# Analysis of Search and Rescue Tactics in Single-Story Single-Family Homes Part III: Tactical Considerations

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May 17, 2022

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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 21 experiments in two identical purpose-built single-story, single-family residential structures 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.

Eleven experiments examined bedroom fires, 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.

# Acknowledgments

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Fire Service Technical Panel

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

# Contents

# List of Abbreviations

| | |
|---|---|
| ACHP | Air changes per hour |
| BR | Bedroom |
| $CO_2$ | Carbon dioxide |
| CO | Carbon monoxide |
| HVAC | Heating ventilation and air conditioning |
| NFPA | National Fire Protection Agency |
| $O_2$ | Oxygen |
| PPE | Personal protective equipment |
| 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). The purpose of this report is to present the tactical considerations developed based on the analysis of the 11 bedroom experiments discussed in Part I [5] and the 8 kitchen and 2 living room experiments discussed in Part II [6]. A tactical consideration is an evidence-based concept for the fire service to consider implementing to enhance efficiency and effectiveness and to increase knowledge to accomplish their mission.

## 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 Experimental Configuration

## 2.1 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 2.1 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 2.1: Representative exterior photographs of the four sides of the experimental structures.

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 2.2.

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

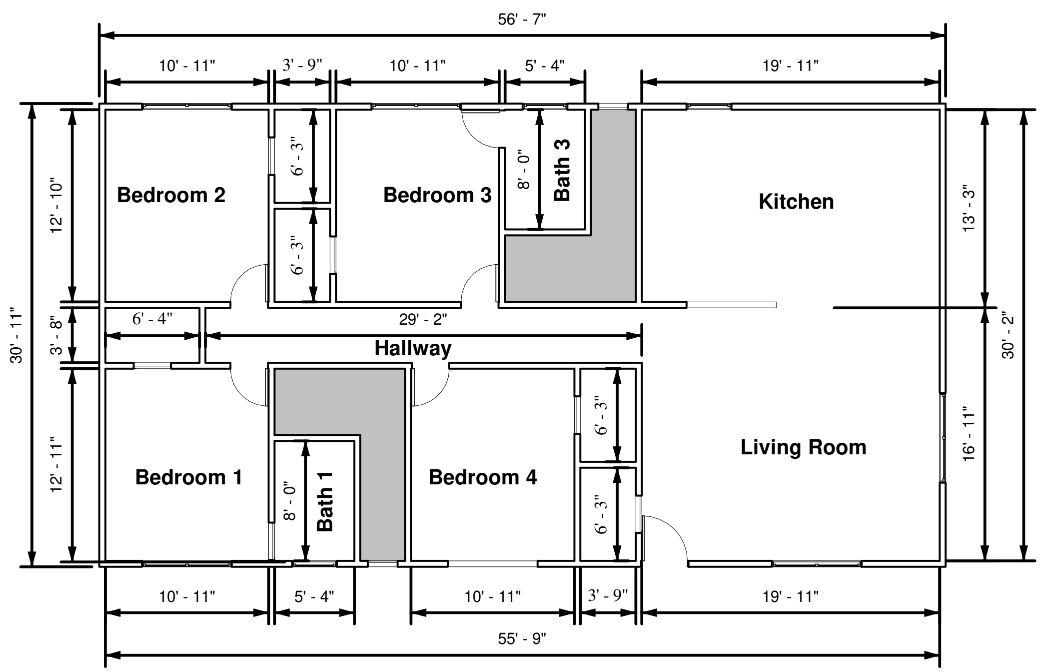
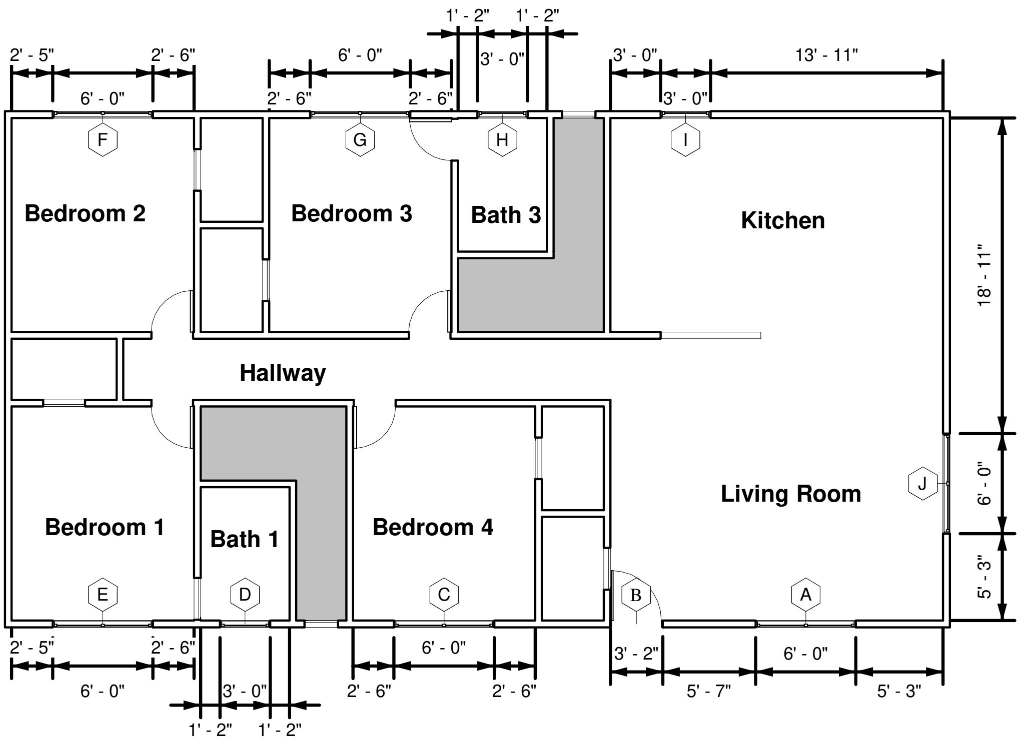



Figure 2.2: Dimensioned layout of structure.

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 2.3 shows the location of the 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 (shown in gray between kitchen and bedroom 3 in Figure 2.3) 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 [7]. The condensing unit for the HVAC system was located along the back




| 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 2.3: Dimensioned layout of exterior vents.

side of the structure below the mechanical room.

To characterize the natural ventilation of the structures, a leakage test was conducted with all exterior vents closed. ASTM E 779, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization," was followed to determine the air changes per hour [8]. 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 [9]. The average leakage in the test structures across the 21 experiments was $1.58 \pm 0.1$ ACPH at 50 Pa (0.007 psi) which falls within the acceptable IECC range.

## 2.2 Fuel Load

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 of fuels in the structure are presented in Figure 2.4.

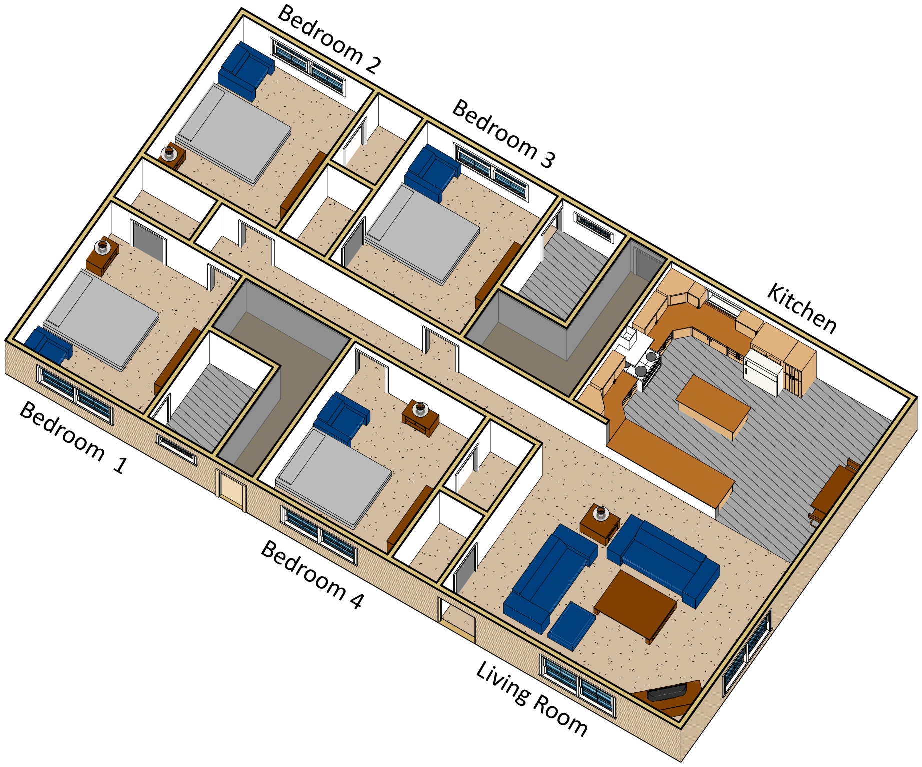



Figure 2.4: Layout of bedroom, kitchen, and living room fuels.

The furnishings were dimensioned and weighed, and where possible, the base materials used in their construction were determined and documented. Specific details regarding the fuel loads used in experiments can be found in Parts I and II [5, 6].

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 2.5a. Each bedroom floor was covered with polyethylene terephthalate (PET) carpet, polyurethane (PU) foam padding, and an oriented strand board subfloor. In addition to the fuel load in each of the bedrooms, the two bathrooms were also furnished with a vanity and toilet. 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 2.5b. 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 2.5c.

(a) Bedroom

(b) Kitchen

(c) Living Room

Figure 2.5: Photographs showing representative fuel loads in a bedroom, the kitchen, and the living room.

## 2.3 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 were determined. Flow rates through the HVAC supply and returns were measured, and the effective leakage area (Section 2.1) 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 experiment, video camera positions were set, and photographs were taken to document the interior and exterior of the structure.

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.

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 was set to flow 150 gpm at 50 psi, and the smooth bore nozzle was a 7/8 in. tip set to flow 160 gpm at 50 psi. 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.

## 2.4 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 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 2.1 provides an overview of the experiments conducted based on their fire location, the tactic studied, and the timing of the search relative to suppression actions. Experimental overviews, including the timing of interventions and how gas flows within the structure changed as a result of the interventions, are included in Appendix C. More detailed analysis on the fire dynamics of each experiments can be found in Part I [5] (Experiments 1-10) and Part II [6] (Experiments 11-20).

Table 2.1: 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.

# 3 Exposure Estimates to Occupants and Firefighters

## 3.1 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, FED values can be used to assess the effects of firefighting interventions, but should not necessarily be employed as a predictor of lethality.

FED can be used to describe the percentage of the population for which conditions become untenable. Although a detailed description of the mathematical relationship is beyond the scope of this report, FED is related to the probability of the conditions being non-tenable for a certain percentage of the population through a lognormal distribution. An 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 FED and the percentage of people incapacitated is unknown. However, an 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 FED of 3.0 will likely incapacitate all but the least sensitive people. The FED equation for toxic exposure can include a number of products of combustion, but these experiments focused on the most common gases produced at high concentrations from burning hydrocarbon-based fuels. In this case, the general N-gas equation can be simplified to [10]:

$$FED_{toxic} = (FED_{CO} * HV_{CO_2}) + FED_{O_2} \tag{3.1}$$

In Equation 3.1, $FED_{CO}$ 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.

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% [11]. It is important to recognize that incapacitating levels of COHb have been found in surviving fire victims [10]. Active subjects are typically more severely affected by COHb concentrations than sleeping subjects.

For a more detailed analysis of toxic gas FED, see the Discussion section in Part I [5] or Part II [6].

## 3.2 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 [12]. Exposure to air over 15 minutes at temperatures over 120 °C (248 °F) for dry air and 85 °C (185 °F) for saturated 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 [13].

Pain threshold is reached when the temperature at 0.1 mm depth of the skin reaches 44.8 °C (112 °F) [13]. These effects on the skin are independent of the mode of heat transfer [14]. 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) [14].

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 [15]. The maximum breathable saturated air is 60 °C (140 °F) [16].

The thermal FED is therefore a combination of radiative ($t_{rad}(t)$) and convective effects ($t_{conv}(t)$), expressed as by Equation 3.2 [12]:

$$FED_{thermal}(t) = \int_{t_1}^{t_2} \left( \frac{1}{t_{rad}(t)} + \frac{1}{t_{conv}(t)} \right) dt \tag{3.2}$$

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.

For a more detailed analysis of thermal FED, see the Discussion section in Part I [5] or Part II [6].

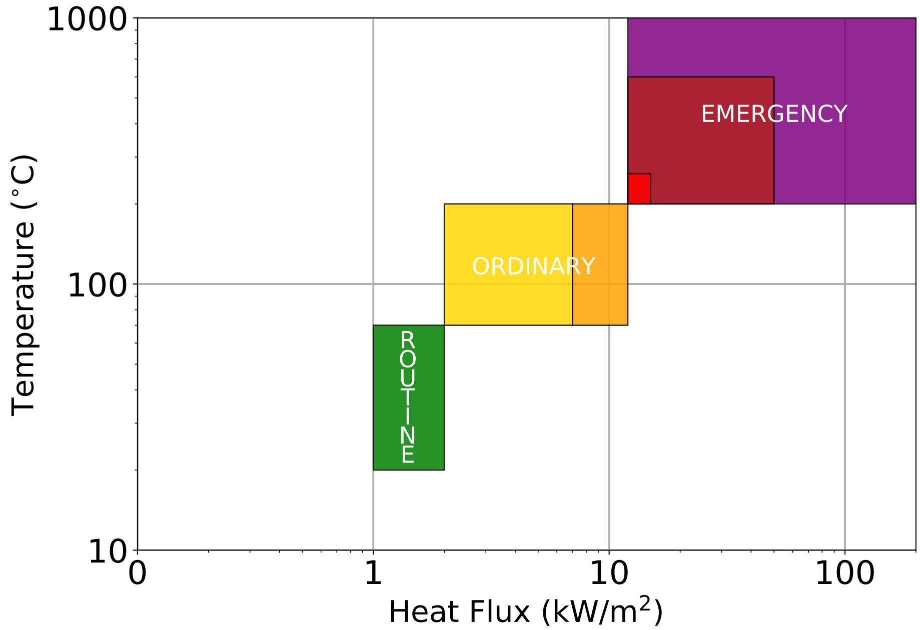
## 3.3 Estimated Firefighter Thermal Exposure

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 advantageous 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 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 [17]. 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.

In 2017, Madrzykowski [18] 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. The ordinary operating class is split into two levels based on heat flux exposures. Provided firefighters were not previously 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 [19]. 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 3.1.




| 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 3.1: Modified Thermal Operating Classes

## 3.4 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 3.2.

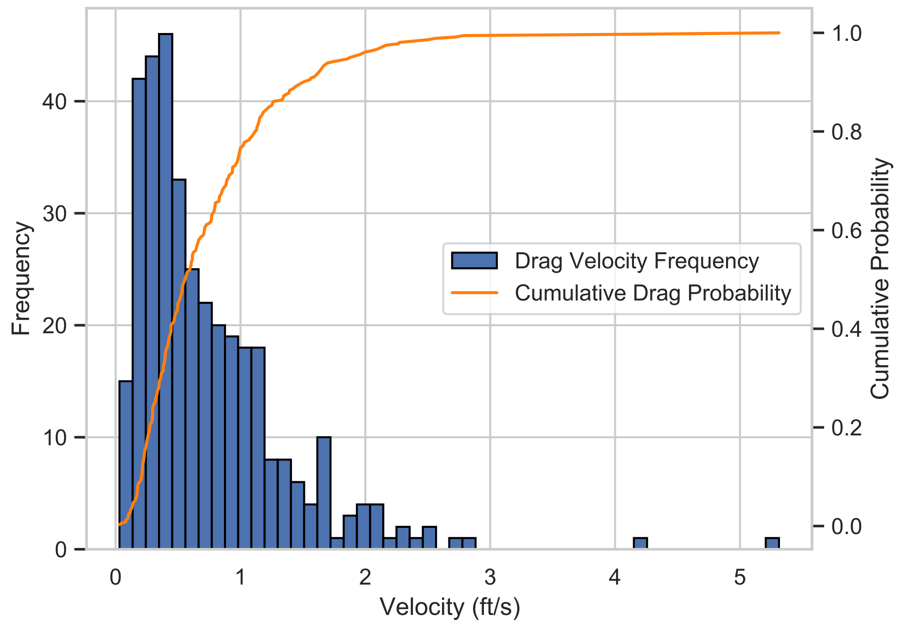



Figure 3.2: Histogram of victim removal velocity and cumulative distribution probability based on project technical panel time to task data for 360 individual time-to-task experiments.

As the range of data in Figure 3.2 shows, using a single value to represent drag velocity would provide an incomplete assessment. Therefore to better capture the rate at which potentially trapped occupants could be removed from the structure, the 25th and 75th quartile values are used to provide the middle 50% of speeds. These quartiles correspond to 0.32 ft/s (25th) and 1.0 ft/s (75th) and are used to show the range of exposures associated with the range of rescue velocities.

To assess the impact of removal of a potentially trapped occupant, both the toxic and thermal FEDs were calculated by summing the respective contributions from the different locations within the structure based on the different movement speeds. The toxic and thermal FEDs at the rescue point of origin were subtracted from the removal FEDs to determine a relative FED. Essentially, if the relative FED is positive, the occupant would have received additional exposure compared to being left in place. If the relative FED is negative, the occupant would have received a lower exposure compared to being left in place.

# 4 Pathways for Search Crews

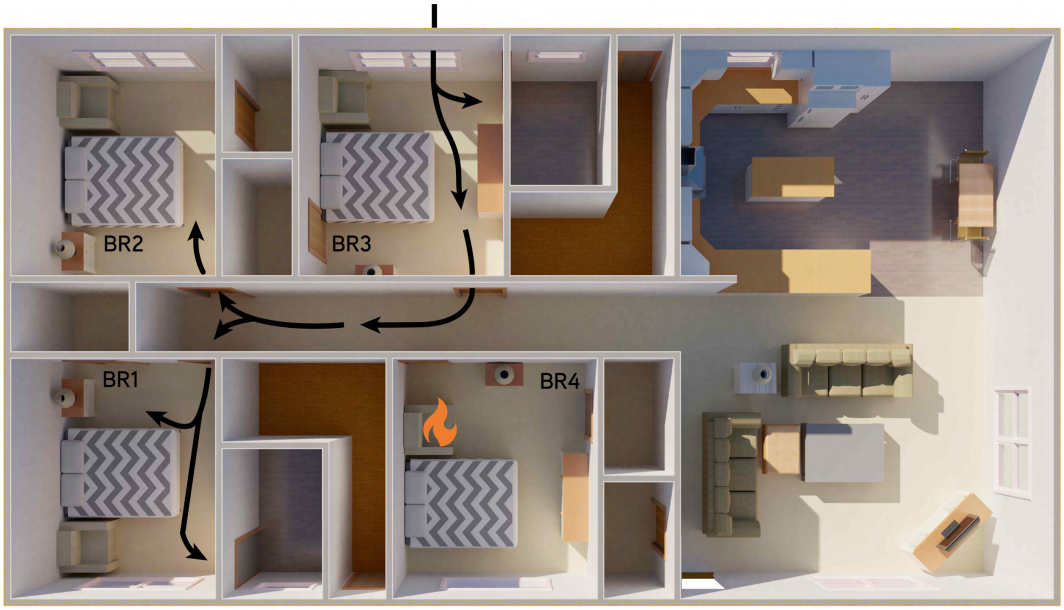
For the 10 bedroom 4 fires, 8 kitchen fires, and 2 living room fires that included search operations (excluding the baseline experiments, Experiment 10 and Experiment 18), there were six different pathways that defined how the search crews moved within the interior of the structure. In these experiments, 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 3.3. In Figures 4.1 – 4.6, 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. In Figures 4.4 – 4.6, 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.

Figure 4.1 shows the routes taken for the crews for window initiated search that occurred into bedrooms 2 and 3 simultaneously for a bedroom 4 fire. Crews entered the structure by taking the bedroom windows, and the firefighters that entered into bedroom 2 proceeded to search beyond the room of entry by entering a previously isolated bedroom 1. Experiments 1–5 utilized this approach. The key variables that changed were if the bedroom of entry was isolated after entry and the timing of suppression relative to the start of search operations.


| Experiment | Details |
|---|---|
| 1, 2, 3 | Isolation of bedroom 3 post entry, varied suppression timing |
| 4, 5 | Isolation of bedroom 2 post entry, varied suppression timing |

Figure 4.1: Window initiated search pathways that originated simultaneously from bedrooms 2 and 3 for a bedroom 4 fire. Black lines represent pathways the search crews took.

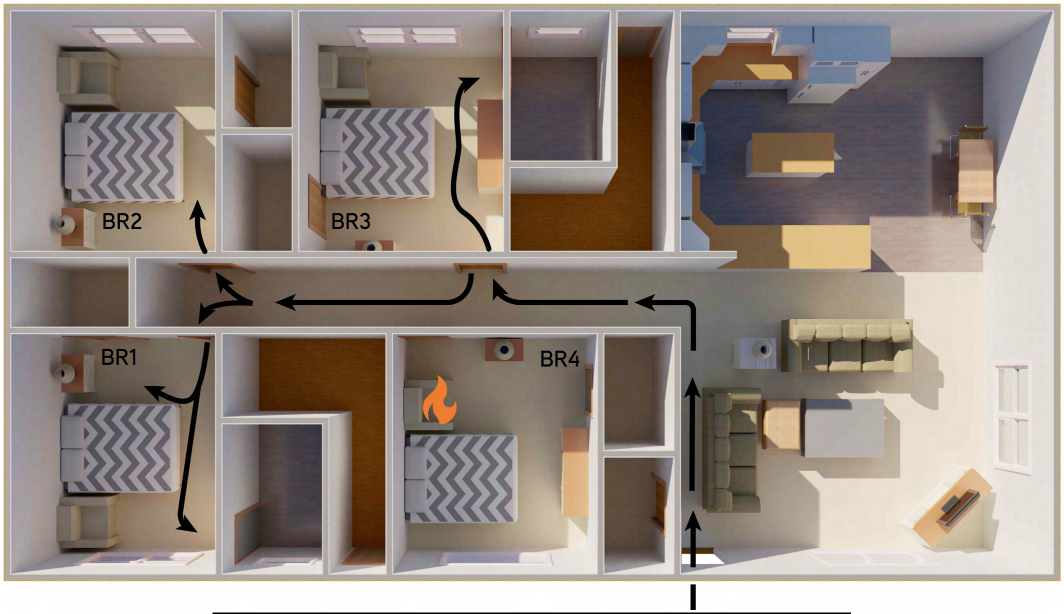
Two window initiated search experiments for a bedroom 4 fire examined entry only into bedroom 3. In Experiment 8, the crew entered bedroom 3 through the window, proceeded across the hallway to isolate bedroom 4 before moving down the hallway to search bedroom 1 and 2. For Experiment 8b, the bedroom 3 door was closed prior to the window initiated search. Following a search of bedroom 3, a pressurized water fire extinguisher was used in the hallway as the search crew moved down the hallway, past the fire compartment which could not be isolated, to search bedrooms 1 and 2. Figure 4.2 shows the routes taken for the crews for these 2 experiments.




| Experiment | Details |
|---|---|
| 8 | Isolation of bedroom 4 post entry |
| 8b | Isolation of bedroom 3 prior to entry |

Figure 4.2: Window initiated search pathways that originated from bedroom 3 for a bedroom 4 fire. Black lines represent pathways the search crews took.

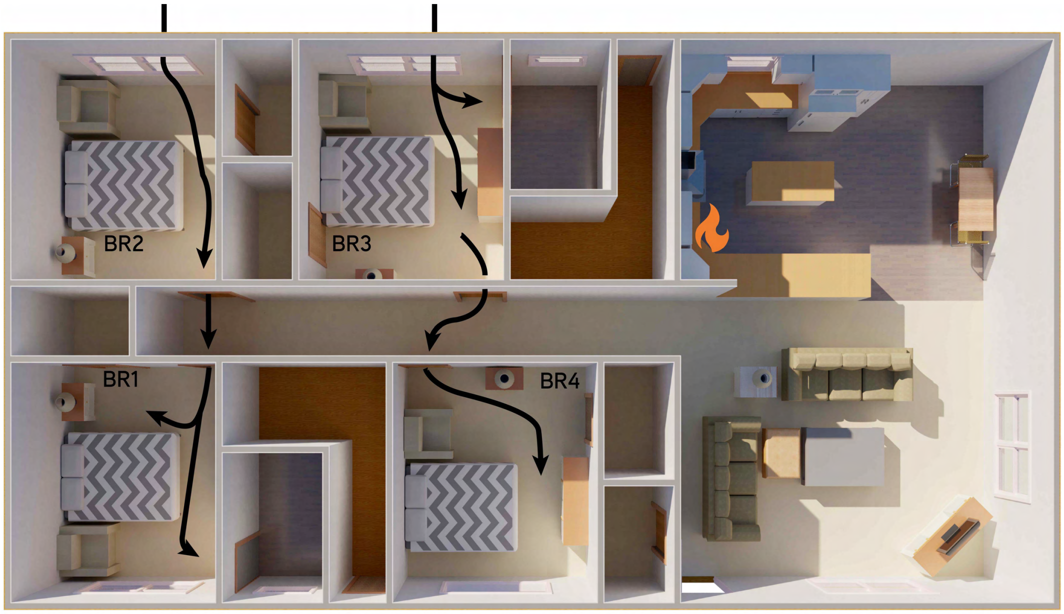
Three bedroom experiments included door initiated search. In these experiments, the crews entered the open front and traveled down the hallway to search bedroom 3, then re-entered the hallway to travel past the fire room to search bedrooms 1 and 2. The variables changed were isolation of the front door (Experiment 6), isolation of the fire compartment (Experiment 7), and search during suppression (Experiment 9). Figure 4.3 shows the routes taken for the crews for these 3 experiments.




| Experiment | Details |
|---|---|
| 6 | Isolation of front door post entry |
| 7 | Isolation of bedroom 4 post entry |
| 9 | During suppression |

Figure 4.3: Door initiated search pathways for a bedroom 4 fire. Black lines represent pathways the search crews took.

The pathways for window initiated search into bedrooms 2 and 3 that occurred simultaneously for a kitchen or living room fire are shown in Figure 4.4. 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.

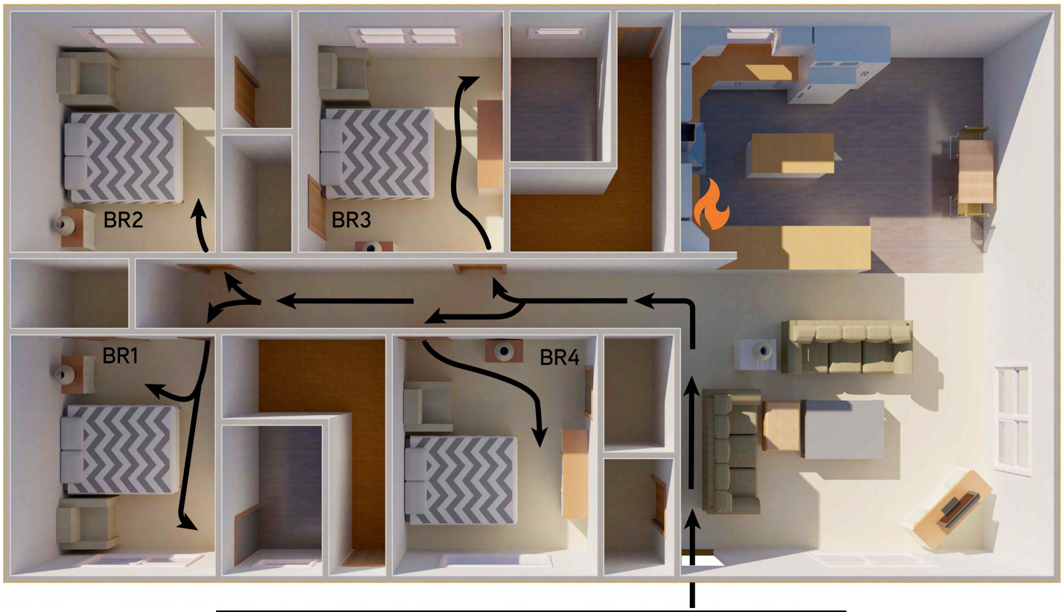



| Experiment | Details |
|---|---|
| 11, 12 | Isolation of bedroom 3 post entry, varied suppression timing |
| 13, 19 * | Isolation of bedroom 2 post entry, varied suppression timing |

* Living room ignition

Figure 4.4: 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 4.5 shows the routes taken for the crews for these four experiments.

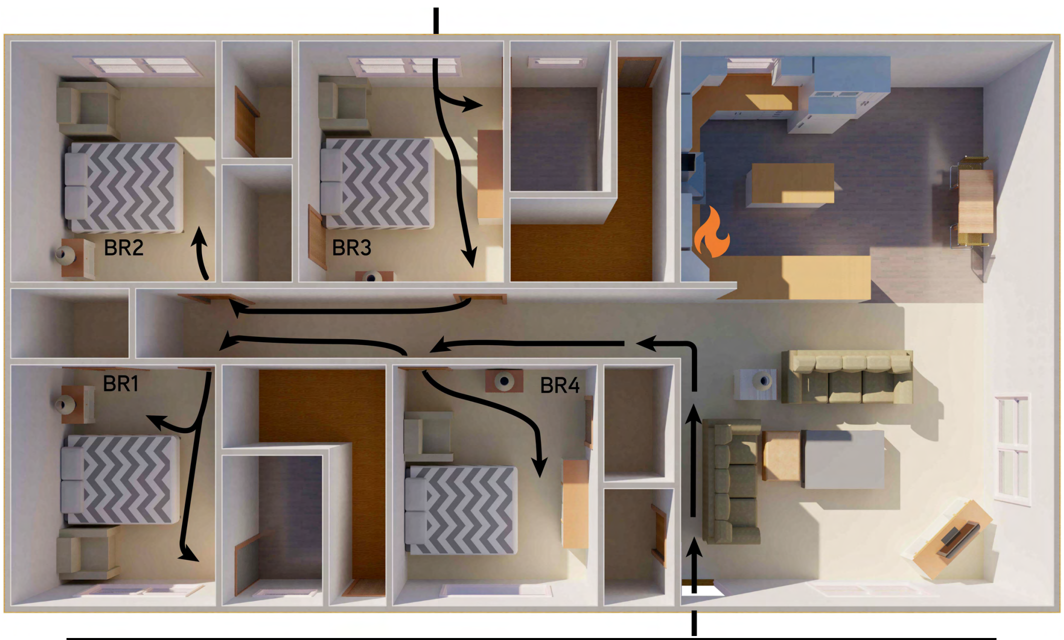



| Experiment | Details |
|---|---|
| 14 | Post suppression |
| 15 | Isolation of front door post entry |
| 17 | Pre-suppression |
| 20 * | During suppression |

* Living room ignition

Figure 4.5: 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 4.6 shows the routes taken for the crews for this experiment.




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

Figure 4.6: Window initiated search pathways that originated from front door and bedroom 3 window for kitchen fire. Black lines represent pathways the search crews took.

# 5 Tactical Considerations

Ultimately, the choice to conduct search operations, and the specific tactics deployed in support of that decision, are determined by department policy, the incident commander, and the specific incident. The 21 experiments conducted were designed with the project technical panel to best fulfill the four objectives set forth in Section 1.1 and are based on current fire service tactical approaches. The resulting changes in fire dynamics measured across the experimental series as a function of search and rescue tactics were analyzed with respect to toxic gas and thermal exposures to firefighters and potentially trapped occupants. The analysis led to the development of several tactical considerations.

A tactical consideration is defined as an evidence-based concept for the fire service to consider implementing to enhance efficiency and effectiveness, and to increase knowledge to accomplish their mission. The following considerations are meant to inform and further educate the fire service. They are recommendations from research that provide information to the fire service allowing firefighters to determine how, what, and when to utilize the information as it relates to their department and response model. Tactical considerations are not policy and are not specifications on how to enact or carry out a specific tactic. The application of tactical considerations also depends upon many factors such as building structure and geometry, capabilities and resources available to the responding fire department(s), and availability of automatic or mutual aid.

Additional context and limitations of the tactical considerations include:

- All experiments were conducted in single-story structures without a basement. Therefore, universal extrapolation of the tactical considerations to other structure types, in particular multi-story open-floor plan structures, should be avoided.
- 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.

When interpreting the following tactical considerations and/or those from prior research, it is important to keep in mind that this information can be leveraged either as individual components or as a set of considerations. Moreover, tactical considerations are best utilized in conjunction with prior training and experience due to the complexities of the fireground.

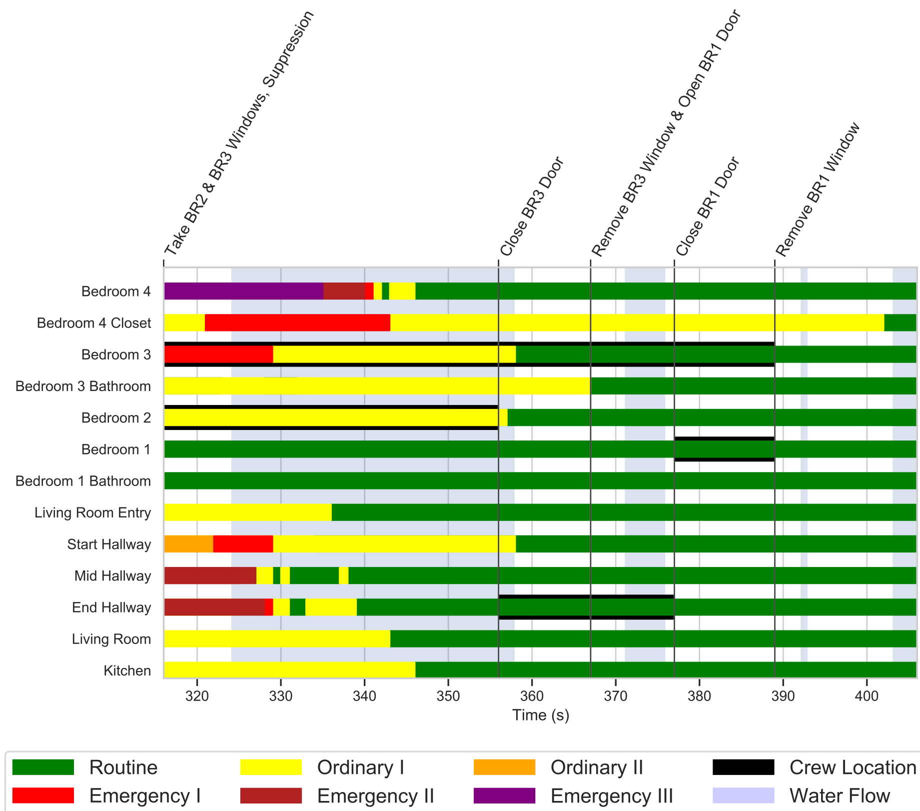
## 5.1 Timing of Suppression and Search

Previous FSRI research studies have shown that survival spaces exist upon arrival [20–22]. Results from the fire attack study, which incorporated the use of purpose-built victim packages, led to a tactical consideration pertaining to the timing of suppression and search operations titled *Fire Attack and Search & Rescue Can Occur Simultaneously* that in part states: "Although survivable spaces exist at the time of fire department arrival, the survivability potential decreases as the time of exposure increases. When resources permit, interior search and rescue operations can and should proceed simultaneously regardless of the fire attack tactic selected [20]."

> Provided effective interior and/or exterior suppression and sufficient resources, consideration should be given to the simultaneous execution of suppression, search, and rescue operations.

To further substantiate this consideration developed from the fire attack study, experiments examined search operations that occurred during suppression that was initiated from both interior and exterior positions. Experiment 2 was designed to examine a bedroom 4 fire where window initiated searches were conducted into bedrooms 2 and 3 simultaneous with the call for suppression. The suppression crew proceeded to enter the structure and began flowing water in the hallway within 8 s using a flow-and-move technique. They continued to flow water for a total of 35 s as they reached bedroom 4 and completed a primary knockdown of the post-flashover fire. Figure 5.1 shows the thermal operating classes corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 2, in each room of the structure as a function of time. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

As the thermal class data indicates in Figure 5.1, suppression was effective at reducing thermal exposures throughout the structure. Within 1 minute 20 s of the start of water flow, all thermal classes had returned to routine levels. Of particular interest were changes to the conditions in bedrooms 2 and 3, where exterior vents were created that coincided with the call for suppression. As the tabular data included with Figure 5.1 shows, gas concentrations, heat fluxes, and 3 ft temperatures all improved toward ambient conditions within 60 s post suppression.




| | | Pre-Suppression | | |
|---|---|---|---|---|
| Location | Oxygen | Carbon Monoxide | 3 ft Temperature | Heat Flux |
| Bedroom 2 Bed (3 ft) | 11.2% | 1.1% (11,000 PPM) | 198 °C (388 °F) | 4.5 kW/m$^2$ |
| Bathroom 3 (1 ft) | 13% | 1.4% (14,000 PPM) | 164 °C (327 °F) | 2.2 kW/m$^2$ |

| | | 60 s Post Suppression | | |
|---|---|---|---|---|
| Location | Oxygen | Carbon Monoxide | 3 ft Temperature | Heat Flux |
| Bedroom 2 Bed (3 ft) | 18.8% | 0.2% (2,000 PPM) | 44 °C (111 °F) | 0.8 kW/m$^2$ |
| Bathroom 3 (1 ft) | 17.7% | 0.7% (7,000 PPM) | 47 °C (117 °F) | 0.3 kW/m$^2$ |

Figure 5.1: Thermal operating conditions in Experiment 2 based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for during-suppression (initial interior suppression) window initiated search into bedrooms 2 and 3 for a bedroom 4 fire.

Experiment 3 was similar to Experiment 2 from a search tactics perspective – bedroom 4 fire where window-initiated searches were conducted into bedrooms 2 and 3 simultaneous with the call for suppression. The difference was that the suppression crew initially flowed water from an exterior position into bedroom 4 for 18 s before moving to the interior 7 s later to complete suppression with 16 s of additional water flow. Figure 5.2 shows a series of images that show the initial water flow from the exterior, window conditions upon completion of exterior water flow, and the flaming combustion along the carpet encountered as the suppression crew moved to the interior.

Air entrainment research has shown the need to be cognizant of stream type (solid or straight stream versus fog stream) and movement to avoid occluding the opening [23]. Tight stream patterns with limited movement were shown to minimize gas movement within a structure during exterior water application. Further, water mapping research [24] has shown that a steep angle is effective at distributing water within the compartment, but also that a hose stream without deflection distributes water in a line-of-site manner. Therefore, movement of the suppression crew to the interior was necessary to suppress the flame spread in the hallway, and complete suppression in the fire compartment due to the furniture that obstructed water mapping during the initial exterior application.

(a) Straight Stream at Steep Angle

(b) Conclusion of Exterior Water

(c) Flaming Combustion at Start Hallway

Figure 5.2: Images of from initial exterior suppression from Experiment 3 and subsequent movement to the interior to complete suppression.

Figure 5.3 shows the thermal operating classes, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 3, in each room of the structure as a function of time. The black bars on the charts correspond to the relative locations of the search crews during the events sequence. During the initial exterior suppression, temperatures throughout the structure decreased and correspondingly the thermal classes decreased throughout the structure with the exception of the mid hallway and end hallway locations which remained nominally steady. The thermal classes remained elevated at these locations due to flame spread along the carpet from the bedroom 4 fire, which was not completely suppressed from the exterior water flow. The 3 ft temperatures dropped by approximately 150 °C (302°F), but remained above 200 °C (392 °F) which is why the two hallway locations remained in the emergency operating class. Once the suppression crew moved to the interior, gases in the hallway were cooled, the carpet fire in the hallway was extinguished, the remainder of flaming combustion in the fire room was extinguished, and all thermal classes returned to routine levels within 35 s.


| | Pre-Suppression | | | |
|---|---|---|---|---|
| Location | Oxygen | Carbon Monoxide | 3 ft Temperature | Heat Flux |
| Bedroom 2 Bed (3 ft) | 13.1% | 0.8% (8,000 PPM) | 154 °C (309 °F) | 3.1 kW/m$^2$ |
| Bathroom 3 (1 ft) | 13.1% | 1.4% (14,000 PPM) | 120 °C (248 °F) | 1.3 kW/m$^2$ |

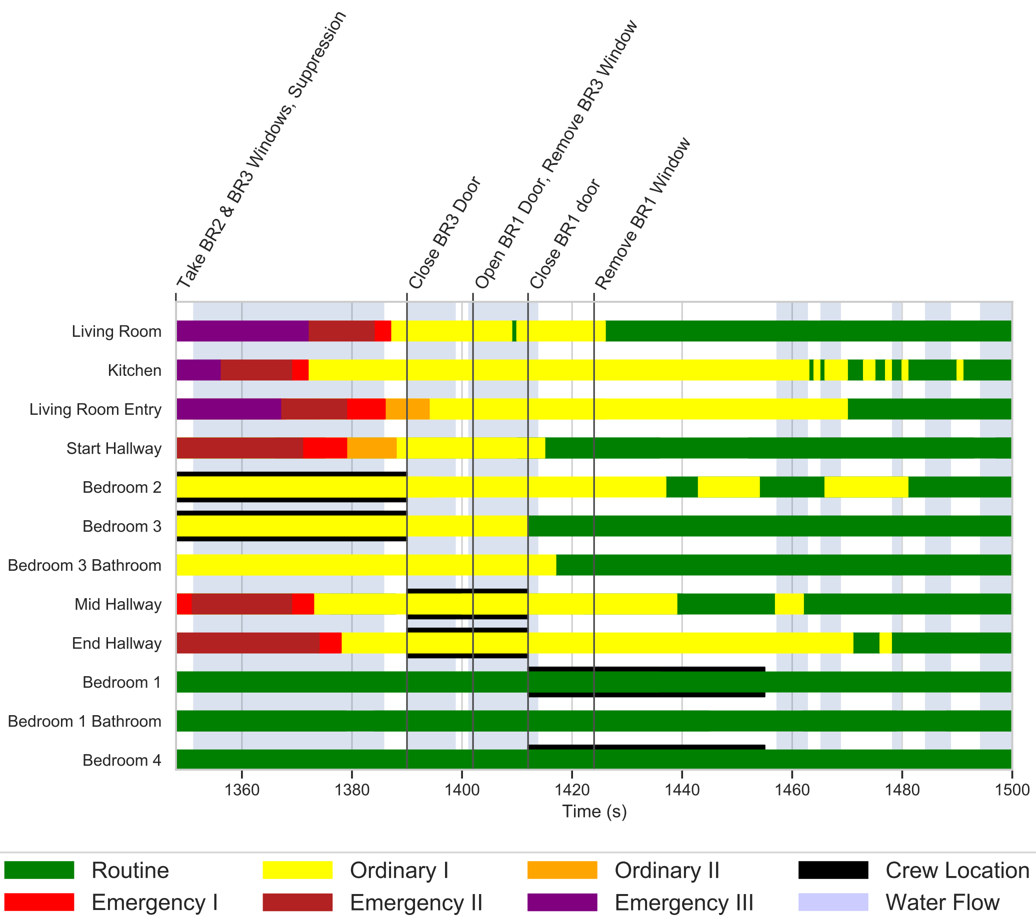
| | 60 s Post Suppression | | | |
|---|---|---|---|---|
| Location | Oxygen | Carbon Monoxide | 3 ft Temperature | Heat Flux |
| Bedroom 2 Bed (3 ft) | 18.5% | 0.2% (2,000 PPM) | 52 °C (126 °F) | 0.1 kW/m$^2$ |
| Bathroom 3 (1 ft) | 17.8% | 0.6% (6,000 PPM) | 49 °C (120 °F) | 0.3 kW/m$^2$ |

Figure 5.3: Thermal operating conditions in Experiment 3 based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for during-suppression (initial exterior suppression) window initiated search into bedrooms 2 and 3 for a bedroom 4 fire.

It is important to highlight that during Experiment 3, even with two open vents on the opposite side of the structure from the fire compartment, the initial exterior suppression from a straight stream did not increase the thermal or toxic hazard to searching firefighters or potentially trapped occupants in the structure. Temperatures in the fire room and those exhausting from the fire room into the hallway all uniformly decreased. The tabular data included with Figure 5.3 also shows that gas concentrations, heat fluxes, and 3 ft temperatures improved toward ambient conditions within 60 s post suppression.

Experiment 12 was also similar to Experiment 2 from a search tactics perspective – window initiated searches were conducted into bedrooms 2 and 3 simultaneous with the call for suppression, except the fire location was the kitchen/living room versus bedroom 4. The suppression crew began to flow water into the living room through the open front door and failed living room windows from an exterior position on the deck before moving interior as the flames that extended out of those vents were knocked down. In total, the crew flowed water for 42 s as part of primary suppression. Figure 5.4 shows the thermal operating classes, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 12, in each room of the structure as a function of time. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

The thermal class data in Figure 5.4 shows that, similar to Experiment 2, suppression was effective at reducing thermal exposures throughout the structure. In bedrooms 2 and 3, where exterior vents were created that coincided with the call for suppression like the two bedroom 4 experiments, there was no increase in the thermal or toxic hazard to searching firefighters or potentially trapped occupants. The tabular data included with Figure 5.1 also shows that gas concentrations, heat fluxes, and 3 ft temperatures all improved toward ambient conditions within 60 s post suppression.




| | Pre-Suppression | | | |
|---|---|---|---|---|
| Location | Oxygen | Carbon Monoxide | 3 ft Temperature | Heat Flux |
| Bedroom 2 Bed (3 ft) | 5.8% | 3.8% (38,000 PPM) | 178 °C (352 °F) | 5.2 kW/m$^2$ |
| Bathroom 3 (1 ft) | 3.5% | 3.2% (32,000 PPM) | 138 °C (280 °F) | 2.6 kW/m$^2$ |

| | 60 s Post Suppression | | | |
|---|---|---|---|---|
| Location | Oxygen | Carbon Monoxide | 3 ft Temperature | Heat Flux |
| Bedroom 2 Bed (3 ft) | 17.8% | 0.5% (5,000 PPM) | 65 °C (149 °F) | 0.9 kW/m$^2$ |
| Bathroom 3 (1 ft) | 19.1% | 0.4% (4,000 PPM) | 48 °C (118 °F) | 0.3 kW/m$^2$ |

Figure 5.4: Thermal operating conditions in Experiment 12 based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for during-suppression window initiated search into bedrooms 2 and 3 for a kitchen fire.

## 5.2 Pre-Suppression Window Initiated Search Into Isolated Space

Ventilation of a bedroom window with an open interior door establishes a flow path between the vent and the fire compartment. Higher pressure combustion gases produced by the fire will flow toward the area of lower pressure created by the open exterior vent. The flow of combustion gases can lead to increases in both the toxic exposure and thermal exposure to firefighters or potentially trapped occupants that are in the exhaust portion of this flow path.

> If an isolated space is identified as part of a thorough size-up, consideration should be given to making entry into that space as part of a window initiated search ahead of suppression. Isolation inhibits the establishment of a flow path between the fire compartment and the newly created vent until the firefighters are prepared to make the opening. If conditions permit searching beyond the compartment of entry, re-isolation upon exiting the space maintains a place of refuge if needed.

In Experiment 8b, ventilation of a window occurred at bedroom 3, where the interior door was closed prior to ignition. An examination of fluid mechanics, or the study of fluids in motion, can be used to understand how the closed door could impact flow into the space.The direction of gas flow is driven by pressure differences. Combustion gases will flow from areas of higher pressure to areas of lower pressure. The combustion gases moving through a space are subject to flow resistance due to both the enclosure and the other gases being displaced. As the area of the enclosure shrinks, the resistance increases. For a fixed pressure difference along two pathways, the pathway with the larger area will have more flow as that option represents the path of least resistance. In the case of a closed door, the area for gas flow is limited to the gaps that exist between the door and the frame. These gaps were sufficiently small such that despite the lower-pressure vent in the bedroom which subsequently dropped the pressure in the bedroom, the flow resistance was high enough to limit the flow of higher pressure combustion gases from the hallway into room. Figure 5.5 shows the negligible change in conditions in bedroom 3 due to the window being ventilated, despite floor-to-ceiling flaming combustion on the hallway side of the bedroom door.

(a) 10 s Prior to Window Ventilation

(b) 1 s Prior to Door Open (30 s Post Window Ventilation)

(c) 1 s Post Door Open

Figure 5.5: Images of bedroom 3 from Experiment 8b prior to window ventilation and before and after interior door opening.

The thermal operating classes (Section 3.3) can be used to quantify the impact of window initiated search into an isolated room on the thermal exposure to searching firefighters. Figure 5.6 shows the difference in thermal hazard at the time of intervention through 30 s after the crew exited bedroom 3 to search beyond the room of entry during Experiment 8b. This included flow from a pressurized water can in the hallway. In bedroom 3, the closed door kept the operating class at the routine level despite the open window while bedroom 2 increased to an ordinary operating class due to the open door.

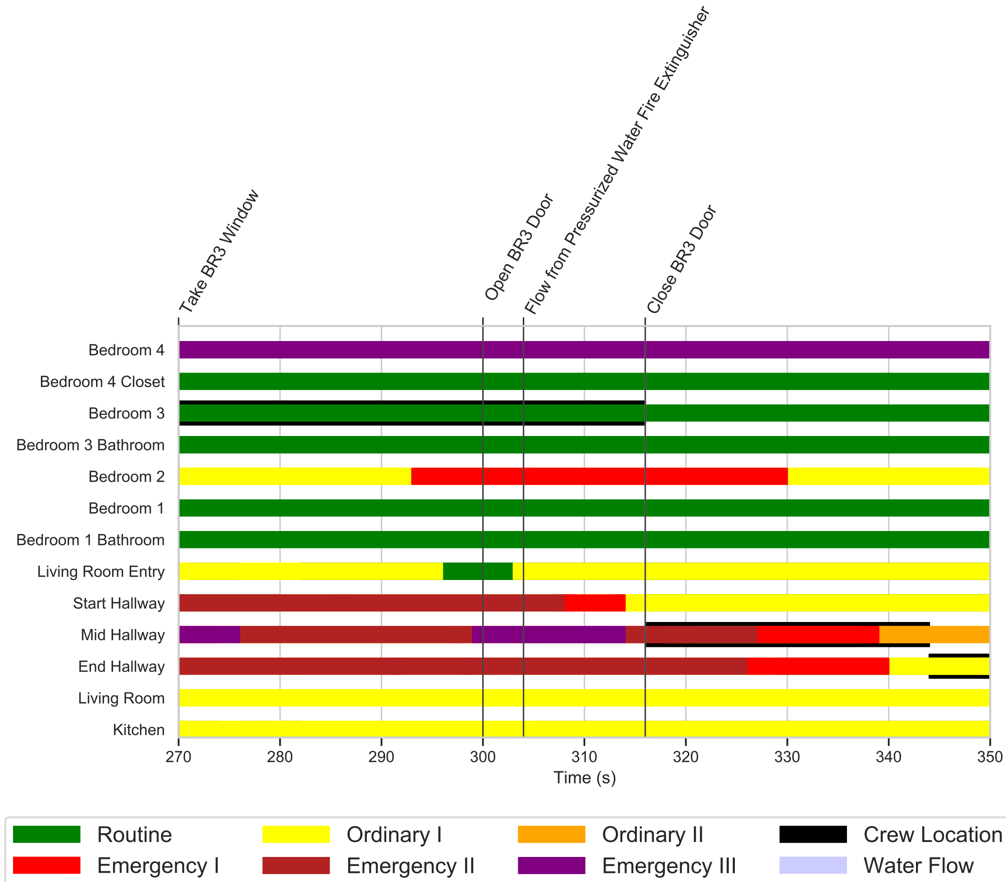



Figure 5.6: Thermal operating conditions in Experiment 8b based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search into an isolated room (bedroom 3).

At the time the bedroom 3 door was opened, the thermal operating class at the start hallway and mid hallway locations were emergency II and emergency III, respectively. Figure 5.7 shows flame spread into the hallway and corresponding temperature and heat fluxes at the start and mid hallway locations. At the time the bedroom 3 door was opened, the hallway immediately outside of the bedroom was in a post-flashover state. These conditions were beyond the limits of personal protective equipment. Although water flow from the pressurized water fire extinguisher reduced the thermal operating class from the emergency III class, mid hallway and end hallway thermal operating classes remained at the emergency I level for 25 s after water flow. Bedroom 4, the fire room, was unaffected by the water flow from the pressurized water fire extinguished and remained at the emergency III level.

The 3 ft temperature in bedroom 3 was at 20 °C (68 °F) prior to the ventilation of the window and increased to 22 degree C (72 °F) in the 30 s until the door was opened. In the open bedroom, bedroom 2, the 3 ft temperature was 165 °C (329 °F) prior to bedroom 3 window ventilation and continued to rise, peaking at 216 °C (421 °F). This coincided with flow from the pressurized water fire extinguisher in the hallway.

| Start Hallway | |
|---|---|
| 3 ft Temperature: | 332 °C (630 °F) |
| Heat Flux: | 5 kW/m$^2$ |
| Operating Class: | Emergency II |

| Mid Hallway | |
|---|---|
| 3 ft Temperature: | 618 °C (1144 °F) |
| Heat Flux: | 12 kW/m$^2$ |
| Operating Class: | Emergency III |


Figure 5.7: Photograph of flame spread into the hallway and thermal conditions at start hallway and mid hallway prior to opening bedroom 3 door in Experiment 8b.

The closed door prior to window ventilation also directly impacted the toxic and thermal exposure to potential occupants. Table 5.1 shows the average rate of change of toxic and thermal FED for bedrooms 2 and 3 from the time at which the bedroom 3 window was vented until 30 s after the bedroom 3 door was opened and closed following the crew leaving the room to search beyond point of entry. The data shows that, in particular, the rate of toxic FED increase was between 2 to 3 orders of magnitude higher in the open bedroom compared to the isolated space. This further shows the impact that a closed, intact door has in reducing exposure and that ventilation into an isolated space does not negatively change conditions.

Table 5.1: Impact of Isolation on Occupant Tenability for Window Initiated Search Pre-Suppression into Isolated Room

| | Isolated | |
|---|---|---|
| Location | Average Toxic FER | Average Thermal FER |
| Bathroom 3 (1 ft) | 2.2e-5 (Exp 8b) | 8.6e-7 (Exp 8b) |
| Bedroom 3 Window (1 ft) | 2.3e-4 (Exp 8b) | 3.5e-6 (Exp 8b) |
| Bedroom 3 Window (3 ft) | 1.63-4 (Exp 8b) | 6.7e-6 (Exp 8b) |
| | Not Isolated | |
| Location | Average Toxic FER | Average Thermal FER |
| Bedroom 2 Bed (3 ft) | 0.24 (Exp 8b) | 0.027 (Exp 8b) |
| Bedroom 2 Window (1 ft) | 0.095 (Exp 8b) | 0.017 (Exp 8b) |
| Bedroom 2 Window (3 ft) | 0.12 (Exp 8b) | 0.038 (Exp 8b) |

## 5.3 Pre-Suppression Isolation of Spaces

Previous UL FSRI research studies have shown the positive impact of a closed door on occupant tenability during a residential fire [20,22,25–28]. Results from the fire attack study, which incorporated the use of purpose-built victim packages, led to a tactical consideration pertaining to search operations and closed doors titled *Search Consideration: Closed Doors Significantly Increase Occupant Survivability* that in part states:

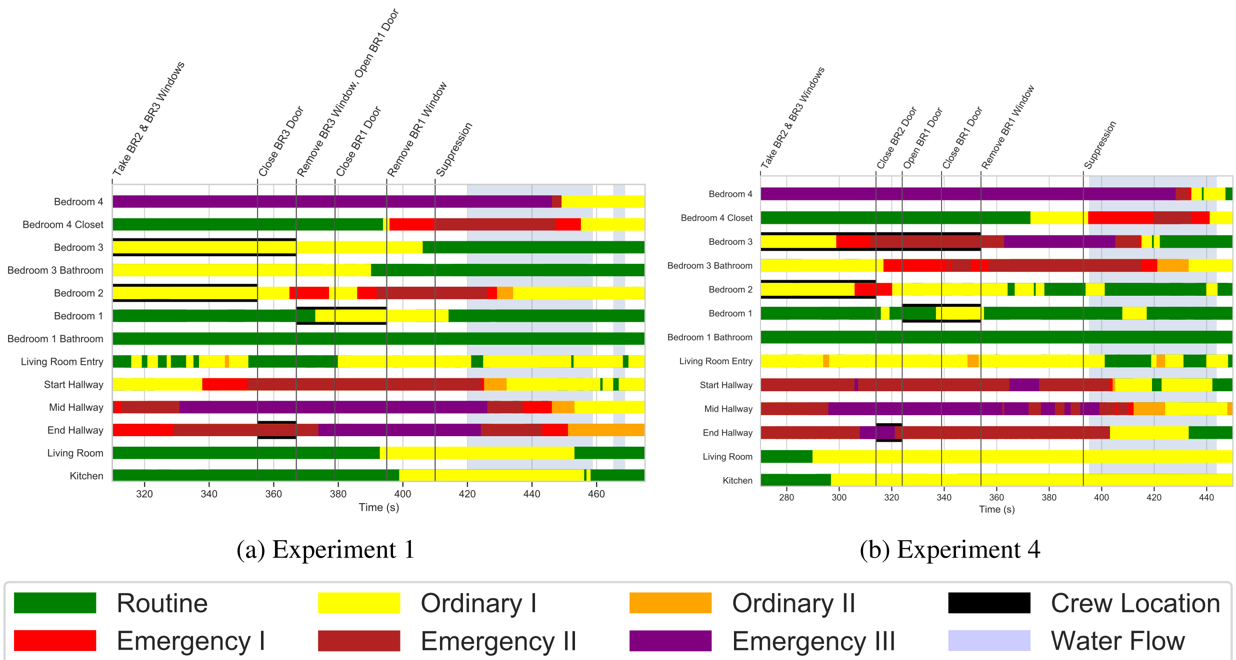
> "A victim located in a bedroom during a search with a closed door between them and the fire has a much higher likelihood of [survival] than a victim with an open bedroom door [20]."

Across this series of experiments, 6 bedroom experiments, 2 kitchen experiments, and 1 living room experiment included pre-suppression search operations where the doorway to bedroom 1 was closed prior to ignition. As part of the search operations, the bedroom 1 door was opened and closed to simulate a crew searching the space. Prior to the door being opened, thermal conditions at the end hallway location reached peak ceiling temperatures above 700 °C (1292 °F) and heat fluxes greater than 14 kW/m$^2$. Over this subset of experiments, gas concentrations 3 ft above the floor at the end hallway dropped to a minimum of 1.2% $O_2$ and maximum of 5% (50,000 ppm) CO (the upper measurement limit of the analyzer). For a fully protected firefighter, the peak thermal conditions would place crews in the emergency II and III operating classes. For an unprotected occupant, these thermal and toxic conditions would be above typical tenability limits. Across the 9 experiments, on the bedroom side of the closed door, the minimum $O_2$ concentration and maximum CO concentration (measured 3 ft above the floor on the bed) was 19.1% and 0.2% (2000 ppm), respectively. The corresponding temperature and heat flux measured on the bed did not exceed 25 °C (77 °F) and 1 kW/m$^2$. This data corroborates the previous research which showed the effectiveness of a door that was closed prior to ignition and remained closed for the duration of the experiment.

Unique to this study was the coupling of door opening and closing actions with common search and rescue tactics. To examine the impact of closing the door to a previously non-isolated space, the thermal operating classes for firefighters and the toxic and thermal exposure rates for potential occupants are compared for isolated and non-isolated bedrooms for two sets of experiments where window initiated search was conducted.

> For window-initiated search into non-isolated spaces prior to suppression, consider isolation of the entry space. Upon isolation, further consideration should be given to increasing the amount of exterior ventilation within that space.
>
> For door-initiated search conducted prior to suppression, consideration should be given to isolating the room being searched from flow paths connected to the fire compartment. Upon isolation, further consideration should be given to opening exterior vents within that space.

Experiments 1 and 4 examined window-initiated search that occurred prior to suppression. The primary difference between the two experiments was which bedroom was isolated following initial entry — bedroom 3 in Experiment 1 compared to bedroom 2 in Experiment 4. To assess the impact of isolation of the space of entry for a window initiated search prior to suppression Figure 5.8 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiments 1 and 4. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.




(a) Experiment 1

(b) Experiment 4

Figure 5.8: Comparison of thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics.

In both Experiments 1 and 4, the doors between the hallway and bedrooms 2 and 3 were open from the time of ignition, which resulted in temperatures consistent with ordinary operating conditions at the time that the bedroom windows were ventilated. In Experiment 1, where bedroom 2 was not isolated, within 75 s of window ventilation 3 ft temperatures exceeded 200 °C (392 °F) and heat flux exceeded 7.5 kW/m$^2$, moving bedroom 2 to the emergency operating class. Temperature and heat flux continued to increase until suppression, reaching peak 3 ft temperature and heat flux values of 465 °C (869 °F) and 24 kW/m$^2$, respectively as shown in Figure 5.9.

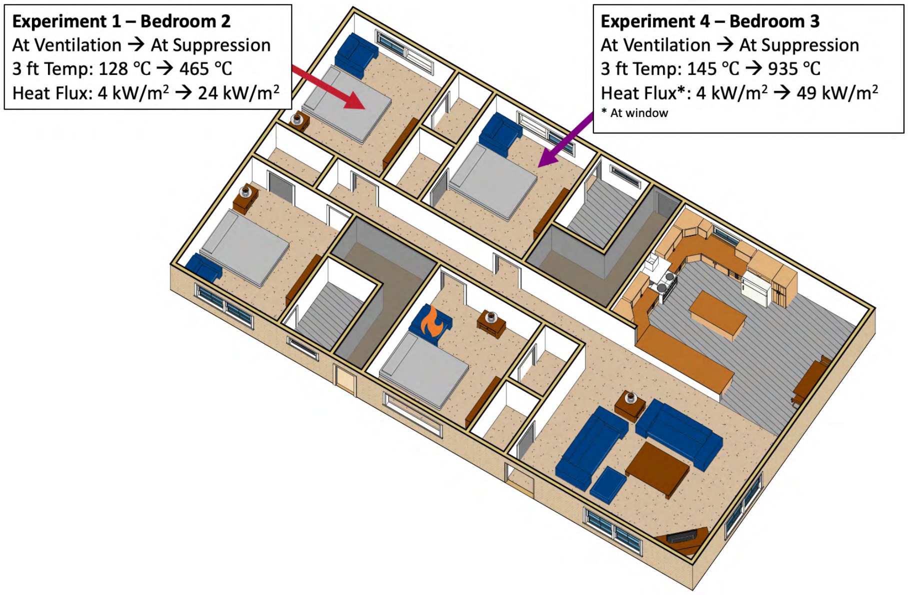



Figure 5.9: Changes in 3 ft temperature and heat flux from prior to window initiated search to the start of suppression in bedroom 2 and 3 for Experiments 1 and 4, respectively. In both experiments, these respective bedroom doors remained open for the duration of the experiment.

In Experiment 4, where bedroom 3 was not isolated, 3 ft temperatures in bedroom 3 steadily rose from 146 °C (295 °F) to 200 °C (392 °F) in the 30 s following window ventilation, which increased the operating class from ordinary to emergency. Over the next 30 s, the lack of isolation, low pressure exhaust vent, and close proximity to the fire compartment resulted in flame spread across the hallway and into bedroom 3. Within 90 s of window ventilation, the 3 ft temperatures crossed 800 °C (1472 °F) and the room transitioned through flashover as shown in Figure 5.10. Bedroom 3 remained in the emergency operating class until suppression, with 3 ft temperatures peaking at 935 °C (1715 °F) and 3 ft window heat flux peaking at 49 kW/$m^2$ (Figure 5.9).

Figure 5.10: Photograph of exterior fire conditions at bedroom 3 window 90 s after window ventilation during Experiment 4.

In contrast to the open bedrooms, the bedrooms which were isolated after ventilation transitioned back to the routine operating class prior to suppression due to the combination of the closed door and local exterior vent. In Experiment 1, 3 ft bedroom 3 temperatures peaked at 145 °C (293 °F), and in Experiment 4, 3 ft bedroom 2 temperatures peaked at 256 °C (493 °F). In both experiments, the peak temperatures in these rooms occurred immediately prior to closure of the respective bedroom doors. Following isolation, the thermal operating classes returned to the routine level prior to suppression further quantifying the thermal protection provided by a closed door due to the isolation from the flow path as shown in Figure 5.11.

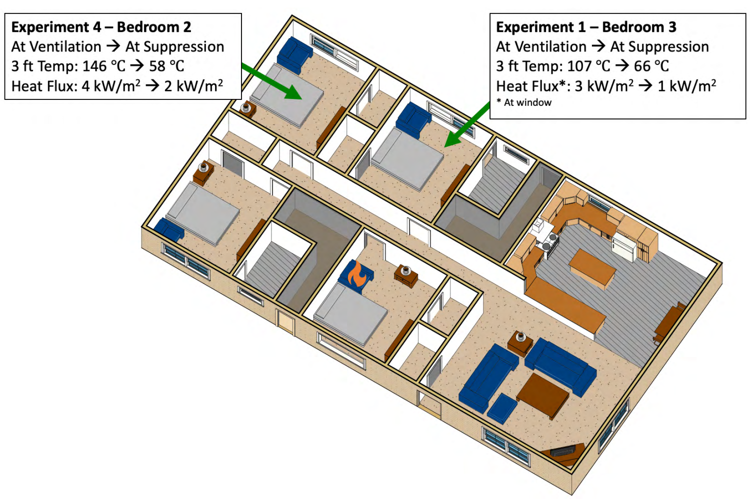



Figure 5.11: Changes in 3 ft temperature and heat flux from prior to window initiated search to the start of suppression in bedroom 2 and 3 for Experiments 1 and 4, respectively. In both experiments, these respective bedroom doors were closed after search crews made entry to the respective bedroom.

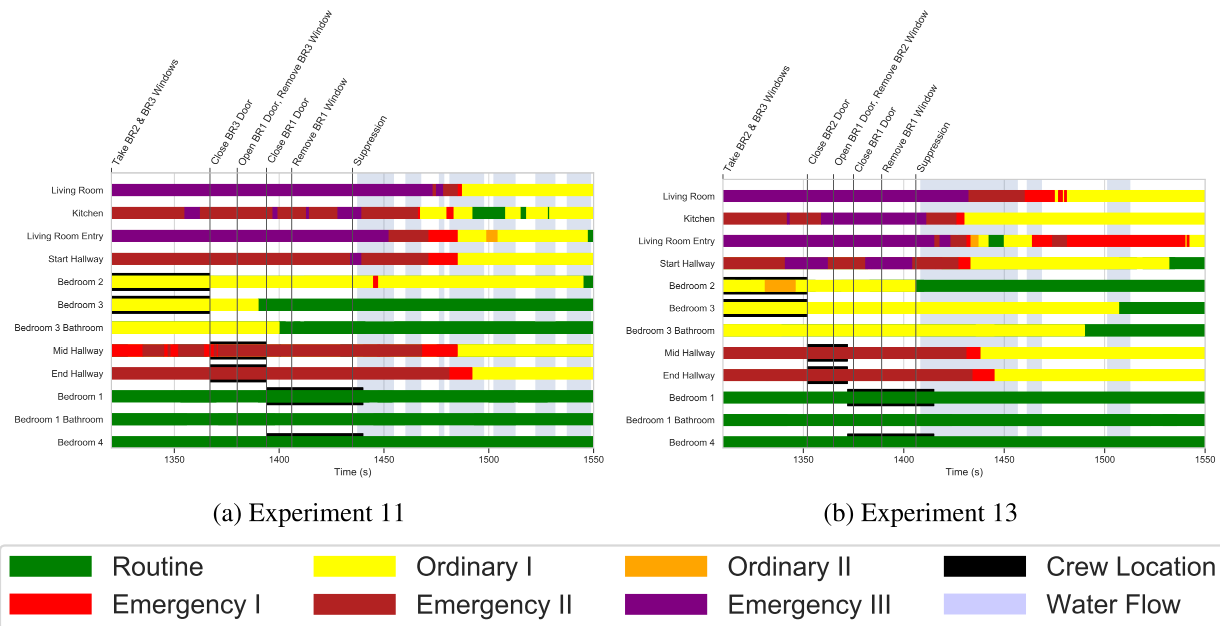
For potentially trapped occupants, the rate of change of toxic and thermal FEDs (FERs) can be used to quantify the effectiveness of the tactics. By definition, FEDs will always increase. The positive impact of the two tactical options can be shown by comparing the magnitudes of the rate of change of the FED. Table 5.2 includes the average toxic and thermal FER from the time of isolation to primary suppression for the bedroom 2 bed, bedroom 2 window, bathroom 3 and bedroom 3 window.

Table 5.2: Impact of Bedroom Isolation on Occupant Tenability for Pre-Suppression Window Initiated Search

| | Average Toxic FER | | Average Thermal FER | |
|---|---|---|---|---|
| Location | Isolated | Not Isolated | Isolated | Not Isolated |
| Bedroom 2 Bed (3 ft) | 0.0065 (Exp 4) | 0.037 (Exp 1) | 0.0018 (Exp 4) | 0.054 (Exp 1) |
| Bedroom 2 Window (1 ft) | 0.0012 (Exp 4) | 0.034 (Exp 1) | 0.0007 (Exp 4) | 0.033 (Exp 1) |
| Bedroom 2 Window (3 ft) | 0.0025 (Exp 4) | 0.088 (Exp 1) | 0.015 (Exp 4) | 0.060 (Exp 1) |
| Bathroom 3 (1 ft) | 0.010 (Exp 1) | 0.34 (Exp 4) | 4.5e-5 (Exp 1) | 0.015 (Exp 4) |
| Bedroom 3 Window (1 ft) | 0.0029 (Exp 1) | 0.25 (Exp 4) | 5.3e-5 (Exp 1) | 0.16 (Exp 4) |
| Bedroom 3 Window (3 ft) | 0.0041 (Exp 1) | 0.90 (Exp 4) | 0.0017 (Exp 1) | 0.59 (Exp 4) |

The rate of exposure data in Table 5.2 shows the impact of isolation after entry on both the toxic gas and thermal exposure to potential occupants. At all locations, the average rate of FED increase (both toxic and thermal) was lower at the locations which were isolated.

Similar results were observed for the two window-initiated search experiments conducted into bedrooms prior to suppression for a kitchen fire (Experiments 11 and 13). 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. Figure 5.12 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 5.12: 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. In the bedrooms where the interior door remained open, following an initial drop in temperature due to the exhaust of combustion gases and entrainment of air, 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 peaked at 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 reached 163 °C (325 °F) 10 s prior to suppression. The change in temperature and heat flux in bedrooms 2 and 3 for these experiments in shown in Figure 5.13. The temperature increase through the start of suppression was associated with combustion gases produced prior to suppression that flowed toward the exterior vents in the bedrooms.

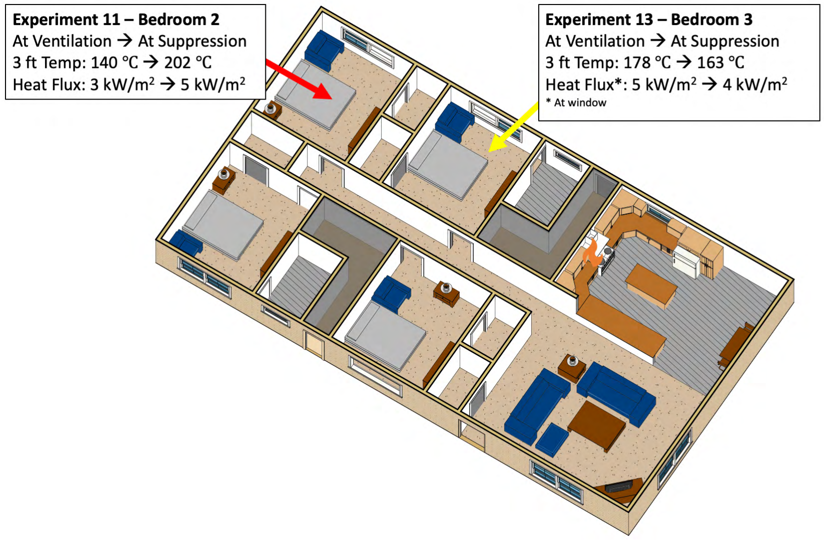



Figure 5.13: Changes in 3 ft temperature and heat flux from prior to window initiated search to the start of suppression in bedroom 2 and 3 for Experiments 11 and 13, respectively. In both experiments, these respective bedroom doors remained open for the duration of the experiment.

Closing the interior bedroom door following the window initiated search had a sustained positive impact on temperature in both Experiments 11 and 13. 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 as further shown by the 3 ft temperature and heat flux in Figure 5.14.

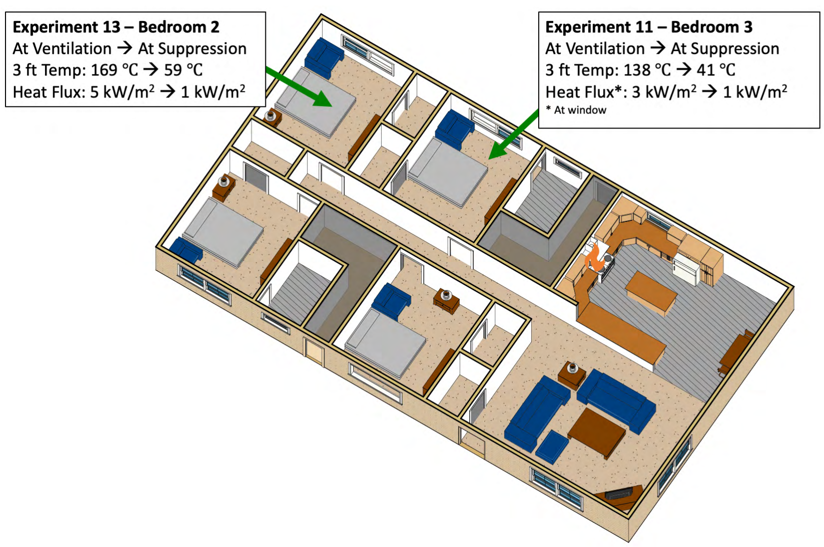



Figure 5.14: Changes in 3 ft temperature and heat flux from prior to window initiated search to the start of suppression in bedroom 2 and 3 for Experiments 11 and 13, respectively. In both experiments, these respective bedroom doors were closed after search crews made entry to the respective bedroom.

For potentially trapped occupants, the rate of change of toxic and thermal FEDs (FERs) is again used to quantify the effectiveness of the tactics. Table 5.3 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 5.3: Impact of Bedroom Isolation on Occupant Tenability for Pre-Suppression Window Initiated Search

| | Average Toxic FER | | Average Thermal FER | |
|---|---|---|---|---|
| Location | Isolated | Not Isolated | Isolated | Not Isolated |
| Bedroom 2 Bed (3 ft) | 0.082 (Exp 13) | 0.11 (Exp 11) | 0.0013 (Exp 13) | 0.0064 (Exp 11) |
| Bedroom 2 Window (1 ft) | 0.0025 (Exp 13) | 0.011 (Exp 11) | 3.5e-5 (Exp 13) | 0.0017 (Exp 11) |
| Bedroom 2 Window (3 ft) | 0.0048 (Exp 13) | 0.029 (Exp 11) | 2.6e-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) | 8.4e-5 (Exp 11) | 0.0048 (Exp 13) |

The rate of exposure data in Table 5.3 shows 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.

The impact of isolation was also quantified for door-initiated search experiments ahead of suppression. Experiment 6 examined door initiated search prior to suppression for a bedroom fire. The front door, bedroom 2, and bedroom 3 doors were open prior to ignition. The front door was closed by the search crew as they entered the structure. The bedroom 3 and bedroom 2 doors were closed upon entry to search the respective rooms. Figure 5.15 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 6. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

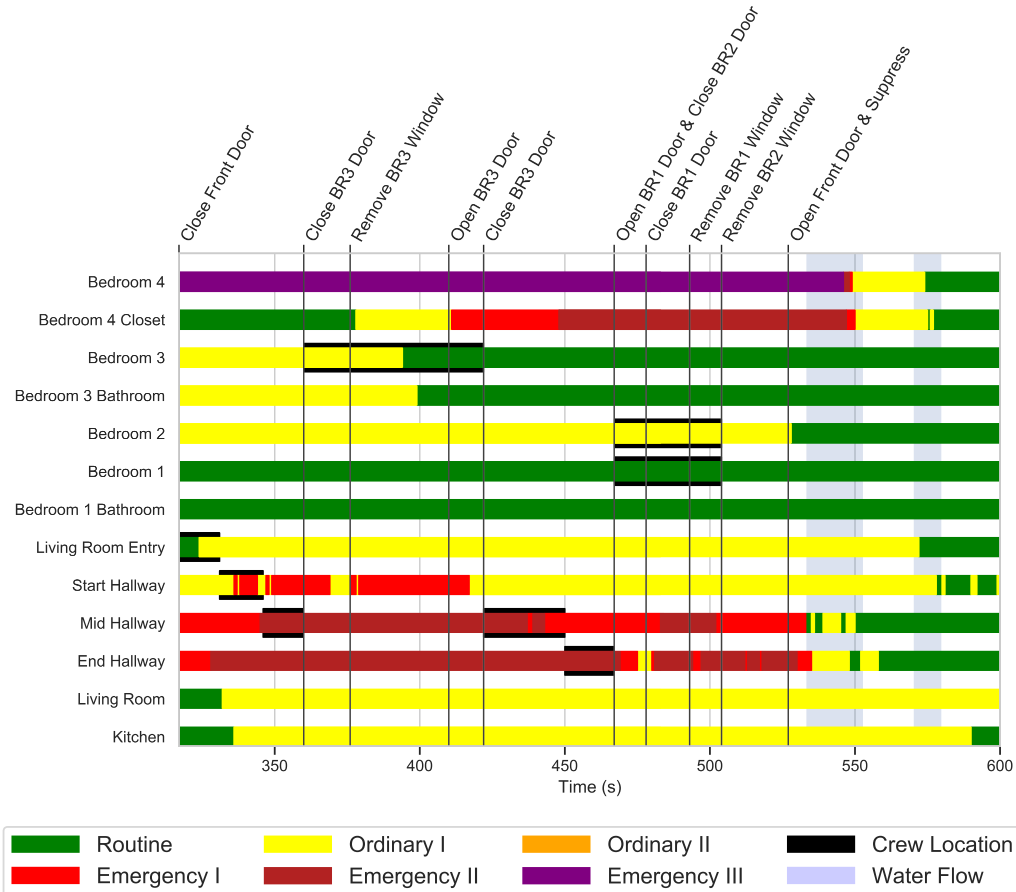



Figure 5.15: Thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression door initiated search tactics in Experiment 6.

In bedroom 3, the 3 ft temperature steadily increased from 130 °C (266 °F) at the time of front door closure to a peak of 147 °C (297 °F), 4 s after the bedroom 3 door was closed. These thermal conditions were consistent with an ordinary level operating class. The bedroom window was removed 16 s after door closure, by which time the 3 ft temperature had already dropped to 126 °C (259 °F). Over the next 18 s, the 3 ft temperature had dropped below 72 °C (162 °F), which reduced the operating class to the routine level. At this same time, the 3 ft temperature and heat flux at the mid hallway location were 298 °C (598 °F) with heat flux of 3.6 kW/m$^2$ which would place firefighters in that location in the emergency operating class.

A similar response was measured in bedroom 2. Prior to isolation, the thermal operating class was at the ordinary level with 3 ft temperatures of 165 °C (329 °F). The temperatures dropped to 120 °(248 °F) in the 37 s before the window was removed before dropping below 72 °C (162 °F) 24 s later which returned the space to the routine operating class. For both bedrooms, the isolation and subsequent ventilation of the space was able to reduce the thermal operating class to the routine class prior to suppression despite the hallway locations being at the emergency level. Figure 5.16 shows the changes 3 ft temperature and heat flux in bedrooms 2 and 3 following isolation and window removal as well as corresponding conditions in the mid hallway location.

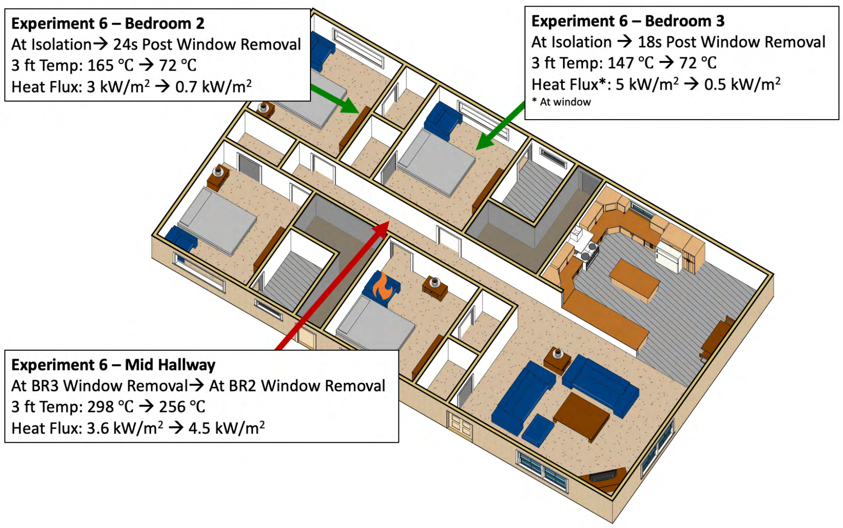



Figure 5.16: Changes in 3 ft temperature and heat flux during door initiated search with front door closure in bedrooms 2 and 3 from time of isolation to time of window removal in Experiment 6.

For potentially trapped occupants, the rate of change of toxic and thermal FEDs (FERs) prior to suppression shows how isolation and corresponding ventilation can be used to reduce the hazard. Table 5.4 includes the average toxic FER before and after isolation for bedroom 2 bed, bedroom 2 window, bathroom 3 and bedroom 3 window.

Table 5.4: Impact of Bedroom Isolation on Occupant Tenability for Pre-Suppression Door Initiated Search of Bedroom Fire

| | Average Toxic FER | | Average Thermal FER | |
|---|---|---|---|---|
| Location | Isolated | Not Isolated | Isolated | Not Isolated |
| Bedroom 2 Bed (3 ft) | 0.056 (Exp 6) | 0.082 (Exp 6) | 0.0019 (Exp 6) | 0.010 (Exp 6) |
| Bedroom 2 Window (1 ft) | 0.060 (Exp 6) | 0.062 (Exp 6) | 8.9e-4 (Exp 6) | 0.016 (Exp 6) |
| Bedroom 2 Window (3 ft) | 0.069 (Exp 6) | 0.075 (Exp 6) | 0.0036 (Exp 6) | 0.019 (Exp 6) |
| Bathroom 3 (1 ft) | 0.0078 (Exp 6) | 0.015 (Exp 6) | 5.3e-5 (Exp 6) | 1.6e-4 (Exp 6) |
| Bedroom 3 Window (1 ft) | 0.0063 (Exp 6) | 0.014 (Exp 6) | 7.8e-5 (Exp 6) | 0.0064 (Exp 6) |
| Bedroom 3 Window (3 ft) | 0.0075 (Exp 6) | 0.016 (Exp 6) | 0.002 (Exp 6) | 0.012 (Exp 6) |

The closed bedroom doors removed the respective bedroom from the flow path that originated in the fire room. As a result, the average thermal FER (rate of FED increase) was an order of magnitude lower after the room was isolated. The closed door alone had less of an impact on the average toxic FER. In bedroom 3, the window was removed 16 s after the closure, which established a flow path local to bedroom 3. The closed door restricted additional combustion gases from entering the room, and the bi-directional flow at the window allowed the accumulated combustion gases to exhaust from the room, which dropped the rate of toxic FED increase by an order of magnitude compared to non-isolated time period. For bedroom 2, the window was removed 37 s after isolation. The longer duration in window removal following isolation in bedroom 2 relative to bedroom 3, resulted in similar toxic FER compared to the non-isolated time period. The data highlights the value of pre-suppression coordination of isolation and ventilation.

Similar to Experiment 6, Experiment 17 examined a door-initiated search that occurred prior to suppression of a kitchen ignition. All interior bedroom doors to the hallway were open from the time of ignition, and the front door remained open for the duration of the experiment. The search crew entered the structure and began to search the open bedrooms, beginning at bedroom 3/4 and moving to bedrooms 1/2. 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. Figure 5.17 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.

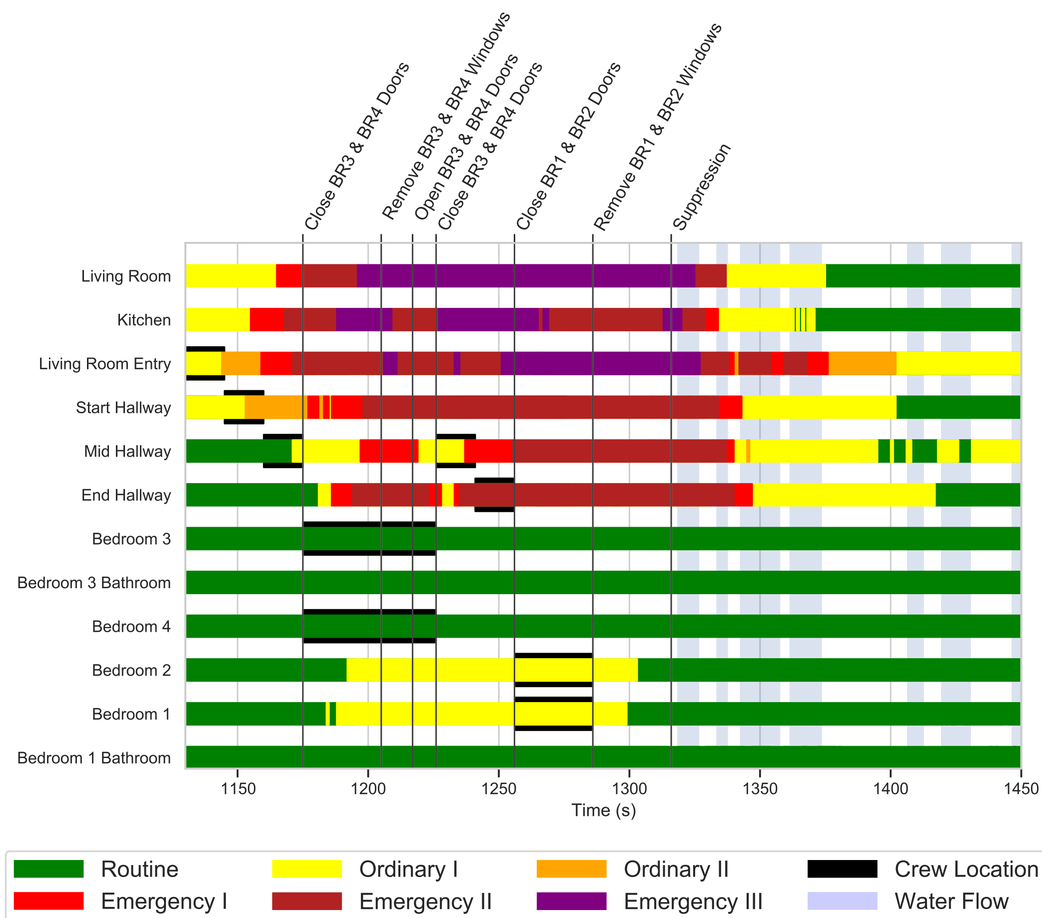



Figure 5.17: Thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression door-initiated search tactics in Experiment 17.

Crews entered the structure while the fire was still contained to the kitchen and conditions 3 ft above the floor at the living room entry 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 which both reached an ordinary thermal class exposure. 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 reached levels consistent with an emergency II/III operating class exposure. At this point, in the absence of suppression, paths of egress for search crews and potentially trapped occupants would be through a bedroom window.

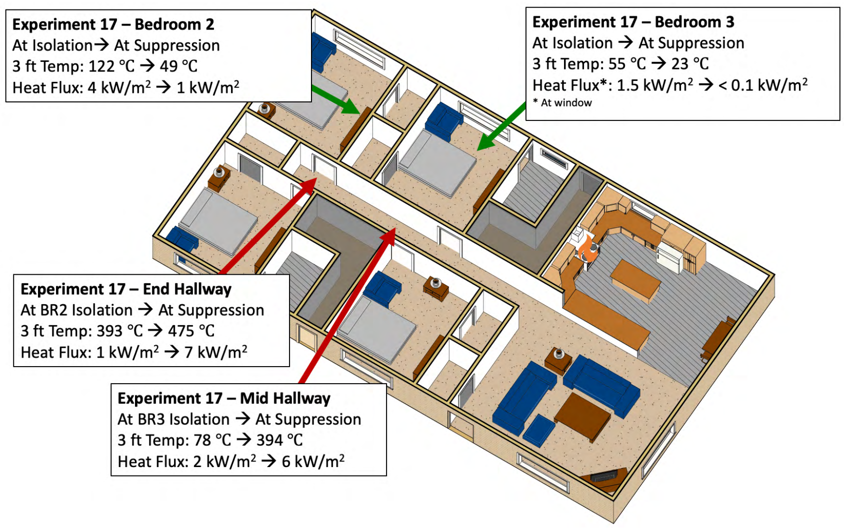



Figure 5.18: Changes in 3 ft temperature and heat flux during door initiated search in bedrooms 2 and 3 from time of isolation to time of suppression in Experiment 17.

When the search crews moved from the first set of bedrooms (bedrooms 3 and 4) and reached the second set of bedrooms (bedrooms 1 and 2), temperatures at the end hallway locations were consistent with emergency class II operating conditions with a 3 ft temperature of 393 °C (739 °F) and a heat flux of 7 kW/m$^2$, beyond the limits of firefighter personal protective equipment. 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, prior to the start of suppression. This was despite emergency class II conditions in the hallway prior to suppression.

The impact of timing and isolation is also shown by the differences in the toxic and thermal FERs (Table 5.5). During the experiment, 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 gases into the bedroom. For bedrooms 1 and 2, the doors were closed after flashover of the kitchen/living room. 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 5.5: Impact of Bedroom Isolation on Occupant Tenability for Door Initiated Search Pre-Suppression for a Kitchen/Living Room Fire

| | Experiment 17 | |
|---|---|---|
| Location | Average Toxic FER | Average Thermal FER |
| Pre-Flashover Isolation | | |
| Bathroom 3 (1 ft) | 0.0030 | 2.0e-6 |
| Bedroom 3 Window (1 ft) | 0.0021 | 3.9e-6 |
| Bedroom 3 Window (3 ft) | 0.0044 | 2.7e-5 |
| Post-Flashover Isolation | | |
| Bedroom 1 Bed (3 ft) | 0.044 | 0.0047 |
| Bathroom 1 (1 ft) | 0.0027 | 2.8e-6 |
| Bedroom 2 Bed (3 ft) | 0.095 | 0.0051 |
| Bedroom 2 Window (1 ft) | 0.044 | 6.9e-4 |
| Bedroom 2 Window (3 ft) | 0.16 | 8.3e-4 |
| No Isolation | | |
| Start Hallway (1 ft) | 0.047 | 0.034 |
| Start Hallway (3 ft) | 0.029 | 0.12 |
| Mid Hallway (1 ft) | 0.0071 | 0.013 |
| Mid Hallway (3 ft) | 0.26 | 0.037 |
| End Hallway (1 ft) | 0.022 | 0.026 |
| End Hallway (3 ft) | 0.39 | 0.072 |

## 5.4 Pre-Suppression Isolation of Fire Compartment(s)

Prior to intervention, the presence and integrity of interior doors may not always be discernible, particularly the door to the fire compartment. Closure of the fire compartment door can limit the oxygen available for combustion and/or remove the source of higher-temperature, higher-pressure combustion within flow paths inside the structure.

> Consideration should be given to isolation of the fire compartment from adjoining spaces and/or isolation of the fire compartment from sources of oxygen supply (e.g., close the bedroom door for a bedroom fire and close the front door for a kitchen/living room fire). Additional consideration should be given to employ further isolation and subsequent exterior ventilation of non-fire compartments during pre-suppression search operations.

The impact of isolation of the fire compartment from adjoining spaces in the structure can be seen in Experiment 8 (a bedroom ignition) and the impact of isolation of the fire compartment from oxygen supply can been seen in Experiment 16 (a kitchen ignition). For the bedroom door isolation experiment ahead of suppression, Experiment 8 started with a window initiated search through bedroom 3 and then proceeded to isolate the fire room across the hallway after searching the room of entry. It is important to recognize that for these experiments the bedroom 4 door was hardened to ensure that it could be closed to quantify the effects of the door closure. There is no guarantee that the fire room door will always be present at the time of fire department arrival due to fire growth. Figure 5.19 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiments 7 and 8. The black bars on the charts correspond to the relative locations of the search crews during the events sequence.

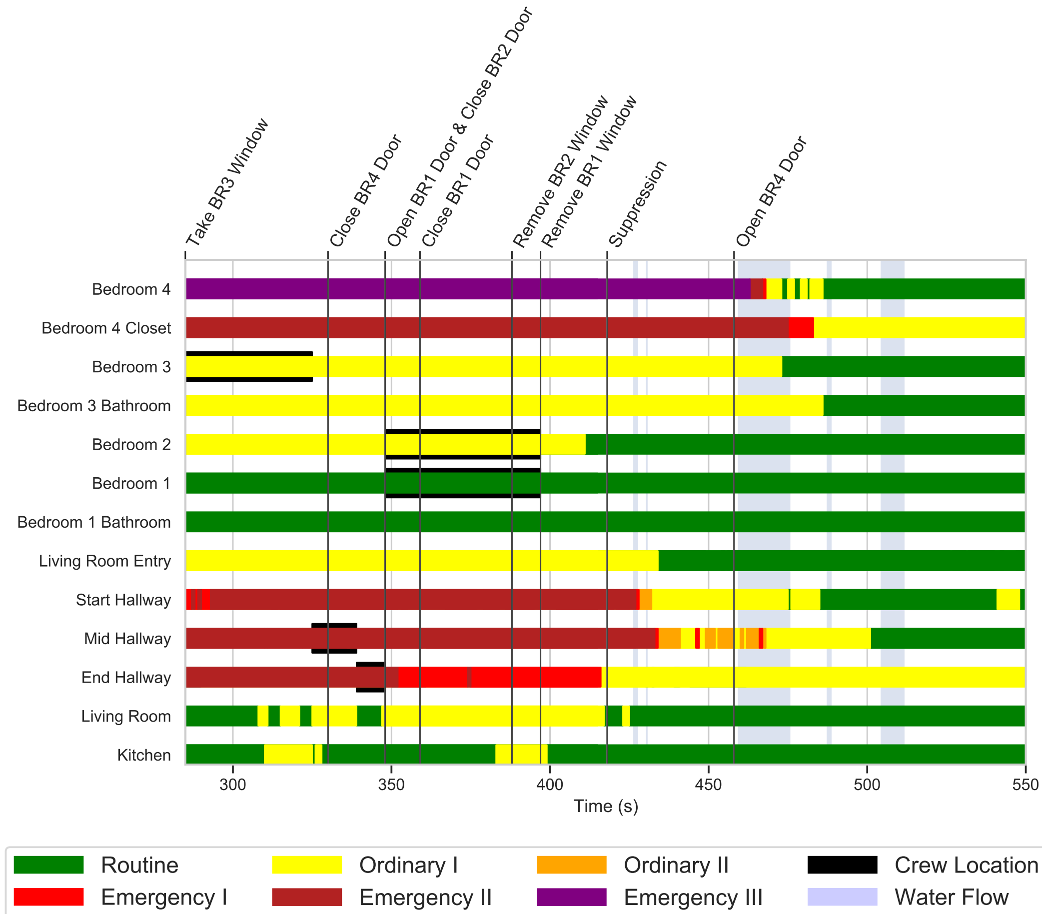
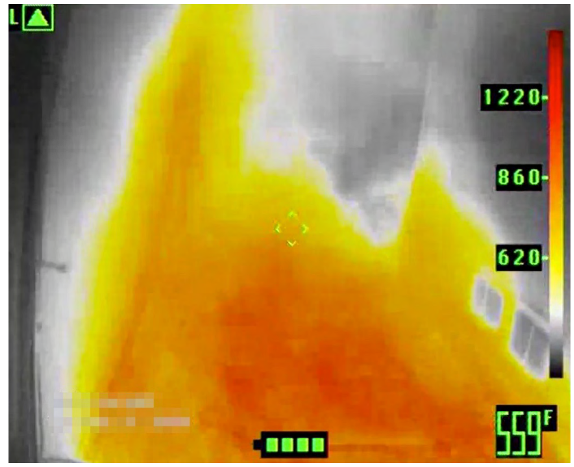



Figure 5.19: Thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression search tactics in Experiment 8.

Ventilation of the bedroom 3 window created a new exterior vent in the structure. Initially, unidirectional exhaust flow was established at the window. The 3 ft temperature in the center of the room was 140 °C (284 °F) prior to ventilation and increased to 180 °C (356 °F) over the 45 s that the crew searched bedroom 3 and then crossed the hallway to close the bedroom 4 door. Temperatures returned to approximately 140 °C (284 °F) as bidirectional flow was established at the window, and remained steady as the higher temperature combustion gases that had accumulated in the structure began to flow toward the vented window. As a result, bedroom 3 remained in the ordinary operating class. Despite remaining in the ordinary operating class, the thermal conditions were noticeably different when compared to Experiment 4, where both the fire room and bedroom were not isolated and bedroom 3 transitioned through flashover (Figure 5.8b).

The mid hallway location was in the emergency operating class at the time the crew crossed the hallway to close the bedroom 4 door. This was driven by both the 3 ft temperature (400 °C (752 °F)) and heat flux to the floor (14 kW/m$^2$). Firefighters remained in the emergency operating class as they moved to the end hallway before entering bedrooms 1 and 2, due to 330 °C (626 °F) 3 ft temperatures. The closure of the bedroom 4 door resulted in a reduction of gas temperatures in the end hallway location, which dropped to an ordinary level after entry into the bedrooms, but the mid hallway and start hallway locations remained in the emergency operating class due to flame spread along the carpet as shown in Figure 5.20.

(a) At Bedroom 4 Door Closure (HD)




(b) At Bedroom 4 Door Closure (IR)


Figure 5.20: Fire conditions from start hallway to mid hallway location at the time of fire room door closure in Experiment 8.

The isolation and subsequent removal of the bedroom 2 window reduced the operating level within bedroom 2 from ordinary to routine. The 3 ft temperatures dropped from 185 °C (365 °F) to 130 °C (266 °F) in the 18 s between isolation and window removal and then to below 72 °C (160 °F) over the next 23 s. The bedroom heat flux similarly dropped from 5 kW/m$^2$ prior to isolation to below 1 kW/m$^2$ following window ventilation. The thermal response shows the value of isolating the space from accumulated combustion gases in the hallway and maximizing the exterior ventilation following isolation to reduce the hazard.

To further assess the impact of fire room isolation during a window-initiated, pre-suppression search, consider the rate of change of toxic and thermal FEDs. Similar to Experiment 4 (Table 5.2), ventilation of the bedroom 3 window ahead of suppression created an exterior vent which initially resulted in unidirectional exhaust flow of combustion gases through the window. Unlike Experiment 4, where the inflow of combustion gases from bedroom 4 eventually resulted in flame spread across the hallway and flashover of bedroom 3, in Experiment 8, the search crew crossed the hallway and closed the bedroom 4 door. Table 5.6 shows the average toxic and thermal FERs in bedroom 3 in the 45 s period following the start of window ventilation until the bedroom 3 door was closed and a similar 45 s period following the closure of the fire room (bedroom 4) door. The data shows that isolation of the fire room door was effective at reducing both the toxic and thermal FER in the rooms where a window was vented for search. An exception was the toxic FER in bathroom 3 which remained nominally the same before and after isolation. Bathroom 3 was adjacent to the flow path established through the vented window and had less efficient gas exchange to the bedroom 3 and, subsequently, the exterior vent. For additional context, the average bedroom 3 FERs following isolation are also compared to bedroom 3 during Experiment 4, where the fire room door remained opened.

Table 5.6: Impact of Fire Room Isolation on Occupant Tenability for Window Initiated Search Pre-Suppression into Non-Isolated Bedroom

| | Post Window Ventilation, Pre Fire Room Isolation | |
|---|---|---|
| Location | Average Toxic FER | Average Thermal FER |
| Bathroom 3 (1 ft) | 0.022 (Exp 8) | 0.0011 (Exp 8) |
| Bedroom 3 Window (1 ft) | 0.018 (Exp 8) | 0.0099 (Exp 8) |
| Bedroom 3 Window (3 ft) | 0.019 (Exp 8) | 0.020 (Exp 8) |
| | Post Fire Room Isolation | |
| Location | Average Toxic FER | Average Thermal FER |
| Bathroom 3 (1 ft) | 0.021 (Exp 8) | 1.8e-4 (Exp 8) |
| Bedroom 3 Window (1 ft) | 0.0083 (Exp 8) | 0.0068 (Exp 8) |
| Bedroom 3 Window (3 ft) | 0.0041 (Exp 8) | 0.0097 (Exp 8) |
| | No Fire Room Isolation | |
| Location | Average Toxic FER | Average Thermal FER |
| Bathroom 3 (1 ft) | 0.34 (Exp 4) | 0.015 (Exp 4) |
| Bedroom 3 Window (1 ft) | 0.25 (Exp 4) | 0.16 (Exp 4) |
| Bedroom 3 Window (3 ft) | 0.90 (Exp 4) | 0.59 (Exp 4) |

Experiment 16 was designed to evaluate both door-initiated search and window-initiated search through bedroom 3 while including closure of the front door after entry, but prior to suppression of a kitchen fire. Prior to suppression, bedroom 1 was isolated as part of the search tactics; bedrooms 2 and 3 doors remained opened. The front door was closed as rollover of flames from the kitchen to the living room were first observed, but before there was flame spread to the living room. Figure 5.21 shows interior conditions within the kitchen and living room before and after the front door was closed. In this structure layout, the front door effectively served as the door to the fire compartment. Closing the door shut down the primary supply of oxygen to support flame spread.

The kitchen window, while open, had a small opening area and high sill height which made it an inefficient vent. Therefore, flaming combustion was limited to the kitchen.

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

Figure 5.21: Fire conditions preceding and following front door closure during Experiment 16.

To visualize the impact of the front door closure, Figure 5.22 shows post-experiment photographs of the kitchen and living room for Experiments 16 and 17. Experiment 17 examined door-initiated search, however the front door remained open for the duration of the experiment, which allowed the kitchen and living room to transition through flashover. The most striking difference between the set of photographs is the comparison of living rooms. 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)

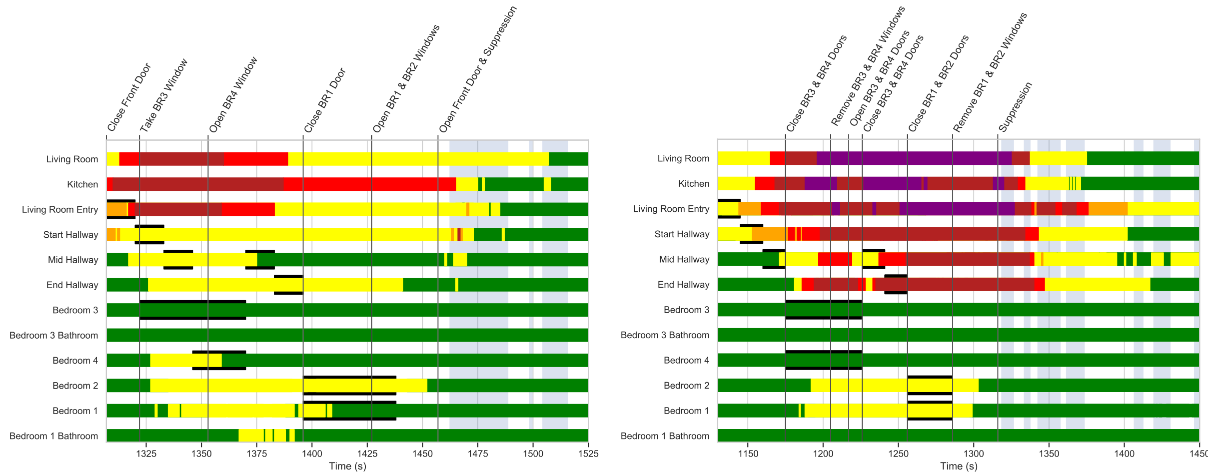
(b) Experiment 17 Kitchen (Not Isolated)

(c) Experiment 16 Living Room (Isolated)

(d) Experiment 17 Living Room (Not Isolated)

Figure 5.22: Post experiment photographs of the kitchen and living room Experiments 16 and 17.

The effects of the front door closure on searching firefighters can be can quantified by comparing the thermal operating classes through the structure as a function of time for Experiments 16 and 17. Figure 5.23 shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiments 16 and 17. The black bars on the charts correspond to the relative locations of the search crews during the events sequence. The most noticeable difference between the experiments is within the kitchen/living room/hallway. In Experiment 17, those areas all reached the emergency operating class as the kitchen and living room transitioned through flashover and remained in the emergency operating class until suppression. In particular, 3 ft hallway temperatures in the mid hallway and end hallway were greater than 400 °C (752 °F) and heat fluxes were greater than 8 kW/m$^2$. For Experiment 16, the closed door limited 3 ft temperatures and heat flux in the mid hallway and start hallway, which remained below 90 °C (194 °F) and 2 kW/m$^2$, respectively.




(a) Experiment 16 (Isolated)

(b) Experiment 17 (Not Isolated)


Figure 5.23: 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.

Examination of the thermal classes in the bedrooms highlights the impact of fire compartment isolation and local (room) isolation combined with ventilation. In Experiment 16, the bedroom 3 window was ventilated and neither bedroom 3 nor 4 were isolated. The resulting peak 3 ft temperatures were 68 °C (154 °F) and 86 °C (187 °F), respectively. In Experiment 17, both bedrooms 3 and 4 were isolated ahead of flashover of the living room, and the respective windows were removed following isolation. As a result, the 3 ft temperatures peaked at 55 °C (131 °F) and 68 °C (154 °F), respectively.

For the bedrooms that were isolated post living room flashover in Experiment 17, the temperatures and corresponding heat flux peaked at 127 °C (261 °F) and 5 $kW/m^2$ in bedroom 1 and 122 °C (252 °F) and 7 $kW/m^2$ in bedroom 2. During Experiment 16, bedroom 1 was isolated while bedroom 2 remained opened. The impact that the closed front door had on the heat release rate of the fire is more evident here as these temperatures and heat fluxes peaked at 74 °C (165 °F) and 3 $kW/m^2$ and 80 °C (176 °F) and 3 $kW/m^2$, respectively.

The toxic and thermal exposure rates for Experiment 16 when analyzed relative to Experiment 17 to further show the effects of isolation and ventilation (Table 5.7). 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 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 17 due to the isolation of the bedroom in that experiment. In bedroom 2, the average toxic FER was lower than Experiment 17 due to the later isolation of that bedroom. In both bedrooms, the reduction of the heat release of the fire due to the closed front door in Experiment 16, resulted in lower average thermal FERs. This data not only shows the impact of reducing the supply of oxygen to the fire compartment, but also the value of timely isolation of spaces coupled with local ventilation when fire room isolation may not be possible.

Table 5.7: Impact of Front Door Isolation (Experiment 16) Versus Non Isolation (Experiment 17) on Occupant Tenability for Pre-Suppression Door Initiated Search

| | Average Toxic FER | | Average Thermal FER | |
|---|---|---|---|---|
| Location | Experiment 16 | Experiment 17 | Experiment 16 | Experiment 17 |
| Bedroom 2 Bed (3 ft) | 0.039 | 0.095 | 1.0e-4 | 0.0014 |
| Bedroom 2 Window (1 ft) | 0.0051 | 0.044 | 8.2e-6 | 1.3e-5 |
| Bedroom 2 Window (3 ft) | 0.0096 | 0.16 | 2.3e-4 | 0.0022 |
| Bathroom 3 (1 ft) | 0.0065 | 0.0030 | 3.2e-6 | 9.9e-6 |
| Bedroom 3 Window (1 ft) | 0.0046 | 0.0021 | 4.0e-6 | 2.0e-5 |
| Bedroom 3 Window (3 ft) | 0.0058 | 0.0044 | 2.2e-5 | 1.6e-4 |

## 5.5 Pre-Suppression Proximity of Entry Point From Fire Compartment

Across the experimental series, 2 experiments (bedroom 4 and kitchen ignition locations) examined window initiated search prior to suppression of a post-flashover fire. In both experiments, two exterior windows were taken (see Appendix A.1) to facilitate window initiated search into bedrooms (bedrooms 2 and 3) with open interior doors. Depending on the experiment, the bedroom door in one of the two bedrooms was closed following entry (isolated), while one remained opened (non-isolated). For the non-isolated bedrooms, a flow path was established between the fire room and the lower-pressure exterior vent.

Following ventilation, there was a temporary period of unidirectional exhaust through the window due to the elevated pressure in the bedroom due to the accumulation of combustion gases. As the pressure dropped, bi-directional flows were established at the window; combustion gases continued to exhaust through the upper portion of the vent, and air was entrained through the lower portion of the vent. The length of the flow path (distance) between the open vents and fire compartment impacted the timeline for a change to occur as well as the rate of change of thermal and toxic conditions local to the compartment that was vented.

> In situations where isolation is not possible during a window-initiated search ahead of suppression, consideration should be given to maximizing the on-plane distance* between the entry location and the fire compartment (i.e., if possible, enter the structure furthest from the fire).
>
> * On-plane refers to horizontal distance between rooms that have the same floor elevation

Table 5.8 provides the distances between flaming combustion in the fire compartment and the created vent for the 4 pre-suppresion experiments.

Table 5.8: Distance from the vent to flaming combustion.

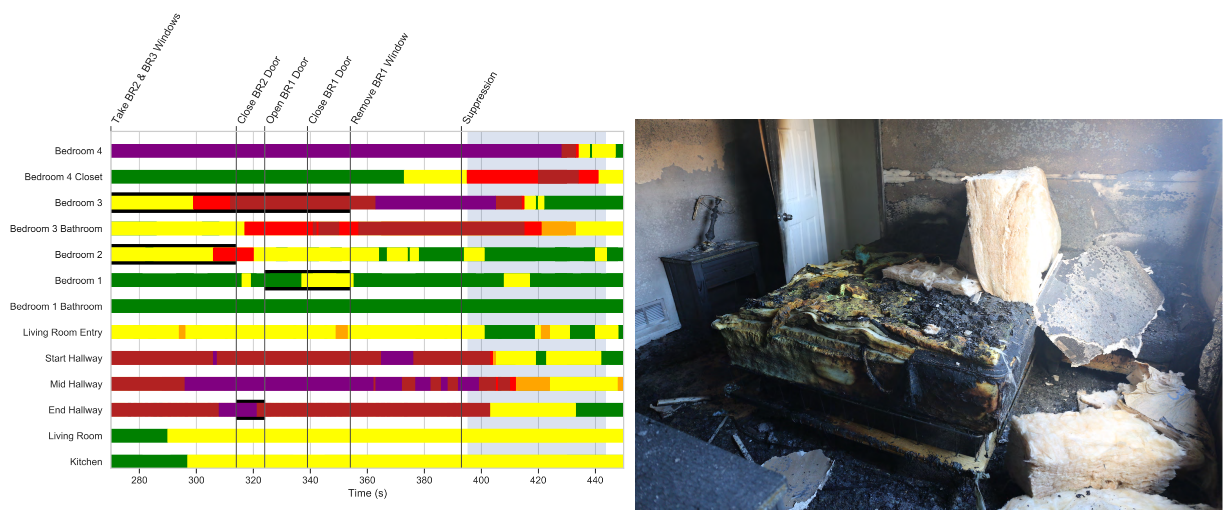
| Experiment | Ignition Location | Vent Location | Distance |
|---|---|---|---|
| 4 | Bedroom 4 | Bedroom 3 | 19 ft * |
| 1 | Bedroom 4 | Bedroom 2 | 28 ft * |
| 13 | Kitchen | Bedroom 3 | 42 ft + |
| 11 | Kitchen | Bedroom 2 | 57 ft + |

* Flaming combustion was observed at bedroom 4 door

\+ Flaming combustion was observed 2 ft from front door/living room windows

To assess the impact of distance from entry point to fire location for a window initiated search prior to suppression, Figure 5.24a shows the thermal conditions, expressed as the thermal operating class, corresponding to both the 3 ft temperature and heat flux (where available) in the period following the initial intervention for Experiment 4. This experiment has the shortest distance between vent location and fire location. In Experiment 4, where bedroom 3 was not isolated, 3 ft temperatures in bedroom 3 steadily rose from 146 °C (295 °F) to over 200 °C (392 °F) in the 30 s following window ventilation, which increased the operating class from ordinary to emergency (Figure 5.24a). Over the next 30 s, the lack of isolation, low pressure exhaust vent, and close proximity to the fire compartment resulted in flame spread across the hallway and into bedroom 3. Within 90 s of window ventilation, the 3 ft temperatures crossed 800 °C (1472 °F) and the room transitioned through flashover. Bedroom 3 remained in the emergency operating class until suppression, with 3 ft temperatures peaking at 935 °C (1715 °F).

Figure 5.24b shows the post-experiment state of bedroom 3. The damage to the gypsum wallboard and mattress in the photograph show the evidence of flaming combustion that occurred in the open bedroom. In addition to the thermal conditions at the 3 ft elevation, the toxic exposure to a potential occupant in the form of average FED rate from ventilation until suppression ranged from 0.25 FED/s 1 ft above the floor at the window to 0.34 FED/s 1 ft above the floor in the bathroom to 0.90 FED/s 3 ft above the floor at the window. The average rates of toxic exposure increase and transition to flashover within the bedroom emphasize the limited time for search and removal of a potentially trapped occupant in the case where the point of entry is into a non-isolated compartment nearest the fire compartment.



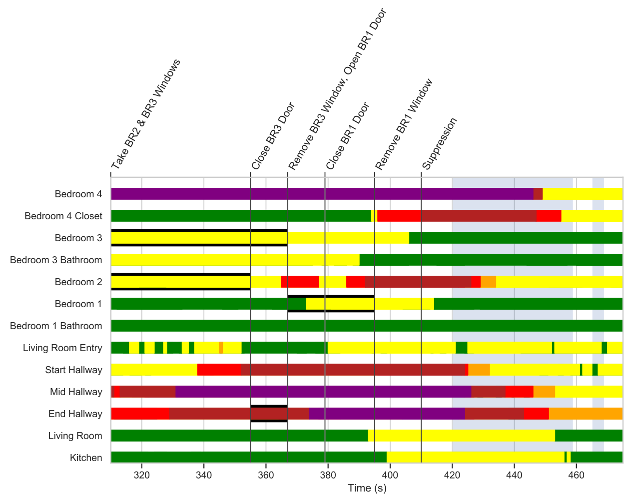

(a) Thermal Operating Classes (Experiment 4)

(b) Non-Isolated Bedroom 3 (Experiment 4)

Routine | Ordinary I | Ordinary II | Crew Location
Emergency I | Emergency II | Emergency III | Water Flow

Figure 5.24: Thermal operating conditions during Experiment 4 based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics (left). Post experiment photographs of bedroom 3 (right).

In Experiment 1, where bedroom 2 was not isolated, 3 ft temperatures steadily rose and reached an intermediate peak of 226 °C (439 °F) 58 s post intervention, values consistent with an emergency operating class (Figure 5.25a). Temperatures temporarily decreased following gas exchange across the hallway while the bedroom 1 door was opened and closed, but within 20 s of bedroom 1 door closure (80 s post window ventilation), the 3 ft temperatures had risen from 130 °C (266 °F) to 300 °C (572 °F) and heat flux had risen from 4.0 kW/m$^2$ to 12.3 kW/m$^2$, moving bedroom 2 from the ordinary operating class back to the emergency operating class. Temperature and heat flux continued to increase until suppression — 3 ft temperature peaked at 465 °C (869 °F) and heat flux peaked at 24 kW/m$^2$. The room remained in the emergency operating class until suppression of the bedroom 4 fire. Figure 5.25b shows the post-experiment state of bedroom 2 for Experiment 1. The photograph shows signs of pyrolysis across the bed and upholstered chair (fabric along top of chair missing).




(a) Thermal Operating Classes (Experiment 1)

(b) Non-Isolated Bedroom 2 (Experiment 1)

Routine | Ordinary I | Ordinary II | Crew Location
Emergency I | Emergency II | Emergency III | Water Flow

Figure 5.25: Thermal operating conditions during Experiment 1 based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics (left). Post experiment photographs of bedroom 2 (right).

Although Figure 5.25b does not indicate that there was flaming combustion in the room, it highlighted the potential hazard to firefighters or potential occupants in that space. The average toxic exposure to a potential occupant in the form of average FED rate from ventilation until suppression ranged from 0.034 FED/s 1 ft above the floor at the window to 0.038 FED/s 3 ft above the floor on the bed to 0.088 FED/s 3 ft above the floor at the window. Compared to bedroom 3 from Experiment 4, the average rates of toxic exposure were an order of magnitude lower in bedroom 2 during Experiment 1. However, similar to the steady rise in temperature and heat flux the instantaneous toxic exposure rate continued to increase until suppression. Examination of conditions in the hallway prior to suppression (Figure 5.26b) shows flame spread from the fire room toward the end hall location and the open bedroom 2 door. Suppression occurred 100 s after window ventilation. Had suppression been delayed, based on the flame spread in the hallway, evidence of combustion on the door (Figure 5.26a) and thermal conditions in bedroom 2 prior to suppression, it is likely that pyrolyzing fuels would have ignited.

(a) Post-Suppression Bedroom 2 Door (b) End Hallway (Outside of Bedroom 2) Flame Spread Prior to Suppression

Figure 5.26: Image looking toward the living room from the end hallway showing post-suppression image of bedroom 2 door (left) and flame spread outside of bedroom 2 in the hallway immediately prior to water flow (right) from Experiment 1.

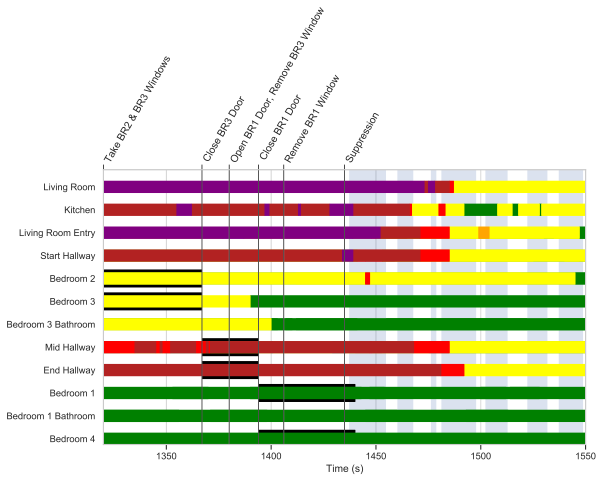
When the ignition location was moved from bedroom 4 to the kitchen, the distance between areas of flaming combustion (approximately 2 ft into the structure from front door) and the vent locations (bedrooms 3 and 2) increased by approximately double compared to the respective bedroom ignition experiments. In Experiment 13, the door between the hallway and bedroom 3 was open from the time of ignition, which resulted in temperatures consistent with ordinary operating conditions at the time that the bedroom window was ventilated (Figure 5.27a). Window ventilation established bi-directional flow through the bedroom. The inflow of air through the window had a cooling effect at the 3 ft measurement locations in the period immediately following intervention. The 3 ft temperature in the bedroom decreased from 178 °C (352 °F) at intervention to a minimum value of 130 °C (266 °F). Temperatures increased 47 s later as the flow of hot gases from the hallway increased, reaching 148 °C (298 °F) immediately prior to suppression. Bedroom 3 remained within the threshold for ordinary operating conditions until the completion of primary suppression operations, 96 s after window ventilation. The flow of combustion gases through the bedroom to the low pressure exterior vent resulted in noticeable soot deposition above 3 ft and the elevated temperatures resulted in thermal damage as seen by the melted window frame and damage to wall artwork as shown in Figure 5.27b. Below 3 ft, bedroom 3 was distinctly different when compared to Figures 5.24b and 5.25b.


(a) Thermal Operating Classes (Experiment 13)

(b) Non-Isolated Bedroom 3 (Experiment 13)

Figure 5.27: Thermal operating conditions during Experiment 13 based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics (left). Post experiment photographs of bedroom 3 (right).

In Experiment 11, the door between the hallway and bedroom 2 was open from the time of ignition, which resulted in temperatures consistent with ordinary operating conditions at the time that the bedroom window was ventilated (Figure 5.28a). Window ventilation established bi-directional flow through the bedroom. The inflow of air through the window had a cooling effect at the 3 ft measurement locations in the period immediately following intervention. 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 steadily increasing 28 s later 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. Peak temperatures in Experiment 11 exceeded Experiment 13 despite the longer distance because suppression began 115 s post-ignition, 19 s later than Experiment 13.




(a) Thermal Operating Classes (Experiment 11)

(b) Non-Isolated Bedroom 2 (Experiment 11)


Figure 5.28: Thermal operating conditions during Experiment 11 based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for pre-suppression window initiated search tactics (left). Post experiment photographs of bedroom 2 (right).

Further, the average toxic rate of change of the toxic exposure to a potential occupant in bedroom 3 during Experiment 13 ranged from 0.0019 FED/s 3 ft above the floor at the window to 0.0039 FED/s 3 ft above the floor at the window to 0.059 FED/s 1 ft above the floor in the bathroom. In bedroom 2 during Experiment 11 the average toxic exposure to a potential occupant in the form of average FED rate, from ventilation until suppression, ranged from 0.011 FED/s 1 ft above the floor at the window to 0.029 FED/s 3 ft above the floor at the window to 0.11 FED/s 3 ft above the floor on the bed. The resulting average increase in toxic exposures to potential occupants showed a similar trend to the thermal exposures, which decreased as the distance increased.

## 5.6 Post-Suppression Ventilation of Spaces

Experiments conducted in this series included changes to both interior and exterior ventilation openings following suppression as the fire conditions shifted from ventilation-controlled to fuel-controlled.

> Following suppression, consideration should be given to opening previously isolated spaces and creating local ventilation openings that establish flow paths to the exterior to facilitate the removal of accumulated combustion gases.

Experiment 20 was designed to examine door-initiated search operations during suppression for a living room fire. Prior to ignition, the interior door to bedroom 1 was closed, while the doors to bedrooms 2, 3, and 4 were opened. At the onset of suppression, the search crew entered through the front door to begin searching. As the crews moved further from the living room, the effects of suppression became more apparent. 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$^2$) as shown in Figure 5.29. Thermal exposures continued to decrease with increased distance from the living room. The isolated bedroom 1 remained in the routine operating class for the duration of the experiment.

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). The search crews reached bedrooms 3 and 4 first, and removed the respective bedroom windows. The 3 ft bedroom temperatures dropped below 72 °C (162 °F) within 17 s and 11 s, respectively. The post-suppression window ventilation resulted in more efficient gas exchange compared to bedroom 2 where the window was still closed. 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.


Figure 5.29: Thermal operating conditions based upon 3 ft elevation temperatures and heat fluxes during post-intervention period for during suppression search tactics in Experiment 20.

The impact of post-suppression window ventilation is shown by comparing the rate of change of toxic and thermal FEDs to potentially trapped occupants for bedrooms 2 and 3 in the time period prior to window ventilation and post window ventilation. Suppression of the living room fire resulted in a rapid drop in temperature in fire compartment – decrease of over 800 °C (1472 °F) at 3 ft above the floor in less than 30 s. Correspondingly, temperatures in connected spaces within the structure dropped. This reduction is shown in the changing thermal operating classes shown in Figure 5.29. Suppression was also effective at reducing the production of combustion gases, but because the only exterior vents were in the kitchen and living room, the composition of the gases within the bedrooms were slow to return to pre-igntition levels which resulted in elevated toxic FERs at both locations. For both bedroom 2 and bedroom 3, ventilation of the respective windows created exterior vents which resulted in increased exhaust flow of combustion gases and inflow of air. The result was a reduction of average toxic gas and thermal FERs as shown by the percent differences in Table 5.9. A negative percent difference represents an improvement in exposure rate.

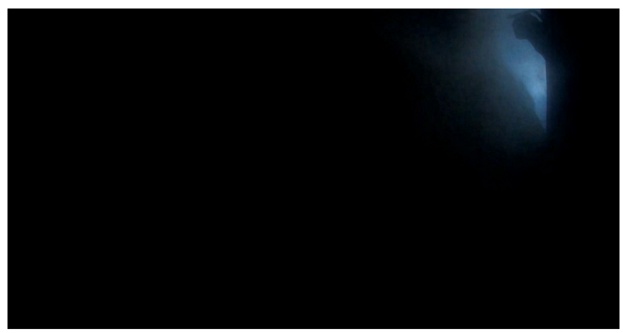
Table 5.9: Percent Difference in Post Suppression Average FER Before and After Window Ventilation (Experiment 20)

| Location | % Difference Toxic FER | % Difference Thermal FER |
|---|---|---|
| Bedroom 2 (3 ft) | -98% | -99% |
| Bedroom 2 Window (1 ft) | -98% | -85% |
| Bedroom 2 Window (3 ft) | -99% | -100% |
| Bathroom 3 (1 ft) | -64% | -71% |
| Bedroom 3 Window (1 ft) | -87% | -73% * |
| Bedroom 3 Window (3 ft) | -98% | -98% |

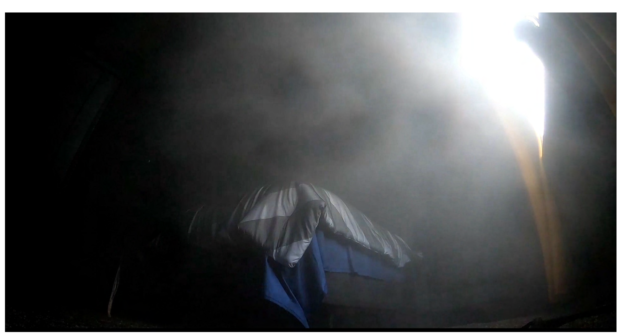
* Only includes convective component of thermal FER due to error in heat flux data signal.

The series of interior images from bedroom 2, shown in Figure 5.30, also highlights the effects of post-suppression ventilation. The first image (Figure 5.30a), which was taken 30 s prior to window ventilation or 70 s post-suppression, shows the lack of visibility in bedroom 2 due to the accumulation of combustion gases. Following removal of the bedroom 2 window visibility began to improve, particularly near the vent location as shown in Figure 5.30b. Within 60 s, the smoke layer had lifted to above the 3 ft elevation (Figure 5.30c).

(a) 30 s Prior to Window Ventilation



(b) At Window Ventilation



(c) 60 s Post Window Ventilation

Figure 5.30: Images of bedroom 2 from Experiment 20 prior to window ventilation, at window ventilation, and post window ventilation.

The thermal operating class data, percent differences in fractional effective rates, and post-fire images highlight the importance of post-suppression ventilation to improve visibility, and to reduce the rate of toxic gas and thermal exposures for firefighters and potentially trapped occupants.

Prior research experiments conducted in support of the *The Study of Coordinated Fire Attack Utilizing Acquired Structures* project also examined mechanical ventilation following post-suppression ventilation [21, 22]. These experiments found that use of positive pressure ventilation and hydraulic ventilation were effective at improving the rate at which gas concentrations improved to pre-ignition values.

Although hydraulic ventilation was used throughout this experimental series, with the exception of Experiment 14, it was employed late in the experimental timeline, often after gas concentrations had returned to near pre-ignition levels. Prior to the ignition of a kitchen fire in Experiment 14, the interior doors to bedrooms 2 and 3 were open. At the time of suppression, the kitchen and living room were in a post-flashover state. Hydraulic ventilation with a wide fog pattern through the failed side D living room window occurred simultaneous with the opening of the bedroom 3 and 4 windows 68 s after primary suppression was completed. The bedroom 2 window was opened 30 s into 82 s duration of hydraulic ventilation. Table 5.10 shows the average toxic and thermal FERs for the post-suppression time periods before and during hydraulic ventilation.

Table 5.10: Impact of Post-Suppression Hydraulic Ventilation on Occupant Tenability for Kitchen Fire

| | Average Toxic FER | | Average Thermal FER | |
|---|---|---|---|---|
| Location | Pre-Hydraulic | During Hydraulic | Pre-Hydraulic | During Hydraulic |
| Bedroom 2 Bed (3 ft) | 0.045 | 0.0047 | 1.6e-4 | 5.3e-5 |
| Bedroom 2 Window (1 ft) | 0.060 | 0.0031 | 6.6e-5 | 2.2e-5 |
| Bedroom 2 Window (3 ft) | 0.016 | 0.0024 | 1.6e-4 | 5.3e-5 |
| Bathroom 3 (1 ft) | 0.082 | 0.020 | 7.4e-5 | 2.0e-5 |
| Bedroom 3 Window (1 ft) | 0.024 | 0.0024 | 6.1e-5 | 1.7e-5 |
| Bedroom 3 Window (3 ft) | 0.024 | 0.0020 | 1.7e-5 | 4.3e-5 |
| Start Hallway (1 ft) | 5.0e-4 | 2.1e-4 | 0.0033 | 1.2e-5 |
| Start Hallway (3 ft) | 6.9e-4 | 3.2e-4 | 0.0034 | 2.3e-5 |
| Mid Hallway (1 ft) | 6.0e-4 | 0.0012 | 5.4e-5 | 2.4e-5 |
| Mid Hallway (3 ft) | 9.6e-4 | 0.0011 | 1.4e-4 | 5.8e-5 |
| End Hallway (1 ft) | 0.0011 | 0.0016 | 9.5e-5 | 3.1e-5 |
| End Hallway (3 ft) | 0.0011 | 0.0017 | 2.0e-4 | 7.0e-5 |

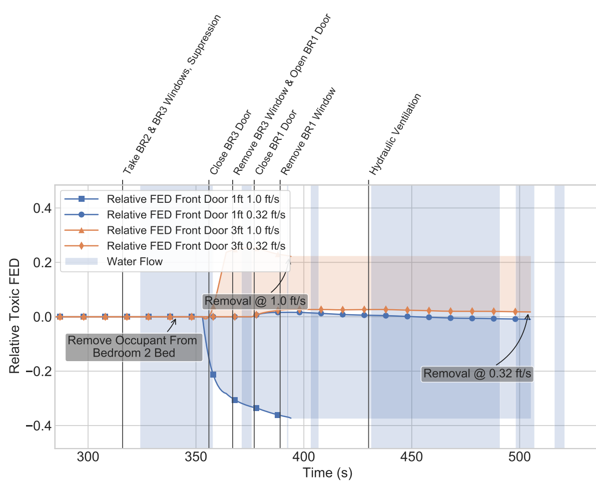
The data in Table 5.10 show that the average toxic FER in both bedrooms was an order of magnitude lower over the 82 s of hydraulic ventilation compared to the 68 s post-suppression. The mid hallway and end hallway locations both show a higher average toxic FER during hydraulic ventilation. In Experiment 14, the area of lower pressure created by the flowing fog stream was in the living room. This resulted in the of intake of air through the respective open bedroom windows and the flow of accumulated combustion gases out through the hallway and toward the living room window. The mid hallway is where the gas flows all four bedrooms came together. As result, the average mid hallway toxic FER were higher during hydraulic ventilation. During hydraulic ventilation, it is important to be cognizant of both the objective (i.e., what spaces to remove combustion gases from) and the vent location through which the water will be flowed (i.e, where the combustion gases will flow toward). The average thermal FERs were uniformly lower during hydraulic ventilation due to continued cooling following suppression and mixing with entrained air.

## 5.7 Impact of Elevation and Speed During Egress

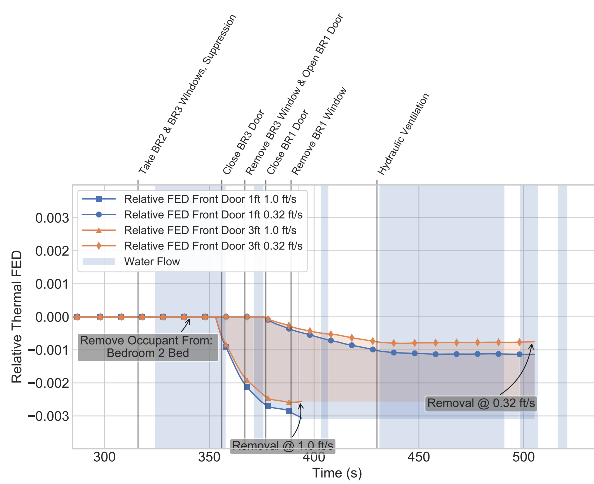
Across the series of experiments, instrumentation was placed at discrete locations along potential egress pathways to quantify the toxic gas and thermal exposure during removal of an occupant. In particular, these instrumentation locations included locations at 1 ft and 3 ft along the hallway to assess the impact of elevation. The impact of elevation and removal speed during egress can be assessed by examining how FED values change along this pathway.

> During removal of an occupant, consideration should be given to removing that occupant as fast as practical and with the occupant's head at the lowest functional elevation.

In Experiment 2 suppression coincided with window-initiated search into bedrooms 2 and 3, both of which had open bedroom doors at the time of intervention. The bedroom 3 door was closed following entry while the bedroom 2 door remained open. Figure 5.31 shows the toxic and thermal FEDs for occupant removal relative to the occupant remaining on the bedroom 2 bed, 3 ft above the floor. Recall from Section 3.4, that to calculate a relative FED, the toxic gas and thermal FEDs at the point of origin were subtracted from respective toxic gas and thermal FEDs calculated along the removal pathway. Essentially, if the relative FED is positive, the occupant would have received additional exposure compared to being left in place. If the relative FED is negative, the occupant would have received a lower exposure compared to being left in place.




(a) Toxic FED Bedroom 2 Bed During Suppression




(b) Thermal FED Bedroom 2 Bed During Suppression

Figure 5.31: Toxic and thermal FED relative to bedroom 2 bed for window-initiated search during suppression of a bedroom fire (Experiment 2). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

The relative toxic FED (Figure 5.31a) shows the impact of removal elevation. The differences are most noticeable once the occupant reached the hallway for the 75th percentile velocity (1 ft/s).

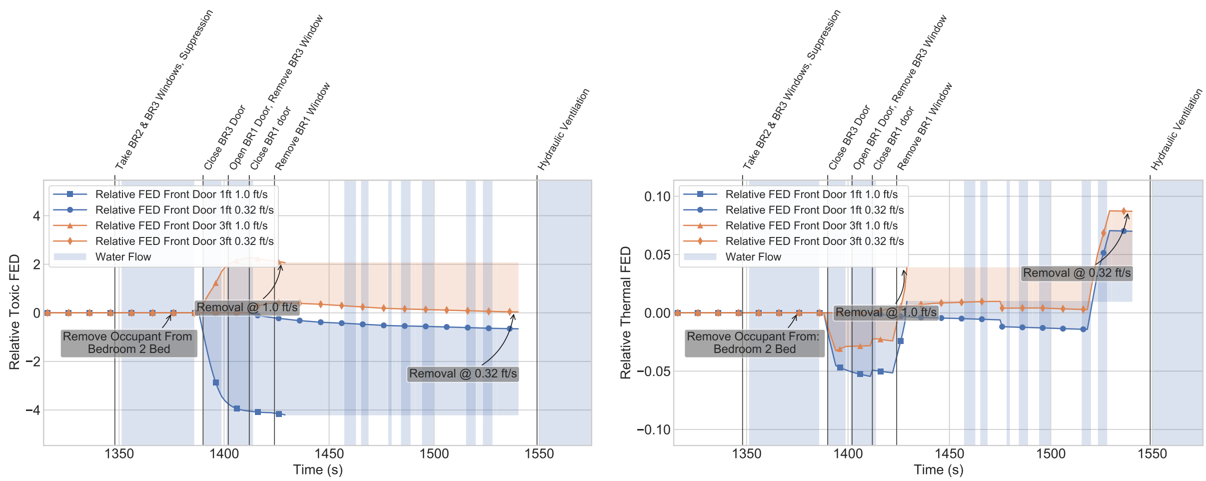
The 1 ft elevation resulted in negative relative FED, or lower toxic gas exposure compared to remaining in place. Conversely, the relative toxic FED increased for the occupant in the hallway at the 3 ft elevation as the occupant was removed through the smoke layer. The impact of the residual smoke layer is illustrated in the pre-suppression and post-suppression images in Figure 5.32. Prior to suppression, Figure 5.32a shows flame spread into the hallway from the bedroom 4 fire and the smoke layer height, which had dropped to the top of the living room sofa (approximately 3 ft above the floor). Suppression was effective at reducing the thermal hazard as shown by the negligible change in relative thermal FED (Figure 5.31b). However, post-suppression there was still a residual smoke layer down the top of the sofa 30 s after suppression (Figure 5.32b), which resulted in the increased relative toxic FED at the 3 ft elevation removal at 1 ft/s.

(a) Prior to Start of Suppression (b) 30 s Post Suppression

Figure 5.32: Images looking from the living room toward the hallway showing smoke layer height in Experiment 2 prior to suppression and post suppression.

Of note is the lower relative differences in toxic gas and thermal FED for the 25th percentile speeds (0.32 ft/s). This is a result of a combination of factors: the baseline FED (bedroom 2 bed) continued to rise, suppression slowed the production of combustion gases and reduced temperatures, and the smoke layer lifted as accumulated gases in the hallway exhausted the structure through the open exterior vents (front door and bedroom 2 window).

Experiment 12 was similar to Experiment 2 – window-initiated search into bedrooms 2 and 3 during suppression with isolation of bedroom 3 – but ignition occurred in the kitchen versus bedroom 4. Figure 5.33 shows the toxic and thermal FEDs for occupant removal relative to the occupant remaining on the bedroom 2 bed, 3 ft above the floor. Similar to Experiment 2, the relative toxic FED (Figure 5.33a) shows the impact of removal at a lower elevation, lower exposures across the median 50% of removal velocities. The differences are most noticeable once the occupant traveled through the end hallway, mid hallway, and start hallway locations, where the 1 ft elevation resulted in negative relative toxic gas FED (approximately -4) and the 3 ft elevation resulted in a positive relative toxic gas FED (approximately +2) compared to the potential occupant remaining in place on the bed in bedroom 2. The magnitudes of relative toxic FEDs compared to Experiment 2 (Figure 5.33a versus Figure 5.31a) are larger because of the higher peak HRR of the kitchen/living room fire, the longer time from ignition to intervention for gas accumulation, and the position of the fire room along the removal pathway (i.e., occupant needed to travel from bedroom 2 down the length of the hallway and through the living room before passing the fire compartment). Suppression was effective at reducing the thermal hazard as shown by the lower change in relative thermal FED (Figure 5.33b) compared to toxic gas FED. The noticeable increases in thermal FED (< 0.1) occurred as occupants were removed through the living room, which remained at elevated temperatures due to residual heat flux from the living room walls which took longer to cool than the local gas temperatures.

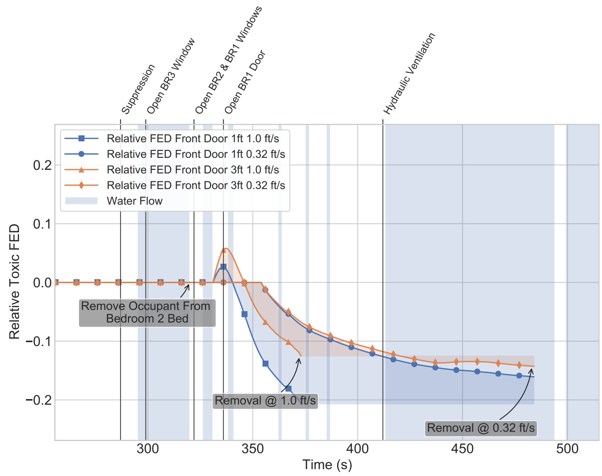



(a) Toxic FED Bedroom 2 Bed During Suppression

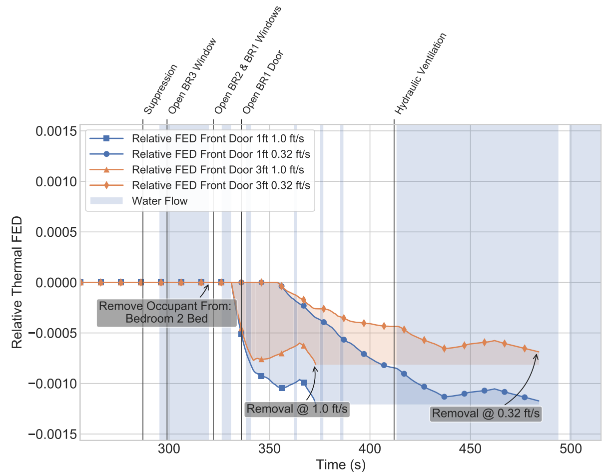
(b) Thermal FED Bedroom 2 Bed During Suppression

Figure 5.33: Toxic and thermal FED relative to bedroom 2 bed for window-initiated search during suppression of a kitchen/living room fire (Experiment 12). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

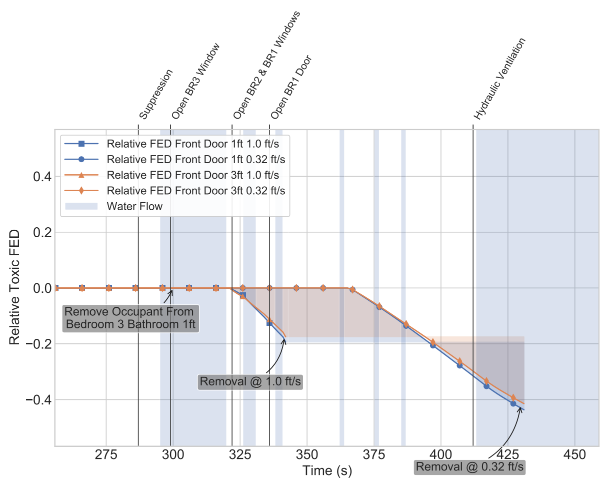
Experiment 9 examined door-initiated search operations that occurred during suppression. The relative toxic gas and thermal FEDs for bedroom 2 and bedroom 3, both of which remained open for the duration of the experiment, are included Figure 5.34. The search crew followed the suppression crew into the structure and opened the windows (see Appendix A.2) as the respective rooms were searched. Suppression was effective at reducing the thermal hazard and for both bedrooms, there were negligible changes in relative thermal FED (approximately $\pm$ 0.001). For both the bedroom 2 and bathroom 3 location, the removal of the occupant through the hallway at both elevations resulted in lower relative toxic FED compared to leaving the occupant in place. A comparison between bedroom 2 and bathroom 3 shows that for the same speeds, removal at a lower elevation resulted in a larger decrease in relative toxic gas exposure. The differences were more pronounced for removal from bedroom 2 due to the later ventilation of the bedroom 2 window which resulted in a slower recovery of the 3 ft elevation gas concentrations at both the end hallway and mid hallway locations due to their distances from exterior vents. Additionally, the longer distance of removal amplifies the effects of elevation and speed.



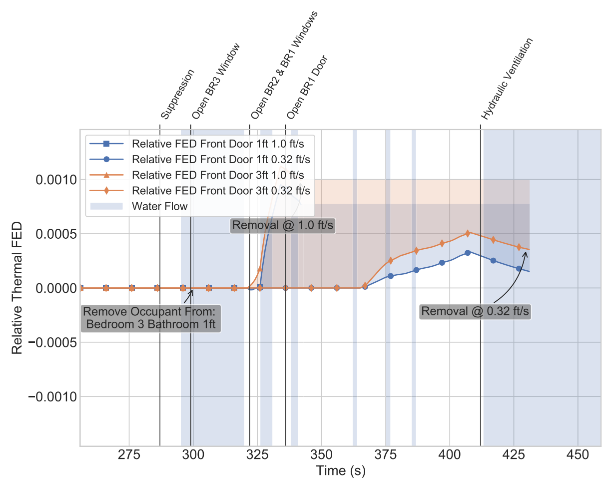

(a) Toxic FED Bedroom 2 Bed During Suppression




(b) Thermal FED Bedroom 2 Bed During Suppression



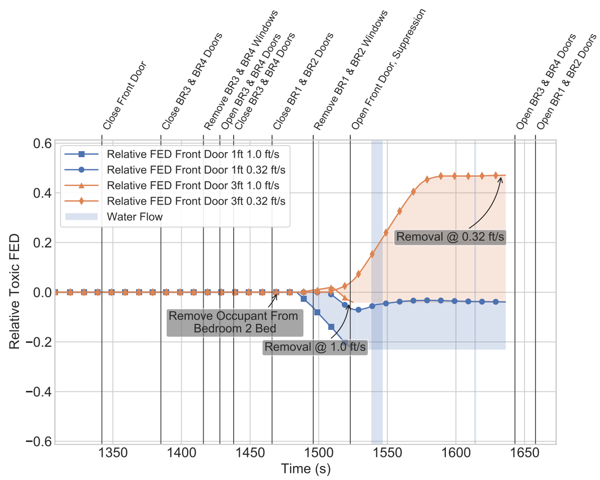

(c) Toxic FED Bathroom 3 During Suppression



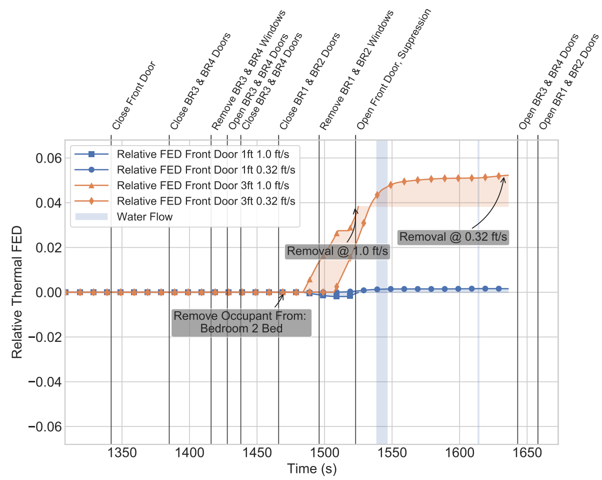

(d) Thermal FED Bathroom 3 During Suppression

Figure 5.34: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for door initiated search during suppression (Experiment 9). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant speed exited the structure. The fill extends to the 25th percentile to show the final assessment.

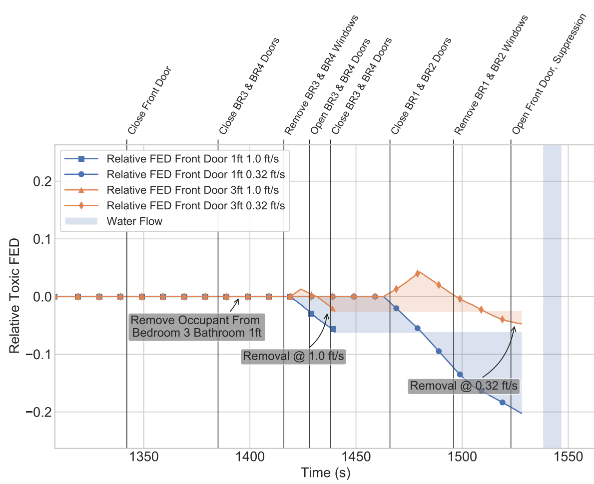
Experiment 15 was designed to examine the impact of front door closure during search operations for a kitchen fire. Prior to ignition all bedroom doors were opened and were subsequently isolated as part of the search operations. Figure 5.35 shows the relative toxic gas and thermal FEDs for a potential occupant being removed from bedroom 2 or bathroom 3 through the front door. 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. At the time the front door was closed, the fire was still contained to the kitchen cabinets near the point of ignition. The closed door prevented additional fire spread, which correspondingly restricted the total energy released from combustion. However, the fire was not suppressed and higher-temperature combustion gases continued to accumulate within the structure due to the lack of exterior vents. The development of a smoke layer is evident in both the relative toxic FEDs (Figures 5.35a and 5.35c) and relative thermal FEDs (Figures 5.35b and 5.35d). For both locations, removal at 1 ft resulted in lower relative toxic gas FED compared to the occupant remaining in place. At the 3 ft elevation, the impact of a smoke layer that has descended to approximately the 3 ft elevation was evident, particularly at slower velocities from bedroom 2 where there was a maximum relative toxic gas FED increase of approximately 0.5. Relative thermal FEDs were also higher for the 3 ft elevation removal from both locations, but the magnitude (peak relative thermal increase of 0.05) was smaller than the toxic gas exposure because of the aforementioned closed front door.



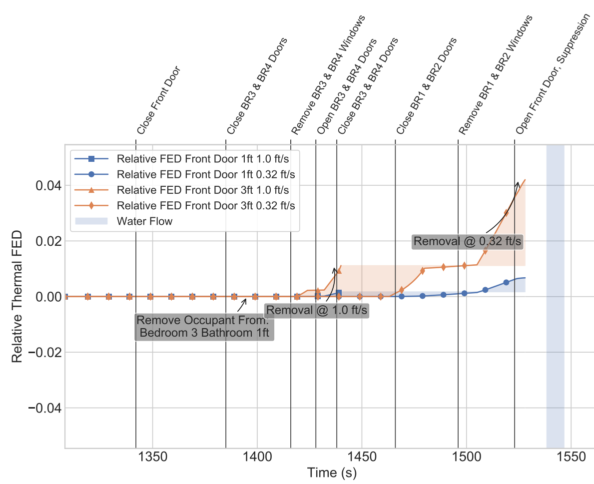

(a) Toxic FED Bedroom 2 Bed




(b) Thermal FED Bedroom 2 Bed




(c) Toxic FED Bathroom 3




(d) Thermal FED Bathroom 3

Figure 5.35: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for door initiated search ahead of suppression with isolation of the fire room (front door) for Experiment 15. 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 speed exited the structure. The fill extends to the 25th percentile to show the final assessment.

## 5.8 Impact of Removal Pathway

In experiments where search occurred prior to suppression and in the absence of fire compartment isolation, flashover of the fire compartment 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.

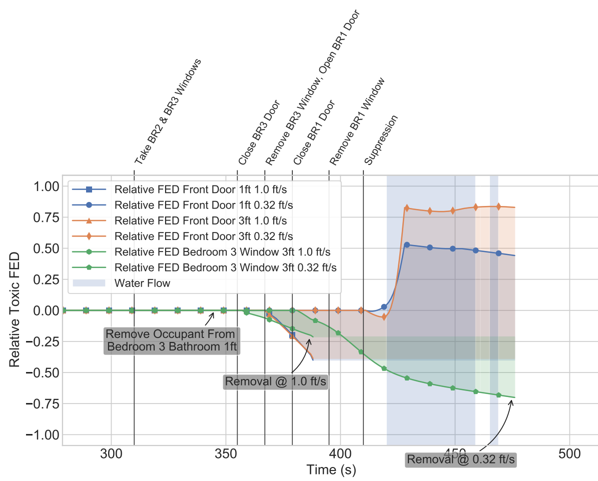
> For fires where occupant removal may precede suppression, consideration should be given to an egress route that does not pass the fire compartment along the path of travel. This route may differ from that taken by the firefighters who commenced the search.

A limitation of the analysis in this tactical consideration 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 the same time it took for removal through the front door over the range of removal velocities.

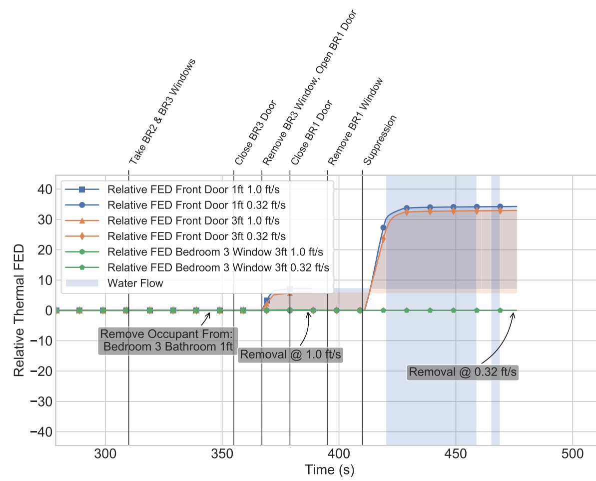
If the occupant were instead moved across the plane of the window at sill height, such that their head was outside of the structure, a further reduction of the toxic gas exposure would be expected. Additionally, it is important to remain cognizant of the potential increases in thermal exposures due to increased elevation of the occupant, particularly if the compartment is not isolated from flow paths connected to the fire compartment.

In Experiment 1, window-initiated search occurred in bedrooms 2 and 3 with isolation of bedroom 3 following entry. Figure 5.36 shows the relative toxic and thermal FEDs for Experiment 1 for an occupant in both bedrooms removed through the front door (at 3 ft and 1 ft above the floor) and moved to 3 ft above the floor at the open window. Recall from Section 3.4, that to calculate a relative FED, the toxic gas and thermal FEDs at the point of origin were subtracted from respective toxic gas and thermal FEDs calculated along the removal pathway. Essentially, if the relative FED is positive, the occupant would have received additional exposure compared to being left in place. If the relative FED is negative, the occupant would have received a lower exposure compared to being left in place.

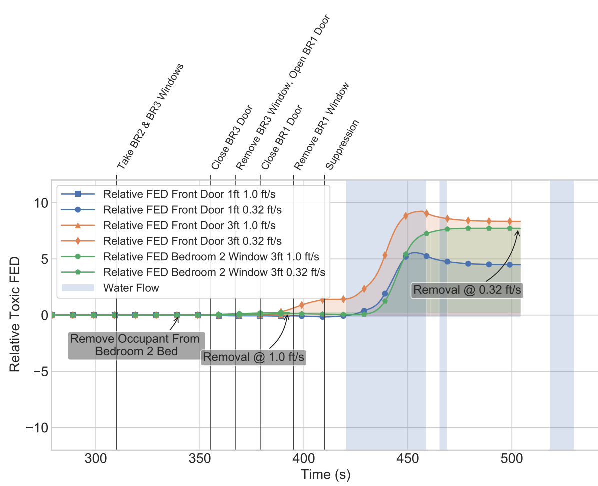
In the isolated bedroom 3, moving the occupant from 1 ft above the floor to 3 ft above the floor at the window sill resulted in a decrease in relative toxic FED (Figure 5.36a). The combination of ventilation and isolation established a different flow path – one that that began and ended at the bedroom 3 window. Here, firefighters could leverage the bidirectional flow through the window (high exhaust of combustion gases and low entertainment of air) to reduce to toxic exposure. The change in elevation (3 ft vs. 1 ft) combined with the exhaust of combustion gases resulted in an increase in thermal FED due to increased convective heat transfer associated with the increased flow of higher temperature gases. Although the relative thermal FED increase peaked at 0.18, this was nearly two orders of magnitude lower (approximately 100 times lower) compared to removing the occupant through the hallway at either elevation (Figure 5.36b).



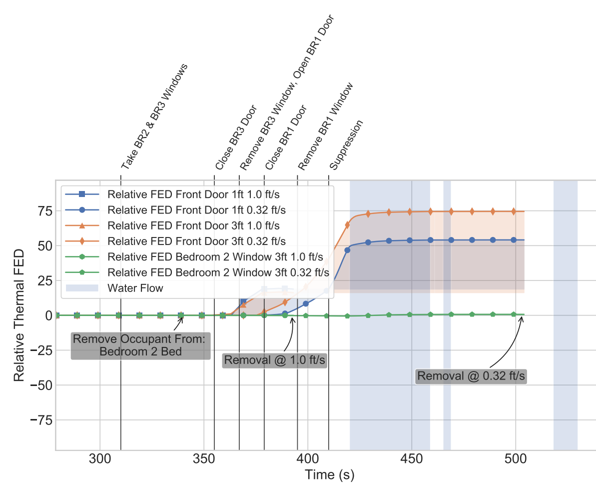

(a) Toxic FED Bathroom 3 Pre-Suppression




(b) Thermal FED Bathroom 3 Pre-Suppression




(c) Toxic FED Bedroom 2 Bed Pre-Suppression



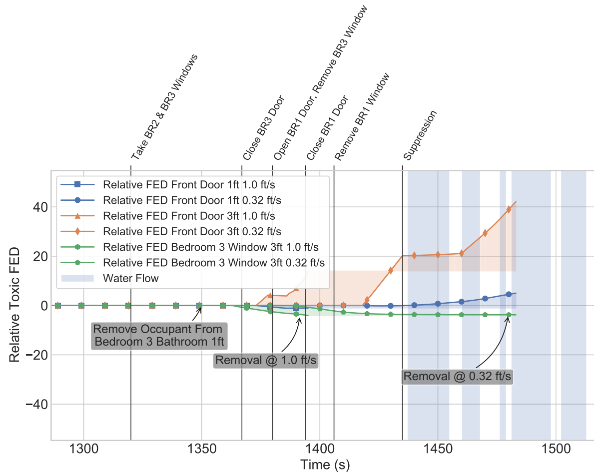

(d) Thermal FED Bedroom 2 Bed Pre-Suppression

Figure 5.36: Toxic and thermal FED relative to bedroom 2 bed and bathroom 3 for window initiated search prior to suppression (Experiment 1). The comparisons include removing the occupant through the front door and moving to the respective bedroom window at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant speed exited the structure. The fill extends to the 25th percentile to show the final assessment.

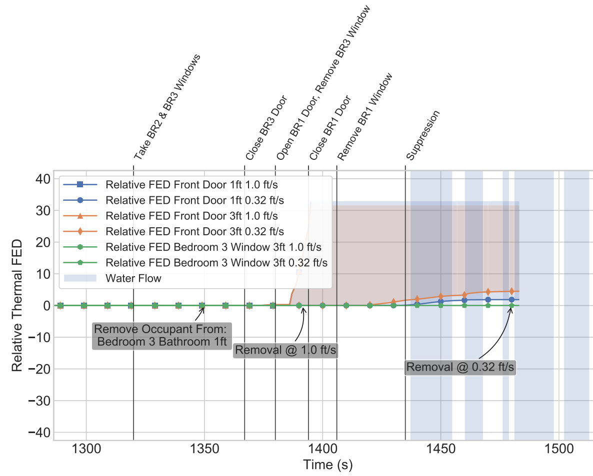
In the non-isolated bedroom prior to suppression, moving the occupant to the window at the 75th percentile speed resulted in a negligible increase in relative toxic FED (Figure 5.36c) and a decrease in relative thermal FED of 0.5 (Figure 5.36d). Similar to bedroom 3, the flow path established between the fire room and the bedroom 2 window resulted in bi-directional flow at the window. Intake of air through the lower portion of the window reduced thermal exposure compared to the bed which was adjacent to the flow path.

If the occupant remained at the window through the duration of the 25th percentile removal velocity, there was an increase in both the relative toxic and thermal FED at the onset of suppression. This may appear counter-intuitive, but recognition of flow paths and hose stream mechanics explains this result. The crew utilized a flow and move tactic from a 7/8 in. smooth bore nozzle. As the suppression team proceeded toward bedroom 4, water flow was needed in the hallway to cool gases and suppress flames. The area of higher pressure generated ahead of the hose from the flowing water moved toward an area of lower pressure. Bedroom 4 was pressurized from the fire and the doors to bedrooms 1 and 3 were closed, therefore, the only path toward lower pressure was through bedroom 2 to the open vent. As a result, gas velocities at the bedroom 2 window temporarily became unidirectional exhaust as the higher-temperature, higher-pressure gases in the hallway flowed through the open bedroom. This is shown by an increase in relative toxic FED to approximately 7.5 and an increase in relative thermal FED from -0.5 to 0.75 at the bedroom 2 window. It is important to quantify and compare these increases against the 3 ft removal through the front at the 25th percentile velocity where the relative toxic FED exceeded 8 and relative thermal FED exceeded 75. The change in exposures during suppression highlights the value of pre-suppression isolation and knowledge of gas transport along flow paths.

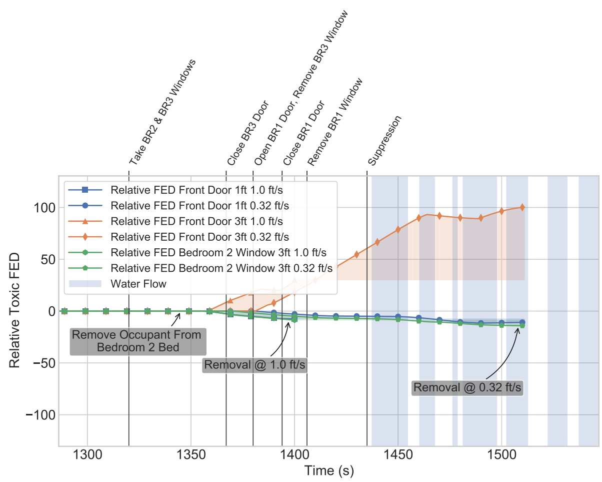
Experiment 11 was similar to Experiment 1 (window initiated search that occurred in bedrooms 2 and 3 with isolation of bedroom 3 following entry) except that the ignition location moved from bedroom 4 to the kitchen. At the time search operations began, the kitchen and living room had already transitioned through flashover and flames extended out through the open front door and failed living room windows. Figure 5.37 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 in toxic FED of 4.0 (Figure 5.37a). The combination of ventilation and isolation established a different flow path – one that that began and ended at the bedroom 3 window. Similar to Experiment 1, firefighters leveraged the bidirectional flow through the window (high exhaust of combustion gases and low entertainment of air) to reduce 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 at the 25th percentile removal speed this relative thermal FED was approximately three orders of magnitude lower (1000 times lower) compared to removing the occupant through the front door (Figure 5.37b).



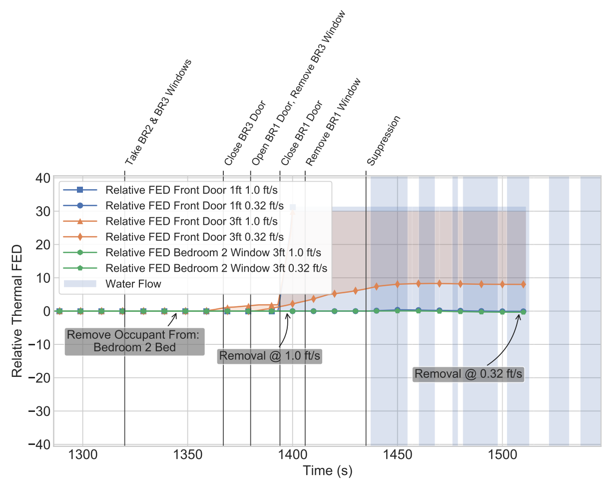

(a) Toxic FED Bathroom 3 Pre-Suppression




(b) Thermal FED Bathroom 3 Pre-Suppression




(c) Toxic FED Bedroom 2 Bed Pre-Suppression

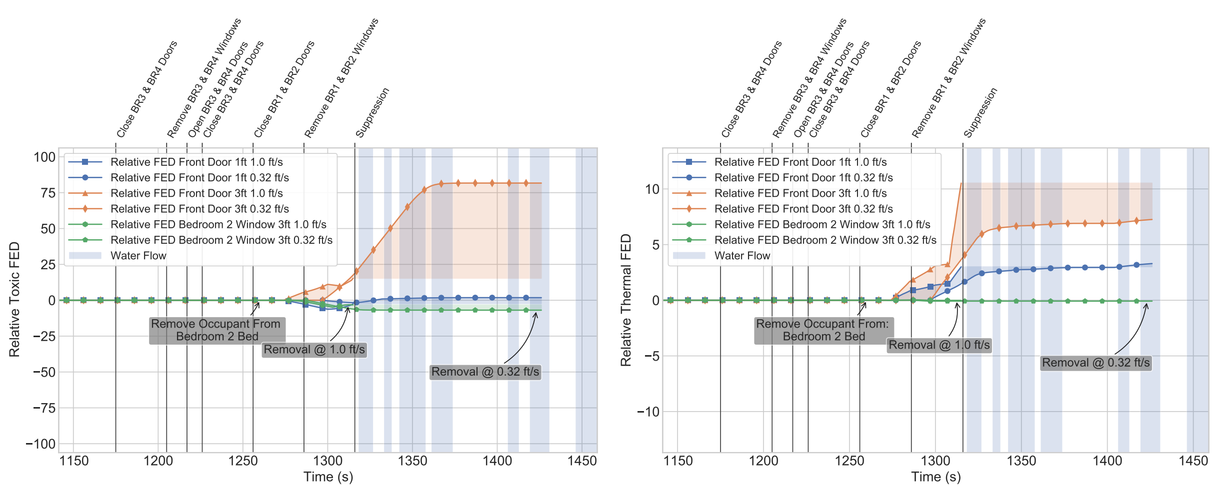



(d) Thermal FED Bedroom 2 Bed Pre-Suppression

Figure 5.37: 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 speed exited the structure. The fill extends to the 25th percentile to show the final assessment.

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 5.37c and 5.37d. 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 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. For an occupant removed through the front door, the relative thermal FED would have increased by 1-2 orders of magnitude (10 to 100 times increase).

Experiment 17 was designed to examine 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 5.38 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. This began after bedroom 2 was isolated and the window in bedroom 2 was removed. 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. Had an occupant been removed through the front door (following the initial pathway of the search crew), the toxic gas and thermal exposures would have been noticeably higher, particularly if removed at the 3 ft elevation or if the removal speed was slowed.




(a) Toxic FED Bedroom 2 Bed Pre-Suppression

(b) Thermal FED Bedroom 2 Bed Pre-Suppression

Figure 5.38: 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 speed exited the structure. The fill extends to the 25th percentile to show the final assessment.

## 5.9 Delayed Removal with Isolation in Protected Space

For the experiments where search operations occurred prior to suppression, and in the absence of fire compartment isolation, flashover of the fire compartment created thermal conditions equivalent to the emergency operating class. A removal pathway that includes passing an non-isolated fire compartment can place an occupant in areas where the toxic gas and thermal exposures are above tenability limits.

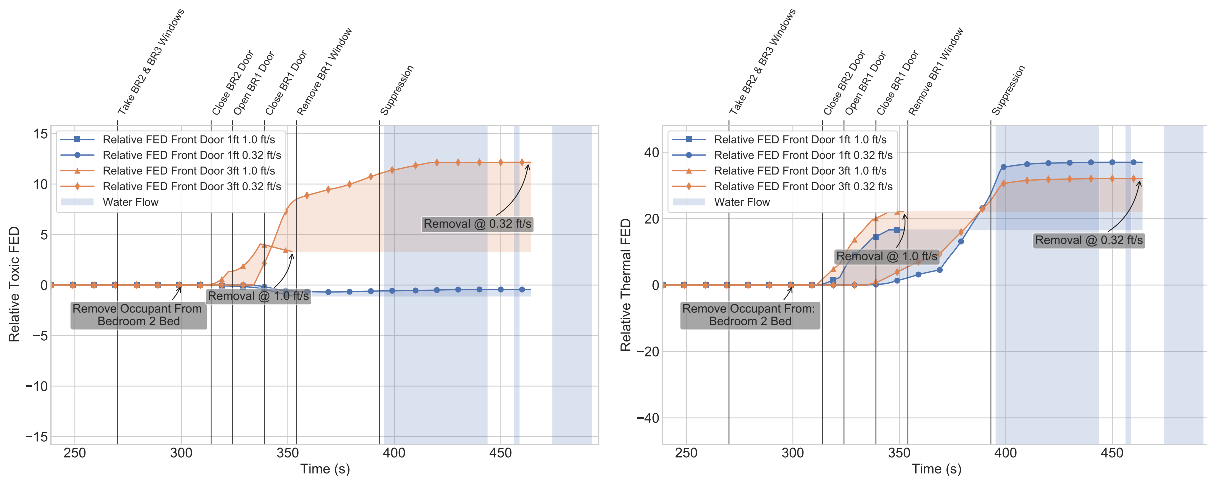
> In situations such as the pre-suppression removal of a trapped occupant past a non-isolated fire compartment or an inability for an expedient occupant removal (e.g. hoarder conditions), consideration should be given to delaying removal until the toxic and thermal hazards along the egress path are reduced, provided the occupant is in a space isolated from fire induced flows.

For fires where delayed removal of an occupant is considered, if possible, it is important for firefighters to create an area of refuge through isolation and local ventilation. Subsequently, firefighters should communicate these tactical decisions to incident command to coordinate suppression and the remaining search.

Experiment 4 examined window initiated search that occurred prior to suppression for a bedroom fire. In this experiment, the doors to bedrooms 2 and 3 were open prior to ignition. Following ventilation of those two windows, the door bedroom 2 was closed and the door to bedroom 3 remained opened. Figure 5.39 shows the relative toxic gas and thermal FEDs from Experiment 4 for a potential occupant on bedroom 2 being removed through the hallway to the front door. Recall from Section 3.4, that to calculate a relative FED, the toxic gas and thermal FEDs at the point of origin were subtracted from respective toxic gas and thermal FEDs calculated along the removal pathway. Essentially, if the relative FED is positive, the occupant would have received additional exposure compared to being left in place. If the relative FED is negative, the occupant would have received a lower exposure compared to being left in place.

The relative toxic FED (Figure 5.39a) shows that removal of the occupant through the front door at the 1 ft elevation through the range of velocities was effective at reducing the toxic exposure compared to leaving the occupant on the bed in an isolated bedroom. Removal at the 3 ft elevation however, would have resulted in an increased FED compared to remaining in the isolated space as the smoke layer as the smoke layer descended to approximately 3 ft above the floor.

The relative thermal FED shown in Figure 5.39b highlights the increased hazard associated with when the rescue path is past a non-isolated fire room and occurs prior to suppression. Prior to suppression, the end hallway, mid hallway, and start hallway locations had all reached the emergency operating class I and above. At 314 s, just as the bedroom 2 door was closed, the mid hallway flux increased to more than 60 $kW/m^2$ due to flame spread from bedroom 4 into the hallway. This eventually led to flashover of the non-isolated bedroom, bedroom 3. This resulted in relative thermal FEDs at 1 ft/s and 3 ft above the floor to exceed 20. Although the measurement instrumentation allowed for a computation of the relative thermal FED in the hallway, flaming combustion throughout the mid hallway location would have made removal of an unprotected occupant along this pathway intractable.




(a) Toxic FED Relative to Bedroom 2 Bed

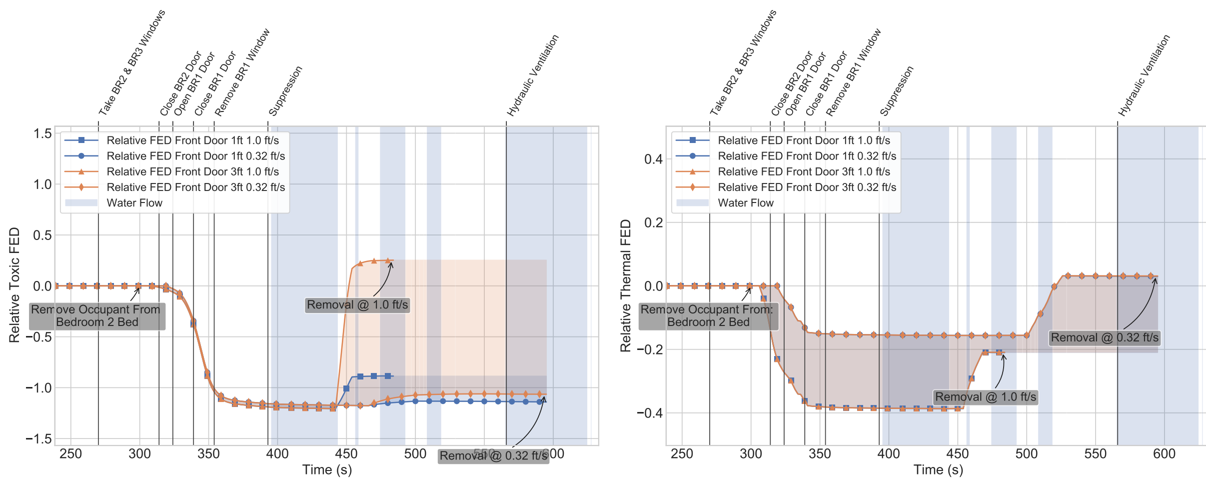
(b) Thermal FED Relative Bedroom 2 Bed

Figure 5.39: Cumulative toxic and thermal FED relative to an isolated location on bedroom 2 bed for window initiated search ahead of suppression (Experiment 4). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

In Experiment 4, bedroom 2 was isolated as the crew entered the space. Consider the scenario, where the occupant was moved from the bed (at 3 ft) to the 1 ft elevation below the vented bedroom 2 window and remained at that location until the suppression crew completed an initial knock down of the fire in bedrooms 3 and 4. Figure 5.40 shows the relative toxic and thermal FED during removal that occurred 40 s after the start of the suppression.

Movement from the bed to the 1 ft elevation at the window following isolation of bedroom from the flow of combustion gases resulted in a reduction in both relative toxic gas and thermal FEDs. The closed bedroom door resulted in bi-directional flow being established at the bedroom 2 window – effectively a new flow path was created that began and ended at the window. Air inflow at the window resulted in improved gas concentrations compared the higher elevation bed location which was offset from the window which was vented for entry, and thus a reduction in relative toxic gas FED (Figure 5.40a). After the occupant was moved into the hallway for removal, the relative toxic gas began to increase, particularly for removal at the higher elevation as there was still residual combustion gases that accumulated pre-suppression. Additionally, the slower removal velocity had a smaller increase as the smoke layer continued to lift following suppression.

Similar to the relative toxic gas FED, the lower elevation and air intake through the window resulted in lower temperatures and heat fluxes and therefore lower relative thermal FEDs compared to remaining on the bed. The relative thermal FEDs also increased as the occupant was moved into the hallway due to heat transfer from the walls, floor, and ceiling that had been heated over the duration of the experiment. In contrast to the relative toxic gas FEDs, the slower removal speed resulted in higher relative thermal FEDs as the compartment remained at above ambient temperatures longer than it took for the smoke layer to rise above 3 ft. Ultimately, though, the delayed removal from bedroom 2 until suppression resulted in lower toxic gas and thermal exposures for a potentially trapped occupant.



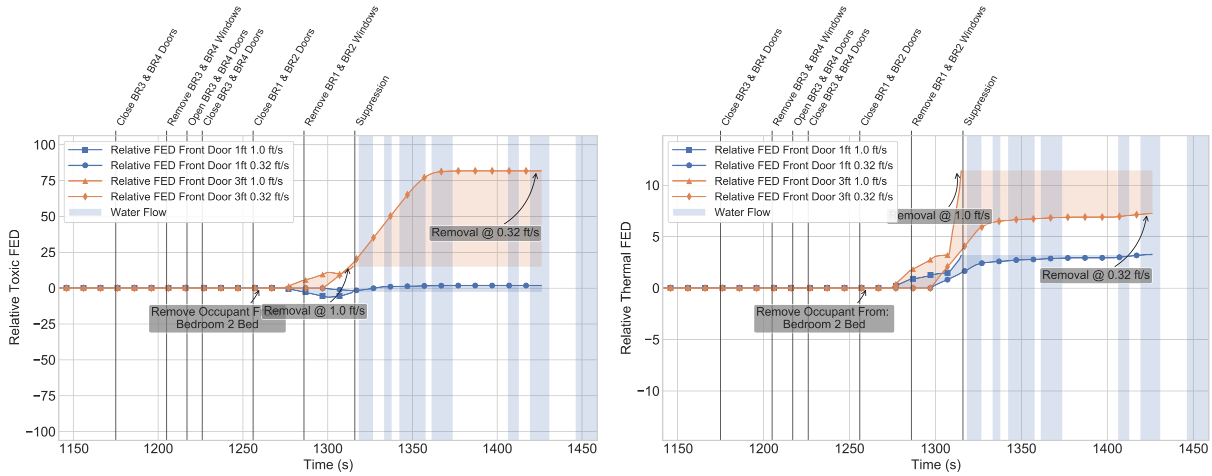

(a) Toxic FED Relative to Bedroom 2 Bed

(b) Thermal FED Relative Bedroom 2 Bed

Figure 5.40: Cumulative toxic and thermal FED relative to an isolated location on bedroom 2 bed for post-suppression removal following window initiated search ahead of suppression (Experiment 4). The comparisons include removing the occupant through the front door at both the 25th percentile velocity (0.32 ft/s) and 75th percentile velocity (1.0 ft/s). The solid lines terminate at the time when the respective occupant exited the structure. The fill extends to the 25th percentile to show the final assessment.

Experiment 17 included door initiated search ahead of suppression for a kitchen fire. The open front door for the duration of the experiment 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 was 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 (remaining on the bed in bedroom 2), see Figure 5.41. 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 $\approx$ 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.



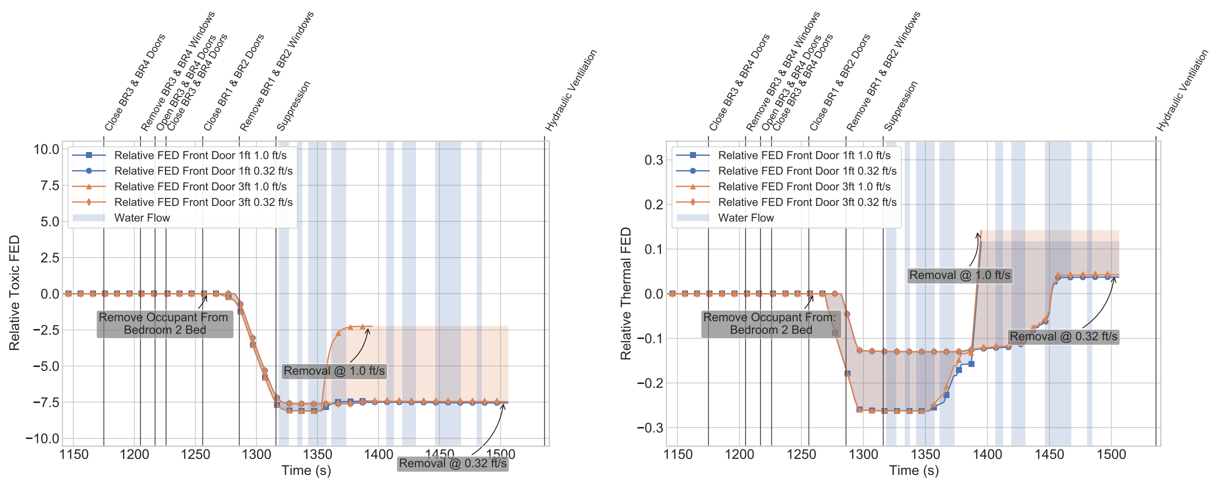

(a) Toxic FED Bedroom 2 Bed (Experiment 17) (b) Thermal FED Bedroom 2 Bed (Experiment 17)

Figure 5.41: 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 5.42 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 5.42a). 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 5.41a)

The relative thermal FED (Figure 5.42b) 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 5.42: 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.

# 6 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 as 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, as well as 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.

# 7 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. Search operations originated through a window, door, or both and occurred pre-suppression, during suppression, or post-suppression. Temperature, velocity, and pressure were measured throughout each structure to assess the fire dynamics. Heat flux and gas concentrations were employed to assess the impact of tactics on occupant tenability.

The relatively small number of experiments and a single structure type limit the ability to make universal, definitive assessments of tactical performance; however, several trends were identified that could influence tactical decisions on the fireground:

1. Prior to intervention, there were statistically significant differences in toxic and thermal exposures to occupants as a function of elevation. The higher the elevation, the higher the exposure to the potentially trapped occupant.

2. Prior to intervention, it was shown that spaces isolated prior to ignition had statistically lower measured exposures compared to non-isolated spaces.

3. Prior to intervention, positions at increased distances from the fire along established flow paths (intake versus exhaust/end point) were shown to have lower exposures; however, the intake portion was a supply of oxygen which facilitated fire growth, so this was a temporary factor.

4. A closed door to the fire compartment (e.g., close the bedroom door for a bedroom fire and close the front door for a kitchen/living room fire) was effective at reducing flame spread as well as reducing the operating class for searching firefighters and toxic and thermal exposure rates for potentially trapped occupants.

5. For scenarios where ventilation preceded suppression as part of search operations, isolation of spaces was shown to be effective at reducing the thermal operating class for firefighters and the toxic and thermal exposure rates compared to spaces that were not isolated.

6. Prior to suppression, removal of an isolated occupant along a pathway that required passing the fire compartment was shown to increase the exposure to the occupant compared to remaining isolated.

7. Removal of an occupant lower in the space (1 ft above the floor) was shown to result in a lower accumulated exposure compared to higher elevations (3 ft above the floor) even if the higher elevation egress occurred at a rate that was 3 times as fast.

8. Suppression, both interior and exterior, was effective at reducing the thermal operating class for searching firefighters and the rate of thermal exposure increase to occupants, however for

scenarios without corresponding ventilation, the toxic exposure rate remained elevated when compared to scenarios where ventilation was coordinated with suppression.

9. Less than 230 gallons (108 gallons $\pm$ 48 gallons) were used during the initial suppression period across all 21 experiments and less than 500 gallons, including hydraulic ventilation, were used in total for suppression for each of the bedroom, 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)

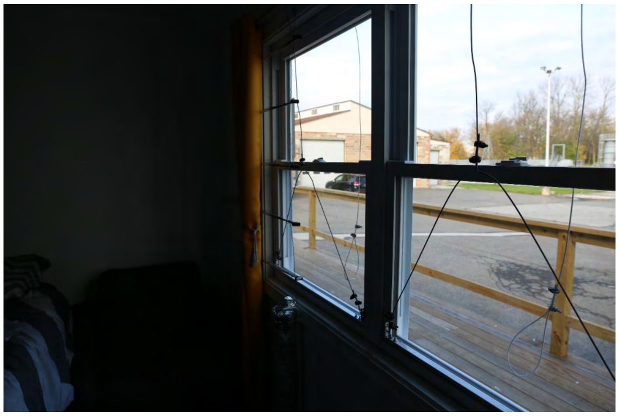

(b) Take Window (During)

(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 search 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 $kW/m^2$ [29] |
| Tenability threshold for burns | 2.5 $kW/m^2$ [14] |
| Pain to skin within seconds | 3-5 $kW/m^2$ [14] |
| Threshold to floor for flashover | 20 $kW/m^2$ [30] |
| TPP test | 84 $kW/m^2$ [19] |
| Flames over surface | 60-200 $kW/m^2$ [31] |

# Appendix C Experimental Overviews

## C.1 Experiment 1

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

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

Table C.1: Experiment 1 Event Times

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

## C.2 Experiment 2

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

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

Table C.2: Experiment 2 Event Times

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

## C.3 Experiment 3

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

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

Table C.3: Experiment 3 Event Times

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

## C.4 Experiment 4

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

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

Table C.4: Experiment 4 Event Times

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

## C.5 Experiment 5

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

Post bedroom 4 flashover, the suppression crew entered the structure through the front door and began suppression. Simultaneously, the crews on side C of the structure ventilated half of the double-wide windows in bedroom 2 and bedroom 3. The crews entered each bedroom and proceeded toward the hallway doors. The crew in bedroom 3 were unable to close the door. The crew bedroom 2 entered the hallway and closed the door behind them. The crew crossed the hallway and opened the door to bedroom 1. After entry into the space the crew closed the door and removed the bedroom 1 double-wide window. At this point, the search tactic comparison was complete. Upon the suppression crew announcement of 'fire under control', hydraulic ventilation occurred out of the failed bedroom 4 window. 106 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 281 gallons. Table C.5 provides the timing of each event relative to ignition and to the first intervention, which in this experiment was simultaneous interior suppression and ventilation of the bedrooms 2 and 3 windows.

Table C.5: Experiment 5 Event Times

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

## C.6 Experiment 6

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

Post bedroom 4 flashover, the crew on side A entered the structure through the front door and closed the door behind them. The crew proceeded through the structure and entered bedroom 3. The crew closed the bedroom 3 door and then removed the bedroom 3 window. The bedroom 3 door was opened for reentry into the hallway and subsequently closed. The crew proceeded down the hall toward bedrooms 1 and 2. The crew split to enter both bedrooms. Simultaneously, the door to bedroom 1 was opened and the door to bedroom 2 was closed. The bedroom 1 door was closed after the crew entered the bedroom. The double-wide window in each bedroom was removed. At this point, the search tactic comparison was complete. The front door was opened and the suppression crew proceeded to the fire room. Upon the suppression crew announcement of ‘fire under control’, hydraulic ventilation occurred out of the failed bedroom 4 window. 75 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 245 gallons. Table C.6 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was the closing the front door.

Table C.6: Experiment 6 Event Times

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

## C.7 Experiment 7

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

Post bedroom 4 flashover, the crew on side A of the structure entered the common space with a 2 1/2 gallon pressurized water fire extinguisher. The crew suppressed flaming combustion in the hallway and proceeded to the fire room. The crew closed the bedroom 4 door, which terminated the flow of higher-pressure combustion gases from the fire room to lower-pressure, open volumes of the structure. The crew proceeded into bedroom 3 and closed the door behind them. The bedroom 3 window was removed. The door to bedroom 3 was opened for entry into the hallway and subsequently closed. The crew proceeded down the hall toward bedrooms 1 and 2, then split to enter both bedrooms. Simultaneously, the door to bedroom 1 was opened and the door to bedroom 2 was closed. The bedroom 1 door was closed after the crew entered the bedroom. The double-wide window in each bedroom was removed. At this point, the search tactic comparison was complete. The suppression crew entered the structure through the front door, flowing water as needed to advance to the fire room. The suppression crew began flowing water as the fire room door was opened. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed bedroom 4 window. During hydraulic ventilation the bedroom 1 door was opened. 84 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 317 gallons. Table C.7 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was water flow from a pressurized water fire extinguisher.

Table C.7: Experiment 7 Event Times

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

## C.8 Experiment 8

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

Post bedroom 4 flashover, the crew on side C of the structure ventilated half of the double-wide window in bedroom 3. The crew entered bedroom 3 and proceeded toward the hallway door. The crew was unable to close the bedroom 3 door. The crew crossed the hallway and closed the bedroom 4 door. The crew proceeded down the hall toward bedrooms 1 and 2. The crew split to enter both bedrooms. Simultaneously, the door to bedroom 1 was opened and the door to bedroom 2 was closed. The bedroom 1 door was closed after the crew entered the bedroom. The double-wide window in each bedroom was removed. At this point, the search tactic comparison was complete. The suppression crew entered the structure through the front door, flowing water as needed to advance to the fire room. The suppression crew began flowing water as the fire room door was opened. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed bedroom 4 window. 75 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 275 gallons. Table C.8 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was ventilation of half the bedroom 3 double-wide window.

Table C.8: Experiment 8 Event Times

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

## C.9 Experiment 8b

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

Post bedroom 4 flashover, crews on side C of the structure ventilated half of the double-wide windows in bedroom 3. The crew entered bedroom 3 and proceeded toward the hallway door. Thew crew opened the bedroom 3 door and flowed water from a 2 1/2 gallon pressurized water fire extinguisher to suppress flaming combustion in the hallway. After expending the contents of the extinguisher, the crew entered the hallway and closed the bedroom 3 door behind them. The crew attempted to close the fire room door, however the door had burned through. The crew then proceeded down the hall toward bedroom 1 and bedroom 2. The crew split to enter both bedrooms. The door to bedroom 1 was opened for entry and subsequently closed as the crew entered. The door to bedroom 2 remained open. The windows in the respective rooms were then removed. At this point, the search tactic comparison was complete and the suppression crew entered the structure through the front door. The suppression crew flowed water in the hallway during their advance to the fire room door. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the failed bedroom 4 windows. 68 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 223 gallons. Table C.9 provides the timing of each event relative to ignition and to the first fire department intervention, which in this experiment was ventilation of half the bedroom 3 double-wide window.

Table C.9: Experiment 8b Event Times

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

## C.10 Experiment 9

The search tactics in Experiment 9 were designed to evaluate door initiated operations conducted during interior suppression of a bedroom fire (bedroom 4). Prior to ignition, the lower panes of the double-wide window in the bedroom 4 were removed and the door to bedroom 4 was opened. The front door, doors to bedrooms 2 and 3, and door to bathroom 3 were opened. The doors to bedroom 1 and bathroom 1 were closed. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4.

Post bedroom 4 flashover, the suppression crew entered through the front door and began interior operations. As the suppression crew reached the fire compartment and flowed water, the search crew proceeded to bedroom 3 and opened the lower panes of the double-wide bedroom 3 window. The crew then proceeded to bedroom 2. Simultaneously, the interior crew opened the lower panes of the double-wide bedroom 2 window and an exterior crew on side A opened the lower panes of the double-wide bedroom 1 window. The exterior crew entered bedroom 1 and opened the bedroom 1 door. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the bedroom 4 windows. 91 gallons were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 336 gallons.

Table C.10: Experiment 9 Event Times

| Event | Elapsed Time From Ignition (mm:ss) | (s) | From Intervention (mm:ss) | (s) |
|---|---|---|---|---|
| Ignition | 00:00 | 0 | — | — |
| Suppression | 04:47 | 287 | 00:00 | 0 |
| Open BR3 Window | 04:59 | 299 | 00:12 | 12 |
| Open BR1 & BR2 Windows | 05:22 | 322 | 00:35 | 35 |
| Open BR1 Door | 05:36 | 336 | 00:49 | 49 |
| Hydraulic Ventilation | 06:52 | 412 | 02:05 | 125 |

## C.11 Experiment 10

Experiment 10 was designed to establish the baseline conditions for comparison to the other nine experiments with bedroom 4 ignitions. At the time of ignition, the lower panes of the double window in bedroom 4 were removed, the door to bedroom 4 was opened, and the front door was opened. The interior door to bedroom 1 was closed, while the doors to bedrooms 2 and 3 were opened. The fire was ignited in the sofa chair adjacent to the mattress in bedroom 4. The fire reached a post-flashover state, at which point interior suppression occurred. Upon the suppression crew announcement of fire under control, hydraulic ventilation occurred out of the bedroom 4 windows. The experiment was considered to be complete at the end of hydraulic ventilation. 66 gallons of water were flowed during suppression. The total amount of water flowed during suppression and hydraulic ventilation was 231 gallons. All interior doors and exterior windows remained in their initial positions for the duration of the experiment. Table C.11 provides the timing of each event relative to ignition as well as relative to the first intervention, which in this experiment was suppression.

Table C.11: Experiment 10 Event Times

| Event | Elapsed Time From Ignition (mm:ss) | (s) | From Intervention (mm:ss) | (s) |
|---|---|---|---|---|
| Ignition | 00:00 | 0 | — | — |
| Suppression | 05:01 | 301 | 00:00 | 0 |
| Hydraulic Ventilation | 06:51 | 411 | 01:50 | 110 |

## C.12 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 C.12 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.

Table C.12: 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 |

## C.13 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 C.13 lists the times at which events occurred during Experiment 12.

Table C.13: 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 |

## C.14 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 C.14.

Table C.14: Experiment 13 Event Times

| Event | Elapsed Time | | | |
|---|---|---|---|---|
| | From Ignition | | From Intervention | |
| | (mm:ss) | (s) | (mm:ss) | (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 |

## C.15 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 C.15.

Table C.15: Experiment 14 Event Times

| Event | Elapsed Time | | | |
|---|---|---|---|---|
| | From Ignition | | From Intervention | |
| | (mm:ss) | (s) | (mm:ss) | (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 |

## C.16 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 C.16.

Table C.16: Experiment 15 Event Times

| Event | Elapsed Time From Ignition (mm:ss) | Elapsed Time From Ignition (s) | Elapsed Time From Intervention (mm:ss) | Elapsed Time 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 |

## C.17 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 C.17 lists the sequence of events along with the times at which they occurred.

Table C.17: Experiment 16 Event Times

| Event | Elapsed Time | | | |
|---|---|---|---|---|
| | From Ignition | | From Intervention | |
| | (mm:ss) | (s) | (mm:ss) | (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 |

## C.18 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 C.18. 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 C.18: 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 |

## C.19 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 C.19 proivdes the times at which interventions took place.

Table C.19: 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 |

## C.20 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 C.20 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 C.20: Experiment 19 Event Times

| Event | Elapsed Time From Ignition (mm:ss) | From Ignition (s) | From Intervention (mm:ss) | From Intervention (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 |

## C.21 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 C.21.

Table C.21: 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 |