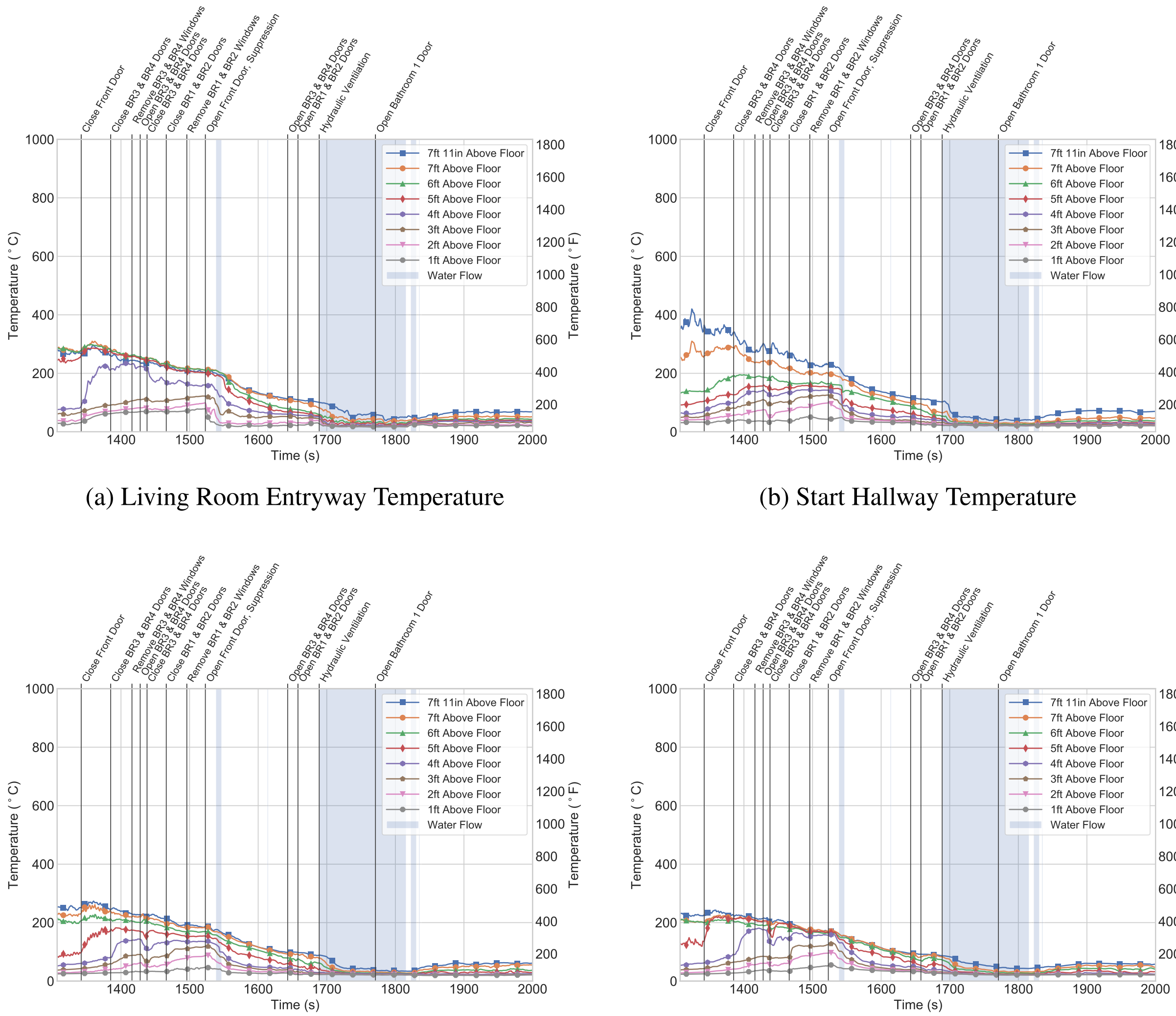
The suppression crew opened the front door and advanced the line to the kitchen 181 s after the initial fire department intervention. Immediately prior to water flow, the fire conditions visible to the suppression crew were comparable to those when the front door was initially closed, with the majority of visible fire confined to the kitchen area, as shown in Figure 5.64. The suppression crew flowed water for 10 s, which caused kitchen temperatures to drop sharply. This suppression action similarly caused living room temperatures to decrease, although the decrease was more gradual. Hydraulic ventilation caused living room temperatures to decrease below 65 °C (149 °F) at all elevations.

Figure 5.64: Looking through side C kitchen window, fire conditions immediately prior to suppression during Experiment 15.

5.5.2 Hallway

Figure 5.65 shows the time histories of temperature at the living room entryway and hallway measurement locations during Experiment 15. Immediately prior to the front being closed, temperatures in the living room entryway were stratified into two distinct zones, a reflection of the bidirectional flow through the doorway (Figure 5.65a). Temperatures from the ceiling to 5 ft above the floor ranged from 275 °C to 250 °C (527 °F to 482 °F). Temperatures 4 ft and below ranged from 80 °C to 30 °C (176 °F to 86 °F). Immediately after the front door was closed, the 4 ft temperature sharply increased as the flow path in the front door was eliminated and the hot gas layer descended below 4 ft. In the period between the closing of the front door and the opening of the door for suppression, temperatures between 5 ft and the ceiling gradually decreased, while temperatures 1-3 ft above the floor gradually increased. The opening of the front door 181 s after intervention caused temperatures 4 ft and below to decrease as fresh air was entrained through the lower portion of the doorway. Suppression caused temperatures at all elevations to begin to decrease, which was further accelerated hydraulic ventilation.

Temperatures in the hallway, shown in Figures 5.65b, 5.65c, and 5.65d, generally followed a similar trend to those in the living room entryway. At the time of intervention, temperatures ranged from 340 °C to 33 °C (644 °F to 91 °F) at the start hallway, 250 °C to 26 °C (482 °F to 79 °F) at the mid-hallway, and 225 °C to 33 °C (437 °F to 91 °F) at the end hallway. At each location, two distinct zones were evident, with higher temperatures at elevations closer to the ceiling and lower temperatures at elevations closer to the floor.



(a) Living Room Entryway Temperature

(b) Start Hallway Temperature

(c) Mid Hallway Temperature

(d) End Hallway Temperature

Figure 5.65: Temperature time histories in the hallway in the period following fire department intervention in Experiment 15.

In the period between the closing of the front door and suppression, flaming combustion was local to the kitchen. The lack of fire growth resulted in temperatures close to the ceiling at all three locations to gradually decrease as gas flows decreased once the space filled and the pressure rose. Temperatures close to the floor gradually increased as the smoke layer continued to descend.

At the start hall location, temperatures followed this trend without any noticeable effect from the opening and closing of hallway doors. At the mid and end hallway locations, ceiling temperatures followed a similar trend to the start hall and end hall locations, but temperatures 4 ft and below fluctuated with the opening and closing of the bedroom 3 and 4 doors. Immediately following the closing of these doors, 43 s after intervention, temperatures 4 ft and below increased as the volume of the bedrooms was cutoff. The smoke layer descended further. The opposite trend was observed when the doors were reopened 86 s after intervention, when a sharp decrease in temperatures was observed at elevations 5 ft and below. When the door was temporarily reopened, the respective bedroom windows has been opened. This allowed combustion gases to exhaust through those rooms and the smoke layer to rise. After the front door was opened and suppression began, temperature began to continuously decrease. This decrease was accelerated by hydraulic ventilation, which caused temperatures to decrease uniformly below 50 °C (122 °F).

Figure 5.66 shows the time histories of heat flux at the living room entryway and three hallway locations. At the time of intervention, the living room entryway and start hallway heat fluxes were 2.0 kW/m^2 and 1.8 kW/m^2, respectively, while the mid and end hallway heat fluxes were both below 0.5 kW/m^2. The low heat flux values reflect the pre-flashover conditions at the time that the front door was closed.

Following the closing of the front door, the heat flux at the living room entryway began to gradually decrease as the exhaust flow over this gauge was eliminated. This decrease continued while the front was closed, and became steeper once the front door was re-opened to allow entry of the suppression crew. The open front door re-established the inlet flow path through the front door, which had a cooling effect at the living room measurement location. Heat flux in the living room decreased below 0.5 kW/m^2 prior to the suppression action.

The start hallway heat flux exhibited a similar decrease following the closing of the front door, although the decrease in heat flux at this location occurred at a more rapid rate. The start hallway heat flux decreased below 0.5 kW/m^2 prior to the closing of the bedrooms 1 and 2 doors. Heat flux at the mid and end-hallway locations maintained steady values for the duration of the search sequence. Following suppression, all heat flux values at the entryway and hallway measurement locations remained below 0.5 kW/m^2.

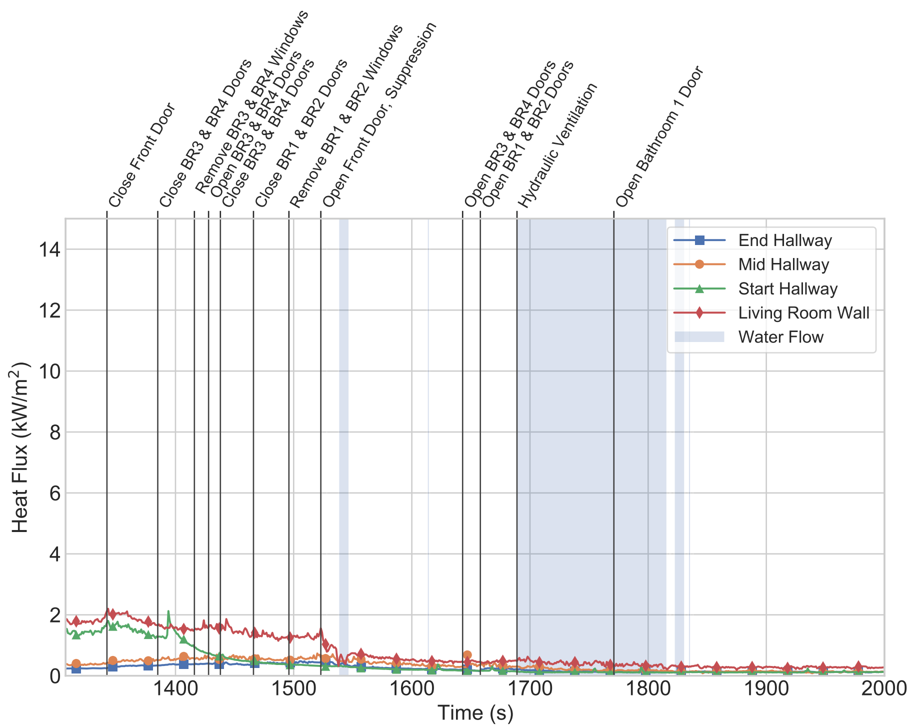


Figure 5.66: Heat flux time histories in the hallway in post-intervention period during Experiment 15.

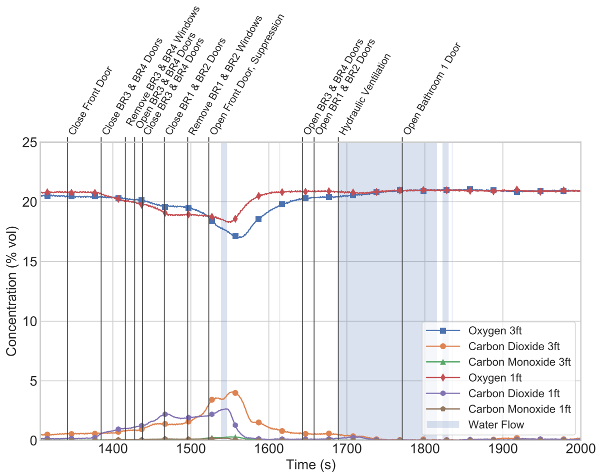
Table 5.10 show gas concentrations at intervention and Figure 5.67 shows the time histories of gas concentration in the living room entryway and at the three hallway measurement locations during Experiment 15. Immediately prior to intervention, the front door acted as a bidirectional vent, with smoke exhausting from the upper portion of the doorway and the lower portion of the doorway acting as an air inlet. Since the kitchen fire had not spread to the living room, this sustained flow of fresh air through the living room resulted in concentrations of O_2, CO and CO_2 concentrations close to pre-ignition levels, as shown by the values in Table 5.10. When the front door was closed, the bidirectional flow through the front door was eliminated. In the period between the initial front door control action and the re-opening of the front door for suppression, CO and CO_2 concentrations in the living room gradually increased while O_2 gradually decreased (Figure 5.67a). When the front door was re-opened to allow entry of the suppression team 181 s after intervention, the bidirectional flow was re-established in the front door. CO and CO_2 concentrations continued to increase initially following door opening, reaching peak values 32 s and 25 s after door opening at the 3 ft and 1 ft elevations, respectively. The combination of the interior suppression action and the inlet flow through the living room caused gas concentrations to trend toward ambient for the remainder of the experiment.

At the time of intervention, gas concentrations at the three hallway locations that were not located in the flow path between the front door and kitchen were characterized by slightly higher concentrations of CO and CO_2 and lower concentrations of O_2 than in the living room (Table 5.10). This was most notable at the 3 ft elevation compared to the 1 ft elevation.

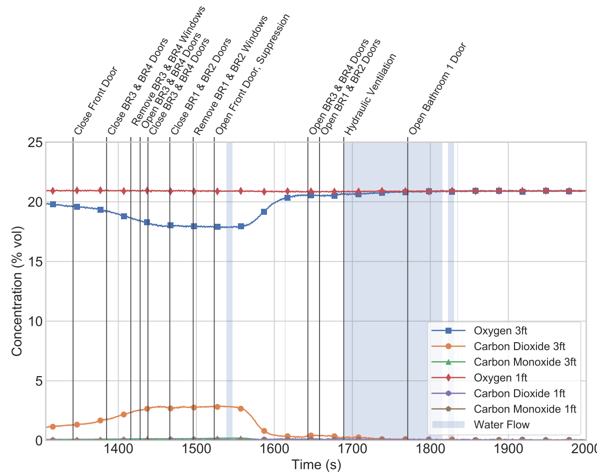
Table 5.10: Hallway Gas Concentrations at Intervention for Experiment 15

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	20.2	0.6	0
	1 ft	20.8	0.2	0
Start Hallway	3 ft	19.6	1.3	0.1
	1 ft	20.9	0	0
Mid Hallway	3 ft	18.1	2.8	0.2
	1 ft	20.6	0.4	0
End Hallway	3 ft	18.3	2.5	0.7
	1 ft	20.3	0.6	0

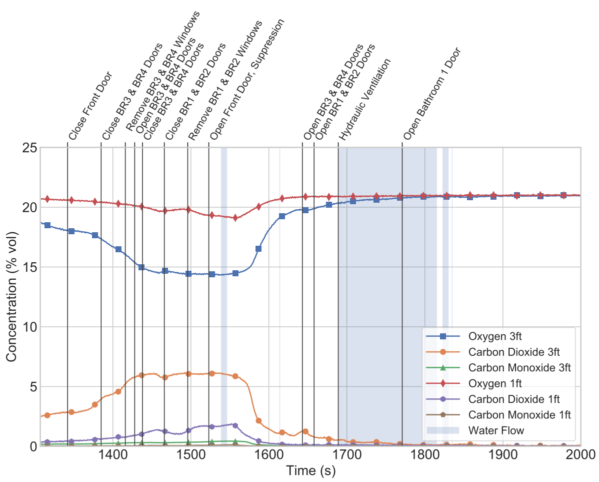
Immediately following the front door closure, the rate of change of hallway gas concentrations increased as the smoke layer descended due to the kitchen window being the only exhaust vent. CO and CO_2 concentrations continued to increase to a steady state that occurred starting at approximately 1418 s after ignition. During this steady state, CO and CO_2 concentrations were highest at the end hallway location and lowest at the start hallway location, where gas concentrations at the 1 ft elevation remained approximately ambient for the duration of the experiment. CO concentrations remained below 0.2% at the 1 ft measurement locations and below 0.4% at the 3 ft measurement locations. Following the re-opening of the front door and suppression actions, the hallway measurement locations were not in the flow path, which caused gas concentrations in the hallway to remain steady until approximately 220 s after intervention (1562 s after ignition), when gas concentrations began to trend toward ambient. Hydraulic elevation accelerated the rate at which CO and CO_2 concentrations decreased at the hallway measurement locations, with gas concentrations returning to approximately ambient conditions prior to the end of hydraulic ventilation.



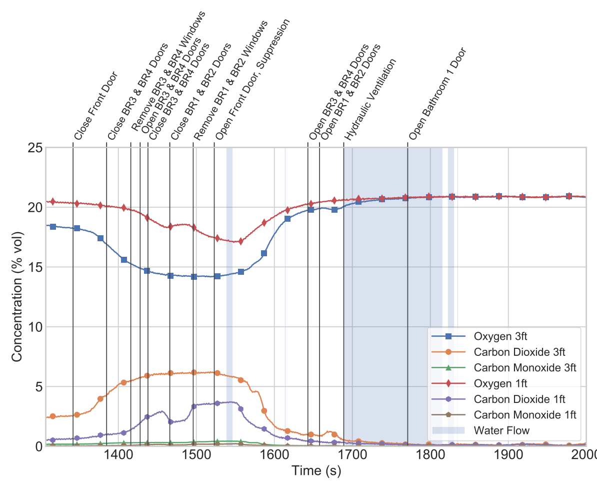
(a) Living Room Entryway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.67: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 15.

5.5.3 Bedroom 3

Figure 5.68 shows the time history of temperature in bedroom 3 during Experiment 15. The door between bedroom 3 and the hallway was open prior to ignition, which allowed products of combustion to flow into the room as the kitchen fire grew. At the time that the front door was closed, temperatures in bedroom 3 ranged from 130 °C at the ceiling (266 °F) to 23 °C (74 °F) 1 ft above the floor. Temperatures continued to increase in the period between the closing of the front door and closing the bedroom 3 door. Products of combustion flowed into bedroom 3 through the open hallway door. When the bedroom 3 door was closed, the flow path was changed; bedroom 3 was isolated from the hallway, which resulted in a decrease in temperature at all elevations. This decrease was accelerated when the bedroom 3 window was removed, and continued until the bedroom 3 door was briefly re-opened. There was a temporary increase in temperature between 6 ft above the floor and the ceiling in the 10 s between the re-opening of the door and subsequent closing as products of combustion flowed into the room. Following this local peak, temperatures continuously decreased for the rest of the experiment. Temperatures in the room had uniformly decreased below 40 °C (104 °F) when the door was re-opened for a second time following suppression but prior to hydraulic ventilation. This caused temperatures to decrease to pre-ignition conditions.

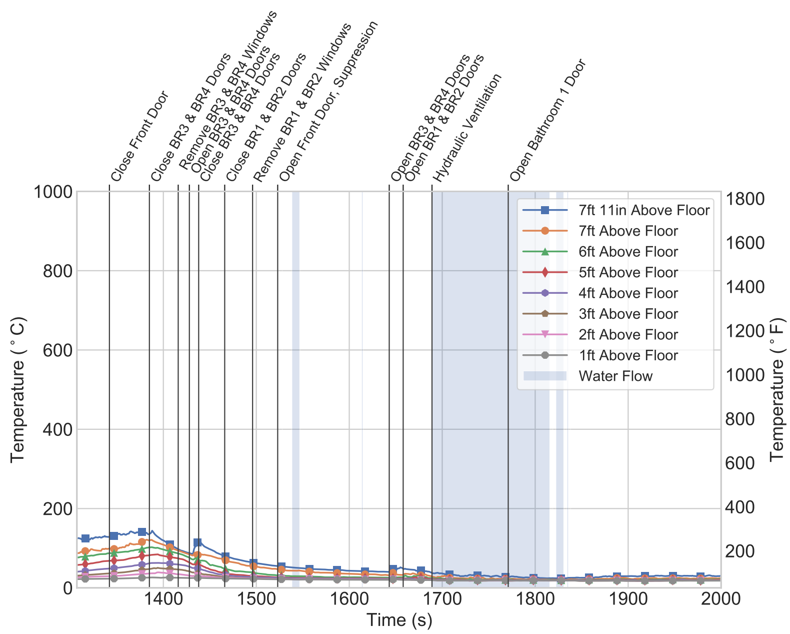
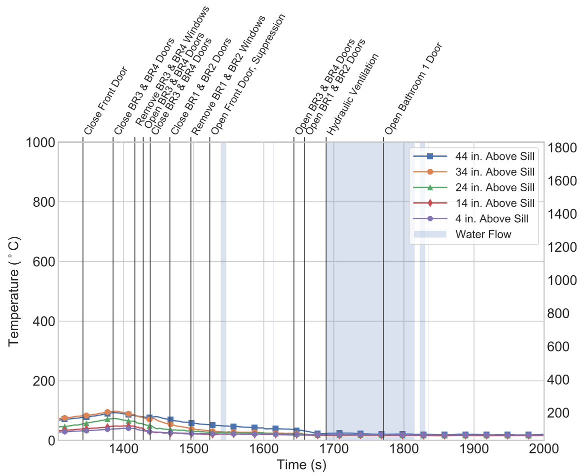


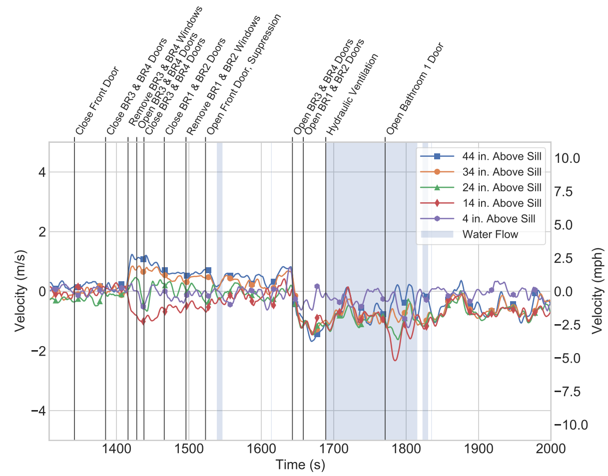
Figure 5.68: Post-intervention bedroom 3 temperature during Experiment 15.

Figure 5.69 shows the temperature, velocity, heat flux, and gas concentrations measured in the bedroom 3 window. The window temperatures (Figure 5.69a) generally followed a similar trend to the temperatures in the room itself. Temperatures increased through intervention to a peak coincident with the closing of the bedroom 3 door. When the bedroom 3 window was opened, the window temperature (Figure 5.69a) and velocity data (Figure 5.69b) indicated that bidirectional flow was established through the bedroom 3 window. Higher temperature, higher pressure products of combustion trapped in the room to exhausted through the upper portion of the window and were replaced with inflowing air through the lower portion of the window. The exhaust temperatures continuously decreased following the removal of the window, with the exception of a local peak simultaneous with the cycling of the bedroom 3 door. The bidirectional flow through the bedroom window was maintained until the bedroom 3 door was re-opened following suppression, 301 s after intervention (1623 s after ignition), when the flow path in the window changed to a unidirectional inlet. This inlet was maintained through the hydraulic ventilation action, as fresh air was drawn in through the bedroom 3 window toward the area of low pressure created by the flowing water at the side C kitchen window.

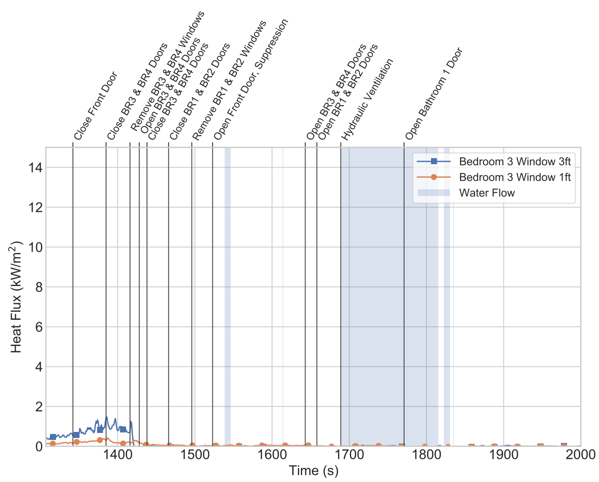
Heat flux in the bedroom 3 window, shown in Figure 5.69c, also trended similarly to the temperatures in bedroom 3. When the front door was closed, the heat flux was 0.7 and 0.2 kW/m^2 at the



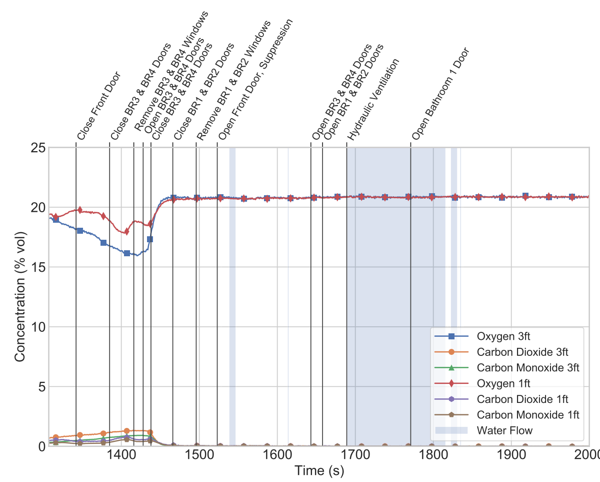
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.69: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 15.

3 ft and 1 ft measurement elevations, respectively. Following intervention, the heat flux at both elevations increased to peak values simultaneous with the closing of the bedroom 3 door. The peak heat flux measured at the 3 ft and 1 ft elevations was 1.5 kW/m^2 and 0.5 kW/m^2, respectively. Following this peak, heat flux continuously decreased at both elevations as the bedroom 3 window was removed, resulting in heat flux measurements that were negligible prior to the second closing of the bedroom 3 door 96 s after intervention (1418 s after ignition).

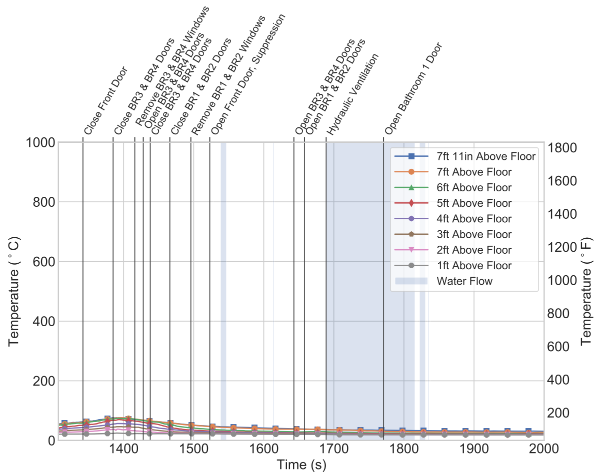
Figure 5.69d shows the time history of gas concentration in the bedroom 3 window. At the time of intervention, the smoke layer in bedroom 3 was continuing to descend as products of combustion from the kitchen fire flowed into the bedroom via the open hallway door. As the smoke layer reached the floor, products of combustion began to mix with the cooler air close to the floor, resulting in a gradual increase in CO and CO_2 concentrations and gradual decrease in O_2 concentrations.

When the front door was closed, gas concentrations were 18.2% O_2, 0.9% CO_2, and 0.5% CO at the 3 ft elevation and 19.8% O_2, 0.4% CO_2, and 0.2% CO at the 1 ft elevation.

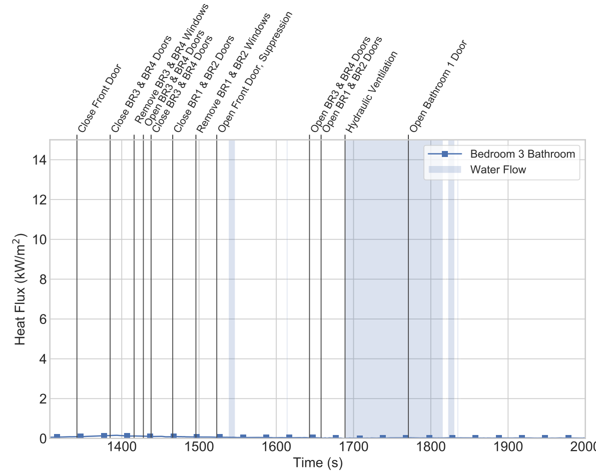
Following intervention, the increase in CO and CO_2 and decrease in O_2 continued as bedroom 3 filled with products of combustion. The combined action of closing the bedroom 3 door and removal of the bedroom 3 window stopped the flow of products of combustion into bedroom 3 and created an exhaust point for trapped smoke. CO and CO_2 concentrations started to decrease. Peak gas concentrations were observed 75 s after intervention (1415 s after ignition), measuring 16.1% O_2, 1.3% CO_2, and 0.9% CO 3 ft above the floor and 18.8% O_2, 0.6% CO_2, and 0.5% CO 1 ft above the floor. Gas concentrations returned to pre-ignition levels within 30 s of bedroom 3 getting closed (1480 s post ignition).

Figure 5.70 shows the temperature, heat flux, and gas concentration time histories measured in bathroom 3 during Experiment 15. Temperatures measured in the bathroom generally followed a similar trend to those in the adjacent bedroom, although the magnitude of the temperatures was lower, with values at the time of intervention ranging from 61 °C (142 °F) to 22 °C (72 °F). Following intervention, these temperatures continued to increase to peaks ranging from 76 °C to 25 °C (169 °F to 77 °F), which were observed approximately 10 s after the bedroom 3 door was closed. This isolated bathroom 3 from the flow of hot products from the hallway. Following this peak, temperatures uniformly decrease for the remainder of the experiment, with the removal of the bedroom 3 window accelerating this decrease. As a result of the comparatively lower temperatures in bathroom 3, the heat flux in the bathroom, shown in Figure 5.70b, were negligible for the duration of the experiment.

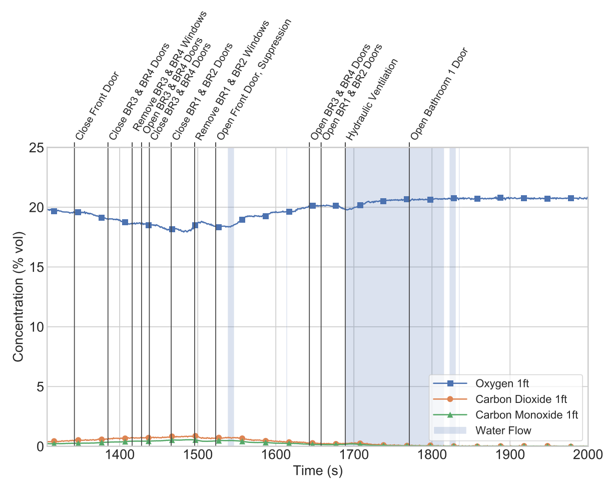
Gas concentrations in bathroom 3, shown in Figure 5.70c, were comparable to those at the corresponding location in bedroom 3. O_2, CO_2, and CO concentrations were 19.6%, 0.5%, and 0.3%, respectively at the time of intervention. Since the door between bedroom and bathroom 3 was open throughout the experiment, gas concentrations in bathroom 3 followed a similar trend to those in the adjacent bedroom. The peak CO and CO_2 concentrations were observed 155 s after intervention (1495 s after ignition), with O_2, CO_2, and CO concentrations of 18.3%, 0.8%, and 0.6%. These peaks are comparable to those observed 1 ft above the ground in bedroom 3, although they were observed later in the experiment because of the further distance from the vents. Following this peak, gas concentrations gradually trended toward ambient, returning to pre-experiment conditions during hydraulic ventilation.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux

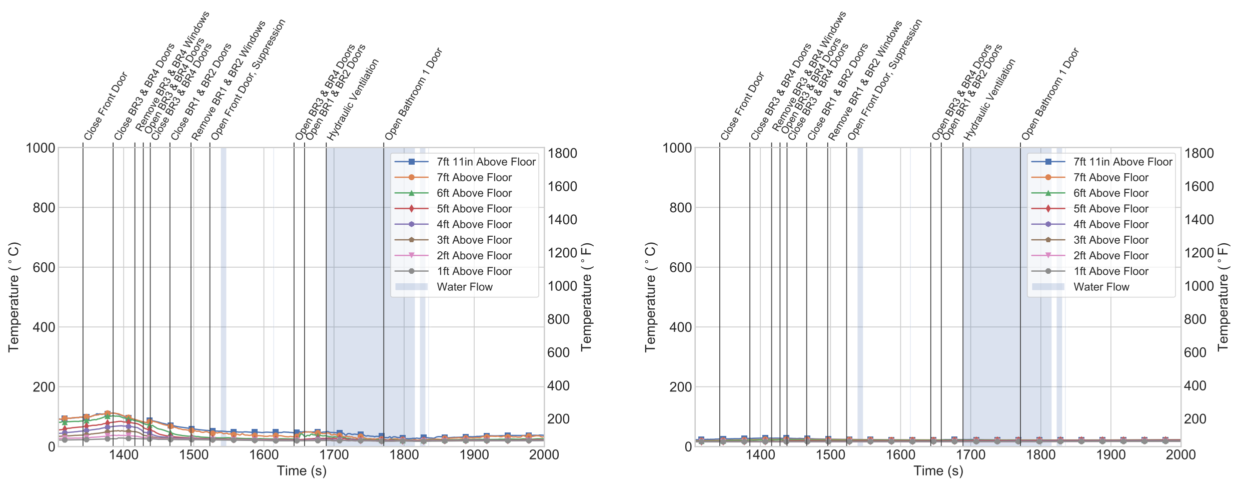


(c) Bathroom 3 Gas Concentration

Figure 5.70: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 15.

5.5.4 Bedroom 4

Figure 5.71 shows the temperatures measured in bedroom 4 and the attached closet during Experiment 15. The door between bedroom 4 and the hallway was open from the beginning of the experiment, allowing products of combustion to flow into the room as the kitchen fire grew. At the time that the front door was closed, temperatures in bedroom 4 ranged from 98 °C to 23 °C (208 °F to 73 °F). Temperatures continued to increase in the period between the closing of the front door and the closing of the bedroom 4 door as products of combustion continued to flow into bedroom 4 through the open hallway door. When the bedroom 4 door was closed, the flow path was changed, isolating bedroom 4 from the hallway and resulting in a decrease in temperature at all elevations. This decrease was accelerated when the bedroom 4 window was removed and continued until the bedroom 4 door was briefly re-opened. A brief increase in temperature was measured between 6 ft and the ceiling in the 10 s between the re-opening of the door and subsequent closing as products of combustion flowed into the room. Following this temporary peak, temperatures continuously decreased for the rest of the experiment. Temperatures in the room had uniformly decreased below 50 °C (122 °F) when the door was re-opened for a second time prior to hydraulic ventilation. Hydraulic ventilation caused temperatures to return to pre-ignition conditions. Temperatures in the bedroom 4 closet, which was closed for the duration of the experiment and lacked an HVAC supply, remained below 30 °C (86 °F) for the duration of the experiment (Figure 5.71b).



(a) Bedroom 4 Temperature

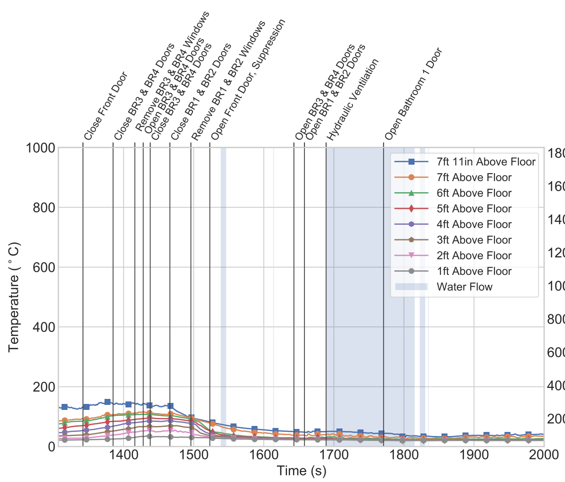
(b) Bedroom 4 Closet

Figure 5.71: Post-intervention temperature measurements in bedroom 4 during Experiment 15.

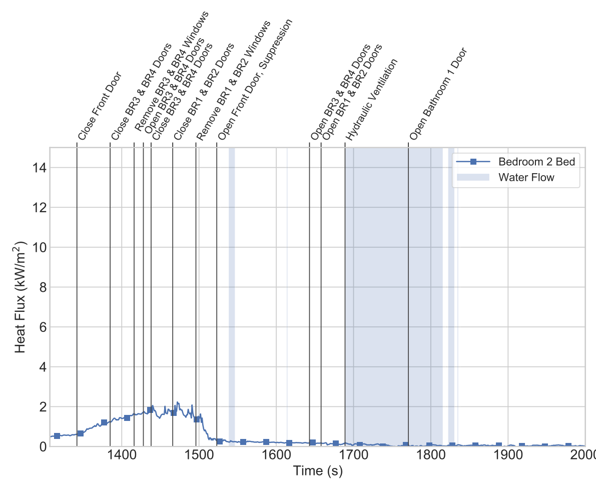
5.5.5 Bedroom 2

Figure 5.72 shows the time history of temperature, heat flux, and gas concentration in bedroom 2 during Experiment 15. The door between bedroom 2 and the hallway was open prior to ignition, which allowed products of combustion to flow into the room as the kitchen fire grew. At the time that the front door was closed, temperatures in bedroom 2 were comparable to those in bedroom 3, ranging from 127 °C to 22 °C (260 °F to 72 °F). Temperatures continued to gradually increase until the doorway to the hallway was closed. Peak temperatures in bedroom 2 ranged from 135 °C to 35 °C (275 °F to 95 °F). When the bedroom 2 door was closed, the flow path was changed. Bedroom 2 was isolated from the flow of hot gases from hallway and as a result, temperatures decreased at all elevations. This decrease was accelerated when the bedroom 2 window was removed 254 s after intervention (1476 s after ignition). A new flow path was created. Products of combustion that were trapped behind the closed door exhausted through the window. Temperatures had uniformly decreased below 50 °C (122 °F) prior to the start of hydraulic ventilation, and further decreased during the hydraulic ventilation action to approximately ambient temperatures.

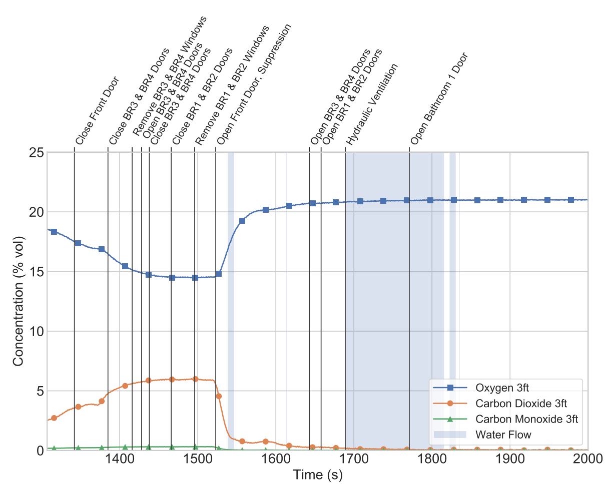
Figure 5.72b shows the time history of heat flux on the bed, 3 ft above the floor in bedroom 2. Heat flux at this location trended similarly to the temperatures. The heat flux gradually increased from 0.6 kW/m^2 at the time of intervention to a peak of 2.2 kW/m^2 that coincided with the bedroom 2 door closure. The heat flux remained steady in the period between the closing of the bedroom door and the removal of the window, as products of combustion remained trapped in the bedroom. Heat flux sharply decreased to negligible values after the bedroom 2 window was removed, which allowed products of combustion to exhaust from the bedroom.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux

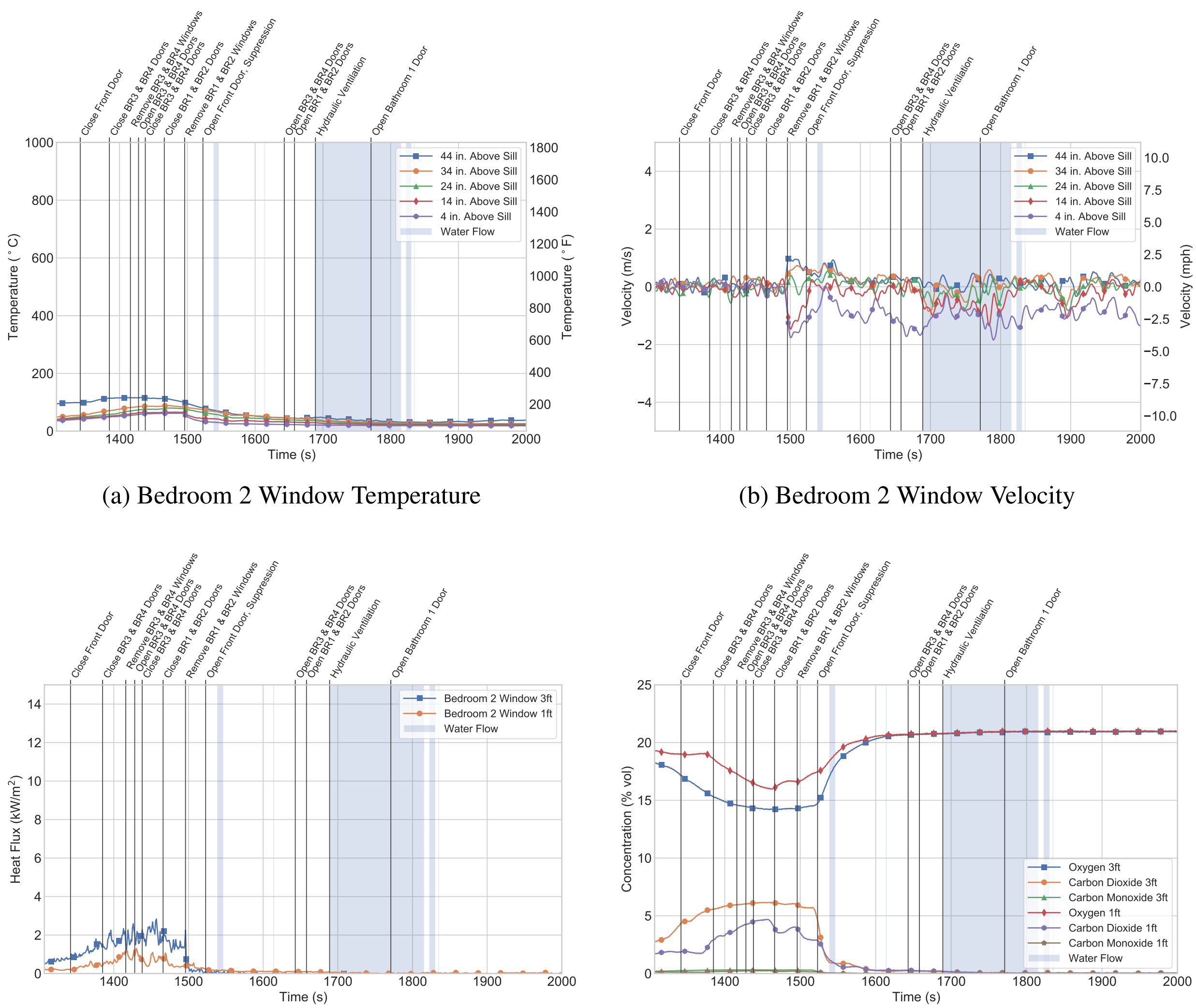


(c) Bedroom 2 Gas Concentration

Figure 5.72: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 2 during Experiment 15.

Figure 5.72c shows the time history of gas concentration on the bed, 3 ft above the floor in bedroom 2. At the time of intervention, the smoke layer in bedroom 2 continued to descend as products of combustion from the kitchen fire flowed into the bedroom via the open hallway door. O_2, CO_2, and CO concentrations were 17.6%, 3.5%, and 0.2%, respectively when the front door was closed. The closing of the front door restricted the amount of oxygen that was available to the kitchen fire, resulting in a reduction in the amount of products of combustion that the fire was able to produce. As a result of this restriction in fire growth, gas concentrations started to plateau approximately 100 s after intervention (1440 s after ignition) to O_2, CO_2, and CO values of 14.5%, 6.0%, and 0.3%, respectively. These steady gas concentrations were maintained through the closing of the bedroom 2 door and the removal of the bedroom 2 window. Approximately 30 s after the window was removed, CO and CO_2 concentrations started to decrease and O_2 started to increase as smoke was exhausted through the open bedroom 2 window and replaced with air. CO and CO_2 concentrations had decreased to negligible values prior to the start of hydraulic ventilation.

Figure 5.73 shows the time histories of temperature, velocity, heat flux, and gas concentration in the bedroom 2 window during Experiment 15. In the period prior to removal of the bedroom 2 window, temperatures continuously increased, similar to the temperatures measured in the center in the room, as shown in Figure 5.73a. After the bedroom 2 window was removed, the temperature and velocity measurements show that bidirectional flow was established in the bedroom 2 window (Figure 5.73b). Higher temperature, higher pressure products of combustion exhausted through the exterior vent. After the bedroom 2 door was re-opened and hydraulic ventilation was initiated, the flow path through bedroom 2 changed such that the window acted as a unidirectional inlet, as gases were drawn from bedroom 2 toward the exterior vent created at the kitchen window.



(a) Bedroom 2 Window Temperature

(b) Bedroom 2 Window Velocity

(c) Bedroom 2 Window Heat Flux

(d) Bedroom 2 Window Gas Concentration

Figure 5.73: Post-intervention temperature, velocity, heat flux measurements at bedroom 2 window during Experiment 15.

The heat flux measured 3 ft and 1 ft above the floor in the window trended similarly to the bed heat flux, as shown in Figure 5.73c. At the time of intervention the peak values were 2.8 kW/m^2 and 0.9 kW/m^2 at 3 ft and 1 ft, respectively, simultaneous with the closing of the bedroom 2 door. The heat flux at both elevations began to decrease with the closure of the bedroom door and dropped sharply to negligible values immediately after the bedroom window was removed, as a result of the entrained air through the inlet portion of the window.

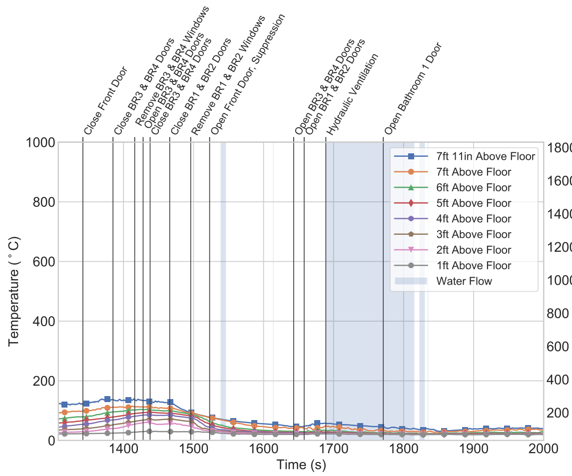
Figure 5.73d shows the time history of gas concentration at the bedroom 2 window locations. At the time of intervention, gas concentrations were 17.2% O_2, 4.3% CO_2, and 0.1% CO 3 ft above the floor and 19.0% O_2, 1.8% CO_2, and 0.1% CO 1 ft above the floor. These concentrations were consistent with the gas concentrations measured at similar respective elevations in bedrooms 2 and 3 at the time that the front door was closed. Following the closing of the front door, CO and CO_2 concentrations gradually increased and O_2 concentrations gradually decreased to steady values which began approximately 100 s after intervention. During this steady period, gas concentrations were approximately 14.2% O_2, 6.2% CO_2, and 0.3$ CO 3 ft above the floor and 16.0% O_2, 4.7% CO_2, and 0.2% CO 1 ft above the floor. These concentrations were maintained through the closing of the bedroom 2 door and the removal of the bedroom 2 window. Similar to the gas concentrations on the bed in bedroom 2, gas concentrations at the bedroom 2 window measurement locations began to return toward pre-ignition levels as fresh air entrained into the room through the inlet in the window replaced the products of combustion that had previously been trapped in the room.

5.5.6 Bedroom 1

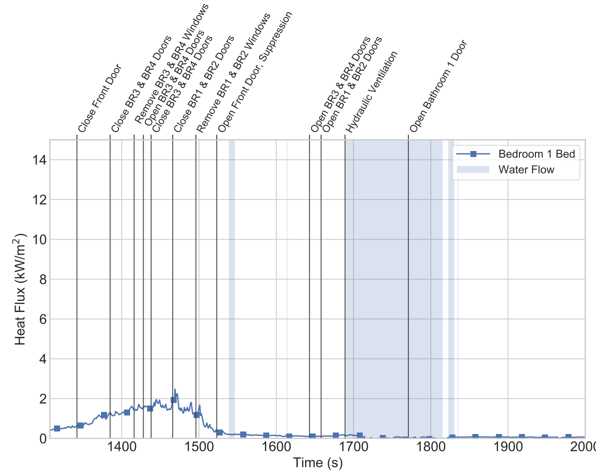
Figure 5.74 shows the time histories of temperature, heat flux, and gas concentration in bedroom 1. Like bedroom 2, the door between bedroom 1 and the hallway was open from the start of the experiment, resulting in temperatures (Figure 5.74a). Temperatures in bedroom 1 ranged from 125 °C to 22 °C (257 °F to 72 °F) at the time that the front door was closed. Temperatures continued to increase and peaked simultaneous with the closing of the bedroom 1 door 124 s after intervention (1446 s after ignition). Temperatures in bedroom 1 ranged from 127 °C to 30 °C (261 °F to 86 °F). When the bedroom 1 door was closed, the flow path was changed. Bedroom 1 was isolated from the flow of hot gases from hallway which resulted in an immediate decrease in temperature at all elevations. This decrease was accelerated when the bedroom 1 window was removed 254 s after intervention (1476 s after ignition). A new flow path was created which started and and ended at the bedroom 1 window. Products of combustion exhausted from the room through the exterior vent. During hydraulic ventilation temperatures had decreased to approximately ambient temperatures.

Figure 5.74b shows the time history of heat flux on the bed 3 ft above the floor in bedroom 1. Heat flux in bedroom 1 followed a similar trend to the bed location in bedroom 2. Following the closing of the front door, the heat flux gradually increased from 0.6 kW/m^2 at the time of intervention to a peak of 2.5 kW/m^2 immediately after the bedroom 1 door was closed. The heat flux remained steady in the period between the closing of the bedroom door and the removal of the window as products of combustion remained in the bedroom. The measured heat flux decreased to negligible values after the bedroom 1 window was removed as products of combustion exhausted through the open bedroom window.

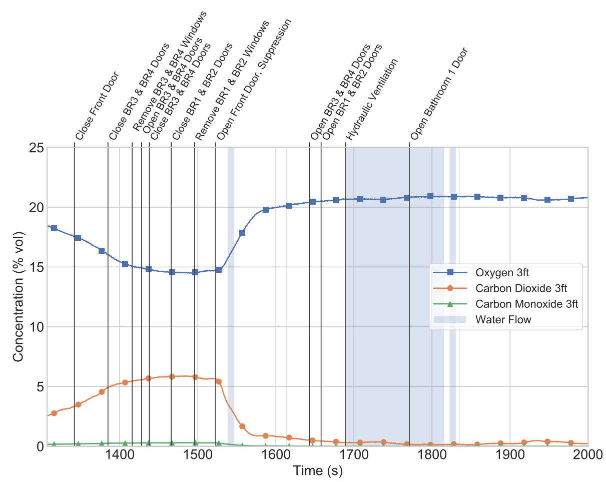
Figure 5.74c shows the time history of gas concentration 3 ft above the floor on the bed in bedroom 1. At the time of intervention, the smoke layer in bedroom 1 descended as products of combustion from the kitchen fire flowed into the bedroom via the open hallway door. O_2, CO_2, and CO concentrations were 17.6%, 3.3%, and 0.2%, respectively when the front door was closed. The closing of the front door restricted the amount of oxygen that was available to the kitchen fire, which resulted in a reduction in the amount of products of combustion that the fire was able to produce. As a result of this restriction in fire growth, gas concentrations started to plateau approximately 100 s after intervention (1440 s after ignition) to O_2, CO_2, and CO values of 14.6%, 5.8%, and 0.3%, respectively. These steady gas concentrations were maintained through the closing of the bedroom 1 door and the removal of the bedroom 1 window. At approximately the same



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux

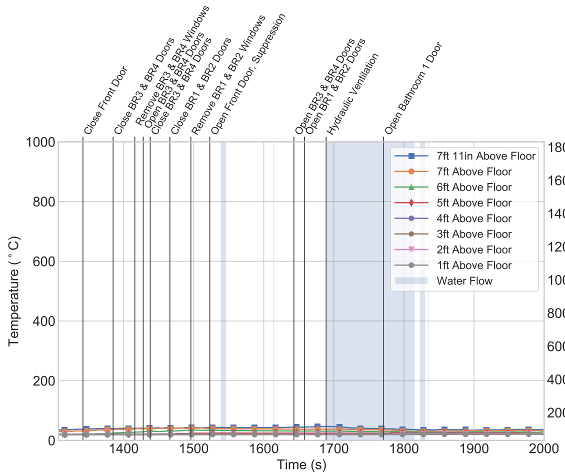


(c) Bedroom 1 Gas Concentration

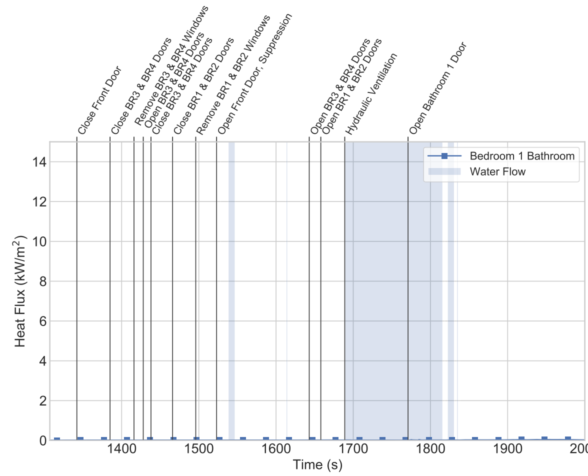
Figure 5.74: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 15.

time that the front door was opened to allow suppression, CO and CO_2 concentrations started to decrease and O_2 started to increase as smoke was exhausted through the open bedroom 1 window and replaced with fresh air. CO and CO_2 concentrations had decreased to negligible values prior to the start of hydraulic ventilation.

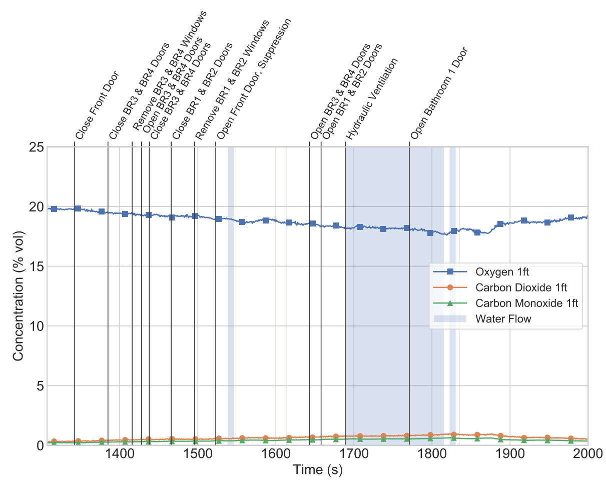
Figure 5.75 shows the time histories of temperature, heat flux, and gas concentrations in bathroom 1 during Experiment 15. The door between bathroom 1 and the bedroom 1 was closed from the start of Experiment 15, which result in low peak temperatures. When the front door was closed, temperatures in the bathroom were uniformly less than 40 °C (104 °F). Temperatures 6 ft and above began to increase as smoke leaked around the closed door and through the HVAC supply vent. Temperatures gradually increased to a steady state, with peak ceiling temperatures reaching 47 °C (117 °F) immediately prior to hydraulic ventilation. Temperatures in the bathroom remained steady until 85 s into hydraulic ventilation, when the bathroom door was opened and temperatures began to decrease. As a result of the low temperatures in the bathroom, heat flux measured 1 ft above the floor was negligible for the duration of the experiment, as shown in Figure 5.75b.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Heat Flux



(c) Bathroom 1 Gas Concentration

Figure 5.75: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 15.

Figure 5.75c shows the time history of gas concentrations in bathroom 1. The closed door between the bathroom and bedroom 1 prevented smoke from freely flowing into the bathroom during the initial growth stages of the fire, resulting in low concentrations of CO and CO_2 at the time of intervention of 0.2% and 0.4%, respectively, with a corresponding O_2 concentration of 19.7%. Following the closing of the front door, CO and CO_2 concentrations gradually increased while O_2 concentrations gradually decreased. There was no noticeable effect from the closing of the bedroom 1 door or the removal of the bedroom 1 window. Gas concentrations began to gradually decrease once the bathroom 1 door was opened, allowing trapped smoke to flow into the rest of the structure and be replaced with air. Peak O_2, CO_2, and CO concentrations were observed during hydraulic ventilation, and were 18.3%, 0.8%, and 0.6%, respectively. Although gas concentrations began to trend toward ambient during the hydraulic ventilation action, the effectiveness of that tactic on ventilating bathroom 1 was limited by the lack of an inlet vent in the bathroom itself.

5.6 Experiment 16

The search tactics in Experiment 16 were designed to evaluate both door initiated and window initiated operations through bedroom 3 with door control of the front door prior to suppression. At the time of ignition, the kitchen window and front door were opened. The interior doors to all four bedrooms were opened. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets, which led to flashover of the kitchen. At this point, crews entered the structure through the front door and closed it behind them. As the first crew started their search, a second crew broke one-half the bedroom 3 window and began searching bedroom 3. The interior search crew entered bedroom 4, searched the space, and opened the window. Both crews completed the respective searches of bedroom 3 and bedroom 4 and continued down the hallway. The crews then arrived at bedroom 1 and bedroom 2. The crew in bedroom 1 closed the door behind them as they entered the space. The crew in bedroom 2 searched the space without isolation. The crews then opened the respective bedroom windows. At this point the search tactics were complete and interior suppression began by opening the front door. 99 gallons of water were flowed during suppression. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the kitchen window. The total amount of water flowed during suppression and hydraulic ventilation was 412 gallons. Table 5.11 lists the sequence of events along with the times at which they occurred.

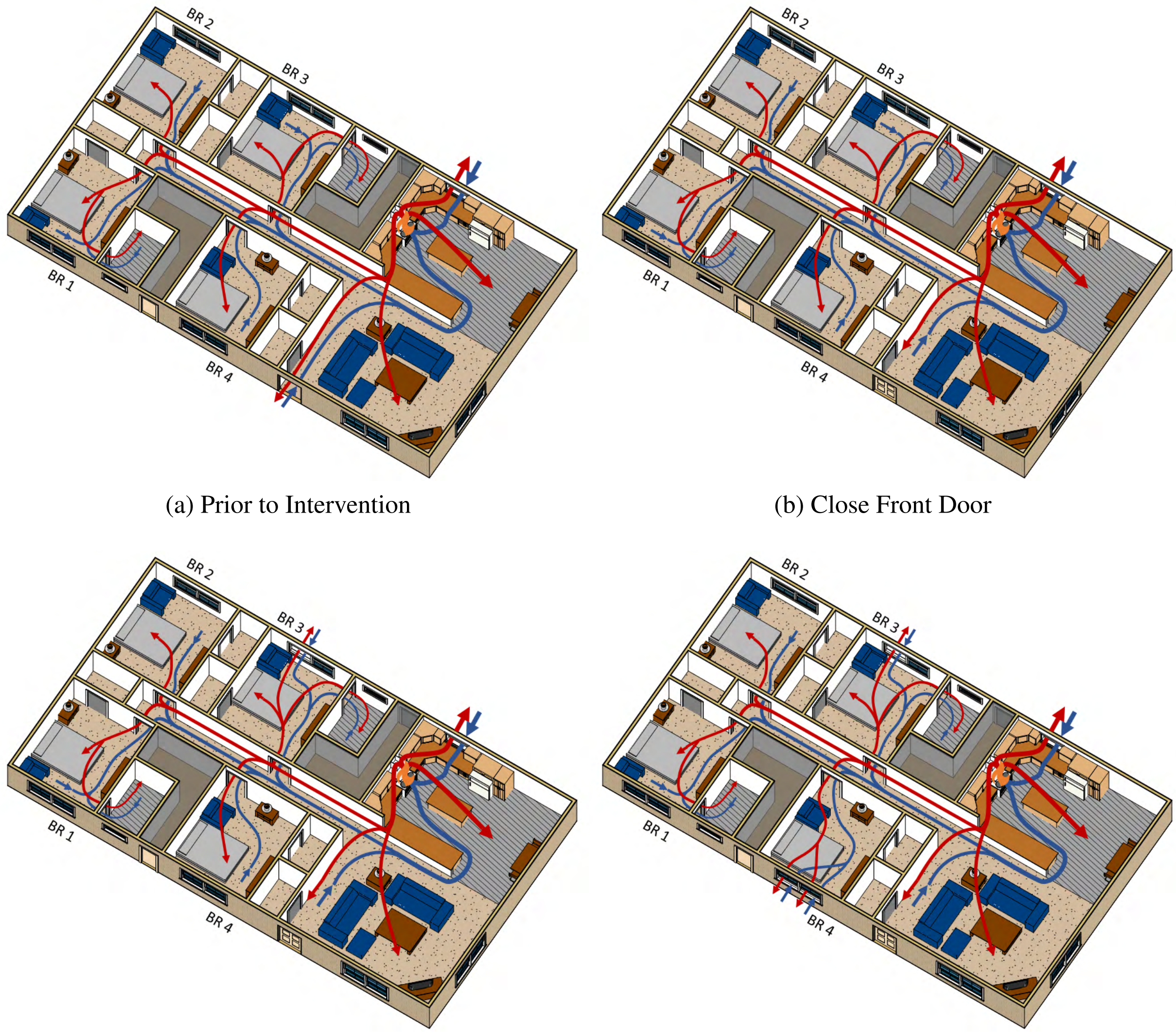
Table 5.11: Experiment 16 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	06:27	387	—	—
Close Front Door	21:47	1307	00:00	0
Take BR3 Window	22:02	1322	00:15	15
Open BR4 Window	22:33	1353	00:46	46
Close BR1 Door	23:16	1396	01:29	89
Open BR1 & BR2 Windows	23:47	1427	02:00	120
Open Front Door & Suppression	24:17	1342	02:30	150
Hydraulic Ventilation	26:48	1608	05:01	301
Open BR1 Door	27:18	1638	05:31	331

Figures 5.76 and 5.77 show the changes in flow in the structure in the period immediately preceding and following fire department intervention in Experiment 16. Prior to suppression, the kitchen fire was in a growth stage. Bidirectional vents were maintained at the side C kitchen window and the front door, which provided the kitchen fire with constant sources of air through the lower portion of the vents while products of combustion were exhausted through the upper portion of the vents, as shown in Figure 5.76a. Additionally, as the kitchen fire grew, hot products of combustion were transported from the kitchen to remote areas of the structure, such as the hallway and bedrooms.

Meanwhile, air from these spaces was drawn toward the kitchen. Although the fire was largely confined to the kitchen at the time of intervention, it was beginning to extend to the living room, with rollover observed along the ceiling in the living room and hallway.

The initial fire department intervention was the closing of the front door, simulating a search crew making entry to the structure and closing the door behind them. This action eliminated the flow path between the kitchen fire and the front door, as shown in Figure 5.76b. By cutting off this flow path, the amount of air that was available for use in combustion was reduced, which limited fire growth. Importantly, this action prevented the fire from transitioning through flashover and reduced the rate at which products of combustion were produced. As the first crew searched bedroom 4, a second crew ventilated half of the bedroom 3 window and began to search that space. This created a new flow path through bedroom 3, as shown in Figure 5.76c. Hot products of combustion exhausted from the structure through the upper portion of the window while air was entrained into the structure through the lower portion of the window. The lower panes of the bedroom 4 windows were opened 31 s later, as shown in Figure 5.76d, which simulated the initial crew opening the windows while searching bedroom 4. Similarly, this created bidirectional flows through bedroom 4. Hot products of combustion exhausted from the structure through the upper portion of the window while air was entrained into the structure through the lower portion of the window.



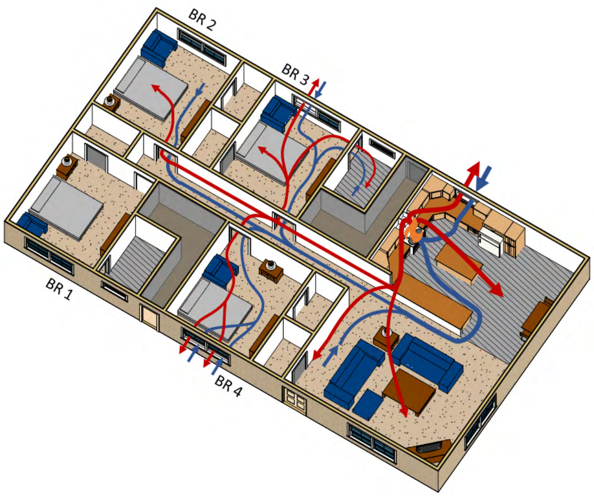
(a) Prior to Intervention (b) Close Front Door

(c) Take BR3 Window (d) Open BR4 Window

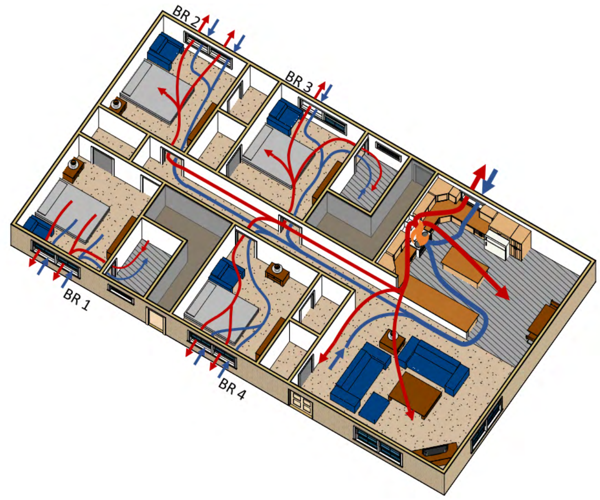
Figure 5.76: Changes in gas flows in the structure following fire department interventions in Experiment 16.

The bedroom 1 door was closed 43 s after the bedroom 4 window was opened. The crew completed their search of bedroom 4, moved down the hallway to bedroom 1 and closed the door behind them. This action isolated bedroom 1 from the flow of products of combustion from the hallway, as shown in Figure 5.77a. The lower panes of the bedroom 1 window were opened 31 s later. This created a new flow path in the room. Products of combustion behind the closed door exhausted through the window and were replaced with air (Figure 5.77b). Simultaneous with this action, the lower panes of the bedroom 2 window were opened. The second search crew ventilated bedroom 1 after completing a search of bedroom 3. Since this crew did not isolate the door between the hallway and bedroom 2, a flow path was established through the room, with products of combustion exhausting from the structure through the upper portion of the window while cool air was entrained into the structure through the lower portion of the window.

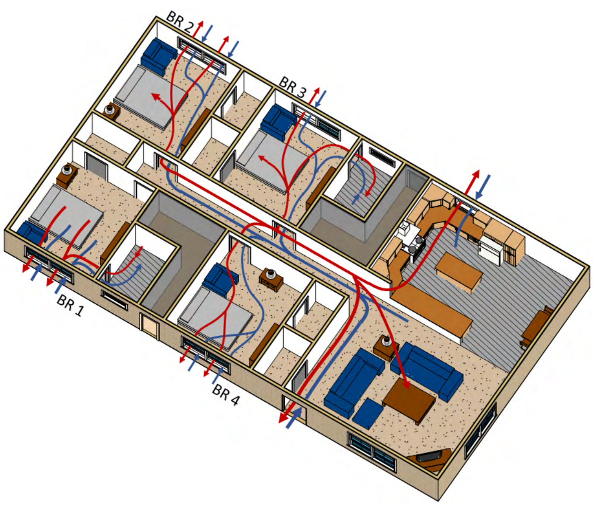
The front door was re-opened 150 s after it was initially closed for the suppression crew to enter and extinguish the fire. By opening the front door, the suppression crew briefly re-established the flow path between the front door and the kitchen (Figure 5.77c). A 1 3/4 in. handline equipped with a 7/8 in. smooth bore nozzle and nominal flow rate of 160 gpm was used for suppression. Following suppression, hydraulic ventilation occurred out the side C kitchen window with the tip off and fully opened nozzle rotated in an O-pattern. This created a lower-pressure area in the kitchen, drawing gases from elsewhere in the structure toward that location and allowing the open bedroom windows to act as inlets, as shown in Figure 5.77d.



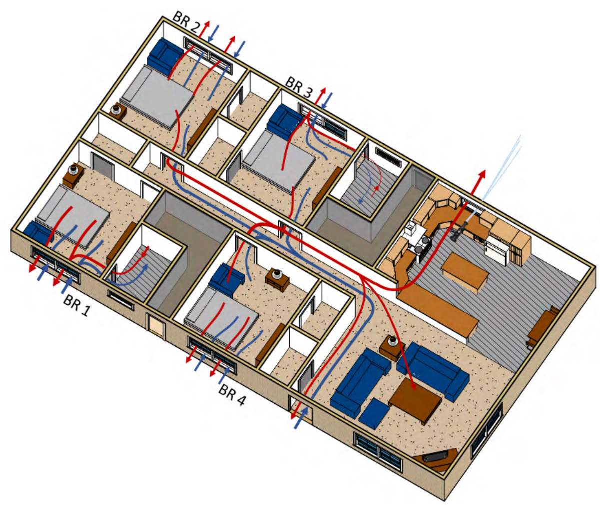
(a) Close BR1 Door



(b) Open BR1 & BR2 Windows



(c) Open Front Door, Suppression

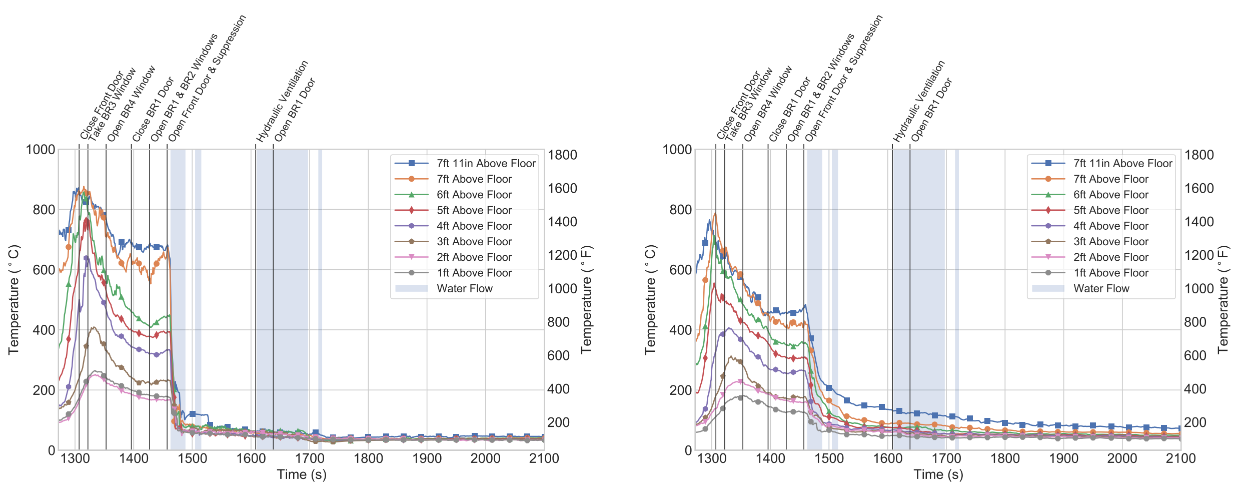


(d) Hydraulic Ventilation

Figure 5.77: Changes in gas flows in the structure following fire department interventions in Experiment 16.

5.6.1 Common Space

Figure 5.78 shows the temperatures in the kitchen and living room in the period following intervention during Experiment 16. Immediately prior to intervention, the kitchen fire was in a pre-flashover state, with temperatures stratified between 872 °C (1602 °F) at the ceiling and 158 °C (316 °F) 1 ft above the floor. Temperatures were increasing at all elevations in the kitchen at the time that the front door was closed. Temperatures were slightly lower in the living room, where they ranged from 785 °C (1445 °F) at the ceiling to 108 °C (226 °F) 1 ft above the floor at the time of intervention. At the time that the front door was closed, rollover was observed along the ceiling of the kitchen and living room, as shown in Figure 5.79a. Temperatures 6 ft and above in both the living room and the kitchen were in excess of 600 °C (1112 °F). Bidirectional flows existed from the kitchen to living room through the front door, which allowed hot gases from the kitchen to exhaust through the upper portion of the front door and air to be entrained through lower portion of the front door toward the kitchen. When the front door was closed, this flow path was eliminated, causing temperatures to begin to decrease. Interior camera views indicated that this decrease in temperatures was coupled with a reduction in visible flaming in the living room following front door closure, as shown in Figures 5.79b and 5.79c.



(a) Kitchen Temperature

(b) Living Room Temperature

Figure 5.78: Temperature time histories in the common space for the period following fire department intervention in Experiment 16.

(a) 3 s Before Door Closed (b) 3 s After Door Closed (c) 6 s After Door Closed

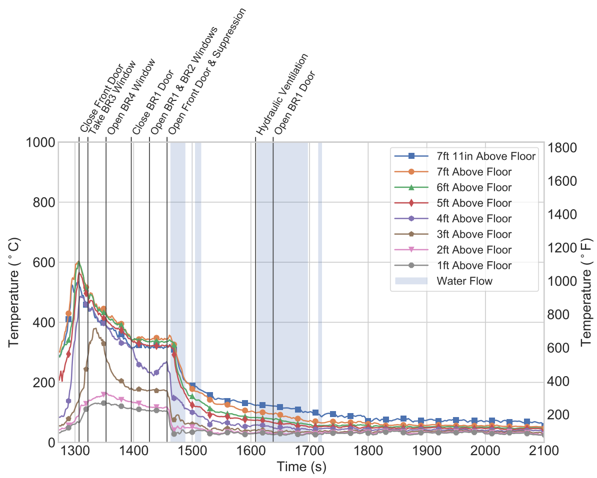
Figure 5.79: Fire conditions preceding and following front door closure during Experiment 16.

The decrease in air entrainment to the structure following the change in flow path caused temperatures at all elevations in the kitchen and living room to decrease. This decrease gradually gave way to a steady temperature profile at both locations as the kitchen fire reached a sustainable heat release rate based on the amount of ventilation that the open kitchen window was able to provide. No noticeable changes in temperature were observed as a result of ventilation actions to the bedroom windows or doors in the period between intervention and suppression. Prior to suppression, kitchen temperatures ranged from 676 °C to 166 °C (1249 °F to 331 °F) and living room temperatures ranged from 475 °C to 126 °C (887 °F to 259 °F). The front door was re-opened 150 s after ignition to allow suppression crew entry. The fire was confined to the kitchen. The suppression crew flowed water for 28 s, which caused temperatures in the kitchen and living room to immediately decrease to negligible values.

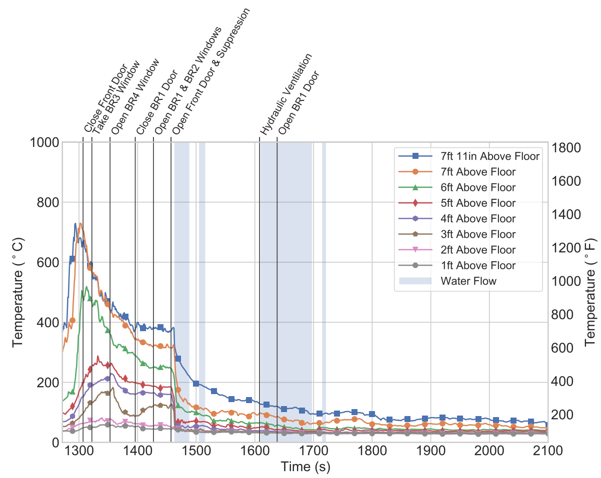
5.6.2 Hallway

Figure 5.80 shows the temperatures at the living room entryway and three hallway measurement locations during Experiment 16. Temperatures at the living room entryway, shown in Figure 5.80a, generally followed a similar trend as those in the center of the living room. Prior to the closing of the front door, temperatures between 4 ft and the ceiling were increasing as rollover was observed along the ceiling of the living room. At the time that the front door was closed, temperatures ranged from 604 °C (1119 °F) at the ceiling to 66 °C (151 °F) 1 ft above the floor. Ceiling temperature began to decrease immediately after the front door was closed, as the exhaust flow path through the living room entryway was eliminated. Temperatures close to the floor were also increasing at the time of intervention, but were considerably lower than those close to the ceiling because of the inflow of air through the door.

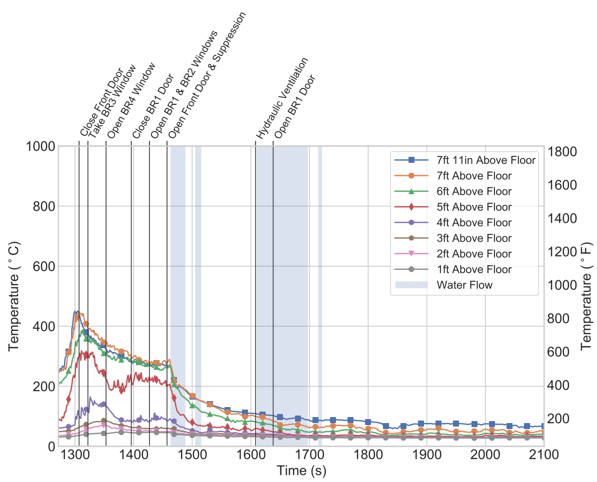
When the bidirectional flow was eliminated following the front door closure, temperatures close to the floor continued to increase for another 30 s as the living room continued to fill with products of combustion. After these peaks were observed, temperatures at all elevations gradually decreased throughout until the front door was reopened for suppression with no noticeable changes as a result of the opening of bedroom doors or windows. Immediately prior to suppression, temperatures in the living room entryway ranged from 345 °C to 97 °C (653 °F to 207 °F). The rate of temperature decline increased due to the start of suppression, and continued to decrease as the kitchen fire was extinguished.



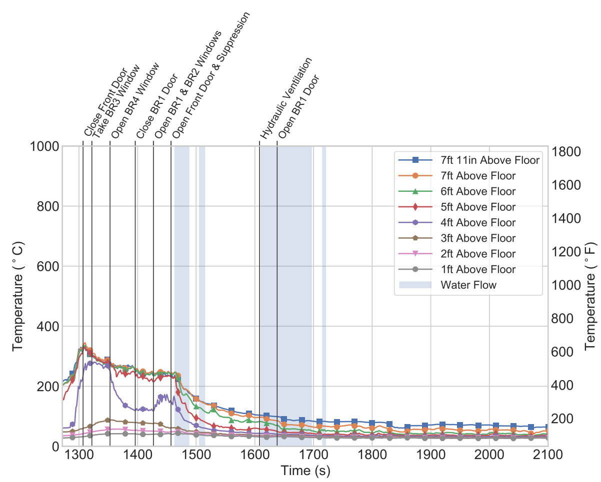
(a) Living Room Entry Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature

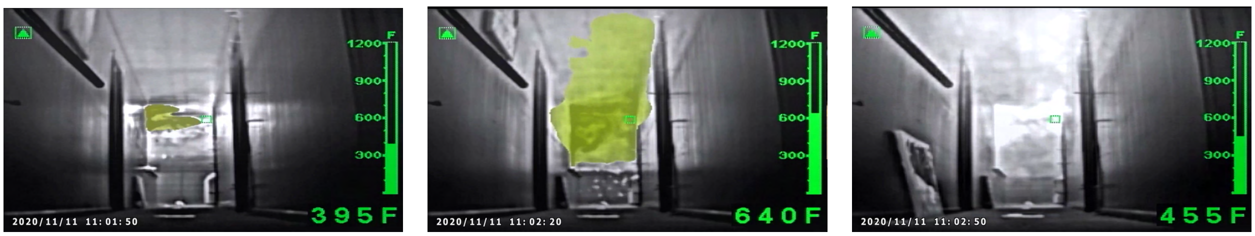


(d) End Hallway Temperature

Figure 5.80: Temperature time histories in the hallway in the period following fire department intervention in Experiment 16.

Temperatures at the the start, mid, and end hallway locations are shown in Figures 5.80b, 5.80c, and 5.80d, respectively. At each of these three locations temperatures close to the ceiling (above 5–6 ft) increased in the 30 s prior to door closure as rollover from the kitchen extended down the hallway, resulting in peak ceiling temperatures of 700 °C (1292 °F), 450 °C (842 °F), and 350 °C (662 °F) at the start, mid, and end hallway locations, respectively. The decrease in burning in the kitchen following the front door closure resulted in a decrease in ceiling temperature at all three hallway measurement locations. This change in hallway temperatures prior to and following intervention is shown in the changes in hallway IR camera, shown in Figure 5.81. Ceiling temperatures continued to steadily decrease until the beginning of suppression, which caused ceiling temperatures to sharply decrease at all three elevations.

Similar to the higher elevations at the time of front door closure, temperatures 4–5 ft and below were steadily increasing at each of the three hallway locations but noticeably lower in magnitude. The gap between the temperatures was a result of the hot gas layer descending only about halfway down to the floor. Temperatures close to the floor were more noticeably impacted by the opening of the bedrooms 3 and 4 windows 15 s and 46 s after intervention, respectively. These ventilation actions established bidirectional flows between both bedroom windows and the hallway, allowing hot gases to exhaust through the upper portion of the vents and air entrainment through the lower portion of the vents. Temperatures close to the floor at the three hallway locations remained steady prior to suppression and decreased sharply following suppression.



(a) 30 s before door closed (b) Front door closed (c) 30 s after door closed

Figure 5.81: Hallway IR view in period preceding and following front door closure in Experiment 16.

The heat flux measured in the hallway, shown in Figure 5.82, followed a similar trend to the temperatures at each of the hallway locations. Immediately prior to front door closure, an increase in heat flux at the living room and start hall locations was observed simultaneous with the start of rollover in the living room at hallway. At the time of intervention, the heat flux at these locations was 11.4 kW/m^2 and 8.0 kW/m^2, respectively. Front door closure caused heat flux to decrease as burning in the living room and hallway subsided and the gas flows across these gauges decreased. The decrease in heat flux continued through suppression. The heat flux at the mid and end hallway locations was considerably lower at the time of intervention - 1.6 kW/m^2 and 0.8 kW/m^2, respectively. Similar to temperatures at these locations, heat flux began to decrease approximately 30 s after intervention and remained steady until suppression. Suppression caused heat flux at the living room entryway and all three hallway locations to decrease to negligible values.

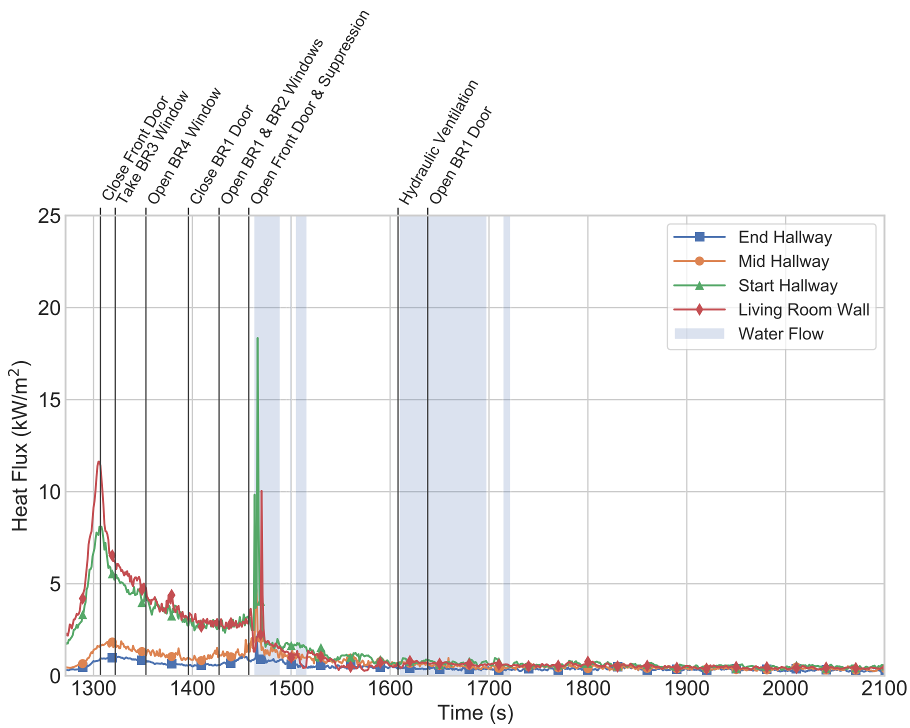


Figure 5.82: Heat flux time histories in the hallway in post-intervention period during Experiment 16.

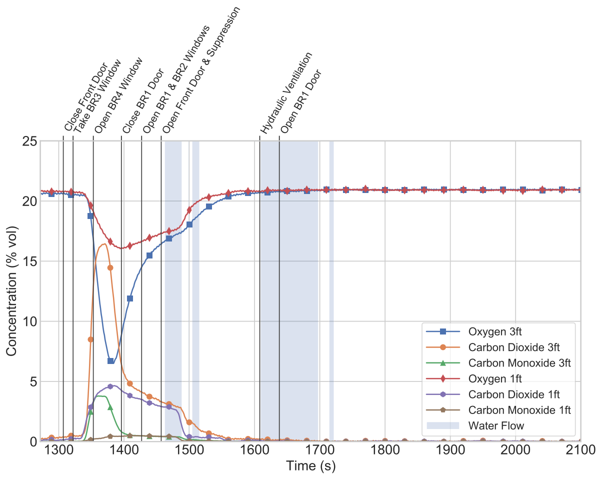
Gas concentrations at the living room entryway and hallway locations at intervention are shown in Table 5.12 and the time histories are shown in Figure 5.83.

Table 5.12: Hallway Gas Concentrations at Intervention for Experiment 16

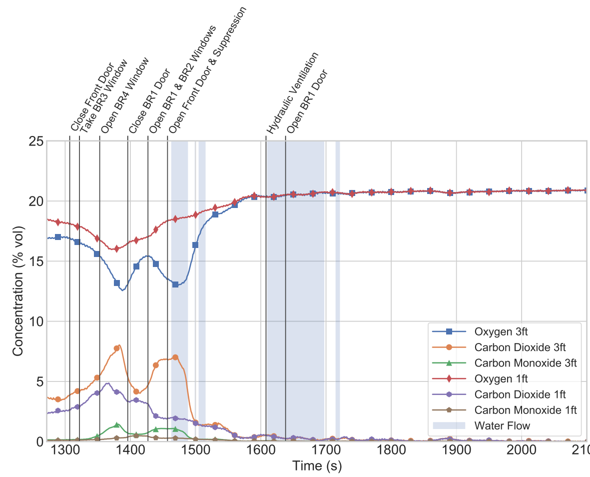
Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	20.6	0.4	0
	1 ft	20.8	0.1	0
Start Hallway	3 ft	16.9	3.8	0.2
	1 ft	18.1	2.6	0.1
Mid Hallway	3 ft	15.2	5.3	0.2
	1 ft	18.2	2.5	0.1
End Hallway	3 ft	15.6	4.7	0.2
	1 ft	18.8	2.3	0.1

At the time that the front door was closed, the air entrained through the inlet flow path in the front door resulted in low CO and CO_2 concentrations and approximately ambient O_2 concentration in the living room entryway (Table 5.12). When the front door was closed, the inlet flow was eliminated and the living room began to fill with smoke produced by the kitchen fire, resulting in an increase in CO and CO2 and rapid decrease in O_2 starting approximately 20 s after intervention

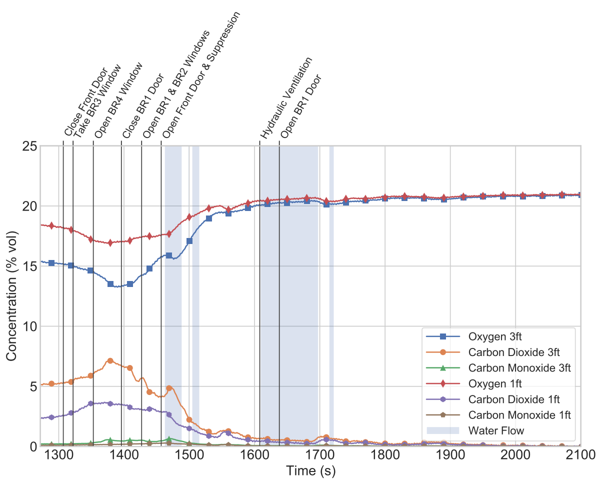
(Figure 5.83a). CO and CO_2 concentrations in the living room peaked and began to decrease approximately 60 s after intervention. This decrease occurred simultaneous with the cooling and contracting of the hot gas layer in the living room, as indicated by decrease in temperature at that time. Additionally, the gas flow toward the kitchen fire from the open bedroom 3 and 4 windows further caused O_2 concentrations to increase and CO and CO_2 concentrations to decrease. When the front door was re-opened which re-established gas exchange and suppression was initiated, the CO and CO_2 concentrations to sharply decrease and O_2 concentration to sharply increase. Gas concentrations returned to pre-experiment conditions prior to the start of hydraulic ventilation.



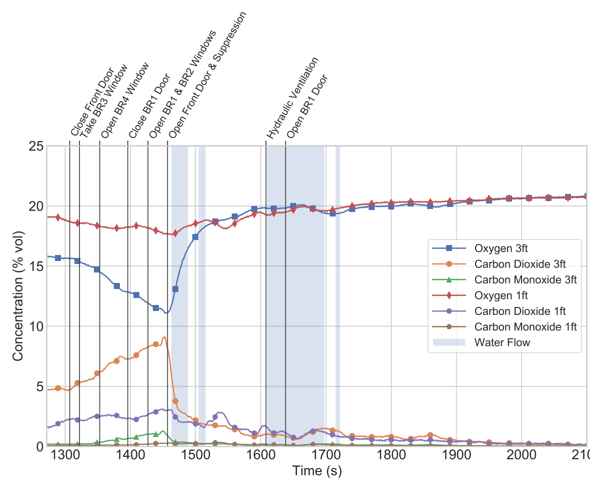
(a) Living Room Entryway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.83: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 16.

Figures 5.83b, 5.83c, and 5.83d show the time histories of gas concentrations at the start, mid, and end hallway measurement locations, respectively. At the time of intervention, O_2 concentrations ranged between 15% and 19%, CO_2 concentrations ranged between 2.3% and 5.3%, and CO concentrations were less than 0.2%. These concentrations indicate that the smoke layer in the hallway had not yet descended past the 3 ft measurement location and products of combustion were mixing with air close to the floor, resulting in the relatively low concentrations of products of combustion at the 3 ft and 1 ft elevations in the hallway.

Prior to ventilation of the bedroom 3 window, bidirectional flow was observed in the hallway. Hot products of combustion in the upper portion of the space flowed toward the bedrooms while cooler air from remote areas of the structure was drawn toward the kitchen fire through the lower portion of the hallway. When the bedroom 3 window was ventilated, these flows were supplemented as a new flow path was created at the bedroom 3 window. A similar phenomenon was observed when the lower panes of the bedroom 4 window were opened. As a result of the air entrainment from bedrooms 3 and 4, CO and CO_2 concentrations at the start and mid hallway locations began to decrease while O_2 concentrations increased approximately 80 s after intervention (1307 s after ignition). At the mid hallway location, this trend toward ambient continued at both elevations through suppression, with CO and CO_2 concentrations decreasing to negligible values by the end of hydraulic ventilation. Although the 1 ft gas concentrations at the start hall location trended similarly to those at the mid hall location, CO and CO_2 concentrations at the 3 ft elevation began to increase again approximately 30 s after the initial decrease was observed, possibly as a result of fire growth in the kitchen caused by the air entrainment through the windows. This increase continued until suppression actions resulted in a permanent decrease in CO and CO_2 concentrations at 3 ft above the floor at the start hall location.

Gas concentrations at the end hall location were not impacted by the flows established by ventilation of the bedrooms 3 and 4 windows as end hall was not along the flow path between those vents and the fire. CO and CO_2 concentrations at both measurement locations increased steadily following front door closure as products of combustion continued to fill the hallway. This increase was halted by ventilation of the bedroom 1 and 2 windows, which established new flow paths. The air entrainment along these newly created flow paths resulted in a decrease in CO and CO_2 concentrations and increase in O_2 concentrations at the end hall measurement location, which continued as suppression actions extinguished the kitchen fire.

5.6.3 Bedroom 3

Figure 5.84 shows the time history of temperature in bedroom 3 during Experiment 16. The door between bedroom 3 and the hallway was open from the start of the experiment, allowing products of combustion to flow into bedroom 3 through the upper portion of the doorway while air was drawn toward the kitchen fire. A sharp increase in temperatures close to the ceiling was observed in the 30 s prior to intervention, as rollover began to extend down the hallway. Temperatures in bedroom 3 at the time of front door closure ranged from 198 °C to 29 °C (388 °F to 84 °F). When the front door was closed, fire growth was restricted. This decreased the rate at which hot gases flowed into bedroom 3 from the hallway, causing ceiling temperature to plateau at approximately steady values until suppression. Temperatures maintained this steady state through the ventilation of half of the bedroom 3 window, which established a flow path through bedroom 3. Higher temperature, higher pressure gases flowed into the room from the hallway and exhausted through the upper portion of the window while air was entrained through the lower portion of the window and flowed toward the kitchen fire. Suppression actions resulted in a decrease in temperature at all elevations, which continued through hydraulic ventilation.

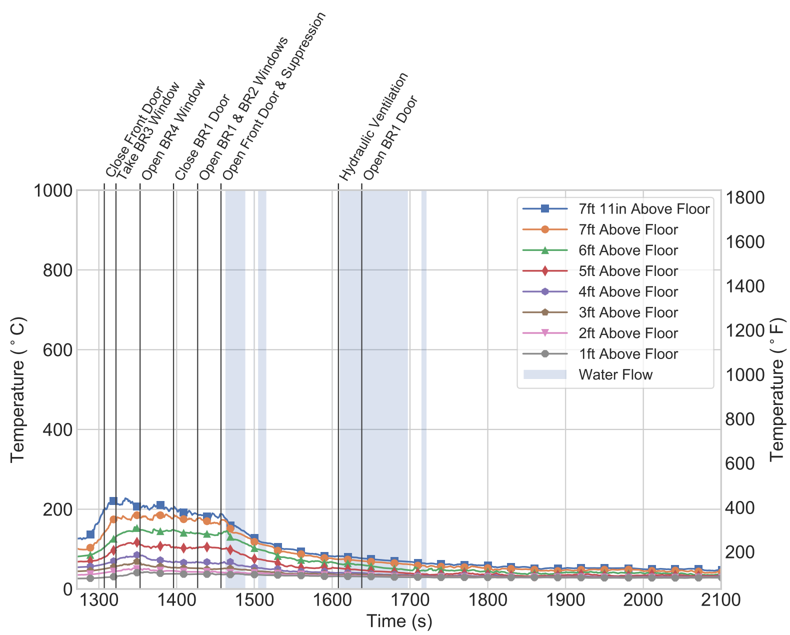
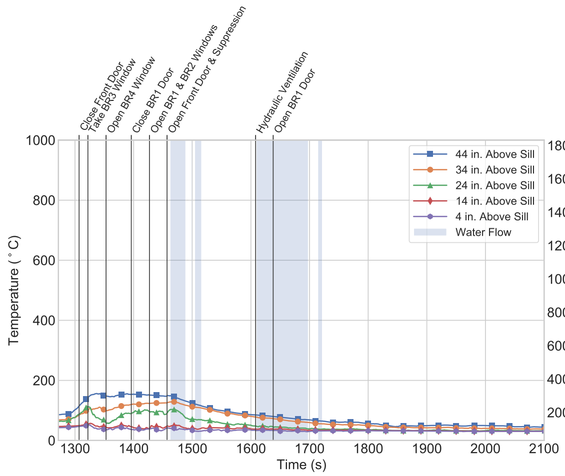
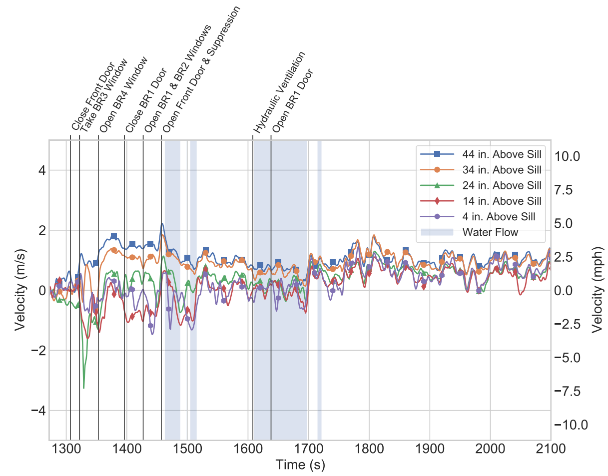


Figure 5.84: Post-intervention bedroom 3 temperature during Experiment 16.

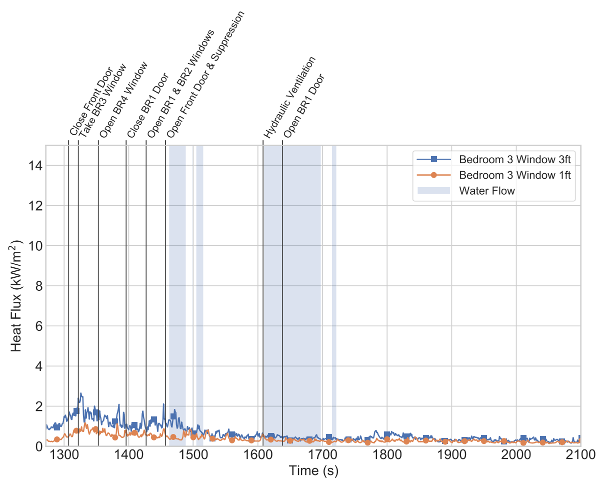
Figure 5.85 shows the temperature, velocity, heat flux, and gas concentrations measured in the bedroom 3 window. Similar to the temperature in the room, window temperatures were increasing in the period leading up to window ventilation as a result of the rollover down the hallway. Immediately following ventilation, temperatures at the 4 in., 14 in., and 24 in. measurement locations sharply decreased as cooler air began to flow through the lower portion of the window. Temperatures 44 in. and 34 in. above the window sill continued to increase as higher temperature gases exhausted through the upper portion of the window. Exhaust temperatures ranged from 155 °C to 100 °C (311 °F to 212 °F) with corresponding velocities of 2 m/s to 1 m/s (4.5 mph to 2.2 mph). Entrainment temperatures ranged from 60 °C to 40 °C (140 °F to 104 °F) with corresponding velocities from -0.5 m/s to 2 m/s (-1.1 mph to -4.5 mph). This bidirectional flow was maintained until suppression actions extinguished the kitchen fire, which caused exhaust temperatures to continuously decrease and exhaust and entrainment velocities to converge toward 0 m/s. Hydraulic ventilation briefly caused the window to act as a unidirectional inlet, as cool air was drawn into the window toward the exterior vent created at the side C kitchen window.



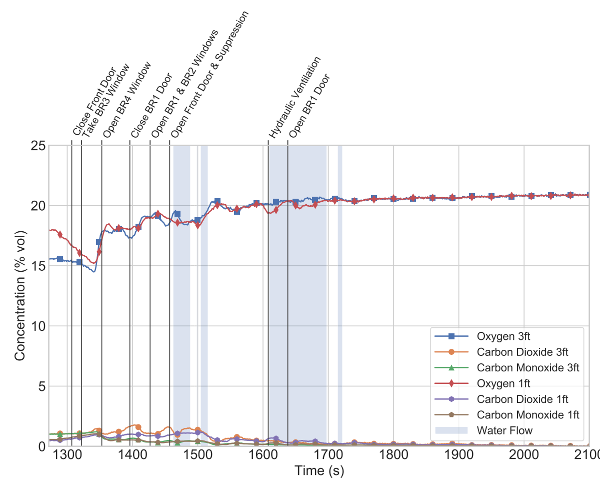
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



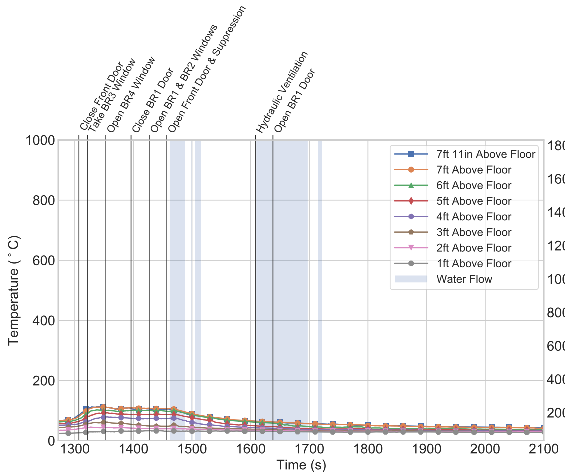
(d) Bedroom 3 Window Gas Concentration

Figure 5.85: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 16.

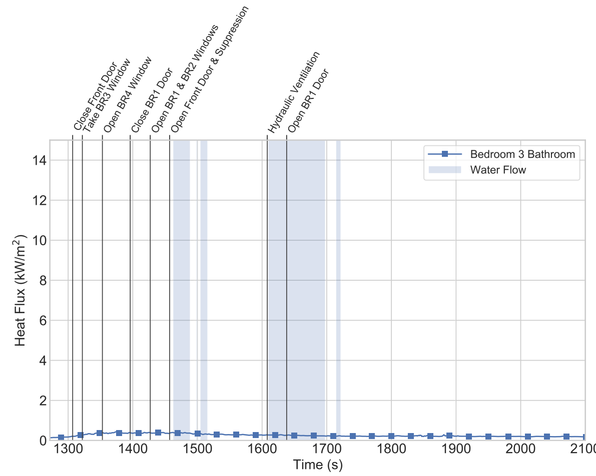
Immediately prior to intervention, the heat flux was 1.5 kW/m^2 and 0.5 kW/m^2 at the 3 ft and 1 ft window measurement locations, respectively. The 3 ft heat flux briefly increased to a peak of 2.7 kW/m^2 immediately after window ventilation before heat flux at both elevations began to decrease as cooler air flowed through the lower portion of the bedroom 3 window. This decrease continued through the onset of suppression, when heat flux values at 3 ft and 1 ft were 1.2 kW/m^2 and 0.4 kW/m^2, respectively. The heat flux at both measurement locations decreased to negligible values as the kitchen fire was extinguished.

At the time of intervention, CO and CO_2 concentrations were increasing at both bedroom 3 window measurement locations while O_2 concentrations were decreasing, as shown in Figure 5.85d. Gas concentrations were 15.5% O_2, 1.1% CO_2, and 1.1% CO 3 ft above the floor and 16.7% O_2, 0.7% CO_2, and 0.6% CO 1 ft above the floor. This increase in CO and CO_2 continued until 20 s after the bedroom 3 window was ventilated, as cooler air replaced products of combustion which flowed out of the bedroom 3 window. At the peak, gas concentrations were 14.5% O_2, 1.4% CO_2, and 1.2% CO 3 ft above the floor and 15.2% O_2, 0.9% CO_2, and 1.0% CO 1 ft above the floor. Following this peak, O_2 concentrations increased and CO and CO_2 concentrations decreased through the suppression actions, reaching approximately pre-ignition concentrations by the start of hydraulic ventilation.

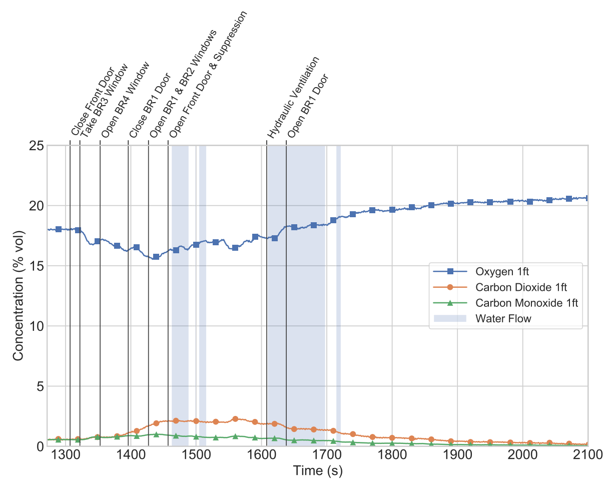
Figure 5.86 shows the temperature, heat flux, and gas concentrations measured in bathroom 3. Although temperatures measured in bathroom 3 (Figure 5.86a) were generally lower than those in the adjacent bedroom, they followed a comparable trend. Bathroom temperatures ranged from 86 °C to 26 °C (187 °F to 79 °F) at the time of intervention. Bathroom temperatures plateaued to a steady state approximately 10 s after the bedroom 3 window was opened ranging from 110 °C to 30 °C (230 °F to 86 °F). This steady state was maintained until suppression resulted in a decrease in bathroom temperatures, which continued through hydraulic ventilation. As a result of the low temperatures and limited gas flow in the bathroom, the heat flux measured 1 ft above the floor remained lower than 0.5 kW/m^2 for the duration of the experiment, as shown in Figure 5.86b.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



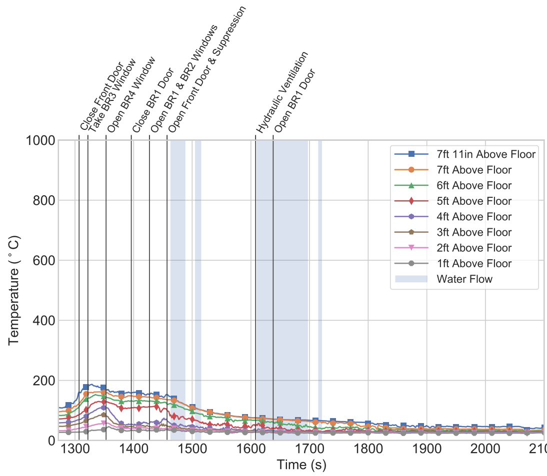
(c) Bathroom 3 Gas Concentration

Figure 5.86: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 16.

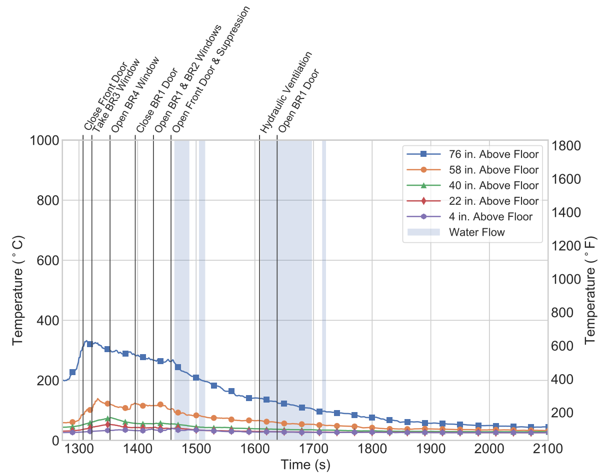
At the time of intervention, O_2, CO_2, and CO concentrations in bathroom 3 were comparable to those at the same elevation in bedroom 3, with values of 18.1%, 0.6%, and 0.6%, respectively. In the period following front door closure, bathroom 3 continued to fill with products of combustion from the kitchen fire, resulting in a steady increase in CO and CO_2 concentrations and a steady decrease in O_2 concentration. This trend continued until approximately 125 s after intervention (1431 s after ignition), when air entrained through the open bedroom 3 window caused O_2 concentrations to begin to increase and CO and CO_2 concentrations to begin to decrease. Peak O_2, CO_2, and CO concentrations in bathroom 3 were 15.6%, 2.2%, and 1.0%, respectively. Although gas concentrations began to trend toward pre-experiment concentrations following this peak, the lack of a vent in the bathroom itself hampered the effectiveness of hydraulic ventilation. As a result, gas concentrations in the bathroom remained elevated after the conclusion of hydraulic ventilation.

5.6.4 Bedroom 4

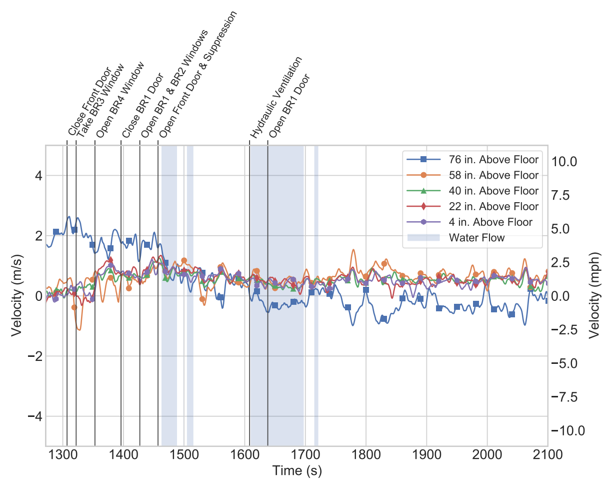
Figure 5.87 shows the time histories of temperature, doorway temperature, and doorway velocity in bedroom 4 and temperature in the bedroom 4 closet. The door between bedroom 4 and the hallway was open from the start of the experiment. At the time that the front door was closed, products of combustion were flowing into the room through the top of the open doorway, as indicated by the temperature and negative velocity data in Figures 5.87b and 5.87c. As as result of the room filling with products of combustion, temperatures were hottest close to the ceiling at the time of intervention and were increasing at all elevations, ranging from 162 °C to 28 °C (324 °F to 82 °F). The lower panes of the bedroom 4 windows were opened 46 s after front door closure, changing the flow path in the room. The doorway velocity data shows that hot gases continued to flow into bedroom 4 through the upper portion of the doorway while the measurement locations 58 in. above the floor and below indicated that cooler air began to flow through bedroom 4 toward the kitchen fire. This flow path was maintained until the onset of suppression, with temperature data indicating two distinct zones: a hot gas layer close to the ceiling and a cooler gas layer close to the floor, with an interface between 4 ft and 5 ft. Temperatures 5 ft and above ranged from 108 °C to 158 °C (226 °F to 316 °F) while temperatures 4 ft and below ranged from 52 °C to 32 °C (126 °F to 90 °F). Suppression resulted in a temperature decrease at all elevations, which continued through hydraulic ventilation. Doorway velocity data suggested that the flow through bedroom 4 was unidirectional out of the bedroom into the hallway for the duration of the hydraulic ventilation action. Temperatures in the bedroom 4 closet remained below 45 °C (113 °F) for the duration of the experiment due to the lack of gas transport into the closet.



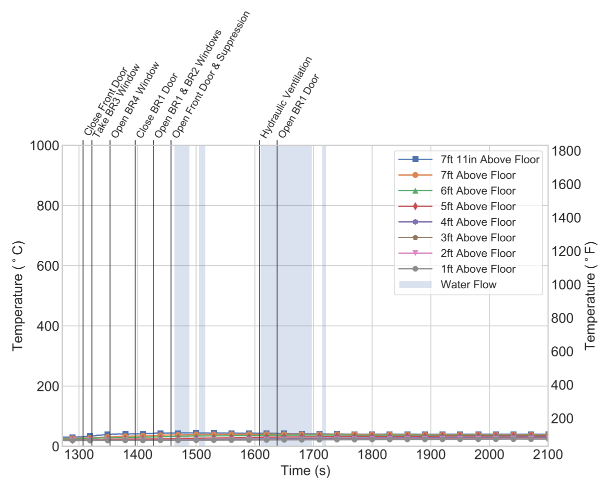
(a) Bedroom 4 Temperature



(b) Bedroom 4 Doorway Temperature



(c) Bedroom 4 Doorway Velocity



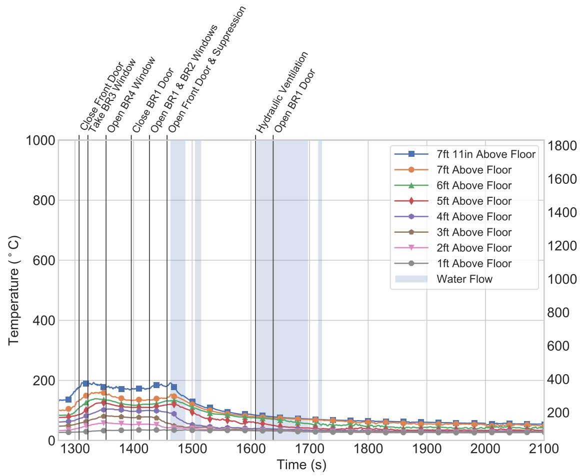
(d) Bedroom 4 Closet

Figure 5.87: Post-intervention temperature and velocity measurements in bedroom 4 during Experiment 16.

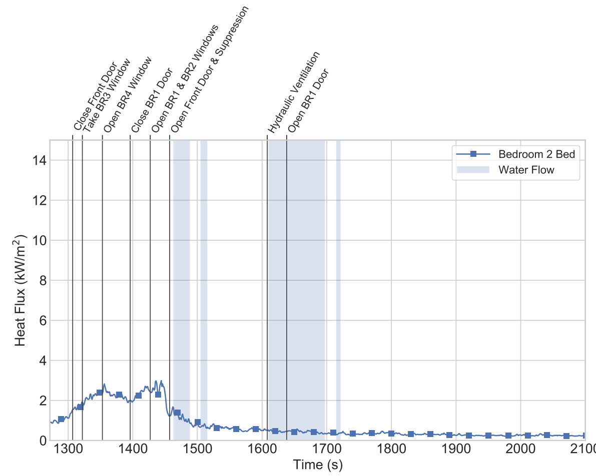
5.6.5 Bedroom 2

Figure 5.88 shows the time history of temperature, heat flux, and gas concentration in bedroom 2. The door between bedroom 2 and the hallway was open from the start of the experiment. This allowed products of combustion to flow into bedroom 2 through the upper portion of the door way while cooler air was drawn toward the kitchen fire. An increase in temperatures close to the ceiling was observed in the 30 s prior to intervention, as rollover from the kitchen began to extend down the hallway. Temperatures in bedroom 2 at the time of front door closure ranged from 175 °C to 28 °C (347 °F to 82 °F). When the front door was closed, fire growth was restricted. This decreased the rate at which hot gases flowed into bedroom 2 from the hallway, causing ceiling temperature to plateau until suppression. Temperatures maintained this steady state through the ventilation of half of the bedroom 2 window, which established a flow path through bedroom 2. Higher temperatures gases flowed into the room from the hallway and exhausted through the upper portion of the open window while cooler air was entrained through the lower portion of the window and flowed toward the kitchen fire. Suppression actions resulted in a decrease in temperature at all elevations, which continued through hydraulic ventilation.

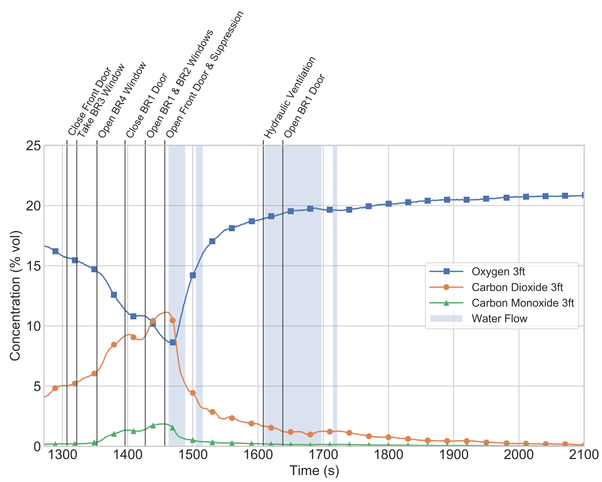
Similar to the temperatures in bedroom 2, heat flux measured 3 ft above the bed in bedroom 2 was increasing at the time of intervention. Heat flux increased from 1.5 kW/m^2 at the time of intervention to a peak of 2.8 kW/m^2 simultaneous with the end of rollover in the hallway. Following this peak, heat flux in the bedroom decreased as the growth of the fire slowed due to a lack of gas flow. Heat flux again began to increase after the bedroom 1 door was closed, which isolated that room from the flow of products of combustion. As a result, additional combustion gases flowed in bedroom 2. Bedroom 2 began to fill with products of combustion at a more rapid rate, resulting in an increase in heat flux which continued until the lower panes of the bedroom 2 window were opened. This again changed the flow path, allowing cool air to flow into bedroom 2 through the lower portion of the vent while products of combustion exhausted through the top. The flow of air through the inlet flow path had a cooling effect at the measurement location, resulting in a decrease in heat flux. The re-opening of the front door and subsequent suppression actions further decreased heat flux, which had decreased below 0.5 kW/m^2 prior to the start of hydraulic ventilation.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



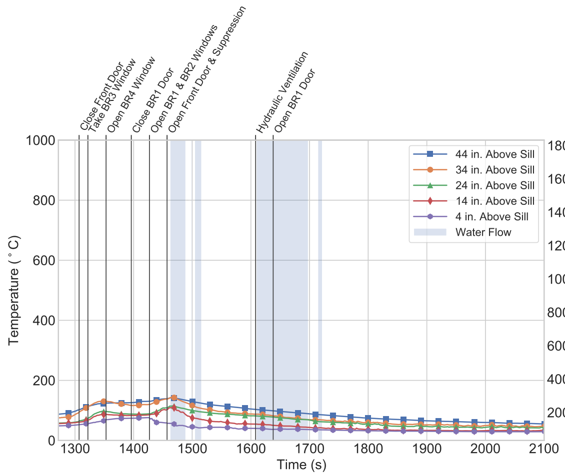
(c) Bedroom 2 Gas Concentration

Figure 5.88: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 2 during Experiment 16.

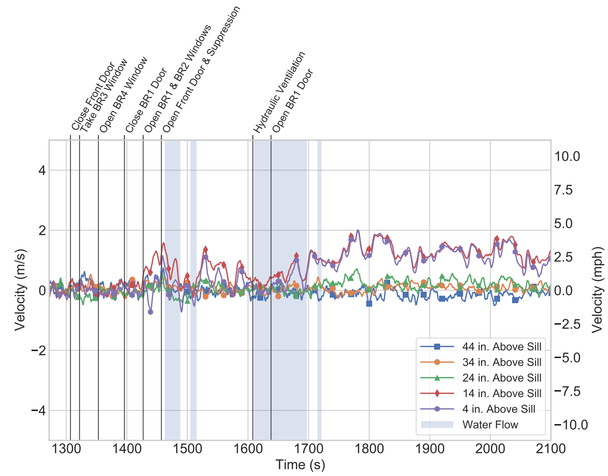
Figure 5.88c shows the time histories of gas concentrations on the bed 3 ft above the floor in bedroom 2. Approximately 30 s prior to front door closure, CO and CO_2 concentrations began to increase while the O_2 concentration began to decrease as the kitchen fire started to spread to the living room and rollover was observed down the hallway. At the time of intervention, O_2, CO_2, and CO concentrations were 15.6%, 5.0%, and 0.2%, respectively. Following front door closure, CO and CO_2 concentrations at the measurement location on the bed continued to increase as the room continued to fill with products of combustion from the kitchen fire. During this period, products of combustion and air were exchanged through the open bedroom 2 door. When the lower panes of the bedroom 2 window were opened 120 s after intervention, a new flow path was established. Products of combustion exhausted to the exterior through the upper portion of the vent while air was entrained through the lower portion of the vent. CO and CO_2 concentrations peaked and began to decrease 35 s after the windows were opened. Peak O_2, CO_2, and CO concentrations were 8.8%, 11.1%, and 1.9%, respectively. Note that these peaks are considerably higher than those measured elsewhere in the structure. This discrepancy is likely a result of the longer time that elapsed between intervention and ventilation of the bedroom 2 window and the lack of isolation to the bedroom. CO and CO_2 concentrations continued to decrease while the O_2 increased as suppression actions extinguished the kitchen fire. Gas concentrations 3 ft above the floor in bedroom 2 returned to pre-experiment conditions well after the completion of hydraulic ventilation.

Temperature, velocity, heat flux, and gas concentrations measured in the bedroom 2 window followed similar trends to the same quantities measured in the center of the room, as shown in Figure 5.89. The window temperature and velocity data in Figures 5.89a and 5.89b show that after the lower pane of the bedroom 2 windows was opened, bidirectional flow was established. The velocity probe 14 in. above the sill indicated exhaust velocities between 0.5 m/s and 1.5 m/s (1.1 mph to 3.3 mph) with temperatures increasing from 85 °C (185 °F) to a peak of 110 °C (230 °F). The velocity probe 4 in. above the sill indicated entrainment velocities between -1.0 and -1.3 m/s (-2.2 mph to -2.9 mph) with continuously decreasing temperatures.

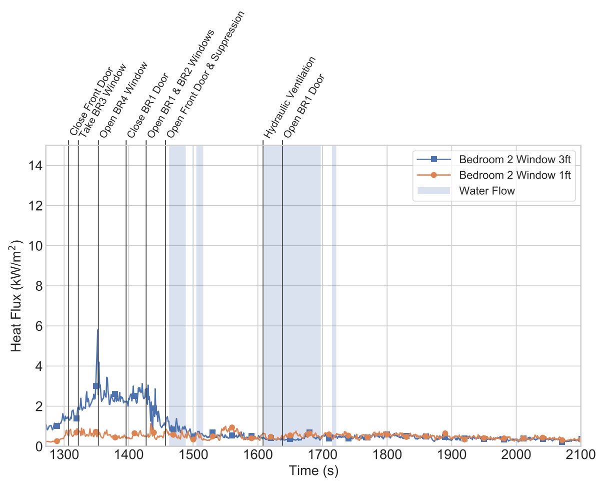
Heat flux at the measurement locations 3 ft and 1 ft above the floor in the window, shown in Figure 5.89c, trended similarly to the temperatures in the room. At the time of intervention, the heat flux was 1.5 kW/m^2 and 0.5 kW/m^2 at the 3 ft and 1 ft elevations, respectively. Heat flux at both elevations continued to increase as bedroom 2 filled with products of combustion. The 3 ft heat flux reached a brief peak of 5.8 kW/m^2 approximately 30 s after intervention before dropping to a steady value of approximately 2.5 kW/m^2. During the same period, the 1 ft heat flux remained steady below 1.0 kW/m^2. Air entrainment through the bedroom 2 window secondary to window opening had a cooling effect at the window measurement locations, resulting in a decrease in heat flux at both elevations. Suppression caused heat flux to continued to decrease to negligible values.



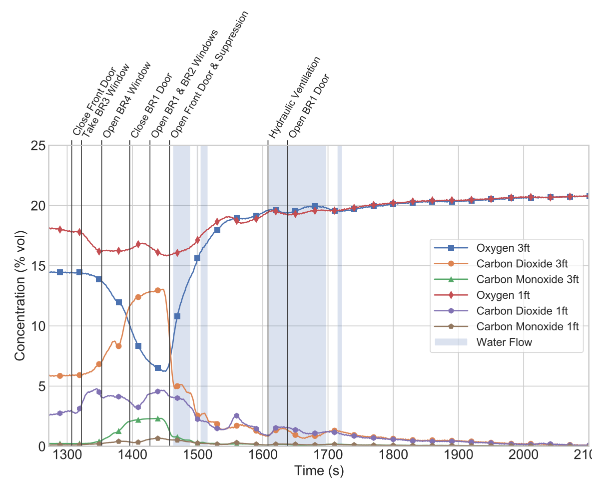
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

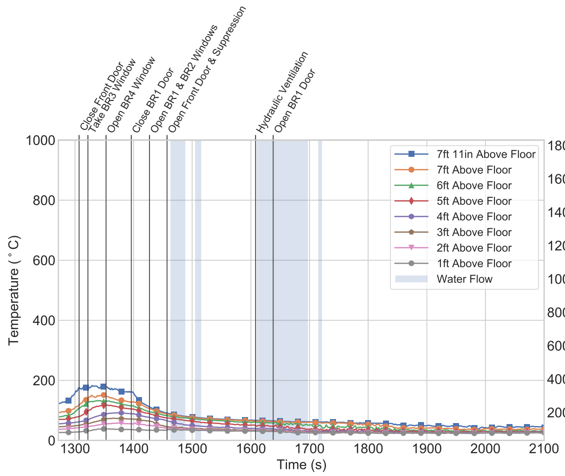
Figure 5.89: Post-intervention temperature, velocity, heat flux measurements at bedroom 2 window during Experiment 16.

Gas concentrations 3 ft and 1 ft above the floor were steady in the period prior to intervention, as shown in Figure 5.89d. At the time of intervention, gas concentrations were 14.5% O_2, 5.9% CO_2, and 0.2% CO 3 ft above the floor and 17.8% O_2, 3.0% CO_2, and 0.1% CO 1 ft above the floor — values which are comparable to those measured 3 ft above the floor on the bed. The 3 ft gas concentrations first exhibited a change after front door closure, with CO and CO_2 concentrations beginning to increase as products of combustion filled bedroom 2, while O_2 concentrations decreased. This trend continued until the lower panes of the bedroom 2 window were opened, which established a local bidirectional vent. Peak O_2, CO_2, and CO concentrations 3 ft above the floor were 6.4%, 13.0%, and 2.3%, respectively. Following this peak, air entrainment through the inlet portion of the open window caused CO and CO_2 concentrations to decrease. This decrease continued as the suppression crew extinguished the kitchen fire. The 1 ft gas concentrations however, exhibited little change from their values at the time of intervention until approximately 20 s after the bedroom 2 window was opened, when they began to gradually decrease. Hydraulic ventilation did not have a noticeable impact on the rate of change of gas concentrations, and CO and CO_2 concentrations at both elevations remained elevated well after the completion of hydraulic ventilation. In contrast to bedroom 3 where the top and bottom panes were removed, the bedroom 2 window was opened, meaning the top pane was still intact. This limited the efficiency of the vent to exchange gases with the exterior. As a result, hydraulic ventilation was less effective.

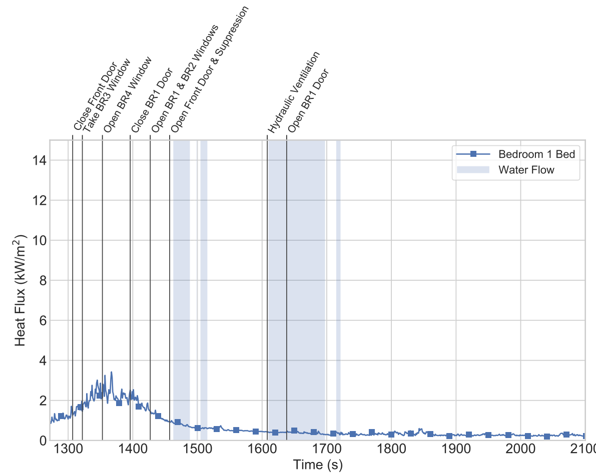
5.6.6 Bedroom 1

Figure 5.90 shows the time history of temperature, heat flux, and gas concentration in bedroom 1. The door between bedroom 1 and the hallway was open from the start of the experiment, which allowed products of combustion to flow into bedroom 1. An increase in temperatures close to the ceiling was observed in the 30 s prior to intervention, as rollover began to extend down the hallway. Temperatures in bedroom 1 at the time of front door closure ranged from 174 °C to 29 °C (345 °F to 84 °F). When the front door was closed, fire growth was restricted. This decreased the rate at which hot gases flowed into bedroom 1 from the hallway. Ceiling temperatures plateaued until the bedroom 1 door was closed. This action changed the flow path, isolating bedroom 1 from the flow of hot gases from the hallway and resulting in a decrease in temperature at all elevations. This decrease was accelerated when the lower panes of the bedroom 1 window were opened, which allowed trapped products of combustion to exhaust through the window and continued through suppression. Prior to the re-opening of the bedroom 1 door, hydraulic ventilation did not impact the rate at which temperatures decreased. After the door was opened, the window acted as a unidirectional inlet, resulting in a decrease in temperatures as air flowed toward the exterior vent in the kitchen.

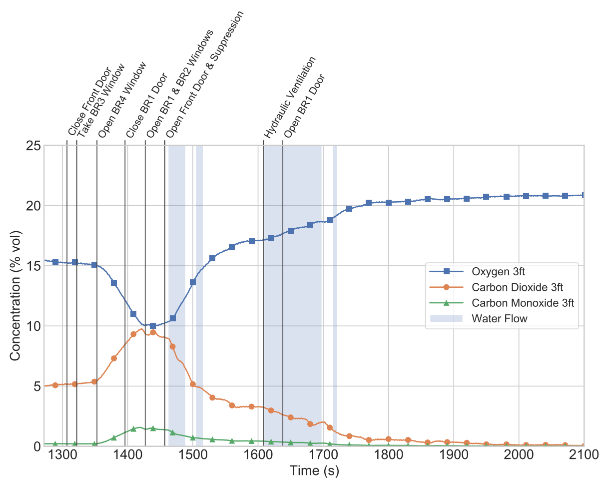
Figure 5.90b shows the time history of heat flux measured 3 ft above the floor on the bed in bedroom 1. At the time of intervention, the heat flux was 1.5 kW/m^2. The heat flux continued to increase as products of combustion filled bedroom 1 in the period following front door closure. Similar to the bedroom 1 temperatures, heat flux reached a steady state starting approximately 30 s after front door closure, as rollover in the hallway subsided. This steady state was maintained until the bedroom 1 door was closed, with heat flux values fluctuating between 2.0 kW/m^2 and 2.5 kW/m^2. The closure of the bedroom 1 door isolated bedroom 1 from the flow of products of combustion from the hallway, causing heat flux to decrease. This trend continued through the opening of the lower pane of the bedroom 1 windows, decreasing below 0.5 kW/m^2 by the end of suppression.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux

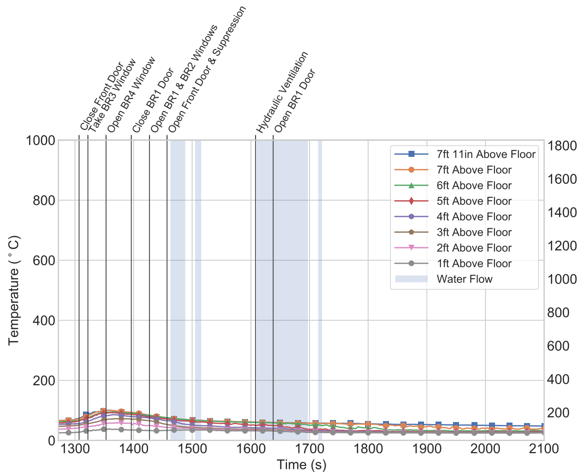


(c) Bedroom 1 Gas Concentration

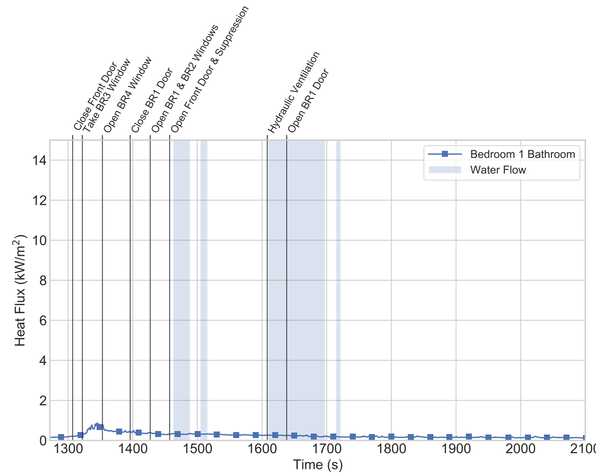
Figure 5.90: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 16.

Figure 5.90c shows that O_2, CO_2, and CO concentrations at the time of intervention were steady at 15.2%, 5.2%, and 0.2%, respectively. As bedroom 1 continued to fill with products of combustion following front door closure, gas concentrations began to change as the smoke layer descended below the 3 ft bed measurement location. When the bedroom 1 door was closed, the flow of products of combustion into the room was halted, causing CO and CO_2 concentrations to reach a peak approximately 25 s after the bedroom 1 door closure. O_2, CO_2, and CO concentrations at this peak were 10.3%, 9.7%, and 1.6%, respectively. Although the increase in CO and CO_2 concentrations was halted, products of combustion were trapped behind the closed bedroom 1 door, resulting in approximately steady gas concentrations until the bedroom 1 window was ventilated. This established a new flow path, allowing trapped smoke to exhaust from bedroom 1, causing CO and CO_2 concentrations to begin to decrease. Gas concentrations gradually trended toward pre-experiment conditions, with little impact from suppression or hydraulic ventilation due to the isolation. Gas concentrations returned to pre-experiment conditions after the conclusion of hydraulic ventilation.

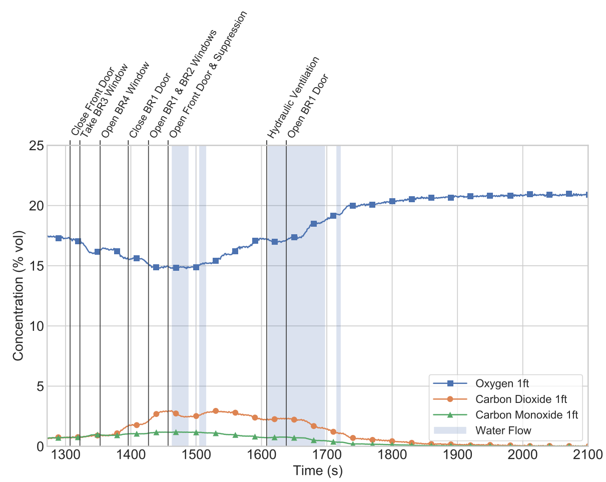
Figure 5.91 shows the temperature, heat flux, and gas concentrations measured in bathroom 1. The door between bedroom 1 and bathroom 1 was closed from the beginning of the experiment, isolating the bathroom from the flow of products of combustion from the rest of the structure. As a result, temperatures measured in bathroom 1 were considerably lower than those in the adjacent bedroom. At the time of intervention, temperatures in the bathroom ranged from 73 °C to 27 °C (163 °F to 81 °F) and were increasing in concert with the temperatures in bedroom 1. Ceiling temperatures peaked approximately 30 s after intervention, at the same time as other locations in the structure, with temperatures ranging from 101 °C to 35 °C (214 °F to 95 °F). Heat flux measured 1 ft above the ground in the bathroom (Figure 5.91b) peaked simultaneously at 0.9 kW/m^2. Following this peak, temperature and heat flux gradually decreased. Since the door between the bathroom and bedroom 1 remained closed for the duration of the experiment, inhibiting gas exchange between the bathroom and the rest of the structure, suppression actions and hydraulic ventilation did not noticeably change the rate at which these values decreased.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Heat Flux



(c) Bathroom 1 Gas Concentration

Figure 5.91: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 16.

The time histories of gas concentrations measured 1 ft above the floor in bathroom 1 are shown in Figure 5.91c. At the time of intervention, O_2, CO_2, and CO concentrations were 17.3%, 0.8%, and 0.7%, respectively. The increase in CO and CO_2 was gradual immediately after intervention, but accelerated approximately 70 s after front door closure, reaching a steady peak simultaneous with the re-opening of the front door for suppression. During this peak period, O_2, CO_2, and CO concentrations were 14.8%, 2.8%, and 1.2%, respectively. Gas concentrations gradually began to trend toward ambient during hydraulic ventilation, retuning to pre-experiment concentrations well after the completion of that action.

5.7 Experiment 17

The search tactics in Experiment 17 were designed to evaluate door initiated operations prior to suppression. The timing of the sequence of events is shown in Table 5.13. At the time of ignition, the kitchen window and front door were opened. The interior doors to all four bedrooms were opened. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets which led to flashover of the kitchen. At this point, crews entered the structure through the front door. The crews traveled to bedroom 3 and bedroom 4, split to enter each bedroom, and isolated (closed the doors after entry). The crews proceeded to remove the bedroom 3 and bedroom 4 windows, respectively. After searching bedroom 3 and bedroom 4, the crews left the respective rooms, and closed the doors upon exiting. The crews then proceeded down to hall toward bedroom 1 and bedroom 2. At this point, the fire had spread from the kitchen to the living room. The crews split again, entered bedroom 1 and bedroom 2, and isolated both bedrooms. The windows in the respective rooms were then removed. At this point the search tactic comparison was complete and suppression began with interior operations. 154 gallons of water were flowed during suppression. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side D living room windows. The total amount of water flowed during suppression and hydraulic ventilation was 432 gallons.

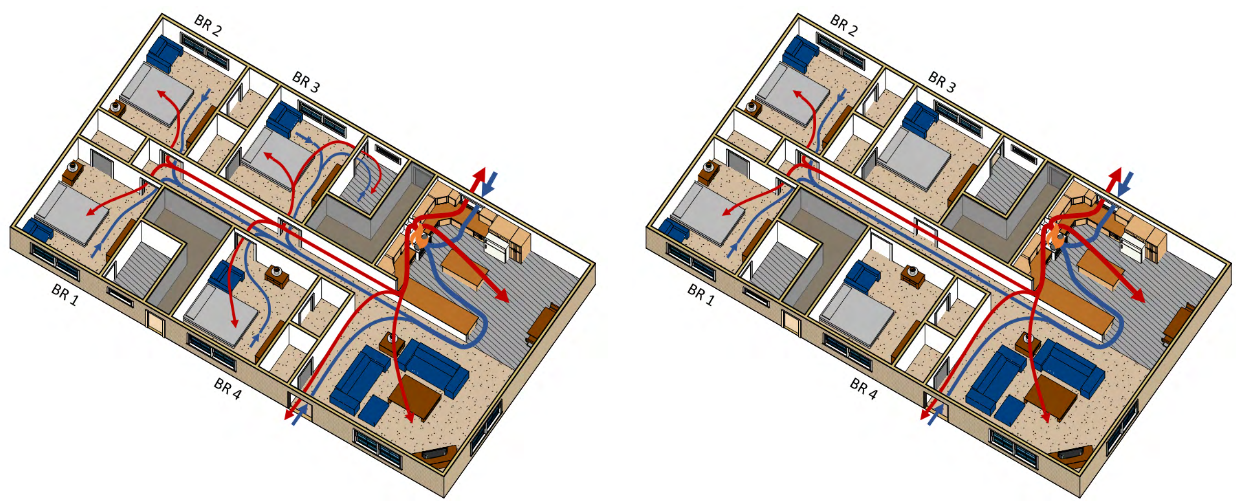
Table 5.13: Experiment 17 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	06:45	405	—	—
Search Crew Entry	18:50	1130	00:00	0
Close BR3 & BR4 Doors	19:35	1175	00:45	45
Remove BR3 & BR4 Windows	20:05	1205	01:15	75
Open BR3 & BR4 Doors	20:17	1217	01:27	87
Close BR3 & BR4 Doors	20:26	1226	01:36	96
Close BR1 & BR2 Doors	20:56	1256	02:06	126
Remove BR1 & BR2 Windows	21:26	1286	02:36	156
Suppression	21:56	1316	03:06	186
Hydraulic Ventilation	25:36	1536	06:46	406
Open BR3 & BR4 Doors	26:17	1577	07:27	447
Open BR1 & BR2 Doors	26:38	1598	07:48	468

Figures 5.92—5.94 show the changes in flow in the structure in the period immediately preceding and following fire department intervention in Experiment 17. Prior to suppression, the kitchen fire was in a growth stage. Bidirectional flows were maintained at the side C kitchen window and the front door, which provided the kitchen fire with air through the lower portion of the vents while

products of combustion were exhausted through the upper portion of the vents (Figure 5.92a). Additionally, as the kitchen fire grew, products of combustion were transported from the kitchen to remote areas of the structure (i.e., hallway and bedrooms). Meanwhile, cooler air from these spaces was drawn toward the kitchen. Although the fire was confined to the kitchen at the time of intervention, it was beginning to extend to the living room, with rollover observed along the ceiling in the living room and hallway.

The initial fire department intervention was the entry of the search crew. In contrast to Experiments 15 and 16, the search team did not close the front door behind them as they made entry. Shortly after the search team made entry, flames began to roll into the living room and hallway, and spread throughout the kitchen cabinets. The search crew split and entered bedrooms 3 and bedroom 4 simultaneously to search both rooms. Each team closed the respective bedroom door behind them. This eliminated the flow path between bedrooms 3 and 4 and the hallway, as shown in Figure 5.92b.

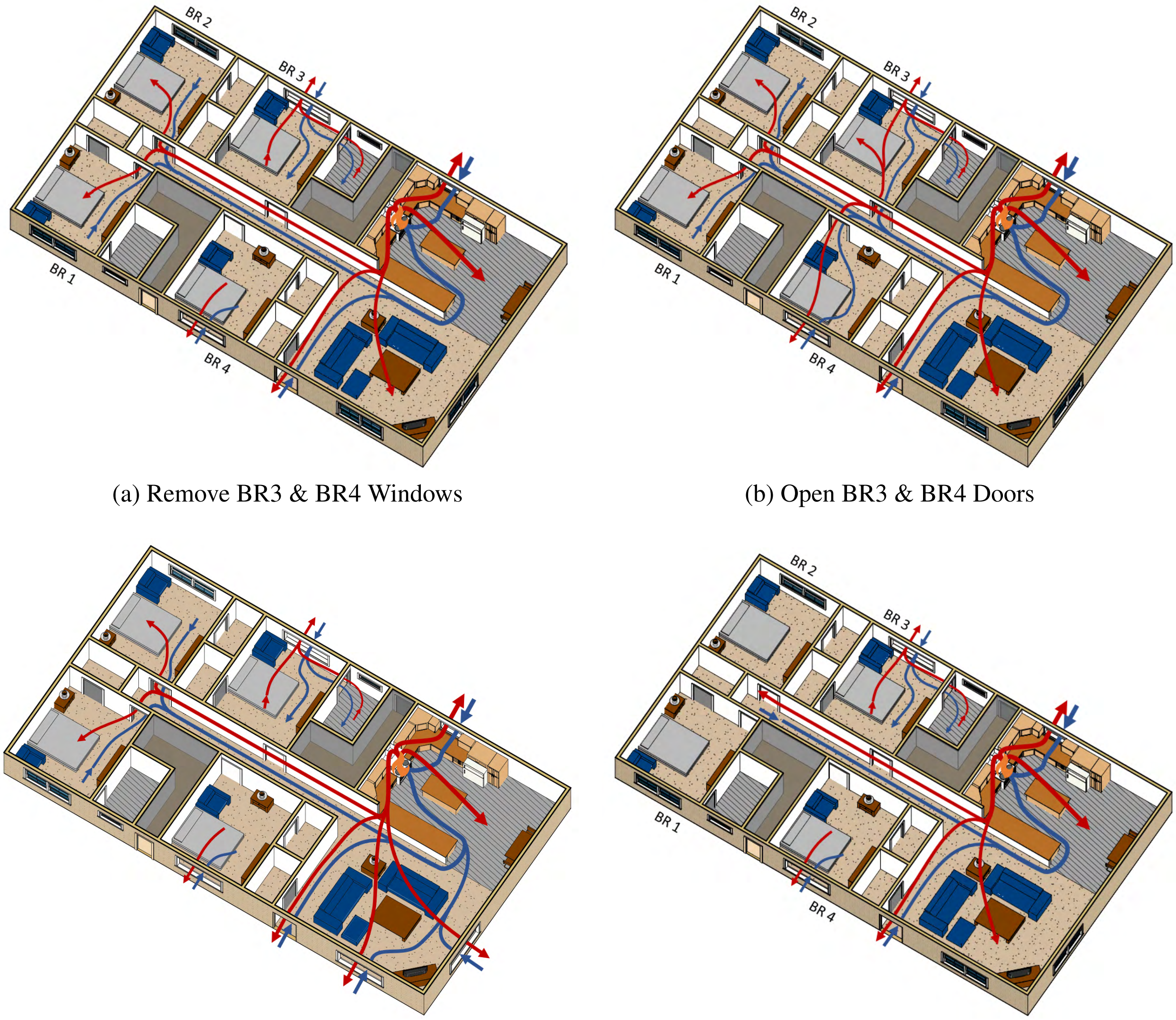


(a) Flows Prior to Intervention

(b) Close BR3 & BR4 Doors

Figure 5.92: Changes in gas flows in the structure following fire department interventions in Experiment 17.

Although the bedroom door closure isolated these rooms from the flow of hot gases from the hallway, products of combustion that had previously entered the room remained until the bedroom 3 and bedroom 4 windows were removed. This action was intended to simulate the search crews ventilating the bedroom windows as the space was searched. A new flow path was established in each room (Figure 5.93a). Higher temperature products of combustion exhausted through the upper portion of the windows while cooler air flowed into the room through the lower portion of the windows. The bedroom doors were subsequently re-opened, as the crews finishing their respective searches – opening the door, and exiting the rooms. This action briefly re-established the bidirectional flows between bedrooms 3 and 4 and the hallway. Products of combustion once again flowed into the two bedrooms, as shown in Figure 5.93b. When the doors were closed again 10 s later, this flow path was eliminated and products of combustion that accumulated in the respective rooms were exchanged to the environment via the open windows (Figure 5.93c). After the search crew exited bedrooms 3 and 4 and closed the doors, they made their way down the hallway to search bedrooms 1 and 2. Just as with bedrooms 3 and 4, the bedroom doors were closed upon entry. This eliminated the flow between bedrooms 1 and 2 and the hallway, as shown in Figure 5.93d.



(a) Remove BR3 & BR4 Windows

(b) Open BR3 & BR4 Doors

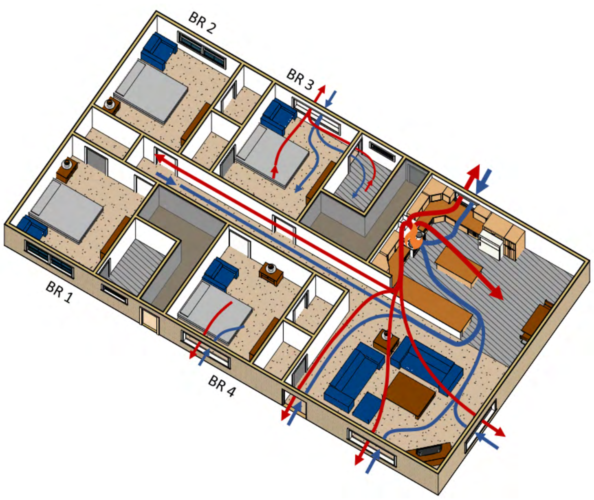
(c) Close BR3 & BR4 Doors

(d) Close BR1 & BR2 Doors

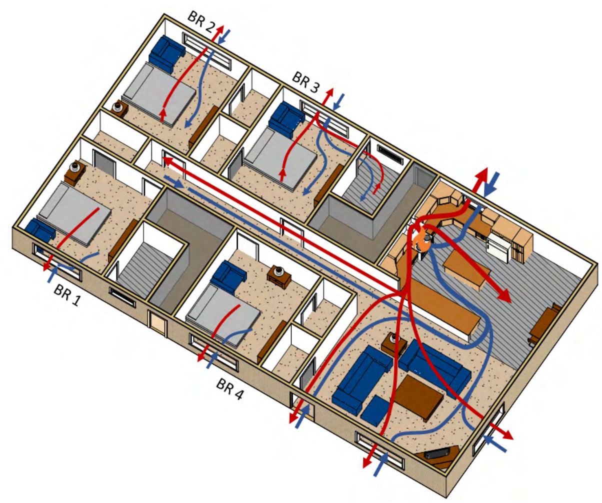
Figure 5.93: Changes in gas flows in the structure following fire department interventions in Experiment 17.

While the crews were searching bedrooms 1 and 2, the side A and side D living room windows failed and the common space fire transitioned through flashover. Bidirectional flows were established at both living room windows. There was an increase in temperatures and gas concentrations in areas of the structure which were open to the common space, including the hallway and bedrooms 1 and 2 (Figure 5.94a). The bedrooms 1 and 2 windows were removed 30 s after the respective doors were closed. The ventilation created a flow path in the respective bedrooms allowing trapped products of combustion to exhaust and be replaced with cooler air from the exterior, as shown in Figure 5.94b.

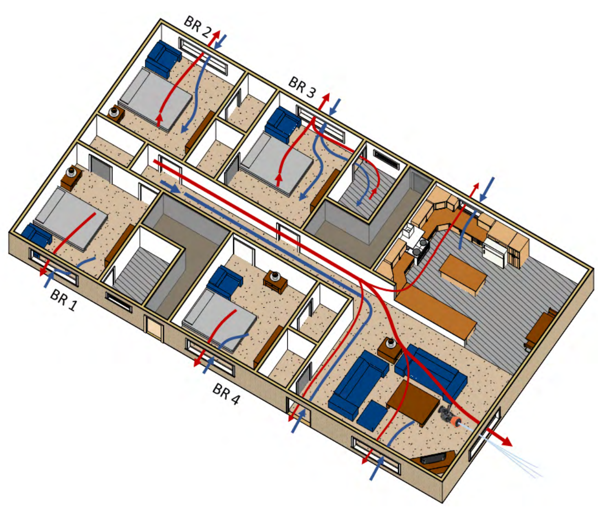
Upon completion of the search operations, the suppression crew began flowing water from the deck on side A, and used a flow-and-move technique with 7/8 in. smooth bore nozzle nominally flowing 165 gpm from a 1 3/4 in. hoseline to extinguish the common space fire. After the fire was brought under control, the doors to the bedrooms 1 and 2 doors were opened, allowing gas exchange between these spaces and the rest of the structure. Immediately afterwards, the bedrooms 3 and 4 doors were opened, which re-established the gas exchange between the hallway with those rooms. The suppression crew initiated hydraulic ventilation through the side D living room window with tip on and fully opened nozzle rotated in an O-pattern (Figure 5.94c). This created an exterior vent in the living room, drawing air and products of combustion from remote locations in the structure, and allowing the bedroom windows to act as inlets.



(a) Living Room Window Failure



(b) Remove BR1 & BR2 Windows

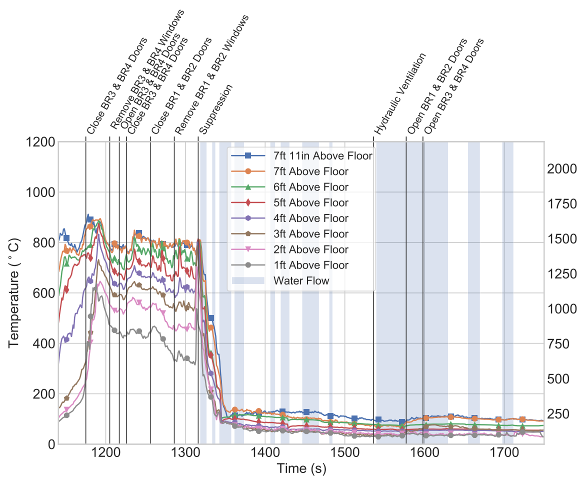


(c) Hydraulic Ventilation

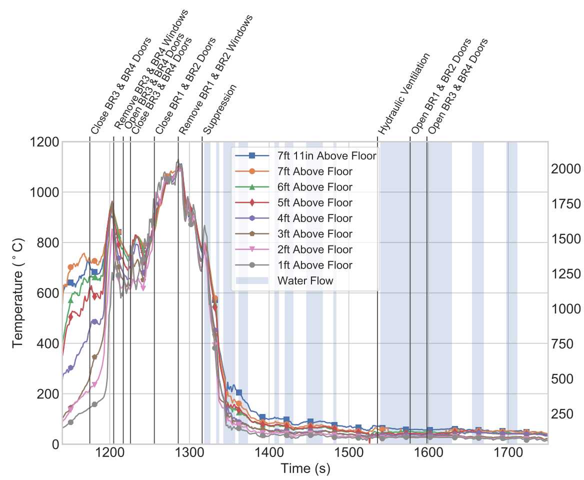
Figure 5.94: Changes in gas flows in the structure following fire department interventions in Experiment 17.

5.7.1 Common Space

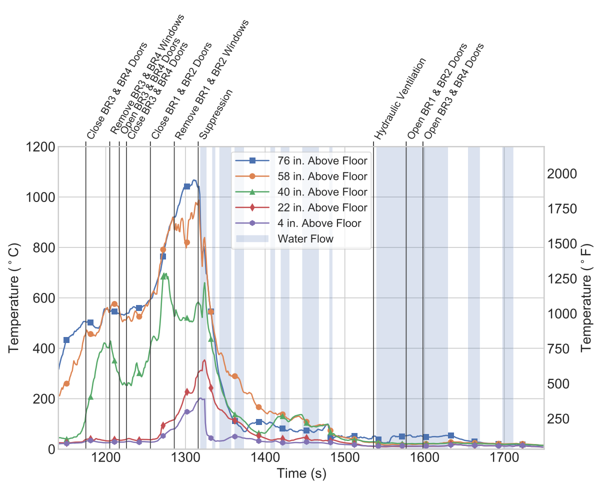
Figure 5.95 shows the time histories of temperatures in the kitchen, living room, and front door and velocity in the front door. At 1130 s post pilot ignition, when the search team made entry, the kitchen fire was in a growth stage; temperatures in the kitchen and living room ranged from 875 °C (1607 °F) at the ceiling to 145 °C (293 °F) 1 ft above the floor at the time of intervention (Figures 5.95a and 5.95b). The front door was open from the time of ignition. Temperature and velocity measurements (Figures 5.95c and 5.95d) show that bidirectional flows were maintained as the kitchen fire grew. Air was supplied to the fire through the lower portion of the door while products of combustion exhausted through the upper portion of the door.



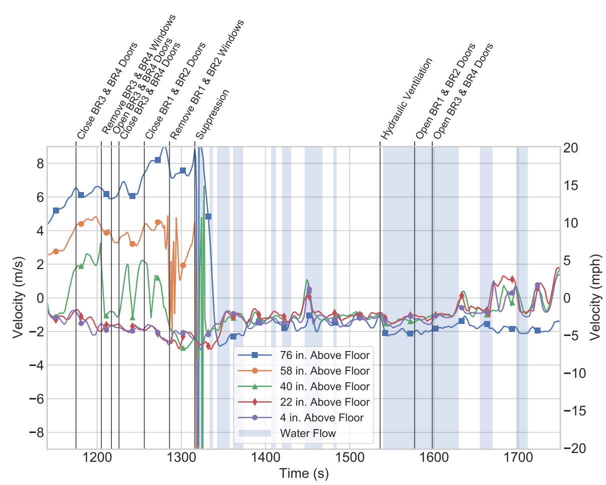
(a) Kitchen Temperature



(b) Living Room Temperature



(c) Front Doorway Temperature



(d) Front Doorway Velocity

Figure 5.95: Post-intervention temperatures front doorway velocity, and front doorway temperatures in the common space in Experiment 17.

Visibility close to the floor was maintained as a result of the inlet flow, and the the fire was largely contained to the kitchen area which is shown in Figure 5.96. Following search team entry, temperatures in the kitchen and living room continued to increase as the air flow through the front door facilitated further fire growth. The kitchen fire transitioned through flashover 60 s after intervention (1190 s after ignition), which led to flashover of the living room 12 s later at 72 s after intervention (1202 s after ignition). The post-flashover conditions in the living room caused the side A and D living room windows to fail, resulting in fire showing through the front door and both living room windows. Temperatures in the living room were consistent with post-flashover conditions up until suppression was initiated. After flashover was observed in the common space, the only air available for combustion in the kitchen was what could be entrained by the kitchen window. The small opening and high sill height limited the supply of oxygen which resulted in lower, post-flashover temperature that were stratified between 825 °C and 425 °C (1517 °F and 797 °F).

Figure 5.96: Fire conditions immediately prior to search crew entering structure during Experiment 17.

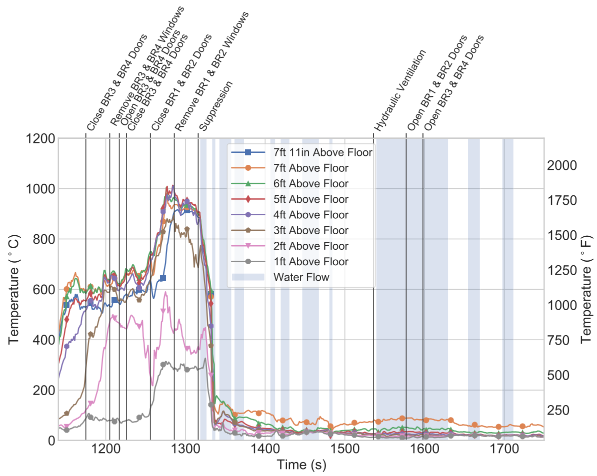
Temperature and velocity measurements in the front door showed that the exhaust from the front door transitioned from smoke to flames approximately 120 s after intervention (1250 s after ignition) . Immediately afterward, the side A living room failed, resulting in flames showing from both the front door and the side A living room window.

Suppression was initiated 186 s after intervention (1316 s after ignition). In the period between intervention and suppression, the fire had spread from a pre-flashover kitchen fire confined to the kitchen to a post-flashover common space fire involving both the kitchen and living room with fire showing from the front door, side A living room window, side D living room window, and side C kitchen window. Figure 5.97 shows the side A conditions upon start of suppression. The initial suppression action of water from the deck resulted in an immediate decrease in temperatures in both the living room and kitchen. The common space fire was extinguished within 60 s of the initial suppression action.

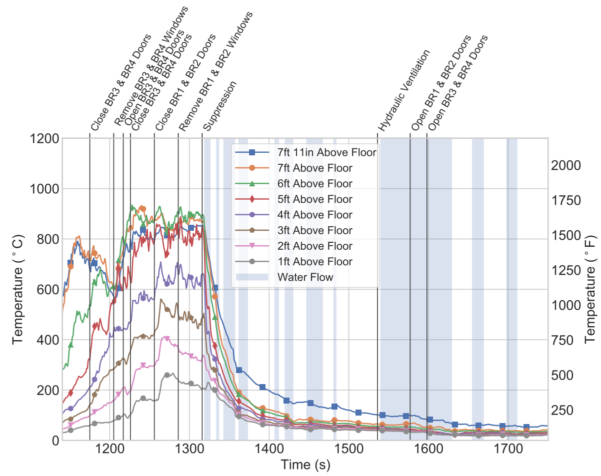
Figure 5.97: Side A fire conditions immediately prior to suppression during Experiment 17.

5.7.2 Hallway

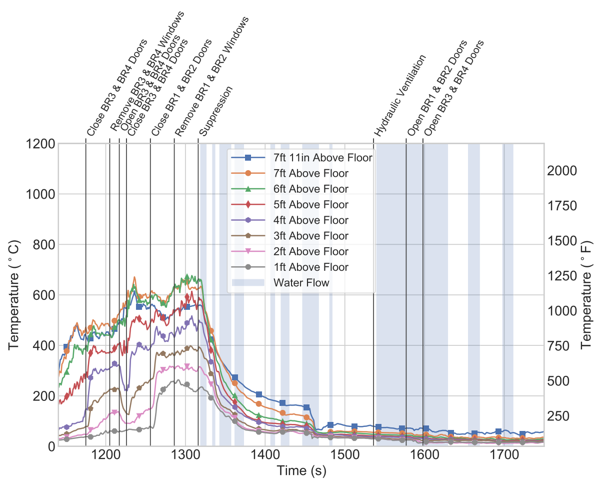
Figure 5.98 shows the time histories of temperature in the living room entryway and at the three hallway measurement locations. At the time of intervention, temperatures in the living room entryway were less than those measured in the center of the living room, ranging from 590 °C (1094 °F) at the ceiling to 87 °C (189 °F) 1 ft above the floor (Figure 5.98a). Proximity to the inlet flow through the front door kept the temperature below 4 ft cooler for a longer duration. Temperatures 4 ft and above began to sharply increase immediately after intervention as rollover was observed across the living room ceiling, as shown in Figure 5.99. Rollover was visible until the living room flashed over 72 s after intervention (1202 s after ignition), with temperatures 4 ft and above exceeding 600 °C (1112 °F). Following flashover in the living room, entry hallway temperatures between 3 ft and the ceiling increased to in excess of 800 °C (1472 °F), while 1 ft and 2 ft temperatures remained between 300 °C (572 °F) and 600 °C (1112 °). These relatively lower temperatures close to the floor were indicative of the bidirectional flow that was maintained through the front door. Temperatures in the living room entry hallway began to decrease immediately after the start of suppression, and continued to decrease as suppression actions continued.



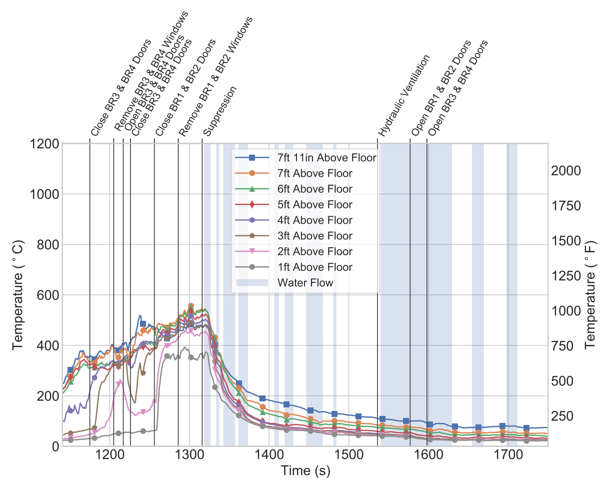
(a) Living Room Entry Hallway Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.98: Temperature time histories in the hallway in the period following fire department intervention in Experiment 17.

At the time of intervention, temperatures were highest at the start hallway location, which ranged from 714 °C (1317 °F) at the ceiling to 60 °C (140 °F) 1 ft above the floor. Temperatures at the mid hallway and end hallway locations were lower, ranging from 472 °C to 38 °C (882 °F to 100 °F) and 359 °C to 31 °C (678 °F to 88 °F), respectively. Similar to the temperatures in the living room entryway, temperatures close to the ceiling began to sharply increase at each of the three hallway locations due to the rollover observed from the kitchen to the living room shortly after the time of intervention. Temperatures close to the floor at the start and mid hallway locations began to increase as the common space fire transitioned through flashover. This increase was punctuated by a decrease at both locations simultaneous with the re-opening of the bedroom 3 and 4 doors, which re-established the flow path between the hallway and those rooms. The fresh air that was entrained along the inlet flow paths had a cooling effect at measurement elevations between 3 ft and the floor

Figure 5.99: Fire conditions 30 s after intervention in Experiment 17.

during the 10 s before the bedrooms 3 and 4 doors were closed.

Temperatures at all three measurement locations, most notably at 2 ft and below exhibited a sharp increase after the bedrooms 1 and 2 doors were closed. The door closures reduced the volume available for the flow of hot gases. This coincided with the failure of living room windows which precipitated flashover of the living room. As a result, combustion gases filled the hallway. Temperatures at each of the three hallway locations began to decrease immediately after the start of suppression, and continued to decrease as the suppression crew extinguished the common space fire.

Figure 5.100 shows the time histories of heat flux in the living room entryway and at the three hallway measurement locations. Immediately after intervention, the heat flux increased in concert with temperatures at that measurement location, reaching a local peak of 23.0 kW/m^2 simultaneous with the closing of the bedrooms 3 and 4 doors. Although the living room fire transitioned through flashover 72 s after intervention (1202 s after ignition), the heat flux at the living room entryway remained below 35 kW/m^2, a magnitude consistent with the transition to flashover. This is because the heat flux gauge was located in the inlet portion of the flow path between the fire and the front door. The heat flux at this location began to increase sharply once the exhaust from the front door transitioned from smoke to fire, approximately 140 s after intervention (1270 s after ignition). After this point, heat flux in the living room entryway maintained a steady value of approximately 40 kW/m^2 (consistent with post-flashover conditions), until suppression was initiated. Suppression actions generally caused heat flux to decrease, although a brief peak above 60 kW/m^2 was observed during the initial suppression action. This peak was likely a result of burning debris which landed in the area of the heat flux gauge that was extinguished shortly thereafter by the suppression crew. Heat flux in the living room entryway was reduced to negligible values prior to the start of hydraulic ventilation.

Heat flux at the start hallway location exhibited a similar initial trend to that at the living room entryway—increasing from 2.2 kW/m^2 at intervention to a 12.5 kW/m^2 simultaneous with closure of the bedrooms 3 and 4 doors. The timing of this peak was consistent with the rollover that was

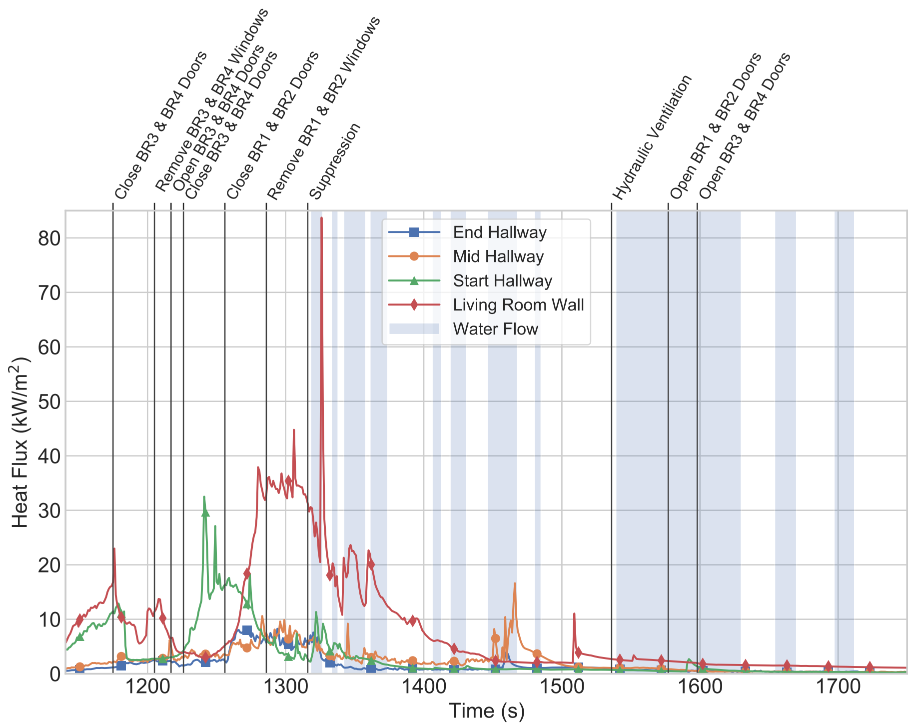


Figure 5.100: Heat flux time histories in the hallway in post-intervention period during Experiment 17.

observed in the area of the start hallway at the same time. Following this initial peak, heat flux sharply decreased as flaming subsided in the hallway due to a lack of oxygen. Start hallway heat flux began to increase again as the living room fire transitioned through flashover to a peak of 32.5 kW/m^2, before again decreasing prior to suppression once the bedroom 1 and 2 doors were closed. Heat flux at the start hallway began to decrease after the start of suppression, reaching negligible values prior to the start of hydraulic ventilation.

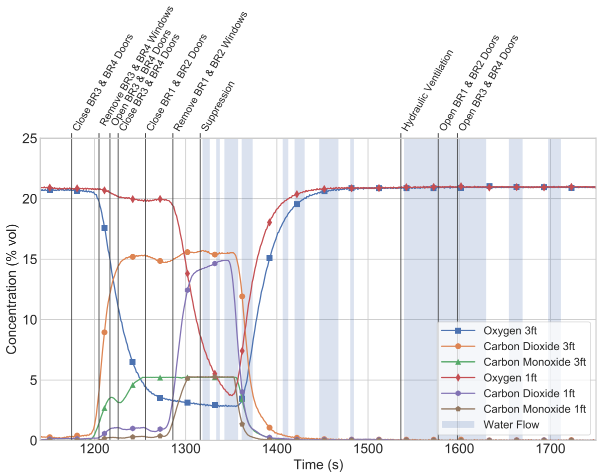
Peak heat fluxes measured at the mid and end hallway locations were considerably lower than those at the start hallway and living room entryway due to the lack of burning that was observed at those locations. Heat flux at the mid and end hallway locations were negligible at the time of intervention, and only exhibited a substantial increase after the common space fire transitioned through flashover. A sharp increase in heat flux at both locations was observed coincident with the closing of the bedrooms 1 and 2 doors, which was consistent with the temperatures measured at the mid and end hallway locations. Heat flux increased from 3.4 kW/m^2 to 5.7 kW/m^2 at the mid-hallway and from 2.3 kW/m^2 to 7.9 kW/m^2 at the end hallway. These values were maintained until the beginning of suppression, which immediately caused heat flux to decrease to negligible values.

At the time of intervention, gas concentrations had just started to change at all four locations, listed in Table 5.14. Figure 5.101 shows the time histories of gas concentrations in the living room entryway and at the three hallway locations. In the living room entryway, gas concentrations maintained these comparatively low values until approximately 70 s after intervention (1200 s after ignition)—shortly before the living room fire transitioned through flashover (Figure 5.101a). At this time, the 3 ft gas concentrations began to increase to the upper measurement threshold of the gas analyzers (CO_2 concentration of 15%, CO concentration of 5.0%) as the smoke layer in the living room entryway descended below the 3 ft measurement location. Although the 3 ft gas concentrations were consistent with the post-flashover conditions observed in the common space, CO and CO_2 concentrations at the 1 ft elevation remained low as a result of the air entrainment through the front door. As the front door exhaust transitioned from smoke to fire, the 1 ft living room entryway measurement location was no longer in the inlet flow path, which resulted in an increase in CO and CO_2 concentrations approximately 150 s after intervention (1280 s after ignition). Gas concentrations maintained these elevated CO and CO_2 values and low O_2 concentrations until 40 s after the beginning of suppression. Suppression actions caused gas concentrations to sharply trend toward ambient, with CO and CO_2 concentrations at both elevations in the living room entryway decreasing to negligible values prior to the start of hydraulic ventilation.

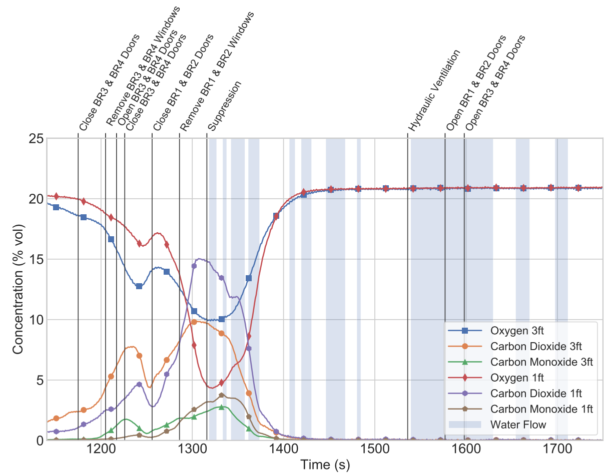
Table 5.14: Hallway Gas Concentrations at Intervention for Experiment 17

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	20.8	0.3	0.1
	1 ft	20.9	0.1	0
Start Hallway	3 ft	20.0	1.3	0.1
	1 ft	20.4	0.6	0
Mid Hallway	3 ft	19.2	2.0	0.1
	1 ft	20.7	0.3	0
End Hallway	3 ft	18.5	2.8	0
	1 ft	20.6	0.3	0

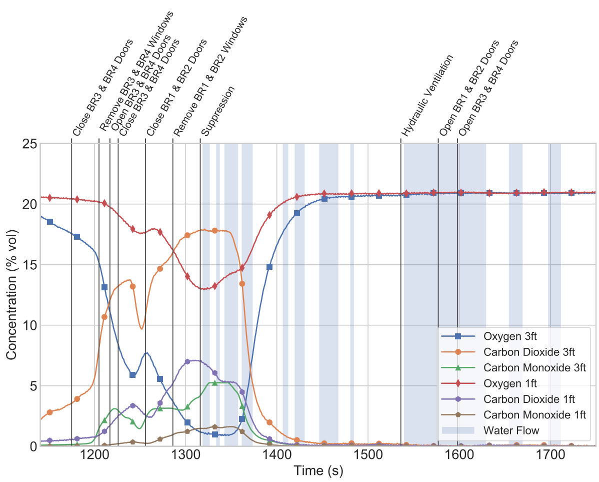
Gas concentrations at the start, mid, and end hallway locations trended similarly to each other. Following intervention, when CO and CO_2 concentrations were low, products of combustion continued to flow down the hallway as the kitchen fire continued to grow and spread to the living room. As a result, CO and CO_2 concentrations at the three hallway locations continued to increase while O_2 concentrations continued to decrease. The rate at which CO and CO_2 increased began to accelerate approximately 72 s after intervention, as the common space fire transitioned through flashover and greater quantities of combustion products were exhausted to remote areas of the structure. The increase in CO and CO_2 was interrupted by a brief decrease in these values (and simultaneous increase in O_2 concentrations), following the re-opening of the bedrooms 3 and 4 doors, as cool air from the inlet of the flow path in those rooms flowed down the hallway. Once the doors were closed again, CO and CO_2 concentrations continued to increase while O_2 concentrations decreased. Gas concentrations at all three hallway measurement locations began to trend toward ambient 40 s after the beginning of suppression (1356 s after ignition), as suppression actions extinguished the common space fire. Prior to the beginning of hydraulic ventilation, CO and CO_2 concentrations at the hallway measurement locations had decreased to negligible values.



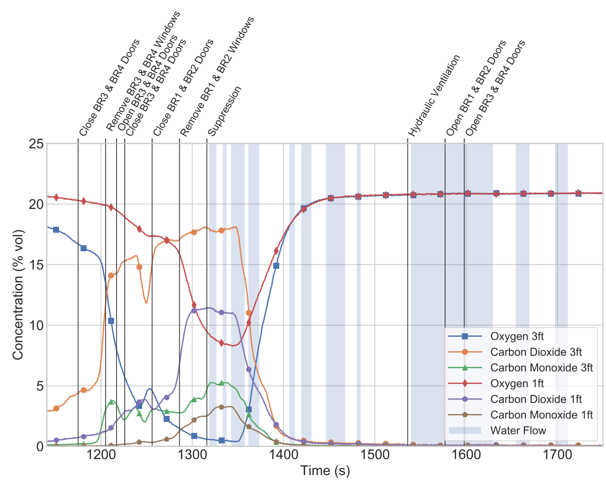
(a) Living Room Entryway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.101: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 17.

5.7.3 Bedroom 3

Figure 5.102 shows the time history of temperature in bedroom 3 during Experiment 17. The door between bedroom 3 and the hallway was open from ignition, allowing bedroom 3 to fill with products of combustion as the common space fire grew. At the time of intervention, temperatures ranged from 212 °C to 27 °C (414 °F to 81 °F) and were increasing as products of combustion continued to flow into the room. This temperature increase continued until the bedroom 3 door was closed 45 s after intervention. This isolated bedroom 3 from the flow of products of combustion from the hallway, resulting in a decrease in temperature at all elevations. This temperature decrease was accelerated when the bedroom 3 window was removed, establishing a flow path in the window. This new bidirectional flow path allowed products of combustion which were trapped in bedroom 3 following door closure to exhaust through the upper portion of the vent while cooler air flowed into the room through the lower portion of the vent. The bedroom 3 door was re-opened 87 s after intervention, re-establishing the bidirectional flows between bedroom 3 and the common space fire, resulting in an increase in temperatures above 5 ft as higher temperature gases flowed toward the vented window. In particular, the ceiling temperature increased from 123 °C to 425 °C (253 °F to 797 °F) in the 10 s between door opening and door closing. When the bedroom 3 door was closed, the room was once again isolated from the flow of products of combustion from the hallway, causing temperatures at all elevations to continuously decrease for the remainder of the experiment. Temperatures had uniformly decreased below 50 °C prior to the start of hydraulic ventilation. Once the bedroom 3 door was re-opened during the hydraulic ventilation action 447 s after intervention, temperatures further decreased to approximately pre-experiment values.

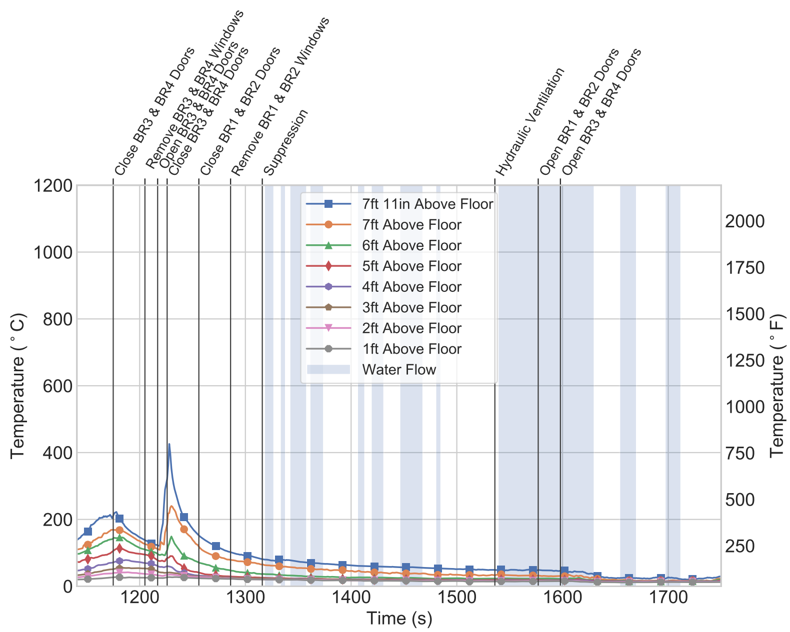
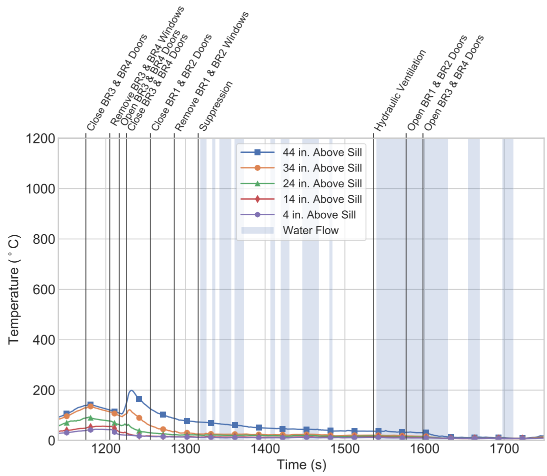
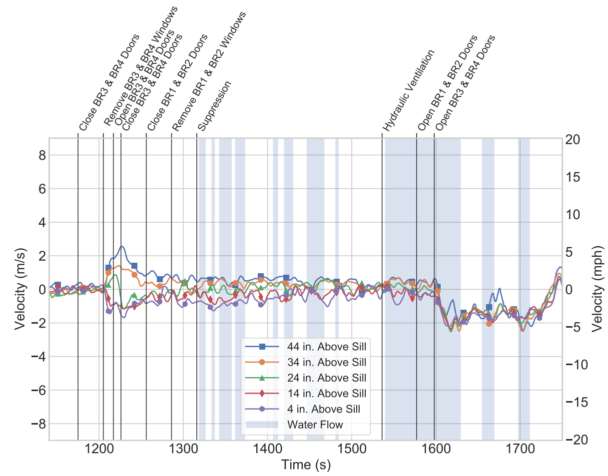


Figure 5.102: Post-intervention bedroom 3 temperature during Experiment 17.

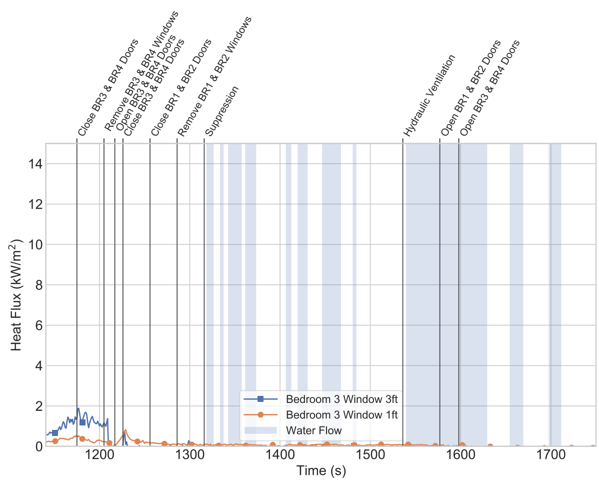
Figure 5.103 shows the temperature, velocity, heat flux, and gas concentration measured in the bedroom 3 window. Window temperatures (Figure 5.103a) generally followed a similar trend to the temperatures in the center of the bedroom. Window velocities (Figure 5.107b) show that bidirectional flows were established in the window following ventilation. Exhaust velocities ranged from 1 m/s to 2 m/s (2.2 mph to 4.5 mph), while entrainment velocities ranged from -1 m/s to 2 m/s (-2.2 mph to -4.5 mph). A brief increase in exhaust velocity was observed when the bedroom 3 door was re-opened, but decreased when the door was closed again. Following the second closure of the bedroom 3 door, velocities gradually converged toward 0 m/s as the products of combustion that were trapped in bedroom 3 were exhausted and replaced with air from the exterior of the structure. Bidirectional flows were maintained through the start of the hydraulic ventilation action. Hydraulic ventilation did not impact window velocities prior to the opening of the bedroom 3 door, which re-established the flow path between bedroom 3 and the hallway. After the door was opened, the window acted as a unidirectional vent with inlet velocities between -1 m/s and -3 m/s (-2.2 mph to -6.7 mph) until hydraulic ventilation was completed.



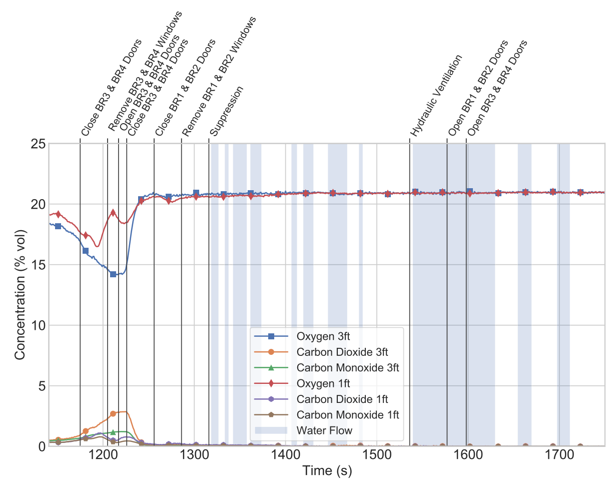
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



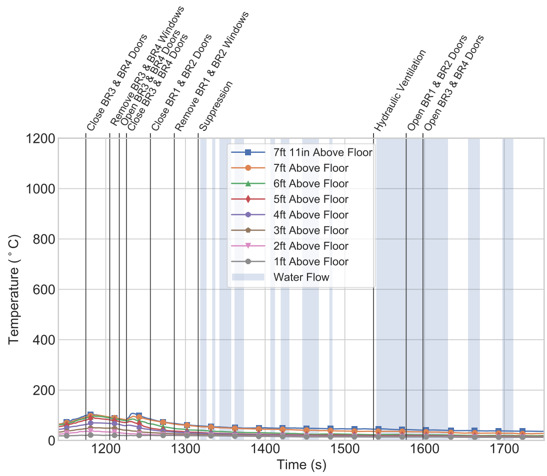
(d) Bedroom 3 Window Gas Concentration

Figure 5.103: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 17.

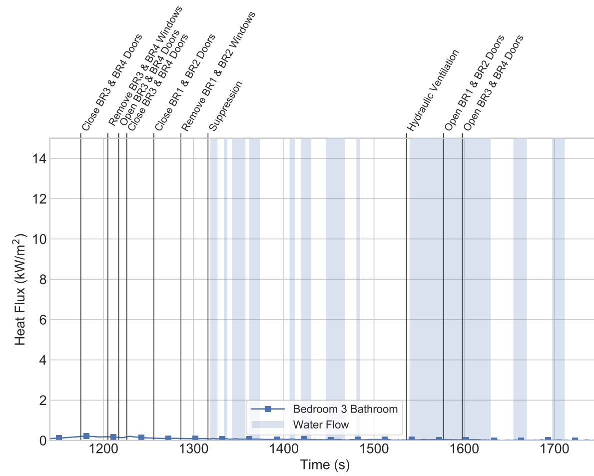
Figure 5.103c shows the heat flux measured 3 ft and 1 ft above the floor in the bedroom 3 window. At the time of intervention, heat flux was increasing at both elevations in concert with the temperatures in the room. Heat flux at the time of intervention was 1.4 kW/m^2 and 0.5 kW/m^2 at the 3 ft and 1 ft measurement locations, respectively. Similar to the trend observed with the bedroom 3 temperatures, when the door was closed, the room was isolated from the flow of hot gases from the hallway, resulting in a decrease in heat flux. This decrease was accelerated when the bedroom 3 window was removed, which caused heat flux at both elevations to decrease to negligible values. A momentary peak in heat flux was observed when the flow path with the hallway was re-established following the re-opening of the bedroom door. After the bedroom 3 door was closed again, the heat flux at both elevations decreased to negligible values for the remainder of the experiment.

Figure 5.103d shows the time histories of gas concentrations at the bedroom 3 window measurement locations. Gas concentrations were 16.9% O_2, 0.9% CO_2, and 0.7% CO 3 ft above the floor and 17.7% O_2, 0.6% CO_2, and 0.5% CO 1 ft above the floor. CO and CO_2 concentrations increased while O_2 concentrations decreased as bedroom 3 continued to fill with products of combustion. Although the closing of the bedroom 3 door isolated the room from the flow of products of combustion, CO and CO_2 concentrations continued to increase after door closure due to the products of combustion which were trapped in the room. 1 ft gas concentrations began to trend toward ambient 15 s after bedroom door closure, while 3 ft gas concentrations did not begin to trend toward ambient until 42 s after bedroom door closure—after the bedroom 3 window was removed, which allowed products of combustion to be replaced with air from the exterior. The combination of the closed bedroom door and the bidirectional vent in bedroom 3 caused CO and CO_2 concentrations to decrease to negligible within a minute.

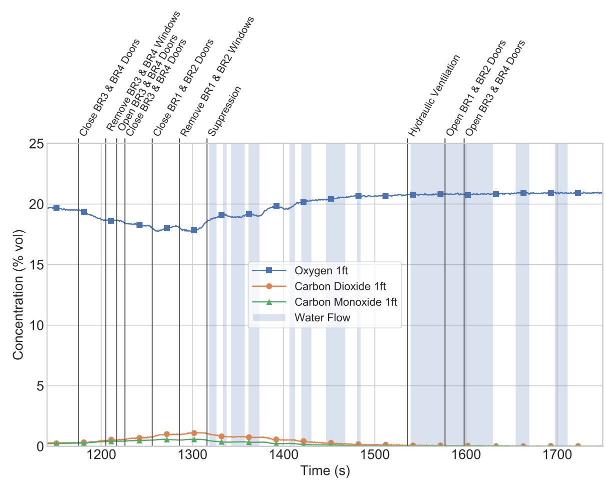
Figure 5.104 shows the time histories of temperature, heat flux, and gas concentrations in bathroom 3. The door between bedroom 3 and bathroom 3 was open for the duration of the experiment, allowing bathroom 3 to fill with products of combustion as the kitchen fire grew. Temperatures in the bathroom trended similarly to those in the adjacent bedroom, although the magnitude of the temperatures was considerably lower. Temperatures ranged from 61 °C to 18 °C (142 °F to 64 °F) at the time of intervention, and increased to a peak when the bedroom 3 door was closed. Peak temperatures in the bathroom ranged from 104 °C to 22 °C (219 °F to 72 °F). Temperatures began to decrease after this space was isolated from the hallway. This decrease was accelerated when the bedroom 3 window was opened, which established a new flow path. Similar to bedroom 3, this decrease in temperature was punctuated by a momentary increase in temperature between 4 ft and the ceiling when the bedroom 3 door was opened and re-established the flow path with the hallway. Following this local peak, bathroom temperatures continuously decreased for the remainder of the experiment. As a result of the comparatively low temperatures that were measured in bathroom 3, the heat flux remained below 0.5 kW/m^2 for the duration of the experiment, as shown in Figure 5.104b.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

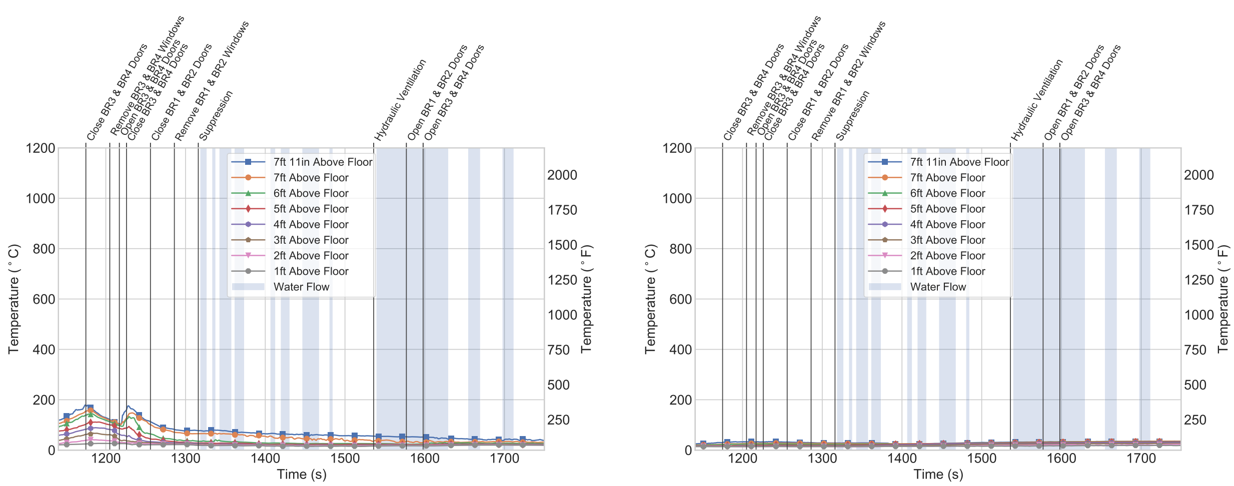
Figure 5.104: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 17.

Figure 5.104c shows the time histories of gas concentrations 1 ft above the floor in bathroom 3 during Experiment 17. At the time of intervention, O_2, CO_2, and CO concentrations were 19.8%, 0.3%, and 0.2%, respectively. These comparatively low CO and CO_2 concentrations indicate that the smoke layer in the bathroom had not descended past the 1 ft measurement elevation. Following intervention, CO and CO_2 concentrations gradually increased while the O_2 concentration gradually decreased. Gas concentrations in the bathroom did not immediately respond to door closure or ventilation actions, which is due to both the relatively low concentrations of CO and CO_2 and that the bathroom 3 measurement location was not directly in the flow path established the window. CO and CO_2 concentrations in the bathroom reached a peak approximately 170 s after intervention (1300 s after ignition). At the peak, O_2, CO_2, and CO concentrations were 17.7%, 1.1%, and 0.6%. Following this peak, gas concentrations gradually trended toward ambient, with CO and

CO_2 decreasing to negligible values prior to the start of hydraulic ventilation.

5.7.4 Bedroom 4

Figure 5.105 shows the time history of temperature in bedroom 4 and the bedroom 4 closet. The door between bedroom 3 and the hallway was open from ignition, allowing bedroom 4 to fill with products of combustion as the common space fire grew. At the time of intervention, temperatures ranged from 178 °C to 24 °C (352 °F to 75 °F). Temperatures continued to increase until 45 s after intervention, when the bedroom 4 door was closed. This isolated bedroom 4 from the flow of products of combustion from the hallway, and resulted in a decrease in temperature at all elevations. This temperature decrease was accelerated when the bedroom 4 window was removed, establishing a flow path in the window. Bidirectional flow was established at the window which allowed products of combustion that were trapped in bedroom 4 following door closure to exhaust through the upper portion of the vent. Cooler air flowed into the room through the lower portion of the vent. The bedroom 4 door was re-opened 87 s after intervention, re-establishing the flow path between bedroom 4 and the common space fire, resulting in an increase in temperatures above 5 ft as hot gases flowed toward the window. When the bedroom 4 door was closed, the room was once again isolated from the flow of products of combustion from the hallway. Temperatures at all elevations decreased for the remainder of the experiment. Temperatures had uniformly decreased below 50 °C (122 °F) prior to the start of hydraulic ventilation. Once the bedroom 4 door was re-opened during the hydraulic ventilation action 447 s after intervention, temperatures further decreased to approximately pre-experiment values. Since the door between bedroom 4 and the bedroom 4 closet remained closed from the time of ignition, temperatures remained below 35 °C (95 °F) at all elevations for the duration of the experiment, as shown in Figure 5.105b.



(a) Bedroom 4 Temperature

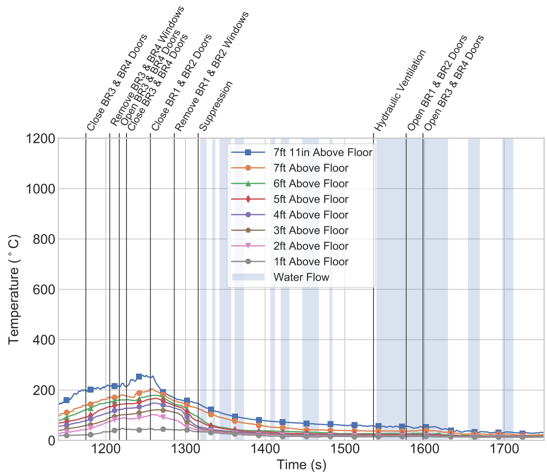
(b) Bedroom 4 Closet

Figure 5.105: Bedroom 4 temperatures, doorway temperature, doorway velocity, gas concentrations, and heat flux time histories in bedroom 4 during Experiment 17.

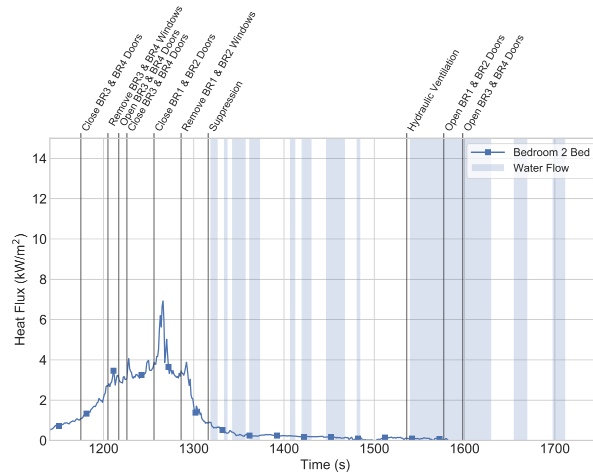
5.7.5 Bedroom 2

Figure 5.106 shows the time history of temperature, heat flux, and gas concentration in bedroom 2. The door between bedroom 2 and the hallway was open from ignition which allowed the space to fill with products of combustion as the common space fire grew. At the time of intervention, temperatures ranged from 200 °C to 22 °C (392 °F to 72 °F). Temperatures increased until the bedroom 2 door was closed 126 s after intervention. This isolated bedroom 2 from the flow of products of combustion from the hallway, and resulted in a decrease in temperature at all elevations. Prior to this decrease, peak temperatures ranged from 262 °C to 45 °C (504 °F to 113 °F). These peak temperatures were higher than those observed in bedrooms 3 and 4 as a result of the longer elapsed time between intervention and bedroom door closure.

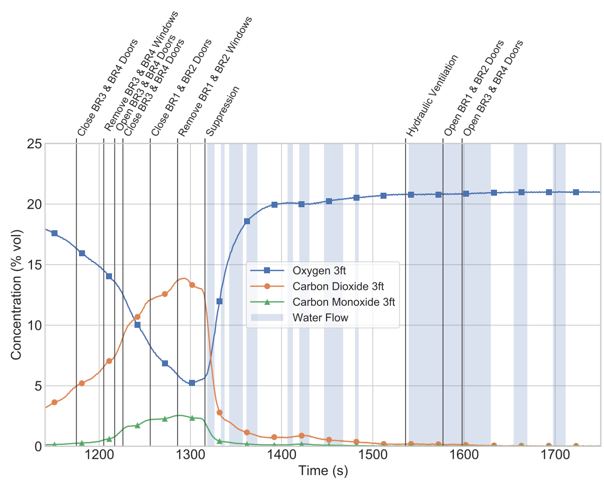
The rate at which temperatures decreased following door closure was accelerated when the bedroom 2 window was removed. A flow path was established at the window. Products of combustion exhausted through the upper portion of the vent while cooler air flowed into the room through the lower portion of the vent. Temperatures continued to decrease but were generally not impacted by suppression due to the closed door. Hydraulic ventilation had no effect on bedroom 2 temperatures until the bedroom 2 door was opened, after which temperatures decreased to approximately pre-experiment values.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



(c) Bedroom 2 Gas Concentration

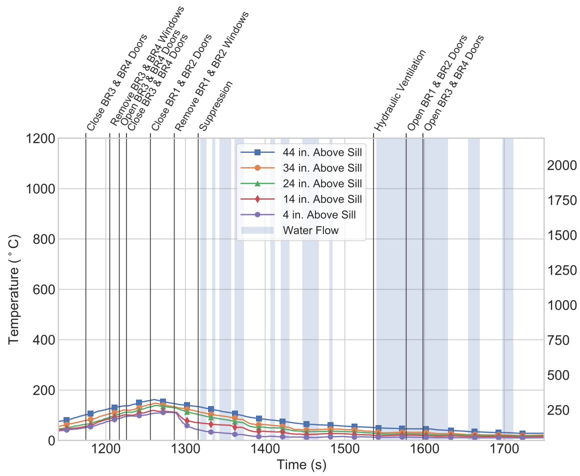
Figure 5.106: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 2 during Experiment 17.

Heat flux in bedroom 2 (Figure 5.106b) trended similarly to temperature at that location. At the time of intervention, the heat flux measured 3 ft above the floor on the bed in bedroom 2 was 1.1 kW/m^2. The heat flux continued to increase as the common space fire transitioned through flashover and bedroom 2 filled with products of combustion. The heat flux had increased to 3.9 kW/m^2 when the door to bedroom 2 was closed. The heat flux briefly increased to a peak of 6.9 kW/m^2 before starting to decrease following the door closure. When the bedroom 2 window was opened and combustion gases began to exhaust through the exterior vent, heat flux sharply decreased, dropping below 1.0 kW/m^2 prior to the start of suppression.

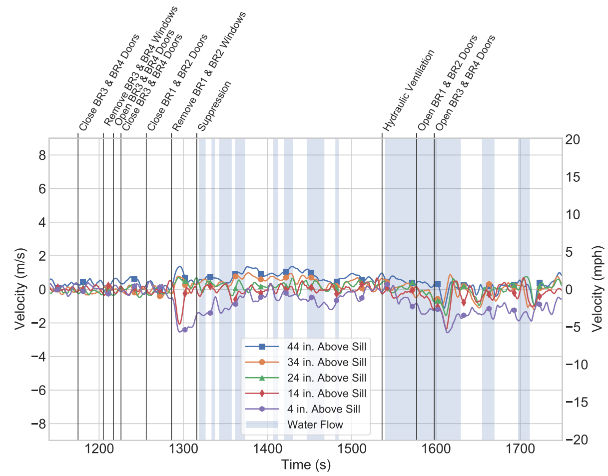
Figure 5.106c shows the time histories of gas concentrations at the measurement location 3 ft above the bed in bedroom 2. O_2, CO_2, and CO concentrations at the time of intervention were 16.3%, 5.0%, and 0.3%, respectively. CO and CO_2 concentrations continued to increase and O_2

concentrations decreased as bedroom 2 filled with products of combustion. Although the closing of the bedroom 2 door isolated the room from the flow of products of combustion, CO and CO_2 concentrations continued to increase after door closure due to the products of combustion which were trapped in the room. Once the bedroom 2 window was removed, products of combustion that were trapped behind the closed bedroom door were able to exhaust. CO and CO_2 concentrations on the bed reached a peak and began to decrease 42 s after door closure. Peak O_2, CO_2, and CO values in bedroom 2 were 5.3%, 13.8%, and 2.5%, respectively. CO and CO_2 concentrations began to sharply decrease simultaneous with the start of suppression actions, and continued to decrease as the suppression crew extinguished the common space fire. CO and CO_2 had decreased to approximately negligible concentrations prior to the start of hydraulic ventilation.

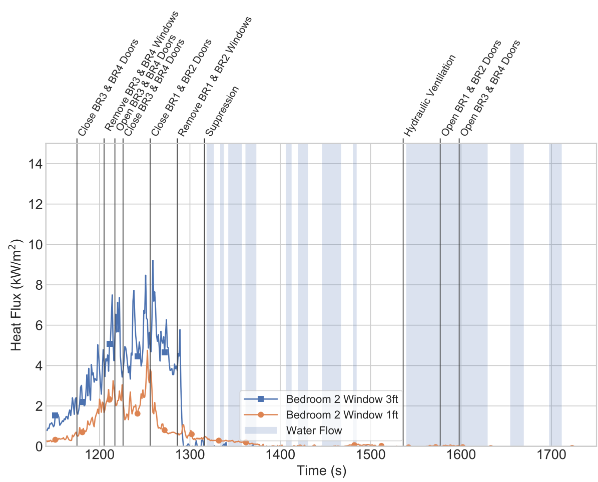
Figure 5.107 shows the temperature, velocity, heat flux ,and gas concentration measured in the bedroom 2 window. Window temperatures (Figure 5.107a) generally followed a similar trend to the temperatures in the center of the bedroom. Window velocities (Figure 5.107b) show that bidirectional flows were established in the window following ventilation. Exhaust velocities ranged from 1 m/s to 1.6 m/s (2.2 mph to 3.6 mph), while entrainment velocities ranged from -1.7 m/s to -3 m/s (-3.8 mph to 6.7 mph). This bidirectional flow was maintained until suppression was initiated, which caused the magnitude of exhaust and entrainment velocities to decrease. In the period between suppression and hydraulic ventilation, products of combustion exhausted through the majority of the window area and were replaced with cooler air flowing through the lower portion of the window. Hydraulic ventilation did not impact window velocities prior to the opening of the bedroom 2 door, which re-established the flow path between bedroom 2 and the hallway. After the door was opened, velocities between 4 in. and 34 in. above the window sill decreased below 0 m/s, indicating that the window acted as an inlet for the hydraulic ventilation action.



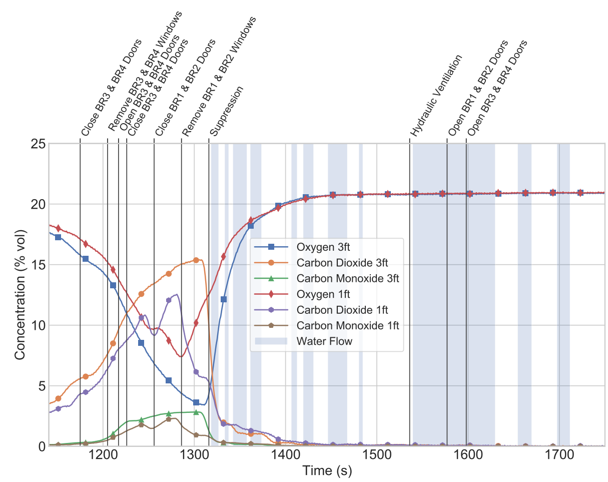
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

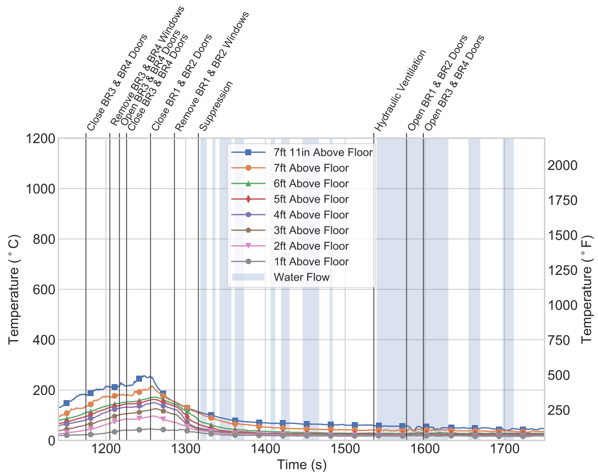
Figure 5.107: Post-intervention temperature, velocity, heat flux measurements at bedroom 2 window during Experiment 17.

Figure 5.107c shows the heat flux measured 3 ft and 1 ft above the floor in the bedroom 2 window. At the time of intervention, heat flux was increasing at both elevations in concert with the temperatures in the room. Heat flux at the time of intervention was 1.6 kW/m^2 and 0.5 kW/m^2 at the 3 ft and 1 ft measurement locations, respectively. Heat flux at the window location continued to increase until the bedroom 2 door was closed as the common space fire transitioned through flashover and the space continued to fill with hot products of combustion. Heat flux at 3 ft and 1 ft reached peaks of 9.2 kW/m^2 and 4.8 kW/m^2, respectively. Similar to the trend observed with the bedroom 2 temperatures, when the door was closed, the room was isolated from the flow of hot gases from the hallway, which resulted in a decrease in heat flux. This decrease was accelerated when the bedroom 2 window was removed, which caused heat flux at both elevations to decrease to negligible values prior to the start of suppression.

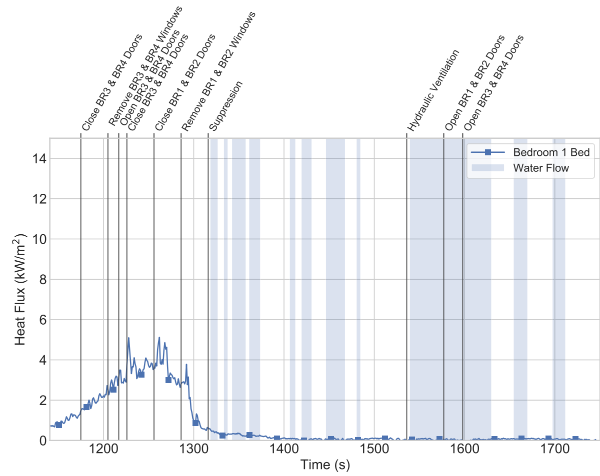
At the bedroom 2 window measurement locations (Figure 5.107d), gas concentrations at the time of intervention were 15.8% O_2, 5.6% CO_2, and 0.3% CO at the 3 ft elevation and 17.1% O_2, 4.4% CO_2, and 0.2% CO at the 1 ft elevation. CO and CO_2 concentrations increased from the time of intervention until after the bedroom 2 door was closed. Although this action isolated bedroom 2 from the flow of hot gases from the hallway, products of combustion remained trapped in the room, causing CO and CO_2 concentrations to continue to increase for an additional 51 s and 24 s after door closure at the 3 ft and 1 ft elevations, respectively. Peak gas concentrations in bedroom 2 were 3.5% O_2, 15.4% CO_2, and 2.8% CO at the 3 ft elevation and 8.1% O_2, 12.4% CO_2, and 2.3% CO at the 1 ft elevation. Note that these peaks were higher than those observed at the window location in bedroom 3 as a result of the longer time that elapsed between intervention and door closure. Following these peaks, gas concentrations trended toward ambient as the bedroom 2 window was removed and suppression was initiated. CO and CO_2 concentrations had decreased to approximately negligible values prior to the start of hydraulic ventilation.

5.7.6 Bedroom 1

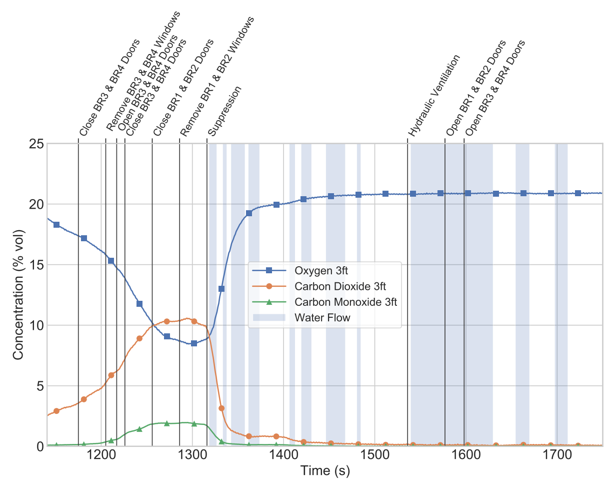
Figure 5.108 shows the time history of temperature, heat flux, and gas concentration in bedroom 1. The door between bedroom 1 and the hallway was open from ignition, allowing the space to fill with products of combustion as the common space fire grew. At the time of intervention, temperatures ranged from 180 °C to 23 °C (356 °F to 73 °F). Temperatures increased until the bedroom 1 door was isolated 126 s after intervention. This isolated bedroom 1 from the flow of products of combustion from the hallway, resulting in a decrease in temperature at all elevations. Prior to this decrease, peak temperatures ranged from 250 °C to 46 °C (482 °F to 115 °F). These peak temperatures are comparable to those observed in bedroom 2, and higher than those observed in bedrooms 3 and 4 as a result of the longer time that elapsed between intervention and bedroom door closure. The rate at which temperatures decreased was accelerated when the bedroom 1 window was removed, establishing bidirectional flow at the window. Products of combustion that were trapped in bedroom 1 following door closure exhausted through the upper portion of the vent while cooler air flowed into the room through the lower portion of the vent. Temperatures continued to decrease through suppression, uniformly dropping below 60 °C (140 °F) prior to the start of hydraulic ventilation. Hydraulic ventilation had minimal effect on bedroom 1 temperatures until the bedroom 1 door was opened, after which temperatures decreased to approximately pre-experiment values.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux



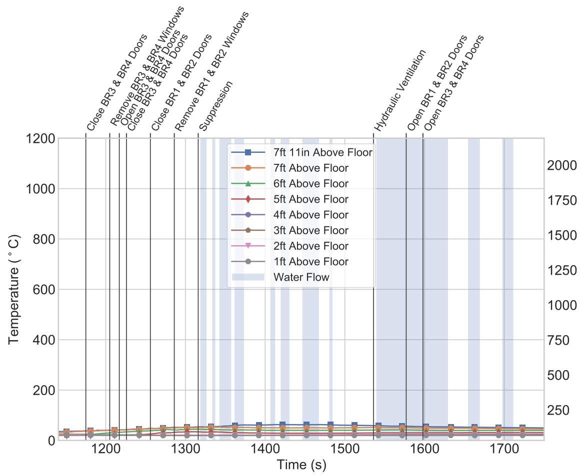
(c) Bedroom 1 Gas Concentration

Figure 5.108: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 17.

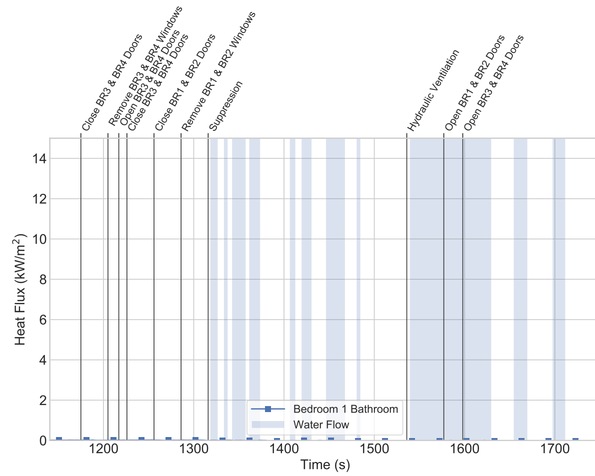
Heat flux in bedroom 1 (Figure 5.108b) followed a similar trend to those measured at the corresponding location across the hall in bedroom 2. At the time of intervention, the heat flux measured 3 ft above the floor on the bed in bedroom 1 was 1.5 kW/m^2. Following intervention, the heat flux continued to increase as the common space fire transitioned through flashover and bedroom 1 continued to fill with products of combustion. The heat flux had increased to 3.8 kW/m^2 when the door to bedroom 1 was closed, which isolated the room from the flow of higher temperature gases from the hallway. The heat flux briefly increased to a peak of 5.1 kW/m^2 before starting to decrease after the door was closed. When the bedroom 1 window was opened and products of combustion began to exhaust from the room the heat flux sharply decreased, dropping below 1.0 kW/m^2 prior to the start of suppression.

Figure 5.108c shows the time histories of gas concentrations at the measurement location 3 ft above the bed in bedroom 1. O_2, CO_2, and CO concentrations at the time of intervention were 17.4%, 3.6%, and 0.1%, respectively—comparable to those measured in bedroom 2 at the same time. Immediately following intervention, CO and CO_2 concentrations were increasing while O_2 concentrations were decreasing as bedroom 1 filled with products of combustion. Although the closing of the bedroom 1 door isolated the room from the flow of products of combustion, CO and CO_2 concentrations continued to increase after door closure due to the products of combustion which were trapped in the room. Once the bedroom 1 window was removed, products of combustion trapped behind the closed bedroom door were able to exhaust the space. CO and CO_2 concentrations on the bed began to decrease 39 s after door closure. Peak O_2, CO_2, and CO values in bedroom 1 were 8.6%, 10.5%, and 2.0%, respectively. These peak gas concentrations were comparable to those measured in bedroom 2, but were substantially higher than those measured in bedrooms 3 and 4 due to the later time of isolation. CO and CO_2 concentrations began to sharply decrease simultaneous with the start of suppression actions, and continued to decrease as the suppression crew extinguished the common space fire. CO and CO_2 had decreased to approximately negligible concentrations prior to the start of hydraulic ventilation.

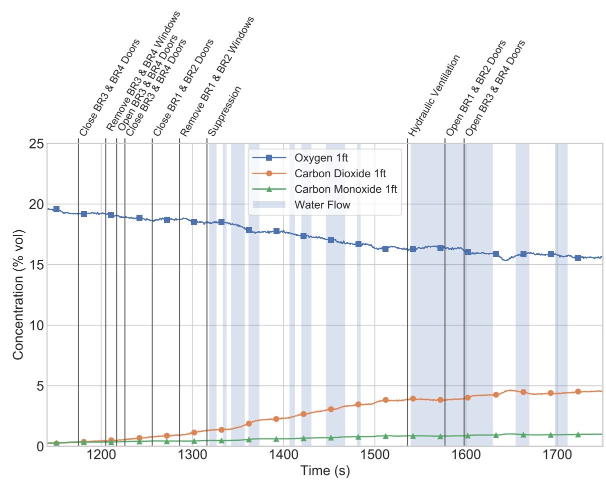
Figure 5.109 shows the time histories of temperature, heat flux, and gas concentration in bathroom 1. The door between bathroom 1 and bedroom 1 was closed for the duration of the experiment. At the time of intervention, temperatures in bathroom 1 had started to increase, ranging from 34 °C (93 °F) at the ceiling to 21 °C (70 °F) 1 ft above the floor. Since the door between bedroom 1 and the bathroom remained closed for the duration of the experiment, the temperature increase following intervention was gradual, despite the smoke-charged conditions that were measured in bedroom 1. Temperature rise was only observed at measurement locations 5 ft and above, and peak temperatures at the ceiling remained below 65 °C (149 °F). As a result of the comparatively low temperatures that were observed in the bathroom, the heat flux measured 1 ft above the floor in the bathroom (Figure 5.109b) was negligible for the duration of the experiment.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Heat Flux



(c) Bathroom 1 Gas Concentration

Figure 5.109: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 17.

Similar to the temperatures and heat flux measured in bathroom 1 at the time of intervention, gas concentrations in the bathroom had just started to increase, as shown in Figure 5.109. O_2, CO_2, and CO concentrations at the time of intervention were 19.7%, 0.3%, and 0.2%, respectively. Following intervention, CO and CO_2 concentrations steadily increased while O_2 decreased as smoke leaked into bathroom 1 through the closed door and through the HVAC supply vent. The increase in CO and CO_2 concentrations continued after ventilation, suppression, and hydraulic ventilation actions, reaching a peak approximately 650 s after intervention (1780 s after ignition) as there was no exhaust vent in the space. O_2, CO_2, and CO concentrations at the peak were 15.2%, 4.8%, and 1.0%, respectively. Note that although these peak gas concentrations were less that those observed elsewhere in the structure, they did not exhibit a decrease until considerably later than other gas concentrations.

5.8 Experiment 18

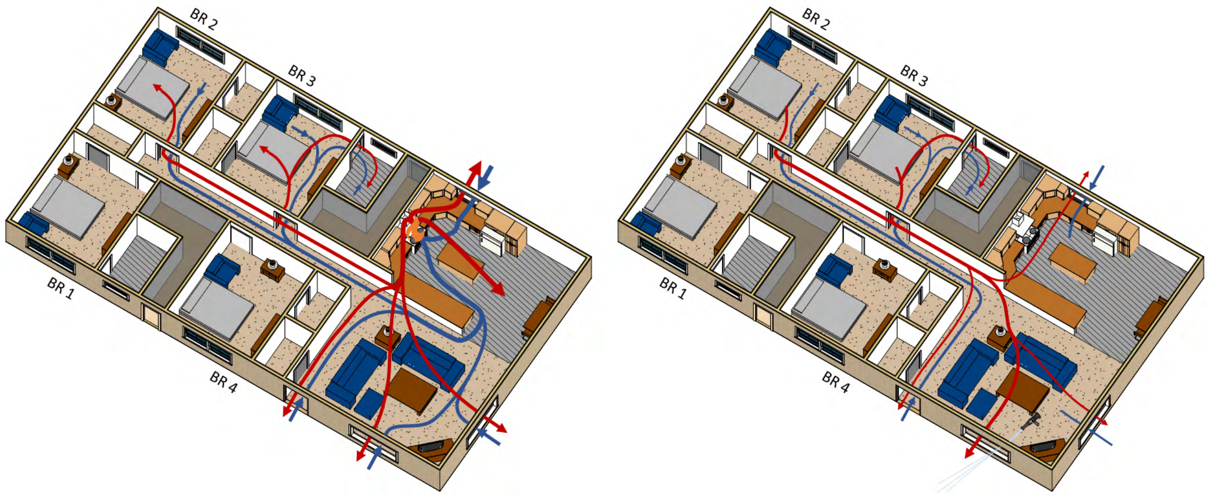
Experiment 18 was designed to establish the baseline conditions for comparison to the other 9 experiments with kitchen or living room ignitions. At the time of ignition, the kitchen window and front door were opened. The doors to bedroom 1 and bedroom 4 were closed, while the doors to bedroom 2 and bedroom 3 were open. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. The fire spread to multiple kitchen cabinets which led to flashover of the kitchen. The fire then spread to the living room, where flashover occurred following the failure of the side A and side D windows. At this point, the suppression crew conducted interior suppression operations. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side A living windows. All interior doors and exterior windows remained in their initial positions for the duration of the experiment. Table 5.15 proivdes the times at which interventions took place.

Table 5.15: Experiment 18 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Pilot Burner Ignition	00:00	0	—	—
Cooking Oil Auto-Ignition	06:10	370	—	—
Suppression	24:15	1455	00:00	0
Hydraulic Ventilation	28:12	1692	03:57	237

At the time of fire department intervention, the common space was in a steady post-flashover state. Bedrooms 2 and 3 were filled with smoke while bedrooms 1 and 4 remained isolated. Figure 5.110a shows that bidirectional flows developed through the open front door, side A living room windows, the side D living room windows, and the side C kitchen window. Air was entrained through the lower portion of these vents while flames and smoke exhausted through the upper portion. The initial fire department intervention was suppression, which was conducted through the front door of the structure using 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 suppression crew first applied water to the interior from a position on the deck, flowing for 12 seconds through the front door and side A living room window in an O-pattern. The suppression crew then applied water for an additional 8 s from the doorway. Once the fire had been controlled to the point where the suppression crew could advance to the interior, the suppression crew crossed the threshold of the doorway and continued suppression operations. 148 gallons of water were flowed during suppression.

Once the fire had been extinguished, the suppression crew initiated hydraulic ventilation through the side A living room window with the tip on and fully opened nozzle rotated in an O-pattern. Hydraulic ventilation created an area of low pressure due to the flowing water through the side A living room window. This drew products of combustion from remote points in the structure through the vent due to a pressure difference (Figure 5.110b). Due to the lack of ventilation openings in the bedrooms, the efficiency of hydraulic ventilation was reduced as distance increased from the common space. The total amount of water flowed during suppression and hydraulic ventilation was 349 gallons.



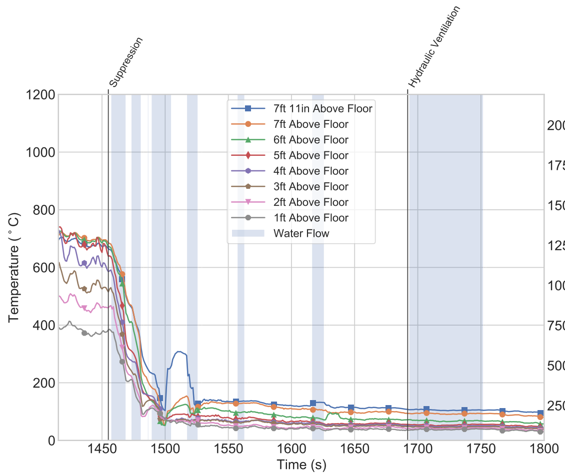
(a) Flows Prior to Intervention (b) Hydraulic Ventilation

Figure 5.110: Changes in gas flows in the structure following fire department interventions in Experiment 18.

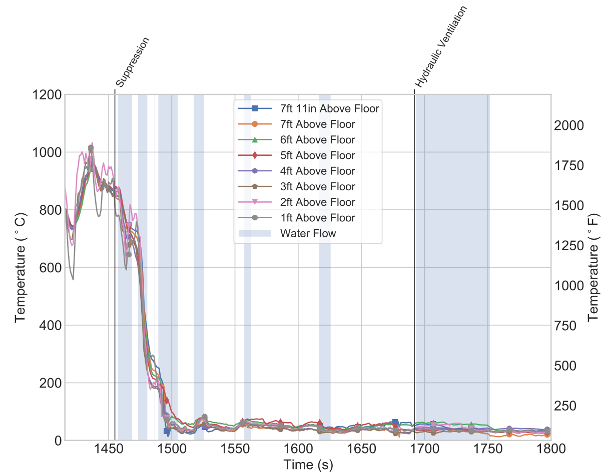
5.8.1 Common Space

Figure 5.111 shows the temperature in the kitchen and the living room and the temperature and velocity measured in the front door in the period following intervention. Immediately prior to ventilation of the bedroom 2 and 3 windows, temperatures in the living room were uniformly in excess of 800 °C (1472 °F), while temperatures in the kitchen were stratified from 690 °C to 370 °C (1274 °F to 698 °F). The living room temperatures were consistent with post-flashover conditions in the common space. The kitchen temperatures were lower, an indication that the lack of ventilation in the kitchen inhibited further flaming combustion.

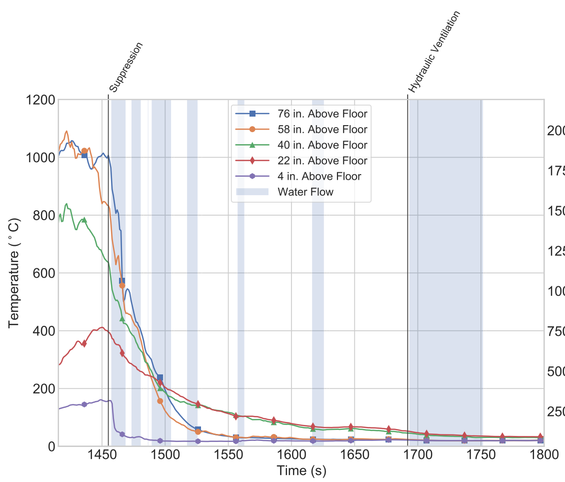
The front door, side A and D living room windows, and side C kitchen window acted as bidirectional vents, with smoke and flames exhausting through the upper portion of these vents while cool air entrained through the lower portion. The temperature and velocity data measured in the front door (Figures 5.111c and 5.111d, respectively), indicated exhaust flow at the probes located 40 in. above the floor and above, with velocities between 5 m/s and 10 m/s (11 mph to 22 mph) at the time of intervention. The corresponding exhaust temperatures were in excess of 600 °C (1112 °F). Air entrainment was recorded at the probes 22 in. and 4 in. above the floor, with velocities of -1.9 m/s and -2.5 m/s (-4.3 mph to -5.6 mph), respectively, and temperatures of 400 °C and 155 °C (752 °F and 311 °F), respectively.



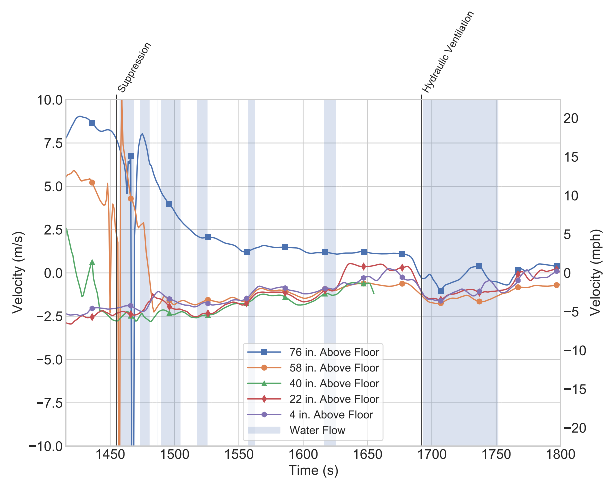
(a) Kitchen Temperature



(b) Living Room Temperature



(c) Front Doorway Temperature



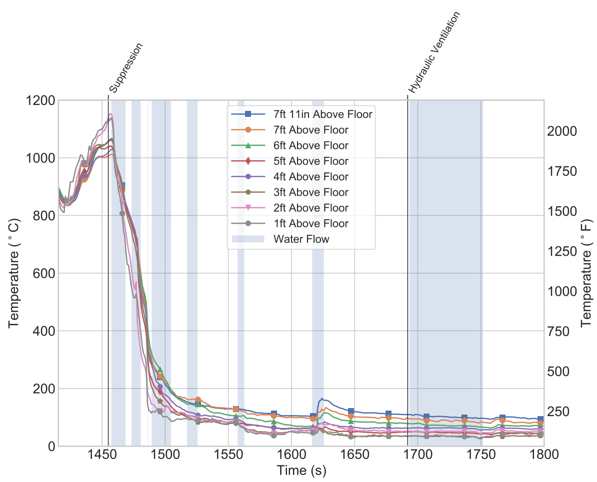
(d) Front Doorway Velocity

Figure 5.111: Post-intervention temperatures front doorway velocity, and front doorway temperatures in the common space in Experiment 18.

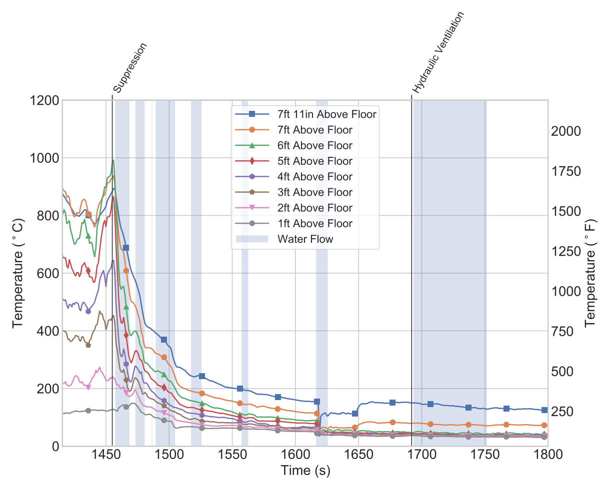
The initial fire department intervention was suppression,which resulted in an immediate decrease in temperature at the front door, living room, and kitchen. Common space temperatures continued to decrease with living room and kitchen temperatures uniformly decreasing below 100 °C (212 °F) prior to the start of hydraulic ventilation. The suppression crew began hydraulic ventilation by flowing out of the side C living room window. This created a new vent at the window, exhausting products of combustion through the window while the side A window and front door acted as unidirectional vents, with entrainment velocities between -1.1 m/s and -5.9 m/s (-2.5 mph and 13 mph).

5.8.2 Hallway

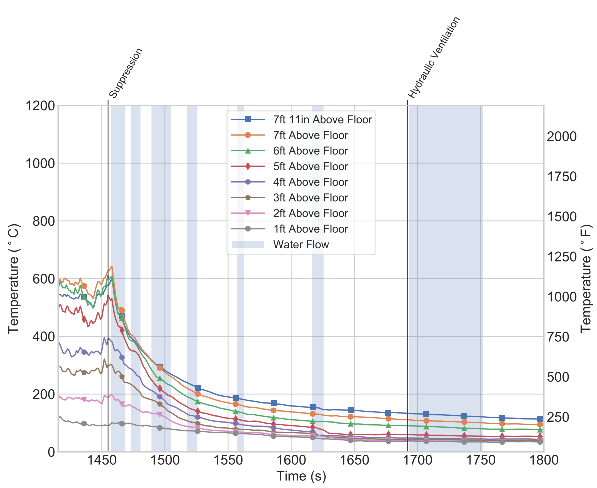
Figure 5.112 shows the time histories of temperature at the living room entryway and at the three hallway measurement locations. At the time of intervention, temperatures in the living room entryway were uniformly in excess of 1000 °C (1832 °F), consistent with the post-flashover conditions observed in the living room at that time (Figure 5.112a). Temperatures began to decrease immediately after the start of suppression and continued to decrease as the suppression crew advanced into the common space to complete extinguishment.



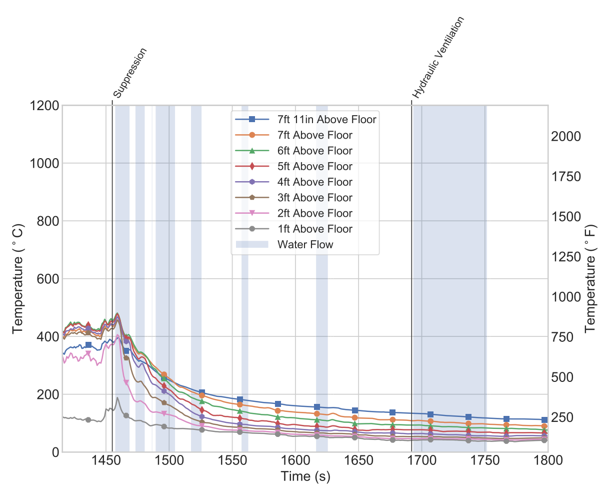
(a) Living Room Entry Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.112: Temperature time histories in the hallway in the period following fire department intervention in Experiment 18.

Temperatures at the start, mid, and end hallway measurement locations were lower than those observed in the living room entryway. At each location, temperatures were stratified at the time of intervention, ranging from 985 °C to 126 °C (1805 °F to 259 °F) at the start hallway, 643 °C

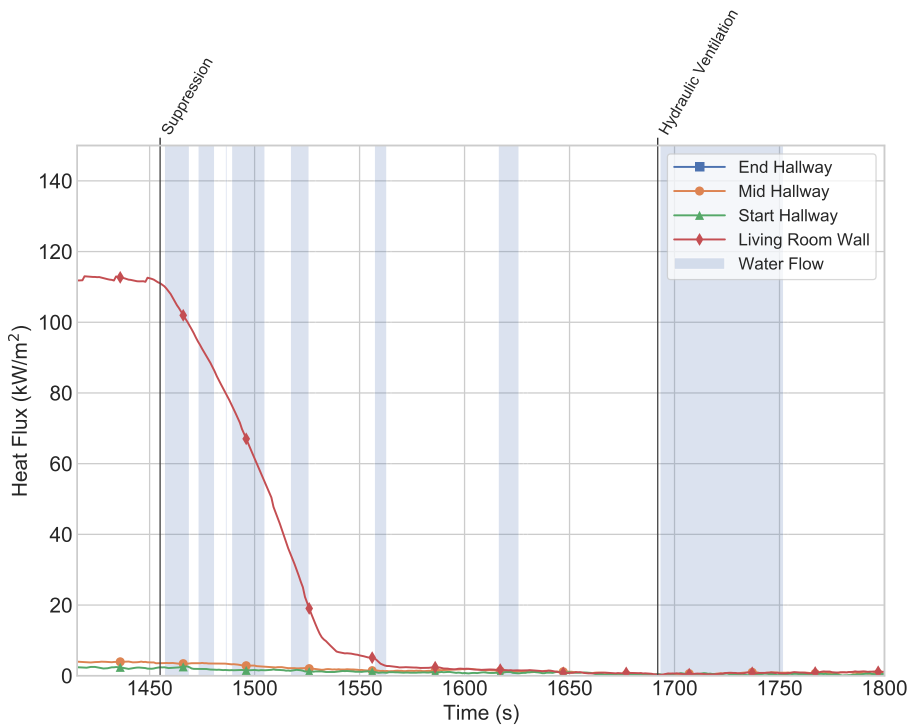


Figure 5.113: Heat flux time histories in the hallway in post-intervention period during Experiment 18.

to 101 °C (1190 °F to 214 °F) at the mid-hallway, and from 476 °C to 165 °C (889 °F to 329 °F) at the end hallway. The start hallway location had the highest temperatures due to proximity to the common space. The mid hallway and end hallway location temperatures decreased with distance from the common space. In a similar manner to the temperatures in the common space, hallway temperatures at each location began to decrease immediately after the start of suppression and continued to decrease through hydraulic ventilation. Due to the lack of ventilation openings intimate to the hallway, hydraulic ventilation did not have a noticeable impact on the rate at which temperatures decreased.

Heat flux values measured in the living room entryway and at the three hallway locations were consistent with the temperatures measured at those locations. The highest heat flux values were measured in the living room entryway, which fluctuated around to 112 kW/m^2 in the 15 s prior to intervention. These magnitudes were consistent with direct flame impingement on the sensor. The heat flux measured at the hallway locations at the same time were considerably lower, ranging from 3.6 kW/m^2 to 1.2 kW/m^2. The lack of exhaust vent in the hallway, limited gas flows once the hallway filled with small which limited heat flux. In a similar manner to the temperature data at these locations, heat flux began to decrease immediately after the start of suppression, reaching negligible values by the end of suppression, approximately 50 s after intervention.

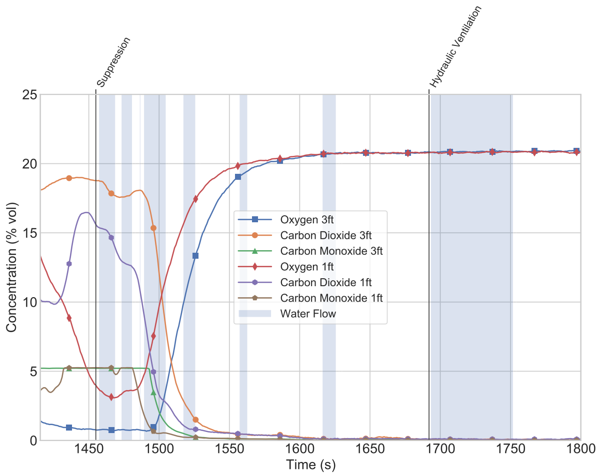
At the time of intervention, the distribution of hallway gases was characterized by high concentrations of CO and CO_2 and low O_2 concentrations, as listed in Table 5.16.

Table 5.16: Hallway Gas Concentrations at Intervention for Experiment 18

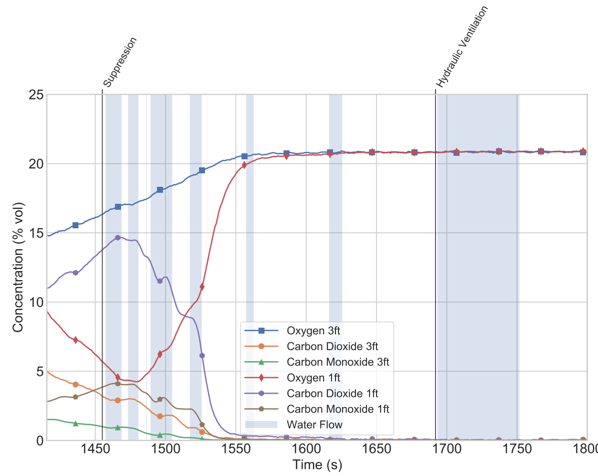
Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	0.8	18.8	5.2
	1 ft	4.3	16.0	5.3
Start Hallway	3 ft	16.3	3.3	1.0
	1 ft	5.9	13.6	3.8
Mid Hallway	3 ft	1.3	17.3	5.2
	1 ft	12.6	7.1	2.0
End Hallway	3 ft	0.4	17.8	5.2
	1 ft	17.7	2.7	0.8

Figure 5.114 shows the time histories of gas concentrations in the living room entryway and at the three hallway locations. The entry hallway location was consistent with the post-flashover conditions observed in the common space. As suppression actions were initiated and more products of combustion began to exhaust through ventilation openings than were produced by the fire, CO and CO_2 concentrations at the living room entryway began to decrease, with peaks observed 32 s and 27 s after the start of suppression at the 3 ft and 1 ft measurement locations, respectively. As CO and CO_2 concentrations decreased, O_2 concentrations increased as air was entrained through the front door and living room windows. Gas concentrations in the living room entryway continued to trend toward ambient with gas concentrations returning to pre-experiment levels prior to the start of hydraulic ventilation.

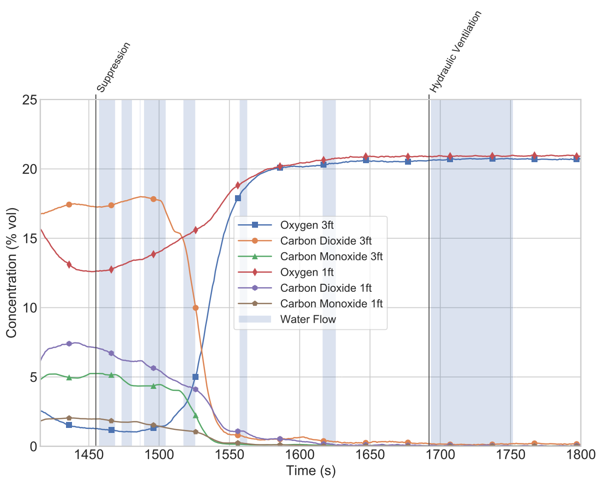
The values in Table 5.16 show that immediately prior to the start of suppression, gas concentrations at the start and mid hallway locations were characterized by high concentrations of CO and CO_2 and low concentrations of O_2, indicating that the smoke layer in these locations had descended below the 1 ft measurement location after the common space fire had transitioned through flashover. Although the 3 ft gas concentrations at the end hallway location were comparable to those at the start and mid hallway locations, the 1 ft gas concentrations exhibited a higher O_2 concentration and lower concentrations of CO and CO_2. Gas concentrations at each of these hallway locations remained nominally steady through the initial suppression actions. As suppression continued and temperatures dropped leading to a decrease in pressure in the structure through gas contraction, products of combustion in the hallway began to exhaust through the available ventilation openings in the common space. CO and CO_2 concentrations began to decrease while O_2 concentrations increased. This was observed between 25 s and 75 s after intervention. Gas concentrations at all three hallway locations continued to trend toward ambient as the suppression crew extinguished the common space fire, with CO and CO_2 concentrations decreasing to negligible values prior to the start of hydraulic ventilation.



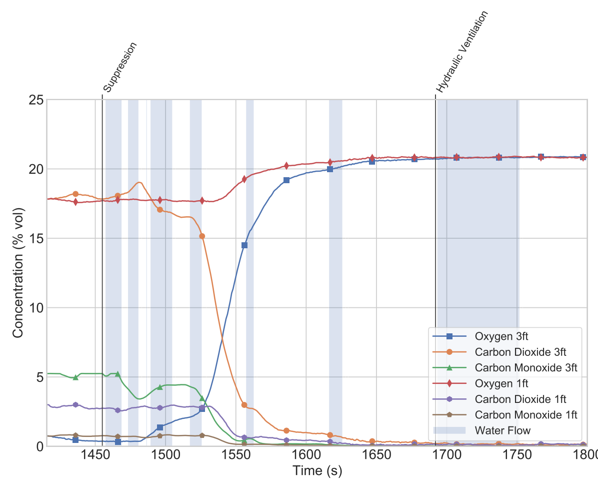
(a) Living Room Entryway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.114: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 18.

5.8.3 Bedroom 3

Figure 5.115 shows the time history of temperature in bedroom 3. The door between bedroom 3 and the hallway was open from the time of ignition, allowing products of combustion to fill the bedroom prior to intervention, resulting in elevated temperatures and toxic gas concentrations, particularly after the common space fire transitioned through flashover. At the time of intervention, temperatures ranged from 367 °C (693 °F) at the ceiling to 80 °C (176 °F) 1 ft above the floor. Temperatures began to decrease at all elevations immediately after the start of suppression. By the end of the initial fire control actions (50 s after intervention), temperatures ranged between 175 °C (347 °F) at the ceiling to 63 °C (145 °F) 1 ft above the floor. The lack of exterior vent local to bedroom 3 limited the efficiency at which combustion gases could be exchanged with air exterior.

Temperatures continued to decrease continued through hydraulic ventilation, at which point they ranged from 100 °C (212 °) to 40 °C (104 °F) throughout bedroom 3. Hydraulic ventilation did not substantially impact temperatures in bedroom 3 due to the lack of ventilation openings in the room.

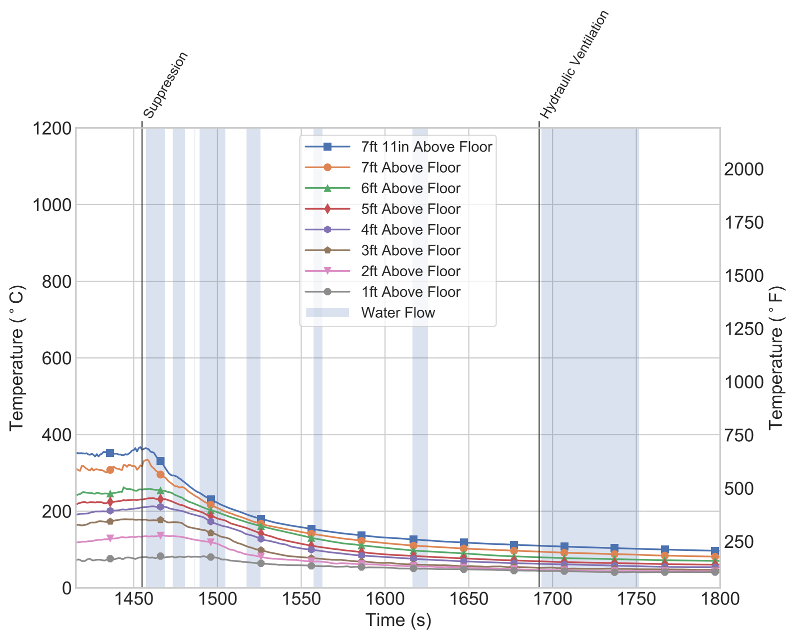
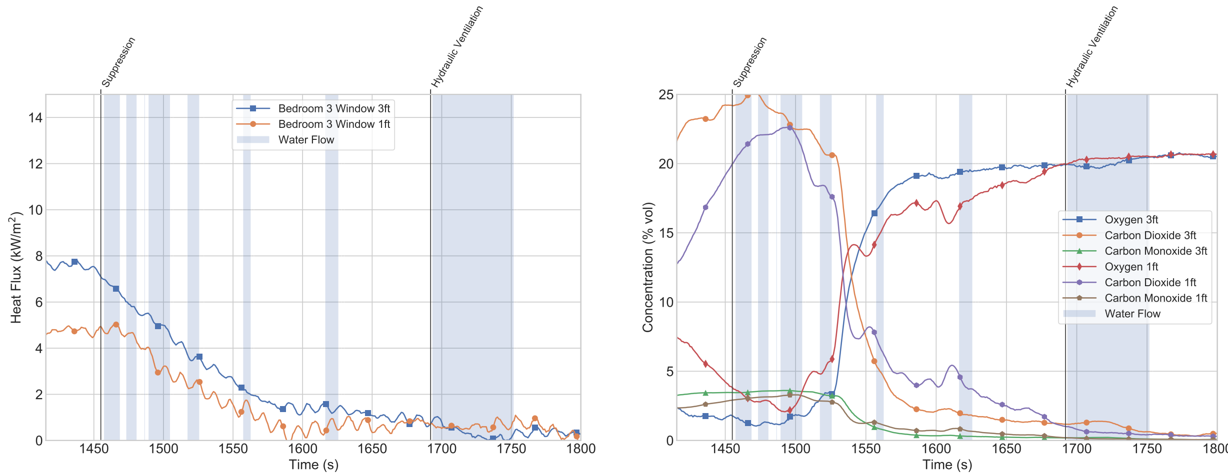


Figure 5.115: Post-intervention bedroom 3 temperature during Experiment 18.

Figure 5.116 shows the time histories of heat flux and gas concentrations measured in the bedroom 3 window. The heat fluxes measured 3 ft and 1 ft above the floor were 7.5 kW/m^2 and 4.9 kW/m^2, respectively. These elevated heat flux values are consistent with the elevated temperatures measured in bedroom 3 following flashover of the common space. Similar to the temperatures, heat flux at both elevations began to decrease immediately after the start of suppression, dropping to values of 4.2 kW/m^2 and 2.6 kW/m^2 at 3 ft and 1 ft, respectively, by the end of the initial fire control actions (50 s after intervention). The heat flux at both elevations continued to decreased through hydraulic ventilation, dropping below 0.5 kW/m^2 by the conclusion of the tactic.



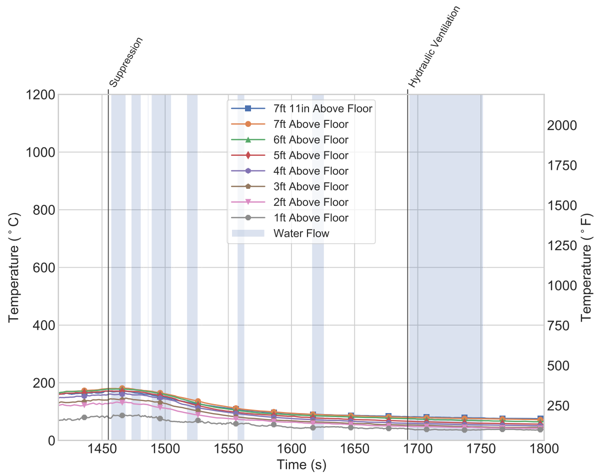
(a) Bedroom 3 Window Heat Flux

(b) Bedroom 3 Window Gas Concentration

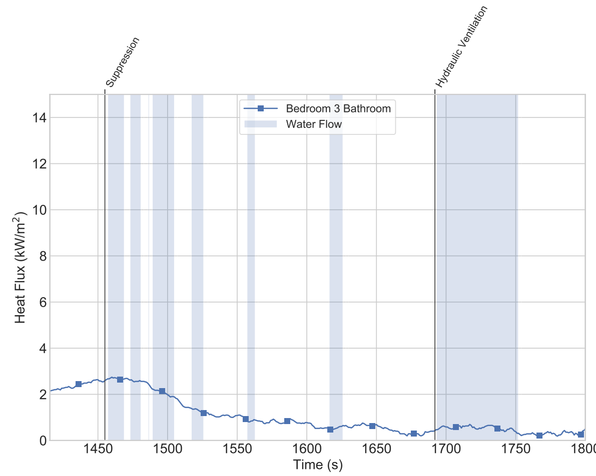
Figure 5.116: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 18.

Figure 5.116b shows the time histories of gas concentration at the bedroom 3 window measurement locations. At the time of intervention, gas concentrations were consistent with a smoke layer that had descended below the 1 ft measurement elevation. Gas concentrations were 1.8% O_2, 24.2% CO_2, and 3.5% CO 3 ft above the floor and 3.9% O_2, 19.8% CO_2, and 2.9% CO 1 ft above the floor. As suppression actions extinguished the fire, hot gases cooled, contracted, and began to exhaust through the available ventilation openings in the common space. This resulted in a decrease in CO and CO_2 concentrations and a recovery in O_2 concentrations at both elevations in bedroom 3 which occurred 75 s after intervention (1529 s after ignition). Initially the decrease in CO and CO_2 concentrations was sharp, the rate of exchange slowed due to the lack of ventilation in bedroom 3. Immediately prior to hydraulic ventilation, gas concentrations were 19.9% O_2, 1.2% CO_2, and 0.2% CO 3 ft above the floor and 20.0% O_2, 1.2% CO_2, and 0.2% CO 1 ft above the floor. Hydraulic ventilation did not noticeably impact gas concentrations in bedroom 3. CO and CO_2 concentrations remained elevated after the conclusion of hydraulic ventilation.

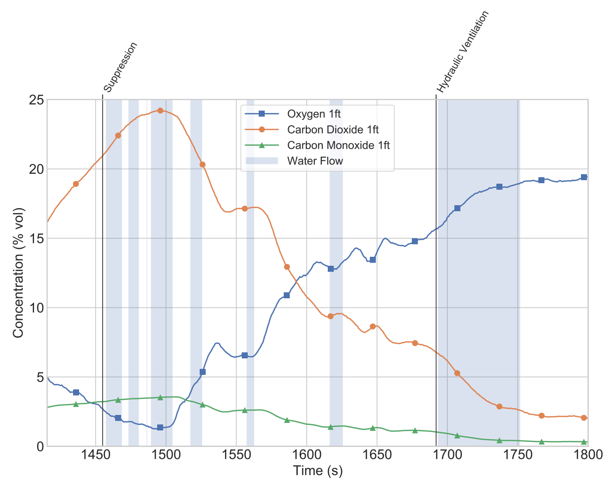
Figure 5.117 shows the time histories of temperature, heat flux, and gas concentration in bathroom 3. The temperature and heat flux values measured in bathroom 3 were similar to those in the adjacent bedroom, although the magnitude of temperature and heat flux peaks were generally lower. At the time of intervention, bathroom temperatures ranged from 180 °C (356 °F) at the ceiling to 85 °C (185 °F) 1 ft above the floor. The heat flux measured 1 ft above the floor was 2.6 kW/m^2. Temperatures and heat flux throughout the bathroom began to decrease immediately after the start of suppression, and continued to decrease through the start of hydraulic ventilation. Hydraulic ventilation did not have a noticeable impact on bathroom temperatures or heat flux.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



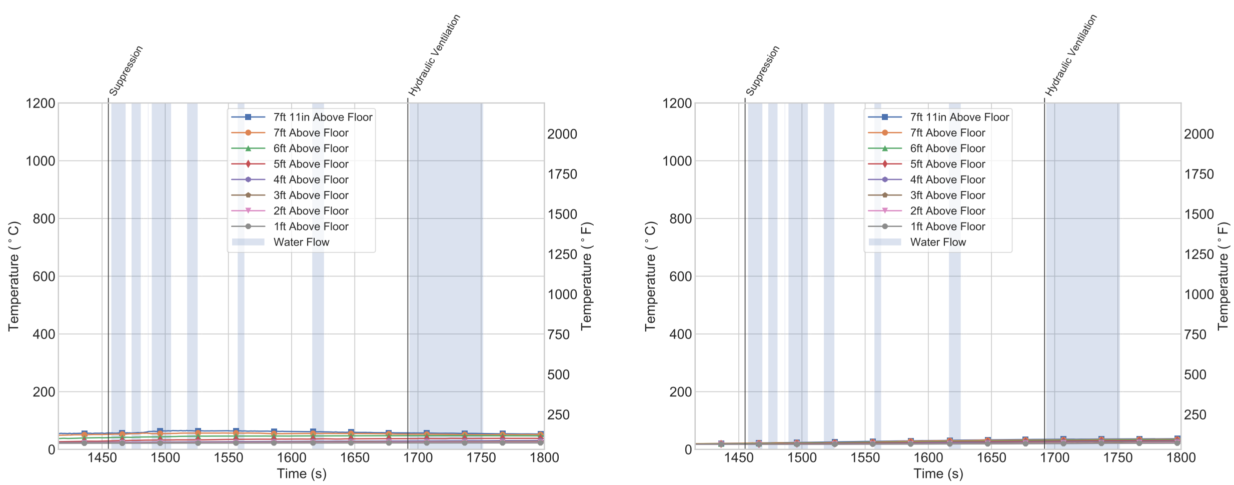
(c) Bathroom 3 Gas Concentration

Figure 5.117: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 18.

Gas concentrations in bathroom 3 at the time of intervention were consistent with a smoke layer that had descended below the 1 ft measurement elevation. O_2, CO_2, and CO concentrations at the beginning of suppression were 2.8%, 20.8%, and 3.2%, respectively. CO and CO_2 concentrations continued to increase for 41 s after the start of suppression, reaching a peak at a similar time to the 1 ft concentrations at the corresponding location in the adjacent bedroom. As suppression actions extinguished the fire, hot gases cooled and contracted and products of combustion began to exhaust through the available ventilation openings in the common space, resulting in a sharp decrease in CO and CO_2 concentrations and sharp increase in the O_2 concentration. Gas concentrations continued to trend toward ambient, but at a more gradual rate than in the adjacent bedroom, 75 s after intervention (1529 s after ignition). As temperatures dropped and correspondingly the pressure dropped, the driver for gas exchange was reduced and gases recovered progressively slower. Hydraulic ventilation accelerated the rate of change of these gas concentrations, but they remained elevated at the end of the action.

5.8.4 Bedroom 4

Figure 5.118 shows the time history of temperatures in bedroom 4 and the bedroom 4 closet. In contrast to bedroom 3, the door between bedroom 4 and the hallway was closed for the duration of the experiment. As a result, the room was isolated from the flow of products of combustion in the hallway, which resulted in lower temperatures at the time of intervention than in bedroom 3. Prior to suppression, temperatures ranged from 57 °C (135 °F) at the ceiling to 22 °C (72 °F) 1 ft above the floor. Temperatures continued to increase after suppression was initiated as products of combustion continued to leak into bedroom 4 around the closed door. Ceiling temperatures reached a peak of 65 °C (149 °F) approximately 75 s after intervention (1538 s after ignition). Temperatures remained steady through hydraulic ventilation, as the closed bedroom door prevented gas exchange with the rest of the structure. Since the door between bedroom 4 and the bedroom 4 closet was also closed from the beginning of the experiment, temperatures remained less than 40 °C (104 °F) for the duration of the experiment.



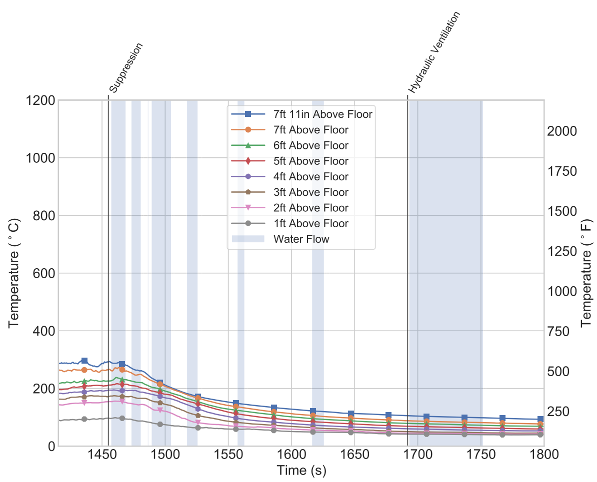
(a) Bedroom 4 Temperature

(b) Bedroom 4 Closet

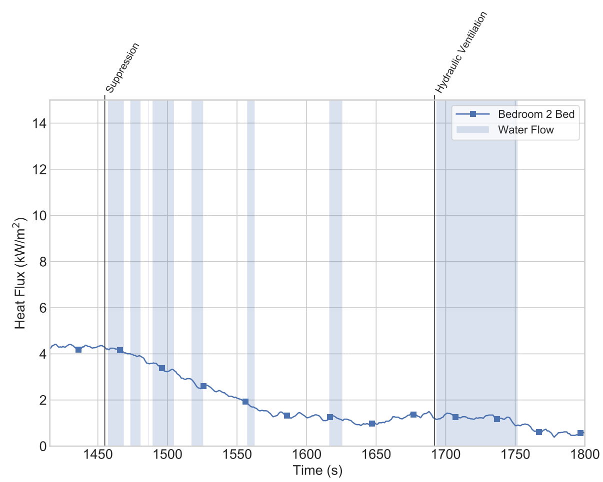
Figure 5.118: Bedroom 4 and bedroom 4 closet temperature time histories for Experiment 18.

5.8.5 Bedroom 2

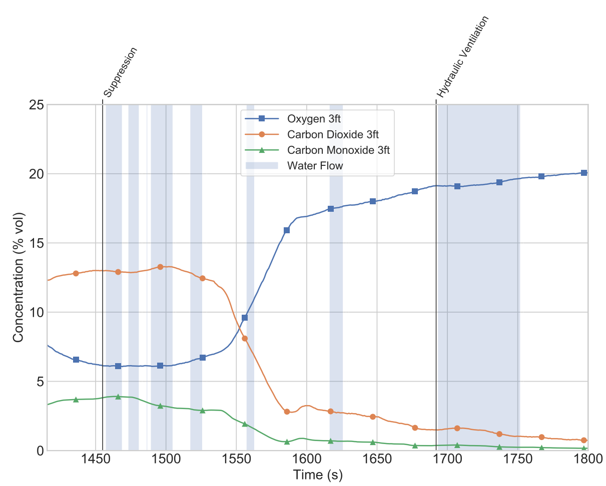
Figure 5.119 shows the time histories of temperature, heat flux, and gas concentration in bedroom 2. Similarly to bedroom 3, the door between bedroom 2 and the hallway was open from the time of ignition, which allowed products of combustion to fill the bedroom prior to intervention. This resulted in elevated temperatures and toxic gas concentrations, particularly after the common space fire transitioned through flashover. At the time of intervention, temperatures ranged from 292 °C (558 °F) at the ceiling to 97 °C (207 °F) 1 ft above the floor. Ceiling temperatures were slightly lower than those measured in bedroom 3 at that time due to the further distance from the common space. Temperatures began to decrease at all elevations immediately after the start of suppression. By the end of the initial fire control actions (50 s after intervention), temperatures had decreased below 200 °C (392 °F) at all elevations. This decrease is consistent with the one observed in bedroom 3, and continued through the start of hydraulic ventilation, at which point temperatures were less than 105 °C (221 °F) throughout bedroom 2. Hydraulic ventilation did not substantially impact temperatures in bedroom 2 due to the lack of ventilation openings in the room.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



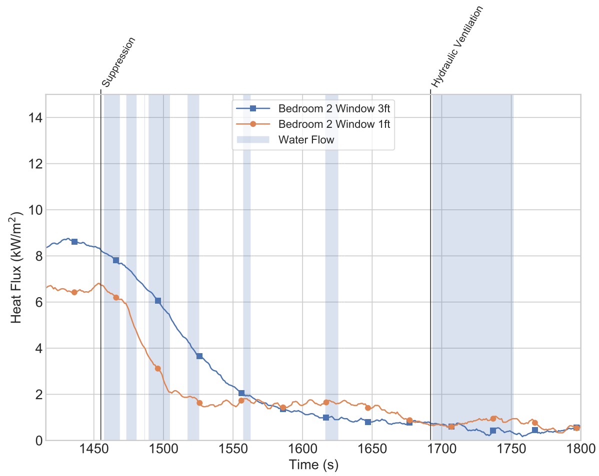
(c) Bedroom 2 Gas Concentration

Figure 5.119: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 2 during Experiment 18.

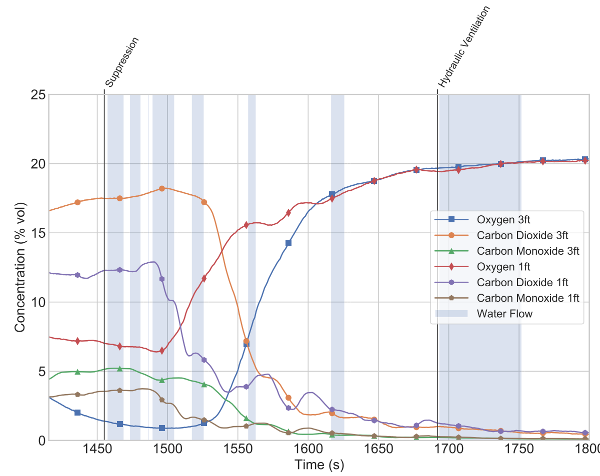
Heat flux (Figure 5.119b) and gas concentrations (Figure 5.119c) were sampled 3 ft above the bed in bedroom 2. Heat flux at this location trended similarly to temperature. At the time of intervention, the heat flux was 4.5 kW/m^2. Immediately after the start of suppression, the heat flux began to decrease due to the lack of combustion gas flow within the space, reaching negligible values by the time that the common space fire was brought under control, approximately 50 s after intervention (1505 s after ignition).

Gas concentrations in bedroom 2 at the time of intervention were consistent with a smoke layer that had descended below the 3 ft measurement elevation. O_2, CO_2, and CO concentrations at the time of intervention were 6.1%, 13.0%, and 3.8%, respectively. These gas concentrations remained steady for approximately 80 s, before CO and CO_2 concentrations began to decrease and the O_2 concentration began to increase as suppression actions extinguished the common space fire. The rate of this decrease in CO and CO_2 was rapid at first, but became more gradual approximately 135 s after intervention as products of combustion remained in bedroom 2 due to a lack of ventilation local to the space. Immediately prior to the start of hydraulic ventilation, O_2, CO_2, and CO concentrations were 19.1%, 1.5%, and 0.4%, respectively. Hydraulic ventilation did not have a noticeable impact on gas concentrations, with CO and CO_2 concentrations remaining elevated after the end of hydraulic ventilation.

Figure 5.120 shows the time histories of heat flux and gas concentrations measured in the bedroom 2 window during Experiment 18. The heat fluxes measured 3 ft and 1 ft above the floor were 8.4 kW/m^2 and 6.7 kW/m^2, respectively. These elevated heat flux values are consistent with the elevated temperatures measured in bedroom 2 following flashover of the common space, although the 3 ft window heat flux was higher than the one measured at the 3 ft bed location. This difference were driven by location; the window heat flux location was in-line with the open door compared to being offset on the bed and therefore was exposed to higher velocity gas flow. Similar to the temperatures, heat flux at both elevations began to decrease immediately after the start of suppression, dropping to values of 3.7 kW/m^2 and 1.8 kW/m^2 at 3 ft and 1 ft, respectively, by the end of suppression (50 s after intervention). Heat flux at both elevations continued to decrease to negligible values prior to the start of hydraulic ventilation.



(a) Bedroom 2 Window Heat Flux



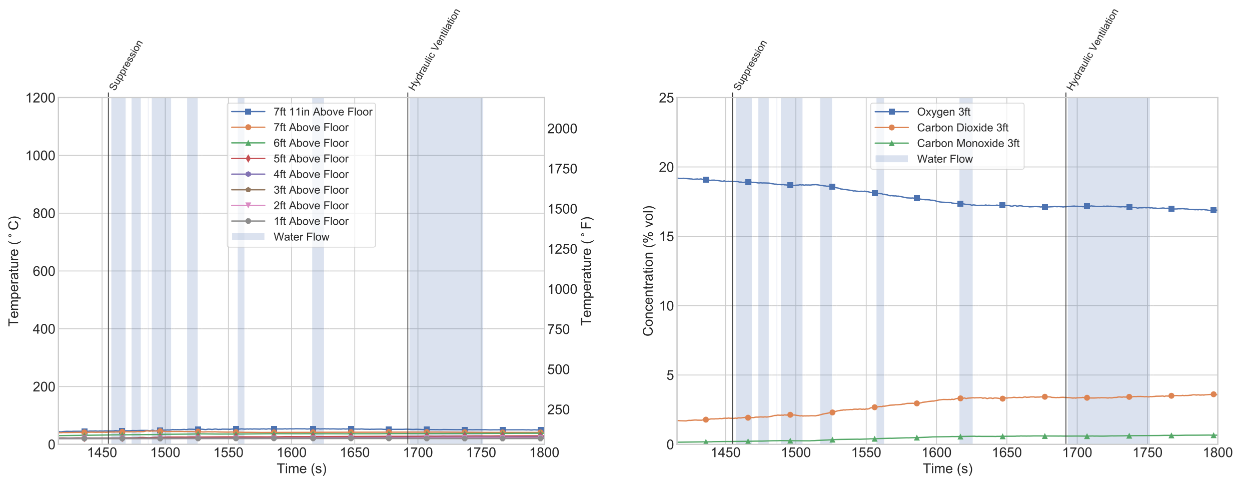
(b) Bedroom 2 Window Gas Concentration

Figure 5.120: Post-intervention heat flux and gas concentration measurements in the bedroom 2 window during Experiment 18.

Figure 5.120b shows the time histories of gas concentration at the bedroom 2 window measurement locations. At the time of intervention, gas concentrations were consistent with a smoke layer that had descended below the 1 ft measurement elevation. Gas concentrations were 1.4% O_2, 17.5% CO_2, and 5.1% CO 3 ft above the floor and 7.1% O_2, 12.3% CO_2, and 3.5% CO 1 ft above the floor. After suppression was initiated, CO and CO_2 continued to increase and O_2 continued to decrease for 72 s and 34 s at the 3 ft and 1 ft elevations, respectively. As suppression actions extinguished the fire, the higher temperature gases began to exhaust through the available ventilation openings in the common space. This resulted in a sharp decrease in CO and CO_2 concentrations and a recovery in O_2 concentrations at both elevations in bedroom 2. Although this initial decrease in CO and CO_2 concentrations was rapid, the lack of ventilation in bedroom 2 caused the rate of decrease to slow. Immediately prior to hydraulic ventilation, gas concentrations were 19.7% O_2, 1.0% CO_2, and 0.2% CO 3 ft above the floor and 19.4% O_2, 1.3% CO_2, and 0.3% CO 1 ft above the floor. Hydraulic ventilation did not noticeably impact gas concentrations in bedroom 2. CO and CO_2 concentrations remained elevated well after the conclusion of hydraulic ventilation.

5.8.6 Bedroom 1

Figure 5.121 shows the time history of temperatures, heat flux, and gas concentration in bedroom 1. In contrast to bedrooms 2 and 3, the door between bedroom 1 and the hallway was closed for the duration of the experiment. As a result, the room was isolated from the flow of products of combustion in the hallway, resulting in considerably lower temperatures at the time of intervention than in bedroom 3. Immediately before the start of suppression, temperatures ranged from 46 °C (115 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor. These temperatures were comparable to those measured in bedroom 4, which was also closed during the experiment. Temperatures continued to increase after suppression was initiated as products of combustion continued to leak into bedroom 4 around the closed door. Ceiling temperatures reached a peak of 55 °C (131 °F) approximately 75 s after intervention (1538 s after ignition). Temperatures remained steady through hydraulic ventilation, as the closed bedroom door prevented gas exchange with the rest of the structure.



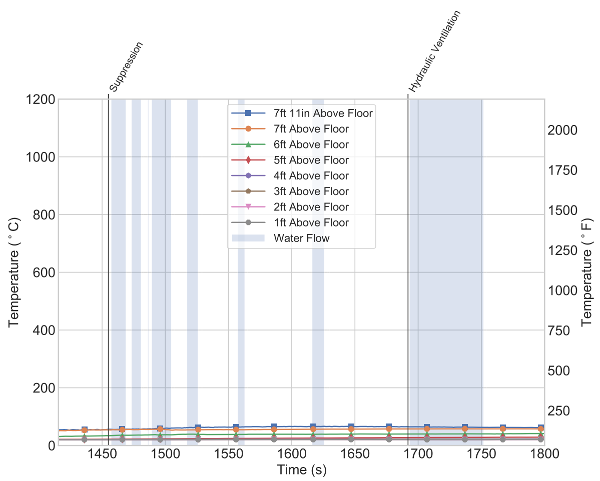
(a) Bedroom 1 Temperature

(b) Bedroom 1 Gas Concentration

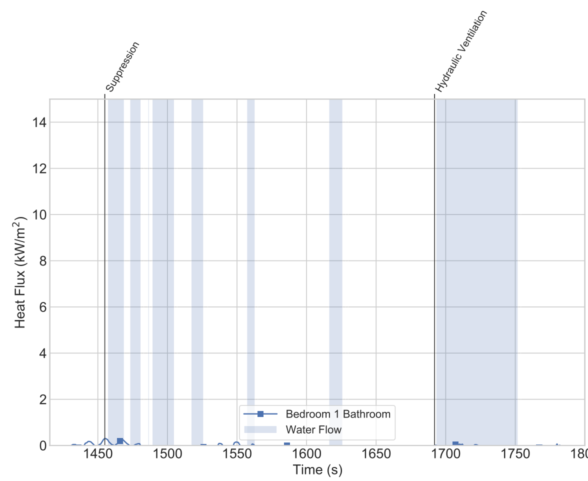
Figure 5.121: Post-intervention temperature and gas concentration measurements in bedroom 1 during Experiment 18.

Figure 5.121b shows the time histories of gas concentration in bedroom 1 during Experiment 18. Since the door between bedroom 1 and the hallway was closed for the duration of the experiment, CO and CO_2 concentrations at the time of intervention were considerably lower than at the corresponding location in bedroom 2. O_2, CO_2, and CO concentrations were 19.0%, 1.9%, 0.2%, respectively, immediately prior to intervention. CO and CO_2 concentrations continued to increase while the O_2 concentration continued to decrease through suppression as products of combustion from the hallway leaked around the closed door. Although the closed door restricted products of combustion from flowing into bedroom 1 from the hallway in the period prior to intervention, it also prevented gas exchange with the rest of the structure after suppression had extinguished the common space fire. As a result, gas concentrations gradually plateaued to a steady state, with no noticeable impact from the hydraulic ventilation action. At the end of hydraulic ventilation, O_2, CO_2, and CO concentrations were steady at 17.1%, 3.4%, and 0.6%, respectively.

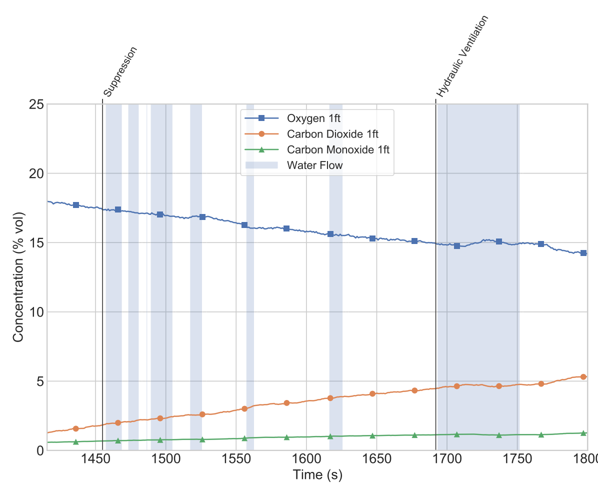
Figure 5.122 shows the time histories of temperature, heat flux, and gas concentrations measured in bathroom 1 during Experiment 18. The door between bedroom 1 and bathroom 1 remained closed for the duration of the experiment. As a result, the only routes for products of combustion to flow into bathroom 1 were via leakage around the closed door and through the HVAC supply located in the bathroom. Peak temperatures in bathroom 1 were comparable to those observed in other closed rooms in the structure. At the time of intervention, temperatures ranged from 56 °C (133 °F) at the ceiling to 20 °C (68 °F) 1 ft above the floor. Temperatures below 6 ft exhibited negligible increases prior to the start of suppression. Bathroom temperatures trended similarly to those in bedroom 1, with ceiling temperatures gradually increasing to a peak of 65 °C (149 °F). Temperatures at all elevations maintained steady values through hydraulic ventilation. As a result of the comparatively low peak temperatures due to the closed bathroom 1 door, heat flux measured 1 ft above the floor (Figure 5.122b) remained below 1.0 kW/m^2 for the duration of the experiment.



(a) Bathroom 1 Temperature



(b) Bathroom 1 Heat Flux



(c) Bathroom 1 Gas Concentration

Figure 5.122: Post-intervention temperature, heat flux and gas concentration measurements in bathroom 1 during Experiment 18.

Figure 5.122c shows the time histories of gas concentration in bathroom 1. CO and CO_2 concentrations at the time of intervention were higher than those observed in bedroom 1 despite being at the 1 ft elevation compared to the 3 ft elevation. The smoke layer dropped to the floor earlier due to the small volume of the bathroom. These values, however, were still considerably lower than those observed in open areas of the structure. O_2, CO_2, and CO concentrations at intervention were 17.4%, 1.8%, 0.7%, respectively. CO and CO_2 concentrations continued to increase while the O_2 concentration continued to decrease through suppression as products of combustion from the hallway leaked into the room around the closed door and via the HVAC supply. Although the closed doors restricted products of combustion from flowing into bedroom 1 from the hallway and then into bathroom 1 in the period prior to intervention, it also prevented gas exchange with the rest of the structure after suppression had extinguished the common space fire. As a result, gas concentrations gradually plateaued to a steady state, with no noticeable impact from the hydraulic ventilation action. At the end of hydraulic ventilation, O_2, CO_2, and CO concentrations were steady at 14.9%, 4.8%, and 1.1%, respectively.

5.9 Experiment 19

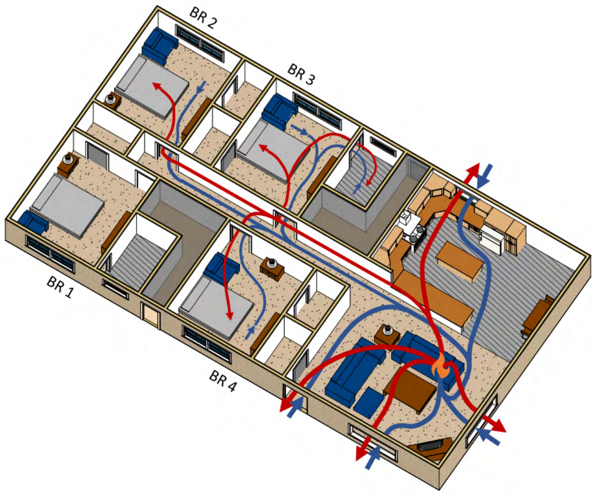
The search tactics in Experiment 19 were designed to evaluate window initiated operations conducted prior to interior suppression of a living room fire. Table 5.17 lists intervention times. At the time of ignition, the bottom pane of the kitchen window and the front door were opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2, 3, and 4 were opened. The fire was ignited in the side D corner of the sofa parallel to the front wall of the house. The fire then spread through the living room, where failure of the side A and side D windows occurred following flashover. Post-flashover of the living room, crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. The crew in bedroom 3 first entered the bedroom and proceeded toward the door to the hallway, and then crossed the hallway to search bedroom 4. At the same time, the crew in bedroom 2 entered the bedroom and proceeded toward the hallway. This crew isolated bedroom 2 as they left and continued across the hallway to bedroom 1. The closed bedroom 1 door was opened to allow for crew entry. The crew closed the door behind them. Once isolated in bedroom 1, the crew proceeded to remove the bedroom 1 window. At this point the search tactic comparison was complete and suppression began with interior suppression with entry to the structure through the front door. 107 gallons of water were flowed during suppression. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side D living room windows. The total amount of water flowed during suppression and hydraulic ventilation was 449 gallons.

Table 5.17: Experiment 19 Event Times

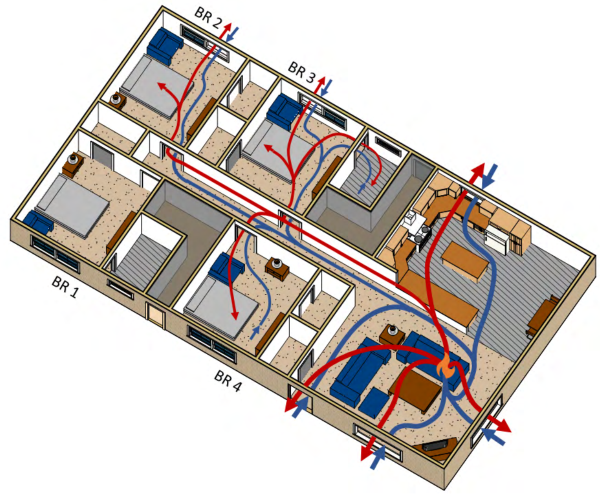
Event	Elapsed Time From Ignition (mm:ss)	(s)	From Intervention (mm:ss)	(s)
Ignition	0:00	0	—	—
Take BR2 & BR3 Windows	6:00	360	00:00	0
Close BR2 Door	6:45	405	00:45	45
Open BR1 Door	6:54	414	00:54	54
Close BR1 Door	7:04	424	01:04	64
Remove BR1 Window	7:18	438	01:18	78
Suppression	7:36	456	01:36	96
Hydraulic Ventilation	9:56	596	03:56	236

Figures 5.123 and 5.124 show the changes in flow in the period immediately preceding and following fire department intervention over the course of Experiment 19. At the time of intervention in Experiment 19, the living room was in a post-flashover state. Bidirectional flows had been established through the kitchen window, the front door, and the side A and side D living room windows; fire and smoke exhausted through the top of the vents while cooler air was entrained through the lower portion of the vents (Figure 5.123a). The initial fire department intervention was the ventilation of the bedrooms 2 and 3 windows, which created two new exterior vents and established bidirectional flows through both bedrooms as shown in Figure 5.123b. Higher temperature gases

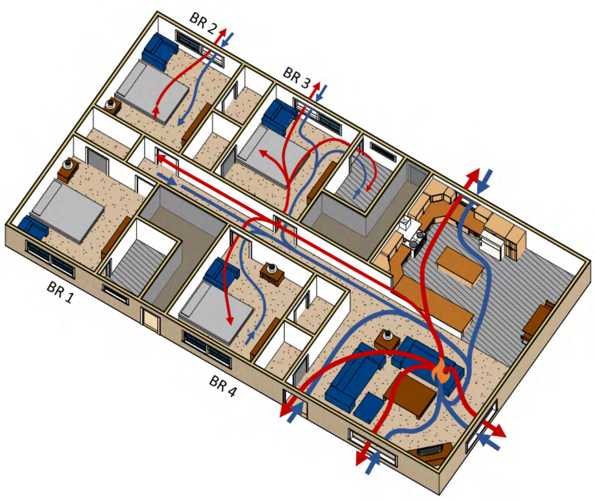
at the ceiling flowed from the hallway into the bedroom and exhausted through the upper portion of the bedroom window while cooler air was entrained through the lower portion of the bedroom window and flowed along the floor through the bedroom toward the common space fire. In bedroom 3, this bidirectional flow was maintained for the duration of the experiment. Conversely, in bedroom 2, the door between the hallway and the room was closed 45 s after intervention. This action isolated bedroom 2 from the products of combustion in the hallway and established a new flow path, with the bedroom 2 window acting as both the intake and exhaust, as shown in Figure 5.123c. This allowed smoke that was already trapped in bedroom 2 to exhaust to the exterior of the structure. After the bedroom 2 door was closed, the bedroom 1 door was opened, simulating a firefighter searching across the hallway from bedroom 2. This briefly established bidirectional flow into bedroom 1, as shown in Figure 5.123d. Products of combustion from the hallway flowed into bedroom 1 and air from bedroom 1 flowed into the hallway.



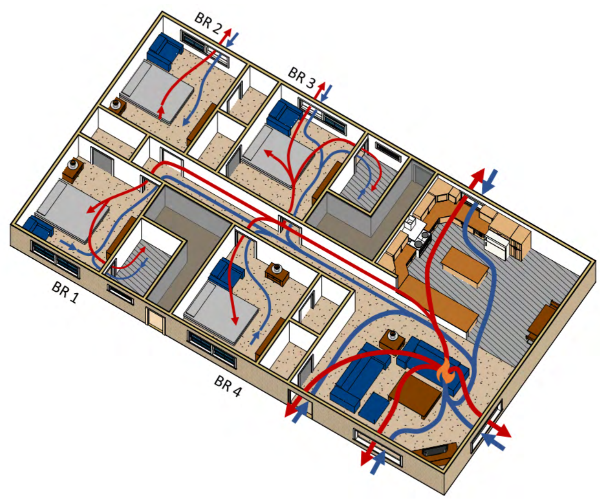
(a) Flows Prior to Intervention



(b) Take BR2 & BR3 Windows



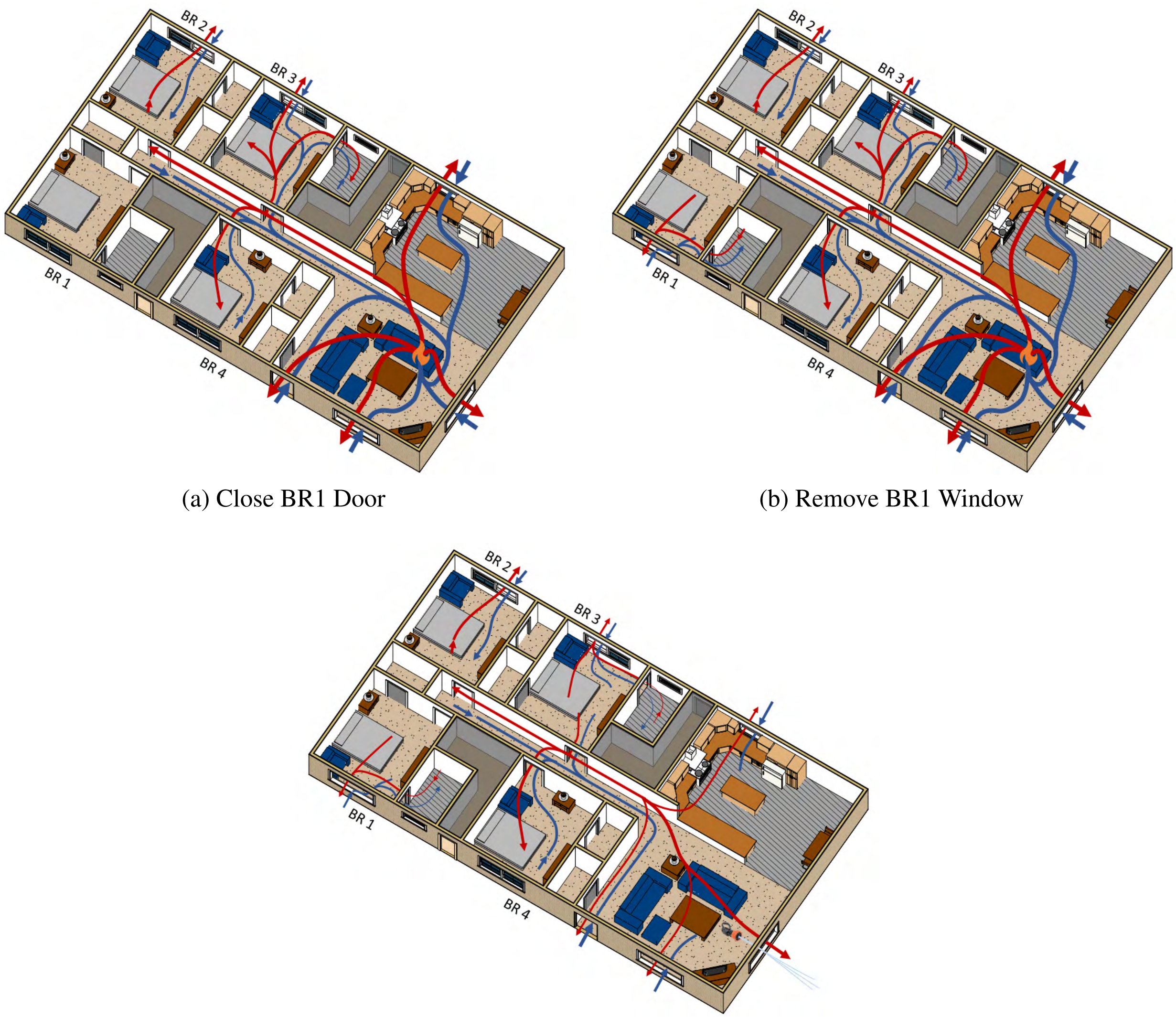
(c) Close BR2 Door



(d) Open BR1 Door

Figure 5.123: Changes in gas flows in the structure following fire department interventions in Experiment 19.

The bedroom 1 door was closed again 10 s later which stopped gas exchange to the hallway as shown in Figure 5.124a. The products of combustion which had flowed into bedroom 1 in the period between opening and closing the door were trapped in the space until 14 s later, when the bedroom 1 window was removed. This created a new flow path which allowed trapped smoke to exhaust through the upper portion of the window and air to flow through the lower portion of the window (Figure 5.124b). After the search sequence was completed, the suppression crew initiated suppression from side A, using a flow-and-move technique with 1 3/4 in. handline equipped with a combination nozzle set to flow a straight stream at 150 gpm. After the the living room fire had been brought under control, the suppression crew began hydraulic ventilation with a narrow-fog stream and fixed pattern through the side D living room window. This action reduced the pressure at the living room window and drew products of combustion from remote locations in the structure toward the living room (Figure 5.124c).



(a) Close BR1 Door

(b) Remove BR1 Window

(c) Hydraulic Ventilation

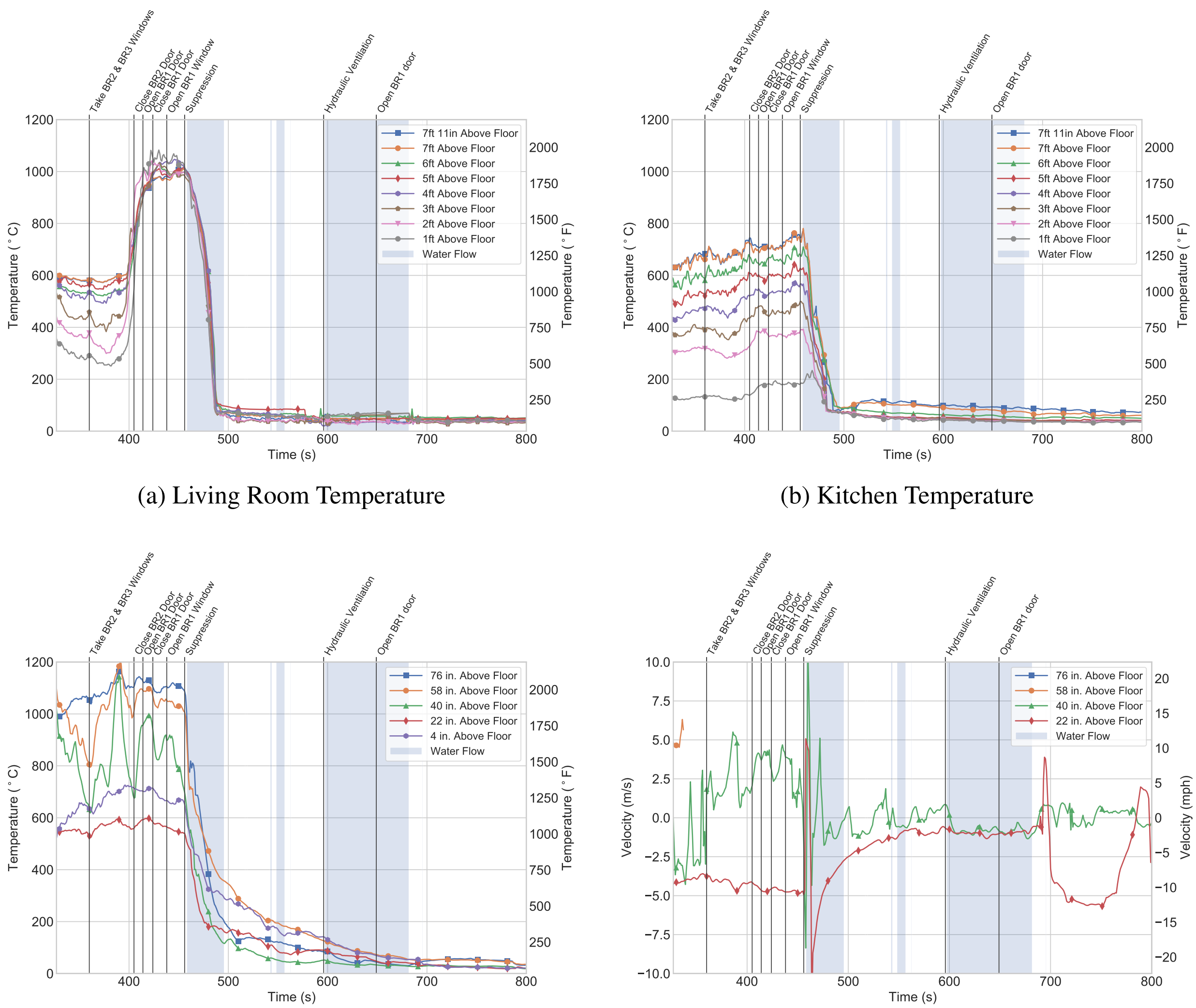
Figure 5.124: Changes in gas flows in the structure following fire department interventions in Experiment 19.

5.9.1 Common Space

Figure 5.125 shows the time histories of temperature in the living room and kitchen and temperatures and velocities recorded in the front door. Prior to intervention, the living room fire had transitioned through flashover and had been burning in a post-flashover state, causing failure of the side A and side D living room windows. Temperatures at the measurement location in the center of the living room (Figure 5.125a) had decreased following flashover and were stratified between 580 °C (1076 °F) at the ceiling and 280 °C (536 °F) 1 ft above the floor. These lower temperatures were caused by a lack of oxygen in the center of the living room, which inhibited burning and thus locally decreased temperatures. Living room temperatures began to increase again approximately 35 s after intervention (400 s after ignition), when the new exhaust vents in the bedrooms allowed additional combustion products to exhaust the structure and subsequently additional air to be entrained through the living room vents. The additional ventilation increased the heat release rate of the living room fire. Living room temperatures increased uniformly above 1000 °C (1832 °F) until the beginning of suppression.

Kitchen temperatures were stratified at the time of intervention, as shown in Figure 5.111a, and ranged from 683 °C (1261 °F) at the ceiling to 133 °C (271 °F) 1 ft above the floor. Temperatures remained steady through the ventilation actions in the bedroom. The small vent area and high window sill height made the kitchen window an inefficient vent. As a result, there was insufficient oxygen available to support flaming combustion.

Suppression was initiated 96 s after intervention (456 s after ignition). Temperatures in the kitchen and living room began to decrease immediately after the start of suppression, dropping below 100 °C (212 °F) prior to the conclusion of the suppression action. At the time of intervention, temperatures at the front door ranged from 1053 °C to 530 °C (1927 °F to 986 °F) from top to bottom (Figure 5.125c). Although some sensors were damaged during the experiment, the remaining probes showed exhaust flow 40 in. above the ground between 7 m/s to 1.5 m/s (15.7 mph to 3.4 mph) until suppression. The probe at 22 in. showed consistent inflow between -4 m/s to -5 m/s (-8.9 mph to -11.2 mph). The bidirectional flow remained until suppression, at which point actions of the suppression crew compromised the measurement accuracy for the remaining duration of the experiment (Figure 5.125d).



(a) Living Room Temperature

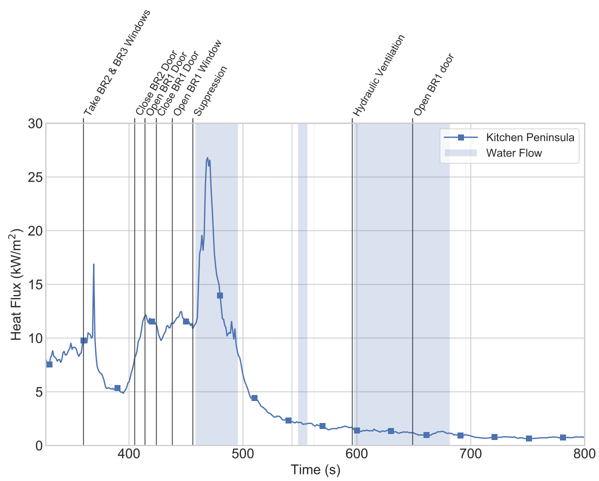
(b) Kitchen Temperature

(c) Front Doorway Temperature

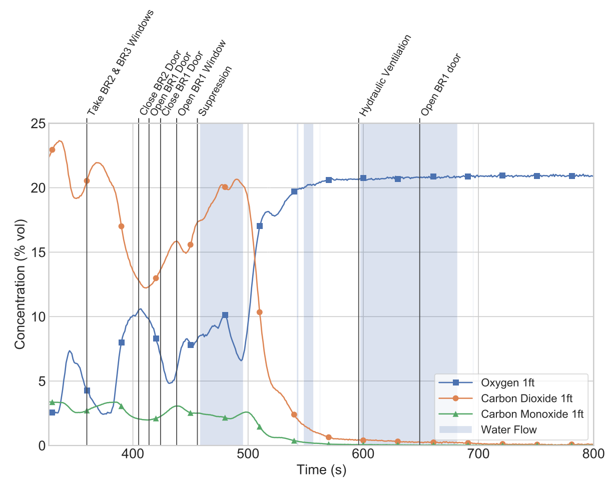
(d) Front Doorway Velocity

Figure 5.125: Post-intervention common space temperatures, front doorway temperatures, and front door velocities in the common space in Experiment 19.

Measurements of heat flux and gas concentration were at the 1 ft elevation in the kitchen between the kitchen island and kitchen peninsula (Figure 5.126). Prior to the ventilation of the bedroom 2 and 3 windows, the kitchen heat flux had steadily increased from 7.5 kW/m^2 to 9.8 kW/m^2 (Figure 5.126a). There was a 1 s spike in heat flux to 16.9 kW/m^2, 9 s after intervention, though it is not clear exactly what caused this spike as it was opposite of the observed trend. Over the first 30 s following intervention, the open bedroom vents led to decrease in heat flux as there was a decrease in gas flow through the open kitchen widow and therefore, over top the heat flux gauge. The heat flux dropped to 4.9 kW/m^2 before increasing to a nominally steady value of approximately 12 kW/m^2. This rise was associated with the increase in heat release of the fire. The heat flux then reached a peak of 26.8 kW/m^2 within the first 10 s of suppression. At this point the suppression crew used an O-pattern to knock down the fire at the front door and side A living room window to cool gases to make entry to the living room. The water flow entrained air and therefore displaced air ahead of the stream. This led to increased gas flow through the kitchen window. Despite the temperature drop shown in Figure 5.125b, the heat flux temporarily increased due to the increased gas flow velocity. Heat flux dropped following the completion of suppression and continued to decrease through hydraulic ventilation.



(a) Kitchen Heat Flux



(b) Kitchen Gas Concentrations

Figure 5.126: Post-intervention heat flux and gas concentrations in the kitchen in Experiment 19.

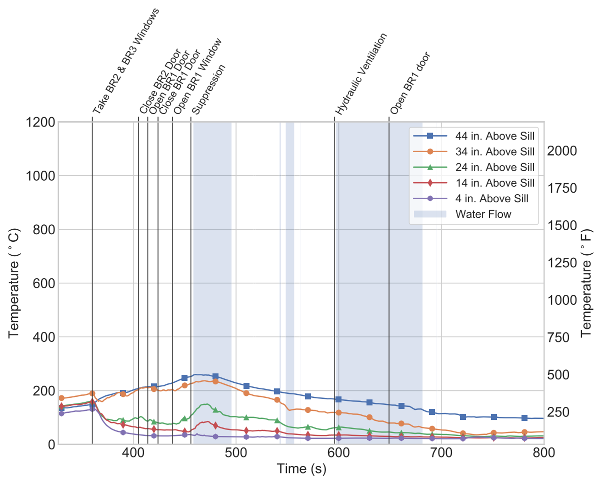
The kitchen gas concentrations had a similar response profile to the co-located heat flux (Figure 5.126b). At the time of intervention, gas concentrations at the kitchen location were characterized by high concentrations of CO and CO_2 and low concentrations of O_2, indicating that the smoke layer had descended past the 1 ft measurement location. O_2, CO_2, and CO concentrations were 4.3%, 20.5%, and 2.7%, respectively. Concentrations continued to increase for the first 10 s following intervention, before a recovery toward pre-ignition levels occurred over the next 40 s. This temporary recovery was driven by the additional exterior vents in bedrooms which led to a decrease in flow out of the kitchen window. CO and CO_2 concentrations began to increase and O_2 began to decrease following the increased burning in the living room. This trend continued through the start of suppression as the initial suppression action increased gas flow through the kitchen window. Following suppression and hydraulic ventilation, gas concentrations returned to near pre-ignition levels. Concentrations did not recover completely as the measurement was taken between the kitchen island and peninsula which limited the efficiency of post-suppression gas flows.

5.9.2 Bedroom 3

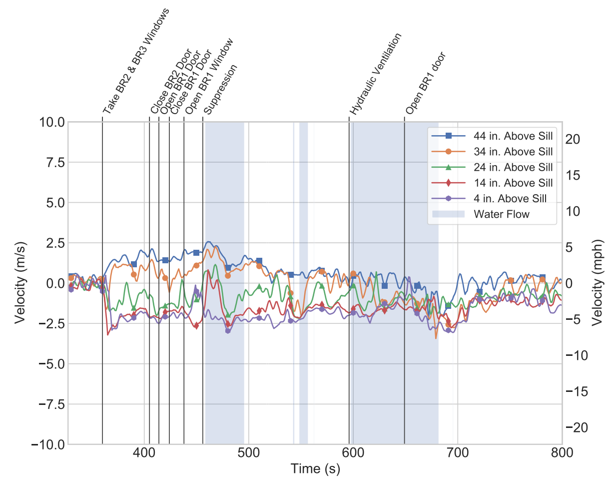
Figure 5.127 shows the time histories of temperature, velocity, heat flux, and gas concentrations measured at the bedroom 3 window. The door between bedroom 3 and the hallway was open from the time of ignition, which allowed products of combustion to fill the space as the living room fire grew and transitioned through flashover. The bedroom 3 window was vented simultaneous with the bedroom 2 window as part of the initial fire department intervention. At the time of intervention, the temperatures measured at the bedroom 3 window ranged from 189 °C to 129 °C (372 °F to 264 °F) from top to bottom at the window. Figure 5.127a shows that immediately following ventilation of the bedroom 3 window, the upper two measurement locations (44 in. and 34 in. above the sill) recorded a temperature increase, while the lower three measurement locations (24 in., 14 in. and 4 in. above the still) recorded a temperature decrease. Bidirectional flow was established in the window. Hot gases exhausted through the upper portion of the window and air was entrained through the lower portion. Peak exhaust velocities ranged from 2.4 m/s to 1.8 m/s (5.4 mph to 4.0 mph), while entrainment velocities ranged from -3.0 m/s to -1.8 m/s (-6.7 mph to -4.0 mph), as shown in Figure 5.34b. The bedroom 3 door remained open for the duration of the experiment, and the lack of door control resulted in sustained bidirectional flow through the bedroom 3 window until the onset of suppression. Exhaust and entrainment velocities remained relatively constant at their post-ventilation values. Exhaust temperatures continuously increased until the start of suppression. Approximately 15 s prior to the start of suppression, temperatures 24 in. and 14 in. above the sill began to increase as a result of the sustained flow of hot gases from the hallway. This increase continued for 15 s after suppression, after which suppression actions began to control the common space fire, causing temperatures at all elevations in the window to continuously decrease for the remainder of the experiment.

Prior to intervention, the heat flux measured at elevations 3 ft and 1 ft above the floor in the bedroom 3 window was increasing to values of 9.0 kW/m^2 and 5.4 kW/m^2, respectively (Figure 5.127c). After the window was ventilated, the flow of air through the lower portion of the bedroom 3 window had a cooling effect at the window measurement location, causing the heat flux at both elevations to decrease. Following this decrease, the heat flux at both elevations remained below 1.0 kW/m^2 until approximately 80 s after intervention (440 s after ignition), when the sustained high-temperature exhaust through the bedroom 3 window caused heat flux at 3 ft and 1 ft to increase to peaks of 4.3 kW/m^2 and 1.5 kW/m^2, respectively. Suppression caused heat flux at both elevations to decrease to negligible values.

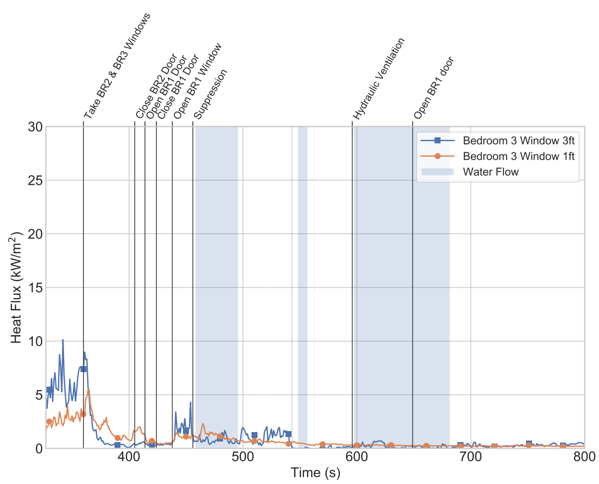
Figure 5.127d shows the time history of gas concentrations at the bedroom 3 window location. At the time of intervention, gas concentrations at the bedroom 3 measurement location were characterized by high concentrations of CO and CO_2 and low concentrations of O_2, indicating that the smoke layer had descended past the 1 ft measurement location. Gas concentrations were 5.3% O_2, 16.6% CO_2, and 2.6% CO at the 3 ft level and 9.1% O_2, 10.8% CO_2, and 1.9% CO at the 1 ft level. Immediately after ventilation, CO and CO_2 concentrations continued to increase for approximately 15 s, before air entrainment through the lower portion of the window resulted in a sharp decrease in CO and CO_2 and increase in the O_2 concentration. Following this improvement in conditions, gas concentrations remained relatively steady until the beginning of suppression, when CO and CO_2 concentrations at both measurement elevations increased to a local peak. Following this local peak, CO and CO_2 concentrations gradually decreased while O_2 increased, with gas concentrations returning to ambient conditions prior to the start of hydraulic ventilation.



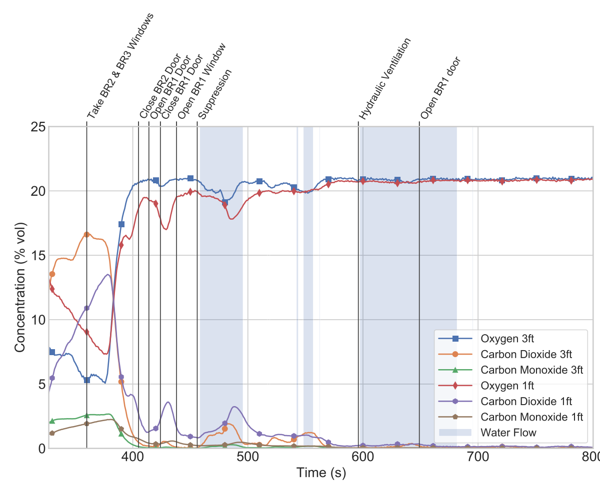
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



(d) Bedroom 3 Window Gas Concentration

Figure 5.127: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 19.

Figure 5.128 shows the time history of temperature in bedroom 3. At the time of intervention, temperatures in bedroom 3 were steady, ranging from 332 °C (630 °F) at the ceiling to 63 °C (145 °F) 1 ft above the floor. After the bedroom 3 window was ventilated, temperatures 4 ft and below began to decrease, as cool air flowed into the room through the lower portion of the window. Temperatures above 4 ft initially began to decrease, however they then increased as hot gases from the hallway flowed through bedroom 3 and out the upper portion of the window. The entrained air continued to have a cooling effect on temperatures close to the floor, which remained steady until the beginning of suppression. Temperatures in the upper half of the room continuously increased in the period preceding suppression, as hot gases continued to flow through the room. Temperatures at all elevations in the room began to decrease after the start of suppression. Temperatures had dropped below 150 °C (302 °F) at all elevations prior to the start of hydraulic ventilation.

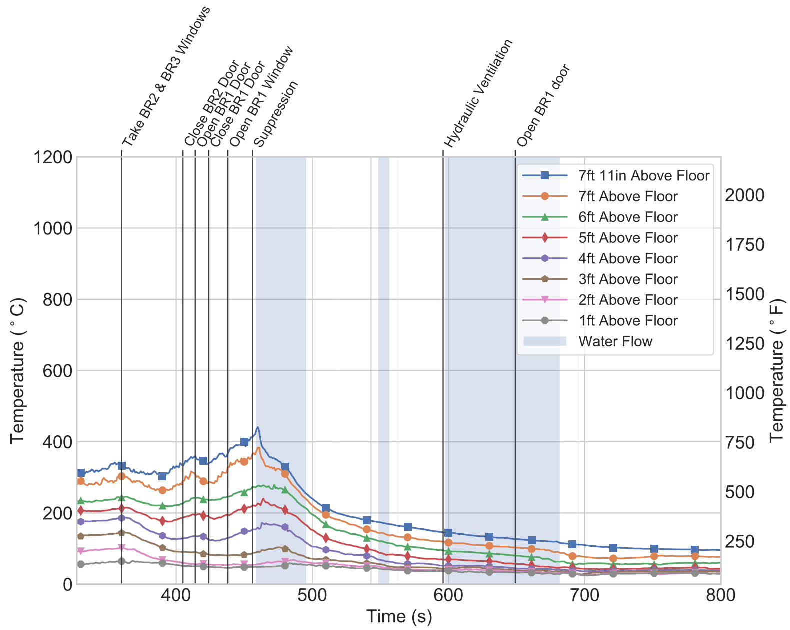
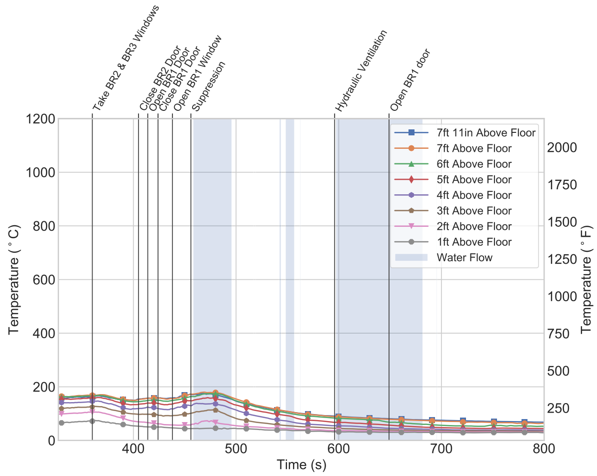
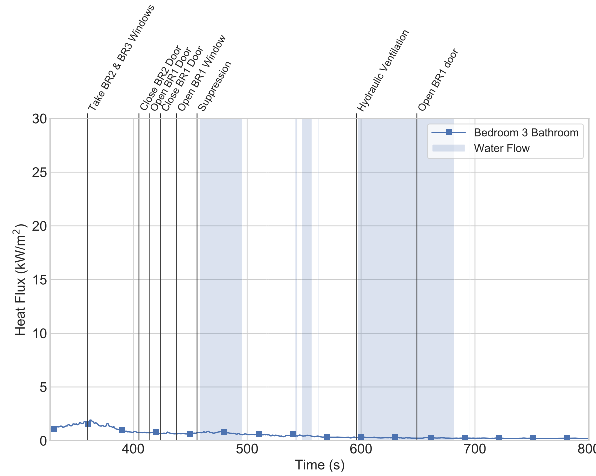


Figure 5.128: Post-intervention bedroom 3 temperature during Experiment 19.

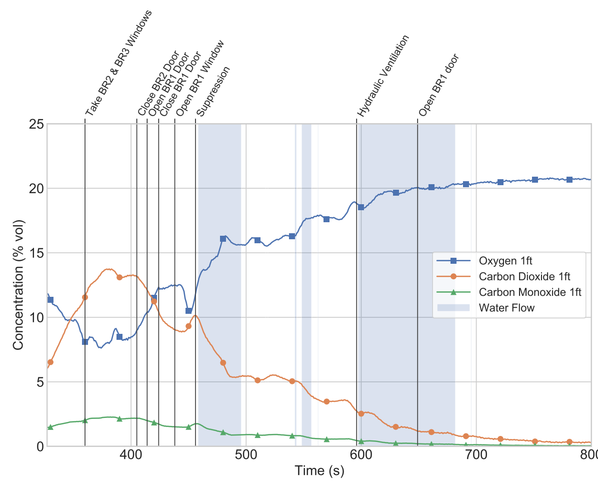
Figure 5.129 shows the time histories of temperature, heat flux, and gas concentration in bathroom 3. The door between bedroom 3 and bathroom 3 was open from ignition, allowing the bathroom to fill with products of combustion as the living room fire grew and transitioned through flashover. At the time of intervention, temperatures in the bathroom ranged from 168 °C (280 °F) at the ceiling to 72 °C (162 °F) 1 ft above the floor. Similar to the temperatures in the lower portion of bedroom 3, temperatures in bathroom 3 decreased following bedroom 3 window ventilation. This decrease continued until approximately 400 s after ignition, when temperatures above 3 ft in the bathroom began to increase. The timing of this increase matches the increase in heat release rate of the living room fire and subsequent increase in temperature of the hot gases flowing through bedroom 3. This increase continued until 115 s after intervention (475 s after ignition), when bathroom temperatures at all elevations began to decrease as suppression actions extinguished the living room fire. This decrease continued through hydraulic ventilation.



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

Figure 5.129: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 19.

Figure 5.129b shows the heat flux measured 1 ft above the floor in bathroom 3. The heat flux at the time of intervention was 1.9 kW/m^2, which is lower than at the corresponding elevation in the adjacent room. After ventilation of the bedroom 3 window, the heat flux at this location began to decrease as a result of the inlet flow through the window. This decrease slowed to a steady value of 0.8 kW/m^2 as the exchange of gases between the bedroom and bathroom slowed. The heat flux maintained this value until hydraulic ventilation was initiated, which caused the heat flux to further decrease to negligible values.

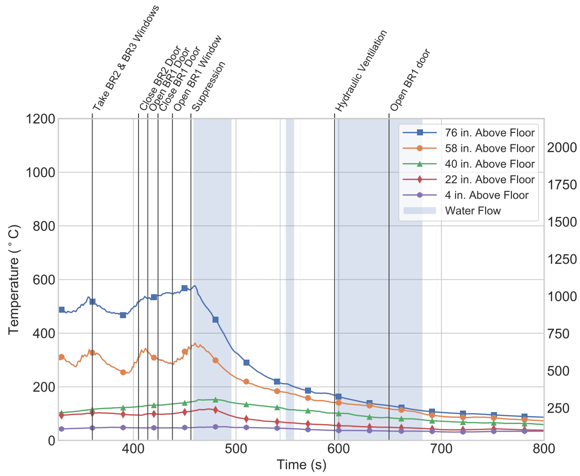
Figure 5.129c shows the time history of gas concentration in bathroom 3. At the time of intervention, O_2, CO_2, and CO concentrations were 8.1%, 11.6%, and 2.0%, respectively, which is comparable to the gas concentrations measured at the corresponding elevation in bedroom 3. Immediately after ventilation, CO and CO_2 concentrations continued to increase for approximately

20 s, before air entrainment through the lower portion of the window resulted in a decrease in CO and CO_2 and increase in the O_2 concentration. Gas concentrations continued to improve until 15 s before the beginning of suppression, when an increase in CO and CO_2 concentrations and sharp decrease in O_2 concentration was observed. This local peak corresponded with the peak in temperature in bedroom 3 and at the bedroom 3 window, and local heat flux spike observed at the bedroom 3 window measurement locations at the same time. Following this local peak, CO and CO_2 concentrations continued to decrease while O_2 increased, with gas concentrations returning to ambient conditions prior to the start of hydraulic ventilation.

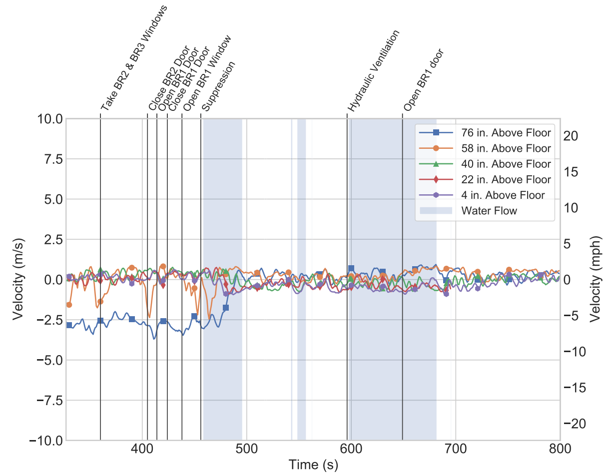
5.9.3 Bedroom 4

Figure 5.130c shows the time history of temperature and velocity at the bedroom 4 doorway and temperature in bedroom 4 and bedroom 4 closet. Like bedroom 3, the door between bedroom 4 and the hallway was open from the time of ignition, allowing the room to fill with products of combustion as the living room fire grew and transitioned through flashover. Figures 5.130a and 5.130b show combustion gases flowed into bedroom 4 near the top of the doorway (76 in. above the floor) at 535 °C (995 °F) and -2.5 m/s (5.6 mph) prior to intervention. The 58 in. location fluctuated between inflow and outflow while the bottom three elevations (40 in and below) indicated outflow (toward the living room) at approximately 0.5 m/s (1.1 mph). At the time of intervention, temperatures in bedroom 4 were steady, ranging from 237 °C (459 °F) at the ceiling to 74 °C (165 °F) 1 ft above the floor. Following the ventilation of the bedroom 2 and 3 windows, temperatures in bedroom 4 remained steady until approximately 40 s after intervention (400 s after ignition), when temperatures began to gradually increase. The timing of this increase corresponded with the temperature rise in the living room as the heat release rate of the fire increased due to the increased exhaust ventilation. This increase continued until approximately 20 s after the beginning of suppression, as the suppression crew began to advance into the living room to extinguish the living room fire. After peaking, temperatures at all elevations at the doorway and in the room continuously decreased. The magnitude of velocity at the doorway at all elevations fluctuated between $\pm$ 0.5 m/s (1.1 mph). Hydraulic ventilation had a limited impact on temperature and velocity because of the lack of a local exhaust vent in bedroom 4.

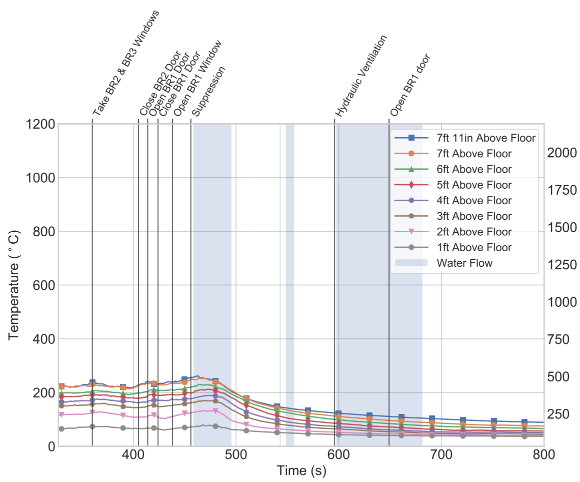
The door between bedroom 4 and the bedroom 4 closet remained closed for the duration of the experiment. This isolated the closet space from the flow of products of combustion from the hallway, resulting in considerably lower temperatures, as shown in Figure 5.130d. The peak ceiling temperature in the closet was 55 °C (131 °F), and was observed simultaneous with the start of suppression.



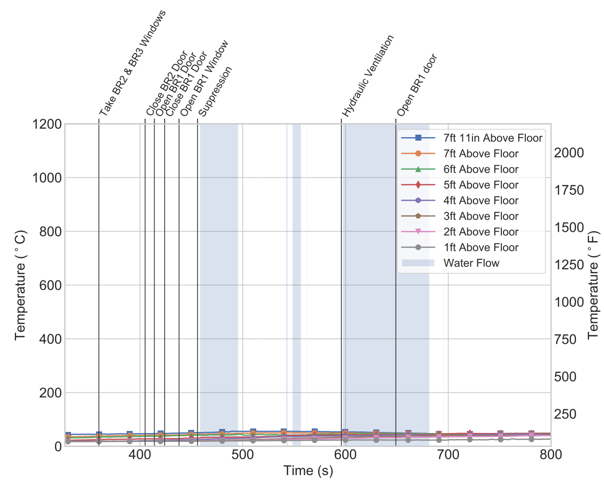
(a) Bedroom 4 Doorway Temperature



(b) Bedroom 4 Doorway Velocity



(c) Bedroom 4 Temperature

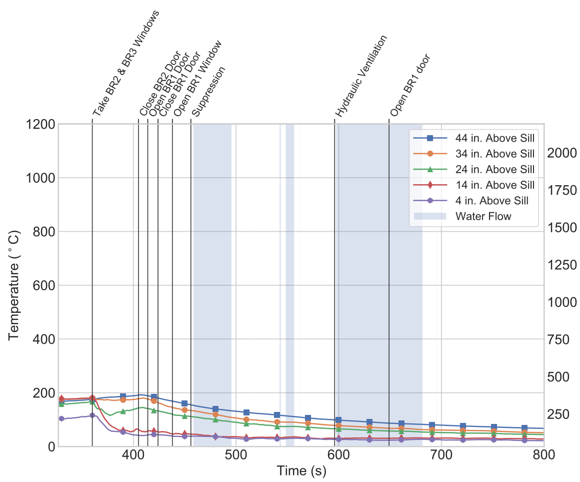


(d) Bedroom 4 Closet

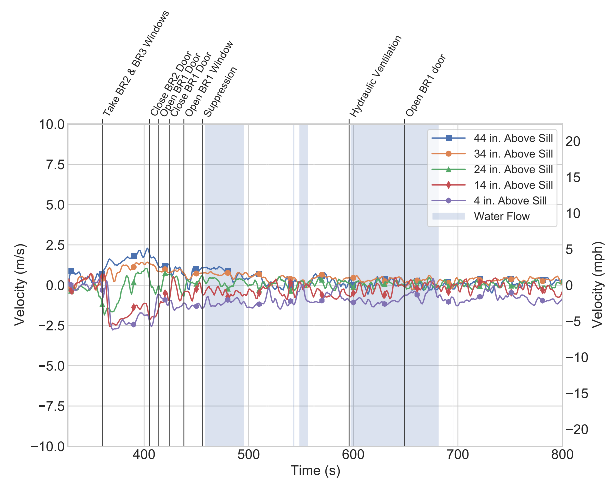
Figure 5.130: Bedroom 4 temperatures, doorway temperature, doorway velocity, gas concentrations, and heat flux time histories in bedroom 4 for Experiment 19.

5.9.4 Bedroom 2

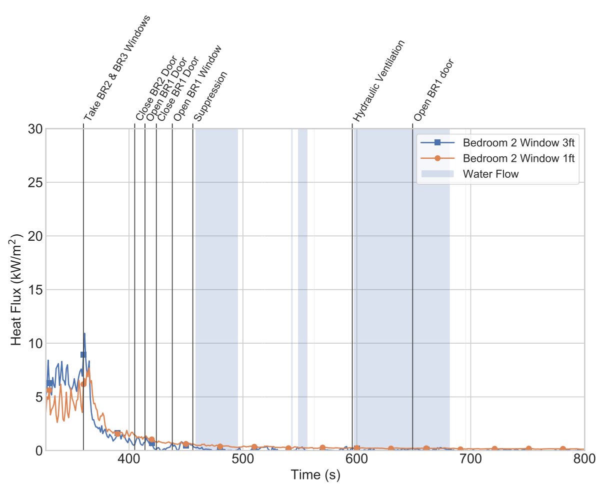
The initial fire department intervention in Experiment 19 was the ventilation of the bedroom 2 and 3 windows. The temperature, heat flux, velocity, and gas concentration measured at the bedroom 2 window are shown in Figure 5.131. Figure 5.131b shows bidirectional flow was established immediately following ventilation of the bedroom 2 window. Temperatures at the upper two measurement locations (44 in. and 34 in. above the sill) increased, while the lower two measurement locations (4 in. and 14 in.) decreased. The middle temperature measurement location (24 in.) decreased for the first 15 s after ventilation before beginning to increase. Figure 5.131b shows that peak exhaust velocities ranged from 2.4 m/s to 1.0 m/s (5.4 mph to 2.2 mph) and entrainment velocities ranged from -3.1 m/s to -0.8 m/s (-6.9 mph to -1.8 mph). Window velocities remained relatively steady in the period after the bedroom 2 window was vented while exhaust temperatures steadily increased to peaks (which occurred when the bedroom 2 door was closed) ranging from 191 °C to 142 °C (376 °F to 288 °F). This action isolated bedroom 2 from the flow of hot gases from the hallway, and resulted in a decrease in exhaust temperatures and exhaust velocities. Exhaust velocities and temperatures continuously decreased as trapped smoke vented through the open window and was replaced with air. No substantial change in window velocity was observed during hydraulic ventilation in bedroom 2 as a result of the closed door.



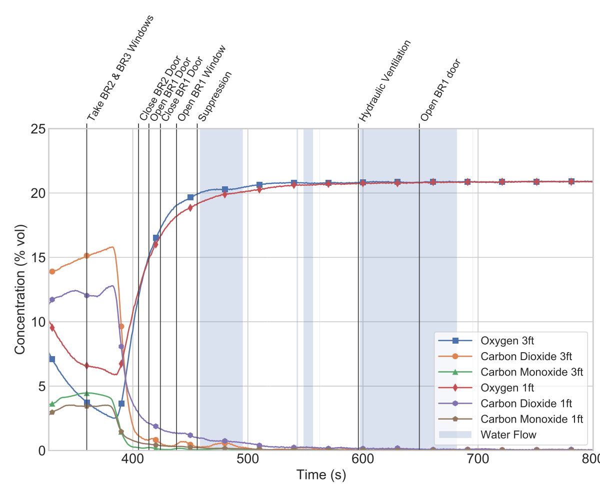
(a) Bedroom 2 Window Temperature



(b) Bedroom 2 Window Velocity



(c) Bedroom 2 Window Heat Flux



(d) Bedroom 2 Window Gas Concentration

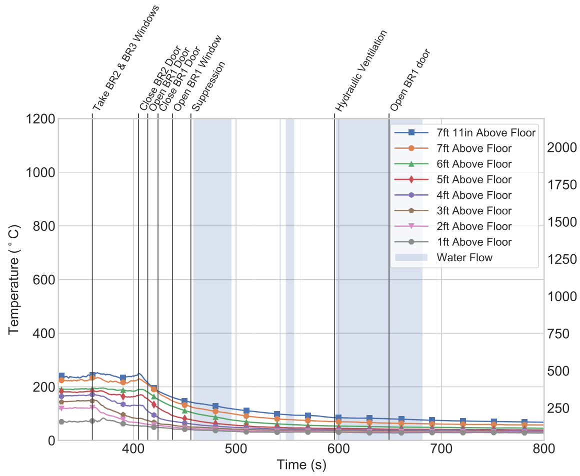
Figure 5.131: Post-intervention temperature, velocity, heat flux measurements at bedroom 2 window during Experiment 19.

Figure 5.131c shows the heat flux measured 3 ft and 1 ft above the floor in the bedroom 2 window at the time of intervention was 10.9 kW/m^2 and 6.7 kW/m^2, respectively. Immediately following window ventilation, the air entrainment through the lower portion of the window caused the heat flux at both elevations to decrease. This decrease continued as the bedroom 2 door was closed, with the heat flux at both elevations decreasing below 1.0 kW/m^2 prior to the start of suppression.

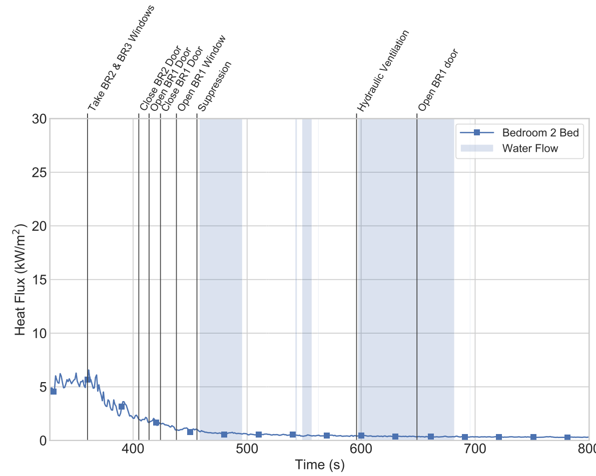
At the time of intervention, gas concentrations in the bedroom 2 window were characterized by high CO and CO_2 concentrations and low O_2 concentrations, consistent with a smoke layer that had descended below the 1 ft measurement location, as shown in Figure 5.131d. CO and CO_2 concentrations were higher at the 3 ft elevation than at the 1 ft elevation. At the time of intervention, gas concentrations were 3.8% O_2, 15.0% CO_2, and 4.5% CO at the 3 ft elevation and 6.6% O_2, 12.0% CO_2, and 3.4% CO at the 1 ft elevation. Following window ventilation, CO and CO_2 continued to increase and O_2 continued to decrease for 22 s after the windows were ventilated. At this time, the fresh air entrained through the inlet portion of the window combined with the exhaust of combustion gases caused CO and CO_2 concentrations to begin to decrease and O_2 concentrations to return to pre-ignition levels. This trend continued as the bedroom 2 door was isolated, with gas concentrations at both elevations returning to approximate initial conditions prior to the start of hydraulic ventilation.

Figure 5.132 shows the time histories of temperature, gas concentration, and heat flux in the center of bedroom 2. Temperatures at all elevations were steady immediately prior to intervention, as shown in Figure 5.132a, and ranged from 242 °C (468 °F) at the ceiling to 75 °C (167 °F) 1 ft above the floor. Immediately after the bedroom 2 window was vented, temperatures 5 ft and above remained steady, while temperatures 4 ft and below began to decrease, reflecting the bidirectional flow that was established following window ventilation. Temperatures close to the ceiling remained steady until the bedroom door was closed. This resulted in a decrease in temperature at all elevations, which continued for the duration of the experiment as products of combustion exhausted through the window. Temperatures had decreased below 150 °C (302 °F) prior to the start of suppression and below 75 °C (167 °F) prior to the start of hydraulic ventilation.

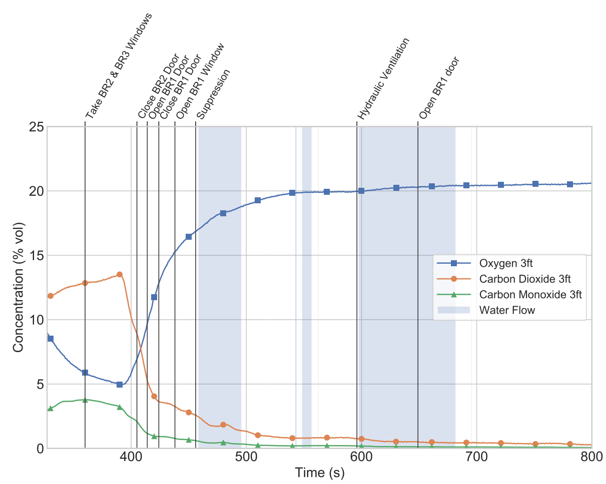
Trends in heat flux measured 3 ft above the floor on the center of the bed (Figure 5.132b) were similar to the room temperatures. At the time of intervention, the heat flux reached a peak value of 6.7 kW/m^2 simultaneous with window ventilation. Immediately following window ventilation, the air entrainment through the lower portion of the window caused the heat flux to decrease. This decrease continued through the closure of the bedroom 2 door, as the supply of high temperature gases was cut off and the velocity of exhaust gases decreased. As a result, the heat flux reached negligible values prior to the start of suppression. This heat flux response was similar to the two locations measured at the window.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



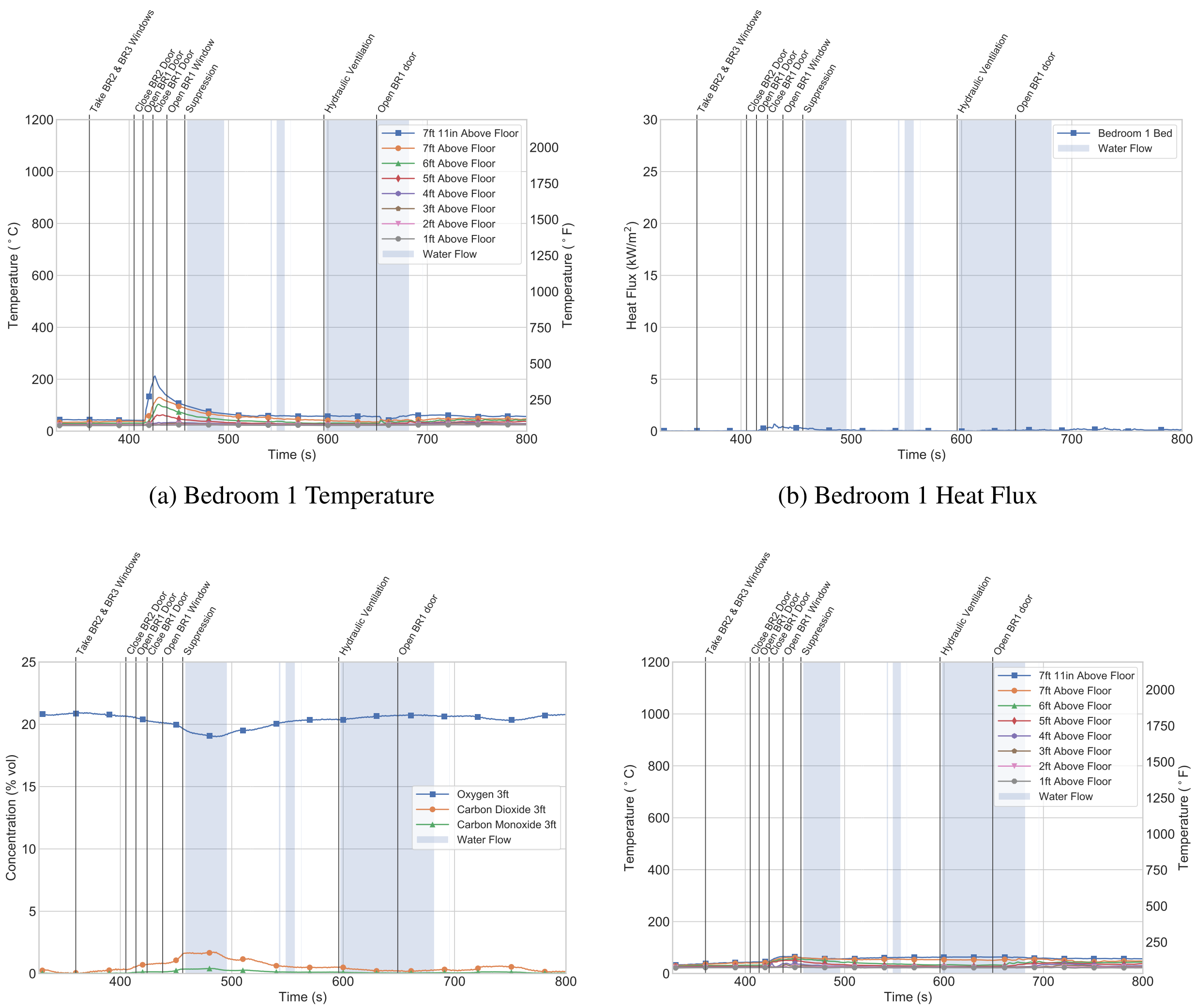
(c) Bedroom 2 Gas Concentration

Figure 5.132: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 2 during Experiment 19.

Figure 5.132c shows the time history of gas concentration 3 ft above the floor on the bed in bedroom 2. At the time of intervention, O_2, CO_2, and CO concentrations on bedroom 2 were 5.9%, 12.8%, and 3.0%, respectively, which were comparable to the values measured at the corresponding window location and were consistent with a smoke layer which had descended below the 3 ft measurement location. An increase in CO and CO_2 continued for 30 s after the window was opened, which was slightly longer than at the window measurement locations as the bed location was offset of the flow path established at the window and further from the window. A decrease in CO and CO_2 and increase in O_2 followed the 30 s after the vent was created. This trend continued as the bedroom 2 door was closed, which isolated the room from the flow of additional products of combustion. Gas concentrations returned to approximately ambient conditions shortly prior to hydraulic ventilation.

5.9.5 Bedroom 1

The door between bedroom 1 and the hallway was closed at the time of ignition. Figure 5.133a shows that at the time of intervention, temperatures in bedroom 1 were uniformly less than 50 °C (122 °F), which is less than the temperatures measured at the same time in the open bedrooms. Temperatures remained steady until the bedroom 1 door was opened. The new flow path established through the doorway caused temperatures close to the ceiling to increase, as higher temperature, higher pressure products of combustion flowed from the hallway into the room. When the bedroom door was closed 10 s later, the flow from the hallway was cut off. Temperatures subsequently began to decrease. Temperatures in bedroom 1 further decreased as the bedroom 1 window was removed. Temperatures uniformly dropped below 60 °C (122 °F) prior to the start of hydraulic ventilation. As a result of the closed door between the bedroom and the hallway, hydraulic ventilation had no noticeable impact on temperatures in bedroom 1. Additionally, as a result of the low temperatures and lack of gas flow in bedroom 1 during Experiment 19, the heat flux values measured 1 ft above the floor were negligible, as shown in Figure 5.133b.



(a) Bedroom 1 Temperature

(b) Bedroom 1 Heat Flux

(c) Bedroom 1 Gas Concentration

(d) Bathroom 1 Temperature

Figure 5.133: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 19.

Figure 5.133c shows the time history of gas concentration at the measurement location 3 ft above the floor on the bed in bedroom 1. At the time of intervention, the O_2 concentration was approximately ambient and the CO and CO_2 concentrations were negligible. In the period following intervention, CO and CO_2 concentrations gradually began to increase as higher pressure gases pushed in from around the door and through transport through the HVAC system. CO and CO_2 concentrations continued to gradually increase through the open and closing of the bedroom 1 door and the opening of the bedroom 1 window. Peak O_2, CO_2, and CO concentrations of 19.2%, 1.6%, and 0.4%, respectively, were observed after the bedroom was isolated and ventilated, during the suppression action. Suppression stopped the flow of gases around the closed door and through the HVAC system. Gas concentrations began to return toward pre-ignition levels as the gases exhausted through the open bedroom window.

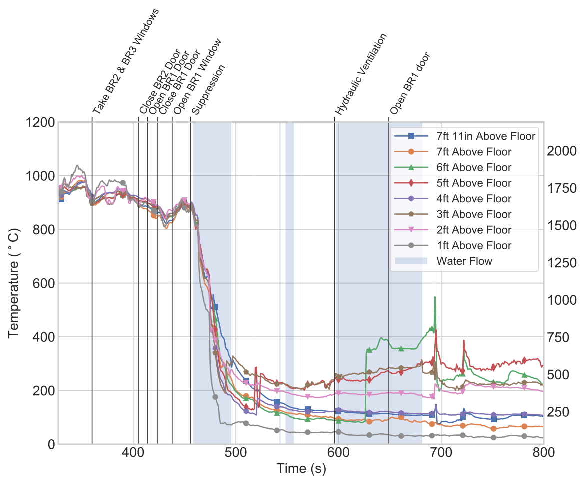
Figure 5.133d shows the time history of temperature in the bathroom adjacent to bedroom 1. The door between bedroom 1 and bathroom 1 remained closed for the duration of the experiment. At the time of intervention, temperatures in bathroom 1 were uniformly below 50 °C (122 °F), comparable to those in the adjacent bedroom. Immediately following the bedroom 1 door being opened, temperatures close to the ceiling increased as products of combustion leaked through the bathroom door. Peak temperatures at the ceiling in bathroom 1 remained below 65 °C (167 °F) and temperatures 1 ft above the floor remained below 30 °C (77 °F) for the duration of the experiment. Temperatures at all elevations began to decrease following suppression. Bathroom temperatures were not substantially impacted by hydraulic ventilation due to the two closed doors between the bathroom and hallway.

5.9.6 Hallway

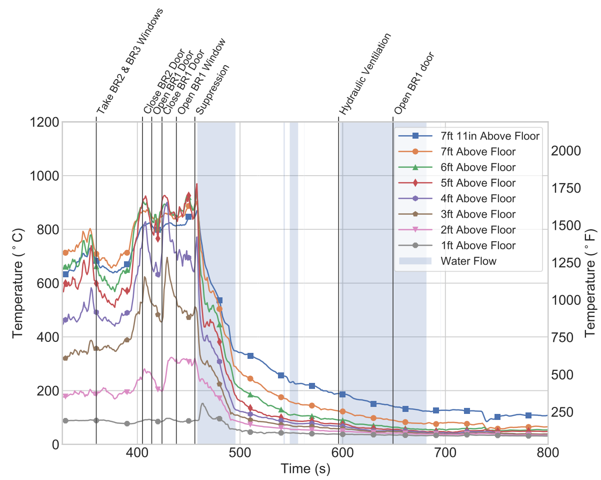
Figure 5.134 shows the time histories of temperature in the living room entryway and at the start, mid, and end hallway measurement locations. Temperatures in the living room entryway were uniformly in excess of 800 °C (1472 °F) from the time of intervention until the beginning of suppression. This contrasts with the trend in temperatures in the center of the living room, shown in Figure 5.125a, which exhibited a decrease prior to intervention before increasing above 600 °C after bedroom windows were vented. This difference can be attributed to the proximity of the living room entryway measurement location to the front door, which sustained flaming combustion in the area of the entryway for the duration of the period between intervention and suppression. Temperatures in the living room entryway began to decrease immediately after the start of suppression, and continued to decrease until the thermocouple tree was damaged at approximately 140 s after intervention (500 s after ignition).

Temperatures at the three hallway measurement locations were stratified at the time of intervention. A lack of oxygen available for combustion prevented flame spread down the hallway. Temperatures were gradually increasing at each of the three hallway locations. Temperatures were highest at the start hallway location, 708 °C (1306 °F) at the ceiling and 89 °C (192 °F) 1 ft above floor due the proximity to the common space fire. The mid hallway and end hallway locations had lower temperature ranges based on distance from the common space, with ceiling and 1 ft above the floor temperatures ranging from 552 °C to 71 °C (1026 °F to 160 °F) at the mid hallway location, and from 439 °C to 65 °C (822 °F to 149 °F) at the end hallway location. Approximatley one minute following ventilation of the windows in bedrooms 2 and 3, temperatures close to the ceiling began to increase at all three locations. New flow paths were established between the common space and the exterior vents at the bedroom windows, which led to increased higher temperature gas flow through the upper portion of the hallway.

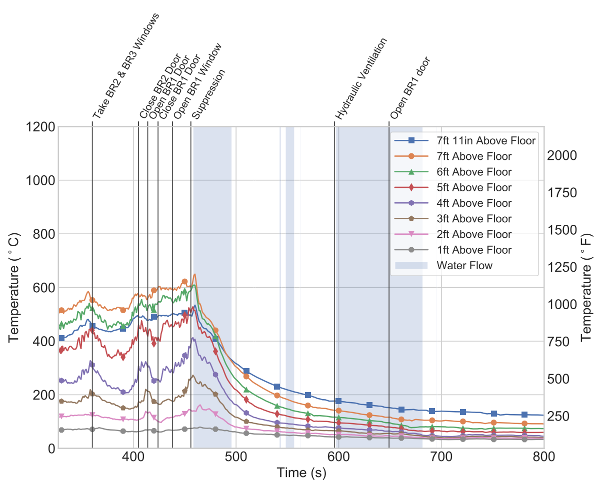
The distance between the start hallway measurement locations and the inlet flow paths at the bedroom windows negated the cooling effect from entrained air that was observed at the bedroom measurement locations. In other words, the inlet air was mixed with higher temperature before flowing into the hallway. A temperature increase was most notable at the start hallway location, where the 3 ft and 4 ft temperatures increased in excess of 600 °C (1112 °F) in the period between ventilation of the bedroom windows and the closing of the bedroom 2 door. In contrast, at the mid and end hallway locations, the entrained air through the bedroom windows initially had a cooling effect, causing temperatures to decrease following intervention, particularly at elevations below 3 ft. Eventually, this cooling effect was negated as the high-temperature exhaust flow continued to mix with the inlet flow, resulting in a temperature increase at all elevations prior to the closing of the bedroom 2 door.



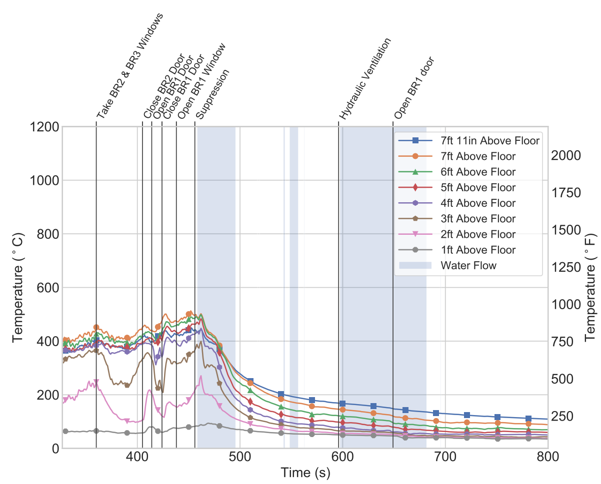
(a) Living Room Entry Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.134: Temperature time histories in the hallway in the period following fire department intervention in Experiment 19.

When the bedroom 2 door was closed 45 s after intervention, the flow path through bedroom 2 was cut off. This restricted the flow of combustion gases through the hallway, as shown by the decrease in temperatures. This decrease continued until the bedroom 1 door opened, which allowed the lower-pressure volume of air that had been trapped behind the closed door to exchange with the hallway. The additional volume of air that flowed toward the common space resulted in an increase in heat release of the fire and an in temperature at all three hallway locations approximately 65 s after intervention (425 s after ignition).

Following the fluctuations in temperatures caused by manipulation of the bedroom 2 door and bedroom 1 door, hallway temperatures maintained a steady state until the beginning of suppression. Hallway temperatures began to uniformly decrease immediately after the beginning of suppression. This decrease continued through hydraulic ventilation.

Figure 5.135 shows the time histories of heat flux in the living room entryway and at the three hallway locations during Experiment 19. Heat flux at the living room entryway fluctuated between 60 kW/m^2 and 250 kW/m^2 for the duration of the period between intervention and the start of suppression, which is consistent with direct flame impingement during a post-flashover fire. Heat flux measurements at the start, mid, and end hallway locations at the time of intervention were considerably lower than in the living room entryway, with values of 1.6 kW/m^2, 1.1 kW/m^2, and 5.2 kW/m^2, respectively. Lower temperatures at these locations combined with lower velocity gas flows and no flaming combustion reduced the heat transfer. In the time period between window ventilation and suppression, the hallway heat flux values remained relatively constant. Following the opening of the bedroom 1 door and subsequent increase in heat release rate of the fire, the start hall heat flux increased from 2.9 kW/m^2 to a peak of 6.7 kW/m^2. This is an indication that there was an increase in flaming combustion near the start hallway location. The start hallway heat flux decreased from the peak value prior to suppression as the oxygen which was supplied from bedroom 1 was consumed. Suppression generally caused heat flux to decrease at all locations. A local peak was measured at the start hallway location following the start of suppression due to the water being flowed across that location to extinguish burning materials.

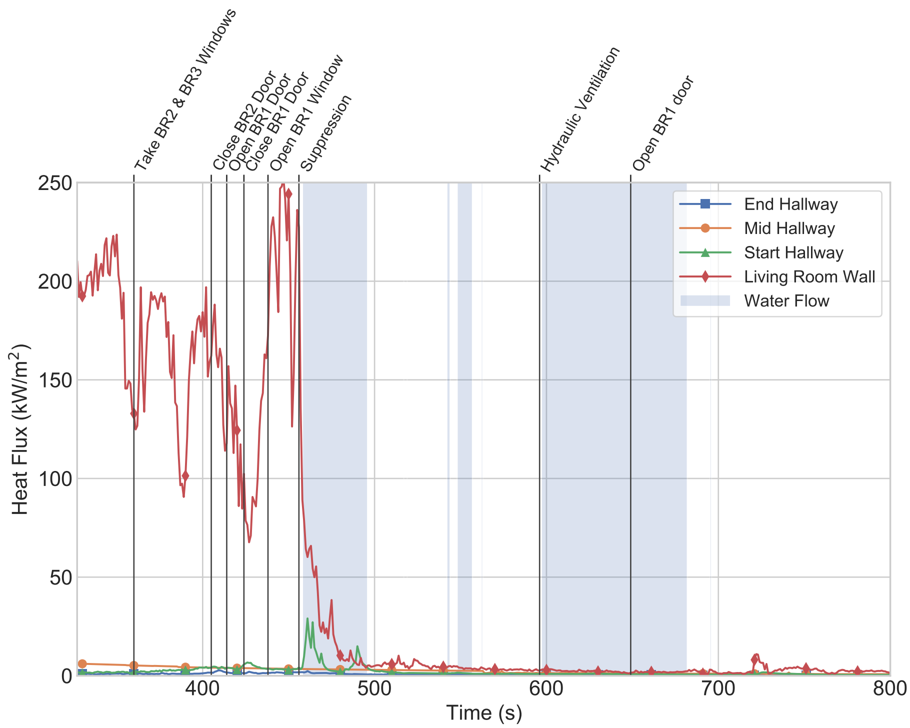
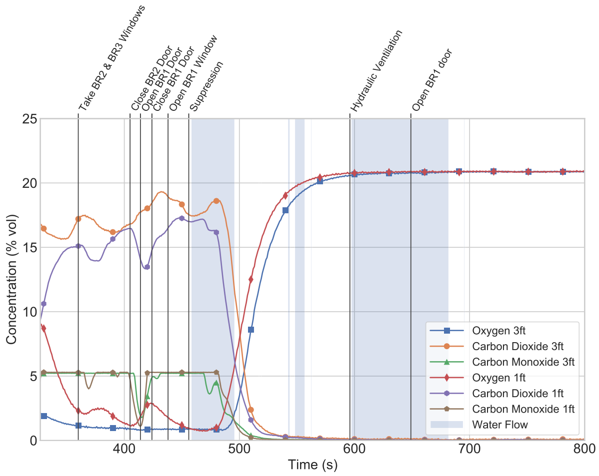


Figure 5.135: Heat flux time histories in the hallway in post-intervention period during Experiment 19.

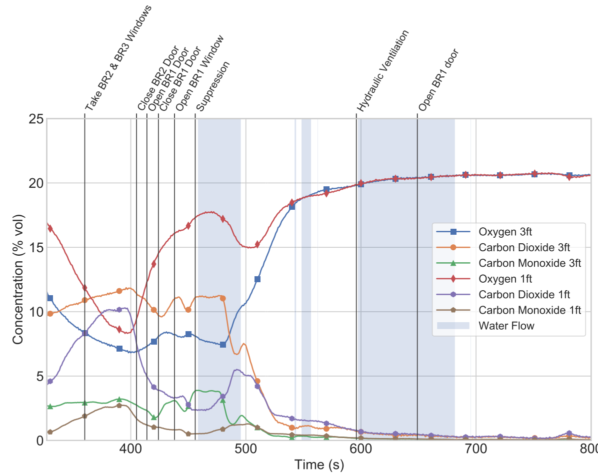
At the time of intervention, the distribution of hallway gases was characterized by high concentrations of CO and CO_2 and a low O_2 concentration, as listed in Table 5.18. Figure 5.136 shows the time histories of gas concentration at the living room entryway and hallway locations during Experiment 19.

Table 5.18: Hallway Gas Concentrations at Intervention for Experiment 19

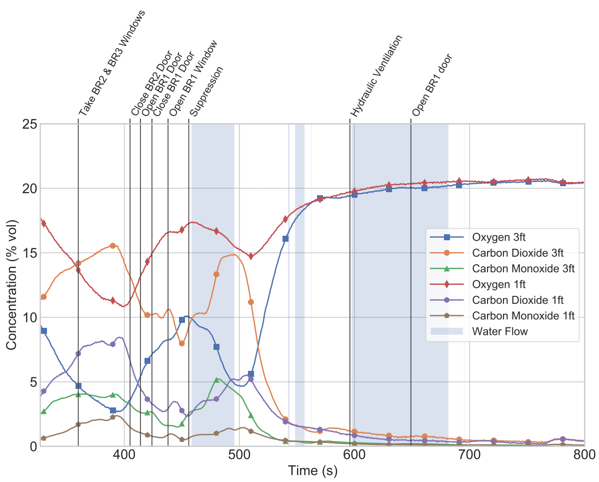
Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	1.1	17.1	5.2
	1 ft	2.4	15.1	5.3
Start Hallway	3 ft	8.3	10.9	2.9
	1 ft	11.9	8.3	1.9
Mid Hallway	3 ft	4.7	14.2	4.0
	1 ft	13.7	7.2	1.7
End Hallway	3 ft	1.1	16.4	4.1
	1 ft	15.8	5.4	1.2



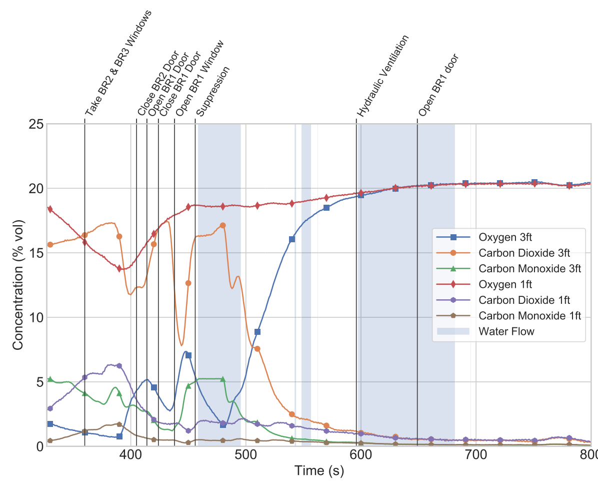
(a) Living Room Entryway Gas Concentration



(b) Start Hallway Gas Concentration



(c) Mid Hallway Gas Concentration



(d) End Hallway Gas Concentration

Figure 5.136: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 19.

The magnitude of O_2, CO_2, and CO concentrations at the time of intervention varied among the three hallway locations, as shown in Table 5.18. At all three hallway locations, CO and CO_2 concentrations at both elevations were increasing and the O_2 was correspondingly decreasing at the time of intervention. Following ventilation of the bedrooms 2 and 3 windows, air began to flow through the lower portion of windows and mix with the gases in the respective bedrooms. As the lower pressure gases flowed into the hallway toward the common space fire, further mixing resulted in a decrease in CO and CO_2 and increase in O_2 at all three hallway measurement locations. This improvement in gas concentrations was most pronounced at the start and mid hallway locations, which were located along the flow path between bedroom 3 to the common space. The bedroom 3 door remained open for the duration of the experiment compared to bedroom 2, which was closed following the window ventilation. At the mid and start hallway locations, CO and CO_2 continued to decrease while O_2 increased until suppression. At the end hallway location, the decrease in CO and CO_2 as a result of air entrainment through the bedroom 2 window was only observed until the bedroom 2 door was closed, which eliminated the inlet flow path from the bedroom 2 window. This action resulted in an increase in CO and CO_2 at the 3 ft elevation prior to the opening of the bedroom 1 door.

After the bedroom 1 door was opened, air that had previously been trapped in that room was drawn toward the common space fire, resulting in a further decrease in CO and CO_2 and increase in O_2 at each hallway measurement location. In contrast to the benefit following window ventilation, the benefit following cycling of the bedroom 1 door was temporary; since the volume of air in bedroom 1 was fixed, the door was only open for a fixed amount of time, and that air led to increased burning near the start hallway location.

Gas concentrations at all three hallway measurement locations began to trend toward ambient approximately 25 s after suppression began. Hydraulic ventilation increased the rate of return to pre-ignition concentrations. This was more effective at the mid hallway location as there was a local exterior vent (bedroom 3 window) that served as a supply of air. The end hallway location return was not as pronounced due to it not being in a flow path.

5.10 Experiment 20

The search tactics in Experiment 20 were designed to evaluate door initiated operations conducted during an interior suppression of a living room fire. At the time of ignition, the bottom pane of the kitchen window and the front door were opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2, 3, and 4 were opened. The fire was ignited in the side D corner of the sofa parallel to the front wall of the house. The fire then spread through the living room, where flashover occurred following the failure of the side A and side D windows. Post-flashover of the living room, the suppression entered the structure and flowed water. At the onset of suppression, the search crew entered through the front door to begin searching bedroom 3 and bedroom 4. The crew split to search both rooms and proceeded to remove the full windows. The crews then exited to continue searching the remaining bedrooms. The crews then arrived at bedroom 1 and bedroom 2. At bedroom 1, the crew opened the door for entry and then closed the door upon entry. The crew proceeded to remove the bedroom 1 window. At bedroom 2, the crew entered and proceeded to remove the bedroom 2 window. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side D living room windows. 82 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 223 gallons. The intervention event times are provided in Table 5.19.

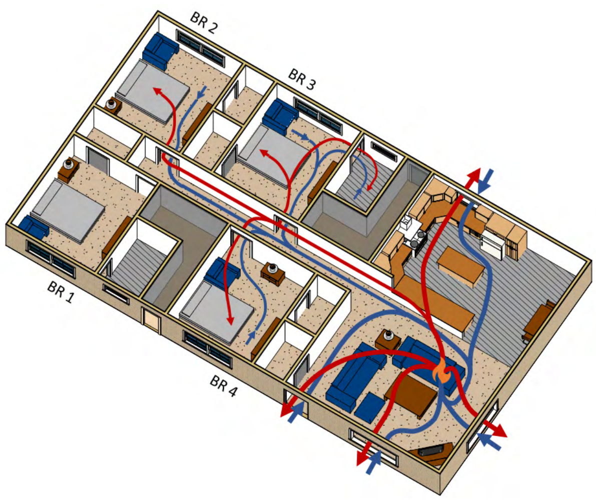
Table 5.19: Experiment 20 Event Times

Event	Elapsed Time From Ignition (mm:ss)	From Ignition (s)	From Intervention (mm:ss)	From Intervention (s)
Ignition	00:00	0	—	—
Suppression	5:59	359	00:00	0
Remove BR3 & BR4 Windows	6:44	404	00:45	45
Open BR1 Door	7:13	433	01:14	64
Close BR1 Door	7:23	443	01:24	74
Remove BR1 & BR2 Window	7:38	458	01:39	99
Hydraulic Ventilation	9:11	551	03:12	192

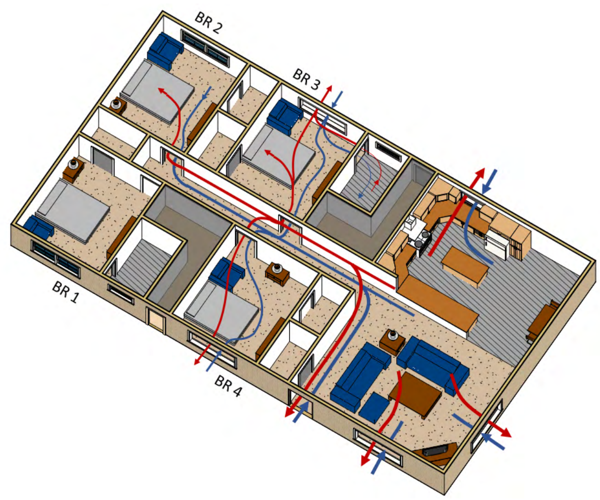
Figures 5.137 and 5.138 show the changes in flow in the period immediately preceding and following fire department intervention over the course of Experiment 20. At the time of intervention, the living room was in a post-flashover state. Bidirectional flows had been established through the kitchen window, the front door, and side A and side D living room windows; fire and smoke exhausted through the top of the vents while fresh air was entrained through the lower portion (Figure 5.137a). The initial fire department intervention was suppression, which was conducted through the front door of the structure using a 7/8 in. smooth bore nozzle with a nominal flow rate of 165 gpm connected to an 1 3/4 in. hoseline. The suppression crew first applied water to the interior from a position on the deck, flowing for 6 s through the front door and side A living room window in an O-pattern. Once the fire had been controlled to the point where the suppression crew could advance to the interior, the suppression crew crossed the threshold of the doorway and

continued suppression operations.

The bedrooms 3 and 4 windows were removed 45 s after the start of suppression, simulating crews searching the two bedrooms simultaneously and venting as they went. These ventilation actions created new exterior vents at these locations which allowed products of combustion to exhaust through the top of the vents while cooler air was entrained through the lower portion of the vents, as shown in Figure 5.137b. Note that wind impacted the flows at these vents; at times, the exhaust flow was limited due to the pressure generated at the opening by the wind.



(a) Flows Prior to Intervention

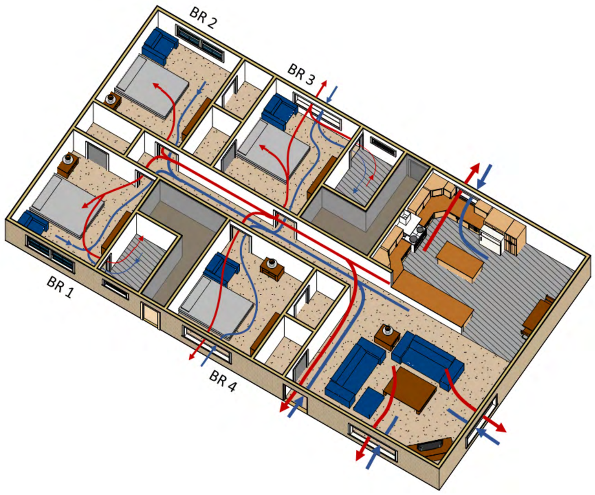


(b) Remove BR3 & BR4 Windows

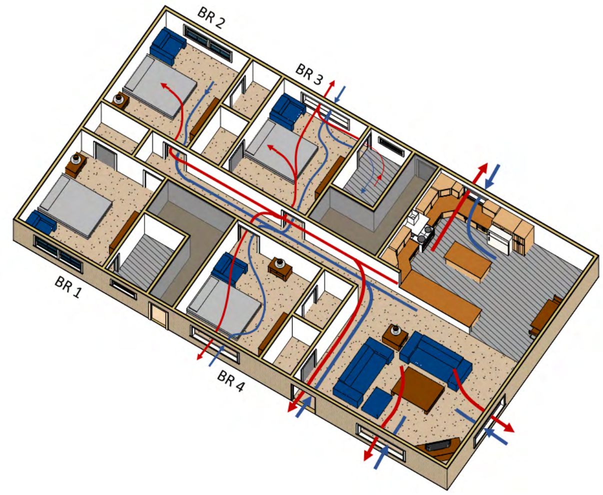
Figure 5.137: Changes in gas flows in the structure following fire department interventions in Experiment 20.

The bedroom 1 door was opened 64 s after the bedrooms 3 and 4 windows were ventilated, as crews had finished searching bedrooms 3 and 4 and had advanced down the hallway to search bedrooms 1 and 2. Opening the bedroom door allowed products of combustion to flow into the previously isolated bedroom 1 (Figure 5.138a). This flow continued until the bedroom 1 door was closed again, 10 s later. Although this action isolated bedroom 1 from the lingering products of combustion in the hallway, it also trapped products of combustion in bedroom 1 with no outlet as shown in Figure 5.138b. These trapped products of combustion remained until the bedrooms 1 and 2 windows were ventilated 15 s later. In bedroom 1, window ventilation established bidirectional flow through the window, allowing trapped smoke to exhaust through the upper portion of the window and cooler air to flow in through the lower portion of the window (Figure 5.138c). In bedroom 2, window ventilation created a similar exterior vent, allowing products of combustion to exhaust from the structure (Figure 5.138c).

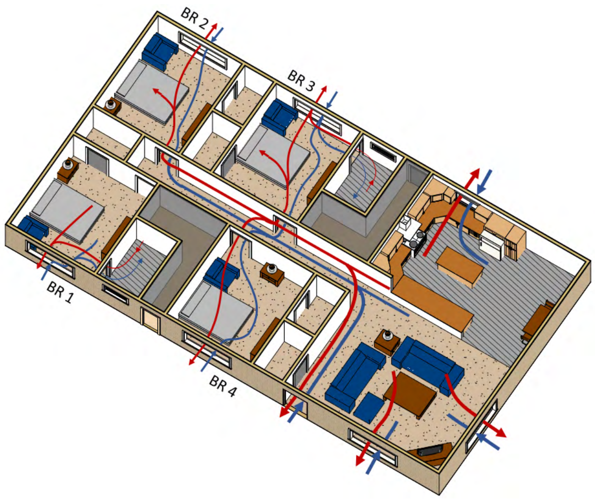
Once the fire had been extinguished and the search sequence was completed, the suppression crew initiated hydraulic ventilation through the side D living room window with the tip off and nozzle opened halfway and rotated in an O-pattern. Hydraulic ventilation created an area of low pressure due to the flowing water through the side D living room window. This drew products of combustion from remote points in the structure through the vent due to a pressure difference (Figure 5.138d).



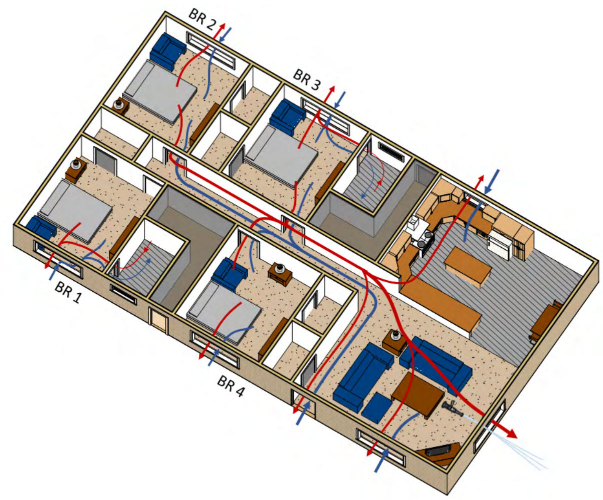
(a) Open BR1 Door



(b) Close BR1 Door



(c) Remove BR1 & BR2 Window



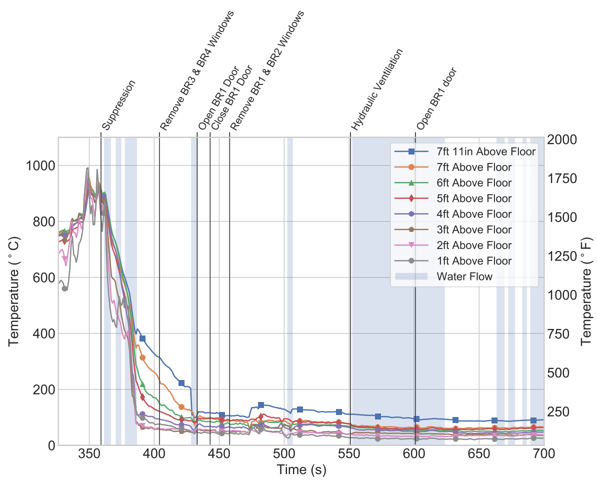
(d) Hydraulic Ventilation

Figure 5.138: Changes in gas flows in the structure following fire department interventions in Experiment 20.

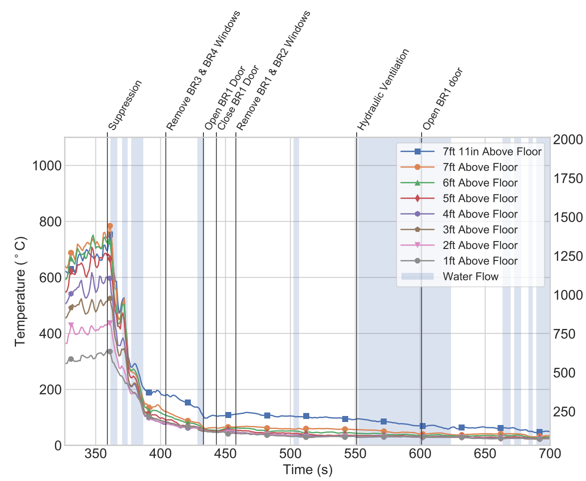
5.10.1 Common Space

Figure 5.139 shows the time histories of temperatures in the living room and kitchen, and temperatures and velocities recorded in the front door. At the time of intervention, the living room fire was in a post-flashover state, with temperatures uniformly in excess of 800 °C (1472 °F), as shown in Figure 5.139a. The front door and living room window acted as bidirectional vents, with flames and smoke exhausting out of the upper portion of the openings as air was entrained through the lower portion of the openings. Temperature measurements at the front door, shown in Figures 5.139c and 5.139d, indicated that exhaust temperatures were in excess of 800 °C (1472 °F) at 7.5 m/s (16.8 mph), while inlet temperatures ranged between 465 °C and 308 °C (869 °F to 586 °F) at -3.5 m/s (-7.8 mph) . Kitchen temperatures were lower than those observed in the living room, and stratified at the time of intervention from 763 °C (1405 °F) at the ceiling to 339 °C (642 °F) 1 ft above the floor, as shown in Figure 5.139b. The lower temperatures in the kitchen were because the kitchen window, with a high sill and small area, was an inefficient vent and therefore there was insufficient oxygen to support combustion local to the kitchen.

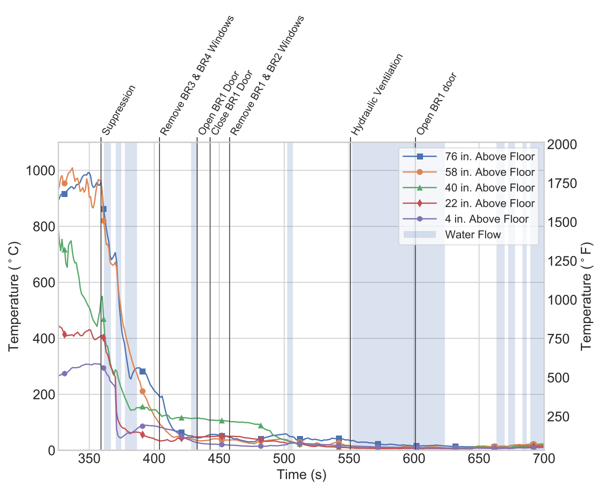
The initial fire department intervention was suppression. Temperatures in the kitchen, the living room, and the front door began to decrease immediately after the start of suppression, and continued to decrease as the suppression crew extinguished the living room fire. Velocities at the front door decreased and fluctuated between ± 1 m/s (± 2.2 mph). During hydraulic ventilation, the door showed approximate velocities of -2.4 m/s (-5.4 mph) and indicated the vent was a unidirectional inlet. Temperatures through the space continued to decrease through hydraulic ventilation.



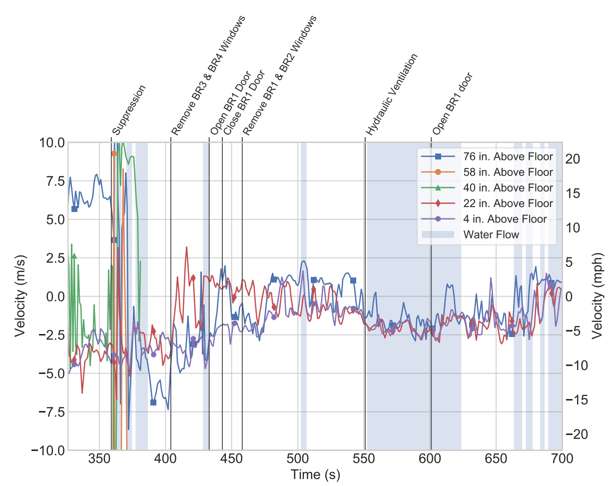
(a) Living Room Temperature



(b) Kitchen Temperature



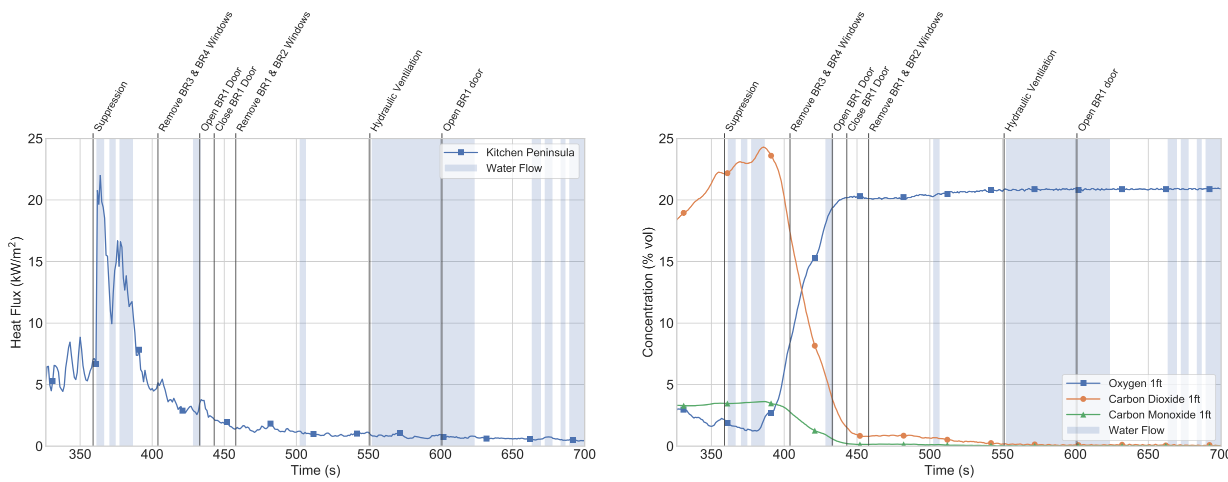
(c) Front Doorway Temperature



(d) Front Doorway Velocity

Figure 5.139: Post-intervention temperatures front doorway velocity, and front doorway temperatures in the common space in Experiment 20.

Measurements of heat flux and gas concentration were at the 1 ft elevation in the kitchen between the kitchen island and kitchen peninsula (Figure 5.140). Prior to suppression, the kitchen heat flux had steadily increased over the prior minute and was at 7.1 kW/m^2 (Figure 5.140a). At the start of suppression, the kitchen heat flux then reached a peak of 22.0 kW/m^2 within the first 10 s of suppression. The suppression crew used an O-pattern to knock down the fire at the front door and side A living room window to cool gases to make entry to the living room. The water flow entrained air and therefore displaced air ahead of the stream. This led to increased gas flow through the kitchen window. Despite the temperature drop shown in Figure 5.139b, the heat flux temporarily increased due to the increased gas flow velocity. Heat flux dropped following the completion of suppression and continued to decrease through hydraulic ventilation.



(a) Kitchen Heat Flux

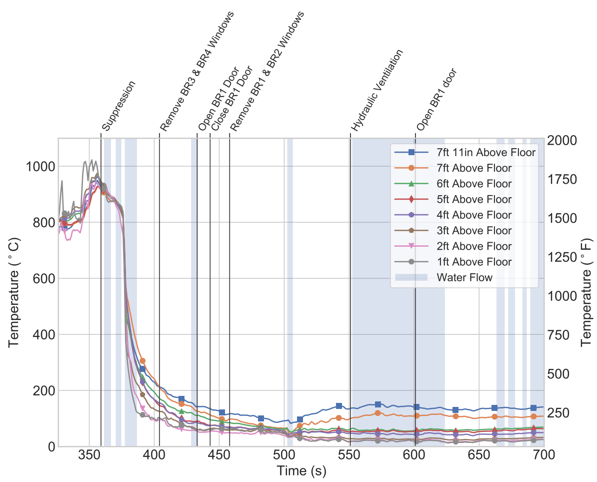
(b) Kitchen Gas Concentrations

Figure 5.140: Post-intervention heat flux and gas concentrations in the kitchen in Experiment 20.

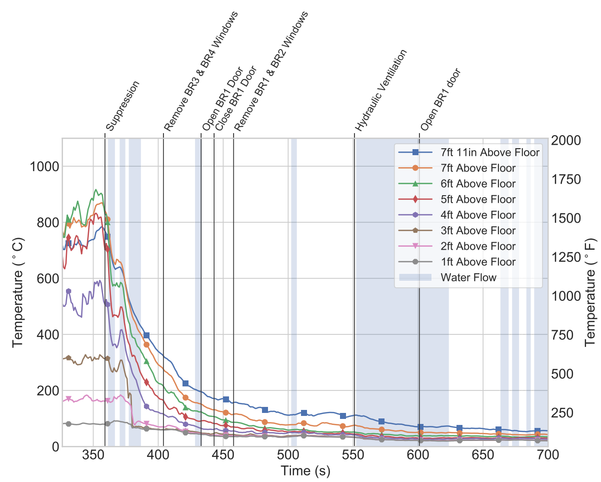
The kitchen gas concentrations had a similar response profile to the co-located heat flux (Figure 5.140b). At the time of intervention, gas concentrations at the kitchen location were characterized by high concentrations of CO and CO_2 and low concentrations of O_2, indicating that the smoke layer had descended past the 1 ft measurement location. O_2, CO_2, and CO concentrations were 2.2%, 22.1%, and 3.5%, respectively. Concentrations continued to increase through the start of suppression as the initial suppression action increased gas flow through the kitchen window. Following suppression, gas concentrations sharply recovered to near pre-ignition levels and reached those levels within 30 s of hydraulic ventilation.

5.10.2 Hallway

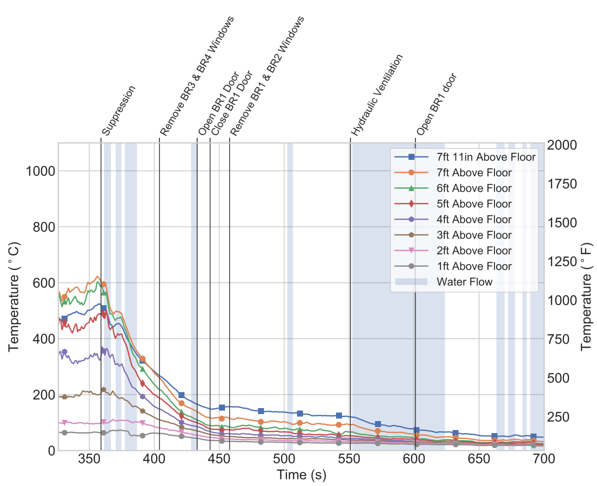
At the time of intervention, the temperatures in the living room entryway were in excess of 800 °C at all elevations, above the threshold of 600 °C (1112 °F) consistent with post-flashover conditions (Figure 5.141). Similar to the temperatures in the common space, the temperatures in the living room entryway and hallway uniformly decreased starting immediately with the onset of suppression. Compared to the entryway, temperatures at the start hallway, mid hallway, and end hallway locations were all stratified prior to suppression. The magnitude of the temperatures decreased with increasing distance from the common space. Temperatures at all hallway measurement locations began to decrease following the start of suppression with the largest impact occurring at the living room entryway and start hallway due to the proximity of the water flow and exhaust vents. Hallway temperatures continued to decrease in the period following suppression, as products of combustion exhausted through ventilation openings in the common space and later in the bedrooms. Temperatures at all four locations decreased below 150 °C (302 °F) prior to the start of hydraulic ventilation, and continued to decrease through the hydraulic ventilation action.



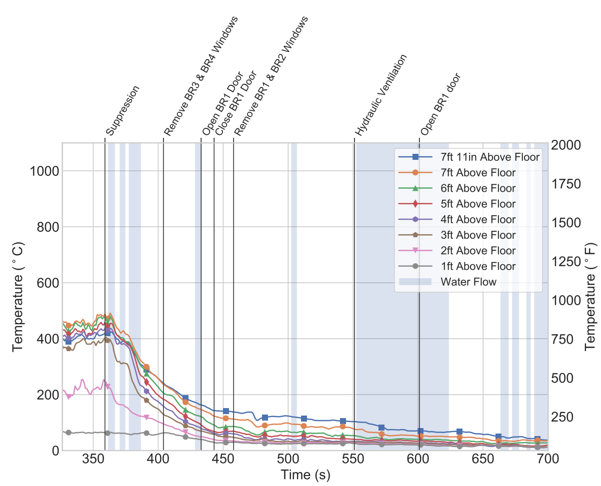
(a) Living Room Entry Hall Temperature



(b) Start Hallway Temperature



(c) Mid Hallway Temperature



(d) End Hallway Temperature

Figure 5.141: Temperature time histories in the hallway in the period following fire department intervention in Experiment 20.

Heat flux values measured in the living room entryway and at the three hallway locations, shown in Figure 5.142, were consistent with the trend in temperatures measured in those locations. At the time of intervention, the heat flux measured in the living room entryway was 187 kW/m^2, consis-

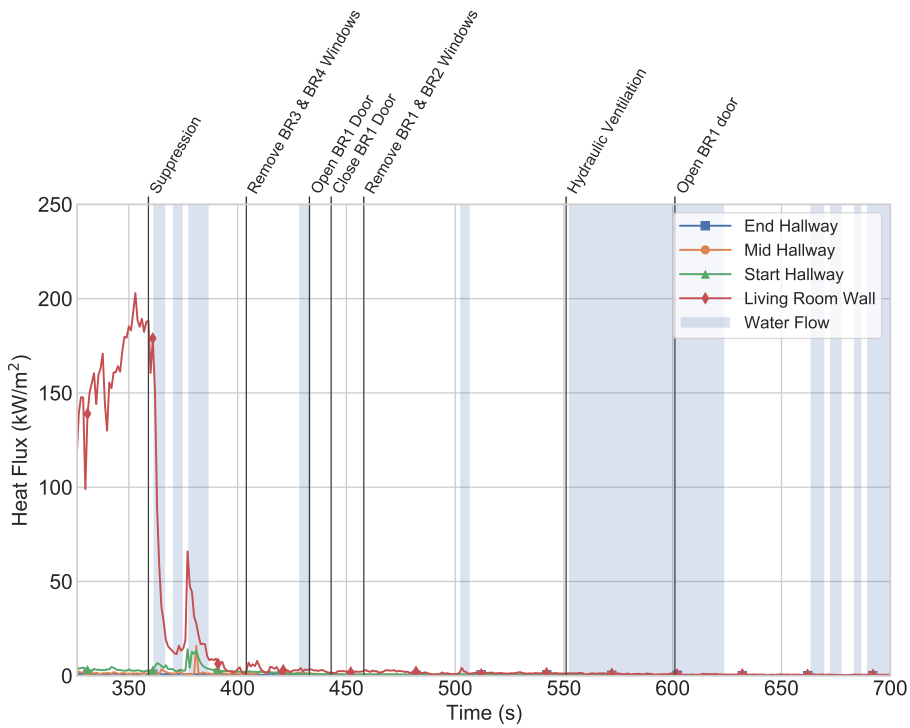


Figure 5.142: Heat flux time histories in the hallway in post-intervention period during Experiment 20.

tent with flame impingement from a post-flashover fire. Hallway heat flux values were all below 3 kW/m^2. Heat flux in the living room began to decrease immediately following the beginning of suppression. This decrease was continuous with the exception of a local peak observed during a break in water flow, 18 s after intervention. This peak was attributed to burning carpet in the area of the measurement location, as the heat flux continued to decrease as the suppression crew extinguished the living room fire. At the start hall location, heat flux fluctuated in the period following suppression, increasing to a peak as high as 15 kW/m^2 likely due to localized burning and/or burning debris. The heat flux at this location decreased in concert with the living room entryway heat flux, dropping to 3.2 kW/m^2 by the end of suppression and continuing to decrease as products of combustion exhausted through the open windows and front door in the common space. Heat flux at the mid hall and end hall locations began to decrease in the period following suppression, and had dropped to values less than 1.0 kW/m^2 prior to the removal of the bedrooms 3 and 4 windows.

Table 5.20 shows that gas concentrations measured in the living room entryway prior to suppression were below the threshold needed to support combustion and were consistent with the post-flashover conditions that were observed at the time of intervention. The table also shows that gas concentrations measured in the hallway were similarly characterized by low O_2 concentrations and elevated CO and CO_2 concentrations, an indication that prior to intervention the smoke layer had descended past the 1 ft measurement location in the hallway.

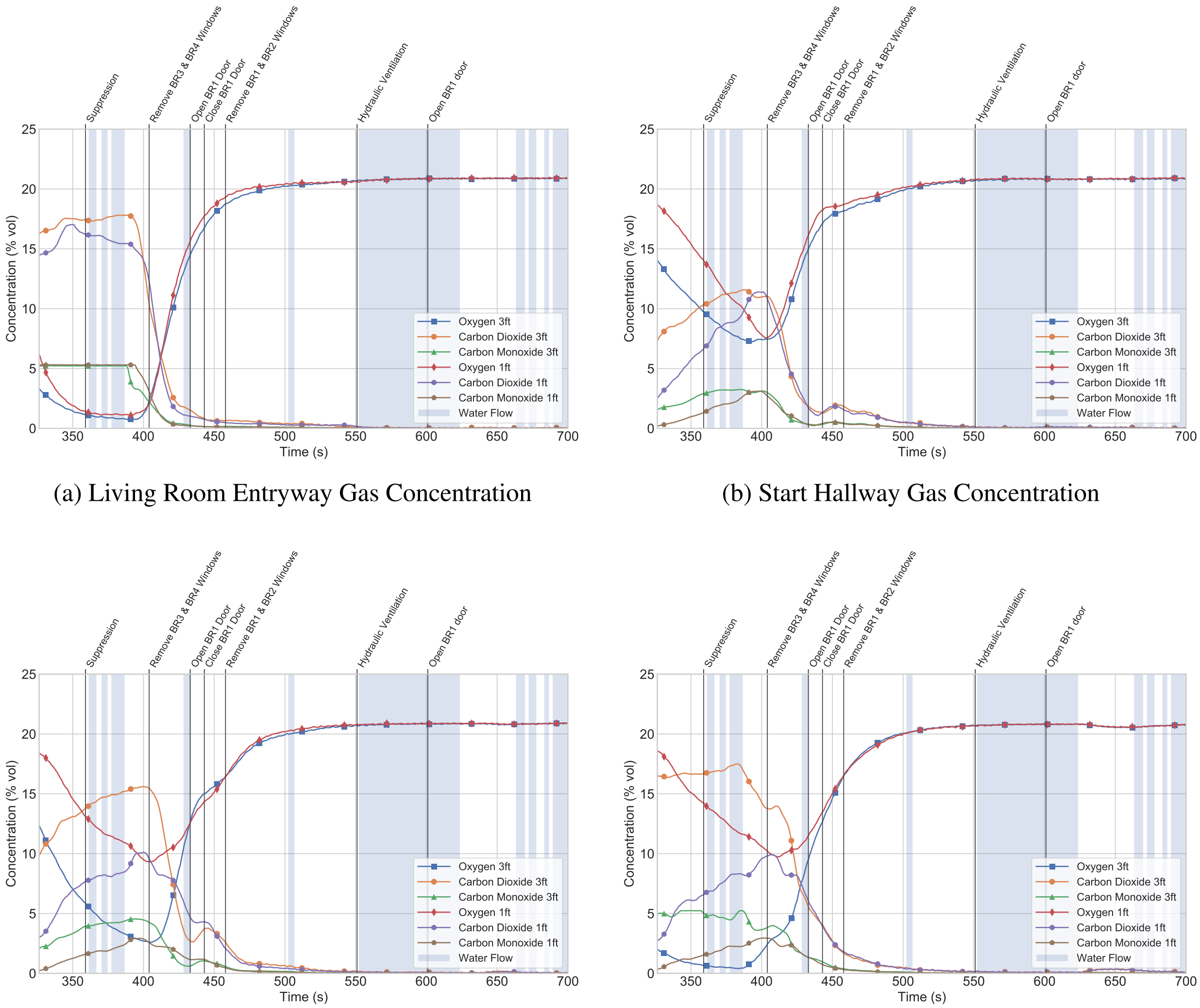
Figure 5.143 shows the time histories of gas concentrations at the living room and hallway mea-

Table 5.20: Hallway Gas Concentrations at Intervention for Experiment 20

Location	Height	O_2 (%)	CO_2 (%)	CO (%)
Living Room Entryway	3 ft	1.2	17.4	5.0
	1 ft	1.5	16.5	5.0
Start Hallway	3 ft	10.3	9.7	2.9
	1 ft	14.0	6.7	1.3
Mid Hallway	3 ft	5.9	13.8	3.9
	1 ft	13.1	7.7	1.6
End Hallway	3 ft	0.6	16.7	5.0
	1 ft	14.2	6.6	1.5

surement locations. Following suppression, O_2 concentrations increased and CO and CO_2 concentrations decreased at all locations and elevations. At the living room entryway measurement location, this change was observed at approximately the same time at the 3 ft and 1 ft elevations, with gas concentrations beginning to trend toward ambient approximately 30 s after the beginning of suppression, as fresh air was entrained into the space and the smoke layer began to lift.

At the three hallway locations, O_2 began to increase and CO and CO_2 began to decrease between 30 to 60 s after the beginning of suppression. The timing of the improvement in conditions was driven by proximity to exterior vents. The higher pressure, higher temperature gases that accumulated in the hallway flowed toward the nearest open vents (bedroom 2, 3, and 4 windows, front door and kitchen window). CO and CO_2 concentrations at all four measurement locations had decreased to comparatively negligible values prior to 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 5.143: Gas concentration time histories in the hallway in period following fire department intervention during Experiment 20.

5.10.3 Bedroom 3

The bedroom 3 door was open for the duration of the experiment, which initially led to the accumulation of combustion gases within the space prior to suppression as there was no local exhaust vent. As a result, temperatures in bedroom 3 rose, but remained stratified between 334 °C (633 °F) at the ceiling to 53 °C (127 °F) 1 ft above the floor (Figure 5.144). These values were below the hallway temperatures as gases that flowed into the bedroom mixed with air and cooled slightly. Temperatures at all elevations began to decrease during the initial suppression action, and continued to decrease as the suppression crew brought the living room fire under control. The opening of the bedroom 3 window accelerated the rate at which temperatures decreased. The higher temperature and higher pressure combustion gases began to flow toward the lower pressure open vent following suppression. By the beginning of hydraulic ventilation, temperatures throughout bedroom 3 had decreased below 75 °C (167 °F). Hydraulic ventilation did not have a noticeable effect on the rate at which temperature continued to decrease.

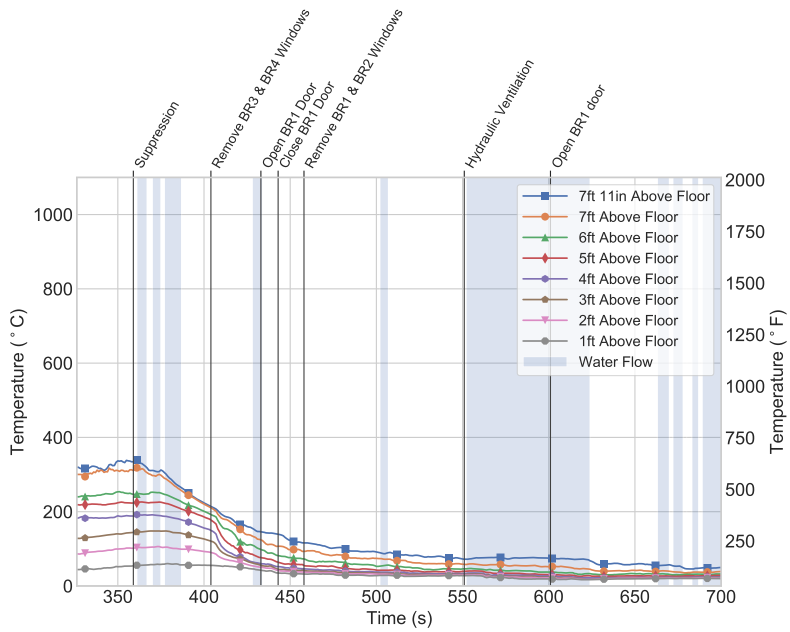
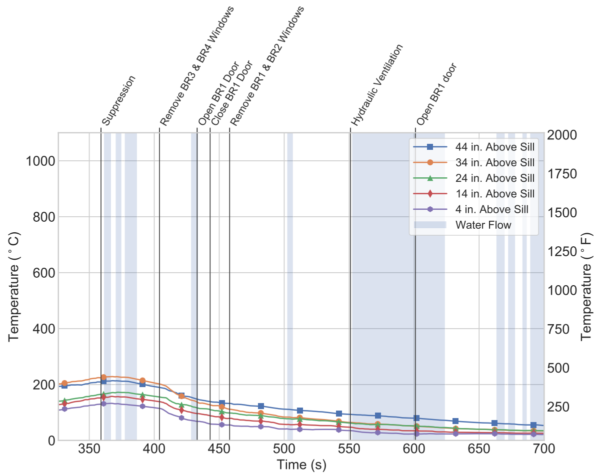


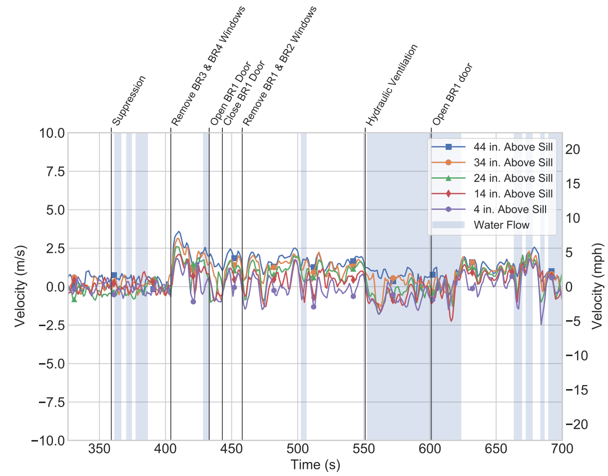
Figure 5.144: Post-intervention bedroom 3 temperature during Experiment 20.

Prior to ventilation of the bedroom 3 window, temperatures at the window were decreasing due to suppression, as shown in Figure 5.145a. The rate of decrease increased following the ventilation of the window. In the period following window ventilation, gas flows fluctuated between unidirectional exhaust with intermittent periods of bidirectional flow. The velocity data shown in Figure 5.145b indicated that peak exhaust flows ranged from 2 m/s to 3 m/s (4.5 mph to 6.7 mph), and peak entrainment flows ranged from -1 m/s to -2 m/s (-2.2 mph to -4.5 mph). Over time, the magnitude of the exhaust flows decreased as the amount of higher-temperature, higher-pressure combustion gases decreased, which dropped the pressure in the room. Differential pressure was the driver of the gas flow. As a result, the influence of wind, via inflow fluctuations, became more noticeable as the pressure dropped in the room. Hydraulic ventilation reversed flow through the window to create a unidirectional intake with velocities that ranged between 0 m/s to -1.5 m/s (0 mph to -3.4 mph).

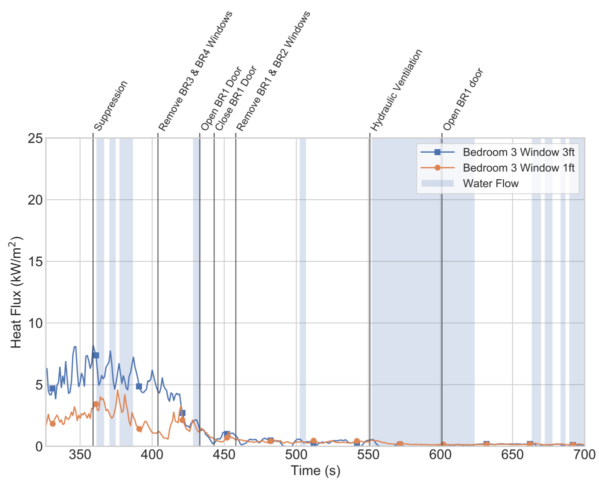
Figure 5.145c shows that immediately prior to intervention, the heat flux at the 3 ft and 1 ft window measurements were approximately 7.7 kW/m^2 and 3.5 kW/m^2, respectively. Heat flux at both elevations began to decrease 20 s after the start of suppression. The decrease in heat flux was gradual immediately after suppression, but window ventilation caused the heat flux to decrease more rapidly. Heat flux at both elevations decreased below 1.5 kW/m^2 approximately 73 s after the beginning of suppression. The continued exhaust of products of combustion through the bedroom 3 windows caused the heat flux to drop and reach values of approximately 0.5 kW/m^2 prior to the start of hydraulic ventilation and negligible values prior to the end of the hydraulic ventilation.



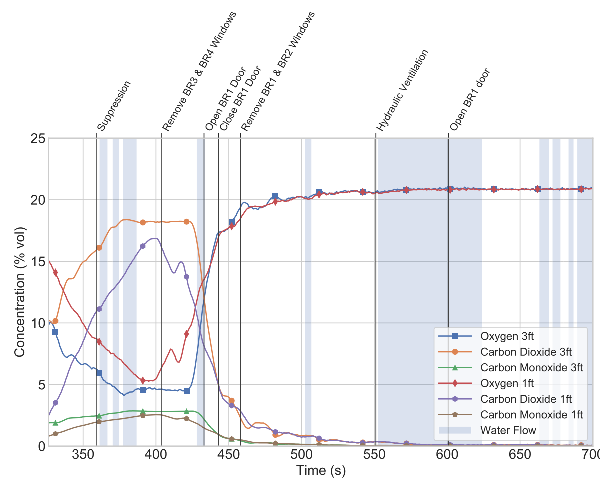
(a) Bedroom 3 Window Temperature



(b) Bedroom 3 Window Velocity



(c) Bedroom 3 Window Heat Flux



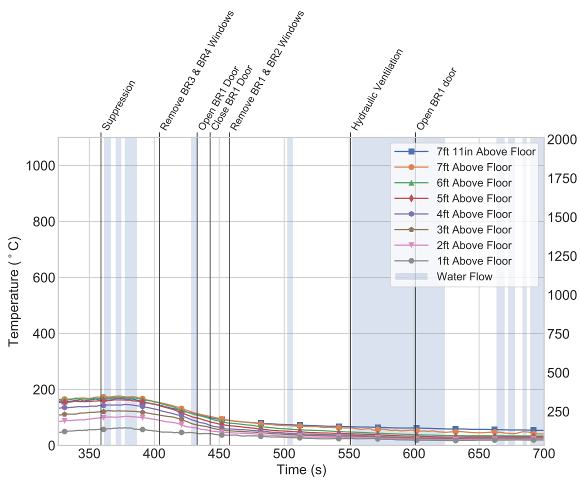
(d) Bedroom 3 Window Gas Concentration

Figure 5.145: Post-intervention window temperature, velocity, heat flux, and gas concentrations in bedroom 3 during Experiment 20.

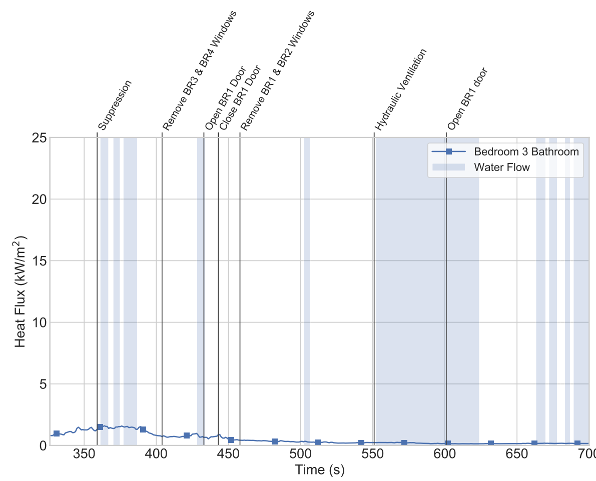
Gas concentrations at the time of intervention in bedroom 3, shown in Figure 5.145d, were comparable in magnitude to those observed at the corresponding elevation at the mid hallway location. The low O_2 concentrations and high CO and CO_2 concentrations suggested that the smoke layer had descended below the 1 ft gas measurement probe in bedroom 3. The 1 ft CO and CO_2 concentrations first began to decrease approximately 39 s after intervention as the smoke layer lifted and the rate increased following the ventilation of the window. The 3 ft concentrations lagged behind, beginning to trend toward ambient 65 s after suppression (after the bedroom 3 window had been ventilated). Gas concentrations continued to trend toward ambient, with CO and CO_2 decreasing below negligible values at both elevations prior to the start of hydraulic ventilation.

Temperatures in bathroom 3 (Figure 5.146a) were lower than those measured in the adjacent bedroom at the time of intervention, ranging from 172 °C (342 °F) at the ceiling to 58 °C (136 °F)

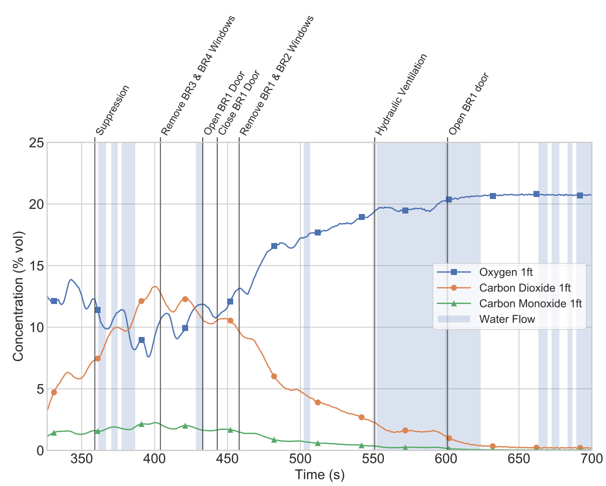
1 ft above the floor. Following suppression, the temperatures followed a similar trend to those in bedroom 3, beginning to decrease during the initial suppression action. This decrease was accelerated after the bedroom 3 window was ventilated. This decrease continued through hydraulic ventilation, by the start of which temperatures had uniformly decreased below 70 °C (158 °F).



(a) Bathroom 3 Temperature



(b) Bathroom 3 Heat Flux



(c) Bathroom 3 Gas Concentration

Figure 5.146: Post-intervention temperatures, heat flux, and gas concentrations in bathroom 3 during Experiment 20.

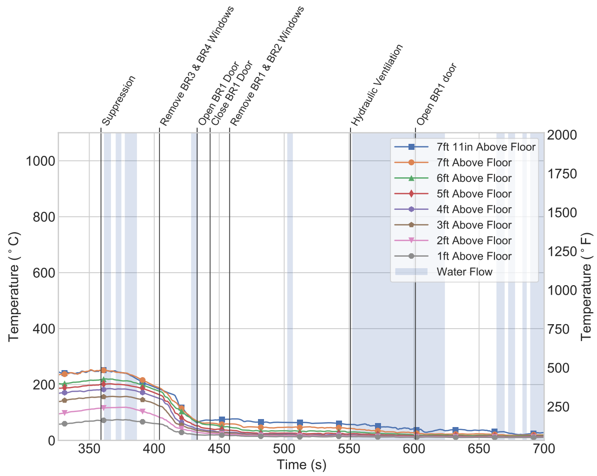
The heat flux measured 1 ft above the floor in bathroom 3 at the time of intervention was 1.4 kW/m^2, which was lower than the value measured at the same elevation in the bedroom 3 window due to the reduced gas flow into the bathroom. Similar to the behavior observed in the adjacent bedroom, the bathroom 3 heat flux decreased 20 s after suppression was initiated, and continued to decrease as the common space fire was extinguished and the flow of combustion gases correspondingly decreased. Heat flux in bathroom 3 decreased below 1.0 kW/m^2, prior to ventilation of the bedroom 3 window, and continued to decrease to a negligible value prior to the start of hydraulic ventilation.

Figure 5.146c shows the time history of gas concentrations 1 ft above the floor in bathroom 3. Immediately prior to intervention, the distribution of bathroom gases was characterized by elevated levels of CO and CO_2 and low levels of oxygen; an indication that the smoke layer in the bathroom had descended past the 1 ft measurement height. These gas concentrations were comparable to those measured 1 ft above the floor in bedroom 3. CO and CO_2 concentrations in the bathroom increased through the initial suppression actions, reaching a peak 42 s after intervention with O_2, CO_2, and CO values of 8.2%, 13.1%, and 2.2%, respectively. Unlike in bedroom 3, where CO and CO_2 concentrations decreased to negligible concentrations prior to hydraulic ventilation, gas concentrations in bathroom 3 trended toward ambient at a more gradual rate, with O_2, CO_2, and CO values of 19.3%, 2.3%, and 0.4%, respectively prior to hydraulic ventilation as the bathroom was offset from a flow path. Following the start of hydraulic ventilation, the decrease in CO and CO_2 concentrations and increase in O_2 concentration continued, although slightly elevated CO concentrations were still measured at the end of hydraulic ventilation.

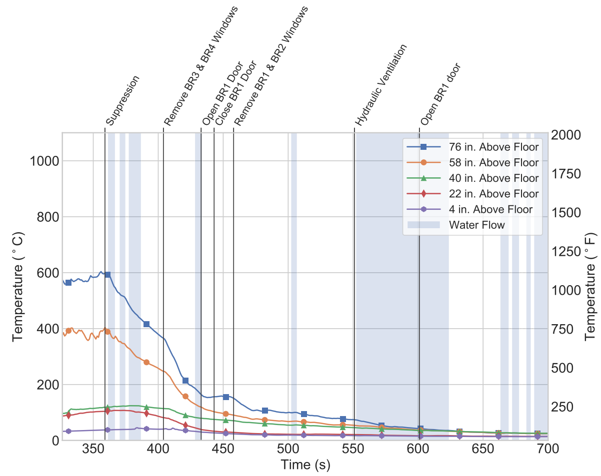
5.10.4 Bedroom 4

Like in bedroom 3, the bedroom 4 door was open for the duration of the experiment, allowing the space to fill with products of combustion. Prior to intervention, flow in the bedroom 4 doorway was bidirectional, with hot gases flowing into the bedroom through the upper portion of the door while air from bedroom 4 was drawn toward the living room fire through the lower portion of the door, as shown in the data measured at the doorway (Figures 5.147b and 5.147c). After suppression was initiated, this bidirectional flow was maintained, but temperatures in the doorway began to decrease as suppression actions extinguished the fire. When the bedrooms 3 and 4 windows were opened, the velocity indicated a unidirectional flow from bedroom 4 into the hallway, which was maintained through hydraulic ventilation. This unidirectional inflow through the bedroom 4 doorway suggests that wind that flowed across side A of structure (from side B toward side D) was impacting flows within the structure. Temperatures continued to decrease in the bedroom 4 doorway in the period following suppression as the wind aided in ventilation of bedroom 4.

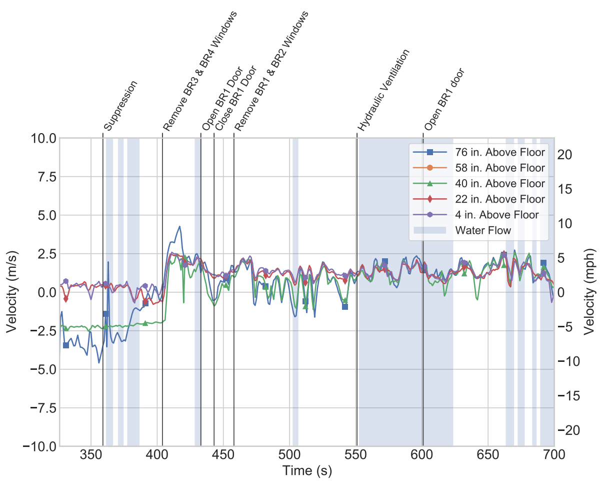
Temperatures in bedroom 4 were stratified between 250 °C (482 °C) at the ceiling to 72 °C (162 °F) 1 ft above the floor (Figure 5.147a). Temperatures at all elevations began to decrease during the initial suppression action, and continued to decrease as the suppression crew brought the living room fire under control. The opening of the bedroom 4 window accelerated the rate at which temperatures decreased as the higher temperature and higher pressure combustion gases flowed out of the lower pressure open window. By the beginning of hydraulic ventilation, temperatures throughout bedroom 3 had decreased below 60 °C (140 °F). Hydraulic ventilation did not have a noticeable effect on the rate at which temperatures in the bedroom continued to decrease. Temperatures in the bedroom 4 closet (Figure 5.147d) remained below 40 °C (104 °F) for the duration of the experiment due to the closed door between the closet and the bedroom.



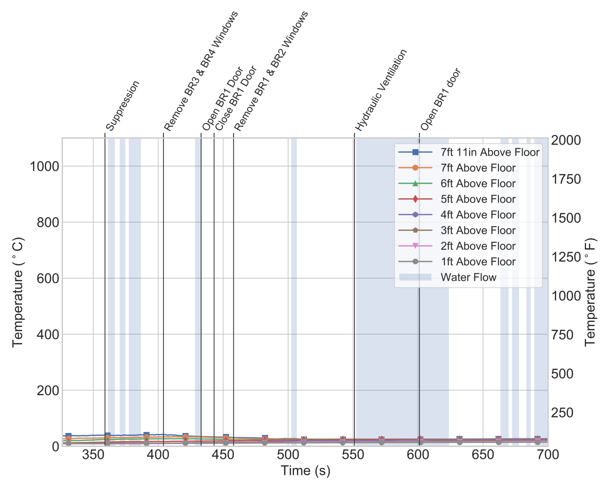
(a) Bedroom 4 Temperature



(b) Bedroom 4 Doorway Temperature



(c) Bedroom 4 Doorway Velocity

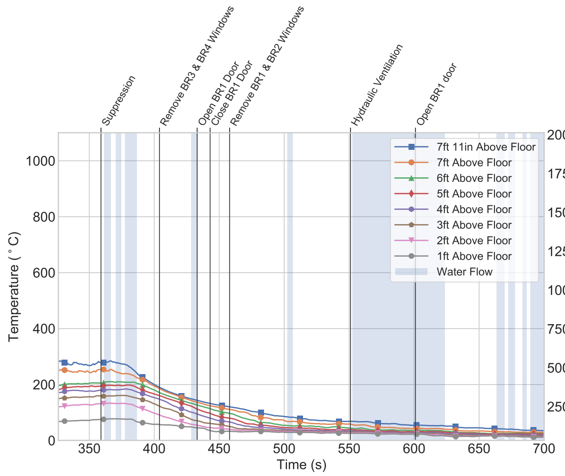


(d) Bedroom 4 Closet

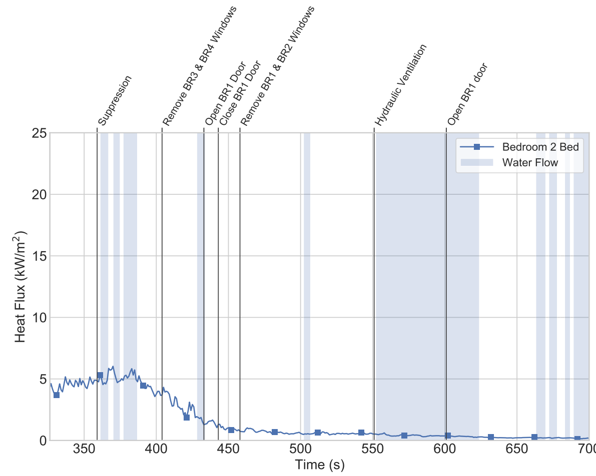
Figure 5.147: Post-intervention temperatures and velocities in bedroom 4 during Experiment 20.

5.10.5 Bedroom 2

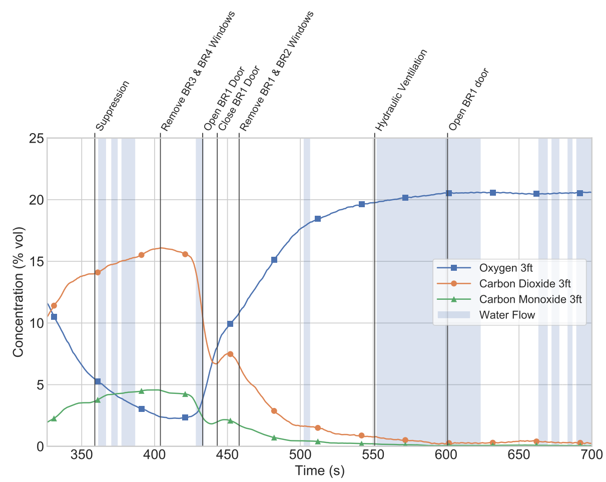
Similar to bedrooms 3 and 4, the door between bedroom 2 and the hallway was open from the time of ignition, allowing the room to fill with products of combustion as the living room fire grew and transitioned through flashover. Prior to suppression, temperatures in the bedroom ranged from 278 °C (532 °F) at the ceiling to 75 °C (167 °F) 1 ft above the floor (Figure 5.148a). This range was comparable to temperatures measured in the other two open bedrooms at that time. Temperatures at all elevations began to decrease during the initial suppression action and continued through the removal of the bedroom 2 window. At this point the temperatures in bedroom 2 ranged from 121 °C (250 °F) at the ceiling to 32 °C (90 °F) 1 ft above the floor. Temperatures had uniformly decreased below 75 °C (167 °F) prior to the start of hydraulic ventilation.



(a) Bedroom 2 Temperature



(b) Bedroom 2 Heat Flux



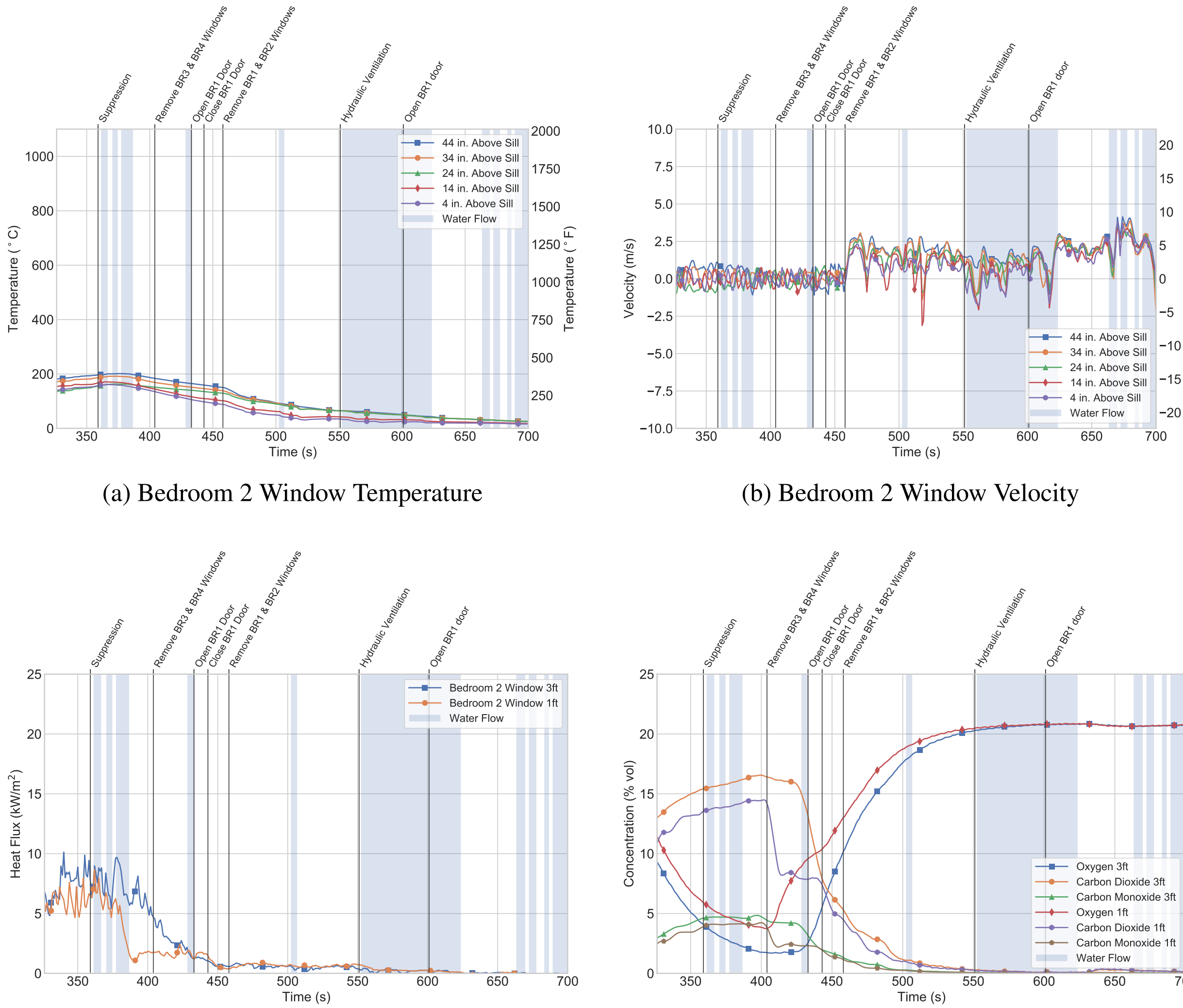
(c) Bedroom 2 Gas Concentration

Figure 5.148: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 2 during Experiment 20.

At the time of intervention, the heat flux measured in bedroom 2 was 4.7 kW/m^2. The bedroom 2 heat flux sensor 3 ft above the floor on the bed measured a decrease 30 s after intervention, as the suppression crew completed interior suppression actions (Figure 5.148b). Similar to temperatures in the room, heat flux continuously decreased in the period following suppression, dropping below 1.0 kW/m^2 prior to the removal of the bedroom 2 window. Window ventilation allowed products of combustion to exhaust from bedroom 2, causing heat flux to further decrease to negligible values prior to the start of hydraulic ventilation.

The gas sample location on the bed (Figure 5.148c) had pre-suppression O_2, CO_2, and CO concentrations of 5.7%, 14.0%, and 3.6%, respectively, an indication that the smoke layer had descended below the top of the bed. The concentrations remained steady until 65 s after suppression, when CO and CO_2 concentrations began to decrease and the O_2 concentration began to increase. This approximately matches the time at which 3 ft gas concentrations in the bedroom 3 window began to trend toward ambient, despite the lack of exterior ventilation local to bedroom 2. The rate at which gas concentrations trended toward ambient was rapid at first, but slowed as the bedroom 1 door was closed. The decrease in CO and CO_2 concentrations continued as the bedroom 2 window was removed, allowing products of combustion in bedroom 2 to directly exhaust to the exterior of the structure. CO and CO_2 concentrations remained elevated at beginning of hydraulic ventilation, but decreased to negligible concentrations by the end of that action.

The window temperatures and velocities shown in Figures 5.149a and 5.149b indicate that when the bedroom 2 window was opened, the window acted as a unidirectional exhaust, similar to the bedroom 3 window. The combustion products that were at a higher temperature and pressure than exterior conditions exhausted from the structure to the outside. As the temperature and pressure in the room dropped, the influence of the wind that flow across side C (from side B to toward side D) became more apparent as seen by the spikes of inflow. Window velocities fluctuated in the period following window ventilation, with exhaust flows between 2 m/s and 2.5 m/s (4.5 mph to 5.6 mph).



(a) Bedroom 2 Window Temperature

(b) Bedroom 2 Window Velocity

(c) Bedroom 2 Window Heat Flux

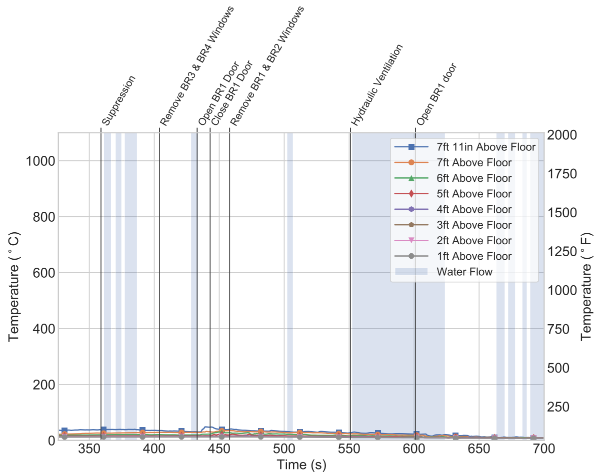
(d) Bedroom 2 Window Gas Concentration

Figure 5.149: Post-intervention temperature, velocity, heat flux measurements at bedroom 2 window during Experiment 20.

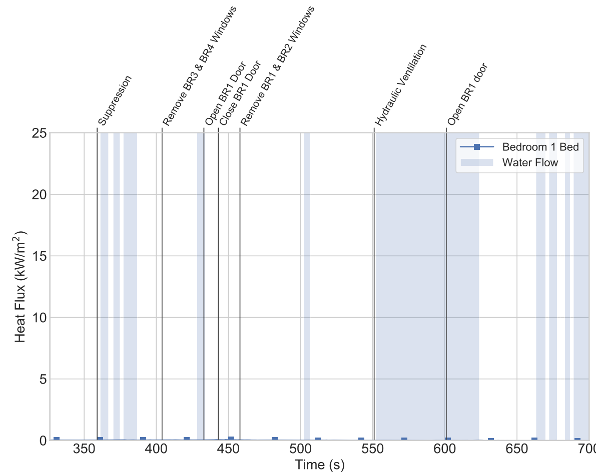
The heat flux values measured immediately prior to suppression 3 ft and 1 ft above the floor below the window were 9.4 kW/m^2, and 6.7 kW/m^2, respectively (Figure 5.149c). These values were comparable to the heat flux measured at the corresponding window locations in bedroom 3 at the time of intervention. In a similar fashion to temperatures, heat flux began to decrease during the initial suppression action. Although this decrease was more gradual at the 3 ft location than at the 1 ft location, both values had decreased below 1.0 kW/m^2 prior to ventilation of the bedroom 2 window. The decrease in heat flux continued as products of combustion were exhausted from the room via the open window, reaching negligible values prior to the start of hydraulic ventilation. Prior to suppression, gas concentrations at the bedroom 2 window were 4.2% O_2, 15.4% CO_2, and 4.6% CO at the 3 ft level and 6.0% O_2, 13.4% CO_2, and 3.8% CO at the 1 ft level (Figure 5.149d). This was an indication the smoke layer had descended to the 1 ft elevation, similar to the other open bedrooms. Concentrations remained approximately steady until 65 s and 43 s after suppression at the 3 ft and 1 ft elevations, respectively. At this point, gas concentrations began to trend toward ambient. The timing of this decrease in CO and CO_2 matches the time at which gas concentrations began to improve at the corresponding location in bedroom 3, indicating that the cooling and subsequent reduction in gas production caused by extinguishment of the living room fire resulted in an improvement in gas concentrations at these locations. Gas concentrations continued to recover through ventilation of the bedroom 2 window, with CO and CO_2 concentrations decreasing to negligible concentrations prior to the start of hydraulic ventilation.

5.10.6 Bedroom 1

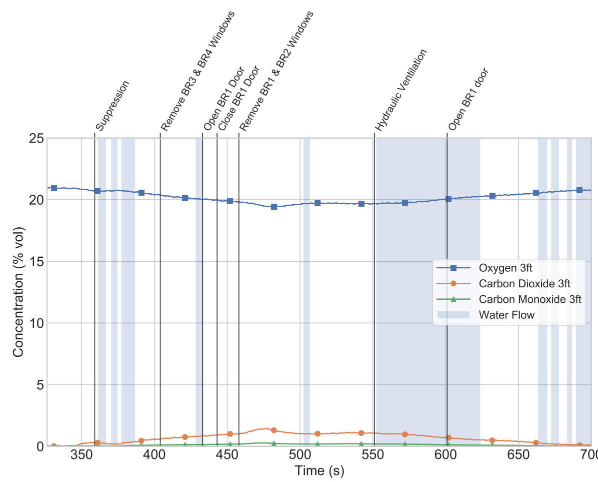
In contrast to bedrooms 2, 3, and 4, the door between bedroom 1 and the hallway was closed from the start of the experiment until 64 s after the beginning of suppression (433 s after ignition). At the time of suppression, temperatures in bedroom 1 were below 40 °C (104 °C) at all elevations (Figure 5.150a), and the heat flux measured 3 ft above the floor at the center of the bed was negligible (Figure 5.150b). After the bedroom door was opened, the ceiling temperature briefly increased to 48 °C (131 °F) before immediately dropping, and the bed heat flux did not exhibit any increase. The magnitude of these increases was minimal, as temperatures and pressures in the hallway and common space had already begun to decrease as a result of suppression.



(a) Bedroom 1 Temperature



(b) Bedroom 1 Heat Flux

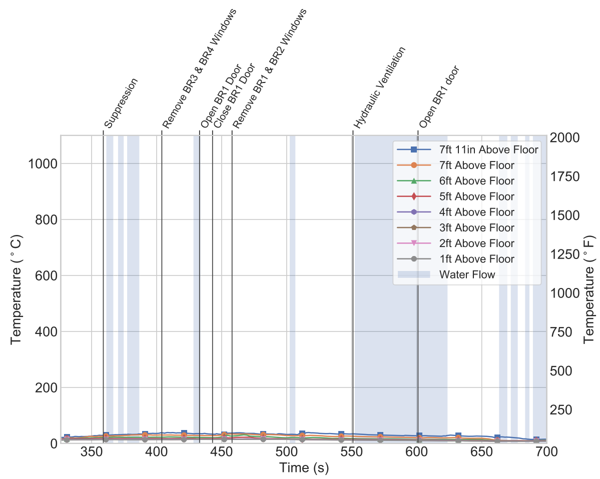


(c) Bedroom 1 Gas Concentration

Figure 5.150: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 20.

As a result of isolation provided by the bedroom 1 door, CO and CO_2 concentrations in bedroom 1 were considerably lower at the time of intervention compared to the open bedrooms (bedroom 2, bedroom 3, and bedroom 4). The primary sources for combustion gases entering the room were from leakage around the door and through the HVAC system. Following suppression, the CO and CO_2 concentrations at the bedroom 1 measurement location continued to increase while the O_2 concentrations continued to decrease, with no substantial impact from the doorway manipulation or window ventilation, as shown in Figure 5.150c. CO and CO_2 peaked 114 s after intervention (473 s after ignition), after the bedroom 1 window was ventilated. Although the peak gas concentrations were observed later in the experiment than other bedrooms, the peak gas concentrations were less severe than those observed in non-isolated areas, with peak O_2, CO_2, and CO concentrations of 19.5%, 1.4%, and 0.3%, respectively.

At the time of intervention, ceiling temperatures in bathroom 1 were 30 °C (86 °F), as shown in Figure 5.151, slightly lower than the adjoining bedroom, despite the closed door between the two spaces. The temperatures briefly increased following the opening of the bedroom 1 door, but the peak ceiling temperature remained below 40 °C (104 °F), and temperatures 4 ft and below did not increase. Similar to bedroom 1, temperatures in bathroom 1 began to decrease following the ventilation of the bedroom 1 window and continued to decrease for the remainder of the experiment.



(a) Bathroom 1 Temperature

Figure 5.151: Post-intervention temperature, heat flux and gas concentration measurements in bedroom 1 during Experiment 20.

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.

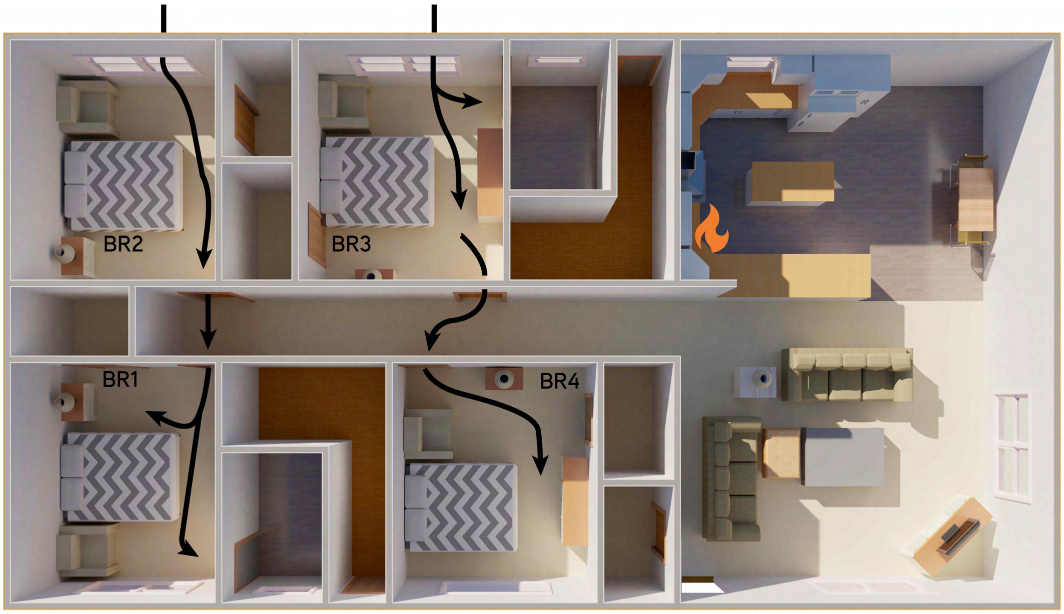
- Interior operations of search crews were simulated by controlling the opening and closing of interior doors by exterior crews and a series of purpose built cable systems. Specific to each experiments, windows were ventilated and doors were opened or closed to simulate search crews moving through the 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 8 kitchen fires and 2 living room fires that included search operations (excluding the baseline experiment, Experiment 18), there were three 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.

For 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. Firefighters that entered into bedrooms 2 and 3 proceeded to search beyond the room of entry by entering bedrooms 1 and 4, respectively. Experiments 11–13, 19 utilized this search approach for both a kitchen fire (Experiments 11–13) and a living room fire (Experiment 19). The key variables that changed were if the room 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.

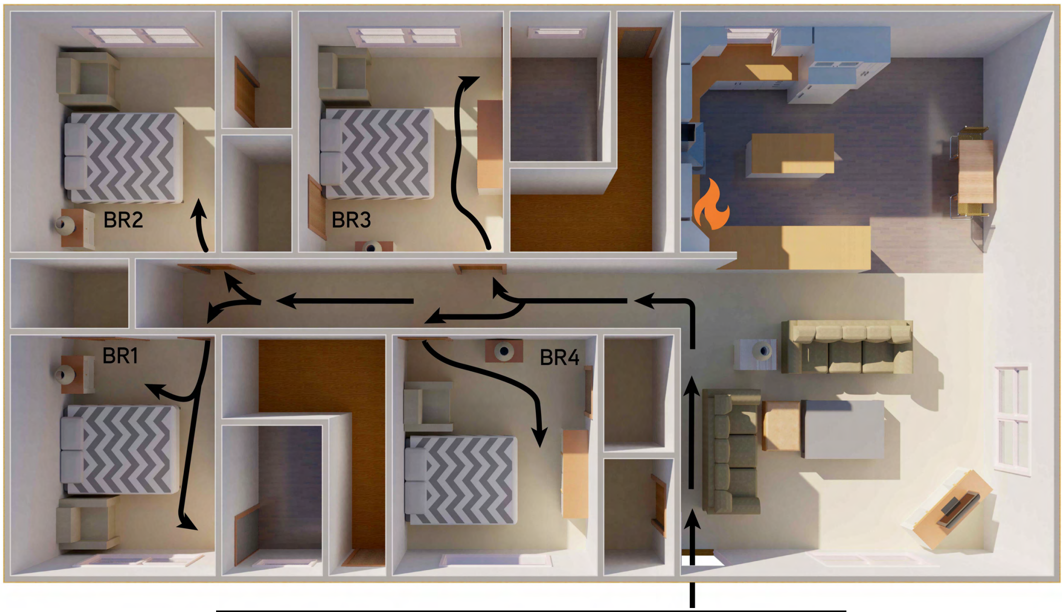


Experiment	Details
11, 12	Isolation of bedroom 3 post entry, varied suppression timing
13, 19 *	Isolation of bedroom 2 post entry, varied suppression timing

* Living room ignition

Figure 6.1: Window initiated search pathways that originated simultaneously from bedrooms 2 and 3 for kitchen and living room fires. Black lines represent pathways the search crews took.

Three kitchen experiments and one living room experiment included door initiated search. In these experiments, the crews entered the open front and traveled down the hallway to search bedrooms 3 and 4, then re-entered the hallway to search bedrooms 1 and 2. The variables changed were timing of suppression relative to search (Experiments 14, 17, 20) and isolation of the front door (Experiment 15). Figure 6.2 shows the routes taken for the crews for these four experiments.

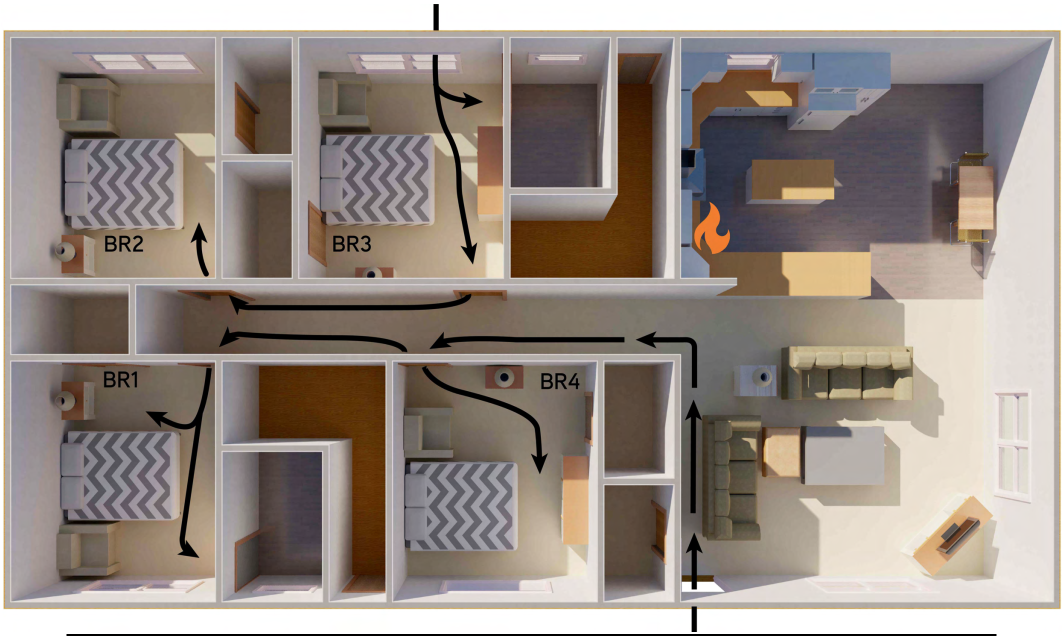


Experiment	Details
14	Post suppression
15	Isolation of front door post entry
17	Pre-suppression
20 *	During suppression

* Living room ignition

Figure 6.2: Door initiated search pathways for a kitchen and living room fires. Black lines represent pathways the search crews took.

In Experiment 16, crews simultaneously entered through the bedroom 3 window and the front door. The crew that entered the window, search bedroom 3 and then continued to search bedroom 2. The crew that entered through the front door, closed it upon entry and then moved to search bedroom 4. After searching bedroom 4, the crew re-entered the hallway and moved to search bedroom 1. Figure 6.3 shows the routes taken for the crews for this experiment.



Experiment	Details
16	Isolation of front door post front door and window entry

Figure 6.3: Window initiated search pathways that originated from front door and bedroom 3 window for kitchen 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 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. An 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 an 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 ignition location, consider only the kitchen ignitions (Experiments 11-18), excluding the living room ignitions (Experiments 19-20). To control for the time of intervention, the analysis will focus on the cumulative toxic FED at the time of earliest intervention across the kitchen experiments, which occurred during Experiment 17 at 1130 s post-ignition of the gas burner. At this point, the fire was still generally contained to the kitchen cabinets near the point of origin. 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 all gas measurement locations within the structure for the 8 kitchen 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 1130 s post pilot burner ignition, the minimum toxic FED values were below 0.065 and maximum values reached approximately 2. 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 (1130 s Post Burner Ignition) for All Kitchen Fires

		Toxic Fractional Effective Dose	
Elevation	Room	Median	Range
3 ft	Bedroom 1	0.048	0.027 — 0.125
	Bedroom 2	0.370	0.032 — 1.26
	Bedroom 2 Window	0.406	0.050 — 1.98
	Bedroom 3 Window	0.550	0.046 — 2.06
	Living Room Entry	0.062	0.044 — 0.133
	Start Hallway	0.124	0.037 — 0.360
	Mid Hallway	0.217	0.036 — 1.29
	End Hallway	0.246	0.042 — 1.60
1 ft	Bathroom 1	0.233	0.036 — 0.463
	Bedroom 2 Window	0.202	0.037 — 0.618
	Bedroom 3 Window	0.337	0.037 — 1.26
	Bathroom 3	0.367	0.065 — 1.05
	Living Room Entry	0.047	0.032 — 0.068
	Start Hallway	0.084	0.033 — 0.252
	Mid Hallway	0.115	0.039 — 0.240
	End Hallway	0.057	0.038 — 0.187

For reference, the cooking oil auto-ignited, on-average, 361 s after the pilot burner was ignited. Therefore, if the start of the clock for fire service response was considered to be oil ignition, the data presented here are approximately 769 s after the cooking oil ignited.

The median 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 only the experiments which contained the same initial conditions. Experiments 11–14 and 18 represent the largest subset of data that have the same initial conditions: closed bedroom 1 door and open bedroom 2 and bedroom 3 doors. The data at the two 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 4.6E-09, 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 other words, toxic gas exposures increase with elevation.

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 closed doors?). Data from the five 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.

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:

- Bedroom 1 toxic FED is lower than the toxic FED at the bedrooms 2 and 3 windows (i.e., position behind a closed bedroom door).
- Living room entry toxic FED is lower than the toxic FED at the bedrooms 2 and 3 windows (i.e., position along intake of flow path through front door versus end point of flow path).
- Start hallway toxic FED is lower than the toxic FED at the bedroom 3 window (i.e., position along intake of flow path within open volumes in the structure versus end point of flow path).

A key takeaway from this analysis is that the cumulative toxic FED in this structure at earliest intervention time was lower in an isolated bedroom compared to non-isolated locations at the 3 ft elevations with open bedroom doors. Additionally, the cumulative toxic FED near the open vent (i.e., open front door and start hallway which were in the inlet portion of the flow path) was lower than non-isolated bedrooms without open vents. Is it important to note that in these kitchen fire experiments, in the absence of intervention, the kitchen fire spread to the living room, which subsequently transitioned through flashover. The open front door limited the accumulation of combustion gases, but was also an intake for air which aided the flame spread from the kitchen to living room.

An assessment of the relation between each of the measurements at the 1 ft elevation, similarly resulted in several differences in toxic FED values that were statistically significant:

- Living room entry toxic FED is lower than the toxic FED at the bedroom 2 window, the bedroom 3 window, and the bedroom 3 bathroom (i.e., position along intake of flow path through front door versus end point of flow path).
- Start hallway toxic FED is lower than the toxic FED at the bedroom 3 bathroom (i.e., position along intake of flow path within open volumes in the structure versus end point of flow path).

Like the 3 ft elevation, the cumulative toxic FED near the open vent at 1 ft (i.e., near the open front door) was lower than the 1 ft elevations in the non-isolated bedrooms with open doors. Further, likely driven by gas exchange with bedroom 2, the cumulative end hallway location was lower than the bedroom 3 measurements at the window and the bathroom. Unlike the 3 ft elevation, the 1 ft measurement in bathroom 1 was not statistically different than the non-isolated bedrooms at the same elevation. This was likely driven by gas accumulation through the HVAC supply vent, the lack of an HVAC return vent, and the small volume of the space compared to the adjoining bedroom.

The limited number of living room experiments, prevented a statistical analysis of toxic FED data, but there were still several key takeaways. Figure 6.5 shows the locations for exposure measurements of potentially trapped occupants and the data presented in Table 6.2 shows the cumulative toxic FED at the time of earliest intervention for the living room experiments (359 s). In both Experiments 19 and 20, the living room was in a post-flashover state prior to intervention.

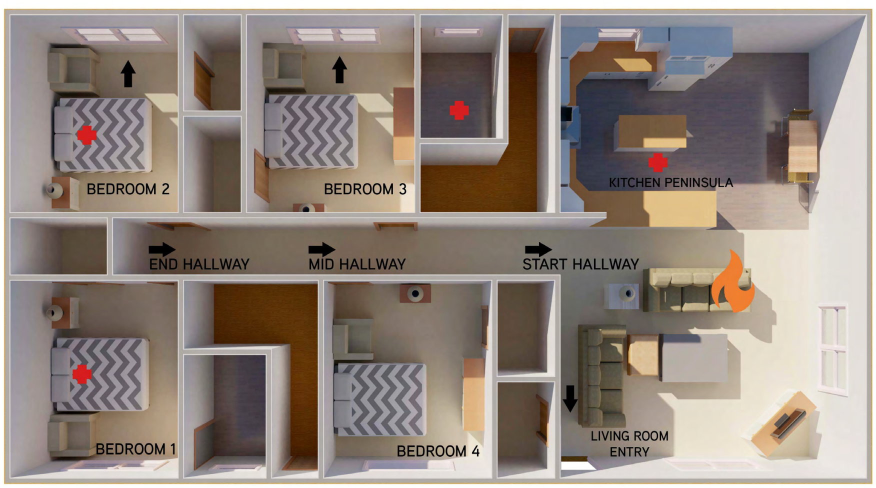


Figure 6.5: Toxic gas exposure measurement locations. The red plus signs are locations of potentially trapped occupants and the black arrows are measurement locations along potential egress pathways.

At the 3 ft elevation the closed door in bedroom 1 limited the flow of combustion gases, and as a result, the toxic FED values were demonstratively lower than the open spaces at the same elevation. Similar to the kitchen ignition experiments, this shows the impact of a closed door on limiting gas transport, even when the living room was in a post flashover state. Cumulative toxic FEDs at the 1 ft elevation indicate that there were spaces where the smoke layer did not descend to the floor, particularly in the mid hallway and end hallway locations. These two locations did not directly abut with the living room but were not at the termination point of the flow path that was between the living room and bedroom 2.

Table 6.2: Toxic Exposures at Time of Earliest Intervention (359 s Post Burner Ignition) for All Living Room Fires

Elevation	Room	Toxic Fractional Effective Dose Exp 19	Exp 20
3 ft	Bedroom 1	0.013	0.010
	Bedroom 2	13.2	10.8
	Bedroom 2 Window	24.1	20.3
	Bedroom 3 Window	11.9	9.1
	Living Room Entry	80.8	73.8
	Start Hallway	6.91	3.64
	Mid Hallway	13.8	9.33
	End Hallway	67.2	63.9
1 ft	Kitchen Peninsula	83.3	58.8
	Bedroom 2 Window	11.5	11.0
	Bedroom 3 Window	2.18	1.69
	Bathroom 3	3.02	1.23
	Living Room Entry	26.7	41.6
	Start Hallway	1.14	0.47
	Mid Hallway	0.77	0.77
	End Hallway	0.42	0.73

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:

$$t_{rad}(t) = \frac{q_c}{q(t)^{4/3}} \text{ for } q(t) > 2.5\ kW/m^2 \tag{6.6}$$

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]

$$t_{conv}(t) = C_q T(t)^{-n} \tag{6.7}$$

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 ignition location, consider only the kitchen ignitions (Experiments 11-18), excluding the living room ignitions (Experiments 19-20). To control for the time of intervention, the analysis will focus on the cumulative FED at the time of earliest intervention across the kitchen experiments, which occurred during Experiment 17 at 1130 s post-ignition of the gas burner. Figure 6.6 shows the locations for exposure measurements of potentially trapped occupants and Table 6.3 presents the median and range of cumulative FED at all temperature and heat flux measurement locations within the structure for the 8 kitchen experiments.

Figure 6.6: 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 6.3 shows that at both the 3 ft and 1 ft elevations the thermal FEDs were generally lower than their respective toxic FED for the kitchen experiments. At the time of earliest intervention, the kitchen was in a pre-flashover state. At 1130 s post-ignition, the fire was contained to the kitchen cabinets with some flame rollover toward the living room and open front door. As a result, despite the lack of accumulation of toxic gases at the living room entry and start hallway relative to other open spaces in the structure (see Table 6.1), the flow of combustion gases from the kitchen fire toward the front door in the kitchen ignition experiments resulted in higher peak thermal FEDs at these locations.

To determine if the perceived differences in Table 6.3 were significant, a statistical analysis was performed. Experiments 11–14 and 18 represent the largest subset of data that have the same initial conditions: closed bedroom 1 door and open bedroom 2 and bedroom 3 doors. The data at the two 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 3.6E-08, less than 0.05, which indicated that the differences between the 3 ft thermal FEDs and 1 ft thermal FEDs are statistically significant.

Table 6.3: Thermal Exposures at Time of Earliest Intervention (1130 s Post Burner Ignition) for All Kitchen Fires

Elevation	Room	Thermal Fractional Effective Dose Median	Range
3 ft	Bedroom 1	0.0019	0.0016 — 0.0044
	Bedroom 2	0.0062	0.0015 — 0.12
	Bedroom 2 Window	0.0052	0.0015 — 0.038
	Bedroom 3 Window	0.0035	0.0013 — 0.034
	Living Room Entry	0.054	0.0021 — 0.74
	Start Hallway	0.0089	0.0019 — 0.33
	Mid Hallway	0.0044	0.0017 — 0.023
	End Hallway	0.0056	0.0016 — 0.048
1 ft	Bathroom 1	0.0020	0.0015 — 0.0059
	Bedroom 2 Window	0.0020	7.0e-4 — 0.0038
	Bedroom 3 Window	0.0020	7.4e-4 — 0.0036
	Bathroom 3	0.0017	6.8e-4 — 0.0028
	Living Room Entry	0.026	0.0015 — 0.72
	Start Hallway	0.0028	0.0012 — 0.32
	Mid Hallway	0.0023	7.8e-4 — 0.0050
	End Hallway	0.0021	7.4e-4 — 0.0041

For reference, the cooking oil auto-ignited, on-average, 361 s after the pilot burner was ignited. Therefore, if the start of the clock for fire service response was considered to be oil ignition, the data presented here are approximately 769 s after the cooking oil ignited.

Similar to the toxic FED analysis, data from the 5 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 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 the analysis revealed the follow differences to be statistically significant:

- Bedroom 1 thermal FEDs were lower than the living room entry and start hallway locations (i.e., position behind a closed bedroom door).
- Bedroom 3 window and the mid hallway thermal FEDs were lower than the living room entry location (i.e., proximity of location to fire compartment).

The 1 ft elevation showed similar statistical differences to the 3 ft elevation:

- Bathroom 1, bathroom 3, and bedroom 3 window thermal FEDs were lower than the living room entry location (i.e., position both adjacent to flow path and proximity of location to fire compartment).
- Bathroom 3 thermal FEDs were lower than the start hallway location (i.e., position both adjacent to flow path and proximity of location to fire compartment).

Both elevations showed a similar trend. Isolated spaces and spaces adjacent to the flow of gases had lower thermal FEDs than those areas where flame rollover from the kitchen fire increased the radiative heat transfer and the flow of higher temperature combustion gases increased the convective heat transfer.

The limited number of living room experiments, prevented a statistical analysis of thermal FED data, but there were still several key takeaways. Figure 6.7 shows the locations for exposure measurements of potentially trapped occupants and the data presented in Table 6.4 shows the cumulative thermal FED at the time of earliest intervention for the living room experiments (359 s), Experiments 19 and 20. In both experiments, the living room was in a post-flashover state prior to intervention compared to the pre-flashover state for the earliest intervention time for the kitchen experiments.

Figure 6.7: 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.

Table 6.4: Thermal Exposures at Time of Earliest Intervention (359 s Post Burner Ignition) for All Living Room Fires

		Toxic Fractional Effective Dose	
Elevation	Room	Exp 19	Exp 20
3 ft	Bedroom 1	0.001	1.4e-4
	Bedroom 2	1.29	0.84
	Bedroom 2 Window	1.83	1.88
	Bedroom 3 Window	1.40	1.33
	Living Room Entry	422	285
	Start Hallway	12.0	18.7
	Mid Hallway	2.80	0.64
	End Hallway	5.31	6.29
1 ft	Kitchen Peninsula	77.7	4.95
	Bedroom 2 Window	0.97	1.07
	Bedroom 3 Window	0.16	0.086
	Bathroom 3	0.011	0.003
	Living Room Entry	373	243
	Start Hallway	2.56	7.73
	Mid Hallway	2.38	0.17
	End Hallway	0.012	0.008

At the 3 ft elevation the closed door in bedroom 1 limited the flow of higher temperature combustion gases and similar to the toxic FED, the thermal FED values were demonstratively lower than the open spaces at the same elevation. Similar to the kitchen ignition experiments, this shows the impact of a closed door on limiting gas transport and therefore limiting the heat transfer, even in the living room experiments where the common space was in a post flashover state at the time of first intervention. Cumulative thermal FEDs at both the 3 ft and 1 ft elevation indicate that as the distance between the living room and measurement location increased, the thermal FED decreased due to heat losses to the structure and mixing with cooler air in the space prior to ignition. It is important to note the elevated thermal FED of the kitchen peninsula location. This location was designed to be shielded horizontally but not shielded vertically. In these experiments flame rollover from the living room resulted in a high radiative flux to the location, which resulted in the elevated thermal FEDs.

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 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 6.8.

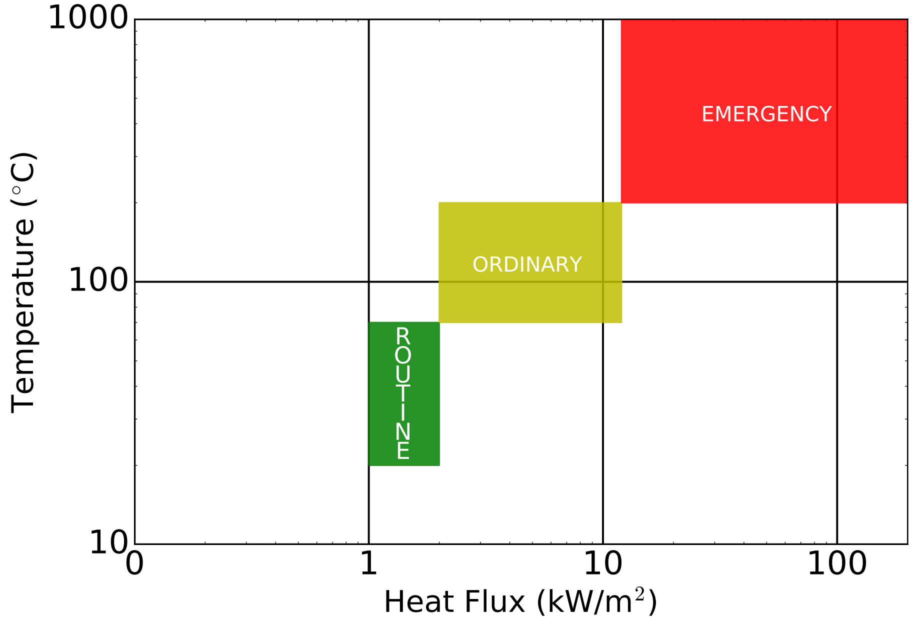


Figure 6.8: Thermal Operating Classes [94, 95]

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 6.9. 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.

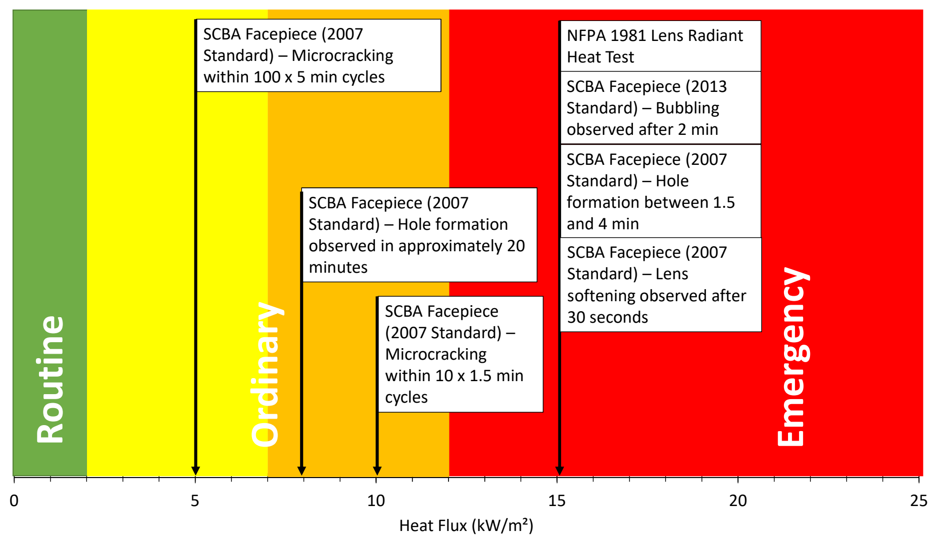
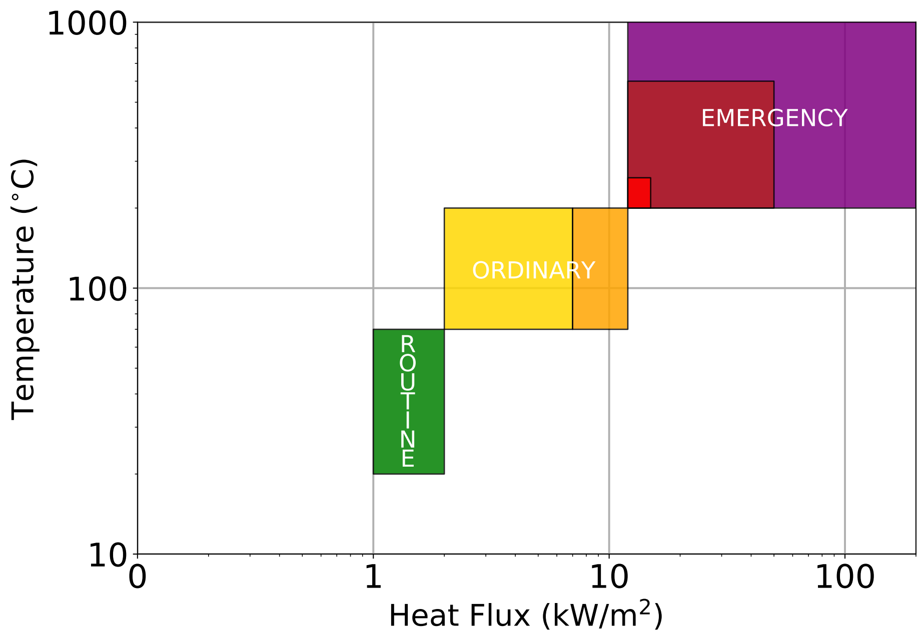


Figure 6.9: Comparison of thermal operating classes with modern PPE performance limits from [97–100]

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 6.9, 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 6.10.



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 6.10: Modified Thermal Operating Classes

Consider the baseline kitchen ignition experiment, Experiment 18. The fire was ignited on the kitchen counter near the range to simulate an unattended cooking fire. At the time of ignition, the kitchen window and front door were opened. The doors to bedroom 1 and bedroom 4 were closed, while the doors to bedroom 2 and bedroom 3 were open. The fire spread to multiple kitchen cabinets which led to flashover of the kitchen. The fire then spread to the living room, where flashover occurred following the failure of the side A and side D windows. At this point, the suppression crew conducted interior suppression operations. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the side A living 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 6.11 shows the shows the thermal conditions expressed in terms of thermal operating classes corresponding to the 3 ft temperatures and corresponding heat fluxes in the period following intervention for Experiment 18.

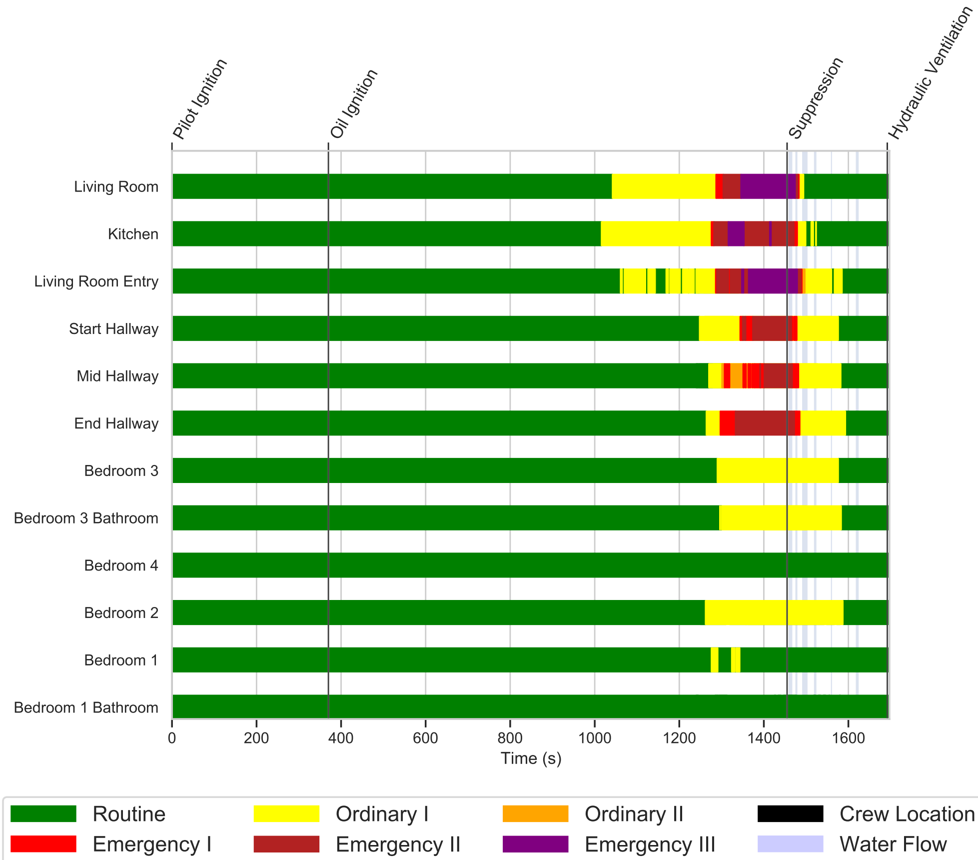


Figure 6.11: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes for baseline kitchen ignition experiment without interventions (Experiment 18.)

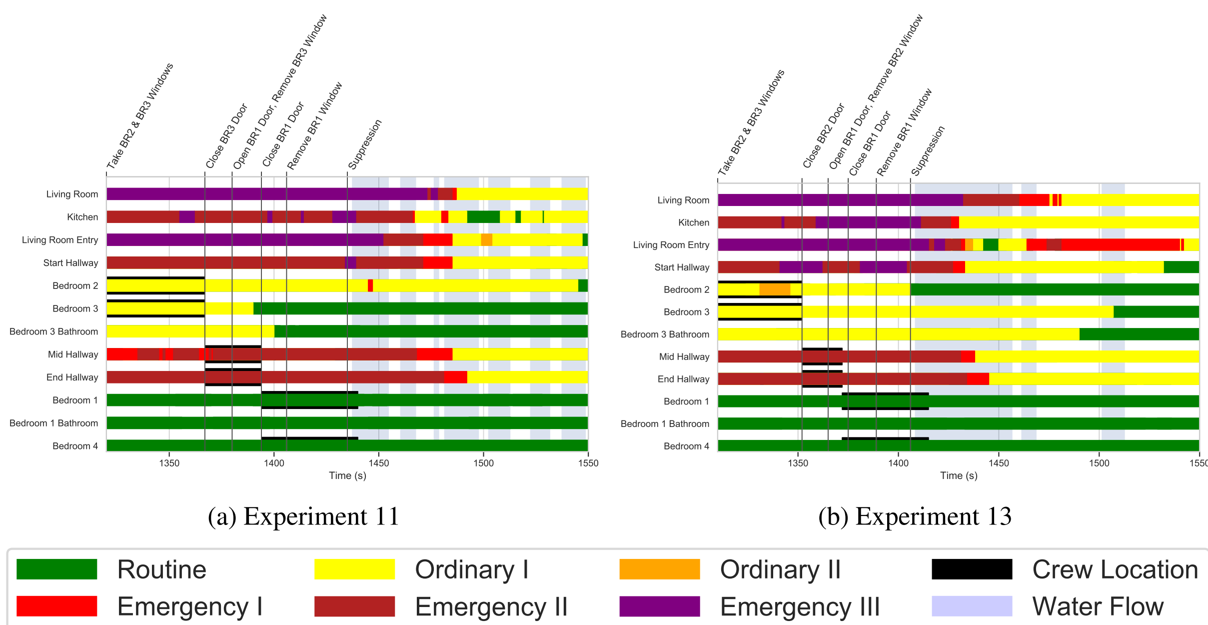
Early in the experiment, while the fire was predominately contained to the area of ignition in the kitchen, thermal classes at the 3 ft elevation were uniform throughout the structure at the routine level. As the fire in the kitchen spread into multiple cabinets and there was rollover from the kitchen to the living room approximately 630 s after the cooking oil ignition, the common kitchen and living room space increased to a routine operating class. As both the kitchen and living room transitioned through flashover, the operating classes at 3 ft level in the kitchen, living room, and throughout the hallway all increased to the emergency operating class with peak temperatures ranging from 1062 °F (1944 °F) at the living room entry to 322 °C (612 °F) at the mid hallway. At this point, the post-flashover conditions in the common space would limit operations initiated through the front door ahead of suppression.

For the two bedrooms where the hallway door was open through the duration of the experiment, bedrooms 2 and 3, the operating level reached ordinary levels and 3 ft temperatures peaked at 179 °C (354 °F) and 175 °C (347 °F), respectively. In contrast, the operating levels in bedrooms which were isolated from the start of the experiment (bedrooms 1 and 4) remained at the routine level with 3 ft temperatures remaining below 30 °C (86 °F).

6.3.1 Impact of Isolation

Window Initiated Search Pre-Suppression

Experiments 11 and 13 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 11 compared to bedroom 2 in Experiment 13. To assess the impact of isolation of the space of entry for a window initiated search prior to suppression Figure 6.12 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 intervention for Experiments 11 and 13.



(a) Experiment 11 (b) Experiment 13

Figure 6.12: 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 11 and 13, 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 flow through the bedrooms in both experiments. The inflow of air through the respective windows had a cooling effect at the 3 ft measurement locations in the period immediately following intervention. In the bedrooms where the interior door remained open, the decrease in temperature was temporary. Temperatures began to increase 28 s and 47 s after intervention in Experiments 11 and 13, respectively. In Experiment 11, temperatures at 3 ft in bedroom 2 decreased from 140 °C (284 °F) at the time of window ventilation to a minimum value of 99 °C (210 °F) before increasing 28 s to a peak of 201 °C (396 °F) 10 s after the start of suppression. The operating class increased to the emergency level for 3 s before dropping back into the ordinary level. A similar trend was observed in Experiment 13, where bedroom 3 remained open. The 3 ft temperature decreased from 178 °C (352 °F) at intervention to a minimum value of 130 °C (266 °F). Temperatures increased as the flow of hot gases from the hallway continued, reaching 148 °C (298 °F) immediately prior to suppression. Despite the temporary temperature decrease, 3 ft temperatures in bedrooms 2 and 3 remained within the threshold for ordinary operating conditions until the completion of suppression operations.

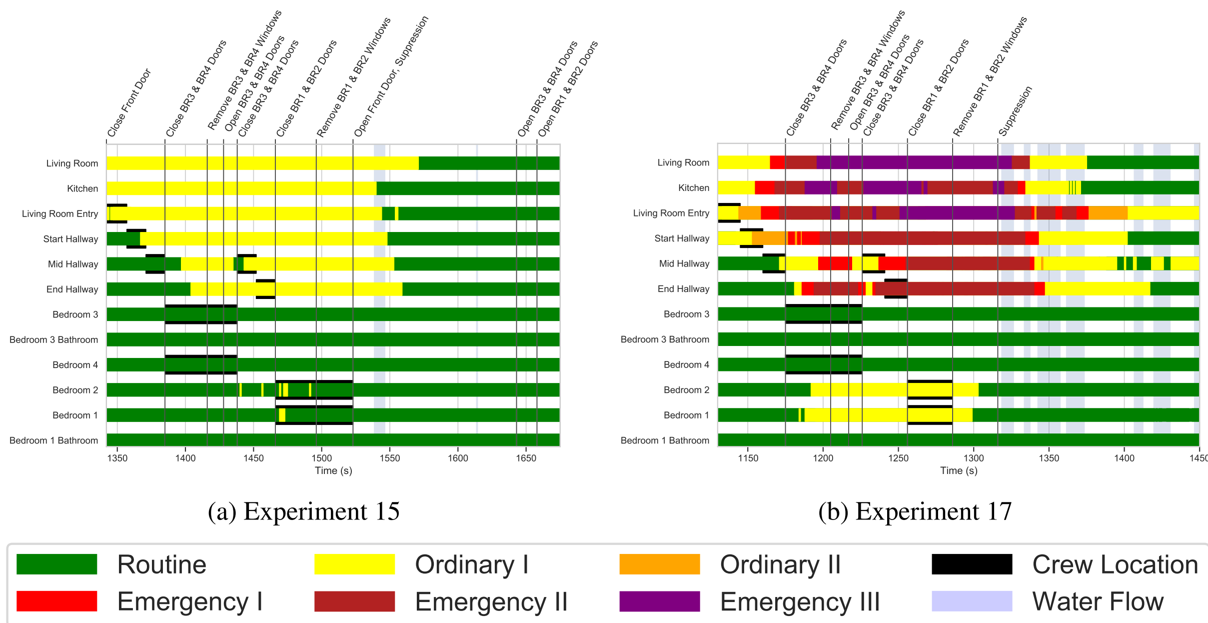
Closing the interior bedroom door following the window initiated search had a sustained positive impact on temperature in both Experiments 11 and 13. In each case, the bedroom door was closed prior to the temperature increase that was observed in the corresponding open bedrooms. As a result, temperatures decreased continuously in the closed bedroom following door closure and the closed bedrooms transitioned from ordinary operating conditions to routine operating conditions prior to the start of suppression. This contrasts with conditions in the open bedrooms, which were consistent with ordinary operating conditions until after the end of suppression. Thus, isolation of the bedroom door would likely result in a lower thermal exposure to firefighters operating in the space.

The doors between bedrooms 1 and 4 and the hallway were closed from the time of ignition. As a result, temperatures were lower than comparable open spaces. In both experiments, peak temperatures in the closed bedrooms remained below 50 °C (122 °F), which is within the routine operating class. Peak temperature between bedrooms 1 and 4 were comparable between the two experiments, indicating that the 10 s period during which the bedroom 1 door was open did not substantially impact the 3 ft temperatures for firefighters conducting a search compared to bedroom 4, where the hallway door remained closed for the duration of the experiment.

During the window-initiated searches ahead of suppression, the location in which the crew would have been exposed to the most severe thermal conditions was in the hallway, during the period when the search crews moved from the bedrooms of entry on side C (bedrooms 2 and 3) to those on side A (bedrooms 1 and 4). Temperatures at the mid-hallway and end-hallway locations were consistent with emergency operating conditions for the duration of the search sequence, peaking at the emergency II level. In Experiments 11 and 13, peak mid-hallway temperatures were 425 °C (797 °F) and 520 °C (968 °F), respectively, and peak end hallway temperatures were 522 °C (972 °F) and 562 °C (1044 °F), respectively. Peak thermal conditions (emergency class II) were beyond the testing limits of PPE and would limit the residence time of firefighters attempting to traverse the hallway.

Door Initiated Search Pre-Suppression

Experiments 15 and 17 examined a door initiated search that occurred prior to suppression. The primary difference between the two experiments was that in Experiment 15 the initial action was closing the front door compared to Experiment 17 where the front door was open for the duration of the experiment. To assess the impact of isolation of the space of entry for a door initiated search prior to suppression, Figure 6.13 shows the thermal conditions, expressed as the thermal operating class corresponding to the 3 ft temperature and heat flux (where available) in the period following intervention. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.



(a) Experiment 15 (b) Experiment 17

Figure 6.13: Comparison of thermal operating conditions based upon 3 ft elevation temperatures during post-intervention period for pre-suppression door initiated search tactics.

In both Experiments 15 and 17, all interior bedroom doors to the hallway were open from the time of ignition. In Experiment 15, the front door was closed as the kitchen fire spread to involve multiple cabinets, but prior to flashover of the kitchen. At this point, 3 ft temperatures in the kitchen and living room had reached levels consistent with an ordinary operation conditions. The closed front door in Experiment 15 limited the oxygen available for combustion which kept the fire contained to the kitchen cabinets near the area of ignition. Higher-temperature combustion gases accumulated within the space and as a result, kitchen, living room, and connected hallway spaces had temperatures at the 3 ft elevation that were consistent with an ordinary operating condition. Temperatures peaked in hallway at 126 °C (259 °F) at the start hallway location where ordinary conditions remained until after the front door was opened for suppression. Bedrooms 3 and 4 remained in the routine class for the duration of the experiment. The 3 ft temperatures in both rooms peaked at approximately 50 °C (122 °F) before decreasing following the closure of the interior door and removal of the respective windows. For bedrooms 1 and 2, which were isolated later, 3 ft temperatures reached 70 °C (158 °F) and heat fluxes reached 2 kW/m^2. As a result, at the time crews occupied these bedrooms, operating conditions reached the ordinary class before dropping to the routine operating class following isolation.

In contrast to Experiment 15, the front door remained open in Experiment 17. Although crews entered the structure while the fire was still contained to the kitchen (recall Figure 5.96), conditions 3 ft above the floor at the living room entry had reached the ordinary exposure class. The crews continued to the start hallway location and then toward the mid hallway location, where they entered bedrooms 3 and 4, and isolated the rooms behind them. Isolation and subsequent local ventilation of bedrooms 3 and 4 kept those spaces within the routine exposure class, with peak 3 ft temperatures at 55 °C (131 °F) and 68 °C (154 °F), respectively. After searching bedrooms 3 and 4, the crews returned to the hallway and proceeded to bedrooms 1 and 2. Upon reentry to the hallway, the crews began searching at the ordinary operating class levels despite the start hallway and living room reaching the emergency class due to their position being at further distance from the fire. Air entrainment into the structure through the open front door facilitated flame spread, which led to an increased heat release rate from the fire, and eventual flashover of the kitchen and living room. As a result, the pathway the search crews took to initiate the search had now reached levels consistent with an emergency operating class, preventing egress along the pathway of entry.

During the period when the search crews moved from the first set of bedrooms (bedrooms 3 and 4) to the second set of bedrooms (bedrooms 1 and 2), temperatures at the mid hallway and end hallway locations were consistent with emergency operating conditions, of 250 °C (482 °F) and 370 °C (698 °F) respectively. Additionally, heat flux at the mid hallway and end hallway locations were 4.5 kW/m^2 and 2.5 kW/m^2, respectively. When the crews reached bedrooms 1 and 2, the spaces were isolated and the respective bedroom windows were ventilated. Conditions remained at the ordinary operating class until gas exchange through the windows returned 3 ft temperatures to a routine operating class level despite emergency conditions in the hallway prior to suppression. Note, that although the order of opening and closing of interior doors in Experiment 17 was set prior to ignition, at the time at which the crews entered bedrooms 3 and 4, the far bedrooms (1 and 2) were still at routine operating class levels and likely would have remained at similar levels had all four bedrooms been isolated at the same time.

Table 6.5 lists the peak temperature and peak heat flux at each of those locations that the search crews occupied for Experiments 15 and 17. The data from these experiments show both the value of isolating the fire compartment from a supply of oxygen and compartmentalization and subsequent localized ventilation of spaces within the larger structure.

Table 6.5: Peak 3 ft elevation temperatures and corresponding heat flux measurements during post-intervention period for pre-suppression door initiated search tactics for kitchen ignitions (Experiments 15 and 17).

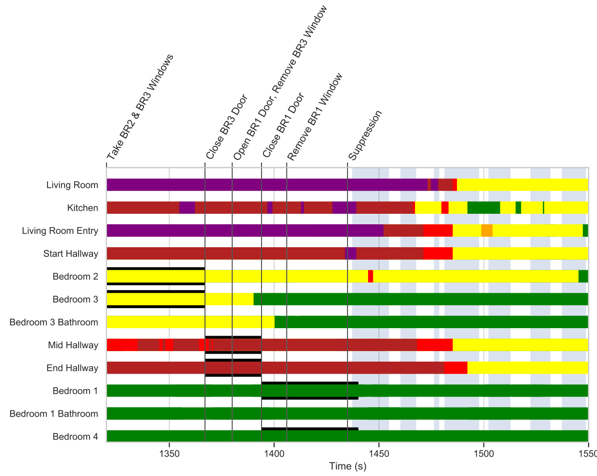
Room*	Experiment 15		Experiment 17	
	Peak Temp [°C]	Peak Heat Flux [kW/m^2]	Peak Temp [°C]	Peak Heat Flux [kW/m^2]
Living Room Entry	123	2	892	84
Start Hallway	126	2	561	32
Mid Hallway	119	1	398	17
End Hallway	132	1	491	8
Bedroom 3	51	–	55	–
Bathroom 3	46	1	51	1
Bedroom 4	53	–	68	–
Bedroom 1	72	2	126	5
Bedroom 2	70	2	122	7

* The order of the rooms is based on the position of the search crew.

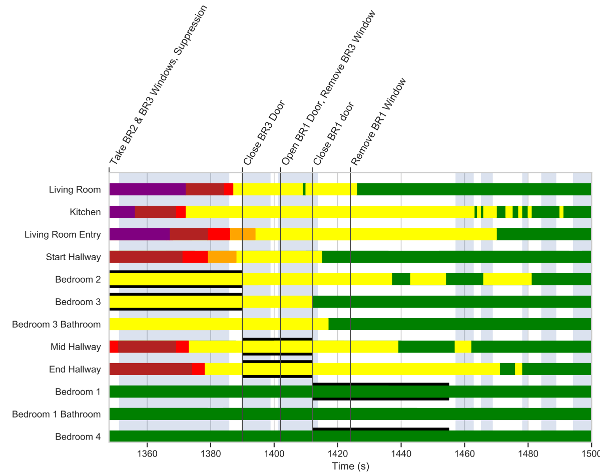
6.3.2 Impact of Search Timing Relative to Suppression

Kitchen Ignition — Pre-Suppression, During-Suppression, and Post-Suppression Search

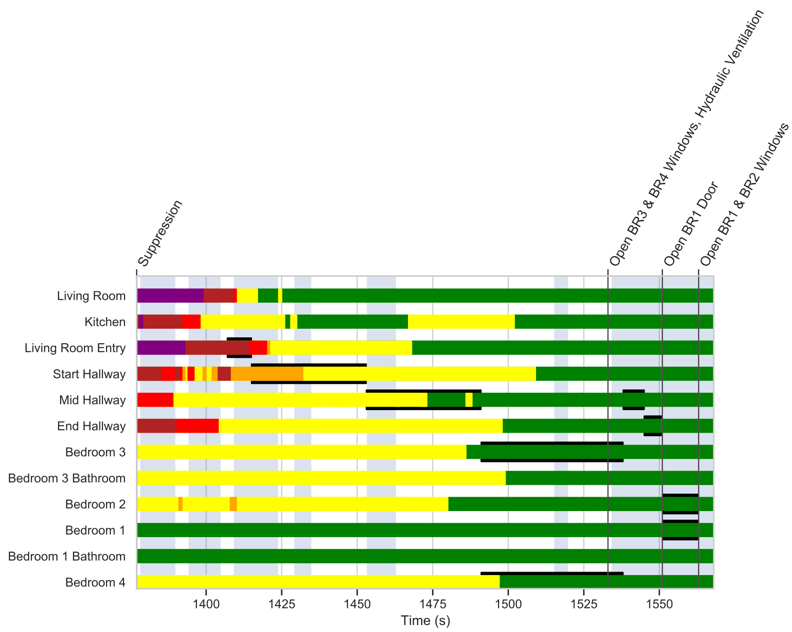
Experiments 11, 12, and 14 examined window initiated search that occurred prior to suppression (Experiment 11) and during suppression (Experiment 12) and door initiated search that occurred post suppression (Experiment 14). The primary difference between the experiments was when search was initiated relative to suppression for a post-flashover kitchen and living room fire and the corresponding change in entry location. The interior doors to bedrooms 2 and 3 were open and the interior door to bedroom 1 was closed prior to ignition for all three experiments. In Experiment 14, the door to bedroom 4 was open for the the duration of the experiment while it was closed in Experiments 11 and 12. To assess the impact of search relative to suppression actions, Figure 6.14 shows the thermal conditions, expressed as the thermal operating class, corresponding to the 3 ft temperature in the period following intervention for Experiments 11, 12, and 14.



(a) Experiment 11 (Pre-Suppression)



(b) Experiment 12 (During Suppression)



(c) Experiment 14 (Post Suppression)

Figure 6.14: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and corresponding heat flux throughout the structure for search operations relative to suppression timing.

In Experiments 11 and 12, the kitchen and living room were in a post flashover state. At the living room entry, the 3 ft temperatures and corresponding heat fluxes were approximately 800 °C (1472 °F) and 50 kW/m^2, magnitudes which precipitated the window initiated search operations.

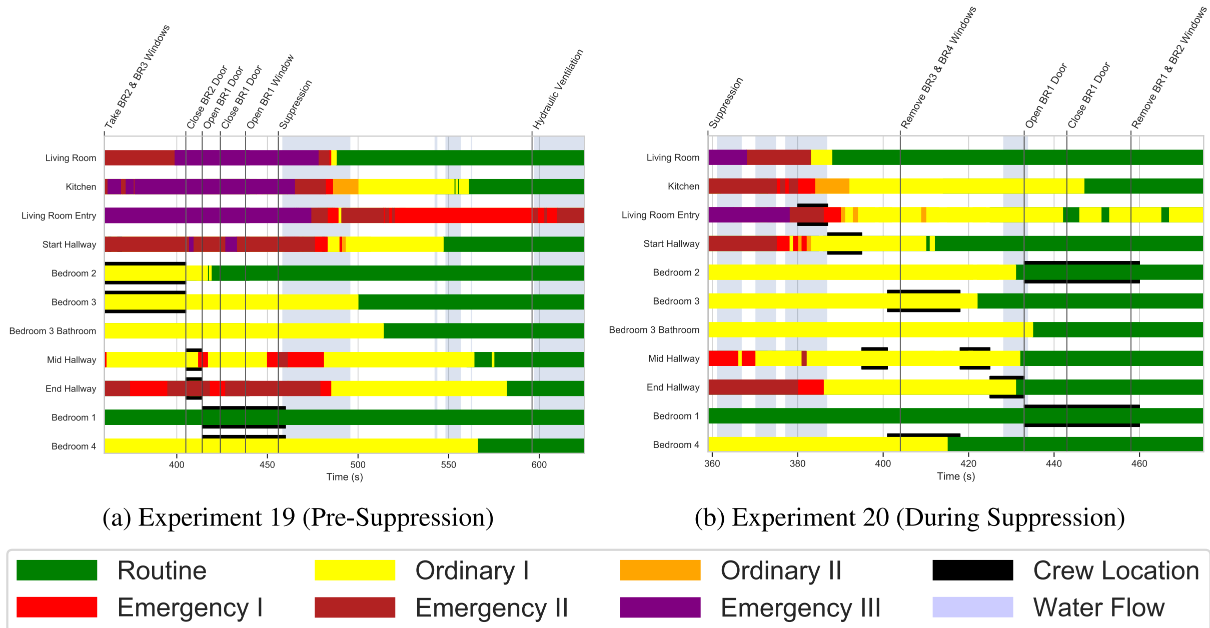
In both of these experiments, the crews entered bedrooms that had thermal conditions representative of an ordinary operating class due to their open interior doors. For bedroom 3, where the interior door was closed after entry, conditions returned to a routine operating class sooner than bedroom 2, which was not isolated. The impact of suppression timing was most evident when the crews searched in rooms beyond the room of entry. In Experiment 12, the coordinated search and suppression actions dropped hallway conditions to 110 °C (230 °F) and 135 °C (275 °F) at the mid hallway and end hallway locations, respectively, compared to emergency II levels of 425 °C (797 °F) and 522 °C (972 °F) for the same locations when search preceded suppression. In both experiments, bedrooms 1 and 4 remained at routine operating levels due to the closed doors prior to ignition.

For Experiment 14, where suppression preceded search, the living room entry temperatures were 350 °C (662 °F) and 11 kW/m^2 as the search crew followed the suppression crew into the structure. These thermal conditions were at the emergency class level, but dropped below 200 °C (352 °F) and 5 kW/m^2 (ordinary exposure class) as the crew approached the start hallway location and the main body of fire was knocked down. As the search crew searched the first set of bedrooms, bedrooms 3 and 4, the thermal operating class returned to routine levels. Thermal conditions remained at the routine level as crews completed searching the remaining rooms. Note, that bedroom 1, which had a door closed prior to ignition, remaining the routine thermal operating class for the duration of the experiment.

The comparison of these experiments highlight the effects of isolation, ventilation of spaces following isolation, and suppression timing on reducing the thermal classes for operating search crews.

Living Room Ignition — Pre-Suppression and Post-Suppression Search

Experiments 19 and 20 examined a window initiated search and door initiated search, respectively, for a living room ignition. In both experiments, the fire in the living room reached a post-flashover state before any firefighter interventions occurred. The interior doors to bedrooms 2, 3, and 4 were open and the bedroom 1 door was closed prior to ignition. The point of entry for the search operations was driven by the relative timing of suppression. In both experiments, temperatures at the 3 ft elevation living room entry were above 900 °C (1652 °F) and the corresponding heat fluxes were approximately 200 kW/m^2, an indication of direct flame impingement. As shown in Figure 6.15, at the time of first intervention of both experiments, the living room entry as well at the kitchen and start hallway locations were in the emergency operating class.



(a) Experiment 19 (Pre-Suppression)

(b) Experiment 20 (During Suppression)

Figure 6.15: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and corresponding heat flux throughout the structure for search operations relative to suppression timing.

In Experiment 19, the combination of search ahead of suppression and the thermal conditions at the front door forced search operations to originate through the bedroom 2 and bedroom 3 windows. Similar to Experiments 11 and 13, temperatures at the 3 ft elevation initially decreased following the ventilation of the bedroom windows as air was entrained through the bottom portion of the window and combustion gases exhausted through the top. Temperatures 3 ft above the floor dropped from approximately 150 °C (302 °F) to 90 °C (194 °F). After searching bedrooms 2 and 3, the crews subsequently moved across the hallway to search bedrooms 1 and 4, respectively. Upon exiting bedroom 2, that crew closed the door behind them, isolating bedroom 2 from the hallway. Bedroom 2 temperatures continued to decrease due the isolation and local exterior ventilation, reaching 50 °C (122 °) at 3 ft prior to suppression. As a result, the operating class returned to a routine level prior to suppression. The decrease in temperature in the non-isolated bedroom 3 was temporary. Temperatures began to increase approximately 90 s after ventilation, from a minimum of 80 °C (176 °F) back up to 90 °C (194 °F) prior to suppression. Bedroom 3 remained in the ordinary level until after suppression.

The hallway locations represented the highest hazard from an operating class perspective and thermal exposure for the searching firefighters in Experiment 19. At the time of intervention, 3 ft temperatures at the mid hallway and end hallway locations were approximately 200 °C (392 °F) and 360 °C (680 °F), respectively. Both hallway locations showed a drop in temperature, similar to the bedrooms, following intervention as air was entrained from the exterior through the open bedroom vents. Temperatures dropped to 150 °C (302 °F) and 240 °C (464 °F) at the mid hallway and end hallway locations, respectively. This is evident in the change in thermal operating class from emergency to ordinary at the end hallway in Figure 6.15a following the ventilation of the bedroom 2 and 3 windows. This decrease in temperature was temporary. New flow paths were established between the living room fire and the exterior vents at the bedroom windows. The areas of lower pressure at the exterior vents in the bedrooms led to increased combustion gas flow through the hallway and eventual temperature rise. Mid hallway and end hallway 3 ft temperatures increased back to 220 °C (428 °F) and 360 °C (680 °F), respectively. The temperature rise at the mid hallway location returned conditions to emergency levels which coincided with firefighters crossing the hallway to search beyond the point of entry. This data show that exterior vents effect locations throughout the corresponding flow path created, not just areas intimate with the vent.

The impact of isolation is also noticeable in bedrooms 1 and 4. For bedroom 1, which was isolated for the duration of the experiment with the exception of the door being opened and then closed for firefighter entry, the operating class remained at the routine level. Temperatures at the 3 ft elevation in bedroom 1 peaked at 32 °C (90 °F) following firefighter entry into the space compared to the non-isolated bedroom 4 where 3 ft elevation temperature peaked at 160 °C (320 °F) following ventilation of the bedroom 2 and 3 windows.

As discussed previously, the interior thermal conditions at the time of intervention in Experiment 20 were similar to those in Experiment 19. The primary difference was that in Experiment 20, the first intervention was suppression. As a result, the search crews followed the suppression crew into the living room and then continued along the hallway to search the bedrooms. As the crews moved further from the living room and the effects of suppression became more apparent. As the crew moved from the living room entry to the start hallway location, the operating class dropped from the emergency level (227 °C (441 °F) and 13 kW/m^2) to ordinary levels (90 °C (194 °F) and 1.5 kW/m^2). Thermal exposures continued to decrease with distance from the living room.Similar to Experiment 19, the isolated bedroom 1 remained in the routine operating class for the duration of the experiment. In Experiment 20, the door was opened after suppression which resulted in only a 2 °C (3.6 °F) increase.

Of note is the time for bedrooms 2, 3, and 4 to return to routine operating levels. Prior to intervention, all three bedrooms reached ordinary operating levels with 3 ft temperatures of approximately 150 °C (302 °F) for all three bedrooms. The search crews reached bedrooms 3 and 4 first and removed the respective bedroom windows and the 3 ft bedroom temperatures dropped below 72 °C (162 °F) with 17 s and 11 s, respectively. This post-suppression, window ventilation resulted in more efficient gas exchange compared to bedroom 2 where the window was still closed and bedroom 2 remained in the ordinary operating class for 10 s longer than bedroom 3. The thermal exposures for searching firefighters in bedrooms with local ventilation recovered to routine levels faster than the bedroom without ventilation.

Comparison of Experiments 19 and 20 showed the impact of ventilation and isolation. In the rooms where ventilation occurred ahead suppression and without isolation, the exterior vent resulted in a temporary temperature decrease but ultimately an increase in temperature due the additional gas flow along the newly created flow paths. The same exterior vents created during/post suppression resulted in a continued temperature decrease, highlighting the value of post-suppression ventilation.

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 definition, FED always increases, the FER can be used to assess the rate at which the exposure to a potential occupant is increasing. Further, a decreasing FER over time would indicate that a particular intervention is improving conditions.

6.4.1 Impact of Isolation

Window Initiated Search Pre-Suppression

Experiments 11 and 13 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 11 compared to bedroom 2 in Experiment 13. 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, Table 6.6 includes the average toxic FER from isolation to primary suppression for the bedroom 2 bed, bedroom 2 window, bathroom 3 and bedroom 3 window.

Table 6.6: 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)	0.082 (Exp 13)	0.11 (Exp 11)	0.0011 (Exp 13)	0.0064 (Exp 11)
Bedroom 2 Window (1 ft)	0.0025 (Exp 13)	0.011 (Exp 11)	3.6e-5 (Exp 13)	0.0017 (Exp 11)
Bedroom 2 Window (3 ft)	0.0048 (Exp 13)	0.029 (Exp 11)	2.9e-4 (Exp 13)	0.0047 (Exp 11)
Bathroom 3 (1 ft)	0.039 (Exp 11)	0.059 (Exp 13)	1.7e-5 (Exp 11)	1.1e-4 (Exp 13)
Bedroom 3 Window (1 ft)	0.0026 (Exp 11)	0.0039 (Exp 13)	3.5e-5 (Exp 11)	1.1e-4 (Exp 13)
Bedroom 3 Window (3 ft)	0.0034 (Exp 11)	0.0019 (Exp 13)	1.2e-4 (Exp 11)	0.0015 (Exp 13)

The rate of exposure increase data in Table 6.6 show the impact of isolation after entry on both the toxic gas and thermal exposure to potential occupants. Across both experiments, the average rate of FED increase (both toxic and thermal) was lower at the locations which were isolated. Ventilation of the windows resulted in increased gas flows through the respective bedrooms. Peak exhaust flows through bedroom 2 were approximately 1 m/s (2.2 mph) greater in bedroom 2 versus bedroom 3. The increased velocity was responsible for increased flow of combustion gases and increased convective heat transfer. As a result, the differences between isolated and non-isolated were more pronounced in bedroom 2, approximately an order of magnitude lower FERs following isolation, due its position at the end of the hallway.

Door Initiated Search Pre-Suppression

Experiments 15 and 17 examined a door initiated search that occurred prior to suppression. The primary difference between the two experiments was that in Experiment 15 the initial action was closing the front door after entry compared to Experiment 17 where the front door was open for the duration of the experiment. In Experiment 15, closure of the front door limited the ventilation in the structure to only the kitchen window, which was an inefficient vent for air supply due to the high sill height. As a result, the fire remained contained to the kitchen compared to Experiment 17 where the open door provided sufficient oxygen for the fire to spread from kitchen to living room and to support a transition to flashover over the space. To visualize the impact of the front door closure, Figure 6.16 shows post-experiment photographs of the kitchen and living room for Experiments 15 and 17. The most striking difference between the set of photographs is the comparison of living rooms.

(a) Experiment 15 Kitchen (Isolated)

(b) Experiment 17 Kitchen (Not Isolated)

(c) Experiment 15 Living Room (Isolated)

(d) Experiment 17 Living Room (Not Isolated)

Figure 6.16: Post experiment photographs of the kitchen and living room Experiments 15 and 17.

To quantify the impact of the front door closure on occupant tenability, consider the average rate of increase of the toxic and thermal FEDs in bedroom 1, bedroom 2, bedroom 3, and along the hallway. Table 6.7 presents the average FERs from entry until suppression for Experiments 15 and 17. Included in the respective average rates are isolation and window removal of bedrooms. Note: The time period from entry until suppression for these two experiments were nominally the same; 186 s for Experiment 15 and 183 s for Experiment 17.

The rate data show that throughout the hallway the rate of increase of toxic and thermal FED for occupants was at least an order of magnitude lower for the case when the front door was closed versus left open. The differences between the exposure rates widened with increasing elevation, highlighting that occupants lower in a space have lower exposure rates.

In both experiments, the search crews entered the structure and began to search the open bedrooms, beginning at bedroom 3 and and moving to bedrooms 1 and 2. At each bedroom, the door was closed upon entry, and the windows were removed as the room was searched. The respective bedroom doors were closed upon exit of the space. The impact of timing and isolation is shown by the differences in the toxic and thermal FERs. Since bedroom 3 was the first bedroom which was isolated, the differences between experiments are minimal. Recall that in Experiment 15, the closed front door kept the fire contained to the kitchen cabinets and in Experiment 17, the kitchen-living room area transitioned to flashover after the bedroom 3 door was closed. The closed bedroom 3 door limited the spread of combustion cases into the bedroom and had a similar effect as the closed front door. For bedrooms 1 and 2, the doors were closed in Experiment 17 after flashover. After isolation, the windows of each bedroom were removed. As a result of the later isolation time, the rate of toxic exposure increase was an order of magnitude higher. The rate of thermal FED increases were of similar magnitude due to the longer distance from the fire.

Table 6.7: Impact of Front Door Isolation (Experiment 15) Versus Non Isolation (Experiment 17) on Occupant Tenability for Pre-Suppression Door Initiated Search

	Average Toxic FER		Average Thermal FER	
Location	Experiment 15	Experiment 17	Experiment 15	Experiment 17
Bedroom 1 Bed (3 ft)	0.0050	0.044	1.1e-4	0.0047
Bathroom 1 (1 ft)	0.0021	0.0027	1.9e-6	2.8e-6
Bedroom 2 Bed (3 ft)	0.0054	0.095	1.0e-4	0.0051
Bedroom 2 Window (1 ft)	0.0023	0.044	8.2e-6	6.9e-4
Bedroom 2 Window (3 ft)	0.0060	0.16	2.3e-4	8.3e-4
Bathroom 3 (1 ft)	0.0030	0.0030	3.3e-6	2.0e-6
Bedroom 3 Window (1 ft)	0.0017	0.0021	4.0e-6	3.9e-6
Bedroom 3 Window (3 ft)	0.0035	0.0044	2.2e-5	2.7e-5
Start Hallway (1 ft)	2.6e-5	0.047	2.5e-5	0.034
Start Hallway (3 ft)	0.0013	0.029	7.3e-4	0.12
Mid Hallway (1 ft)	4.1e-4	0.0071	1.5e-5	0.013
Mid Hallway (3 ft)	0.0053	0.26	4.7e-4	0.037
End Hallway (1 ft)	0.0011	0.022	2.2e-5	0.026
End Hallway (3 ft)	0.0056	0.39	5.5e-4	0.072

Comparison of the toxic and thermal exposure rates illustrate the importance of isolation, isolation plus ventilation, the timing of isolation, and elevation on reducing the hazard to potential occupants. The data in Table 6.7 confirms the reduction in operating class for searching firefighters highlighted in Section 6.3.1.

Experiment 16 was designed to evaluate both door initiated search and window initiated search through bedroom 3 while also including door control of the front door prior to suppression. In addition to the window initiated search component, Experiment 16 differed from Experiment 15 in that only bedroom 1 was isolated as part of the search tactics; bedrooms 2 and 3 doors remained opened. Although in both experiments the fire was still contained to the kitchen when the front door was closed, the front door in Experiment 16 was closed later in fire growth in the kitchen compared to Experiment 15. Kitchen temperatures at the ceiling in Experiment 15 were 500 °C (932 °F) compared to Experiment 16 where the 4 ft elevation crossed 500 °C (932 °F). With an open front door (Experiment 17), floor to ceiling temperatures were in excess of 500 °C (932 °F). Figure 6.17

shows post-experiment photographs of the kitchen and living room for Experiment 16. The most noticeable difference between Figures 6.16c and 6.17b is the damage to the living room sofas. Although the fire produced sufficient heat to begin to pyrolize the sofas, there was insufficient heat and available oxygen to support flame spread into the living room.

(a) Experiment 16 Kitchen (Isolated)

(b) Experiment 16 Living Room (Isolated)

Figure 6.17: Post experiment photographs of the kitchen and living room Experiment 16.

The toxic and thermal exposure rates for Experiment 16 when analyzed relative to Experiments 15 and 17 further show the effects isolation and ventilation (Table 6.8). In Experiment 16, the bedroom 3 window was vented for entry and was not isolated. Although the closed front door was effective at preventing flame spread to the sofas as occurred in Experiment 17, the higher-temperature, higher-pressure combustion gases that had accumulated in the space flowed toward the exterior vent in bedroom 3. As a result, the toxic FERs in bedroom 3 were higher compared to Experiments 15 and 17 due to the isolation of the bedroom in both of those experiments. Bedroom 2 showed a similar trend as bedroom 3; the toxic FERs were higher than in Experiment 15 despite the front door being closed, as bedroom 2 was not isolated and included an exterior vent. Bedroom 1, which was isolated in Experiment 16, had thermal and toxic FERs that were similar to Experiment 15.

The hallway toxic FERs were of similar magnitude as Experiment 17 despite the closed front door because the non-isolated rooms were all vented which increased the flow of accumulated combustion gases into the hallway as gases flowed from the kitchen toward the exterior vents in the open bedrooms. The thermal FERs reflected Experiment 15, because the closed front door ultimately limited the heat release of the fire.

Table 6.8: Impact of Isolation on Occupant Tenability for Window Initiated Search Pre-Suppression (Experiment 16)

	Experiment 16	
Location	Average Toxic FER	Average Thermal FER
Bedroom 1 Bed (3 ft)	0.031	0.0010
Bathroom 1 (1 ft)	0.0087	1.4e-5
Bedroom 2 Bed (3 ft)	0.039	0.0014
Bedroom 2 Window (1 ft)	0.0051	1.3e-5
Bedroom 2 Window (3 ft)	0.0096	0.0022
Bathroom 3 (1 ft)	0.0065	9.9e-6
Bedroom 3 Window (1 ft)	0.0046	2.0e-5
Bedroom 3 Window (3 ft)	0.0058	1.6e-4
Start Hallway (1 ft)	0.0034	0.010
Start Hallway (3 ft)	0.016	0.012
Mid Hallway (1 ft)	0.0021	3.7e-5
Mid Hallway (3 ft)	0.0085	1.9e-5
End Hallway (1 ft)	0.0015	2.6e-5
End Hallway (3 ft)	0.018	2.7e-4

6.4.2 Impact of Search Timing Relative to Suppression

Kitchen Ignition — Pre-Suppression and During-Suppression Window Initiated Search

Experiments 11 and 12 examined a window initiated search that occurred pre-suppression and during suppression, respectively. In both experiments, crews vented the bedroom 2 and 3 windows to create entry points to initiate search operations. In both cases, bedroom 3 was isolated and bedroom 1 was unable to be isolated. The primary difference was that in Experiment 12 water flow coincided with ventilation while in Experiment 11 suppression did not occur until after search was completed. Table 6.9 provides the average rate of toxic and thermal FED increase for both experiments beginning with isolation of bedroom 3 and continuing until suppression in Experiment 11 and search complete in Experiment 12.

The most noticeable differences between the effect of suppression timing can be seen in the average thermal and toxic FERs for the non-isolated spaces (bedroom 2 and hallway locations) where the differences were generally an order of magnitude smaller during search post-suppression (Experiment 12). Suppression was effective at both reducing the temperature of the combustion gases and ultimately the production of combustion gases. There was minimal impact of suppression in the closed bedroom, for the same reason why isolation offers protection prior to suppression. The minimal gaps around the closed door create a high resistance for flow, limits combustion gases from entering the room, but post suppression limits the exchange of gases out of the room.

Table 6.9: Impact of Pre-Suppression (Experiment 11) Versus During-Suppression (Experiment 12) Window Initiated Search on Occupant Tenability

Location	Average Toxic FER Exp 11	Average Toxic FER Exp 12	Average Thermal FER Exp 11	Average Thermal FER Exp 12
Bedroom 2 Bed (3 ft)	0.11	0.033	0.0064	5.0e-4
Bedroom 2 Window (1 ft)	0.011	0.011	0.0017	2.9e-4
Bedroom 2 Window (3 ft)	0.029	0.010	0.0047	2.4e-4
Bathroom 3 (1 ft)	0.039	0.010	1.7e-5	3.1e-5
Bedroom 3 Window (1 ft)	0.0026	0.0095	3.5e-5	4.8e-5
Bedroom 3 Window (3 ft)	0.0034	0.0012	1.2e-4	1.2e-4
Start Hallway (1 ft)	0.035	0.014	0.014	0.0011
Start Hallway (3 ft)	0.044	0.0042	0.11	0.0012
Mid Hallway (1 ft)	0.030	0.0083	0.0054	1.1e-4
Mid Hallway (3 ft)	0.59	0.041	0.043	3.0e-4
End Hallway (1 ft)	0.02	0.0015	0.0043	9.3e-5
End Hallway (3 ft)	0.75	0.053	0.079	4.2e-4

In Experiment 12, the toxic FER in bathroom 3 is noticeably higher than an in Experiment 11, despite the room being ventilated and isolated in the same approximate time frame. Part of this rate difference was driven by experimental variability. Prior to intervention in Experiment 11, O_2, CO_2, and CO concentrations in bathroom 3 were 7.8%, 10.4%, and 2.3%, respectively. In Experiment 12, O_2, CO_2, and CO concentrations in bathroom 3 were 2.9%, 18.7%, and 3.2%, respectively. Since FER is based on gas concentrations, the initial lower concentrations in in Experiment 12 resulted in higher initial FERs. However, in both experiments, gas concentrations returned to pre-ignitions levels prior to hydraulic ventilation.

Living Room Ignition — Pre-Suppression and During-Suppression Search

To further assess the impact of suppression timing on search operations, consider Experiments 19 and 20, which examined window initiated search pre-suppression and door initiated search during suppression for a living room ignition. In Experiment 19, following flashover of the living room, the bedroom 2 and 3 windows were vented to provide entry points into the structure. Following ventilation, bedroom 2 was isolated, while the bedroom 3 door remained opened. In Experiment 20, suppression was initiated following flashover of the living room. Bedroom 2 and 3 doors remained opened for the duration of the experiment.

Table 6.10 shows the average toxic and thermal FERs for the two experiments from the time of first intervention until search and suppression actions were complete, approximately 170 s later. In both experiments, bedroom 1 was isolated prior to ignition and remained isolated except for when the door was temporarily opened to allow for crews to enter to search the room. As a result, both experiments had similar toxic and thermal FERs.

In bedroom 2, the combined effect of isolation and ventilation from Experiment 19 is shown in the toxic and thermal FERs. Despite being pre-suppression, the FERs in Experiment 19 were lower because the isolation of the space limited the influx of combustion gases into the space and bi-directional flow through the ventilated window led to a reduction in accumulated combustion gases. In Experiment 20, where search occurred during-suppression, there was no local path to exchange gases to the exterior until the respective windows were removed and the bedroom 2 FERs were higher. If the time period for analyzing the rate of increase for toxic FED is adjusted to start at window removal in bedroom 2, the bedroom 2 bed, 1 ft window, and 3 ft window FERs reduce to 0.012, 0.0049, and 0.0074, respectively. This data highlights the effectiveness of isolation ahead of suppression (Experiment 19) and coordinated ventilation with suppression (Experiment 20).

Table 6.10: Impact of Pre-Suppression Window Initiated Search (Experiment 19) Versus During-Suppression Door Initiated (Experiment 20) on Occupant Tenability

	Average Toxic FER		Average Thermal FER	
Location	Exp 19	Exp 20	Exp 19	Exp 20
Bedroom 1 Bed (3 ft)	0.0014	0.0011	5.5e-6	5.5e-7
Bedroom 2 Bed (3 ft)	0.087	0.33	0.0026	0.0058
Bedroom 2 Window (1 ft)	0.049	0.18	0.0017	0.0030
Bedroom 2 Window (3 ft)	0.12	0.42	0.0016	0.0084
Bathroom 3 (1 ft)	0.096	0.079	6.7e-5	4.4e-5
Bedroom 3 Window (1 ft)	0.031	0.13	8.0e-4	0.0014
Bedroom 3 Window (3 ft)	0.064	0.32	0.0017	0.0069
Start Hallway (1 ft)	0.040	0.041	0.012	0.0034
Start Hallway (3 ft)	0.14	0.067	0.14	0.0070
Mid Hallway (1 ft)	0.028	0.040	0.0097	6.5e-4
Mid Hallway (3 ft)	0.32	0.22	0.016	0.0022
End Hallway (1 ft)	0.011	0.040	3.1e-4	4.8e-5
End Hallway (3 ft)	0.52	0.37	0.030	0.0094

For both experiments, the bedroom 3 door remained open for the duration of the experiment. Similar to bedroom 2, average FERs over the duration of the experiment does not completely describe the differences. In Experiment 19, ventilation of the bedroom 3 window resulted in bi-directional flow which led to the exhaust of combustion gases and intake of air. Window temperatures between 4 in. above the window sill to 24 in. above the window sill decreased and temperatures at 34 in. and 44 in. above the window sill increased. Within 30 s of ventilation, additional combustion gases from the post-flashover living room fire began to flow toward the exterior vent. Temperatures 6 ft above the floor in the center of the room began to increase. At 90 s post ventilation, the 3 ft elevation temperature began to increase. Suppression occurred 6 s later, which prevented a measurable rise in thermal FERs, however had suppression been delayed, the bedroom 3 FERs would have likely been higher.

During Experiment 20, suppression was effective as reducing the thermal exposures, but the combustion gases that accumulated in bedroom 3 remained until there was local exterior ventilation. If the average toxic rate was computed following window ventilation, the rates in bathroom 3, 1 ft window, and 3 ft window drop to 0.064, 0.060, 0.17, respectively. The average 3 ft window elevation toxic FER remained elevated as strong winds led to circulation of gases at the window. As the winds subsided 20 s after window removal, the average toxic FER also dropped by a factor of 2 to 0.084. Similar to bedroom 2, this data highlights the importance of post-suppression ventilation to reduce the rate of toxic exposure.

At the three hallway locations, the impact of suppression is noticeable, particularly at 3 ft, as average thermal FERs in Experiment 20 are at least an order of magnitude lower than Experiment 19. In both experiments, the toxic FERs in the hallway are of similar magnitude as this data preceded hydraulic ventilation which was performed to help remove combustion products from the structure.

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 6.18.

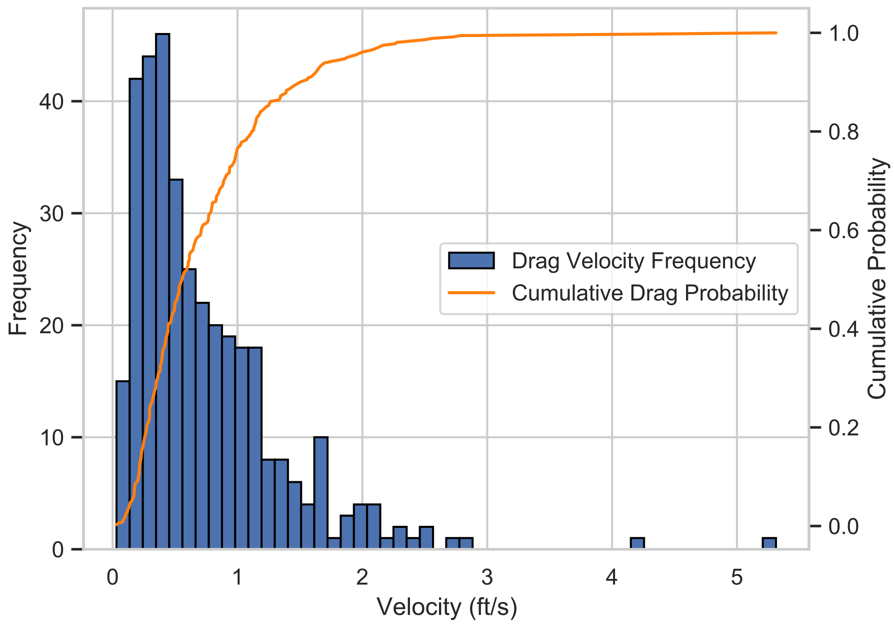


Figure 6.18: Histogram of victim removal velocity and cumulative distribution probability based on project technical panel time to task data for 360 individual time-to-task experiments.

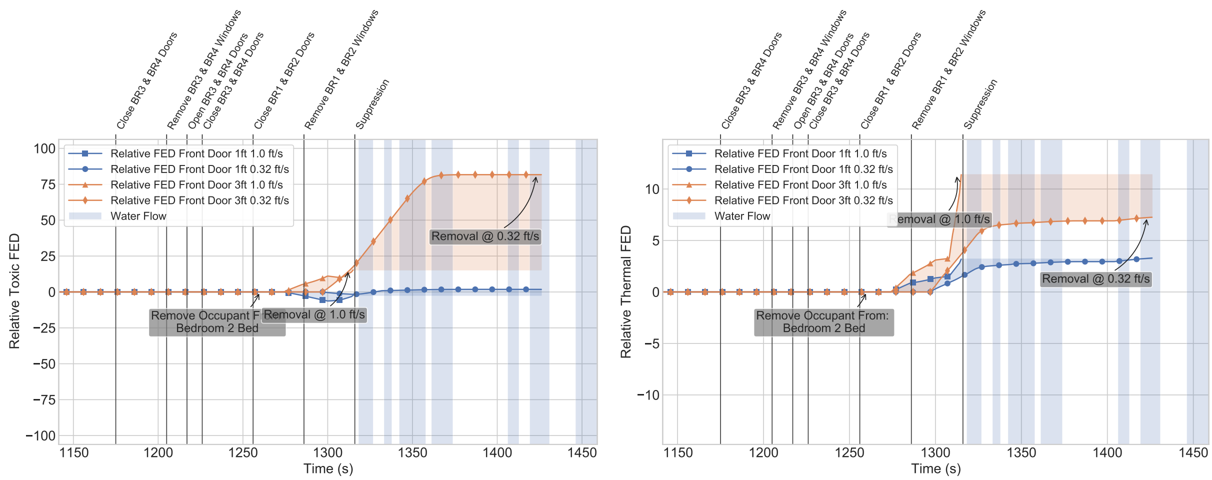
As the range of data in Figure 6.18 shows, using a single value to represent drag velocity would provide an incomplete assessment. Therefore to better capture the rate at which potentially trapped occupants could be removed from the structure, the 25th and 75th quartile values are used to provide the 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 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

To understand the impact of isolation, first consider Experiment 17, which included door initiated search ahead of suppression without closure of the front door. The open front door provided sufficient air to the fire to support flashover of the kitchen and living room. In Experiment 17 and other experiments where the common space reached flashover, egress through the front door prior to suppression would not have been possible for an unprotected occupant and likely above the protection limits of a fully-encapsulated firefighter. For reference, in Experiment 17 at the living room entry, 1 ft temperatures reached 300 °C (572 °F), 3 ft temperatures reached 880 °C (1616 °F), and heat flux to floor exceeded 35 kW/m^2 by 1275 s. To see the relative impact of removing a potentially trapped occupant from an isolated spaced (bedroom 2), see Figure 6.19.

At the 75th percentile velocity (1 ft/s) and 1 ft above the floor, removal of the occupant resulted in a decrease in relative toxic FED compared to remaining in bedroom 2 (decrease of ≈ 3). At living room entry, air entertainment into the living room to support fire growth kept the toxic FED lower. However, the air entertainment also supported fire growth (and higher relative thermal FED) as discussed above, which created thermal conditions in excess of the limits of tenability.



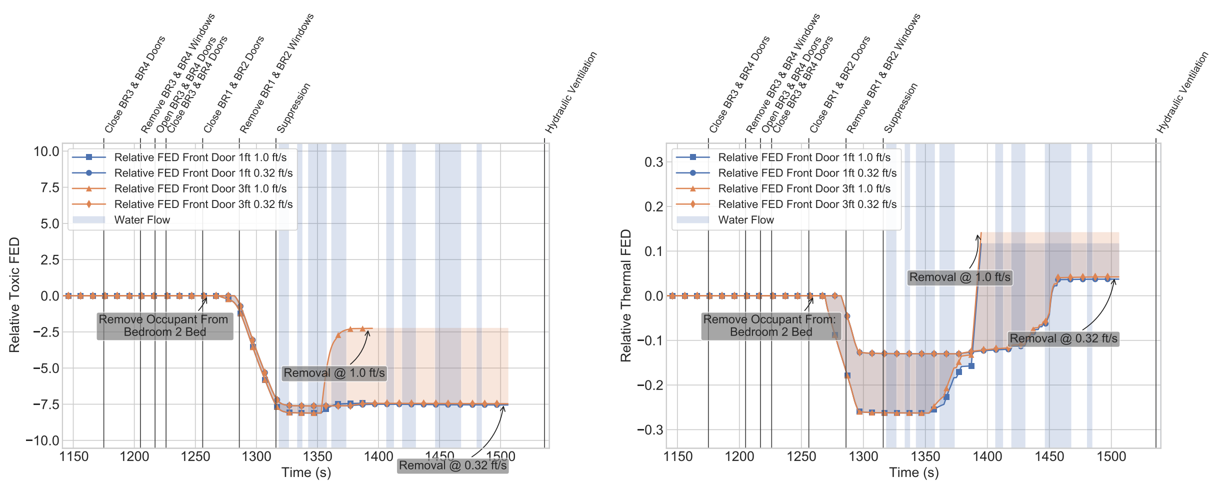
(a) Toxic FED Bedroom 2 Bed (Experiment 17) (b) Thermal FED Bedroom 2 Bed (Experiment 17)

Figure 6.19: Toxic and thermal FED relative to bedroom 2 bed location for door initiated search ahead of suppression (Experiment 17). 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 17, 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. Figure 6.20 shows the relative toxic and thermal FED during removal that occurred 20 s after the start of the suppression.

Most notable, is the relative change in toxic FED by moving the occupant from the 3 ft bed elevation to the 1 ft elevation at the window following the closure of the bedroom 2 door and removal of the bedroom 2 window (Figure 6.20a). Movement of the occupant to a lower elevation as well as to the intake portion of the bi-directional flow established following the window removal. At the 75th percentile velocity (1 ft/s) and 3 ft elevation, there was a sharp rise in relative toxic FED as the occupant reached the living room as accumulated combustion gases were still exhausting through the open front door. This rise still resulted in a lower cumulative toxic FED compared to remaining on the bed in bedroom 2 or removing ahead of suppression (Figure 6.19a)

The relative thermal FED (Figure 6.20b) also decreased with the movement to the 1 ft elevation at the window following isolation of the bedroom and removal the window. The relative thermal FED increased as the occupant moved down the hallway and in particular once the occupant reached the living room due to heat transfer from the walls, floor, and ceiling. The slower removal speed had a lower relative thermal FED compared to the faster removal time due to continued heat loss. Similar to the relative thermal FED, for both speeds and elevations the relative thermal FED for isolation with local ventilation until suppression, was lower than the pre-suppression removal.



(a) Toxic FED Bedroom 2 Bed (Experiment 17) (b) Thermal FED Bedroom 2 Bed (Experiment 17)

Figure 6.20: Toxic and thermal FED relative to bedroom 2 bed for delayed removal from an isolated space until after suppression (Experiment 17). 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

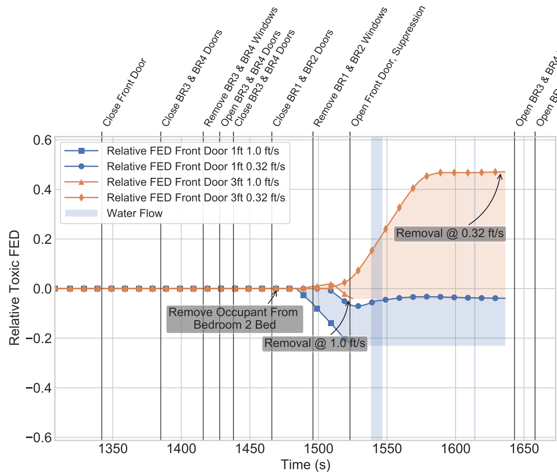
Following similar initiation time relative to fire growth and timing of tactics as Experiment 17, Experiments 15 and 16 were designed to analyze door initiated search and combined door and window initiated search prior to suppression with control of the front door. For the kitchen ignition experiments in these structures, the front door was effectively the fire compartment door. In Experiment 15, closure of the front door limited the ventilation in the structure to only the kitchen window, which was an inefficient vent for air supply due to the high sill height. As a result, the fire remained contained to the kitchen. As the crews searched the bedrooms, each respective was isolated and the windows were removed.

Experiment 16 differed from Experiment 15 in that window initiated search occurred in parallel to door initiated search and only bedroom 1 was isolated as part of the search tactics; bedrooms 2 and

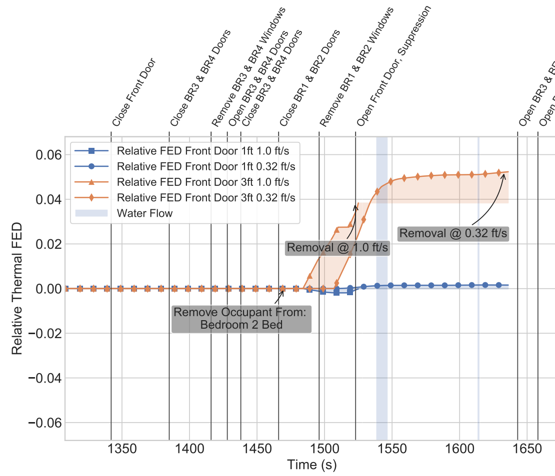
3 doors remained opened. Although in both experiments the fire was still contained to the kitchen when the front door was closed, the front door in Experiment 16 was closed later than Experiment 15, which resulted in additional fire growth in the kitchen.

Note: For the purposes of this analysis, it is assumed that once a potentially trapped occupant reached the closed front door, it would be opened, despite the fact that it may have not yet been opened based on the experiment timing.

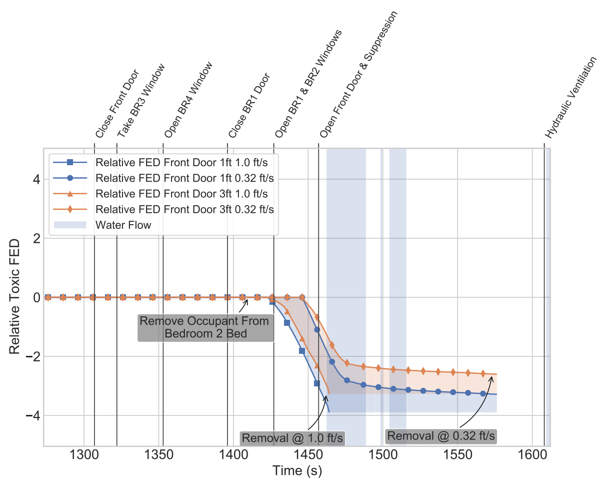
Figure 6.21 shows the toxic and thermal FEDs during removal relative to a potentially trapped occupant remaining in place on the bed in bedroom 2 for Experiments 15 and 16. The relative FEDs show that the front door closure was effective at reducing both the toxic and thermal exposures in both experiments, especially compared to Experiment 17 which lacked isolation. The large relative toxic FED decrease in Experiment 16 (Figure 6.21c) is attributed to the lack of isolation in bedroom 2 compared to Experiment 15. Although the front door limited the fire growth, combustion gases from the fire continued to fill open spaces. As a result, FED in bedroom 2 during Experiment 16 continued to rise. This highlights the value of local isolation in addition to fire room isolation. Additionally, recognition of accumulated combustion gases and the corresponding benefit of keeping occupants low in the space during removal even if the thermal risk has been reduced.



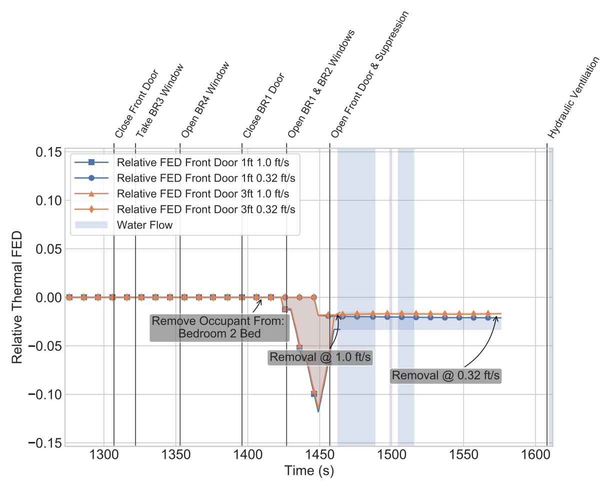
(a) Toxic FED Bedroom 2 Bed (Experiment 15)



(b) Thermal FED Bedroom 2 Bed (Experiment 15)



(c) Toxic FED Bedroom 2 Bed (Experiment 16)



(d) Thermal FED Bedroom 2 Bed (Experiment 16)

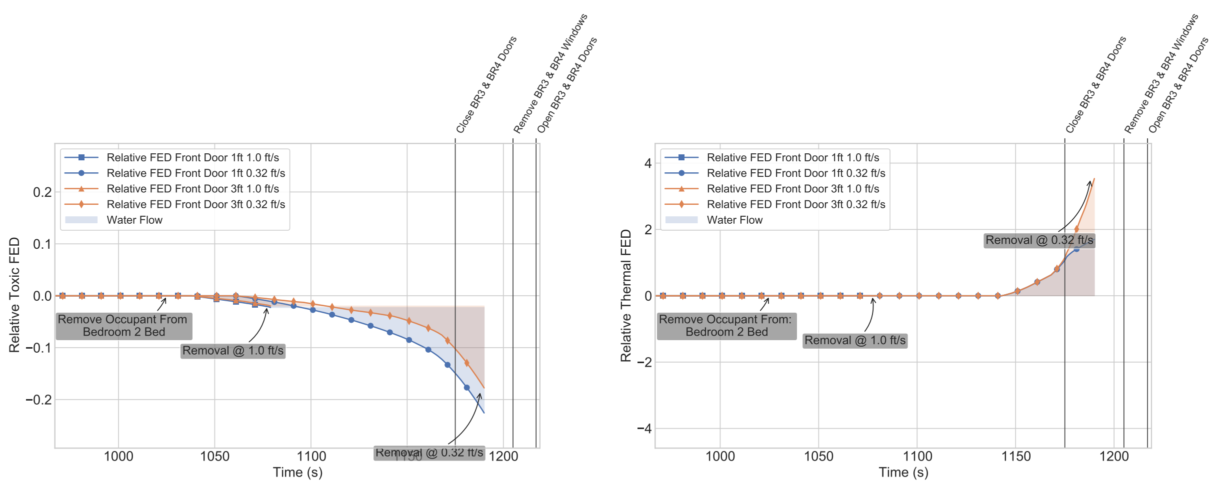
Figure 6.21: Toxic and thermal FED relative to bedroom 2 bed for door initiated search ahead of suppression with isolation of the fire room (Experiment 15 and 16). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile 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.

6.5.2 Impact of Rescue Timing

To assess how timing of rescue could impact occupant exposures, an alternative timeline to Experiment 17 is examined. In this scenario, consider the relative FEDs of a potential occupant in bedroom 2 if the rescue started 3 minutes early. Figure 6.22 shows the toxic and thermal FEDs for an occupant removal through the front door relative to remaining 3 ft above the floor on the bedroom 2 bed.

Figure 6.22a shows that earlier removal of occupant resulted in a reduction of toxic FED relative to bedroom 2 at both elevations. The slower velocities resulted in larger relative decrease in toxic FED, but that difference is a bit misleading when it comes to total cumulative toxic FED. Bedroom 2 was not isolated until later in the experiment so the baseline toxic FED continue to rise as combustion gases flowed into the room.

For the relative thermal FED, Figure 6.22b shows that at either elevation, the 75th percentile velocity resulted in negligible change to occupant exposure, but if the removal speed slowed, the relative thermal FED began to rapidly increase at both elevations. The increase occurred because the smoke layer in the living room descended toward the floor. From 1125 s to 1175 s, the 3 ft temperature increased from 190 °C (374 °F) to 600 °C (1112 °C) and the heat flux increased from 2.5 kW/m^2 to 15 kW/m^2. The large differences in relative FEDs in this scenario compared to that presented in Figure 6.19 highlights the role of time to initiate search tactics on the fireground. This could be a result of a number of factors, including but not limited to, response time, resources availability, or resource allocation/task prioritization.



(a) Toxic FED Bedroom 2 Bed (Experiment 17)

(b) Thermal FED Bedroom 2 Bed (Experiment 17)

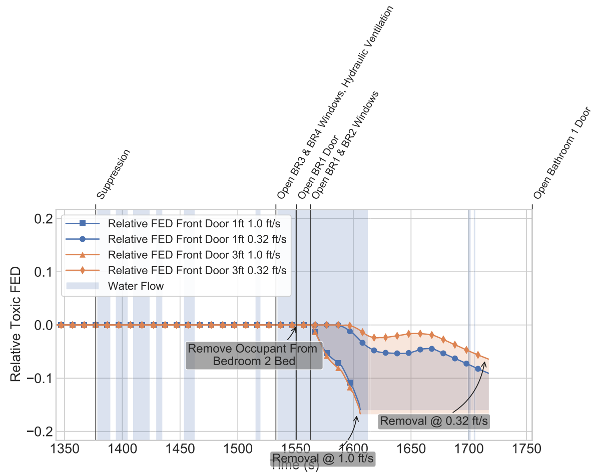
Figure 6.22: Toxic and thermal FED relative to bedroom 2 bed for early response door initiated search ahead of suppression (Experiment 17). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The 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 Suppression Timing

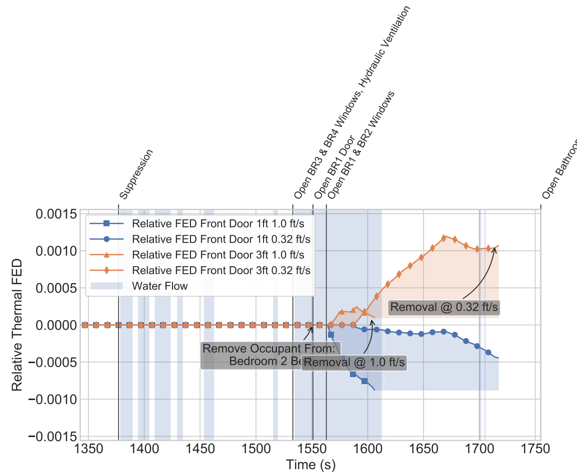
Experiment 14 was designed to analyze door initiated search operations following the completion of suppression of post-flashover kitchen and living room fire. While search operations occurred, the suppression crew changed the nozzle pattern from the straight stream used for suppression to a wide fog pattern to conduct hydraulic ventilation out of the failed, side D living room window.

Figure 6.23 shows the toxic and thermal FEDs for an occupant removal through the front door relative to remaining at the 1 ft elevation in bathroom 3 and the 3 ft elevation on the bed in bedroom 2. The minimal differences in thermal FED indicate the effectiveness of suppression in reducing the thermal hazard throughout the structure.

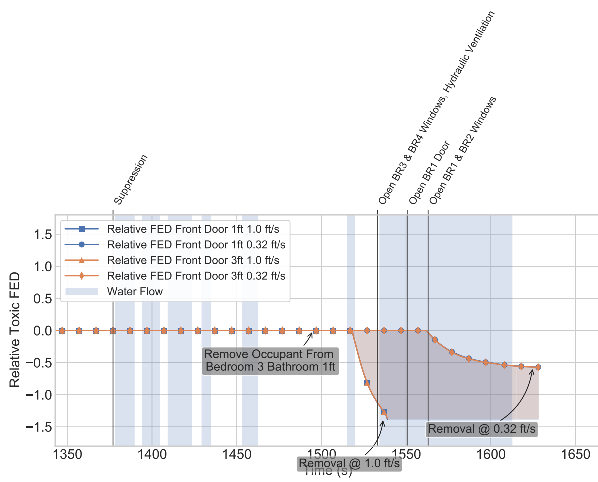
For bathroom 3, the position of the room off of a flow path resulted in an accumulation of combustion gases that were inefficiently removed post suppression and during hydraulic ventilation. As a result the toxic gas FEDs in bathroom 3 remained elevated relative to the rest of the structure. As a result, the impact of occupant removal from bathroom 3 was larger compared to bedroom 2, where combustion gases returned to ambient levels earlier. Although suppression reduced the thermal hazard, evident by the small relative changes in Figures 6.23d and 6.23b, the toxic exposure remained until either the occupant or the combustion gases are removed from the structure. Post-suppression, ventilation local to potential occupant location and forced ventilation such as hydraulic ventilation, is important, especially if occupant removal is delayed.



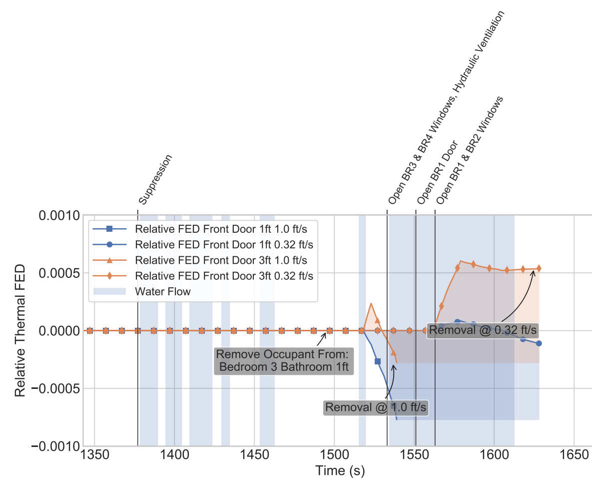
(a) Toxic FED Bedroom 2 Bed (Experiment 14)



(b) Thermal FED Bedroom 2 Bed (Experiment 14)



(c) Toxic FED Bathroom 3 (Experiment 14)



(d) Thermal FED Bathroom 3 (Experiment 14)

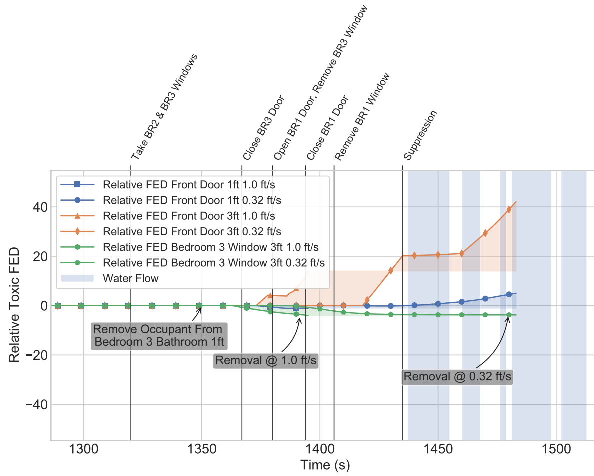
Figure 6.23: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for door initiated search post-suppression (Experiment 14). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

6.5.4 Impact of Egress Pathway

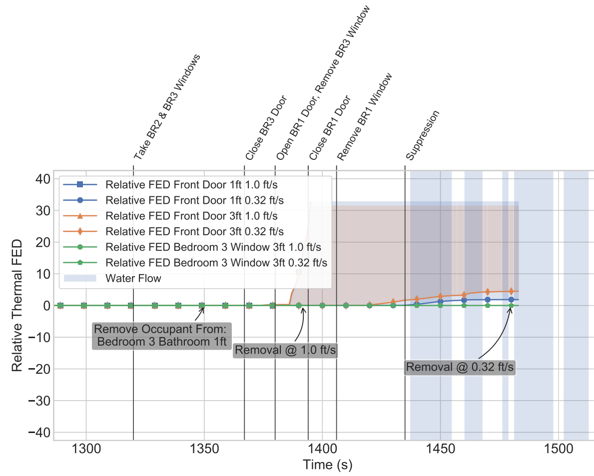
In experiments where search occurred prior to suppression, in the absence of fire compartment isolation, flashover of the kitchen/living room created thermal conditions equivalent to the emergency operating class, which would limit the duration for firefighters to safely occupy the space. These conditions 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 11, window initiated search occurred in bedrooms 2 and 3 with isolation of bedroom 3 following entry. Figure 6.24 shows the relative toxic and thermal FEDs for Experiment 11 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 an approximate relative decrease of -4 in toxic FED (Figure 6.24a). The combination of ventilation and isolation established a different flow path – one that that began and ended at the bedroom 3 window. Here, firefighters leveraged 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) resulted in a negligible increase in thermal FED (relative increase of 0.02) and was up to 3 orders of magnitude lower exposure compared to removing the occupant through the front door (Figure 6.24b).

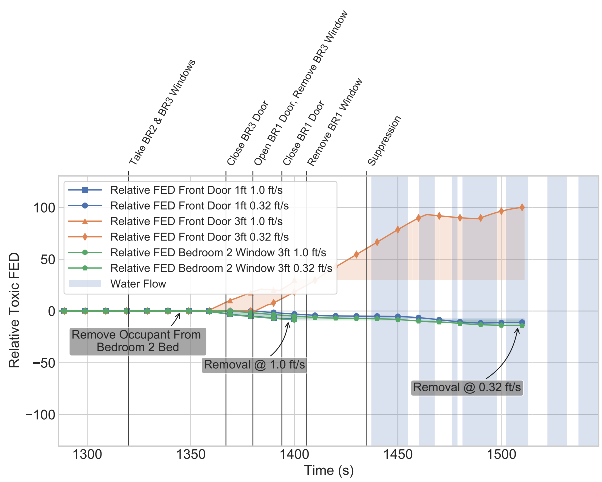
For the non-isolated bedroom prior to suppression, moving the occupant to the window resulted in a decrease in relative toxic FED (approximately -9 for the 75th percentile velocity and approximately -13 for the 25th percentile velocity) and a negligible decrease in relative thermal FED (< 0.05) as shown in Figure 6.24c and 6.24d. 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 toxic exposure compared to the bed which was adjacent to, but not part of the flow path. At the onset of suppression, there was an increase in the relative thermal FED of approximately 0.1. The crew utilized a flow and move tactic from a 7/8 in. smooth bore nozzle. As the suppression team made entry into the living room, water flow was needed at the start hallway to suppress flames along the carpet. An area of higher pressure was generated ahead of the hose stream from the flowing water and gas velocities at the bedroom 2 window temporarily became unidirectional exhaust which increased the convective heat transfer due to the increased velocity. However, for an occupant removed through the front door within this same time interval, the relative thermal FED would have increased by 1-2 orders of magnitude. For a more detailed description see the fire dynamics discussion in Section 5.1.



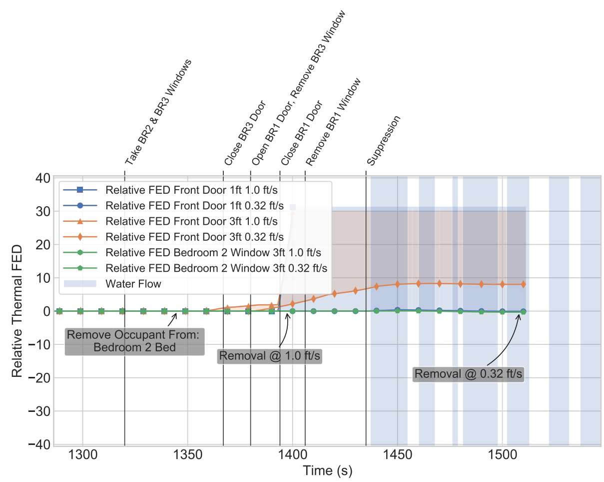
(a) Toxic FED Bathroom 3 Pre-Suppression



(b) Thermal FED Bathroom 3 Pre-Suppression



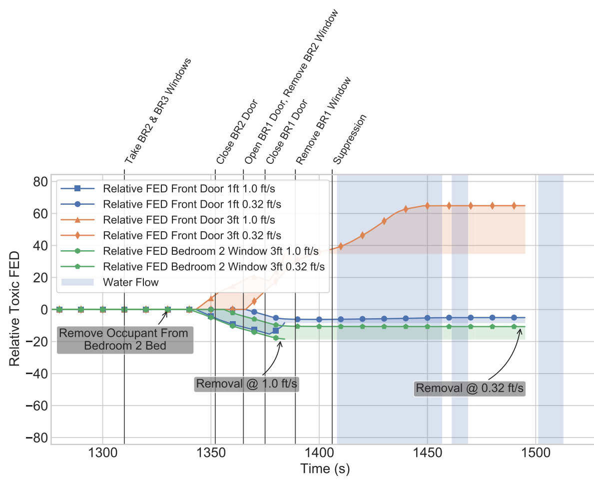
(c) Toxic FED Bedroom 2 Bed Pre-Suppression



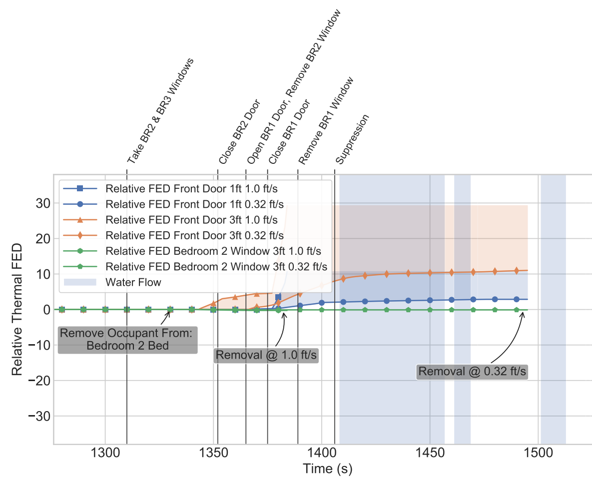
(d) Thermal FED Bedroom 2 Bed Pre-Suppression

Figure 6.24: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for window initiated search prior to suppression (Experiment 11). 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.

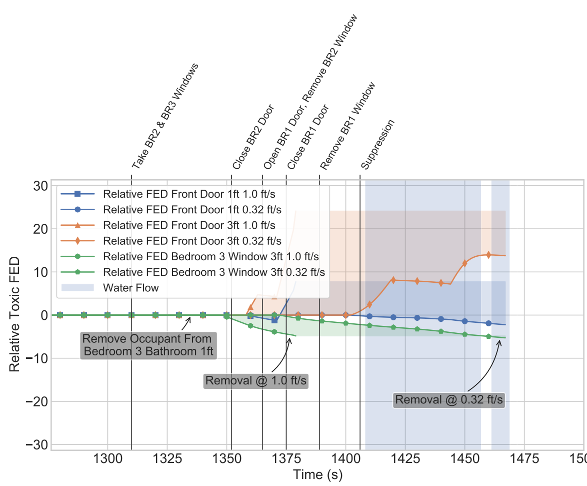
Figure 6.25 shows comparable toxic and thermal FEDs for Experiment 13, which was similar to Experiment 11 except for a change in which bedroom was isolated following pre-suppression window initiated search. Moving occupants to the window sill resulted in a decrease in relative toxic FED due to the intake of air due to bidirectional flow at the vent. For both bedrooms moving the occupant to the window resulted in lower relative FEDs compared to removal through the front door. Further, not only did the isolated bedroom have larger relative FED decreases (approximately double), the temperatures and gas concentrations at all elevations began to improve following isolation compared to the non isolated space which showed a continued increase in hazard.



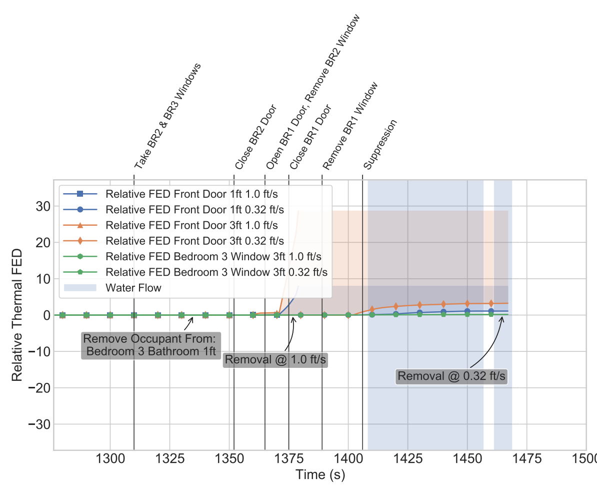
(a) Toxic FED Bedroom 2 Bed Pre-Suppression



(b) Thermal FED Bedroom 2 Bed Pre-Suppression



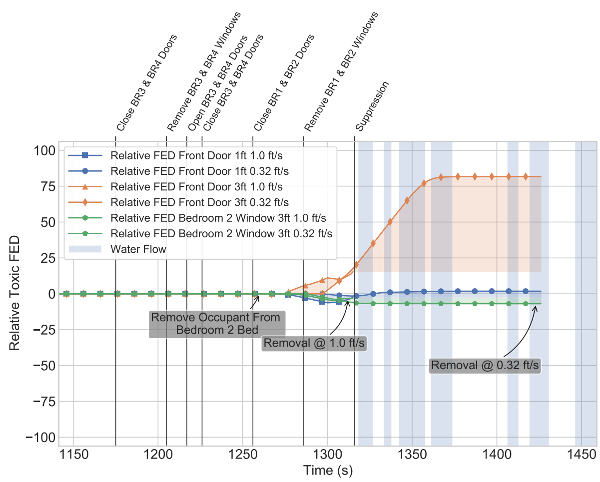
(c) Toxic FED Bathroom 3 Pre-Suppression



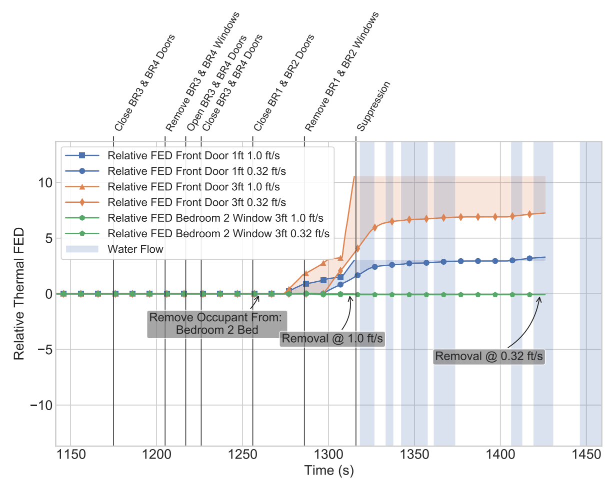
(d) Thermal FED Bathroom 3 Pre-Suppression

Figure 6.25: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for window initiated search prior to suppression (Experiment 13). 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.

Re-examination of relative FEDs in bedroom 2 during Experiment 17 to include moving the occupant to 3 ft elevations provides an example for a removal pathway that is different from the pathway of entry. Experiment 17 was designed to study door initiated search prior to suppression with the front door left open. By the time the search crews reached bedroom 2, the kitchen and living room had transitioned to flashover. This effectively prevented removal through the front door until suppression. Figure 6.26 shows the relative toxic and thermal FEDs in bedroom 2 for removal through the front door and movement to the window, 3 ft above the floor that began after bedroom 2 was isolated and the window in bedroom 2 was removed. The time to move the occupant to the 3 ft elevation at the window was delayed 30 s to account for the window removal action in the experiment. Following the window removal, gas concentrations at the bedroom 2 bed began to recover toward ambient levels 15 s earlier than the 3 ft elevation at the window. Therefore, moving the potential occupant to the window resulted in a range of relative toxic FEDs from an initial increase of 0.75 to a decrease of 0.5. This range was dependent on the speed (and therefore timing) at which the occupant was moved to the window. Changes in relative thermal FED were negligible (< -0.001) as isolation of the bedroom resulted in a reduction to the thermal exposure.



(a) Toxic FED Bedroom 2 Bed Pre-Suppression



(b) Thermal FED Bedroom 2 Bed Pre-Suppression

Figure 6.26: Toxic and thermal FED relative to bedroom 2 bed for door initiated search prior to suppression (Experiment 17). 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.

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 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 kitchen and living room fires. In 4 of the 8 kitchen fires, search operations occurred prior to suppression, in 2 of the 8 kitchen fires search operations occurred during suppression, and in 1 of the 8 kitchen fire experiments search operations occurred post-suppression. The remaining kitchen experiment was the baseline experiment where the initial conditions remained fixed for the duration of the experiment. The pair of living room experiments examined pre-suppression and during suppression search operations. Further, the series of kitchen and living room experiments examined search operations that originated via window (x4), via front door (x4), or both (x1). For each experiment, 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. Reduction of oxygen supply to a kitchen fire via a closed front door 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 230 gallons (127 gallons $\pm$ 57 gallons) was used during the initial suppression period and less than 500 gal including hydraulic ventilation was used in total for suppression for each of the kitchen and living room 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.

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Appendix A Window Interventions

Within this series of experiments, window ventilation occurred via one of three 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)

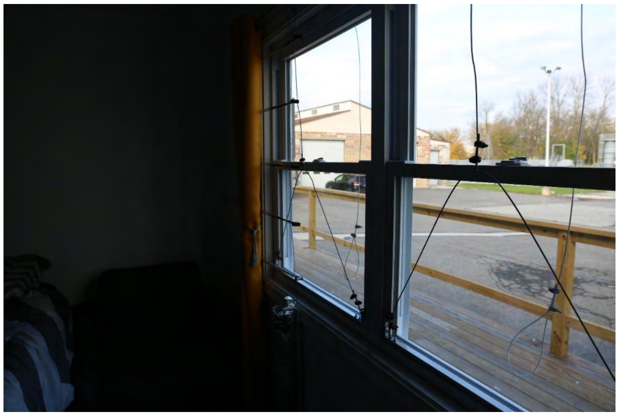
(b) Take Window (During)

(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]