Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival: Full Scale Experiments

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January 25, 2018

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Acknowledgments

This work was funded through a grant from the Department of Homeland Security's Assistance to Firefighters Grant Program under the Fire Prevention and Safety Grants: Research and Development. Without this critical funding and support, this vital fire service research would not be possible.

To assist the design and implementation of the experiments for the Fire Attack study, fire service experts from across the world with knowledge in fire suppression and the impact of interior and exterior fire streams were brought together. The individuals below provided direction for the project, assisted in planning the experiments, witnessed the testing, and developed concrete conclusions. Their tireless support and effort make this project relevant to the fire service across the world.

Fire Service Technical Panel

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Tony Carroll	District of Columbia Fire and Emergency Medical Service Department
Albert Castillo	Houston Fire Department
Chad Christensen	Los Angeles County Fire Department
John Chubb	Dublin Fire Brigade
Danny Doyle	Pittsburgh Fire Department
Aaron Fields	Seattle Fire Department
Jason Floyd	Las Cruces Fire Department
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The authors would also like to acknowledge the UL LLC technical support staff for their assistance in conducting the full-scale fire experiments.

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List of Acronyms

AFG	Assistance to Firefighters Grant program
DHS	U.S Department of Homeland Security
FEMA	Federal Emergency Management Agency
NFPA	National Fire Protection Association
SB	Smooth Bore
SS	Straight Stream
NF	Narrow Fog
PPE	Personal Protective Equipment
UL FSRI	UL Firefighter Safety Research Institute
USFA	United States Fire Administration

Abstract

As research continues into how fire department interventions affect fire dynamics in the modern fire environment, questions continue to arise on the impact and implications of interior versus exterior fire attack on both occupant survivability and firefighter safety. This knowledge gap and lack of previous research into the impact of fire streams has driven the need for further research into fire department interventions at structure fires with a focus on hose streams and suppression tactics.

As the third report in the project "Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival", this report expands upon the fire research conducted to date by analyzing how firefighting tactics, specifically suppression methods, affect the thermal exposure and survivability of both building occupants and firefighters in residential structures.

- Part I: Water Distribution [1].
- Part II: Air Entrainment [2].
- Part III: Full-Scale Residential Fire Experiments.

This report evaluates fire attack in residential structures through twenty-six full-scale structure fire experiments. Two fire attack methods, interior and transitional, were preformed at UL's large fire lab in Northbrook, IL, in a single-story 1,600 ft^2 ranch test structure utilizing three different ventilation configurations. To determine conditions within the test structure it was instrumented for temperature, pressure, gas velocity, heat flux, gas concentration, and moisture content. Additionally, to provide information on occupant burn injuries, five sets of instrumented pig skin were located in pre-determined locations in the structure. The results were analyzed to determine consistent themes in the data. These themes were evaluated in conjunction with a panel of fire service experts to develop 18 tactical considerations for fire ground operations. As you review the following tactical considerations it is important to utilize both these research results and your personal experience to develop your department's polices and implement these considerations during structural firefighting.

These tactical considerations include:

- Interior Suppression With Only Smoke Showing
- Transitional Attack With Fire Showing Near the Entry Point
- Fire Showing Remote from The Primary Entry Point
- There Can Be Survivable Spaces on Arrival at a Single-Family Residential Home
- Fire Attack and Search & Rescue Can Occur Simultaneously

- Search Consideration: Closed Doors Significantly Increase Occupant Survivability
- Water in the Fire Compartment Matters, and so Does Timing
- If You Can Get Water to Where It Needs to Go, You Don't Need Much
- Water Flow Can Impact Flow Path
- Suppression Operations, Both Interior and Transitional, Did Not Increase Potential Burn Injuries to Occupants
- Speed of Transition is the Enemy of Re-growth
- Water Converted to Steam Expands, Hot Gases Cooled Rapidly Contract
- Water Vapor is a Bi-product of Combustion
- Flow and Move vs. Shutdown and Move
- You Should Cool as You Advance
- Understanding the Limitations of a Thermal Imaging Camera Can Increase its Effectiveness
- A Short Burst of Water Cannot Tell You Gas Temperature
- Large Volume Gas Cooling Requires a Large Volume of Water

Although this report covers a significant number of considerations for residential fire suppression, future research is needed to identify and analyze the effectiveness of additional suppression methods. Methods which utilize different suppression equipment may prove more or less effective than the methods evaluated in this study.

Introduction

The purpose of this study is to improve firefighter safety, occupant survivability, fireground tactics, and the knowledge of fire dynamics by providing the fire service with credible scientific information on the impacts and implications of interior and exterior fire attack. This information is obtained from the results of water flow and full-scale fire testing in representative single-family homes. Part I of the study is aimed at determining how water is distributed within a compartment, while Part II quantified the air entrainment by hose streams to provide insight into how different application methods; nozzle types and patterns; pressures/flows; and stream location and angle combinations move air inside buildings. Parts I and II were conducted without the presence of fire to gain a basic understanding of air flow and water flow before full-scale fire experiments were conducted during Part III. These full-scale fire experiments were designed based on the results from Parts I and II of the study.

This report will cover Part III. Twenty-six full-scale fire experiments were conducted in test structures constructed within UL's large fire laboratory in Northbrook, IL. The experiments were designed to evaluate the different interior and transitional fire attack tactics employed throughout the United States and quantify the effectiveness of each under three different ventilation configurations: no vent, single window vent, and two window vents. The test structures were instrumented to measure temperature, gas velocity, pressure, heat flux, moisture content and to provide video feeds. In addition, five victim instrumentation packages incorporating pig skins were located at fixed locations to measure the potential burn injuries which would occur if occupants became trapped.

The fire suppression methods tested involved three main types of extinguishment. Two were versions of interior suppression: the first incorporating the "flow and move" tactic and the second incorporated the "shutdown and move" tactic. The third was a transitional suppression method which incorporated two variations: one where the stream was deflected off the ceiling, followed by the nozzle placed through the window and water applied to the fuel surface, prior to proceeding to the interior; and one where the stream was only deflected off the ceiling after which the crew proceeded to the interior. Each tactic was conducted with a single room of fire with no ventilation, a single room of fire with a single window vent and two rooms of fire with two window vents. Additional variables studied inclided nozzle type (which was varied between smooth bore and combination) and the use of door control.

1 Background

Recent fire service research has highlighted the importance of applying water to the fire as quickly as possible. This tactical consideration has highlighted a knowledge gap and increased the interest in better understanding the impact of water applied as part of an interior or transitional fire attack. Many variables exist in fire attack that may have on impact firefighter effectiveness and victim survivability, including stream placement, the timing required to get water on the fire, stream type, stream movement, air entrainment, position of flow paths, and hot gas cooling and contraction. The fire service's most important tool for many years at structure fires is their hose line. However, many questions have arisen as more research shows the impact of ventilation, flow paths, and exterior fire streams. Whether a fire suppression crew chooses to apply water as part of an interior attack or as part of a transitional attack they need to know what impact their stream has on the fire environment ahead of them. This is difficult on the fire ground because the firefighter experience is from behind the nozzle and visibility is commonly limited. This results in beliefs about conditions (e.g., temperature, steam etc.), ahead of the nozzle and its impact on victim survivability, yet concrete data of the actual impact has not been documented. Additionally, when the fire is ultimately suppressed that does not mean it was done most effectively, efficiently, and safely even if experience gained suggests that it was. Fire service adages such as "don't put water on smoke," "you will steam the victims," and "fog nozzles always disrupt the thermal layer" have been passed on from generation to generation with little context or substantiation. Without context, these concepts area treated like rules which can severely limit a firefighter's understanding of fire suppression.

Many fire training curriculums define three fire attack methods: direct attack, indirect attack, and combination attack. Direct attack involves the discharge of water directly onto the burning fuel. Indirect attack involves directing the stream toward the ceiling of a compartment in order to generate a large amount of steam in order to cool the compartment. It is thought that converting water to steam displaces oxygen, absorbs the heat of the fire, and cools the hot gas layer sufficiently for firefighters to safely enter and make a direct attack. Combination attack extinguishes a fire by using both a direct and indirect attack. Another technique to safely approach a fire that cannot be reached with a direct attack is gas cooling. Gas cooling provides a buffer zone around the suppression crew, but the larger the compartment the less the impact on cooling the hot gas layer. Gas cooling must be a continuous process while advancing toward a shielded fire. Techniques for effective gas cooling and the upper limit of the volume where gas cooling is effective are not well-known.

In fire fighter training there is a lot of emphasis on steam generation but little is taught or demonstrated about the mechanics of suppression. Water vaporized in the upper gas layer reduces the total volume of the hot gases and steam. It is thought that water vaporized on hot surfaces such as the ceiling does not take much energy from the fire and therefore the volume of steam produced lowers the upper layer and makes conditions less tenable. These concepts are very important when the fire can not be directly attacked by applying water on burning fuel but is very difficult to visualize during a fire attack. Thus, gaining an understanding purely from experience is a challenge. Many of these fire suppression concepts are difficult to learn and refine because realistic ventilation limited fires are not safely replicated in firefighter training structures. Conditions created by today's fuels commonly found in occupied structures such as heat release rates and smoke production properties are not allowed when following fire service training standards. Therefore, the impact of hose streams in concrete training structures or metal containers can be misleading to firefighters, resulting in incorrect inferences. This may then lead to inappropriate fire ground tactics with potentially deadly results. The goal of this study is to better understand the impact of hose streams so that proper messages can be taught in fire service training programs.

There are potentially harmful effects of inappropriate water application regardless of the type of hose stream. Since firefighters today are more aware of the need to cool hot smoke (fuel) in the upper layer, it is essential to understand the capabilities and limitations of each type of stream. The impact of hose stream application as one advances during a fire attack is dependent on many factors. This report looks to quantify those factors to allow for the most accurate representation in fire service literature and training manuals.

Fire suppression effectiveness and firefighter safety are not achieved by water flow rate alone, but by the appropriate use of a given flow rate under specific fire ground conditions. A flow rate must meet the critical flow rate to extinguish a fire depending on the heat release rate and should be higher to reduce the time to extinguishment. This can be anywhere between 95 to 165 gpm, depending on conditions. Drastically exceeding the critical flow rate has less impact on time to extinguishment but has a significant impact on the total amount of water used. There is little data to support that dramatically exceeding the critical flow rate results in increased firefighter safety. It has been estimated that only 5 to 10 percent of water applied during fire attack contributes to extinguishment. It is difficult for firefighters to realize the efficiency of various hose stream techniques due to poor visibility on the fire ground. However, this report looks to develop data with realistic structures, fuel sources, and fire scenarios so that important inferences may be developed relative to different hose stream techniques and water usage.

2 Objectives, Scope and Limitations

2.1 Objectives

The purpose of this study was to provide the fire service with scientific knowledge on the impact of interior and transitional fire attack tactics on firefighter safety and trapped occupants while improving training and decision-making on the fire ground. This was accomplished with the completion of the following objectives:

- Increase the knowledge surrounding fire dynamics in residential structures and their impact on victim survivability and firefighter safety.
- Develop knowledge of water streams applied during an interior and transitional fire attack and their impact on victim survivability and firefighter safety.
- Understand where water goes and how air flows during interior and transitional fire attack utilizing common procedures and what that means to the fire dynamics within a structure.
- Gain understanding of the impact of water streams depending on the volume of the fire compartment/structure.
- Advance the understanding of victim survivability in the modern fire environment by working with experts in the use of pig skin.
- Develop and implement a methodology to measure moisture content in the modern fire environment to answer fire service concerns.
- Bring the 'Science to the Streets' by developing science-based tactical considerations founded on experimental results that can be incorporated into firefighting standard operating procedures.

All five of the Technology & Fire Service Science issues facing the fire service determined during the 2nd National Fire Service Research Symposium [3] were incorporated into this study.

2.2 Scope

This study looked at the impact the two main methods of fire attack, interior and transitional, have on victim survivability in residential structures. Due to the significant number of variables on a structure fire, limitations exist in the ability to evaluate them all. The variables selected were chosen to begin to bound the problem and provide insight into the practical application of fire suppression methods.

These variables included house geometry, fuel loading, fire department arrival time, tactical choices, hose stream flow rates, and ventilation locations. The house geometry included a single-story 1,600 ft^2 ranch-style home with a long residential hallway to evaluate the impact of approaching a fire down a hallway. The bedrooms were all located off the long hallway with the fire rooms at the far end. Intervention times were based on fire department personnel arriving after the fire became ventilation-limited. By bounding these variables and controlling the test conditions during firefighting operations, it was possible to evaluate the impact of different fire suppression tactics on fire dynamics and conditions inside a single-family home.

The study did not include differences in hose line deployments. The line was deployed to the front of structure for the first action, advancement through the front door or transitional attack through the front window. The line was charged, and pressure, flow and nozzle position were all checked and set prior to the start of the experiment. The study also did not include evaluation of crew size on timing. The suppression crew consisted of three firefighters, a nozzle firefighter, a backup firefighter and a line advancement firefighter. The firefighters in these positions were consistent though out the experiments. Additionally, the hose streams were flowed from pre-determined positions to evaluate the impact of different tactics, be it transitional (through the window) or interior (down the hallway). Flow based on conditions only occurred when the suppression crew felt it was necessary for their safety.

The fires in this study were content fires and represented a fire event within the living space of the home, not a structure fire with fire extension into the walls or attic space.

2.3 Limitations

Recreating all the variables of a fire department response is a challenge due to the complex nature of a fire scene. Research into the effectiveness of various suppression tactics is not intended to recreate the fire scene in its entirety but to fix as many of the variables as possible to permit a scientific comparison.

This project was conducted solely in a laboratory facility in order to fix the environmental conditions (wind, rain, temperature and pressure). During a fire department response, the environmental conditions will play a role in tactical choices. The Tactical Considerations from this study need to be evaluated against the conditions the fire department is faced with on-scene.

The location of the measurements for victim survivability were chosen to compare the effects of proximity to the fire, being behind a closed door and being elevated off the floor. Although these values can be extrapolated to other similar locations within the structure, due to the complexity of the fire environment, they are not representative off all the possible locations where a victim may be located in a residential structure.

It is important to note that measurement of quantities such as moisture content and burn potential are difficult in the fire environment. This study advanced these measurement techniques; however, not all experiments were successful in recording usable data with regards to these two varriables. The experiments were data was obtained have been analyzed and used to develop tactical considerations where applicable. Future research utilizing these measurement techniques is necessary to fully understand the impact of specific fire suppression tactics.

Additionally, the number of experiments was fixed based on the available budget. This project was not able to test all of the potential tactical choices of a suppression crew; thus it is important to utilize both these research results and your personal experience when making tactical choices.

The tactical considerations developed are intended for similar size (1,620 ft^2) single story residential occupancies with similar compartment sizes (140 to 175 ft^2). Further research is required for larger residential structures (in excess of 3,000 ft^2), two story, and commercial occupancies.

3 Literature Overview

Hose, nozzles and water have been used by the fire service for hundreds of years. Despite their frequent use, there has been little scientific research conducted on the effective use of these tools for fire suppression. It is common in the fire service to find discussions about which nozzle is better or which flow rate is required for what sized fire, but this is based on experience and usually not science.

3.1 Fire Service Training Manuals

One of the early fire service training manuals comes from James Braidwood, who at the time found work relating to fire service training difficult to locate. Braidwood's book "On the Construction of Fire-Engines and Apparatus, The Training of Fireman, and the Method of Proceeding in Cases of Fire" was published in 1830, and discussed evidence-based tactics in use by the Edinburgh Fire Establishment in the 1800s [4]. The work highlights concepts such as limiting the oxygen available to the fire, applying water effectively to the fuels and the need for interior fire suppression, along with a framework for construction of fire engines. Although significant discussion on fire attack methods is included, they are purely experienced-based. This practice of writing fire service training manuals based on experience continues today.

Introductory firefighter training for certification in most states is governed by NFPA 1001, the Standard for Firefighter Professional Qualifications. NFPA 1001 devides job performance requirements into the responsibilities of a Firefighter I (initial level of firefighter) and Firefighter II (subsequent level of firefighter) [5]. These requirements identify what a firefighter should be competent in (for example, interior fire attack) but not necessarly the specific method for completing the tactic. The method and knowledge associated with the skill are left up to the selected training program or manual.

There are four main training manuals used for Firefighter I & II education;=: "Essentials of Firefighting and Fire Department Operations" by IFSTA; "Fundamentals of Firefighting Skills", a collaboration between Jones & Bartlett Learning, NFPA and IAFC.; "Firefighter's Handbook Essentials of Firefighting" by Delmar Learning; and "Fire Engineering's Handbook for Firefighter I & II' by Pennwell Corporations, Fire Engineering [6–9]. All of them reference three different methods of fire attack: direct (applying water to the fuel), indirect (applying water to the hot gases) and combination (a combination of direct and indirect attack). The skills required to complete the three methods are discussed in detail, however limited information exists on when they should be applied. The concept of transitioning is referred to in training manuals as a strategy rather than a tactic. It is discussed with regards to offensive and defensive strategy, where one would transition from one strategy to another. Like Braidwood's book in 1830, these manuals are predominantly experienced-based.

3.2 Research Work

3.2.1 Fire Suppression Methods

In 1950 Chief Lloyd Layman presented a paper titled "Little Drops of Water" at the Fire Department Instructors Conference. He introduced what he called indirect method of attack to suppress interior building fires by using the heat-absorbing properties of expanding and condensing steam, produced in great quantities by fog streams [10]. The conclusions were based on Coast Guard experiments that Layman was in charge of conducting at the Coast Guard Firefighting School at Fort McHenry in Baltimore, MD [11]. Layman continued his experiments and applied his tactic in building fires after he returned to his position as fire chief in Parkersburg, WV. This research had a very large impact on the fire service and suppression techniques to this day.

Throughout the 1950s a National Committee began conducting experiments to collect data on the growth and behavior of interior fires and how to most effectively suppress them. Keith Royer and Bill Nelson were members of this committee, and as the heads of the firemanship training program at the Iowa State University's Engineering Extension, they collected and analyzed data from hundreds of experimental fires. Through this research the fire service was taught about fire behavior and how to suppress fire with a combination fire attack. They examined the amount of heat generated by common fuels, the heat-absorbing capacity of water, the impact of compartment volume during suppression. They developed the Iowa formula, which is a critical rate of flow formula still used today. The formula divides the cubic foot volume of the space by 100 to determine the amount of water needed to control a fire in the largest open space within a structure [12].

While the physics of fire development has not changed over time, the fire environment for the single-family home has evolved. Several factors including home size, geometry, contents and construction materials have changed significantly over the past 50 or more years. Each of these factors has impacted firefighter and occupant safety. Faster fire propagation, shorter times to flashover, rapid changes in fire dynamics and shorter escape times all impact fire service suppression techniques and effectiveness [13–15]. Many of the variables in Royer and Nelson's analysis have changed and more research is needed to see how suppression techniques used in the 1950s with 1950s fuel loads and firefighting tools translates to today's firefighter safety and effectiveness.

Beginning in 1994, the Naval Research Laboratory carried out a series of full-scale fire experiments to compare straight stream attack versus fog pattern attack [16]. These experiments were conducted on the naval ship the USS Shadwell with a fire volume of approximately 2600 ft^3. In these experiments one 60-degree fog pattern was applied at a 45-degree angle into the smoke layer. They examined cooling effects, steam generation and thermal layer disruption. Their experiments examined shielded and non-shielded fires and concluded that using fog to cool the upper layer was more effective and safer than straight stream attack when the fire could not be attacked directly. In addition, the heart rates and body temperatures of firefighters conducting fire ground operations were lower utilizing the fog attack.

In 1998, NIST conducted a series of experiments to demonstrate the suppression effectiveness of water-based firefighting agents [17]. This was a step toward creating test procedures to determine suppression effectiveness by developing a standardized test method for evaluating the firefighting effectiveness of water and other agents. This study was successful at aquiring the data data necessary to develop a firefighting effectiveness test, however additional research is needed on application technique. It sites the importants of having tests which are reflective of the complexities found in firefighting.

In 2002, the National Research Council of Canada conducted a literature search on 3D water fog techniques for firefighting [18]. It discusses the impact of water fog characteristics associated with properties of the nozzle (e,g,, droplet size, momentum, flow rate, spray angle and pattern) and discharge techniques (e.g., discharge angle, and discharge duration related to the burns) on performance of the 3D water fog technique. This technique supplements a direct attack by controlling the environment the firefighters are in until they are able to apply water directly to the fire. Opponents of flowing water into smoke have concerns that include: (i) effectiveness of controlling the fire, compared to traditional straight stream attack; (ii) possible disruption of the thermal balance; (iii) possible generation of a large amount of hot steam that produces burn injuries to firefighters; and (iv) the performance of this technique is complex and requires extensive training. Advocates of this technique have attempted to respond to these concerns but very limited experimental studies have been undertaken due to complexity of the problems. Application techniques and fire conditions on the the performance of fog technique is not well-studied; therefore, there are little guidelines and adoption is greatly limited.

Several theoretical studies had been conducted that examine droplet size and their ability to suppress fire gases. For example, when droplet diameter is reduced from 1000 nanometers to 100 nanometers the total surface area increases 10 times from 6 m^2 to 60 m^2 for 1 liter of water [19]. Since these smaller droplets evaporate sooner, others have examined the lifetime of the droplet to determine how far it can travel based on temperature of the surrounding gases and droplet size [20]. Further complicating this theory is that droplets all have an impact on each other as they turn to steam. Residence time can be further reduced compared to an individual droplet, because leading droplets impart forward momentum to the surrounding gas, reducing the air drag on the following droplets and resulting in better penetration [21]. In 2010, the University of Maryland examined spray characteristics from fire hose nozzles [22]. They examined the breakup of a smooth bore nozzle utilizing techniques such as shadowgraphy and a patternator and concluded that more research was needed to fully understand the water spray from fire hose nozzles.

In 2000, Lund University examined the demand for extinguishing media in manual firefighting [23]. They examined critical flow rates required to suppress fires by reviewing available literature and conducted a series of experiments that examined suppression of wood pallets at a fire training academy. They examined the five ways that water can be applied during fire extinguishment: on hot gases, on flames, on burning fuel, on fuel that is not yet burning and on hot surfaces. They highlighted that what is most effective against the fire is not necessarily best for the firefighters since there are other constraints during firefighting operations such as limited air supply and multiple priorities. The optimum flow rate corresponds to an optimum control time, a control time that gives the lowest total demand for resources. Most of the current data for optimum water flow rate include experiments utilizing wood cribs or pallets, but not today's synthetic fuel loads in actual structures [24–26]. These studies also did not investigate the effect of flow paths or the impact of steam generation on firefighters or victims.

In 2003, a fire service group at the Rockland County (NY) Fire Training Center conducted a series of tests in their concrete training building. They measured the amount of air moved by solid bore and combination nozzles using common fire ground methods. They concluded that air volumes moved by smooth bore nozzles and combination nozzles in the straight stream setting are very similar if not the same, and that combination nozzles in the fog pattern move significant amounts of air which can over-pressurize the fire area and send steam over the suppression crew even with a ventilation opening opposite the suppression crew. These tests were performed either with no fire or with a training fire, which are very different than actual fire conditions. Their tests do provide a good range of airflows that can be expected in our experiments. The authors stated, “Our nozzle testing program was not as controlled and as precise as we would have liked.” They also did not have measurement devices that were able to accurately measure air flows from a fog pattern [27–29].

3.2.2 Firefighters Operational Environment

A variety of methods exist for evaluating the thermal conditions to which firefighters are exposed. In general, they divide the thermal environment into either three or four classes, with the lowest class representing conditions only slightly more severe than ambient, and the highest class representing emergency conditions, tenable for only a few seconds before equipment failure, injury, or death are imminent. Some of these methods, such as the NIST Thermal Classes proposed by Donnelly et al. [30] are used primarily for the purpose of evaluating electronic equipment used by firefighters. The NIST thermal classes specify 4 classes, which are presented in Table 3.1. Since these thermal classes are focused specifically on electronic equipment, PASS alarms in particular, they are not the most appropriate for evaluating the risk of thermal injury to firefighters in training fires. Additionally, heat flux and temperature are treated separately in the NIST thermal classes, so the consideration of only one value may give an incomplete picture of the thermal threat.

Table 3.1: NIST Thermal Classes

Thermal Class	Maximum Time (min)	Maximum Temperature (°C)	Maximum Heat Flux (kW/m^2)
I	25	100	1
II	15	160	2
III	5	260	10
IV	$\leq$1	$\geq$260	$\geq$10

A more appropriate method of characterizing the thermal environment is the thermal operating conditions outlined by Utech [31]. Utech uses the temperature at the firefighter’s height as an approximation of the convective heat transfer to the firefighter’s gear and the incident heat flux as an approximation of the radiative heat transfer to the firefighter’s gear from the surfaces of the room, the upper gas layer, and the fire itself. He combines these two quantities to define three fields of thermal conditions: Routine, Ordinary, and Emergency. According to Utech, routine conditions are defined as those where the surrounding temperature is between 68°F and 158°F with an incident heat flux between 1 and 2 kW/m^2. He maintains that these conditions translate approximately to ambient conditions, not necessarily requiring any thermal protection. As the heat flux and surrounding temperature both increase, the thermal environment crosses into the ordinary operating range. This ordinary range is defined between 158°F and 392°F and between 2 and 12 kW/m^2. Ordinary operating conditions represent more serious fire conditions, such as those next to a flashed over room. According to Utech, firefighters would be able to function under ordinary operating conditions from 10-20 minutes at a time, or in other words for the working duration of an SCBA cylinder. Utech considers ordinary operating conditions those that were typical of a house fire. The final classification is emergency operating conditions, which are those thermal conditions exceeding 12 kW/m^2 and 392°F. These operating conditions are intended to be consistent with an environment dangerous to a firefighter in PPE, such as a firefighter trapped in a room that is flashing over. Utech describes this zone as one in which a firefighter's PPE would only be able to withstand an exposure on the order of a few seconds in the emergency operating range. Figure 3.1 offers a visual chart of the thermal operating classes, where the x-axis is heat flux, plotted on a logarithmic scale, in kW/m^2, and the y-axis is temperature, also plotted on a logarithmic scale, in °C.

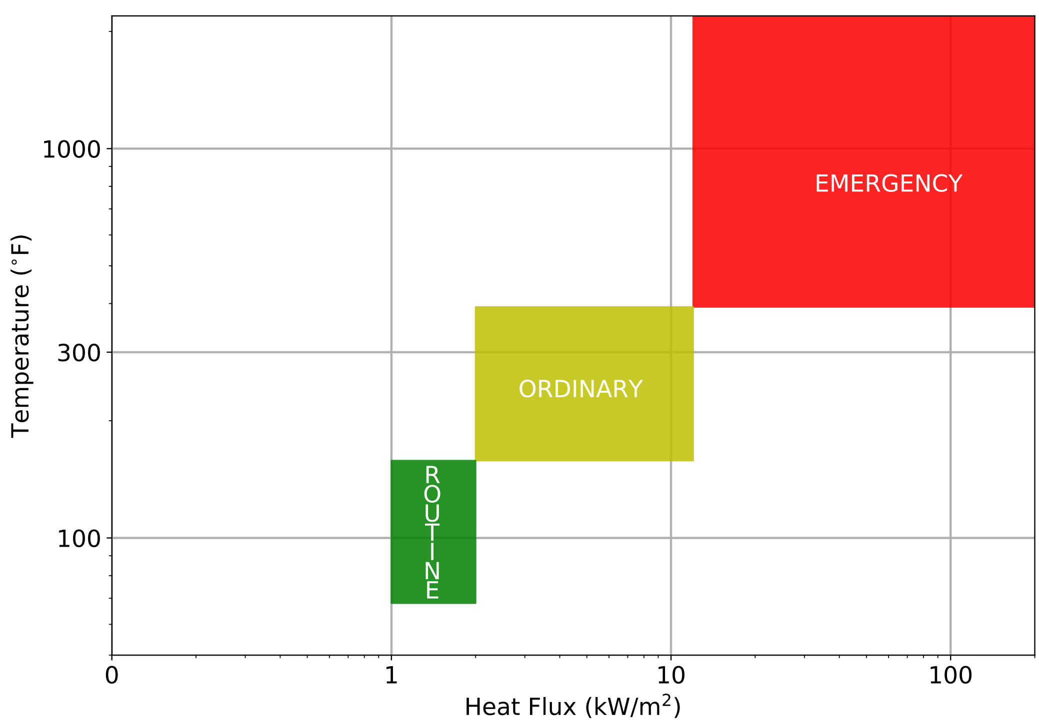
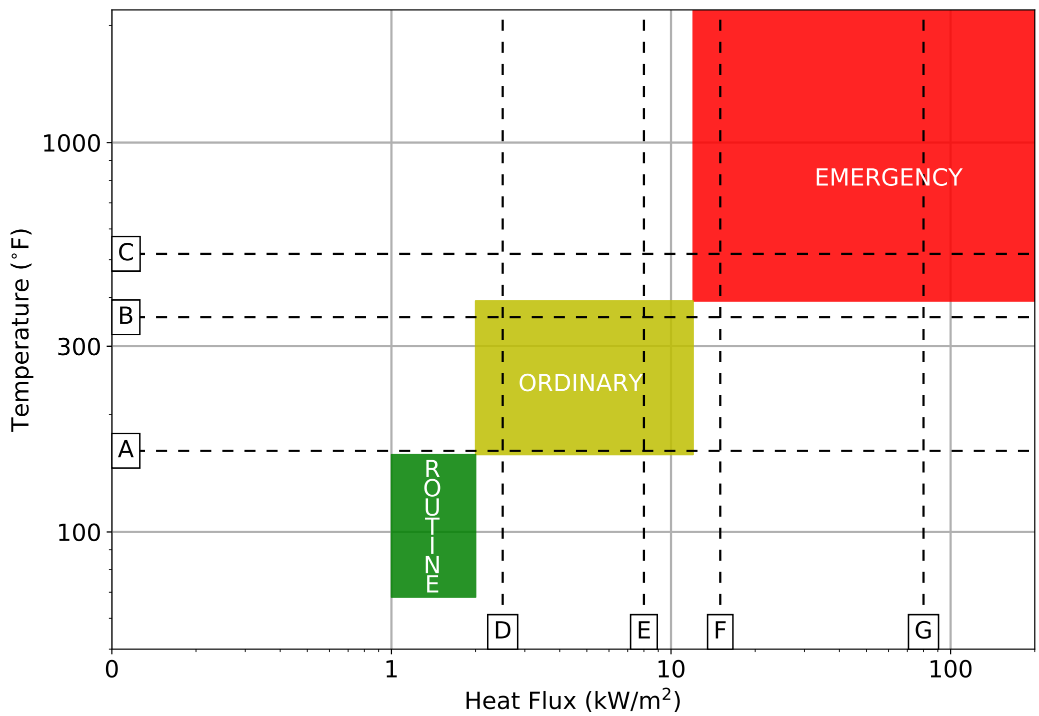


Figure 3.1: Utech's Thermal Exposure Conditions

Rather than representing the threat to electronic equipment, as the NIST thermal classes are intended to do, Utech's thermal operating classes estimate the potential for thermal injury to a firefighter. Utech defined the three operating classes using the results of experiments that had been conducted on contemporary firefighter PPE. The state of the art in firefighter protective equipment has improved significantly since 1973. Modern turnout gear features full encapsulation, with a battery of standard tests which establish minimum performance criteria [32, 33]. Mensch et al. [34] conducted an investigation to quantify the performance of firefighter SCBA facepiece lens under radiant heat flux. The study indicated that the mean temperature of crack formation (180°C) and hole formation (270°C) approximately corresponded to the glass transition temperature and melting point, respectively, of polycarbonate. Further, hole formation was noted at heat fluxes as low as 8 kW/m^2. As the incident heat flux was increased, the time to hole formation decreased. Figure 3.2 shows these benchmarks, as well as the 80 kW/m^2 heat flux that protective ensembles are exposed to during the thermal performance test [32], superimposed on Utech's thermal classes.

Comparison of Figures 3.1 and 3.2 show that the temperature threshold between the ordinary and emergency operating classes approximately is between the temperature that would cause cracking and the temperature that would cause holes to form in SCBA facepieces. Similarly, the threshold between these two operating classes falls between 8 and 15 kW/m^2, which is the range in which hole formation would occur to an SCBA facepiece in several minutes. Thus, the thresholds in Utech's operating classes are representative of thermal conditions which would precipitate the failure of firefighters' PPE. In Utech's chart, there are several areas, such as the areas above and to the right of the ordinary operating class, which do not explicitly fall into any of the three thermal classes. These gaps in the exposure chart are a limitation of Utech's method because, although they do not have a specific hazard classification, such exposures can be hazardous if they exceed the temperature or heat flux criteria presented in Figure 3.2.



A	161.6°F (Temperature at which skin is instantly destroyed [35])
B	356°F (Mean temperature of hole formation in SCBA facepiece lens [34])
C	518°F (Mean temperature of crack formation in SCBA facepiece lens [34])
D	2.5kW/m^2 (Typical firefighter exposure and working environment [36])
E	8 kW/m^2 (Minimum heat flux exposure where lens failure was noted in less than 20 minutes [34])
F	15 kW/m^2 (SCBA facepiece lens failure occurs between 1.5 and 4 minutes [34])
G	80 kW/m^2 (Heat flux which PPE ensemble is exposed to during Thermal Performance Test (TPP) [32])

Figure 3.2: Modern PPE Performance Comparison with Utech Thermal Classes

4 Experimental Configuration

4.1 Test Fixtures

The full-scale fire experiments were conducted in two identical single story ranch structures, constructed in UL's Large Fire Test Facility in Northbrook, IL. The test facility is a 120 ft by 120 ft by 60 ft space with a concrete floor and a movable ceiling. The space is provided with 60,000 CFM of exhaust though a regenerative thermal oxidizer (RTO) system that was running during each test. The make-up air for the system comes from make-up air ducts on the roof of the facility which run down the exterior walls to a grated vent opening at the floor level. Four total vents, one in each corner are balanced to evenly distribute the make-up air without creating air currents in the space.

The test structures were designed to mimic the interior of a 1620 ft^2 ranch home. Figure 4.1 shows the Side A and Side C of the one of the test structures. They were designed by a residential architectural company to be typical of a single-family home constructed in the late-20th century in the United States. The floor plan included 4 bedrooms, a bathroom, a living area, kitchen, and dining room. The bathroom and closet spaces were cordoned off and used as equipment spaces within the structure. Three of the bedrooms were left open during the fire experiments, while one bedroom (Bedroom 3) was left closed, to examine the impact of a closed door on fire behavior. The interior of the house had 8 ft ceilings, and the rooms were separated from each other with walls and doorways. The floor plan of the houses used for these experiments can be seen in Figure 4.2.

Figure 4.1: Exterior photos of test structure in UL's large fire lab. Side 'A' (left) and Side 'C' (right).

The front door of the structure was an insulated metal door typical of a residential building. Windows of the fire rooms (Bedroom 1 & Bedroom 2) were framed plugs with cement board on the interior face. All other windows were hinged pieces of OSB with fiberglass batt insulation on the interior to provide a seal. Window ventilation was intended to be a controlled action; thus windows/plugs were designed to remain in place during fire conditions.

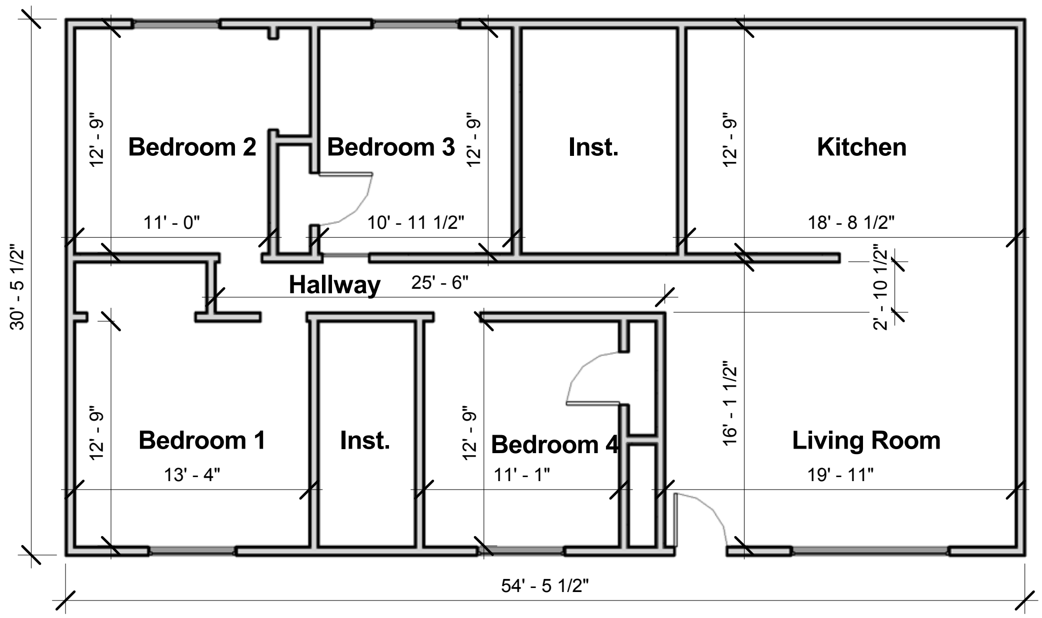


Figure 4.2: Test Structure - Floor Plan

Since the fire experiments were intended to examine room and contents fires, not structure fires, the walls of the fire rooms (Bedroom 1 & 2), and hallway were lined with two layers of gypsum board: a surface layer of 1/2 in lightweight and a base layer of 5/8 in fire resistive board. The remaining interior surfaces in the structure consisted of 1/2 in lightweight board. The exterior walls were covered with cement board to limit exterior fire spread. The kitchen floor was composed of cement board, while the rest of the house was carpeted.

Figure 4.3: Test Structure - Isometric

4.2 Fuel Loads

Fuel loads were selected such that every experiment had the exact same configuration of fuel. The furniture was purchased from a wholesaler of re-purposed furniture, and necessary items such as comforters, polyurethane foam mattress toppers, and pillows were purchased new to ensure the same fuel load for each experiment. Figure 4.4 shows the floor plan of the test fixture with the furniture included in each room. A detailed list of furniture materials and drawings of each room with furniture locations can be found in Appendix B.

Figure 4.4: Test Structure - Furniture Layout

Item	Length (in)	Width (in)	Height (in)	Weight (lbs)
King Mattress	79.0	71.0	10.0	76.0
King Box Spring	78.0	35.0	7.0	46.0
King Headboard	78.0	24.0	1.0	54.0
Pillow	23.5	17.0	4.0	1.5
Comforter	104.0	92.0	1.0	4.6
Mattress Topper 4 in	78.0	75.0	3.9	16.0
Night Stand	18.0	27.0	23.4	60.0
Dresser	22.1	36.0	34.3	120.0
Curtain (Small)	39.0	73.0	0.1	4.5

Table 4.1: Fuel Load Information for Bedrooms 1-4

Bedroom 1

Bedroom 1 was furnished to simulate a typical bedroom in a residential home. The fuel load consisted of a king-sized bed, dresser, TV, nightstand, pillows, 4 in foam mattress topper, 3 stuffed chairs (1 Yellow/Green Chair, 1 Red Lined Chair, and 1 Red Swirl Chair), curtains, carpet, and carpet padding. The orientation of the fuel can be seen in Figure 4.5. The total fuel weight for bedroom 1 was 653.8 pounds. The dimensions and weights of all items can be found in Table 4.1 and Table 4.2.

Figure 4.5: Bedroom 1 Fuel Configuration

Item	Length (in)	Width (in)	Height (in)	Weight (lbs)
Sofa Chair (Yellow/Green)	31.3	31.0	39.0	54.0
Sofa Chair (Red Lines)	34.5	34.0	32.0	63.0
Sofa Chair (Red Swirl)	34.0	34.0	32.0	70.0
Carpet (Room)	13.3	12.8	0.4	47.6
Carpet (Closet)	7.5	2.9	0.4	6.0
Carpet Padding (Room)	13.3	12.8		27.2
Carpet Padding (Closet)	7.5	2.9		3.4

Table 4.2: Bedroom 1 Specific Fuel Load Information

Bedroom 2

Bedroom 2 was furnished to simulate a typical bedroom in a residential home. The fuel load contained 2 stuffed chairs (1 Striped chair and 1 Red Diamond chair), a king-sized bed, dresser, nightstand, pillows, 4 in foam mattress topper, curtains, carpet, and carpet padding. Figure 4.6 shows the fuel load for Bedroom 2. The calculated total fuel weight for Bedroom 2 was 572.3 pounds. The dimensions and weights of all items can be found in Table 4.1 and Table 4.3.

Figure 4.6: Bedroom 2 Fuel Configuration

Item	Length (in)	Width (in)	Height (in)	Weight (lbs)
Sofa Chair (Yellow/Green)	31.3	31.0	39.0	54.0
Sofa Chair (Red Diamond)	35.0	35.0	34.0	69.0
Carpet (Room)	11.0	12.8	0.4	39.3
Carpet (Closet)	6.1	1.9	0.4	3.2
Carpet Padding (Room)	11.0	12.8		22.4
Carpet Padding (Closet)	6.1	1.9		1.8

Table 4.3: Bedroom 2 Specific Fuel Load Information

Bedroom 3

Bedroom 3 contained 1 stuffed chair (Yellow/Green Chair), a king-sized bed, dresser, nightstand, pillows, 4 in foam mattress topper, curtains, carpet, and carpet padding. Figure 4.7 shows the fuel load for Bedroom 3. The calculated total fuel weight for Bedroom 3 was 498.3 pounds. The dimensions and weights of all items can be found in Table 4.1 and Table 4.4.

Figure 4.7: Bedroom 3 Fuel Configuration

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)
Sofa Chair (Yellow/Green)	31.3	31.0	39.0	54.0
Carpet	11.0	12.8	0.4	39.3
Carpet Padding	11.0	12.8		22.4

Table 4.4: Bedroom 3 Specific Fuel Load Information

Bedroom 4

Bedroom 4 contained 1 stuffed chair (Yellow/Green Chair), a king-sized bed, dresser, nightstand, pillows, 4 in foam mattress topper, curtains, carpet, and carpet padding. Figure 4.8 shows the fuel load for Bedroom 4. The calculated total fuel weight for Bedroom 4 was 498.6 pounds. The dimensions and weights of all items can be found in Table 4.1 and Table 4.5.

Figure 4.8: Bedroom 4 Fuel Configuration

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)
Sofa Chair (Yellow/Green)	31.3	31.0	39.0	54.0
Carpet	11.1	12.8	0.4	39.6
Carpet Padding	11.1	12.8		22.6

Table 4.5: Bedroom 4 Specific Fuel Load Information

Kitchen

The kitchen contained a kitchen table and 6 chairs. Figure 4.9 shows the fuel load in the Kitchen. The calculated total fuel weight for the kitchen was 164.6 pounds. The dimensions and weights of all items can be found in Table 4.6.

Figure 4.9: Kitchen Fuel Configuration

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)
Kitchen Table	52.0	26.0	24.5	29.1
Straight Chair (Pink)	18.0	19.0	33.0	15.2
Straight Chair (Blue)	19.0	19.0	38.9	14.9
Carpet	12.8	18.8	0.4	67.1
Carpet Padding	12.8	18.8		38.3

Table 4.6: Kitchen Fuel Load Information

Living Room

The living room contained a bookshelf with shelves lined with a 5 in foam mattress topper, 2 sofas, 1 stuffed chair (Yellow/Green chair) 2 ottomans, a coffee table, end table, lamp, TV, TV stand, large curtains, carpet, and carpet padding. Figure 4.10 shows the fuel load for the Living Room and Table 4.7 shows the itemized object list for the living room. The calculated total fuel weight for Living Room was 607.5 pounds.

Figure 4.10: Living Room Fuel Configuration

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)
Bookcase	11.5	24.6	71.3	46.0
Mattress Topper 5 in	77.5	76.3	4.6	20.1
Sofa	35.0	77.0	30.5	255.0
Sofa Chair (Yellow/Green)	31.3	31.0	39.0	54.0
Ottoman	19.8	25.5	16.0	21.3
Coffee Table	30.0	18.0	18.3	24.4
End Table	24.23	24.3	22.1	32.1
Table Lamp Base	5.8	5.3	31.3	5.9
Table Lame Shade	14.4	14.4		
Curtain (Large)	107.0	73.0	0.1	13.7
Carpet	16.1	19.1	0.4	85.5
Carpet Padding	16.1	19.1		49.5

Table 4.7: Living Room Fuel Load Information

4.2.1 Heat Release Fuel Load Characterization

To characterize the upholstered furniture energy release rates, heat release rate experiments were conducted in a laboratory utilizing oxygen consumption calorimetry. The furniture items were ignited using a electric match. The ignition location changed with differing furniture items. Ignition for the bed was on the side of the mattress using the comforter, while for the chairs and sofa, ignition occurred against the inside of the armrest. For two of the sofa tests, differing ignition locations were examined. For one, the ignition occurred in the middle, low on the inside of the back cushion and for the other, the ignition occurred on the opposite inside armrest. The furniture was permitted to free burn until a smoldering fire was observed. Table 4.8 shows the furniture tested, peak heat release rate, total energy released, and burnout time for each piece of furniture tested.

Furniture	Peak Heat Release Rate (kW)	Total Energy Released (MJ)	Burn duration
Striped Chair 1	1643.4	215	12:59
Striped Chair 2	1855.8	357	22:30
Striped Chair 3	1910.1	458	28:59
Yellow Chair 1	2268.3	195	13:59
Yellow Chair 2	1982.3	227	14:59
Sofa (Left Side Ignition)	2737.4	693	22:60
Sofa (Center Ignition)	4597.3	674	21:59
Sofa (Right Side Ignition)	4946.5	640	18:34
Bed 1	2273.8	939	25:00
Bed 2	1945.4	997	28:59

Table 4.8: Furniture Heat Release Data

The results of the Striped Chair heat release rate characterization experiments are shown in Figure 4.11 along with a photo of the striped chair. The growth of the Striped Chair was very similar between both chairs tested with peak heat release rates occurring within 250 seconds to 500 seconds after ignition. Results for peak heat release rate were within 54.3 kW between minimum and maximum and averaged 1.9 MW. The average total energy released was 408 MJ and varied 101 MJ between minimum and maximum.

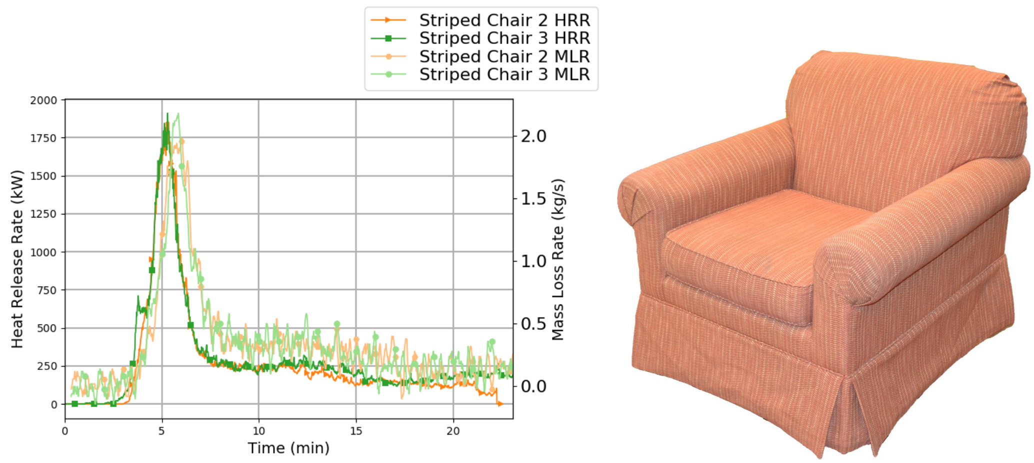


Figure 4.11: Striped Chair Heat Release Rate Characterization Results

The results of the Yellow Chair heat release rate characterization experiments are shown in Figure 4.12 along with a photo of the yellow chair. The growth of the Yellow Chair was very similar for both chairs tested with peak heat release rates occurring within 300 seconds to 400 seconds after ignition. The Yellow Chair 1 grew slightly faster. Results for peak heat release rate were within 286 kW between minimum and maximum and averaged 2.1 MW. The average total energy released was 211 MJ and varied 32 MJ between the minimum and maximum.

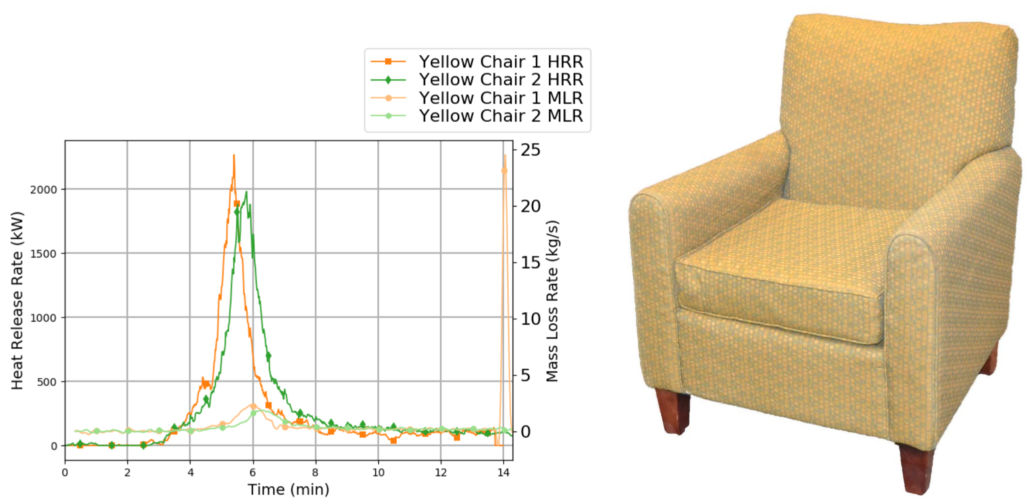


Figure 4.12: Yellow Chair Heat Release Rate Characterization Results

The results of the Sofa heat release rate characterization experiments are shown in Figure 4.13 along with a photo of the sofa. The peak heat release rate occured within 1500 seconds to 2000 seconds after ignition. The peak heat release rate was 1080 kW and the total energy released was 1.2 MJ.

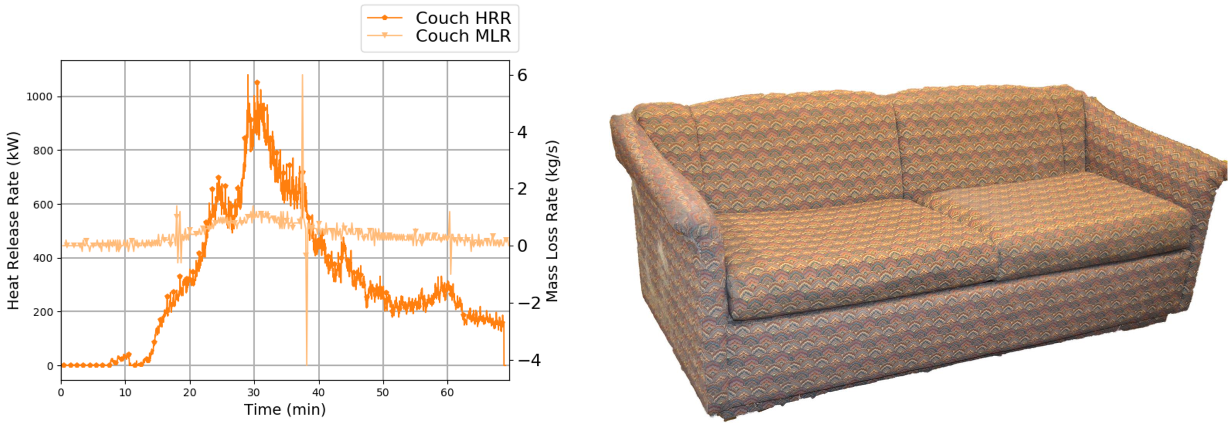


Figure 4.13: Sofa Heat Release Rate Characterization Results

The results of the bed heat release rate characterization experiments are shown in Figure 4.14 along with a photo of the bed. The growth of the beds was very similar for both beds tested with peak heat release rates occurring within 500 seconds to 750 seconds after ignition. Bed 1 grew slightly faster, and reached a higher peak release rate. Results for peak heat release rate were within 328 kW between minimum and maximum and averaged 2.0 MW. The average total energy released was 968 MJ and varied 59 MJ between the minimum and maximum.

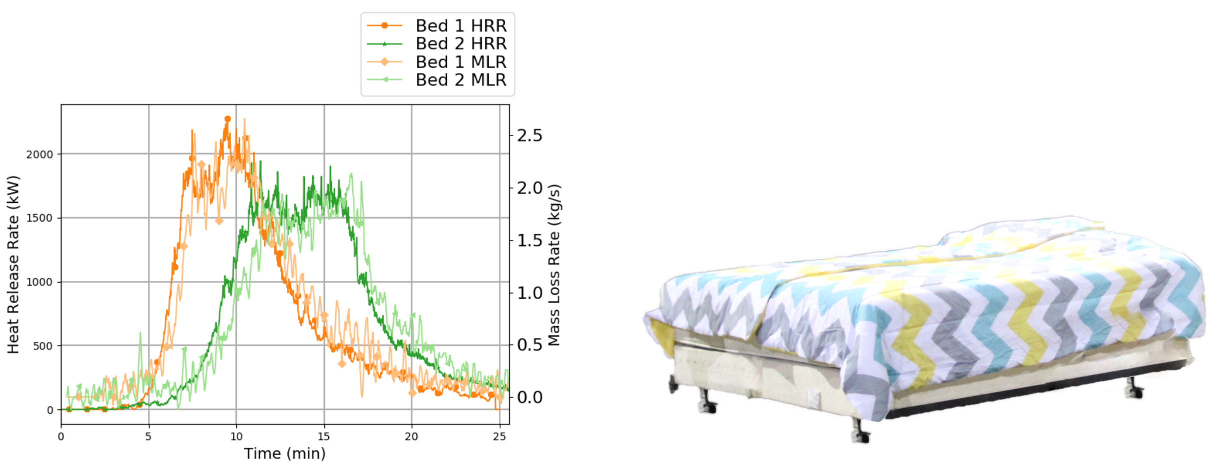


Figure 4.14: Bed Heat Release Rate Characterization Results

4.3 Environment Measurement Instrumentation

Measurements of temperature, heat flux, pressure, and gas velocity were taken at various locations. The same instrumentation was used throughout the duration of the study. The following describes the instrumentation used and uncertainty.

Heat flux measurements were made using a 2.54 cm nominal diameter water-cooled Schmidt-Boelter heat flux gauge (Figure 4.15). The gauges measured the combined radiative and convective heat flux. For these experiments, the dominant form of heat flux is radiative due to the distance of the heat flux gauges from the flames. It should be noted that the convective contribution to the heat flux is dependent upon the surface temperature of the heat flux gauge. The manufacturer gives an uncertainty of ± 3% and results from a study on heat flux calibration found the typical expanded uncertainty to be ± 8% [37].

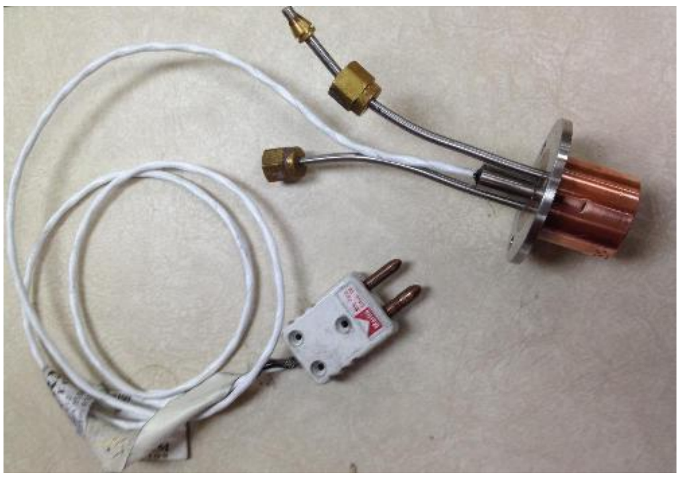


Figure 4.15: Water Cooled Schmidt-Boelter Heat Flux Gauge

Temperatures were recorded using a bare-bead, Chromel-Alumel (Type K) thermocouple with a 0.5 mm nominal diameter (Figure 4.16). The uncertainty given by the manufacturer for the temperature measurements is ± 2.2 °C for temperatures below 293 °C (560 °F) and ± 0.75 % for higher temperatures [38]. The thermocouple readings will be lower than the air temperature when the thermocouple is in the flame region, due to radiative losses to the surrounding cooler environment. When the thermocouples are farther from the flame region, the impact of radiation will result in temperature readings higher than the air temperature. Due to the effect of radiative heat transfer to the thermocouples, the expanded uncertainty is approximately ± 15 %.

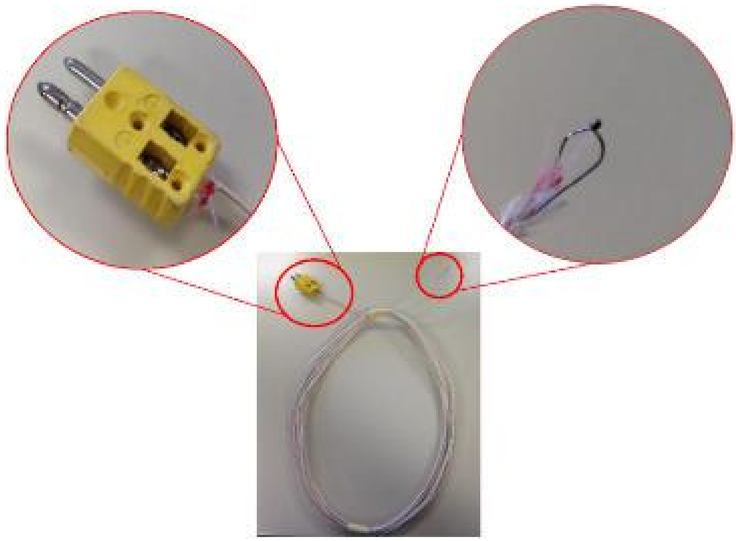


Figure 4.16: Chromel-Alumel (Type K) Thermocouple

To determine the gas velocity, an array of bi-directional probes was utilized in conjunction with differential pressure transducers and inconel thermocouples. The bi-directional probe was constructed of stainless steel and features a 'high' side and a 'low' side which travel back to a pressure transducer that evaluates the differential pressure from ambient pressure. The inconel shielded thermocouples were placed in-line with the bi-directional probes to ensure that the measurements were recorded at the same location. The inconel shielded thermocouple was a 0.063 in diameter type KSL inconel 600 sheathed grounded junction with a type K, 24 gauge glass/glass insulation lead. The differential pressure transducer was a Setra Model 264 with a range of ± 1.0 in WC (± 248.8 Pa). The uncertainty given by the manufacturer is 1 % or 1.2 Pa. The configuration had a velocity range of ± 54 mph (± 24.2 m/s). The pressure transducers were configured in groups of 6, contained in a single plastic box with connections for pressure, temperature and power (Figure 4.17). Five probes were installed in openings where velocity measurements were taken, centered horizontally in the opening (Figure 4.17). Velocity measurement with this configuration was determined to have an estimated expanded uncertainty of ± 18 % [39].

Figure 4.17: Bi-Directional Probe Array. Example of probes in a doorway (left), pressure transducer box (right).

Standard video was obtained through the use of BoschVTC-206F03-4 video cameras (Figure 4.18). Thermal imaging of the front and rear of the structure was taken using Bullard T4X cameras (Figure 4.20). The thermal imaging camera has a fixed emissivity value of 0.9 and was utilized for visual representation of relative conditions. All cameras were recorded Samsung Model SRD-1680 DN digital video recorder set to 24 frames per second with a quality of "high".

Figure 4.18: BoschVTC-206F03-4 video camera

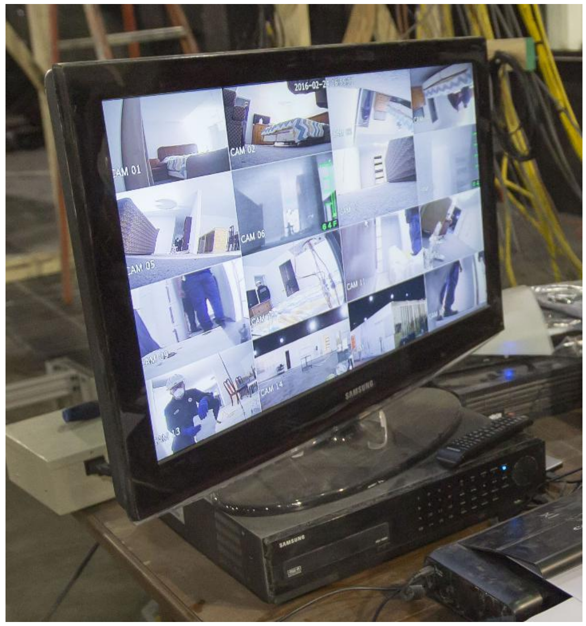


Figure 4.19: Samsung Model SRD-1680 DN Digital Video Recorder with Monitor

Figure 4.20: Bullard T4X Fire Service Thermal Imaging Camera

Gas samples were analyzed through the use of OxyMat6 and UltraMat23 Siemens gas analyzers. Samples were pulled from the structure through the use of Cole Palmer Model L-79200-30 vacuum/pressure diaphragm pump rated at 0.75 CFM via a stainless-steel tube. The sample is filtered through a course filter, Solberg Model 842, 2 micron paper filter before running through a condensing trap to remove moisture. The sample then runs through a drying tube dry fine filter, Perma Pure Model FF-250-SG-2.5G with a 1 micron filter FF-250-E-2.5G before splitting into two branches and entering the UltraMat and OxyMat analyzer. The analyzers are calibrated to measure CO from 0-50000 PPM, CO_2 from 0-20 % and O_2 from 0-25 %.

Figure 4.21: Gas Analyzer Configuration, Gas Sample Point (Top Left), Vacuum Pump - Cole Palmer L-79200-30 (Top Center), Course Filter - Solberg 842 (Top Right), Condensing Tube (Middle Left), Drierite Tube (Middle Center), Fine Filter - Perma Pure FF-250-SG-2.5G (Middle Right), Gas Analyzer Setup (Bottom)

All data was logged through the use of a National Instruments data acquisition system incorporating a SCXI-1001 chassis with 8 SCXI-1102C 32-Channel modules (Figure 4.22). The system is configured for a total of 256 channels capable of reading values between 0-10 volts DC. Values are recorded once a second and translated to quantities of interest through the use of LabVIEW software specifically programmed for use with the system. Data was sampled at 1 hz across all channels.

Figure 4.22: Data Acquisition System

At the University of Illinois, Professor Tonghun Lee's research lab has advanced multiple laser-based measurement techniques to quantify production of gases during internal combustion engine operation that have potential to be adapted to the sooty, dynamic live-fire environment. While there are many techniques to measure moisture, most are not applicable to the situation of high temperature moisture measurements in a combustion environment. Absorption spectrometry is capable of measuring moisture content in harsh, high temperature environments. Water has several absorption bands in the near-infrared range, which allows the use of several classes of laser-based systems to measure the moisture content. With proper thermal and optical control of the laser source and sample train this technique is operable at temperature exceeding 1832 °F (1000 °C), can operate in and compensate for sooty and smoky environments, and has a very rapid response time on the order of seconds. Such approaches have been utilized to perform in-situ analysis from controlled combustion and process exhaust systems. The method used for these experiments was a Tunable near-infrared diode laser to measure the water absorption peak near 1392 nm. Figure 4.23 shows the setup used in the experiments.

Figure 4.23: Near-Infrared Diode Laser System

4.4 Victim Package Instrumentation

4.4.1 Background

Occupants trapped within a structure face the risk of thermal burn injuries, particularly with unprotected skin. Suppression activities by the fire service can reduce this hazard by removing the heat source producing potentially dangerous conditions; however, the additional risks encountered by the conversion of water to steam must be studied. The risk for moisture-related skin burns is likewise present for firefighters applying water to burning materials from inside the structure. While firefighting PPE provides a significant measure of protection, burn injuries are still a significant hazard during interior firefighting operations.

The dangers of thermal injury from exposure to heat and products of combustion and time-temperature characteristics required for skin burns has been researched for several years. Typical studies involve exposing skin to a controlled thermal exposure ti determine the time to an outcome, such as dermal or epidermal temperature changes (typically time to reach 113 °F (44.8 °C) or visual indications of damage. The synergistic effect of elevated temperature and moisture content on increasing risk for skin burns is conceptually understood to be due to the large latent heat and partial pressure of water at temperatures above 160 °F (60 °C). However, the effect of suppression tactics and the rapidly-changing, transient nature of exposure during this time frame (ambient temperatures reducing while the moisture content is increasing) on risk for skin burns has not been measured in response to realistic fire suppression experiments.

An important objective of the study is to better understand the influence of water application to a room and contents fire on trapped occupant exposure - particularly with respect to changing the risk for steam burns. Traditionally, thermal risk is estimated through a combination of thermocouples to measure air temperature and heat flux gages to estimate thermal energy available to increase temperature of the skin surface. These measurements are used to calculate a fractional effective does (FED) representitive of tenibility. However, there are some important limitations to this these techniques and assumptions must be made. The impact of rapidly changing moisture conditions and the interaction of skin with radiation can have significant impact on the results. In order to more accurately measure the impact of typical live-fire environment on human skin, an ex vivo porcine skin model was developed as a means of estimating the human skin exposure. Porcine skin has often been used as a surrogate for human skin in scientific study [40–42], due to the number of similarities between pig skin and human. Utilizing this approach along with traditional fire estimation methods will hopefully provide new understanding of risks for trapped occupants and possibly provide a pathway for calibration of the existing tools to better estimate this risk.

Human skin is the largest organ in the human body, providing important protective and heat transfer biological functions. The skin is comprised of several important components that are typically grouped in three distinct layers. The epidermis is the outer layer of skin, comprised of dead cells and acts as the protective barrier to harmful environmental conditions such as moisture, ultraviolet radiation, and extreme heat [43]. Only part of the epidermis is affected in first degree burns and the dead cells flake off following the burn [43,44]. The human epidermis fluctuates based on body site and has been measured using ultrasonography to vary from less than 0.002 in (40 μm) on the cheek and portions of the truck to over 0.014 in (350 μm) on the fingertip [45]. Typical ranges in thickness from 0.002 in (50 μm) to 0.005 in (120 μm) are reported [46].

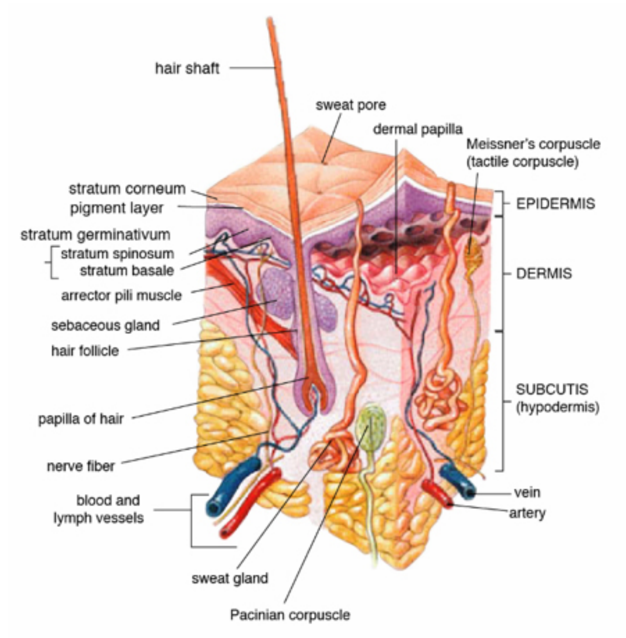


Figure 4.24: Cross Section of Human Skin [43]

The dermis is the second layer of skin which contains important living tissues such as blood vessels and nerve endings [43]. A second-degree burn occurs when the damage reaches the dermis layer, completely destroying the epidermis [43]. Blisters can form in the area between the basal layer of the epidermis and dermis [44]. Like the epidermis, the human dermis fluctuates in thickness from less than 0.04 in (1000 μm) to 0.16 in (4000 μm) based on the area of the body [47,48].

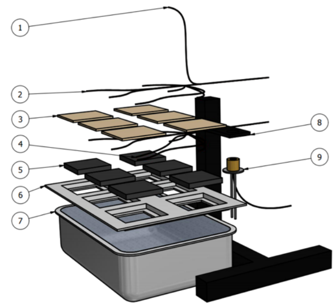
When at least 75% of the dermis has been destroyed and the burn extends to the subcutaneous layer, full necrosis has occurred resulting in a third-degree burn [44]. The subcutaneous layer is the deepest layer of skin and is comprised of fat and connective tissue [43].

Domestic pigs are have been used for decades as surrogates for humans in experiments. The skin of a domestic pig is one feature that is similar to humans in many aspects such as thickness, structure, and composition [49]. Pig skin and human skin both have similar proteins, a sparse hair coat, a thick epidermis, a dermis with a papillary body, a deep layer of subcutaneous fat, and a large content of elastic tissue [41]. Normal pig skin varies by body site just as human skin does. The pig epidermis is described as ranging in thickness from 0.003 in (70 μm) to 0.006 in (140 μm) compared to the human epidermis range [40]. Due to the range of skin thickness throughout the body, a dermal-epidermal ratio ranging from 10:1 to 13:1 proves to be a better measure of thickness and is again, comparable in both pig and human skin [46]. It has been suggested that the structure of the pig's skin is so similar to that of a human skin, that it may be a more superior model than that of nonhuman primate skin [42]. However, there are important differences such as a lower water loss from pig skin at elevated temperatures and lack of blister formation that must be considered when using this model.

Moritz and Henriques conducted a series of experiments with both humans and pigs, such as creating contact burns at different temperatures and durations of time [49]. Their study demonstrated irreversible damage will occur to the epidermis when the surface of skin reaches 111 °F (44 °C), although it can take long periods of exposure. Below this temperature, the rate of recovery exceeds the rate of damage due to burning [50]. The time required to create irreversible damage is reduced by about half with every degree increase between 111 °F (44 °C) and 131 °F (55 °C) [50]. Third degree burns can occur within one second of exposure once the skin reaches temperatures ranging from 135 °F (57 °C) to 145 ° (63 °CF) [50]. Stoll and Green continued the work of Moritz and Henriques and discovered that the destruction of the skin does not only begin when the surface rises above 111 °F (44 °C), but continues as long as the temperature of the layer remains at 111 °F (44 °C) or higher [51]. This means that the cooling phase also needs to be included in predicting methods [52]. Stoll et al. found that destruction rate can be modeled by the following first order chemical reaction rate equation. With the use of this approach, burn injury becomes a function of the time and temperature when the skin exceeds 111 °F (44 °C).

4.4.2 Victim Instrumentation Packages

A new method for estimating skin burn risk based on ex vivo samples of porcine (pig) skin has been developed. Figure 4.25 shows the design and instrumentation of the victim package experimental setup. The victim package provides a transportable system for exposing skin samples to live-fire conditions in relatively repeatable conditions. Up to 6 excised porcine skin samples (surrogate for human epidermal and dermal layers) are introduced on top of 10 mm (0.4 in) thick neoprene rubber slab (surrogate for subcutaneous fat), which sit on top of a basin holding water at 98-100 °F (36.7 to 37.8 °C) (simulate the core of the body). Each exposed skin sample had an exposed surface area of 4 in x 4 in (10 cm x 10 cm) to improve the applicability of a one-dimensional heat transfer scenario (through the skin as opposed to across the skin). Neoprene was used for subcutaneous fat as it has similar thermal and mechanical properties as well as providing a uniform thickness. The thickness of the neoprene was used to simulate the thickest layers of subcutaneous fat. Strips of insulation were used to cover the exposed aluminum on the top of the plate and insulation was wrapped around the basin to help maintain the water bath temperature at human core body temperature.



Victim Package Components		
ITEM	QTY	DESCRIPTION
1	1	Air Thermocouple
2	2	Thermocouple Bundle
3	5	Skin
4	1	Water Thermocouple
5	5	Neoprene
6	1	Support Tray
7	1	Reservoir
8	1	Heat Flux Mount
9	1	Heat Flux Gauge

Figure 4.25: Exploded CAD view of Victim Instrumentation Package

Type K thermocouples were attached to the surface of the neoprene layer to measure sub-dermal temperature using cyanoacrylate glue. Furthermore, an identical thermocouple was placed in the center on the surface of the skin sample after it was deployed. Additionally, thermocouples were also used to measure the temperature of the air surrounding the victim packages and to measure the temperature of the water bath during the test to ensure core body temperature was closely maintained. Vertically oriented heat flux gages were deployed at each location to measure the thermal energy reaching the skin samples. As part of the instrumentation package, local measurements of gas concentration (O_2, CO_2, CO) were also measured at each of these locations.

Figure 4.26: Victim Instrumentation Package Installed

Sample Preparation and Victim Instrumentation Package Deployment

Porcine skin samples were collected from research animals at the University of Illinois after they were euthanized for purposes other than this project. The epidermal/dermal layer was removed immediately from the carcass. After transportation to the lab, subcutaneous fat was removed and the hair was shaved from the top layer of the skin using a razor. The sample was then placed in a plastic bag and stored in a freezer until the live-fire scenarios were to be conducted. Before being deployed into an experiment, the skin was thawed in the plastic bags using a water bath held at 98.6 °F (37 °C) one hour before the experiment began. After the sample was fully thawed, the skin was removed from the bag and its thickness was measured. The average porcine skin thickness in these victim packages was 0.14 in ±0.028 in (3.66 ±0.72 mm).

The samples were then deployed to their locations and attached to the neoprene blocks using cyanoacrylate glue and surface thermocouples were similarly deployed. Damp towels were placed over the specimens to ensure they did not dry out prior to testing and heater and pumps were used to control the water bath temperature. Five minutes before the experiment began, the damp towels were removed and the structure was properly closed off. The temperature of the skin prior to the start of the experiment was typically between 82-92 °F (27.8-33.2 °C) which is representative of human skin temperatures, depending on the area of the body.

For these scenarios, victim packages were deployed to 5 different locations throughout the structure (Figure 4.28. Locations 1, 4, and 5 were placed on the floor, while 2 and 3 were on top of a bed. The top of the bed was 2.2 ft (0.7 m) above the floor. The bedroom door at the entrance to location 2 was closed throughout each scenario.

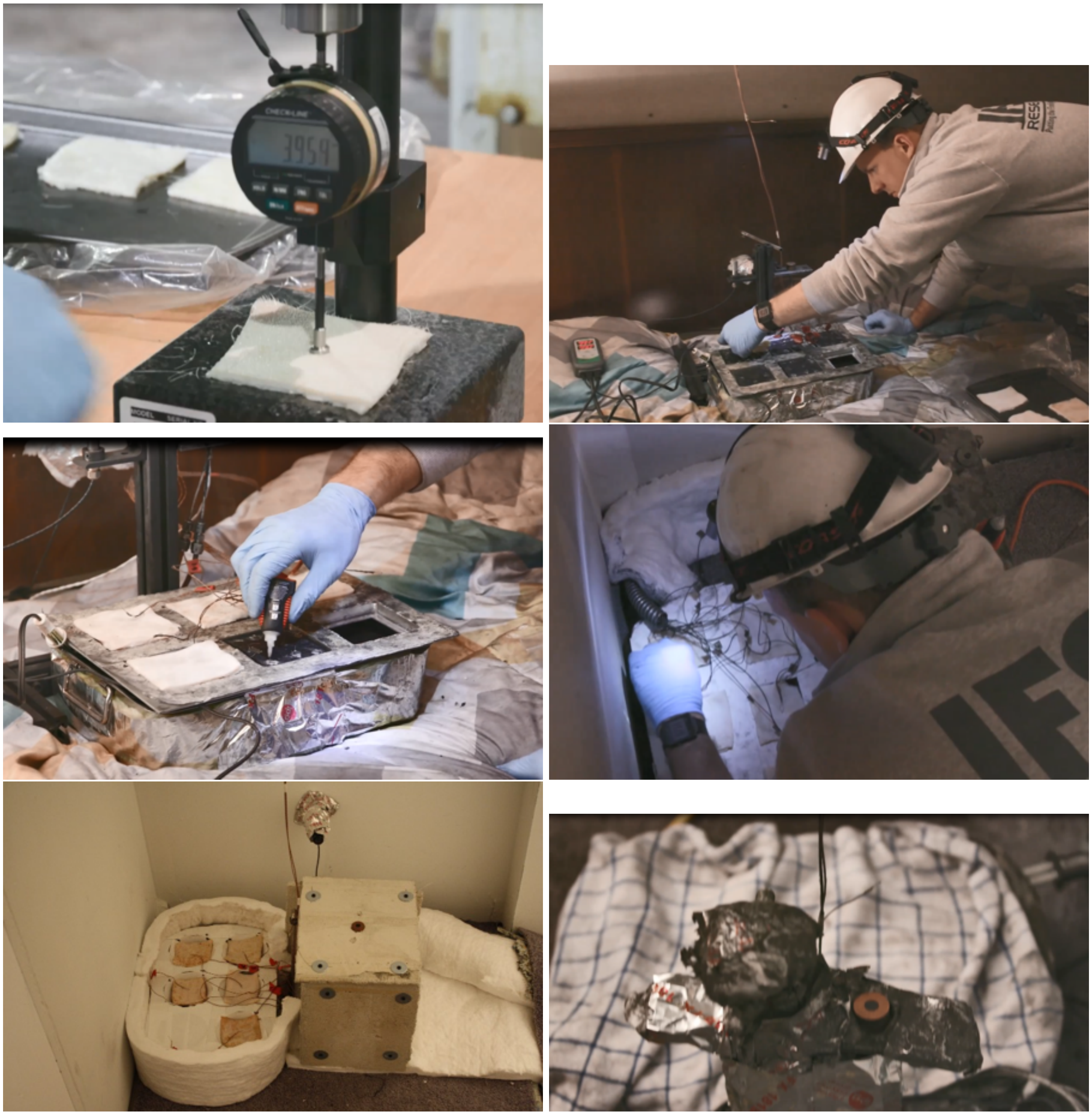


Figure 4.27: Sample prep including thickness measurement, sub-dermal thermocouple attachment (note heating element and circulation pump on left to maintain core “temperature”), gluing skin samples to subcutaneous fat surrogate, surface TC attachment, final victim package (location #1) and damp towel placement that is removed immediately prior to ignition.

4.5 Measurement Locations

In order to collect the data needed for this analysis, sensors were installed and measurements were recorded throughout each structure. Figure 4.28 shows the location and numbering scheme for the instruments utilized. Figure 4.29 shows the location for the instruments utilized in the victim analysis.

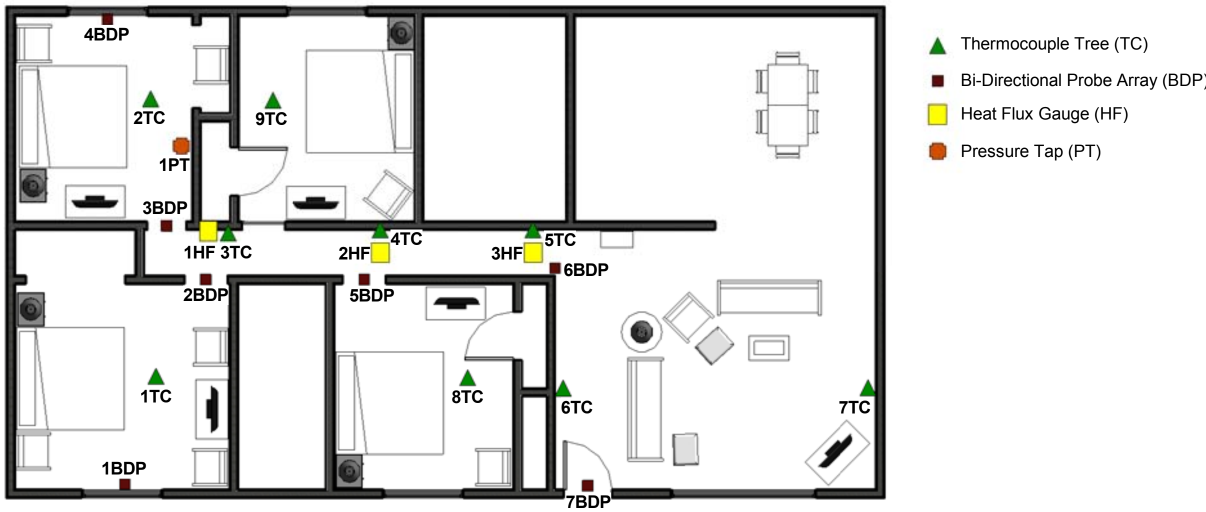


Figure 4.28: Instrumentation Plan

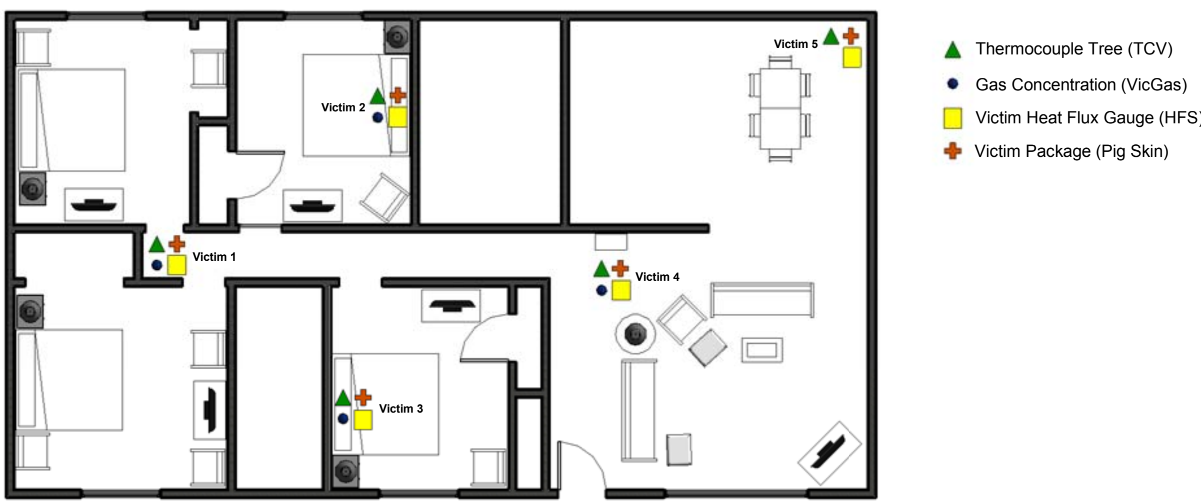


Figure 4.29: Victim Instrumentation Plan

Cameras were located throughout the structure to provide visual data. Figure 4.30 shows the location and type of cameras utilized in the experiments.

Camera Plan		
No.	Discription	Type
1	Bedroom 1	Bullet
2	Bedroom 2	Bullet
3	Bedroom 3	Bullet
4	Bedroom 4	Bullet
5	Hallway	Bullet
6	Hallway IR	Bullard IR
7	Front Door	Bullet
8	Front Door IR	Bullard IR
9	Victim 1	Bullet
10	Victim 2	Bullet
11	Victim 3	Bullet
12	Victim 4	Bullet
13	Victim 5	Bullet
14	Exterior A/D	Sony
15	Exterior B/C	Sony
16	Mid Hall	Bullet

Figure 4.30: Camera Plan

4.6 Equipment Utilized

In order to limit the number of variables, two nozzles were selected for use during the full-scale experiments. Part I [1] and Part II [2] of this project highlighted that no statistically-significant difference exists between manufacturers in terms of air entrainment and rated flow for a given nozzle type and stream configuration. To most closely match the flow and pressure of a single smooth bore nozzle with a single combination nozzle the nozzles listed Table 4.9 were selected.

Table 4.9: Full Scale Structure Fire Nozzle Selection

Nozzle	Tip (in)	Nozzle Pressure (psi)	Approximate Flow Rate (gpm)
Smooth Bore	7/8	50	160
Combination	N/A	75	150

The nozzles were connected to 200 ft of 1 3/4 in hoseline. Pressure was set utilizing a in-line water-filled pressure gauge just behind the nozzle. Real-time flow was measured with a 3 in electromagnetic flow meter, connected prior to the 200 ft of hoseline.

For the Gas Cooling Experiments an adjustable gallonage combination nozzle was utilized at the flow rates listed in Table 4.10.

Table 4.10: Gas Cooling Nozzle Selection

Nozzle	Approximate Flow Rate (gpm)
Combination	95
Combination	150

4.7 Suppression Methods Utilized

The method of approaching a residential fire varies greatly depending on shift, department, state and region. It was not possible to test all the variations, so the project technical panel was polled and the methods used by their representative department/shifts were analyzed and grouped into three major methods. The three methods utilized were titled 'Shutdown & Move Advancement', 'Flow & Move Advancement' and 'Transitional Attack'. Where experiments permitted slight variations, those variations were incorporated to understand their impact on the overall suppression tactic. It is important to note, these methods do not necessarily represent the optimum tactic, merely the method utilized during the experiments.

The need to read the neurtral plane and conditions at the door was developed based on research on horizontal ventilaiton studies by Kerber in 2010 [13]. It was shown that when an opening was made in the compartment the fire was in, the fire did not respond instantaniously. It took several seconds before oxygen made it to the fire and began to change the conditions. The approximetly 10 seconds to read the door conditions was implemented to allow the suppression crew to ensure they were not entering the compartment where the fire was located, which because of the ventilation limited could grow rapidly and cause injury.

4.7.1 Flow & Move Advancement

The 'Flow & Move Advancement' incorporated moving the hoseline (advancing) while flowing water. This was not employed until the crew was in position at the start of the hallway, moving towards the fire compartment at the end of the hall. The method was conducted utilizing the following steps in order:

- Front door open.
- Read neutral plane and conditions at entry door (10 seconds).
- Suppression crew enters to a position approximately 3 ft inside the door.
- Burst Suppression - "Check for Return", crew flows a short burst of water at the ceiling.
- Suppression crew advances to the start of the hallway.
- Flow down hallway from close to far in a 'wall-ceiling-wall' pattern while advancing until arriving at the fire compartment.
- Without shutting down the line, suppression crew applied water to the fire compartment.
- Once fire was 'under control' the crew paused 1 minute to evaluate conditions.
- Suppression crew entered the fire compartment for final suppression.

- All windows were opened for ventilation

This tactic involved variation in the nozzle type (smooth bore, combination straight stream, combination fog) and the use of burst suppression between experiments to evaluate the impact.

4.7.2 Shutdown & Move Advancement

The ‘Shutdown & Move Advancement’ incorporated the same method as the ‘Flow & Move Advancement’ with the exception that the suppression crew was not moving the hoseline (advancing) while flowing water. The method was conducted utilizing the following steps in order:

- Front door open.
- Read neutral plane and conditions at entry door (10 seconds).
- Suppression crew enters to a position approximately 3 ft inside the door.
- Burst Suppression - “Check for Return”, crew flows a short burst of water at the ceiling.
- Suppression crew advances to the start of the hallway.
- Flow from fixed position (5-10 seconds) from close to far in a ‘wall-ceiling-wall’ pattern.
- Advance to a position halfway down the hall.
- Flow from fixed position (5-10 seconds) from close to far in a ‘wall-ceiling-wall’ pattern.
- Advance to the fire compartment and apply water into the compartment.
- Once fire was ‘under control’, visible flames or audible signs of combustion were absent, pause 1 minute to evaluate effectiveness of tactic.
- Suppression crew entered the fire compartment for final suppression.
- All windows were opened for ventilation

This method involved variation in the nozzle type (smooth bore, combination straight stream, combination fog) and the use of burst suppression between experiments to evaluate the impact.

4.7.3 Transitional Attack

The transitional attack involved an initial exterior water application followed by interior suppression. The method was conducted utilizing the following steps in order:

- Exterior water application into the fire compartment.
- Approach compartment and wet surfaces (Not during all experiments)
- Reposition hoseline to front door while evaluating conditions at the door.
- Front door open.
- Suppression crew enters, flows water to cool as they approach, if necessary.
- Apply water to the fire compartment, if necessary
- Once fire was 'under control' pause 1 minute to evaluate effectiveness of tactic.
- Suppression crew entered the fire compartment for final suppression.
- All windows were opened for ventilation

This method involved variation in the nozzle type (smooth bore, combination straight stream, combination fog), if a secondary exterior application was conducted (second room of fire), flow on the advancement down the hallway, front door open prior to or after initial application of water, and need for application of water into the fire compartment from the interior.

5 Full-Scale Residential Fire Experiments

In order to examine different fire attack techniques, twenty-five experiments were conducted in the full-scale residential structure described in Chapter 4. Experiments 1–17 were focused on studying interior fire attack methods, and the remaining eight experiments were focused on studying transitional fire attack methods. Three different ventilation configurations were used throughout all twenty-five experiments: ‘No Vent’, ‘Single Vent’, and ‘Two Vent’. These configurations along with the details of each individual experiment are described in the following sections and Table 5.1.

Fire suppression intervention times were based on conditions within the fire compartment(s) to ensure repeatable conditions and comparability of experiments. For experiments where no ventilation was provided, the point at which the fire became ventilation-limited and temperatures began to decrease was the point where intervention began. For experiments where the window was open prior to ignition, the point at which the fire reached a steady, ventilation-limited state was the time intervention began.

Table 5.1: Summary of Experiments

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
1	Interior	Delayed water application with combination; Shutdown & Move; Straight Stream			Flow path between front door & BR1 fire
2	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path between front door & BR1 fire
3	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path between front door & BR1 fire w/ door control
4	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path between front door & BR1 fire w/ coordinated horizontal vent
5	Interior	Combination	Shutdown & Move	Straight Stream, near to far along hall centerline	Flow path between front door & BR1 fire
6	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path between front door & BR1 fire
7	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
8	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
9	Interior	Combination	Flow & Move	Straight Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
10	Interior	Combination	Shutdown & Move	Straight Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
11	Interior	Combination	Flow & Move	Narrow Fog	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
12	Interior	Delayed water application w/ Combination; Flow & Move; Straight Stream			Flow paths between front door & BR1 fire; BR1 fire & BR1 window
13	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window
14	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window
15	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window w/ door control
16	Interior	Combination	Flow & Move	Narrow Fog	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window
17	Interior	Delayed water application w/ Combination; Flow & Move; Straight Stream			Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window
18	Transitional	Smooth Bore	Steep angle	Solid stream	Flow path between BR1 fire & BR1 window
19	Transitional	Combination	Occlude opening, rebuild, steep angle, fog content suppression	Narrow fog, rebuild, straight stream to content suppression	Flow path between BR1 fire & BR1 window
20	Transitional	Smooth bore	Steep angle to half bale content suppression	Solid stream to half bale content suppression	Flow path between BR1 fire & BR1 window
21	Transitional	Smooth bore	Steep angle to half bale content suppression	Solid stream to half bale content suppression	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
26	Transitional	Combination	Steep angle sweep	Straight stream	Flow paths between front door & BR4 fire; BR4 fire & BR4 window
22	Transitional	Smooth bore	Steep angle to half bale content suppression	Solid stream to half bale content suppression	Flow path between BR1 fire & BR1 window; flow path between BR2 fire & BR2 window
23	Transitional	Combination	Occlude opening	Narrow fog	Flow path between BR1 fire & BR1 window; flow path between BR2 fire & BR2 window
24	Transitional	Combination	Steep angle to half fog content suppression	Straight stream to fog content suppression	Flow path between BR1 fire & BR1 window; flow path between BR2 fire & BR2 window

5.1 Interior

5.1.1 Single Room — No Vent

During Experiments 1–6, an interior attack method was performed to extinguish a fire in the 'No Vent' configuration. This configuration, presented in Figure 5.1, consisted of a fire in Bedroom 1 with all vent openings initially closed. Specific details about the ventilation patterns and the type of interior fire attack method used during Experiments 1–6 are listed in Table 5.2. Following the table, a brief description of each experiment is provided along with a table of interventions and times at which they were performed during the experiment.

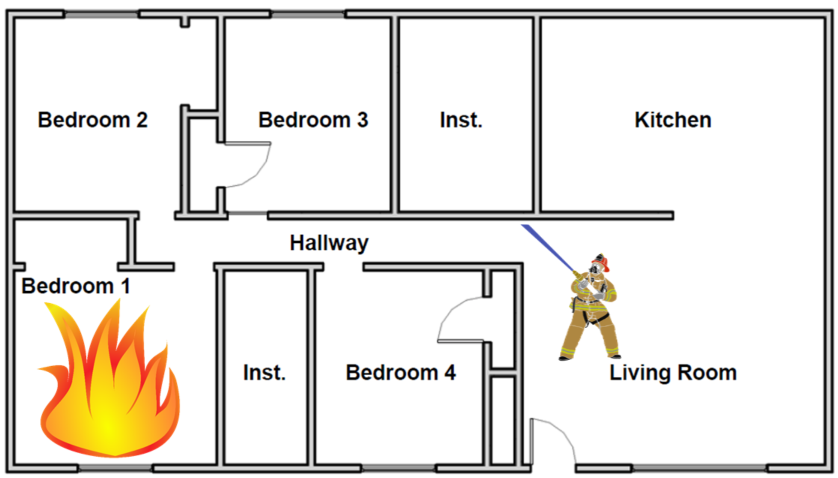


Figure 5.1: 'No Vent' configuration used during Experiments 1–6.

Table 5.2: Summary of Experiments 1–6

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
1	Interior	Delayed water application with combination; Shutdown & Move; Straight Stream			Flow path between front door & BR1 fire
2	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path between front door & BR1 fire
3	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path between front door & BR1 fire w/ door control
4	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path between front door & BR1 fire w/ coordinated horizontal vent
5	Interior	Combination	Shutdown & Move	Straight Stream, near to far along hall centerline	Flow path between front door & BR1 fire
6	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path between front door & BR1 fire

Experiment 1

Experiment 1 looked at the fire dynamics in a typical single-story structure with delayed water application. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and allowed to develop until it became ventilation-limited. Then, the front door was opened to simulate fire department arrival. The open door established a flow path between itself and Bedroom 1. Once the fire reached steady-state, suppression was performed via an interior attack through the front door with a combination nozzle on straight stream. The nozzle was shutdown as the hoseline advanced. Figure 5.1 shows the configuration of the structure and Table 5.3 shows at what times interventions were performed. The results of Experiment 1 can be found in Appendix E.1.

To view the full experiment video Click Here.

Table 5.3: Experiment 1 Interventions

Time	Intervention
00:00	Ignition — Bedroom 1
08:17	Front Door Open
26:47	Suppression Crew Enters
26:54	Hallway Suppression
27:22	Fire Under Control
30:22	Structure Ventilated
32:08	End Experiment

Experiment 2

Experiment 2 looked at the fire dynamics in a single-story structure when suppression is conducted with a smooth bore nozzle, flowing while moving. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and allowed to develop until it reached steady state. Then, the front door was opened to simulate fire department arrival. The open door established a flow path between itself and Bedroom 1. An interior fire attack was initiated through the front door with a solid stream from a smooth bore nozzle. The nozzle continued to flow as the hoseline advanced. Figure 5.1 shows the configuration of the structure and Table 5.4 shows at what times interventions were performed. The results of Experiment 2 can be found in Appendix E.2.

To view the full experiment video Click Here.

Table 5.4: Experiment 2 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
07:05	Front Door Open
07:18	Suppression Crew Enters
07:23	Burst Suppression
07:36	Hallway Suppression
08:13	Fire Under Control
11:36	Structure Ventilated
18:02	End Experiment

Experiment 3

Experiment 3 looked at the fire dynamics in a single-story structure when suppression is conducted with a solid stream and the front door controlled immediately following entry. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and allowed to develop until it became ventilation-limited. Then, the front door was opened to simulate fire department arrival. The open door established a flow path between itself and Bedroom 1. An interior fire attack was initiated through the front door with a solid stream from a smooth bore nozzle. After the suppression crew entered, the door was closed to the width of the hoseline in an effort to limit the amount of fresh air supplied to the fire (Door Control). The nozzle was shut down as the hoseline advanced. Figure 5.1 shows the configuration of the structure and Table 5.5 shows at what times interventions were performed. The results of Experiment 3 can be found in Appendix E.3.

To view the full experiment video Click Here.

Table 5.5: Experiment 3 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
08:26	Front Door Open
08:28	Suppression Crew Enters
08:32	Burst Suppression
08:45	Hallway Suppression
09:32	Fire Under Control
12:36	Structure Ventilated
19:09	End Experiment

Experiment 4

Experiment 4 looked at the fire dynamics in a single-story structure when suppression is conducted with a smooth bore nozzle, with tactical ventilation performed in front of the advancing suppression crew. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and allowed to develop until it became ventilation-limited. Then, the front door was opened to simulate fire department arrival. The open door established a flow path between itself and Bedroom 1. An interior fire attack was initiated through the front door with a solid stream from a smooth bore nozzle. The nozzle continued to flow as the hoseline advanced, and suppression was coordinated with horizontal ventilation of the Bedroom 1 window. Figure 5.1 shows the configuration of the structure and Table 5.6 shows at what times interventions were performed. The results of Experiment 4 can be found in Appendix E.4.

To view the full experiment video Click Here.

Table 5.6: Experiment 4 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
08:25	Front Door Open
08:38	Suppression Crew Enters
08:43	Burst Suppression
08:43	Bedroom 1 Window Open
08:54	Hallway Suppression
09:29	Fire Under Control
12:40	Structure Ventilated
15:23	End Experiment

Experiment 5

Experiment 5 looked at the fire dynamics in a single-story structure when suppression is conducted with a straight stream from a combination nozzle. The fire was ignited in the Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and allowed to develop until it became ventilation-limited. Then, the front door was opened to simulate fire department arrival. The open door established a flow path between itself and Bedroom 1. An interior fire attack was initiated through the front door with a straight stream from a combination nozzle. The nozzle was directed from near to far along the centerline of the hallway ceiling. Suppression occured from the start of the hallway. The crew then advanced directly to the fire room to complete suppression. Figure 5.1 shows the configuration of the structure and Table 5.7 shows at what times interventions were performed. The results of Experiment 5 can be found in Appendix E.5.

To view the full experiment video Click Here.

Table 5.7: Experiment 5 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
06:57	Front Door Open
07:09	Suppression Crew Enters
07:16	Burst Suppression
07:27	Hallway Suppression
08:07	Fire Under Control
10:42	Structure Ventilated
17:54	End Experiment

Experiment 6

Experiment 6 looked at the fire dynamics in a single-story structure when suppression is conducted with a solid stream from a smooth bore nozzle. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and allowed to develop until it became ventilation limited. The front door was opened to simulate fire department arrival. The open door established a flow path between itself and Bedroom 1. An interior fire attack was initiated through the front door with a solid stream from a smooth bore nozzle. The nozzle was shut down as the hoseline advanced. Figure 5.1 shows the configuration of the structure and Table 5.8 shows at what times interventions were performed. The results of Experiment 6 can be found in Appendix E.6.

To view the full experiment video Click Here.

Table 5.8: Experiment 6 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
07:58	Front Door Open
08:13	Suppression Crew Enters
08:18	Burst Suppression
08:27	Hallway Suppression
09:00	Bedroom 1 Window Failure (Uncoordinated)
09:07	Fire Under Control
12:34	Structure Ventilated
14:38	End Experiment

5.1.2 Single Room — Single Vent

During Experiments 7–12, an interior suppression tactic was performed to extinguish a fire in the 'Single Vent' configuration. This configuration, presented in Figure 5.2, consisted of a fire in Bedroom 1 with the Bedroom 1 window open and all other vents initially closed. Specific details about the ventilation patterns and the type of interior fire attack method used during Experiments 7–12 are listed in Table 5.9. Following the table, a brief description of each experiment is provided along with a table of interventions and times at which they were performed during the experiment.

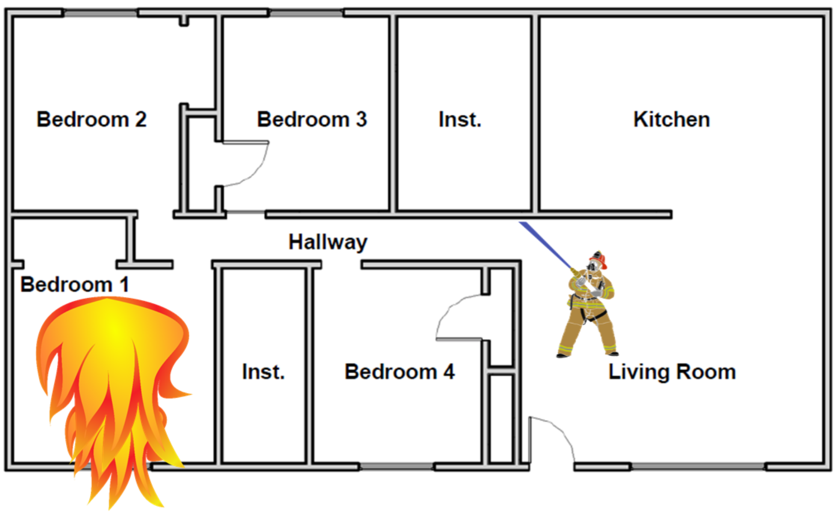


Figure 5.2: Configurations for Experiments 7 to 12

Table 5.9: Experiments 7 through 12

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
7	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
8	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
9	Interior	Combination	Flow & Move	Straight Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
10	Interior	Combination	Shutdown & Move	Straight Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
11	Interior	Combination	Flow & Move	Narrow Fog	Flow paths between front door & BR1 fire; BR1 fire & BR1 window
12	Interior	Delayed water application w/ Combination; Flow & Move; Straight Stream			Flow paths between front door & BR1 fire; BR1 fire & BR1 window

Experiment 7

Experiment 7 looked at the fire dynamics in a single-story structure where suppression was conducted with a solid stream. The fire was ignited in the Bedroom 1 in the arm of the chair in the 'A/B' corner of the room with the Bedroom 1 window open. The fire developed and became ventilation-limited. Once this occurred, the front door was opened, simulating fire department arrival. Two flow paths: one between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack was initiated through the front door, utilizing a solid stream from a smooth bore nozzle. The nozzle was flowing as the hoseline advanced. Figure 5.2 shows the configuration of the structure and Table 5.10 shows at what times interventions were performed. The results of Experiment 7 can be found in Appendix E.7.

To view the full experiment video Click Here.

Table 5.10: Experiment 7 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:55	Front Door Open
06:07	Suppression Crew Enters
06:12	Burst Suppression
06:22	Hallway Suppression
06:56	Fire Under Control
09:30	Structure Ventilated
12:26	End Experiment

Experiment 8

Experiment 8 looked at the fire dynamics in a single-story structure where suppression was conducted with a solid stream. The fire was ignited in the Bedroom 1 in the arm of the chair in the 'A/B' corner of the room with the Bedroom 1 window open. The fire developed and became ventilation-limited. Once this occurred, the front door was opened, simulating fire department arrival. Two flow paths were established: one between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack was initiated through the front door, utilizing a solid stream from a smooth bore nozzle. The nozzle shutdown while the hoseline advanced. Figure 5.2 shows the configuration of the structure and Table 5.11 shows at what times interventions were performed. The results of Experiment 8 can be found in Appendix E.8.

To view the full experiment video Click Here.

Table 5.11: Experiment 8 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:26	Front Door Open
05:40	Suppression Crew Enters
05:45	Burst Suppression
05:54	Hallway Suppression
06:32	Fire Under Control
08:30	Structure Ventilated
11:57	End Experiment

Experiment 9

Experiment 9 looked at the fire dynamics in a single-story structure where suppression was conducted with a straight stream pattern from a combination nozzle. The fire was ignited in the Bedroom 1 in the arm of the chair in the 'A/B' corner of the room with the Bedroom 1 window open. The fire developed and became ventilation limited. Once this occurred, the front door was opened, simulating fire department arrival. Two flow paths were established: one between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack was initiated through the front door, utilizing a straight stream from a combination nozzle. The nozzle was flowing while the hoseline was advanced. Figure 5.2 shows the configuration of the structure and Table 5.12 shows at what times interventions were performed. The results of Experiment 9 can be found in Appendix E.9.

To view the full experiment video Click Here.

Table 5.12: Experiment 9 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:27	Front Door Open
05:38	Suppression Crew Enters
05:45	Burst Suppression
05:53	Hallway Suppression
06:14	Fire Under Control
08:03	Structure Ventilated
11:59	End Experiment

Experiment 10

Experiment 10 looked at examine the fire dynamics in a single-story structure where suppression was conducted with a straight stream. The fire was ignited in the Bedroom 1 in the arm of the chair in the 'A/B' corner of the room with the Bedroom 1 window open. The fire developed and became ventilation limited. Once this occurred, the front door was opened, simulating fire department arrival. Two flow paths were established: one between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack was initiated through the front door, utilizing a straight stream from a combination nozzle. The nozzle was shut down while the hoseline advanced. Figure 5.2 shows the configuration of the structure and Table 5.13 shows at what times interventions were performed. The results of Experiment 10 can be found in Appendix E.10.

To view the full experiment video Click Here.

Table 5.13: Experiment 10 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:27	Front Door Open
05:39	Suppression Crew Enters
05:45	Burst Suppression
05:54	Hallway Suppression
06:32	Fire Under Control
08:04	Structure Ventilated
12:07	End Experiment

Experiment 11

Experiment 11 looked at the fire dynamics in a single-story structure where suppression was conducted with a fog stream pattern from a combination nozzle. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room with the Bedroom 1 window open. The fire developed and became ventilation-limited. Once this occurred, the front door was opened, simulating fire department arrival. Two flow paths were established: oone between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack was initiated through the front door, utilizing a narrow fog stream from a combination nozzle. The nozzle was flowing while the hoseline advanced. Figure 5.2 shows the configuration of the structure and Table 5.14 shows at what times interventions were performed. The results of Experiment 11 can be found in Appendix E.11.

To view the full experiment video Click Here.

Table 5.14: Experiment 11 Interventions

Time	Intervention
00:00	Ignition - Bedroom
06:20	Front Door Open
06:32	Suppression Crew Enters
06:38	Burst Suppression
06:49	Hallway Suppression
07:17	Fire Under Control
10:40	Structure Ventilated
12:24	End Experiment

Experiment 12

Experiment 12 looked at the fire dynamics in a typical single-story structure with delayed water application. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room with the Bedroom 1 window open. Once the fire reached steady-state, the front door was opened, simulating fire department arrival. This established two flow paths: one between the front door and bedroom window and another between the bedroom window and the bedroom. Once the fire reached steady-state again, suppression was initiated via an interior suppression tactic with a combination nozzle set to straight stream. The water flow was shut down while the hoseline was moving. Figure 5.2 shows the configuration of the structure and Table 5.15 shows at what times interventions were performed. The results of Experiment 12 can be found in Appendix E.12.

To view the full experiment video Click Here.

Table 5.15: Experiment 12 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
05:57	Front Door Open
13:29	Suppression Crew Enters
13:32	Burst Suppression
13:40	Hallway Suppression
14:25	Fire Under Control
19:56	Structure Ventilated
20:56	End Experiment

5.1.3 Two Room — Two Vent

During Experiments 13–17, an interior suppression tactic was performed to extinguish a fire in the 'Two Vent' configuration. This configuration, presented in Figure 5.3, consisted of a fire in Bedroom 1 with the Bedroom 1 window open, a fire in Bedroom 2 with the Bedroom 2 window open and all other vents initially closed. Specific details about the ventilation patterns and the type of interior fire attack method used during Experiments 13–17 are listed in Table 5.16. Following the table, a brief description of each experiment is provided along with a table of interventions and times at which they were performed during the experiment.

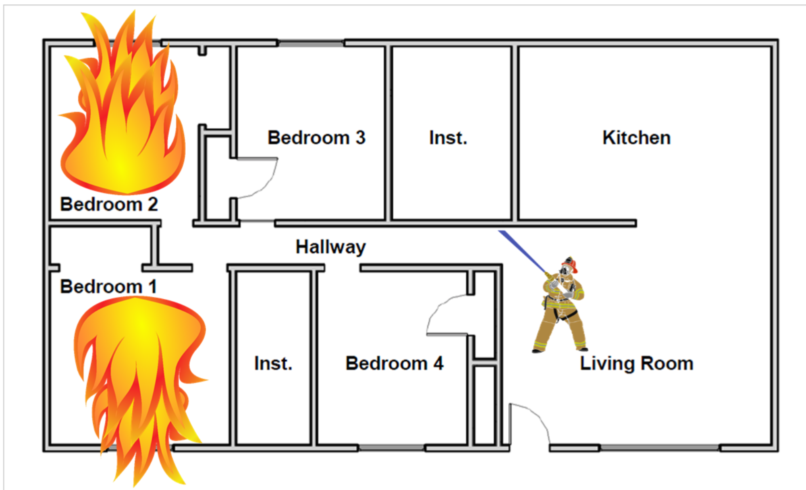


Figure 5.3: Configurations for Experiments 13 to 17

Table 5.16: Experiments 13 through 17

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
13	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window
14	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window
15	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window w/ door control
16	Interior	Combination	Flow & Move	Narrow Fog	Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window
17	Interior	Delayed water application w/ Combination; Flow & Move; Straight Stream			Flow paths between front door & BR1 fire; BR1 fire & BR1 window; front door & BR2 fire; BR2 fire & BR2 window

Experiment 13

Experiment 13 looked at the fire dynamics of a 2-bedroom fire in a single-story structure where suppression was conducted with a solid stream from a smooth bore nozzle. The fire was ignited simultaneously in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and Bedroom 2 in the arm of the chair in the 'B/C' corner of the room with the Bedroom 1 and Bedroom 2 windows open. The fire developed and became ventilation-limited. Once this occurred, the front door was opened, simulating fire department arrival. This created flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack was initiated through the front door, utilizing a solid stream from a smooth bore nozzle. The nozzle was flowing while the hoseline advanced. Figure 5.3 shows the configuration of the structure and Table 5.17 shows at what times interventions were performed. The results of Experiment 13 can be found in Appendix E.13.

To view the full experiment video Click Here.

Table 5.17: Experiment 13 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
05:39	Front Door Open
05:52	Suppression Crew Enters
05:57	Burst Suppression
06:11	Hallway Suppression
06:54	Fire Under Control
10:05	Structure Ventilated
12:06	End Experiment

Experiment 14

Experiment 14 looked at the fire dynamics of a 2-bedroom fire in a single-story structure where suppression was conducted with a straight stream from a combination nozzle. The fire was ignited simultaneously in the Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and Bedroom 2 in the arm of the chair in the 'B/C' corner of the room with the Bedroom 1 and Bedroom 2 windows open. The fire developed and became ventilation-limited. Once this occurred, the front door was opened, simulating fire department arrival. This created flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack was initiated through the front door, utilizing a straight stream from a combination nozzle. The nozzle was shut down while the hoseline advanced. Figure 5.3 shows the configuration of the structure and Table 5.18 shows at what times interventions were performed. The results of Experiment 14 can be found in Appendix E.14.

To view the full experiment video Click Here.

Table 5.18: Experiment 14 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
06:26	Front Door Open
06:39	Suppression Crew Enters
06:43	Burst Suppression
06:50	Hallway Suppression
07:31	Fire Under Control
12:54	Structure Ventilated
15:05	End Experiment

Experiment 15

Experiment 15 looked at the fire dynamics of a 2-bedroom fire in a single-story structure where suppression was conducted with a solid stream from a smooth bore nozzle. The fire is ignited simultaneously in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and in the arm of the chair in the 'B/C' corner of the room Bedroom 2 with the Bedroom 1 and Bedroom 2 windows open. The fire developed and became ventilation-limited. Once this occurred, the front door was opened, simulating fire department arrival. This created flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack was initiated through the front door, utilizing a solid stream from a smooth bore nozzle. After the suppression crew enters, the door was closed to the width of the hoseline in an effort to limit the amount of fresh air supplied to the fire (Door Control). The nozzle was shut down while the hoseline advanced. Figure 5.3 shows the configuration of the structure and Table 5.19 shows at what times interventions were performed. The results of Experiment 15 can be found in Appendix E.15.

To view the full experiment video Click Here.

Table 5.19: Experiment 15 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
05:39	Front Door Open
05:40	Suppression Crew Enters
05:44	Burst Suppression
05:55	Hallway Suppression
06:44	Fire Under Control
09:36	Structure Ventilated
12:06	End Experiment

Experiment 16 Experiment 16 looked at the fire dynamics of a 2-bedroom fire in a single-story structure where suppression was conducted with a narrow fog stream. The fire was ignited simultaneously in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and Bedroom 2 in the arm of the chair in the 'B/C' corner of the room with the Bedroom 1 and Bedroom 2 windows open. The fire develops and becomes ventilation-limited. Once this happens, the front door was opened, simulating fire department arrival. These actions create flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack was initiated through the front door, utilizing a narrow fog stream from a combination nozzle. The nozzle was flowing while the hoseline advanced. Figure 5.3 shows the configuration of the structure and Table 5.20 shows at what times interventions were performed. The results of Experiment 16 can be found in Appendix E.16.

To view the full experiment video Click Here.

Table 5.20: Experiment 16 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
05:23	Front Door Open
05:33	Suppression Crew Enters
05:37	Burst Suppression
05:54	Hallway Suppression
06:27	Fire Under Control
10:15	Structure Ventilated
11:45	End Experiment

Experiment 17 Experiment 17 looked at the fire dynamics of a 2-bedroom fire in a single-story structure where suppression was conducted with delayed suppression. The fire was ignited simultaneously in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and Bedroom 2 in the arm of the chair in the 'B/C' corner of the room with the Bedroom 1 and Bedroom 2 windows open. The fire developed and became ventilation-limited. Once this occurred, the front door was opened, simulating fire department arrival. This created flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack was initiated through the front door, utilizing a straight stream from a combination nozzle. The nozzle was shut down while the hoseline advanced Figure 5.3 shows the configuration of the structure and Table 5.21 shows at what times interventions were performed. The results of Experiment 17 can be found in Appendix E.17.

To view the full experiment video Click Here.

Table 5.21: Experiment 17 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
05:27	Front Door Open
10:32	Suppression Crew Enters
10:36	Burst Suppression
10:47	Hallway Suppression
12:49	Fire Under Control
15:17	Structure Ventilated
23:32	End Experiment

5.2 Transitional

5.2.1 Single Room — Single Vent

During Experiments 18–20, a transitional attack was performed to extinguish a fire in the 'Single Vent' configuration. This configuration, presented in Figure 5.4, consisted of a fire in Bedroom 1 with the Bedroom 1 window open and all other vents initially closed. Specific details about the ventilation patterns and the type of transitional fire attack method used during Experiments 18–20 are listed in Table 5.22.

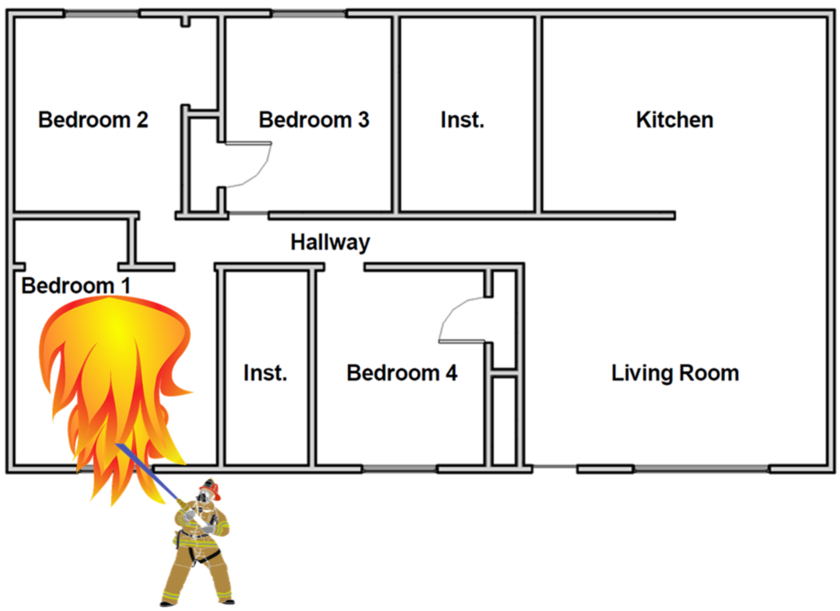


Figure 5.4: Configuration for Experiments 18 through 20.

Table 5.22: Experiments 18 through 20

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
18	Transitional	Smooth bore	Steep angle	Solid stream	Flow path between BR1 fire & BR1 window
19	Transitional	Combination	Occlude opening,rebuild, steep angle to content suppression	Narrow fog, rebuild, straight stream to fog content suppression	Flow path between BR1 fire & BR1 window
20	Transitional	Smooth bore	Steep angle to half bale content suppression	Solid stream to half bale content suppression	Flow path between BR1 fire & BR1 window

During Experiment 21, a transitional attack was performed to extinguish a fire in the 'Single Vent' configuration. This configuration, presented in Figure 5.5, consisted of a fire in Bedroom 1 with the Bedroom 1 window and front door open. All other vents were initially closed. Specific details about the ventilation patterns and the type of transitional fire attack method used during Experiment 21 are listed in Table 5.23.

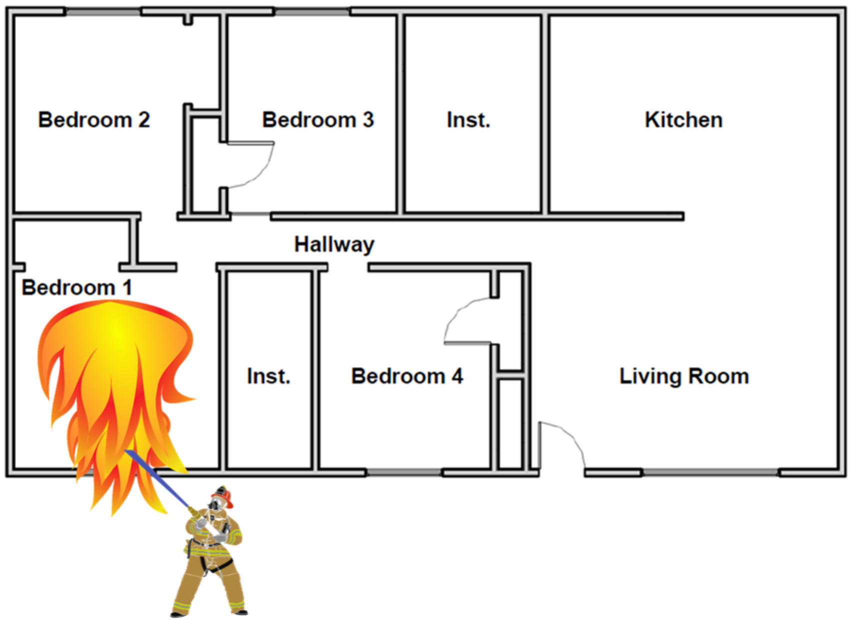


Figure 5.5: Configuration for Experiment 21.

Table 5.23: Experiment 21

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
21	Transitional	Smooth bore	Steep angle to half bale content suppression	Solid stream to half bale content suppression	Flow paths between front door & BR1 fire; BR1 fire & BR1 window

During Experiment 26, a transitional attack was performed to extinguish a fire in the 'Single Vent' configuration. This configuration, presented in Figure 5.6, consisted of a fire in Bedroom 4 with the Bedroom 4 window open and all other vents initially closed. Specific details about the ventilation patterns and the type of transitional fire attack method used during Experiment 26 are listed in Table 5.24.

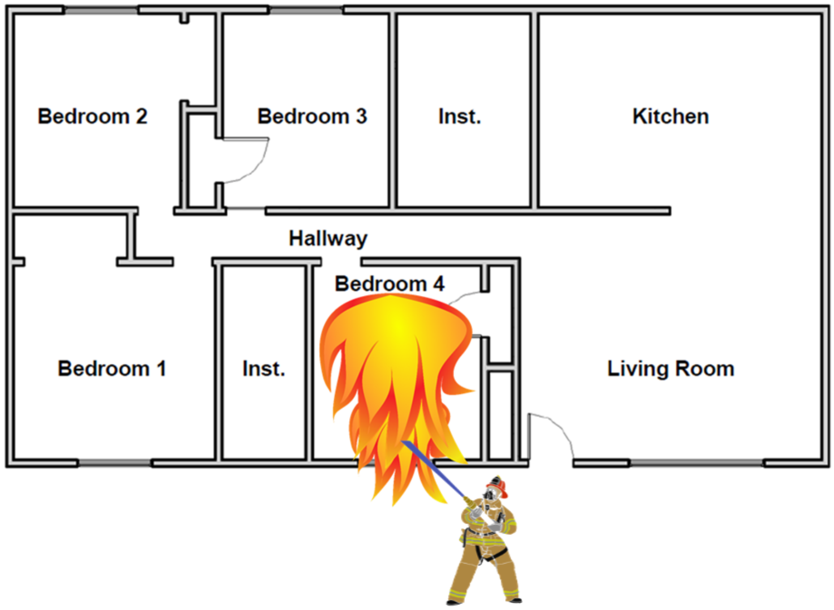


Figure 5.6: Configuration for Experiment 26.

Table 5.24: Experiment 26

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
26	Transitional	Combination	Steep angle sweep	Straight stream	Flow paths between front door & BR4 fire; BR4 fire & BR4 window

The following sections contain a brief description of each experiment along with a table of interventions and times at which they were performed during each experiment.

Experiment 18

Experiment 18 looked at the fire dynamics of a bedroom fire in a single-story structure where suppression was initiated from the exterior of the house. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room. The fire developed and became ventilation-limited. Once this occurred, a transitional attack was initiated, starting at the Bedroom 1 window via a straight stream from a combination nozzle. The suppression crew then transitioned to the interior for final suppression. The crew used a burst suppression to check conditions and then proceeded directly to the fire room. Figure 5.4 shows the configuration of the structure and Table 5.25 shows at what times interventions were performed. The results of Experiment 18 can be found in Appendix E.18.

To view the full experiment video Click Here.

Table 5.25: Experiment 18 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
05:24	Exterior Suppression BR1 Window Solid Stream
05:35	Front Door Open
05:42	Suppression Crew Enters
05:45	Burst Suppression
06:07	Room Suppression
06:13	Fire Under Control
09:18	Structure Ventilated
12:04	End Experiment

Experiment 19

Experiment 19 looked at the fire dynamics of a bedroom fire in a single-story structure where suppression was initiated from the exterior. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room. The fire developed and became ventilation-limited. Once this occurred a exterior water application was initiated through the Bedroom 1 window via a narrow fog stream from a combination nozzle. The fire was knocked back. The nozzle was shut down and the fire was permitted to regrow to the earlier ventilation-limited state. Once this occurred, a transitional fire attack was initiated, starting at the Bedroom 1 window via a straight stream from a combination nozzle. The suppression crew then transitioned to the interior for final suppression. The crew entered the structure and proceeded directly to the fire room before flowing additional water. Figure 5.4 shows the configuration of the structure and Table 5.26 shows at what times interventions were performed. The results of Experiment 19 can be found in Appendix E.19.

To view the full experiment video Click Here.

Table 5.26: Experiment 19 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
05:24	Exterior Suppression BR1 Window Narrow Fog Stream
08:28	Exterior Suppression BR1 Window Straight Stream
08:58	Front Door Open
09:10	Suppression Crew Enters
09:34	Room Suppression
08:48	Fire Under Control
12:25	Structure Ventilated
14:05	End Experiment

Experiment 20

Experiments 20 looked at the fire dynamics of a bedroom fire in a single-story structure where suppression was initiated from the exterior of the house. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room. The fire developed and became ventilation-limited. Once this occurred, a transitional fire attack was initiated, starting at the Bedroom 1 window via a solid stream from a smooth bore nozzle. After the initial application, the suppression crew approached the window, placed the nozzle through the window and opened the bale half way while making an 'O' pattern. The nozzle was shut down and the suppression crew, transitioned to the interior for final suppression. The crew entered the structure and proceeded directly to the fire room before flowing additional water. Figure 5.4 shows the configuration of the structure and Table 5.27 shows at what times interventions were performed. The results of Experiment 20 can be found in Appendix E.20.

To view the full experiment video Click Here.

Table 5.27: Experiment 20 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
06:52	Exterior Suppression BR1 Window Solid Stream
07:24	Front Door Open
07:34	Suppression Crew Enters
07:53	Fire Under Control
08:34	Final Suppression
10:29	Structure Ventilated
12:06	End Experiment

Experiment 21

Experiment 21 looked at the fire dynamics of a bedroom fire in a single-story structure where suppression was initiated from the exterior. The fire was ignited in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room. The fire developed and became ventilation limited. Once this occurred, the front door was opened to simulate an uncoordinated crew entry during a transitional fire attack. This created two flow paths: one between the front door and the bedroom and a second between the bedroom window and the bedroom. Once this occurred, a transitional fire attack was initiated, starting at the Bedroom 1 window via a solid stream from a smooth bore nozzle. After the initial application, the suppression crew approached the window, placed the nozzle through the window and opened the bale half way while making an 'O' pattern. The nozzle was shut down and the suppression crew transitioned to the interior for final suppression. The crew entered the structure and proceeded directly to the fire room before flowing additional water. Figure 5.5 shows the configuration of the structure and Table 5.28 shows at what times interventions were performed. The results of Experiment 21 can be found in Appendix E.21.

To view the full experiment video Click Here.

Table 5.28: Experiment 21 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1
06:24	Front Door Open
06:44	Exterior Suppression BR1 Window Solid Stream
07:05	Suppression Crew Enters
07:24	Fire Under Control
07:46	Final Suppression
09:50	Structure Ventilated
12:23	End Experiment

Experiment 26

Experiment 26 looked at the fire dynamics of a bedroom fire in a single-story structure with transitional suppression. The fire was ignited in Bedroom 4 in the arm of the chair in the 'A/B' corner of the room. The fire develops and becomes ventilation-limited. Once this happened, a transitional fire attack was initiated, starting at the Bedroom 4 window via a straight stream from a combination nozzle. The nozzle was shut down and the suppression crew, transitioned to the interior for final suppression. The crew entered the structure and flowed water as they deemed necessary as they proceeded to the fire room before completing final suppression. Figure 5.6 shows the configuration of the structure and Table 5.29 shows at what times interventions were performed. The results of Experiment 26 can be found in Appendix E.26.

To view the full experiment video Click Here.

Table 5.29: Experiment 26 Interventions

Time	Intervention
00:00	Ignition - Bedroom 4
06:04	Front Door Open
08:09	Exterior Suppression BR4 Window Straight Stream
08:21	Suppression Crew Enters
08:48	Room Suppression
09:34	Fire Under Control
11:21	Structure Ventilated
09:09	End Experiment

5.2.2 Two Room — Two Vent

During Experiments 22–24, a transitional suppression tactic was performed to extinguish a fire in the 'Two Vent' configuration. This configuration, presented in Figure 5.7, consisted of a fire in Bedroom 1 with the b=Bedroom 1 window open, a fire in Bedroom 2 with the Bedroom 2 window open and all other vents initially closed. Specific details about the ventilation patterns and the type of transitional fire attack method used during Experiments 22–24 are listed in Table 5.30.

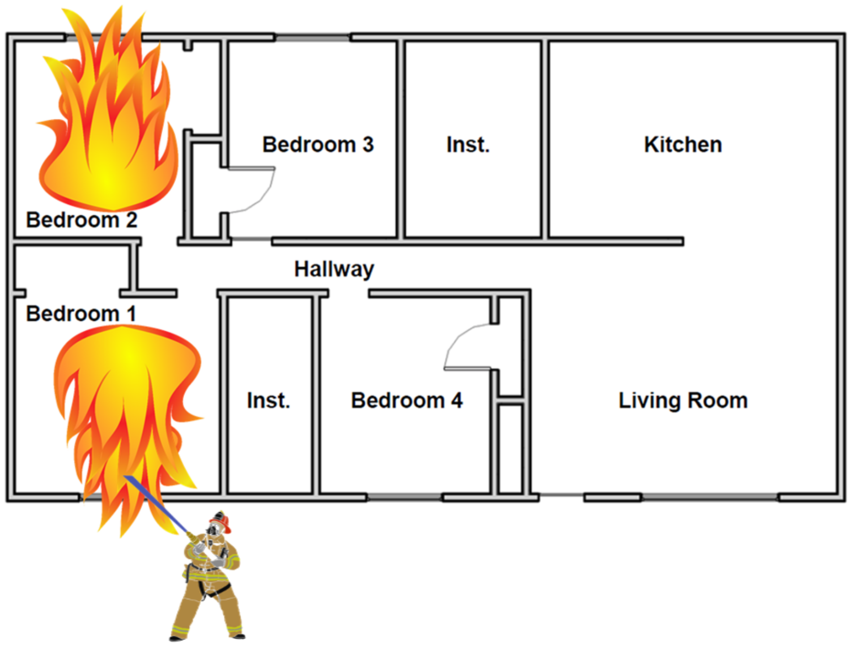


Figure 5.7: Configuration for Experiments 22 through 24.

Table 5.30: Experiments 22 through 24

Experiment	Fire Attack Method	Nozzle	Advancement	Pattern	Ventilation Parameters
22	Transitional	Smooth bore	Steep angle to half bale content suppression	Solid stream to half bale content suppression	Flow path between BR1 fire & BR1 window; flow path between BR2 fire & BR2 window
23	Transitional	Combination	Occlude opening	Narrow fog	Flow path between BR1 fire & BR1 window; flow path between BR2 fire & BR2 window
24	Transitional	Combination	Steep angle to half fog content suppression	Straight stream to fog content suppression	Flow path between BR1 fire & BR1 window; flow path between BR2 fire & BR2 window

Experiment 22

Experiment 22 looked at the fire dynamics of a 2-bedroom fire in a single-story structure with transitional suppression conducted through the Bedroom 1 window before suppression was transitioned to the interior. The fire was ignited simultaneously in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and Bedroom 2 in the arm of the chair in the 'B/C' corner of the room. The Bedroom 1 and Bedroom 2 windows were open. The fire developed and became ventilation-limited. Once this occurred, a transitional fire attack was initiated starting, at the Bedroom 1 window via a solid stream from a smooth bore nozzle. After the initial application, the suppression crew approached the window, placed the nozzle through the window, and opened the bale half way while making an 'O' pattern. The nozzle was shut down and the suppression crew transitioned to the interior for final suppression. The crew entered the structure and conducted a burst suppression at the living room and then proceeded down the hallway with the nozzle flowing while the line was advanced. Figure 5.7 shows the configuration of the structure and Table 5.31 shows at what times interventions were performed. The results of Experiment 22 can be found in Appendix E.22.

To view the full experiment video Click Here.

Table 5.31: Experiment 22 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
05:43	Exterior Suppression BR1 Window Solid Stream
06:07	Front Door Open
06:13	Suppression Crew Enters
06:15	Burst Suppression
06:24	Hall Suppression
07:11	Fire Under Control
11:00	Structure Ventilated
14:25	End Experiment

Experiment 23

Experiment 23 looked at the fire dynamics of a 2-bedroom fire in a single-story structure with transitional suppression via a narrow fog only on the Bedroom 1 window before suppression transitioned to the interior. The fire was ignited simultaneously in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and Bedroom 2 in the arm of the chair in the 'B/C' corner of the room. The Bedroom 1 and Bedroom 2 windows were open. The fire developed and became ventilation-limited. Once this occurred, a transitional fire attack was initiated, starting at the Bedroom 1 window via a narrow fog from a combination nozzle. The nozzle was shut down and the suppression crew transitioned to the interior for final suppression. The crew entered the structure and proceeded down the hallway with the nozzle flowing while the line was advanced. Figure 5.7 shows the configuration of the structure and Table 5.32 shows at what times interventions were performed. The results of Experiment 23 can be found in Appendix E.23.

To view the full experiment video Click Here.

Table 5.32: Experiment 23 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
05:26	Exterior Suppression BR1 Window Narrow Fog Stream
05:41	Front Door Open
05:50	Suppression Crew Enters
06:01	Hall Suppression
06:59	Fire Under Control
09:20	Structure Ventilated
12:05	End Experiment

Experiment 24

Experiment 24 looked at the fire dynamics of a 2-bedroom fire in a single-story structure with transitional suppression on both bedroom windows. The fire was ignited simultaneously in Bedroom 1 in the arm of the chair in the 'A/B' corner of the room and Bedroom 2 in the arm of the chair in the 'B/C' corner of the room. The Bedroom 1 and Bedroom 2 windows were open. The fire developed and became ventilation-limited. Once this occurred, a transitional fire attack was initiated, starting at the Bedroom 1 window via a straight stream from a combination nozzle. The nozzle was shut down and the line re-located to the Bedroom 2 window for a second water application. The nozzle was shut down and the suppression crew transitioned to the interior for final suppression. The crew entered the structure and proceeded to a position directly outside the fire rooms before flowing additional water. Figure 5.7 shows the configuration of the structure and Table 5.33 shows at what times interventions were performed. The results of Experiment 24 can be found in Appendix E.24.

To view the full experiment video Click Here.

Table 5.33: Experiment 24 Interventions

Time	Intervention
00:00	Ignition - Bedroom 1 & 2
05:28	Exterior Suppression BR1 Window Straight Stream
05:56	Exterior Suppression BR2 Window Straight Stream
06:16	Front Door Open
06:30	Suppression Crew Enters
07:08	Room Suppression
07:25	Fire Under Control
08:37	Structure Ventilated
11:55	End Experiment

5.3 Large Volume Gas Cooling

During Experiment 25, all of the interior walls of the structure with the exception of Bedroom 1 'D' side wall were removed. Gas cooling in a large volume was utilized on a fire which could not be directly suppressed. This configuration, presented in Figure 5.8, consisted of a fire in Bedroom 1 with the Bedroom 1 window and front door open, all other vents remained closed.

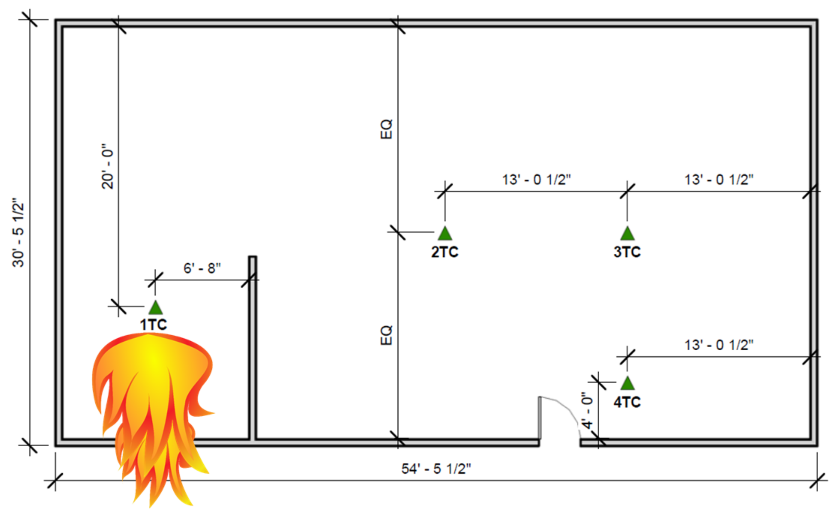


Figure 5.8: Experiment 25 Large Volume Gas Cooling

Experiment 25

Experiment 25 aimed to examine gas cooling through a challenging configuration. In the previous experiments, there was a well-compartmented house that limited the fire growth and fire gas flow, based on ventilation to the fire room via the open window and doorway. The doorway connected to a long hallway which connected to the front door through the living room. To create a larger volume of hot gases, all of the interior walls of the structure with the exception of Bedroom 1 'D' side wall were removed. The one wall was left in place so that water could not be applied directly to the contents on fire, instead only to the hot gases. The fuel load consisted of 2 chairs, 2 ottomans, 2 king-sized mattresses and box springs, 8 rolls of carpet padding and 5 rolls of carpet. One half of the bedroom window was left open for the duration of the entire experiment that provided the oxygen needed to maintain a ventilation-limited fire. The front door also remained open for the duration of the fire. Thermocouples trees in four locations monitored temperatures from floor to ceiling. A vertical 2 in by 6 in support protected by cement board protection was placed in front of each thermocouple array so that water could not directly contact the arrays and the hose stream could not knock the arrays down. The intent was to address the concept of cooling gases by examining if gasses could be cooled enough to allow the suppression crew to advance into the structure and apply water directly to the fire. This would require they advance to a position directly adjacent TC2. Figure 5.8 shows the configuration of the structure and Figure 5.9 shows the interior of the structure. Table 5.34 shows at what times interventions were performed. The results of Experiment 25 can be found in Appendix E.25.

Figure 5.9: Images of the structure configuration, open space (left) and fire room (right)

To view the full experiment video Click Here.

Table 5.34: Experiment 25 Interventions

Time	Event
00:00	Ignition
05:49	Pulse 1 - 95 gpm @ 100psi
06:02	Pulse 2 - 95 gpm @ 100psi
06:58	Long Pulse 1 - 95 gpm @ 100psi
08:42	Long Pulse 2 - 95 gpm @ 100psi
10:32	Sweep Pulse 1 - 95 gpm @ 100psi
11:16	Sweep Pulse 2 - 95 gpm @ 100psi
12:45	Narrow Fog Sweep 1 - 95 gpm @ 100psi
13:07	Narrow Fog Sweep 2 - 95 gpm @ 100psi
13:30	Pulse 1 - 150 gpm @ 100psi
14:14	Pulse 2 - 150 gpm @ 75psi
14:53	Long Pulse 1 - 150 gpm @ 100psi
17:12	Long Pulse 2 - 150 gpm @ 100psi
19:03	Sweep Pulse - 150 gpm @ 100psi
19:46	Narrow Fog Sweep - 150 gpm @ 100psi
20:46	Wall Ceiling Wall(Corner) - 150 gpm @ 100psi
23:46	End Experiment

6 Experiment Analysis

6.1 Repeatability

Repeatability is a measure of the closeness of the agreement between the results of successive measurements of the same physical quantity or property carried out under similar conditions. Keep in mind that no measurement is perfect. All measurements are an estimate of the actual physical quantity of property being measured. Therefore, a measurement is complete only when accompanied by a quantitative statement of its uncertainty [53].

In order to examine the impact of hose streams on structure fires with different ventilation configurations, it is advantageous to have fires that generate similar conditions at the time of water application. This would provide a consistent fire baseline for each of the water application methods to be compared against with a given ventilation configuration.

According to NIST guidelines for evaluating and expressing the uncertainty of measurement results, there are two methods (Type A and Type B), used to evaluate the uncertainty of a measurement. A Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data while a Type B evaluation of standard uncertainty is usually based on scientific judgment using all the relevant information available, which may include previous measurement data, manufacturer's specifications, data provided in calibration and other reports, and uncertainties assigned to reference data taken from handbooks [53].

In Chapter 4, the uncertainties associated with the measurement instruments used in this study were estimated using a Type B evaluation. The measurements are expressed with an expanded uncertainty with a coverage factor of two. In other words, the values within the uncertainty interval have a level of confidence of approximately 95%. In Chapter 4 the expanded uncertainty for thermocouple measures was reported as ± 15%. This will serve as a guide for our assessment of the repeatability of the temperatures from the experiments. For example, if the measured temperature was reported as 500 °F (260 °C) ± 15%, there is a 95% certainty that a similar measure would be within the range of 425 to 575 °F (221 to 299 °C).

In order to evaluate the repeatability of the experiments, a Type A analysis will be conducted based on the comparison of the average temperatures of each thermocouple array. For the Type A analysis, the standard deviation of each type of ventilation configuration experiment average temperatures will be determined and the expanded coverage factor of 2 will be applied to assess the 95% certainty interval range for each thermocouple array.

The experiments were grouped by the ventilation configuration which existed prior to fire department intervention. The three ventilation configurations used were 'No Vent', 'Single Vent' and 'Two Vent'. In the 'No Vent', all the exterior openings on the structure were closed until fire department intervention, and the fire was located in Bedroom 1. In the 'Single Vent', a single window was open in the fire room (Bedroom 1) until fire department intervention. For the 'Two Vent' there were two rooms of fire (Bedroom 1 and Bedroom 2), and the window in each room was open prior to fire department intervention. To compare the effectiveness of the various fire service tactics used in the experiments, it is important to identify if the experiments are comparable across ventilation configurations.

Each set of experiments in the three ventilation configurations were compared to determine repeatability based on ventilation configuration and thus, the applicability of comparing the experiments. The comparison was based on the average temperature measured by the thermocouples in each thermocouple array. The average temperature from each thermocouple array was time-averaged along the period of 60 seconds prior to fire department intervention. In the following sections, the results for each ventilation configuration are presented and discussed.

6.1.1 No Vent

A total of six experiments contained the 'No Vent' ventilation configuration. The average temperature measured by each thermocouple array averaged across the duration of 60 seconds before fire department intervention is shown in the radar plot presented in Figure 6.1. During Experiment 1, the door to Bedroom 3 was open, while during the other five experiments, the door to Bedroom 3 was closed. The open door accounts for the noticeable deviations in Experiment 1's temperatures at the Victim 3 location and at the Bedroom 3 array location. The temperature measurement locations from all 'No Vent' cases can be directly compared with the exception of the Bedroom 3 and Victim 3 locations during Experiment 1, which were outliers and as a result, will not be used in the analysis.

The expanded uncertainty values of most of the measurement positions are ± 12.6% or less. There are two measurement locations with higher values of expanded uncertainty. Bedroom 1 and the End Hall position have unexpanded uncertainties of 24.7% and 17.8% respectively. For this ventilation configuration these two areas are the locations where flames have the potential to impact portions of the thermocouple array creating a broader range of measured values.

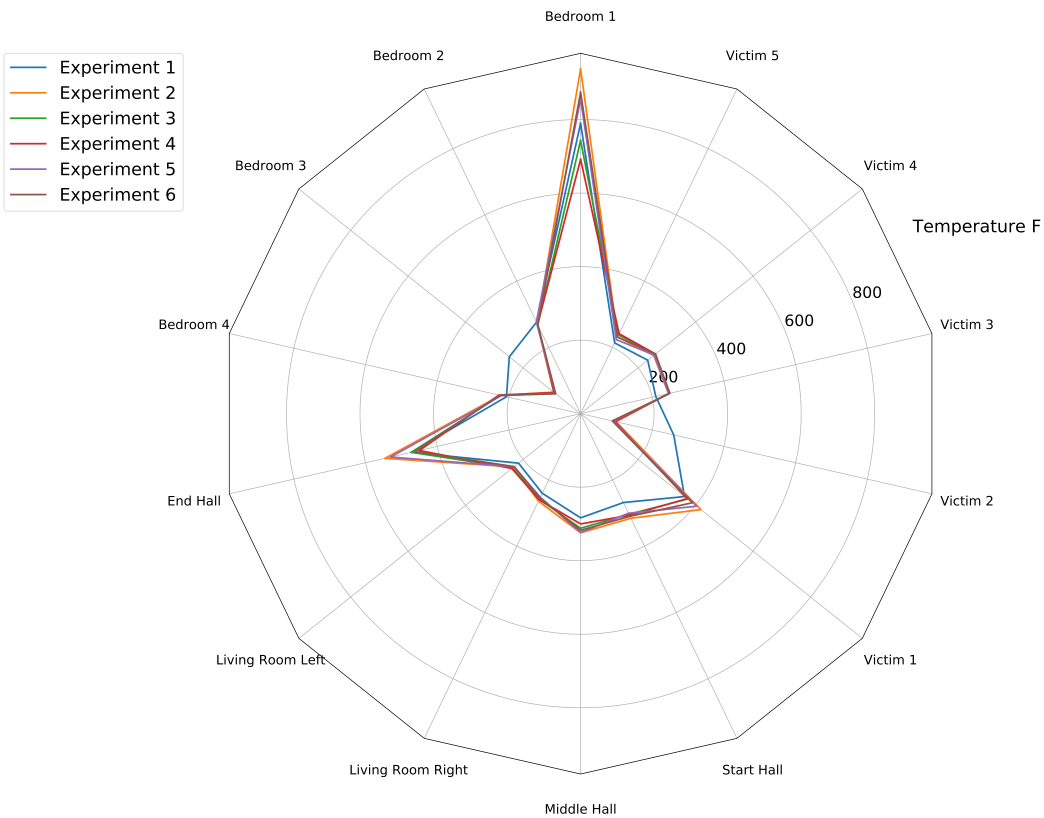


Figure 6.1: Average Thermocouple Array Temperatures - No Ventilation

6.1.2 Single Vent

In the ‘Single Vent’ profile, there were 10 experiments. The average temperature for the time period 60 seconds prior to fire department intervention is shown in Figure 6.2. With the addition of the open window in Bedroom 1 the fire behavior in the room of origin became steadier (post-flashover) than in the "no vent" case. This resulted in an expanded uncertainty of 11.7% for Bedroom 1. However at the thermocouple array locations along the path from Bedroom one toward the Living Room the expanded uncertainties range from a high of 42.9% (End Hall position) to 17.4% (Living Room Left position). The larger measurement range at the positions closer to the room of origin are the result of flames and near flame temperature gases potentially impacting portions of the thermocouple arrays positioned along the hallway and the resulting effects on the adjacent spaces.

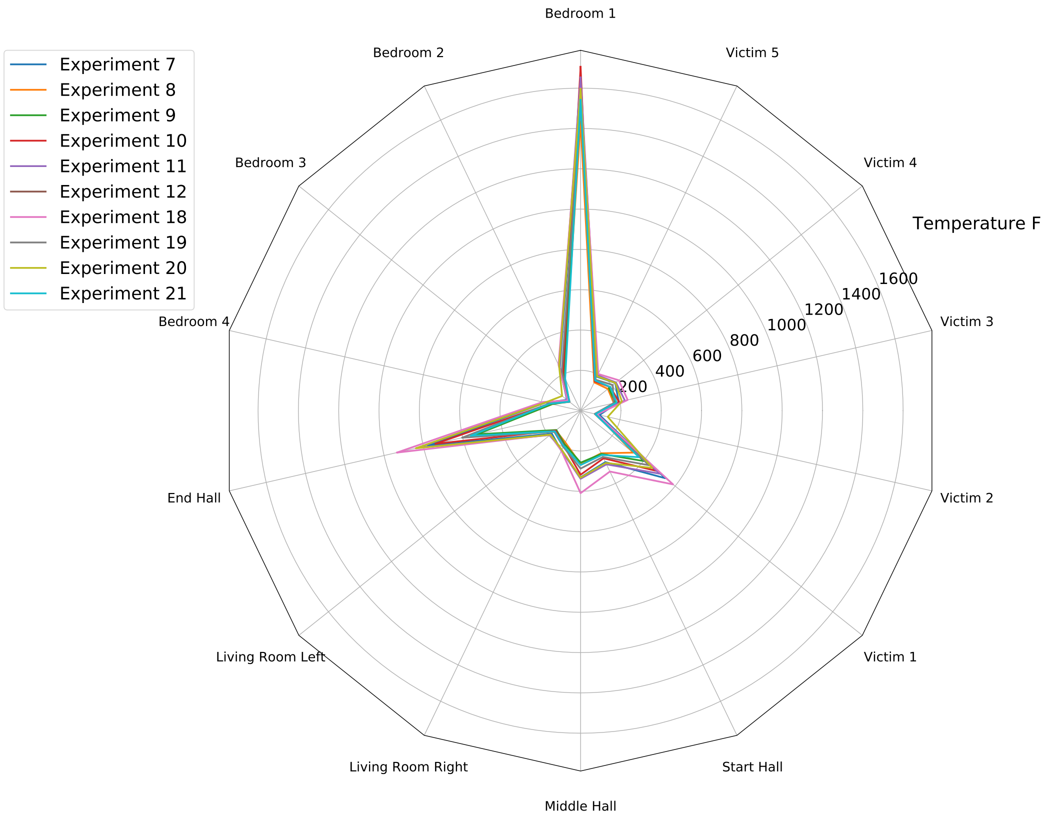


Figure 6.2: Average Thermocouple Array Temperatures - Single Vent

6.1.3 Two Vents

In the 'Two Vent' profile, there were 8 experiments. The average temperature for the time period 60 seconds prior to fire department intervention is shown in Figure 6.3. With the two rooms of fire and two ventilation points (Bedroom 1 and 2), the positions with the highest levels of expanded uncertainty values include End Hall (± 32.4%), Victim 1 (30.2%), and Bedroom 1 (± 28.4%). The expanded uncertainty for the remaining positions throughout the structure were 17.5% or less. With this ventilation configuration, the fire in Bedroom 2 tended to grow at a faster rate than Bedroom 1, which resulted in a broader range of temperature averages in Bedroom 1 and the positions between the Bedroom 1 and Bedroom 2.

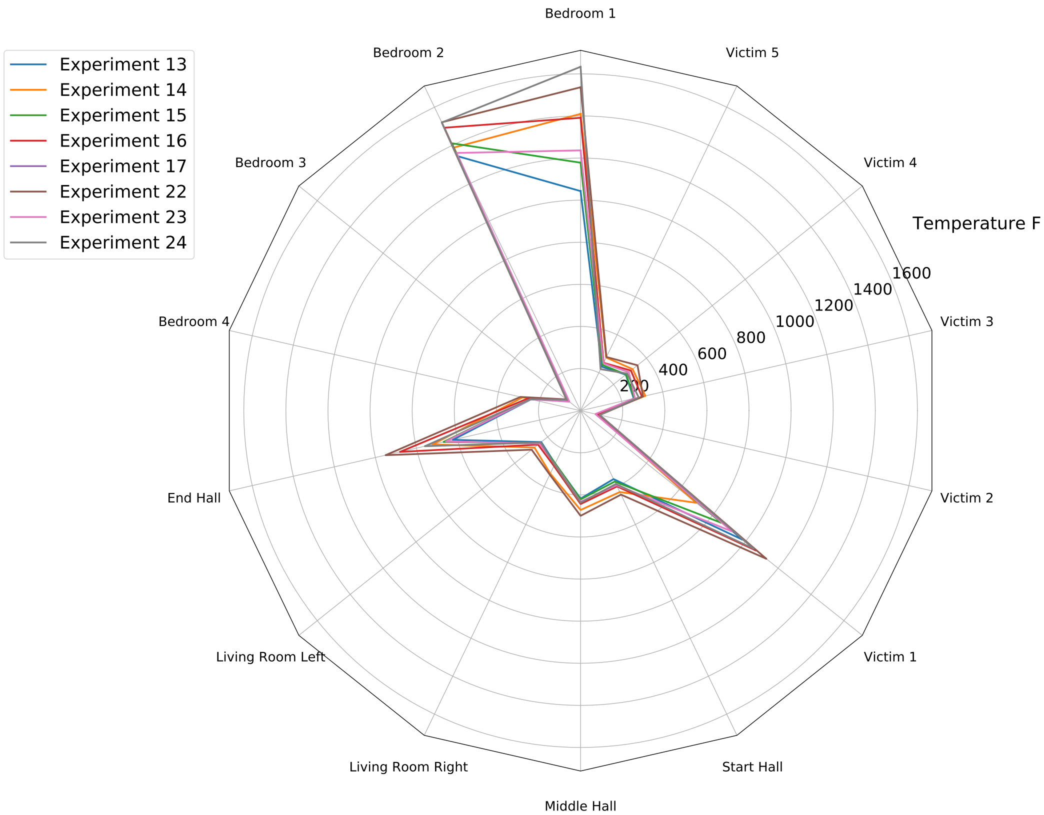


Figure 6.3: Average Thermocouple Array Temperatures - Two Vent

6.1.4 Repeatability Summary

The analysis of the three different ventilation configurations provide a sense of the repeatability of each experimental series. The analysis shows that for each ventilation configuration there are areas within the structure where the averaged floor to ceiling temperatures have smaller uncertainty intervals than others. The average temperature positions with higher uncertainty intervals typically occurred in areas which could have had flames or near flame temperature gases impacting portions of the thermocouple array in some of the cases or during a portion of the 60 second averaging period.

In the no vent configuration, 13 of the 14 thermocouple locations had expanded uncertainties of 17.8% or less. In the configuration with two vents and two fire rooms, 11 of the 14 thermocouple locations had expanded uncertainties of 17.5% or less. The one vent configuration exhibited the highest levels of variability with only 4 out 14 thermocouple locations with expanded uncertainties of 18.0% or less.

The measurement of the thermal environment (fire conditions) of these experiments depend on the type and quantity of fuel, geometry of the structure, ventilation, and properties of the instrumentation. All items considered within the analysis demonstrates that the repeatability for each ventilation configuration can be quantified and there are positions within each experimental series that have a higher level of fire instability than others. As the analysis of these experiments proceeds the expanded uncertainties for each of the ventilation configuration types needs to be considered when determining the significance of a given result.

A Type A analysis is typically not available to the fire community for large-scale structural fire experiments, since replicate experiments are very rare. This analysis provides quantifiable benchmarks other than the typical uncertainty estimate of ± 15% used for thermocouples in full-scale experiments.

6.2 Victim Survivability & Tenability

According to the most recent data from the U.S. Fire Administration, an estimated 2,695 civilian fire fatalities occurred annually from 2013 through 2015. The annual number of residential building fires during this period was estimated at 380,200 [54].

Burns and smoke inhalation combined were the primary symptoms for 48 percent of the fatalities of residential fires. Smoke inhalation alone accounted for an additional 37 percent of residential fire fatalities, and thermal burns alone accounted for only 6 percent of fatalities. The remaining fatalities included symptoms ranging from cardiac arrest to gunshot wounds [54].

In this section, the thermal and gas exposure data collected from the fire attack experiments will be analyzed in an effort to estimate the impact of the fire ventilation configurations and fire department interventions on victim survivability and tenability. Species associated with combustion, CO, CO_2, and O_2, were measured during these experiments while species associated with certain fuel packages, HCN, were not measured. Although many variables were controlled during these experiments, there are uncontrollable factors affecting victim survivability, such as humidity.

Correlations have been developed based on animal testing for estimating the threshold dose of thermal energy that would result in a fatality of fifty percent of the exposed population. This lethal dose threshold is referred to as LD_{50} [36].

Additional correlations, also developed based on animal test results, exist for irritant and toxic gases. These correlations can provide estimates of tenability (the concentration required for the potential occupant to become incapacitated) and of survivability (the concentration required to cause a fatality). The lethal concentration threshold is referred to as the LC_{50} [36].

Although it is possible to estimate the survivability based on thermal exposure and on gas concentrations individually, no reliable method exists to estimate the combined effects of both temperature and toxic gases. The survivability of a person in a particular fire scenario is difficult to quantify.

Factors such as age, gender, and overall health all play a role in how an individual responds to the environment found inside a structure fire. Further there are potential unknowns regarding the application of the animal studies to the human condition.

Both temperature exposure and toxic gas exposure can be quantified through the use of a Fractional Effective Dose (FED) concept where the FED is equal to the dose received in a given time divided by the effective dose required for a specified endpoint, be it incapacitation or death. The higher the FED, the less chance of survivability; the lower the FED, the higher chance that a victim would survive. Threshold criteria or FED equal to 1 indicates that the victim is unconscious and unable to evacuate on their own. For the purpose of this study, a FED of 3 indicates a potential fatal dose. However, these criteria only represent the LC_{50} and LD_{50} or point at which 50% of the population would have received a potentially fatal dose.

$$FED = \frac{\text{Dose received at time } t(Ct)}{\text{Effective } Ct \text{ dose to cause incapacitation or death}} \tag{6.1}$$

The fractional effective dose from carbon monoxide exposure can be calculated as shown in equation 6.2 [36]. The total FED is the integral over the time of exposure t_1 to t_2 of 3.17×10^{-5} multiplied by CO, the carbon monoxide concentration in ppm, multiplied by V, the volume of air breathed per minute, all divided by D the exposure dose of percent carboxyhemoglobin (COHb) for incapacitation, multiplied by the time step. For this analysis a value of 25 L/min was used for V, for a victim walking to escape, and a value of 30% (COHb) for D for an incapacitating dose.

$$FED = \int_{t_1}^{t_2} \left(\frac{3.17 \times 10^{-5} \, (CO)^{1.036} \, (V)}{D} \right) \Delta t \tag{6.2}$$

The method used to evaluate the effective dose of heat energy received over time is based on total energy flux (convective and radiative). The formula involves the integral from the start of exposure t_1 to the end of exposure t_2, of the exposure q at time t to the four thirds power, divided by r the heat exposure dose for the endpoint of fatality, $16.7({}^{kW}/{}_{m^2})^{4/3}$, all multiplied by the exposure time step Δt in minutes [36].

$$FED = \int_{t_1}^{t_2} \left(\frac{q^{4/3}}{r} \right) \Delta t \tag{6.3}$$

To determine survivability and tenability a package of sensors was utilized to simulate victims at five different locations within the structure, as illustrated in figure 6.4. Victim 1 was located at the end of the hall outside the fire room(s); Victim 2 was located on the bed in Bedroom 3 where the bedroom door was closed; Victim 3 was located on the bed in Bedroom 4 where the bedroom door was open; Victim 4 was located in the living room near the entrance to the hall; and Victim 5 was located as remote from the fire room(s) as possible in the back-right corner of the Dining room.

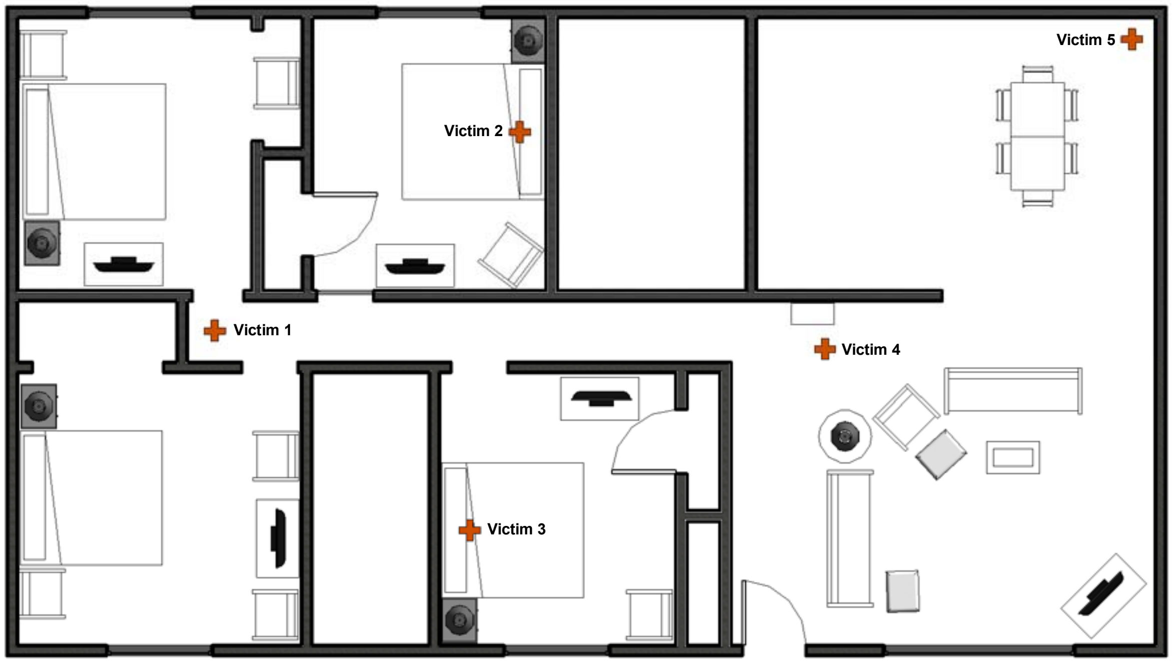


Figure 6.4: Victim Locations

Each location included an array of thermocouples at 1 ft, 3 ft, 5 ft and 7 ft above the floor and Schmidt-Boelter total heat flux gauge oriented such that the view range of the gauge was directed vertically at 1 ft above the floor or above the bed (3.2 ft above the floor). Victims 1-4 had a gas measurement point analyzing carbon monoxide (CO), carbon dioxide (CO_2) and oxygen (O_2) located 1 ft above the floor or above the bed (3.2 ft above the floor). In addition to the sensors, instrumented pig skins were utilized to simulate human skin at each victim location. Figure 6.5 shows an example of a victim instrument package.

Figure 6.5: Example victim instrument package.

The CO, CO_2, and O_2 values from the gas analyzers were utilized in equation 6.2 to determine the fraction of dose required for untenability. The gas sample locations were located 1 ft above the floor for victim packages on the floor (Victims 1, 4, & 5) and 1 ft above the surface of the bed (3.2 ft above the floor) for victims located on the bed (Victims 2 & 3). A value of 1 represents untenable and a value of 3 represents a potentially fatal dose. The total heat flux recorded at the Schmidt-Boelter heat flux gauge was used in equation 6.3 to determine the fraction of a fatal dose received via both convective and radiative heat transfer, where a value of 1 is equivalent to a fatal dose in 50 % of the population. The gauge was oriented vertically 1 ft above the floor for victim packages on the floor (Victims 1, 4, & 5), and 1 ft above the surface of the bed (3.2 ft above the floor) for victims located on the bed (Victims 2 & 3).

This section will analyze the experiments conducted for survivability of the five victim locations shown in based on total energy flux and tenability based on gas concentrations in the period prior to fire department arrival.

6.2.1 Prior To Fire Department Arrival

To examine the potential survivability and tenability prior to fire department intervention the experiments were grouped by the available ventilation configuration. The average fractional effective dose over time was calculated for each victim location along with the value of one standard deviation. The earliest intervention of the group of experiments was used as the initial intervention time in order to remain consistent with regards to exposure time.

No Ventilation

Figure 6.6 represents the no ventilation configuration where all exterior windows/doors were closed. The fire was located in Bedroom 1 and fire department intervention occurred at 6 minutes and 58 seconds, after the fire reached a ventilation limited state.

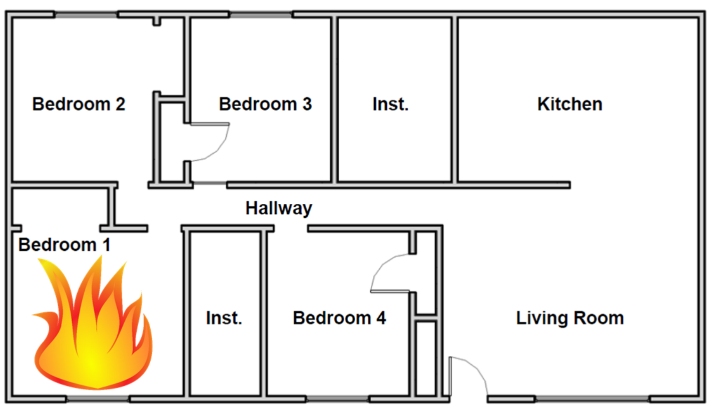


Figure 6.6: Ventilation Configuration - No Ventilation (Experiments 1-6)

Figure 6.7 illustrates the average fractional effective dose over time at each of the victim locations, relative to toxic gases and both radiative and convective heat transfer. The shaded areas represent ± one standard deviation from the average value with the shaded color corresponding to the victim location.

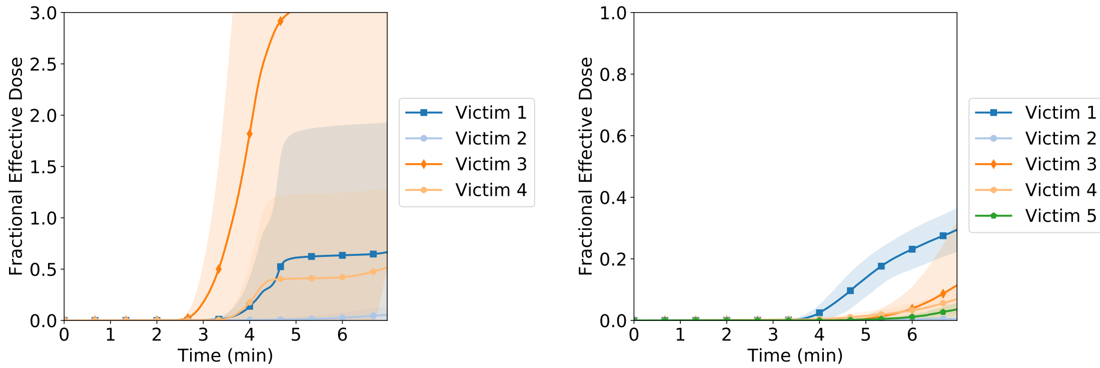


Figure 6.7: No Ventilation Fractional Effective Dose Prior to Fire Department Arrival. Left chart is based on gas concentration, Right chart is based on both convective and radiative transfer.

With regards to the toxic gases both survivability and tenability are related to the elevation in the space, along with the proximity to the fire. Victim 3 was located on the bed in the open bedroom; once the smoke layer reached the victim the FED increased rapidly, exceeding a FED of 3 between 5 min 30 sec and 6 min 30 sec. The smoke took significantly longer to reach Victims located at the floor level, resulting in a lower FED at the time of fire department arrival. Victim 4 being more remote to the fire shows a higher FED than Victim 1 near the fire, as the flow path carried the smoke to the floor level in the remote locations first as the ambient air was drawn back to the fire keeping Victim 1 in the ambient air longer.

Evaluating the survivability in terms of heat energy, indicates all of the victim locations are below the threshold for fatality in 50 % of the population. Victim 1, was shown to have the highest FED value due to the proximity of the fire followed by Victim 3, whose location was within the hot gas layer (3.2 ft above the floor). For the remainder of the locations FED was driven by the proximity to the fire where Victim 4 was closer than Victim 5. The effectiveness of a closed bedroom door is illustrated by the Victim 2 location value being the lowest.

Single Window Vent

Figure 6.8 represents the ventilation configuration where all exterior windows/doors were closed with the exception of the Bedroom 1 window. The fire was located in Bedroom 1 and fire department intervention occurred at 5 minutes and 26 seconds, after the fire reached a flashover.

Figure 6.8: Ventilation Configuration - Single Window Vent (Experiments 7-12 & 18-21)

Figure 6.9 illustrates the average fractional effective dose over time at each of the victim locations, relative to toxic gases and both radiative and convective heat transfer. The shaded areas represent ± one standard deviation from the average value with the shaded color corresponding to the victim location.

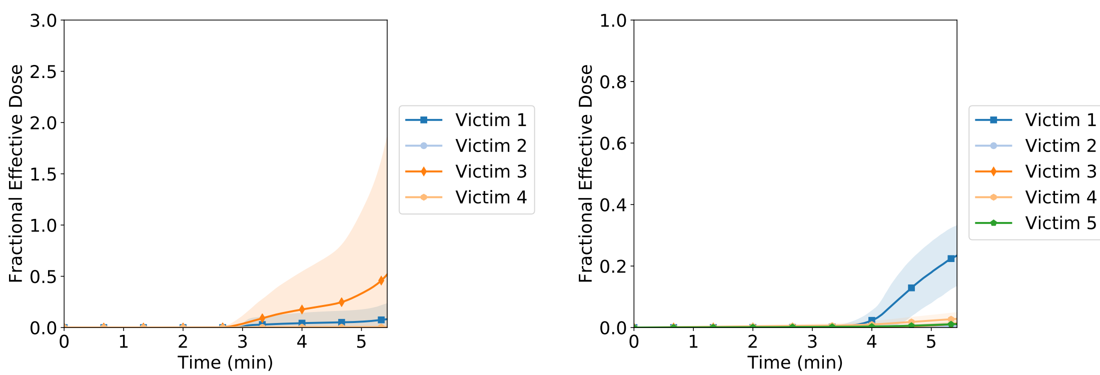


Figure 6.9: Single Window Vent Fractional Effective Dose Prior to Fire Department Arrival. Left chart is based on gas concentration. Right chart is based on both convective and radiative transfer.

The fire department intervention was performed in just over 5 minutes limiting the time available for the gases reach the victim locations. This resulted in an FED from toxic gases at the time of intervention showing a tenable and survivable space at each location. The FED at the Victim 3 location began to increase just before intervention, indicating the time to untenability and fatality is was approaching.

The survivability in terms of heat energy was also less due to the decreased duration of exposure. When the FED based on both radiative and convective heat transfer are examined, all victim locations were below the threshold for fatality in 50 % of the population. The Victim 1 location had the highest FED value due to the proximity of the fire; however, the other four locations show almost no FED.

Two Window Vents, Two Rooms of Fire

Figure 6.10 represents the ventilation configuration where all exterior windows/doors were closed with the exception of the Bedroom 1 and Bedroom 2 windows. The fire was located in both Bedroom 1 and Bedroom 2. Fire department intervention occurred at 5 minutes and 24 seconds, after the fire reached flashover.

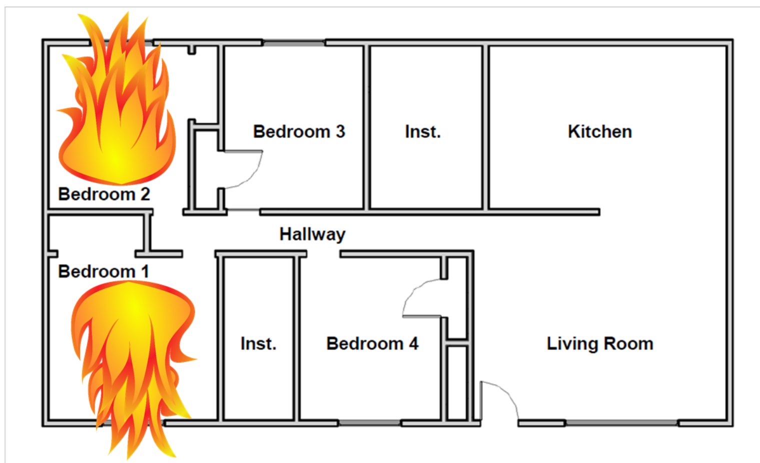


Figure 6.10: Ventilation Configuration - Single Window Vent (Experiments 13-17 & 22-24)

Figure 6.11 illustrates the average fractional effective dose over time at each of the victim locations relative to toxic gases and both radiative and convective heat transfer. The shaded areas represent +/- one standard deviation from the average value with the shaded color corresponding to the victim location.

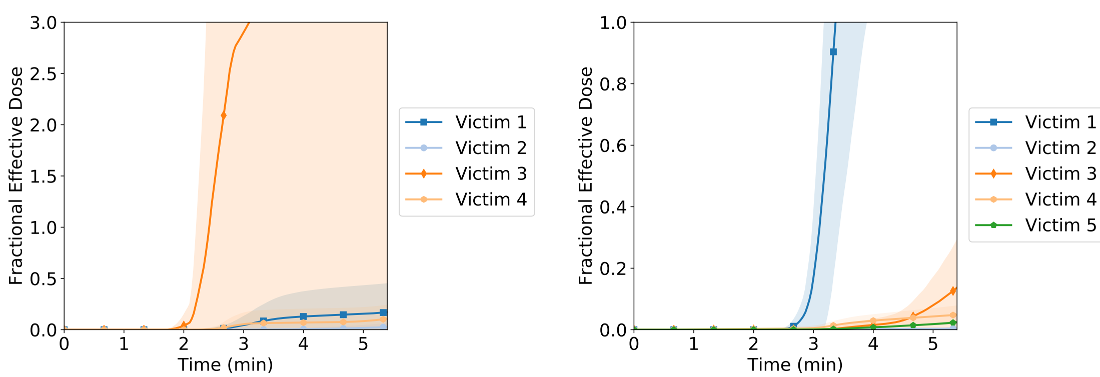


Figure 6.11: Two Window Vent Fractional Effective Dose Prior to Fire Department Arrival. Left chart is based on gas concentration. Right chart is based on both convective and radiative transfer.

The tenability and survivability based on toxic gas was again driven by the elevation in the space. With two rooms of fire and two ventilation openings, the Victim 3 location on the bed in the open bedroom exceeded a FED of 3 in just under 3 minutes. The smoke took longer to reach the 1 ft level, thus all other victim locations show almost no increase in FED at fire department intervention.

When evaluating the survivability in terms of heat energy, the Victim 1 location received a fatal dose in just under 3 minutes 30 seconds. After that point the FED is driven by the elevation; victim locations in the hot gas layer received more FED than those at the floor. After the 5 minute mark all victim locations received a thermal FED with the exception of the Victim 2 location behind the closed door.

6.2.2 Effect of No Intervention

To evaluate the effect of no intervention three experiments were conducted where fire department intervention was delayed so as to analyze the effect not intervening has on potential trapped occupants. Experiment 1 was the delayed intervention experiment when no ventilation was provided. Experiment 12 was the delayed intervention where the ventilation configuration was one room of fire with one window vent. Experiment 17 was the delayed intervention experiment where the ventilation configuration was two rooms of fire, each with one window vent. Figure 6.5 shows where four victim packages were located. The front door was opened, at fire department arrival, however, no other intervention was performed.

Fractional Effective Dose

To evaluate the impact of delaying intervention the toxic gases and thermal conditions were analyzed for the time it takes to receive at fatal dose. Figure 6.12 shows the time history of fractional effective does for each victim location during the three delayed intervention experiments. It is important to keep in mind that a fatal dose represents a LC_{50} which is a lethal concentration for 50% of the population.

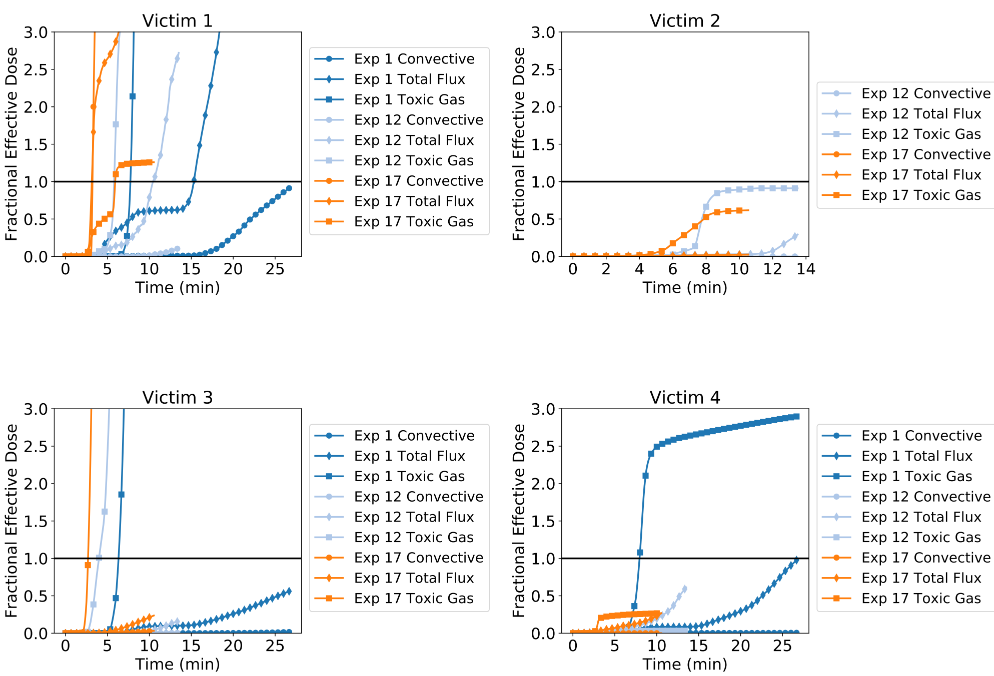


Figure 6.12: Fractional Effective Dose during delayed intervention experiments. Upper left is Victim 1, upper right is Victim 2. Lower left is Victim 3, lower right is Victim 4. A FED of 1.0 for thermal values is the LC_{50} for thermal exposure. For toxic gases a FED of 1.0 represents untenable conditions and a FED of 3.0 is potentially fatal.

Fatal doses were seen for Victim 1 and Victim 3. Victim 2 was behind a closed door and never received a fatal dose. Victim 4 was located remote from the fire in the living room. The delayed intervention experiments were terminated when the conditions threatened the test fixture or laboratory. At the point of termination, the Total Flux FED was exponentially increasing for Victim 4, and in Experiment 1 it would have been reached within seconds. For Experiment 12 it would have been reached within minutes. For those instances where a fatal dose was reached, Table 6.1 shows the time at which it occurred and the causal factor. Keep in mind the values reported in the table provide a relative comparison to demonstrate the impact of ventilation on survivability. The values would not be representative of an exact time of death of a given person.

Table 6.1: Time to LC_{50} FED (Minutes) - Delayed Intervention

Experimnt	Victim	Time to Fatal FED (minutes:seconds)	Driving Factor
Experiment 1	Victim 1	8:10	Toxic Gases
	Victim 3	6:58	Toxic Gases
Experiment 12	Victim 1	6:30	Toxic Gases
	Victim 3	5:14	Toxic Gases
Experiment 17	Victim 1	3:08	Total Flux
	Victim 3	3:06	Toxic Gases

As the ventilation configuration was changed from no ventilation, to a single window and, then further to two windows, the fatal dose was received much faster. Once the conditions started to deteriorate at positions closer to the compartment of origin the fatal dose was reached very quickly (less than 1 minute). In positions further from the compartment of origin, it took significant time (greater than 5 minutes) for the fatal dose to be achieved.

Pig Skin Temperatures

The surface and subsurface temperature of the pig skins can be utilized to quantify the impact of fire department intervention. Table 6.2 shows the average temperature recorded on the surface and subsurface of the pig skin in both the cases where a fire department intervention was performed as compared to those where intervention is delayed.

Table 6.2: Average surface and subsurface pig skin temperatures in experiments where intervention was performed vs. those where intervention was delayed [55].

Ventilation Configuration	Action	Avg. Max Surface Temperature (°F)	Standard Deviation (°F)	Avg. Max Sub-dermal Temperature (°F)	Standard Deviation (°F)
No Vent	Intervention	123.6	10.8	110.3	3.6
	No Intervention	284.0		162.1	
Single Vent	Intervention	124.2	9.7	103.5	4.1
	No Intervention	225.0		151.7	
Two Vent	FD Intervention	207.2	45.9	132.6	8.5
	Intervention	478.4		173.5	

In all cases, regardless of the ventilation configuration, delaying suppression resulted in an increase in the skin surface and subsurface temperatures of the skin.

6.2.3 Effect of Fire Department Intervention

One of the major goals for implementing pig skin into the experimental study was to examine the relative impact of different suppression techniques on burn risk. The fire service discussion regarding interior versus exterior water application has often centered on the concerns that applying water from the exterior will increase the risk for creating steam and burning occupants trapped within the structure. This section will evaluate the skin temperature data in a relative format to compare changes in the conditions before and after water application based on those present prior to application.

Table 6.3: Definition of Burn Injury and Criteria

Degree of Burn	Description	Criteria
1^{st} degree	Superficial burns	> 0.02 Surface Necrosis but < 0.1mm Necrosis Depth
2^{nd} degree	Partial thickness burns	> 0.1mm Surface Necrosis but < 2 mm Necrosis Depth
3^{rd} degree	Full Thickness Burns	> 2 mm Necrosis Depth but < 10 mm Necrosis Depth
4^{th} degree	Beyond Full Thickness	> 10 mm Necrosis Depth

One important limitation of using a harvested porcine skin model is that it does not account for the effect of blood perfusion through the skin. By combining the skin temperature data with an engineering model that describes heat transfer through the skin, additional insights can be gleaned. Since temperatures were measured on skin without blood flow, a simple 1D heat transfer model can be utilized to estimate the necessary heat flux result in such changes. This approach is described in Appendix C and can provide more reliable estimations than the heat flux gauges that are impacted by condensation and moisture-related issues. This approach can be reversed to predict temperatures with a term added to the equation that can include the impact of blood perfusion (Appendix D). Importantly, this model also allows for a simple estimation of the depth of tissue damage (necrosis) to be determined. Through the understanding of depth of tissue damage, estimates of burn risks in the classical sense can be made. To provide a general comparison here, first-degree or "superficial" burns only involve damage to the skin in the epidermal layer (assumed to be less than 0.04 in (0.1 mm)) for the purpose of this analysis this would be a dimensionless surface necrosis value of >0.2. Second-degree or "partialthickness" have significant damage that extends into the dermal layer of the skin, but not yet through thickness (>0.08 in (>2 mm). Third-degree or "full-thickness" burns have damage that extends into the subcutaneous layer of the skin (assumed here to be 0.12 in-0.16 in (34 mm) for the thickest skin) and complete destruction of the dermal layer. Finally, fourth-degree burns are burns that extend into the tissue underneath the skin layer and involves necrosis of the subcutaneous layer. The thickness of skin does vary between various parts of the body, therefore, depending on the thickness of the skin will depend on if the burn is a third or a fourth degree burn. For the purposes of evaluating the potential injury occurring from water application, the criteria is listed in Table 6.3.

Table 6.4: Potential Burn Injury for all Experiments

Test Type	Experiment	Victim 1		Victim 3	
		5 Sec Prior	60 Sec Post	5 Sec Prior	60 Sec Post
No Vent Interior	1*	3^{rd} degree	4^{th} degree	3^{rd} degree	3^{rd} degree
	2	1^{st} degree	1^{st} degree	No Damage	1^{st} degree
	3	No Damage	No Damage	No Damage	No Damage
	4	1^{st} degree	1^{st} degree	2^{nd} degree	2^{nd} degree
	5	1^{st} degree	1^{st} degree	1^{st} degree	1^{st} degree
	6	1^{st} degree	1^{st} degree	1^{st} degree	1^{st} degree
Single Vent Interior	7	2^{nd} degree	2^{nd} degree	No Damage	No Damage
	8	1^{st} degree	1^{st} degree	No Damage	No Damage
	9	1^{st} degree	1^{st} degree	No Damage	No Damage
	10	1^{st} degree	2^{nd} degree	No Damage	No Damage
	11	2^{nd} degree	2^{nd} degree	No Damage	No Damage
	12*	3^{rd} degree	3^{rd} degree	1^{st} degree	1^{st} degree
Two Vent Interior	13	3^{rd} degree	3^{rd} degree	1^{st} degree	1^{st} degree
	14	2^{nd} degree	3^{rd} degree	1^{st} degree	2^{nd} degree
	15	2^{nd} degree	3^{rd} degree	No Damage	1^{st} degree
	16	3^{rd} degree	3^{rd} degree	1^{st} degree	1^{st} degree
	17*	3^{rd} degree	3^{rd} degree	1^{st} degree	1^{st} degree
Single Vent Transitional	18	2^{nd} degree	2^{nd} degree	No Damage	1^{st} degree
	19	1^{st} degree	1^{st} degree	No Damage	No Damage
	20	1^{st} degree	1^{st} degree	No Damage	No Damage
	21	1^{st} degree	1^{st} degree	No Damage	No Damage
Two Vent Transitional	22	3^{rd} degree	3^{rd} degree	1^{st} degree	1^{st} degree
	23	3^{rd} degree	3^{rd} degree	No Damage	No Damage
	24	3^{rd} degree	3^{rd} degree	No Damage	1^{st} degree

* Delayed Intervention Experiment

Table 6.4 provides the estimated burn damage for each experiment at 5 seconds prior to water application and 60 seconds post water application for the Victim 1 and Victim 3 locations. Importantly, this table includes the impact of both the temperature and the time of exposures to characterize burn risk. The burn threat is typically limited to first-degree or less for the 'No Vent' and 'Single Vent' experiments (except when intervention is delayed), though a few scenarios would result in burn that could reach beyond the epidermal layer and into the dermis (second-degree). Delayed intervention resulted in severe burns for the Victim 1 location, reaching depths greater than 10 mm in all three scenarios. The Victim location 3 in the delayed scenario for the "No Vent" experiments was also at risk for third to fourth degree burns.

In some experiments, independent of the application direction of water, an increase in surface necrosis (skin damage), was seen immediately after water application. Figure 6.13 and Figure 6.14 show the potential increase for both an interior or transitional attack. This was not seen in every experiment nor in every victim location. In many instances, the difference in potential damage seen from prior to water application as compared to after water application had little to do with the water application and was more likely a result of the heat penetrating into the deeper layers of tissue. As Stoll indicated, skin will continue to be damaged unless it can be cooled below 112 °F (44 °C) [51]. When compared to the experiments where intervention was delayed, the additional potential injury is minor relative to the potential with delayed intervention.

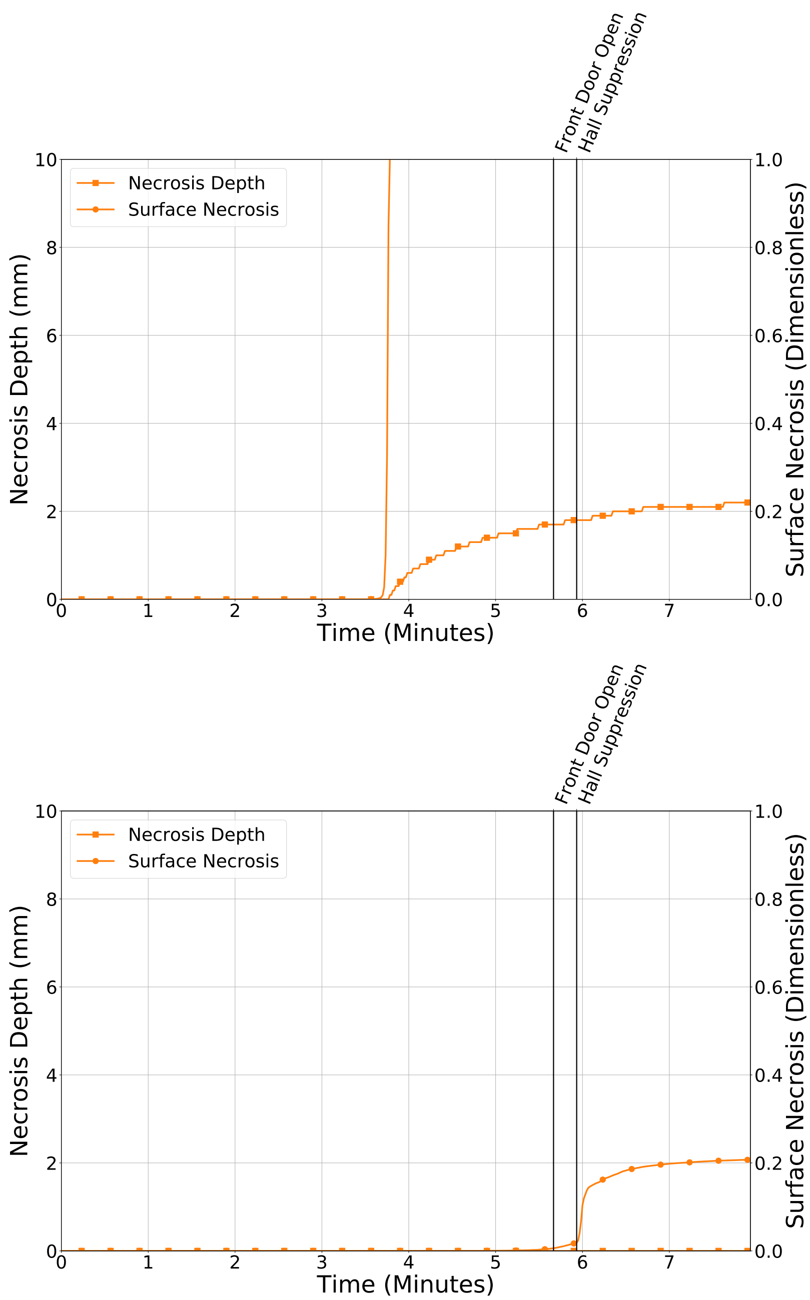
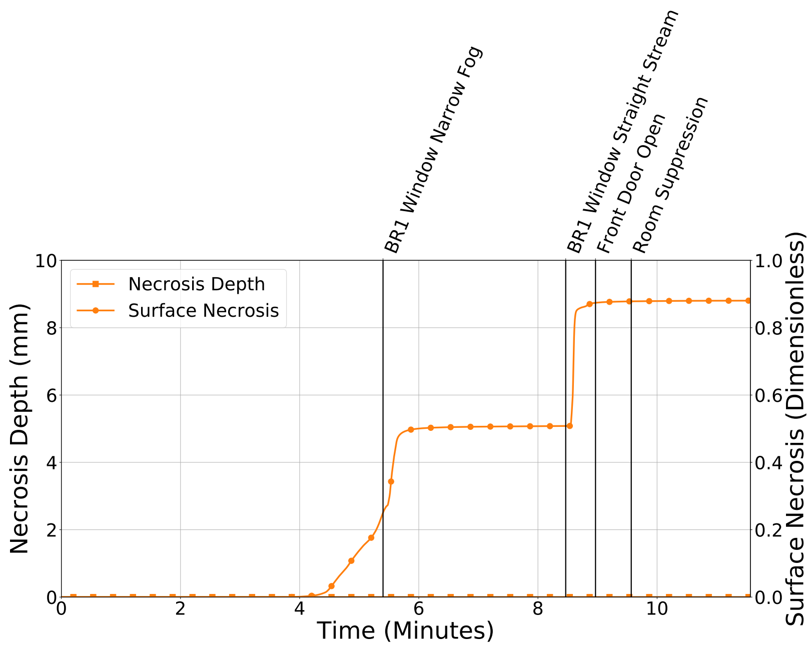


Figure 6.13: Example of Skin Necrosis Depth Increase during Interior Attack (Experiment 15). Victim 1 Location (Top), Victim 3 Location (Bottom). Surface Necrosis exceeding 0.2 is equivalent to a first-degree burn. Necrosis depth exceeding 0.2 mm is equivalent to a second-degree burn.



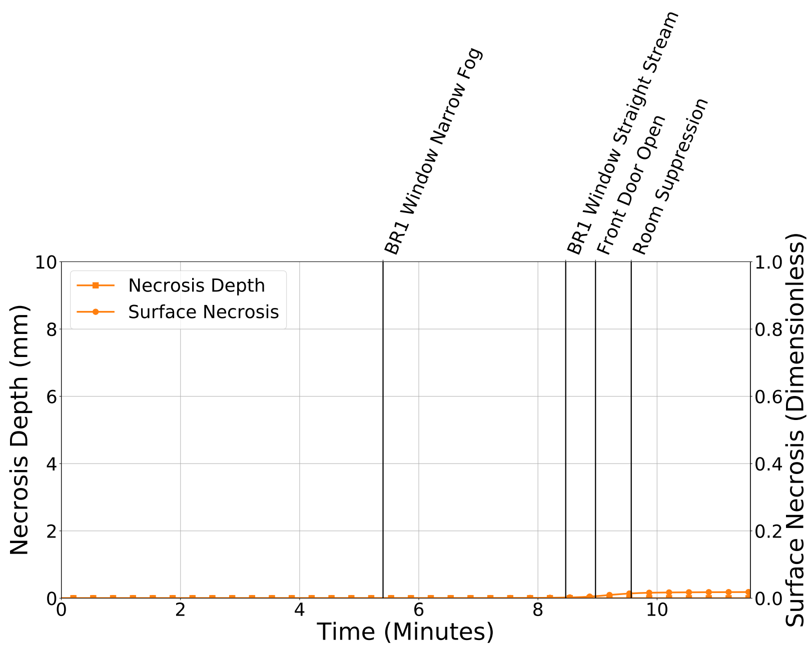


Figure 6.14: Example of Skin Necrosis Depth Increase during Transitional Attack (Experiment 19). Victim 1 Location (Top), Victim 3 Location (Bottom). Surface Necrosis exceeding 0.2 is equivalent to a first-degree burn. Necrosis depth exceeding 0.2 mm is equivalent to a second-degree burn.

The results indicate that increases in burn potential (skin damage) were independent of the method of suppression tactic (interior or transitional) utilized. Additionally, the potential injury seen during delayed intervention cases illustrates the need to apply water regardless of if there a potential for a minor increase in injury potential. Further research on this topic should evaluating the difference between suppression water landing on instrumented skin samples as opposed to when water is being applied to adjacent compartments. Additionally, this measurement and analysis focused on exposed skin, additional research will need to be conducted to evaluate if the increased damage to the skin surface would be more harmful if the injury were to occur to the respiratory track.

6.3 Water Vapor Measurement

There are many terms to describe the amount of "water" in the air. Humidity, vapor, moisture, and steam are a few terms which are generally used to address the topic of water in the air, but these terms and others have very specific meanings in engineering use. While there are many ways to understand the amount of water dissolved into the air or other gaseous environment, the two that we will discuss here are relative humidity and percent moisture by volume.

Relative humidity is a ratio of the amount of moisture in the air relative to the maximum amount of moisture the air can hold at a given temperature up to 100 °C (212 °F). The amount of moisture the air (or gas) can hold is dependent on the temperature of the air (or gas). Percent moisture by volume is the ratio of the number of H_2O molecules per unit volume relative to the total number of molecules per unit volume. This value is an absolute value and does not change with temperature. This is the value that will be used to assess the amount of moisture inside the test structure during the fire experiments.

Let's examine examples of the relationship between relative humidity and percent moisture at temperatures below 100 °C (212 °F). Let's say that the air temperature is 29.4 °C (85 °F) and the RH is 50%, then the percent moisture by volume would be 2%. If the air temperature increased to 36.7 °C (98 °F) and the RH remained at 50%, the percent moisture by volume would have increased to 3%. If the temperature remained at 36.7 °C (98 °F) and the RH increased to 100%, then the percent moisture by volume would have increased to 6%.

Another item to keep in mind regarding moisture in the form of steam. Steam cannot be seen. The cloud that most people refer to as steam is moisture or water vapor that has condensed into water droplets.

Measurement of the moisture content in the fire environment is challenging. Conventional measurement devices are not robust enough to withstand the environmental conditions inside a structure fire. The measurement techniques developed for this project attempted to quantify the water vapor using three different techniques. The most successful technique was effective at measuring water vapor for at least a portion of 11 out of 26 experiments. Three different scenarios provided complete water vapor concentration data and were successful for the entire duration of the experiment. The measurements were taken at three different elevations in Bedroom 4, a height of 1 ft (floor level), a height of 3 ft (bed level) and in the smoke layer at a height of 5 ft. Table 6.5 lists the water vapor measurements at ignition, 5 seconds prior to water application and the peak recorded during the experiment, grouped by the elevation and ventilation type.

Table 6.5: Summary of Water Vapor Measurements in Percent Water Concentration by Volume. (Change in Percentage from Ignition)

Experiment	Concentration at Ignition	Concentration 5 seconds Prior to Suppression (% Change)	Concentration 60 Seconds After Application (% Change)	Peak Concentration (% Change)
No Vent - 1 ft				
4	1.65	N/A (N/A)	N/A (N/A)	4.10 (2.45)
6	1.09	4.40 (3.32)	4.39 (3.30)	4.94 (3.85)
Average	1.37	4.40 (3.32)	4.39 (3.30)	4.52 (3.15)
Single Vent - 1 ft				
18	0.85	1.07 (0.22)	1.73 (0.88)	1.95 (1.09)
19	1.23	1.14 (-0.08)	1.86 (0.63)	4.01 (2.78)
Average	1.04	1.11 (0.07)	1.8 (0.76)	2.98 (1.94)
Single Vent - 3 ft				
20	1.94	2.36 (0.42)	4.55 (2.62)	6.36 (4.42)
Single Vent - 5 ft				
7	1.61	2.61 (1.00)	N/A (N/A)	4.91 (3.30)
10	2.06	6.07 (4.00)	6.99 (4.92)	11.9 (9.84)
11	1.70	N/A (N/A)	6.73 (5.03)	7.25 (5.54)
21	2.26	5.18 (2.92)	6.15 (3.88)	9.41 (7.15)
Average	1.91	4.62 (2.64)	6.62 (4.61)	8.37 (6.46)
Two Vent - 1 ft				
16	1.53	3.37 (1.85)	3.57 (2.04)	3.99 (2.46)
Two Vent - 3 ft				
13	1.62	N/A (N/A)	N/A (N/A)	5.97 (4.35)

Increases in water vapor appeared to correlate with the smoke layer descending in the room where the water vapor was measured. The measurements taken higher in the space (in the smoke layer) resulted in higher values being recorded. When the measurement was taken at the 1 ft level, there was a limited increase in moisture content between 5 seconds prior to suppression and 60 seconds after suppression. At the higher elevations in the space (in the smoke layer), the moisture would increase between approximately 2% by volume during the period between 5 seconds prior to and 60 seconds after suppression. However the moisture would increase by a similar amount from ignition until the time of 5 seconds prior to suppression.

This suggests that at the 1 ft level in a bedroom not in the flow path, where water is not applied in the room, moisture content is not increasing during suppression activities. At the higher elevations, it is not possible to determine whether the increase is due to the application of water or due to transport time for the products of combustion to reach the location of the sensor.

The laser measurement technique utilized encountered a low transmission level (due to smoke obscuration) prior to the end of the experiment, resulting in an incomplete time history for moisture. Once the smoke cleared the transmission level often increased and the signal returned. Figure 6.15 shows the time history of each moisture measurement, grouped by the ventilation configuration and elevation of the reading.

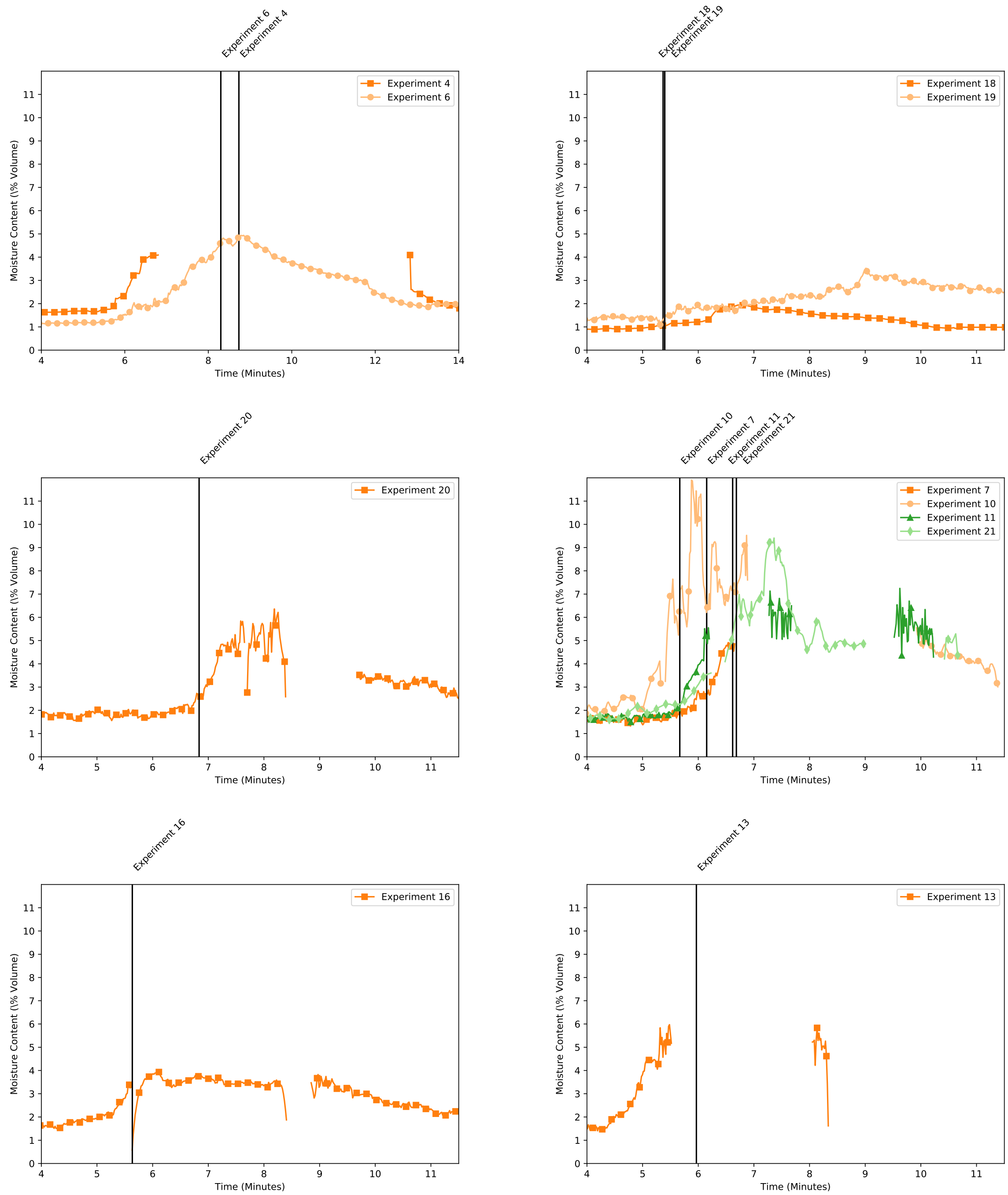


Figure 6.15: Laser moisture measurements for experiments were data was obtained. No vent case - 1 ft (top left), single vent case - 1 ft (top right), single vent case 3 ft (middle left), single vent case - 5 ft (middle right), two vent case 1 ft (bottom left), two vent case 3 ft (bottom right). Vertical line with experiment number is the initial water application. Gaps in time history indicate where measurement was not recorded due to low laser intensity.

Moisture was recorded throughout the entire experiment in Experiments 6, 18 , and 19. The measurement did not exceed 5% by volume at the 1 ft level. This is consistent with other ventilation configurations where the sensor was located at 1 ft. When the sensor was moved vertically in the space the moisture measurement increased. At the 5 ft level the maximum recorded moisture was more than double that at 11%.

6.4 Tactical Effectiveness of Knock Back Capability

In the following subsections, the temperatures measured within the fire room are used to determine the time to "knock back" the fire, which is defined as the period from initial water application to when all measured temperatures in the fire room are less than 400 °F, the upper temperature limit of the 'ordinary' thermal class for firefighter operating conditions proposed by Utech [31]. The "knock back" times are compared between experiments in five different groups based on fire attack method. Three of the groups contain experiments that used an interior fire attack method, and two of the sets contain experiments in which the first suppression event was an exterior fire attack. The differentiating factor between experiments within the three interior fire attack groups is the ventilation configuration, while the main difference between experiments within the two other groups is the ventilation configuration and the fire attack method used after the initial exterior suppression event.

6.4.1 Flow & Move with Solid Stream

The 'flow and move' method with a solid stream from a smooth bore nozzle was the primary fire attack method used during Experiments 2, 7, and 13, which contained the 'No Vent', 'Single Vent', and 'Two Vent' ventilation configurations, respectively. Figure 6.16 contains a plot of the Bedroom 1 temperatures over the duration from six seconds before the start of interior suppression to one minute after for each experiment.

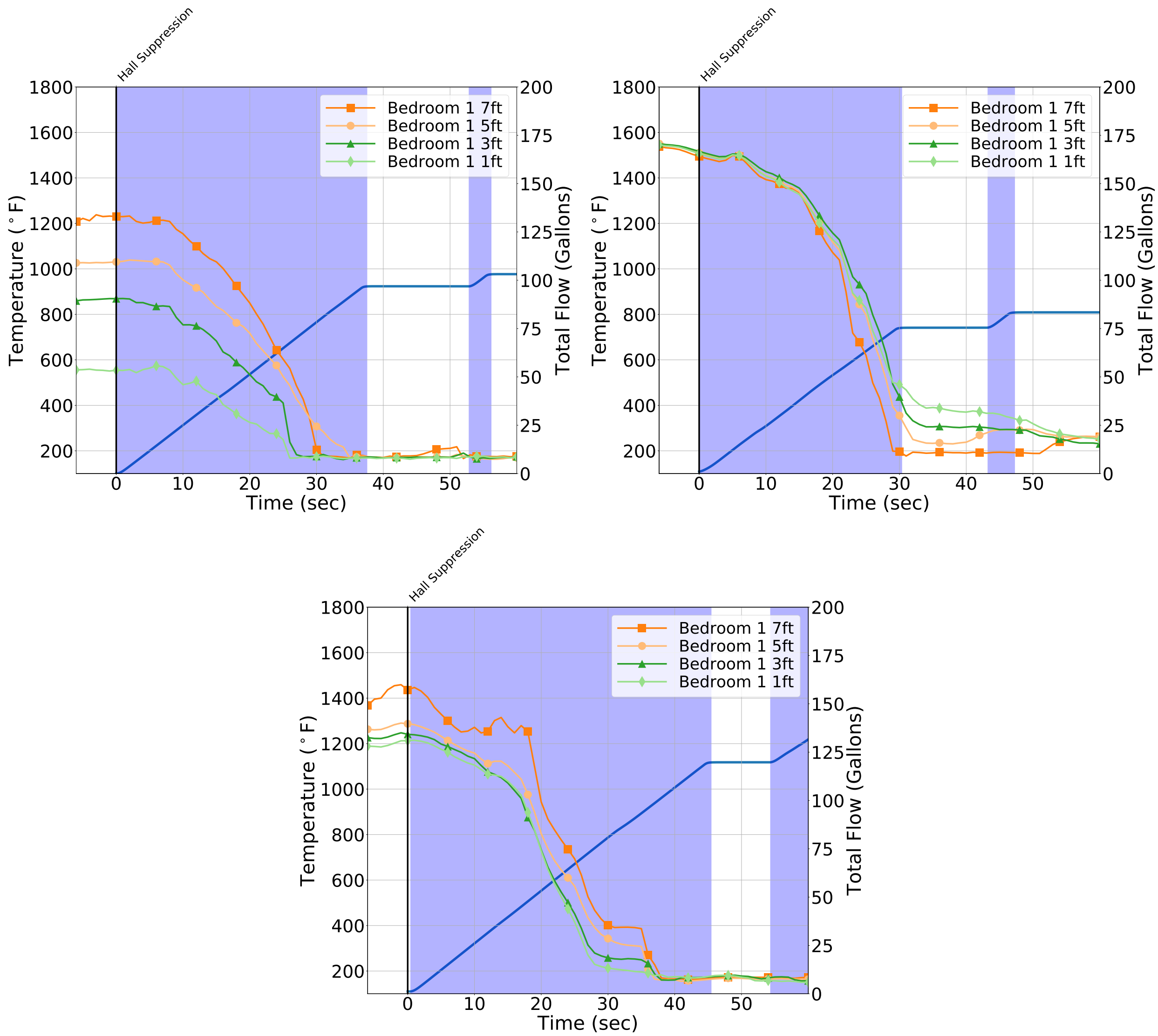


Figure 6.16: Bedroom 1 temperatures over the duration from six seconds before the start of interior suppression to one minute after for Experiments 2 (top left), 7 (top right), and 13 (bottom). The ‘flow and move’ method with a solid stream from a smooth bore nozzle was the primary attack method used during each experiment. The blue shaded areas represent water flow from the hose stream.

Bedroom 1 temperatures before the start of suppression for Experiment 2 are indicative of temperatures before flashover, while the Bedroom 1 temperatures at the same instance during Experiments 7 and 13 are indicative of a room that has transitioned to flashover. The fire room failed to reach flashover in Experiment 2 because the ‘No Vent’ ventilation configuration significantly restricted the flow of oxygen to the fire room, unlike the ‘Single Vent’ and ‘Two Vent’ configurations in which oxygen was provided to the fire room through the open window of Bedroom 1.

Despite the difference in Bedroom 1 temperatures before suppression, the Bedroom 1 temperatures responded similarly to the suppression event in all three experiments: 30 seconds after the start of suppression, Bedroom 1 temperatures decreased to values below 400 °F and eventually converged to values near 200 °F by 50 seconds after the start of suppression.

6.4.2 Shutdown & Move with Solid Stream

The 'shutdown and move' method with a solid stream from a smooth bore nozzle was the primary fire attack method used during Experiments 6, 8, and 14, which contained the 'No Vent', 'Single Vent', and 'Two Vent' ventilation configurations, respectively. Figure 6.17 contains a plot of the Bedroom 1 temperatures over the duration from six seconds before the start of interior suppression to one minute after for each experiment.

The distribution of Bedroom 1 temperatures before suppression in Experiment 6 was significantly larger than the distribution of Bedroom 1 temperatures at the same instance in Experiments 8 and 14. This difference can once again be attributed to the 'No Vent' ventilation configuration that was used for Experiment 6, which significantly restricted the flow of oxygen to the fire room.

Despite the difference in Bedroom 1 temperatures before suppression, the Bedroom 1 temperatures responded similarly to the suppression event in all three experiments: the temperatures only began to significantly decrease during the third period of water flow (around 30 seconds after the start of suppression), when the suppression crew was at the end of the hall near the Bedroom 1 doorway. For Experiment 6, all temperatures dropped below 400 °F by the end of the third instance of water flow.

It's possible that all Bedroom 1 temperatures in Experiment 8 behaved in a manner similar to Experiment 6. At the very least, the Bedroom 1 temperature 7 ft above the floor behaved in a manner similar to Experiment 6. However, the true response of the other three Bedroom 1 temperatures to the third period of water flow is unknown. Based on the sharp rise in the temperature at 1 ft, 3 ft, and 5 ft above the floor during the third period of water flow and erratic behavior that exists in the temperature data from the same locations later in the experiment, it is likely the thermocouples came in contact with material burning on the floor near the thermocouple array.

Although the Bedroom 1 temperatures began to sharply decline during the third instance of water flow during Experiment 14, the temperatures didn't drop below 400 °F until the fourth period of water flow around 45 seconds after the start of suppression. The longer duration of Bedroom 1 temperature decline might be due to the fact that the 'Two Vent' setup used during Experiment 14 contained two fire rooms, so the suppression crew divided water between the two rooms instead of using all the water to extinguish the fire in Bedroom 1.

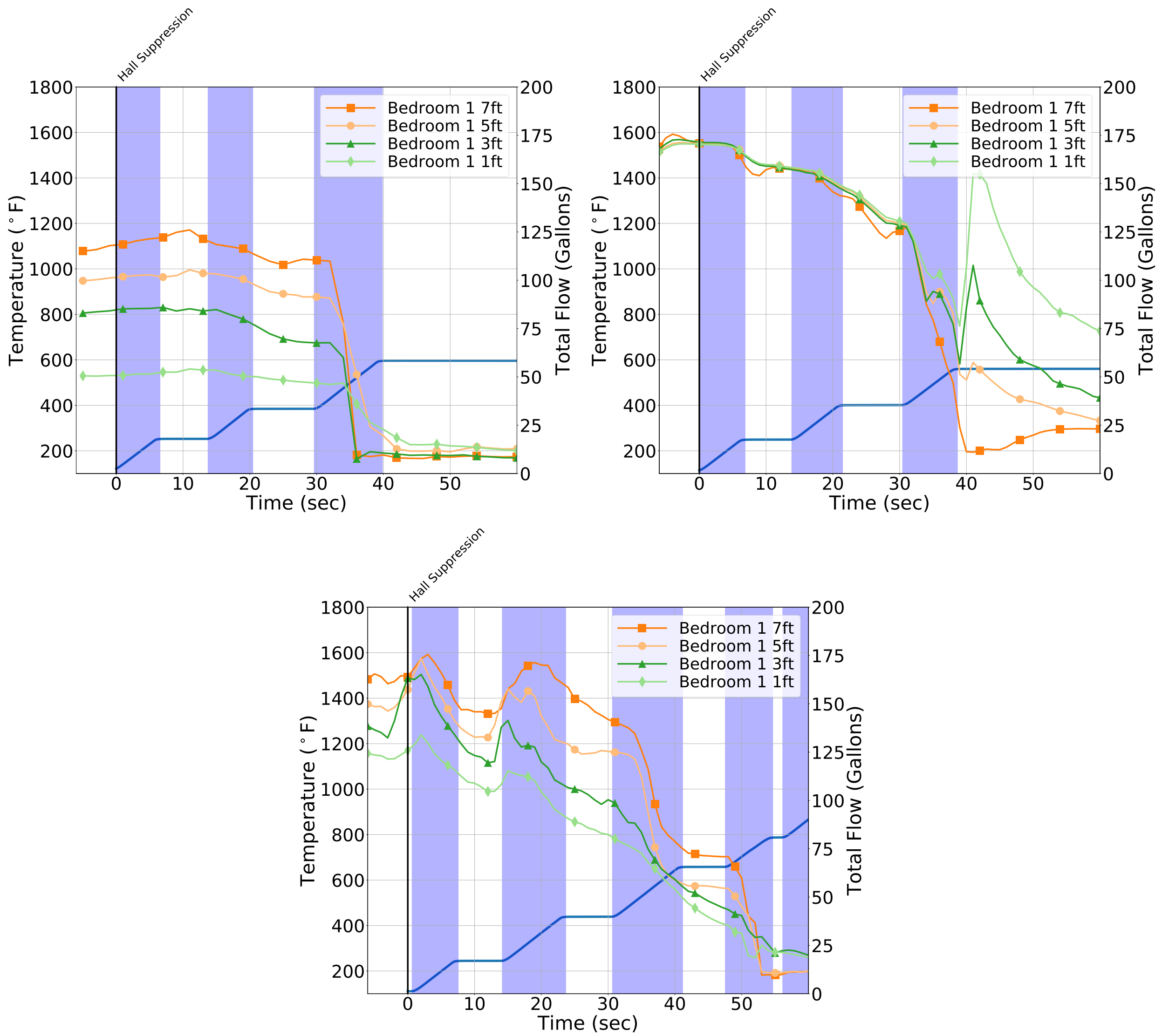


Figure 6.17: Bedroom 1 temperatures over the duration from six seconds before the start of interior suppression to one minute after for Experiments 6 (top left), 8 (top right), and 14 (bottom). The 'shutdown and move' method with a solid stream from a smooth bore nozzle was the primary attack method used during each experiment. The blue shaded areas represent water flow from the hose stream.

6.4.3 Flow & Move with Narrow Fog

The 'flow and move' method with a narrow fog stream from a combination nozzle was the primary fire attack method used during Experiments 11 and 16, which contained the 'Single Vent' and 'Two Vent' ventilation configuration, respectively. Figure 6.18 contains a plot of the Bedroom 1 temperatures over the duration from six seconds before the start of interior suppression to one minute after the event for each experiment.

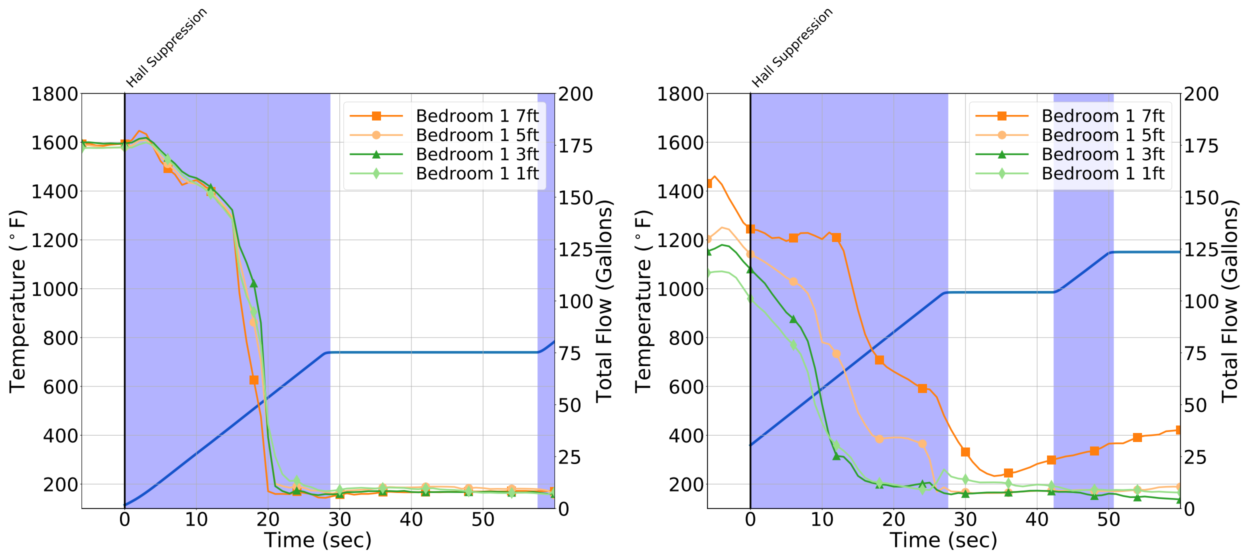


Figure 6.18: Bedroom 1 temperatures over the duration from six seconds before the start of interior suppression to one minute after for Experiments 11 (left) and 16 (right). The 'flow and move' method with a narrow fog stream from a combination nozzle was the primary attack method used during each experiment. The blue shaded areas represent water flow from the hose stream.

In both experiments, all Bedroom 1 temperatures decreased to values around 200 °F after the suppression crew flowed water in a narrow fog stream for less than 30 seconds while moving down the hallway. The Bedroom 1 temperatures decreased at a slightly faster rate in Experiment 11, which can be attributed to the 'Single Vent' configuration used during the experiment, which contained one fire room, while Experiment 16 used the 'Two Vent' configuration, which contained two fire rooms.

6.4.4 Initial Exterior Attack at Bedroom 1 Window

Experiments 18, 20, 22, and 24 each had a similar initial suppression event that involved flowing water from the exterior of the structure into the fire room through the window of Bedroom 1. Water was applied in a solid stream pattern from a smooth bore nozzle during every experiment except Experiment 24, which used a combination nozzle set to a straight stream pattern to flow water. Experiments 18 and 20 contained the 'Single Vent' ventilation configuration, and Experiments 22 and 24 contained the 'Two Vent' ventilation configuration. Figure 6.19 contains a plot of the Bedroom 1 temperatures over the duration from four seconds before the start of the initial suppression to 24 seconds after for each experiment.

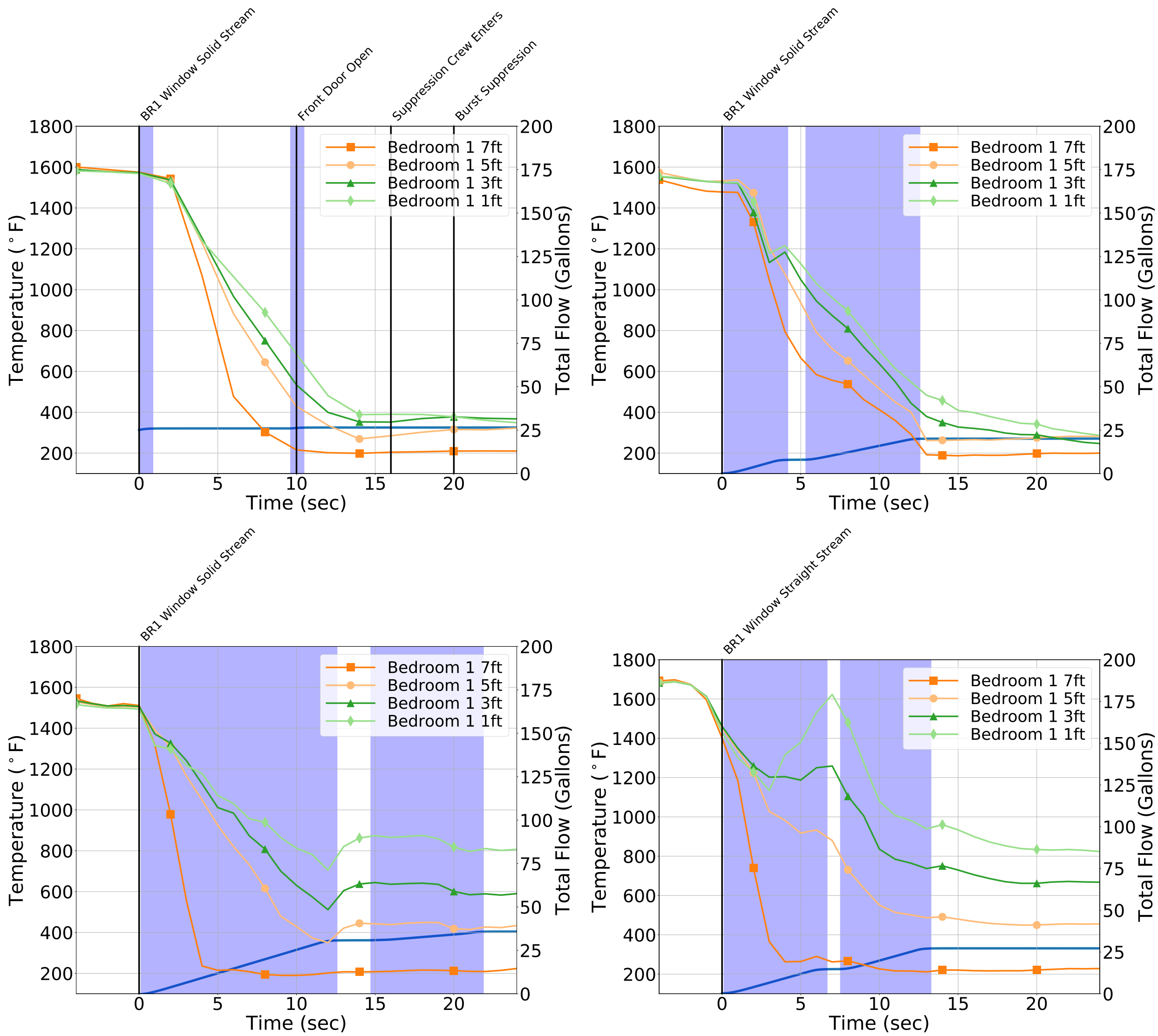


Figure 6.19: Bedroom 1 temperatures from four seconds before the initial exterior suppression event to 24 seconds after the event during Experiments 18 (top left), 20 (top right), 22 (bottom left), and 24 (bottom right). The blue shaded areas represent water flow from the hose stream.

After the initial suppression event, the Bedroom 1 temperatures significantly decreased at a similar rate in all four experiments. Additionally, the temperature distribution became inverted once the temperatures began to decline and remained inverted along the plotted duration.

The value to which the temperatures decreased is dependent upon the experimental configuration. During Experiments 18 and 20, which used the 'Single Vent' setup, the largest temperature recorded after the initial suppression event was below 400 °F, while the largest temperature recorded after the initial suppression event was between 800 °F and 900 °F for Experiments 22 and 24, which used the 'Two Vent' setup. The discrepancy in maximum temperature after the suppression event can be partially attributed to the fact that the fire in the 'Two Vent' configuration was larger than the fire in the ‘Single Vent’ configuration.

6.4.5 Exterior Suppression at Bedroom 1 Window with Additional Attack

Experiments 22 and 24 each had a similar initial suppression event that involved flowing water from the exterior of the structure into the fire room through the window of Bedroom 1 using a solid stream from a smooth bore nozzle and a straight stream from a combination nozzle, respectively. Both experiments contained the ‘Two Vent’ ventilation configuration. However, the interventions performed after the initial suppression event differ between the two experiments.

After the initial exterior suppression in Experiment 22, the suppression crew performed an interior suppression that resembled the ‘shutdown and move’ attack method. After the initial exterior attack in Experiment 24, the suppression crew moved to the window of Bedroom 2 and performed a second exterior attack by flowing water into the second fire room through the window of Bedroom 2. The temperatures measured by four different thermocouple arrays over the duration from six seconds before the start of the initial exterior suppression event to 95 seconds after were plotted for each experiment. Figure 6.20 contains a plot of the Bedroom 1 temperatures and a plot of the Bedroom 2 temperatures for each experiment. A plot of the temperatures at the end of the hallway and a plot of the temperatures in Bedroom 4 (bedroom with open door) for each experiment are provided in Figure 6.21.

Based on the plots of the temperatures within the two fire rooms, the initial exterior attack during each experiment had a very similar effect on the fire environments in Bedroom 1 and Bedroom 2. As a result of the initial attack, the Bedroom 1 temperatures significantly decreased and became inverted. The Bedroom 1 temperatures in each experiment decreased according to the following: the temperature at 7 ft above the floor decreased to a value around 200 °F; the temperature at 5 ft decreased to a value between 400 °F and 500 °F; the temperature at 3 ft decreased to a value between 600 °F and 700 °F; and the temperature at 1 ft decreased to a value between 800 °F and 900 °F. Furthermore, despite the differences in attack methods after the exterior suppression at the Bedroom 1 window, the Bedroom 1 temperatures continued to decrease in a similar manner over the plotted duration for both experiments, suggesting the initial attack extinguished most of the fire in Bedroom 1.

The initial exterior attack at the Bedroom 1 window caused the Bedroom 2 temperatures to slightly decrease in both experiments. However, the decrease was only temporary; during the time period between the end of the initial exterior attack and the next intervention, the temperatures increased and nearly returned to their original values in each of the experiments. An additional slight decrease in Bedroom 2 temperatures occurred during Experiment 22 after hall suppression began. Then, as the suppression crew moved down the hall closer to Bedroom 2, the temperatures started to significantly decrease as the crew flowed water. While the Bedroom 2 temperatures decreased at a significant rate in response to the interior suppression during Experiment 22, the Bedroom 2 temperatures decreased at a faster rate during the exterior attack performed at the window of Bedroom 2 during Experiment 24.

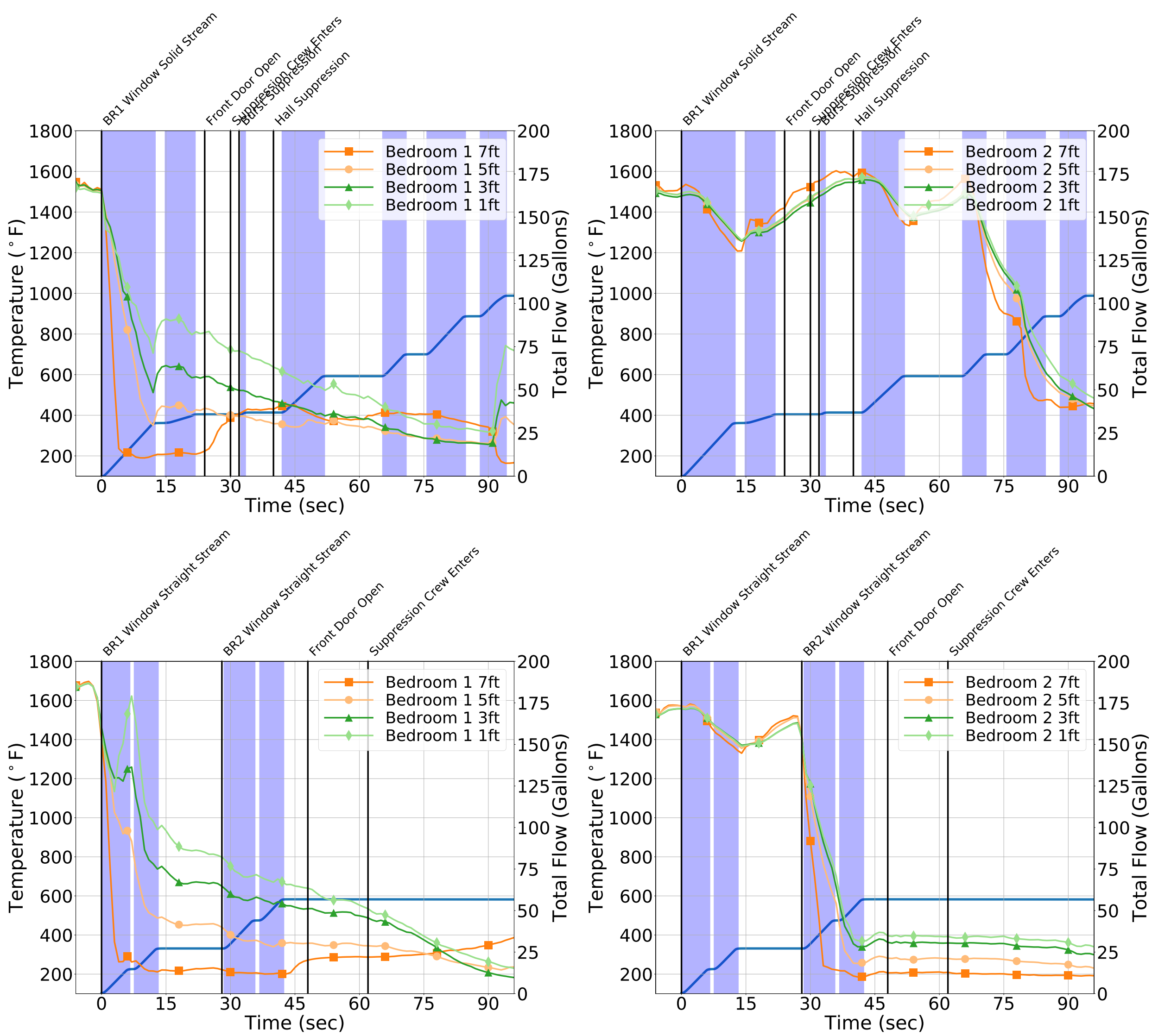


Figure 6.20: Experiments 22 (top) and 24 (bottom) Bedroom 1 temperatures (left column) and Bedroom 2 temperatures (right column) during suppression events. The blue shaded areas represent water flow from the hose stream.

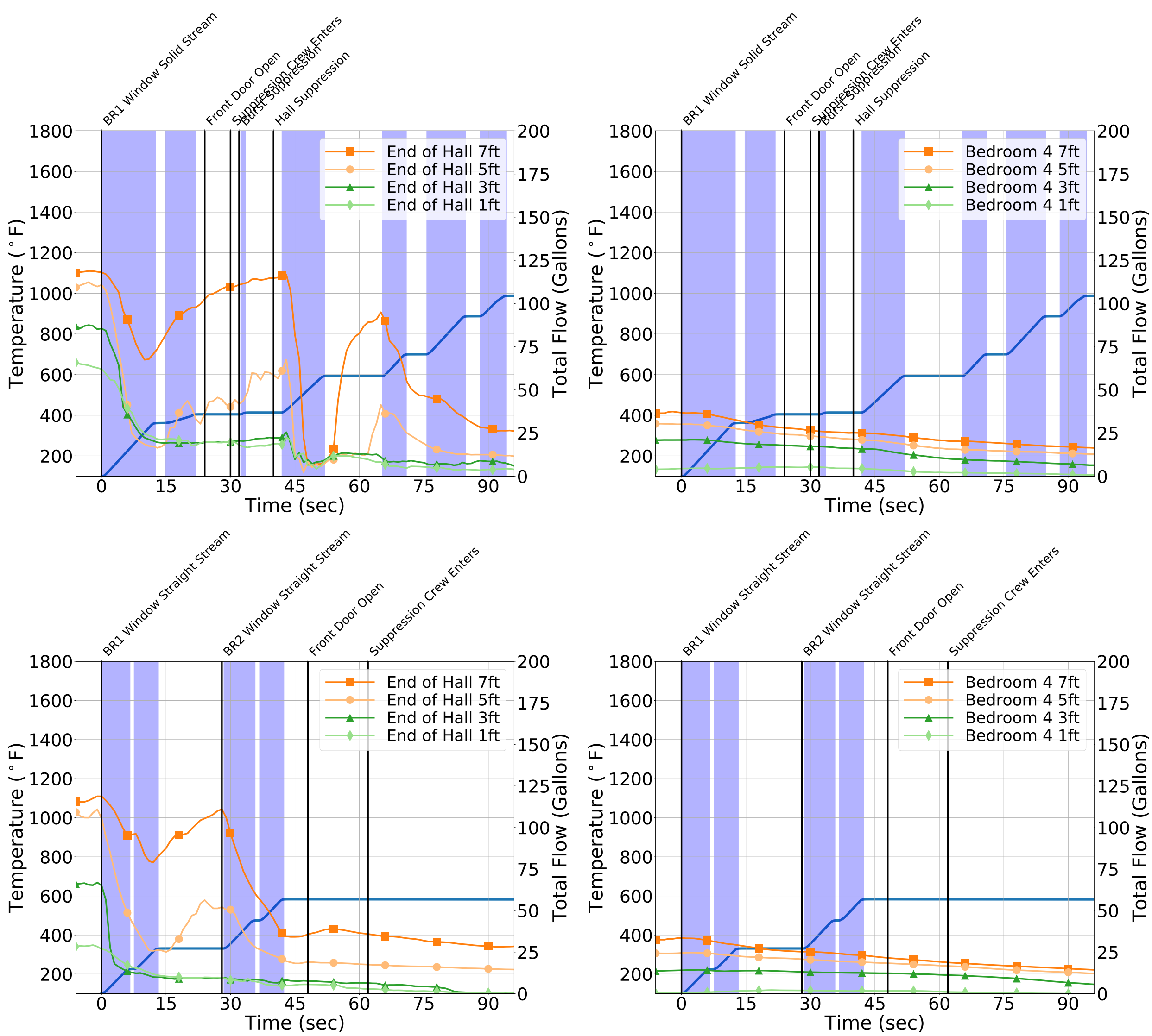


Figure 6.21: Experiments 22 (top) and 24 (bottom) end of the hall temperatures (left column) and Bedroom 4 temperatures (right column) during suppression events. The blue shaded areas represent water flow from the hose stream.

The plots in Figure 6.21 show that the temperatures at the end of the hall along with the temperatures in Bedroom 4 behaved similarly in Experiments 22 and 24. The temperatures at the end of the hall initially decreased in response to the first exterior suppression event. Following the end of water flow from the initial event, the temperatures measured at 5 ft and 7 ft above the floor at the end of the hall began to increase. In fact, the temperature 7 ft above the floor nearly returned to its original value before the next intervention in each experiment. The hall temperatures decreased significantly in response to the second suppression event performed in each experiment. However, they declined at a faster rate in response to the hall suppression event during the interior suppression in Experiment 22. Additionally, after the second exterior attack in Experiment 24, the hall temperatures at 7 ft and 5 ft began to increase and approach their values before suppression. The hallway temperatures decreased permanently only after an interior suppression was initiated following the two exterior attacks. The Bedroom 4 temperatures had a nearly identical response to the first suppression intervention during Experiments 22 and 24: they began to steadily decline following the event and continued to decline at a similar rate as the remaining experimental interventions were performed.

6.5 Ability to Influence the Flow of Products of Combustion

This test series included specific instrumentation to evaluate the ability of hose streams to move products of combustion in residential structure fires. Gas velocity instrumentation was installed at the window opening, at the door to the fire room, and at the start of the hallways to evaluate the flows during the different suppression tactics. To narrow the focus of this analysis the experiments featuring of a single bedroom fire in Bedroom 1, with the Bedroom 1 window open were utilized for both the interior and exterior section. Additionally, the flow and move cases were evaluated as they were the methods where the crew intended to alter the flow of the products of combustion during interior suppression operations. In order to allow for a direct comparison between the interior and exterior case, the same fire location and window ventilation was selected. During the exterior operations, the method intended to limit the degree to which the stream altered the flow, thus both the straight stream and narrow fog methods were evaluated.

6.5.1 Interior

During the interior suppression, the velocity probes at the start of the hallway and the window to the fire room showed that flowing water down the hallway had the ability to stop the flow of smoke out of the hallway while additionally impacting the flow in the vented bedroom window. Figures 6.22, 6.23, and 6.24 shows the flows at the start of the front door, start of the hallway, and bedroom window for the single room of fire and single open window ventilation cases where the flow and move tactic was utilized.

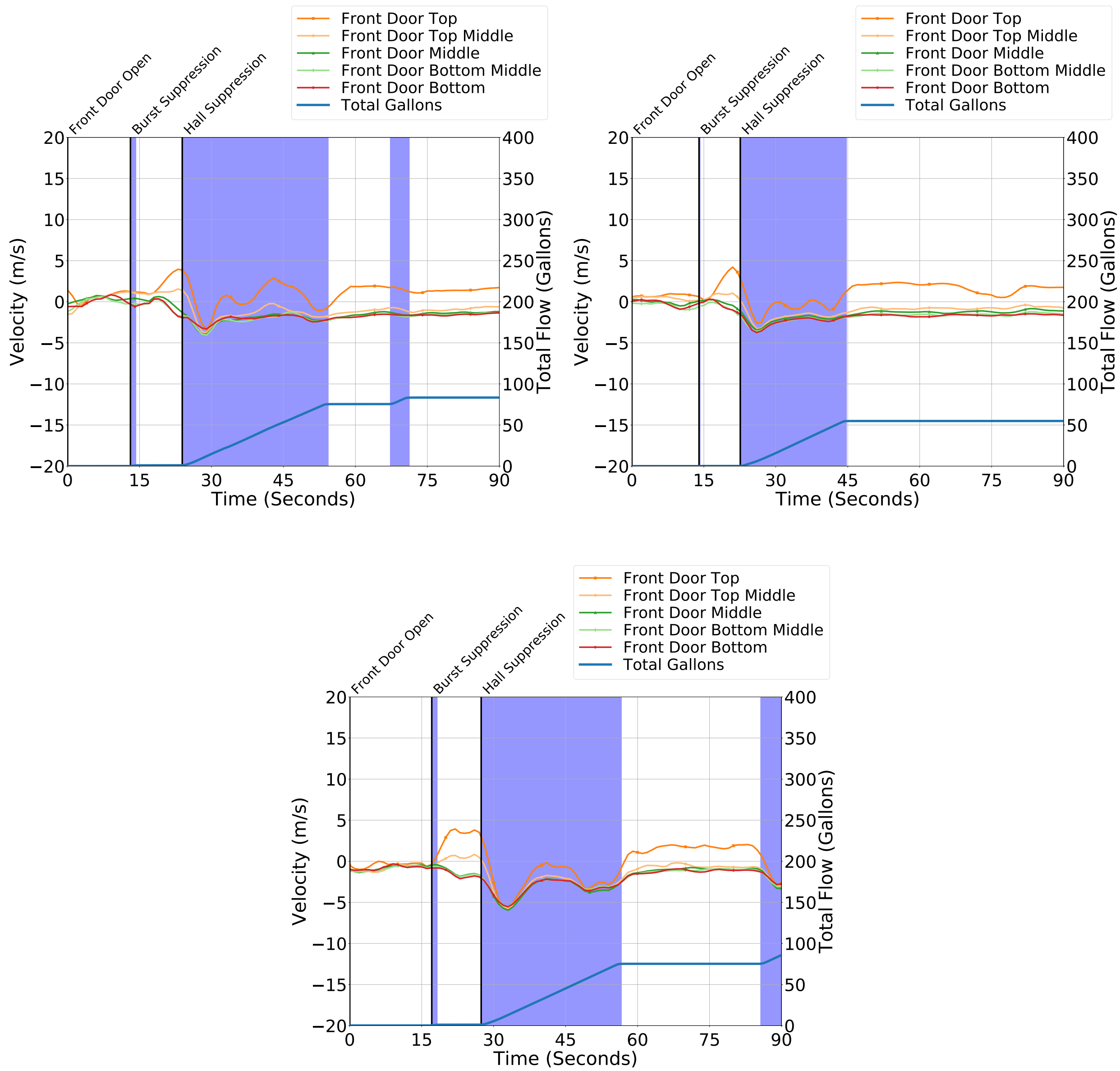


Figure 6.22: Gas velocities at the Front Door for the flow and move interior attacks with one room of fire and a single window vent. Top row is Experiment 7 (left) and Experiment 9 (right), and the bottom row is Experiment 11. The blue shaded areas represent when water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

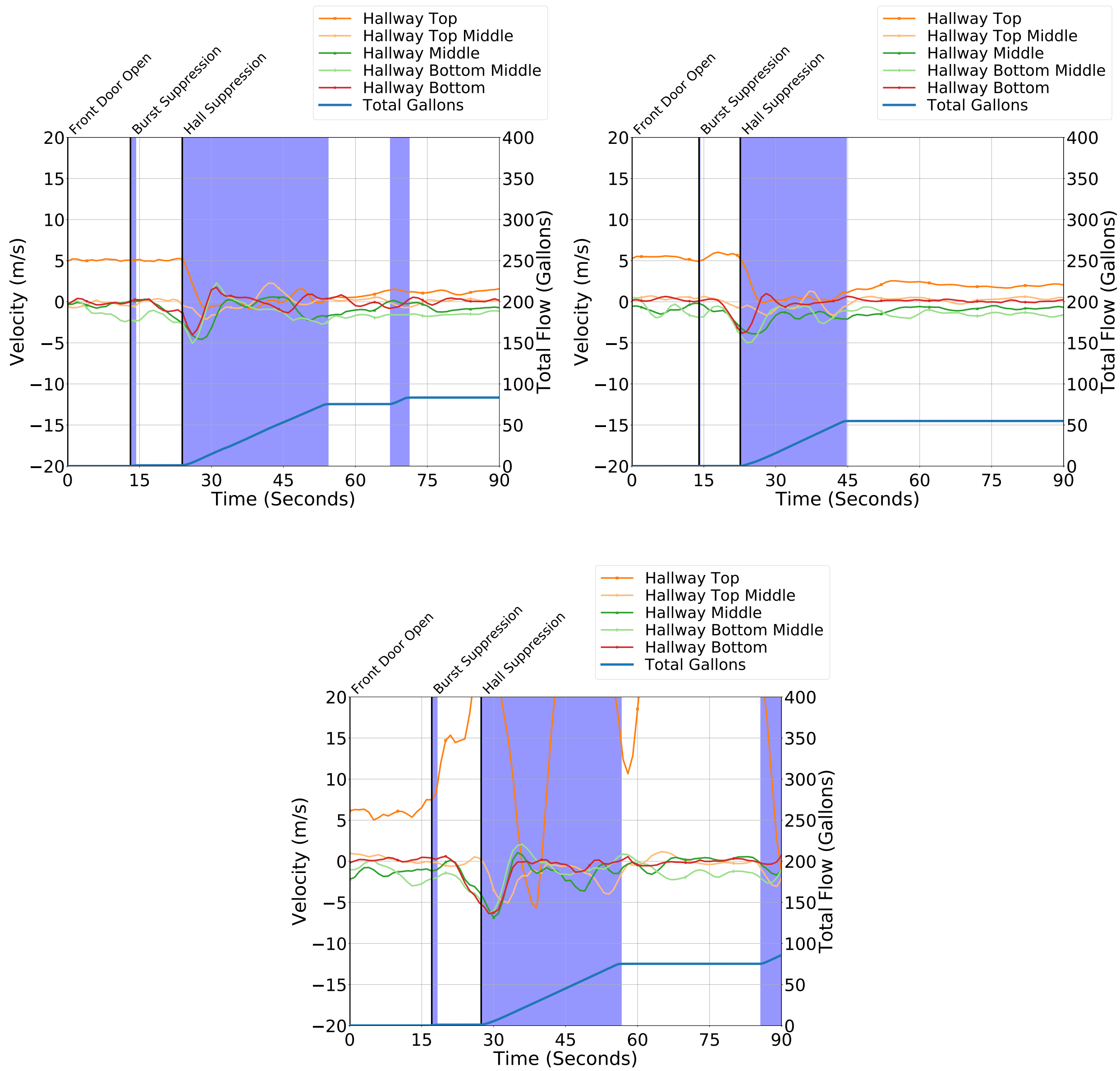


Figure 6.23: Gas velocities at the Start of Hall for the flow and move interior attacks with one room of fire and a single window vent. Top row is Experiment 7 (left) and Experiment 9 (right), and the bottom row is Experiment 11. The blue shaded areas represent when water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

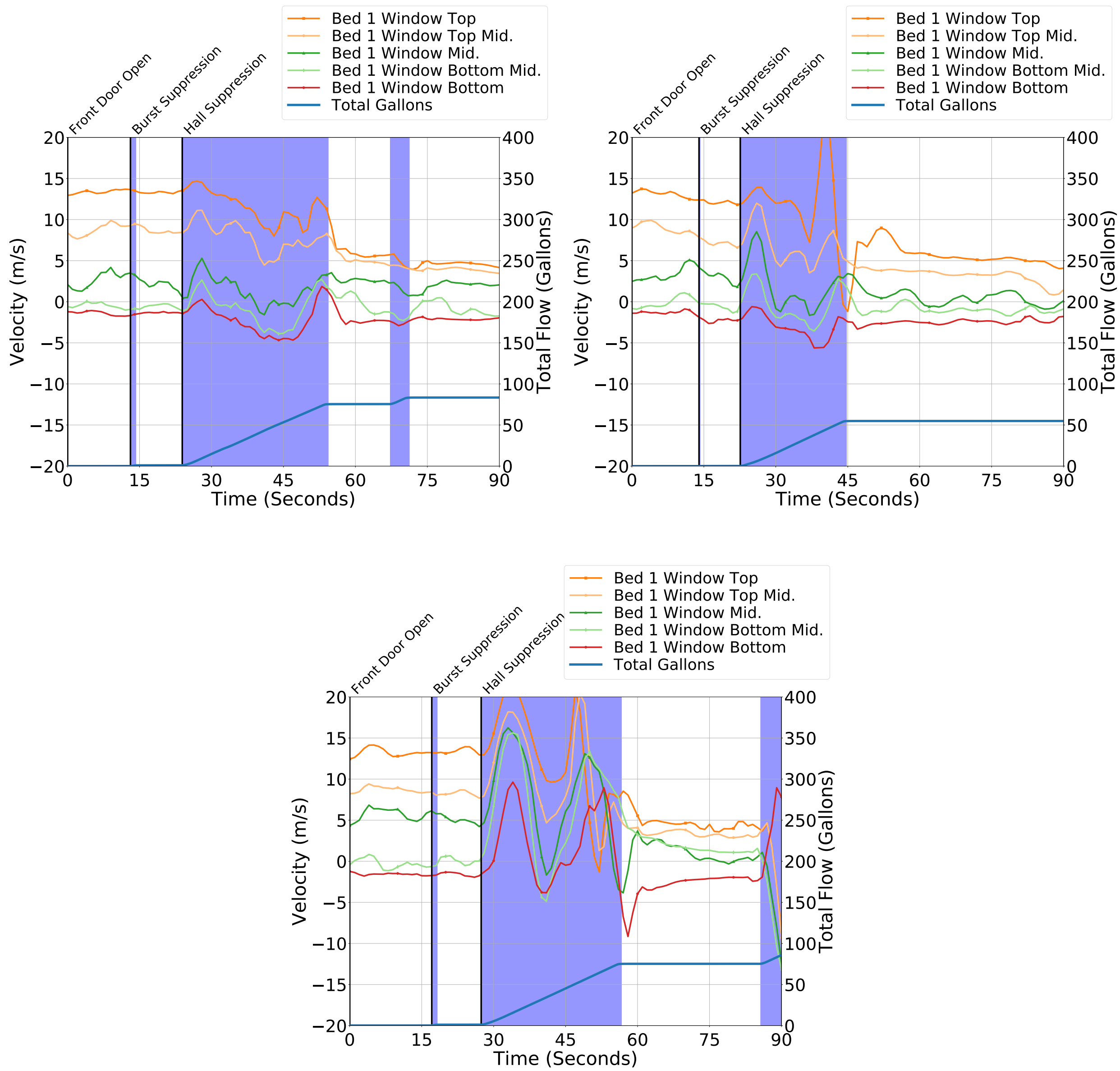


Figure 6.24: Gas velocities at the Fire Room Window for the flow and move interior attacks with one room of fire and a single window vent. Top row is Experiment 7 (left) and Experiment 9 (right), and the bottom row is Experiment 11. The blue shaded areas represent when water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

In all three experiments when the suppression crew made their approach down the hallway flowing water, the velocity of gases at the front door changed. While the line was flowing the velocity of the fresh air flowing in the bottom of the door increased. The velocity of products of combustion exiting the top of the door decreased, almost to no flow at all. As the crew made it further down the hall, the velocity of inflow decreased and the flow out the top of the door resumed.

At the start of the hall, the initial flow of water decreased the velocity with which the products of combustion were exiting out the top of the door from 5 m/s (11.2 mph) to almost zero. The inflow in the hall also decreased, indicating the exchange of gases from the entrance to the hallway and the living room was almost zero.

At the bedroom window vent, the initial water application down the hall initially decreased the velocity of gases exiting the window until the crew makes it to the fire room, at which time the velocity of gases exiting the window increased. Once the water from the hose stream hit the velocity probes, the readings became inaccurate.

Figures 6.25, 6.26, and 6.27 shows the flows at the front door, start of the hallway, and bedroom window for the single room of fire and single open window ventilation cases where the shutdown and move tactic was utilized.

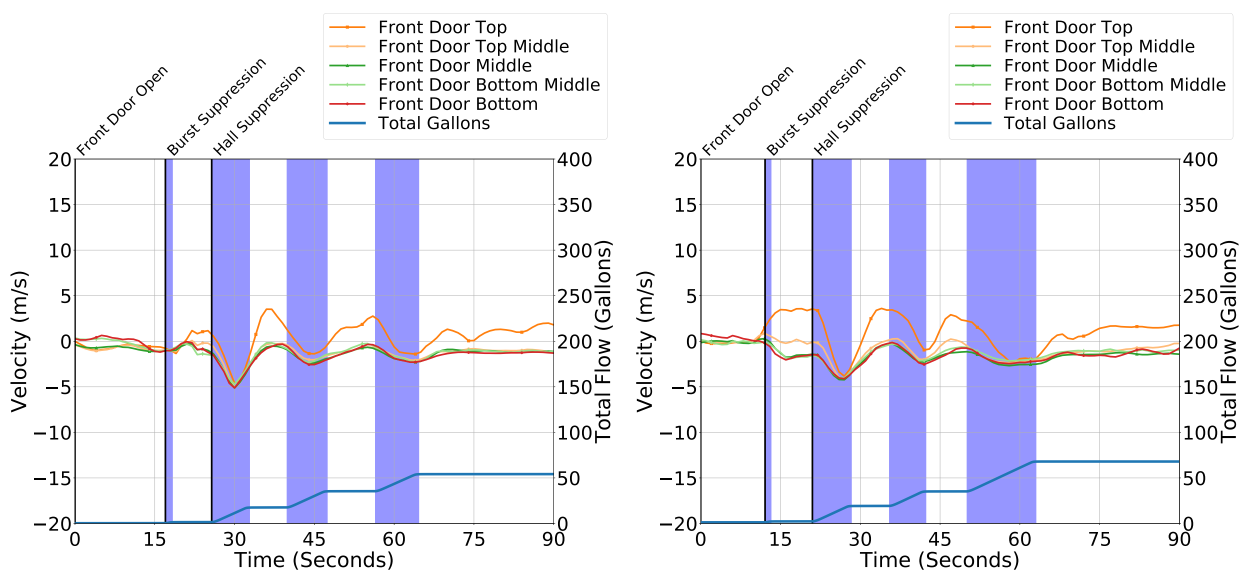


Figure 6.25: Gas velocities at the Front Door for the shutdown and move interior attacks with one room of fire and a single window vent. Experiment 8 is left and experiment 10 is right. The blue shaded areas represent where water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

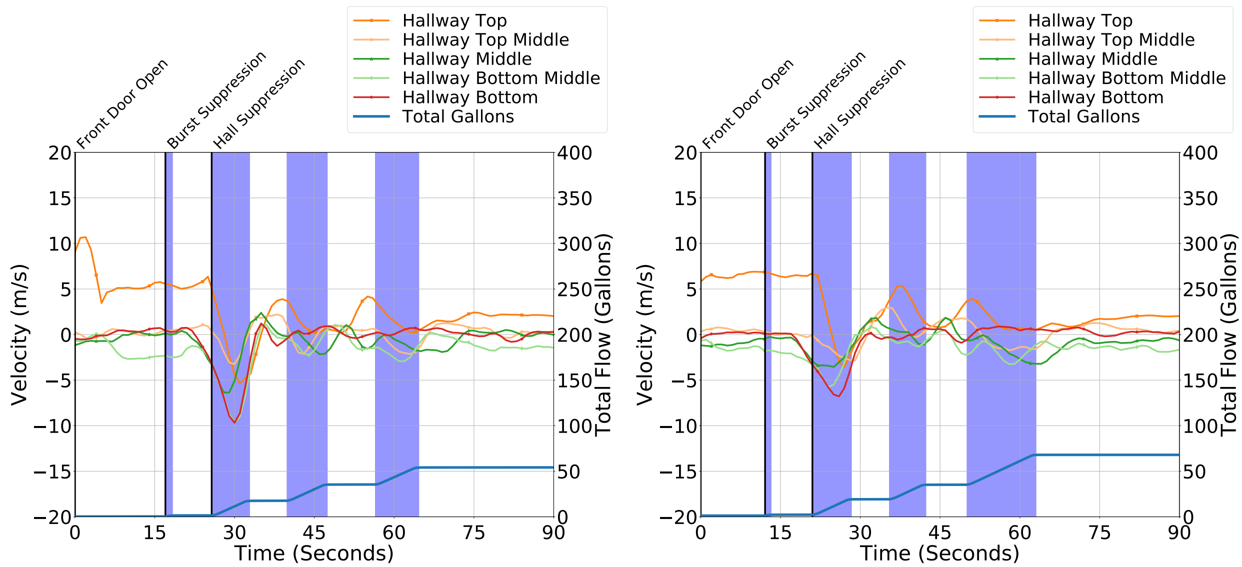


Figure 6.26: Gas velocities at the Start of Hall for the shutdown and move interior attacks with one room of fire and a single window vent. Experiment 8 is left and Experiment 10 is right. The blue shaded areas represent where water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

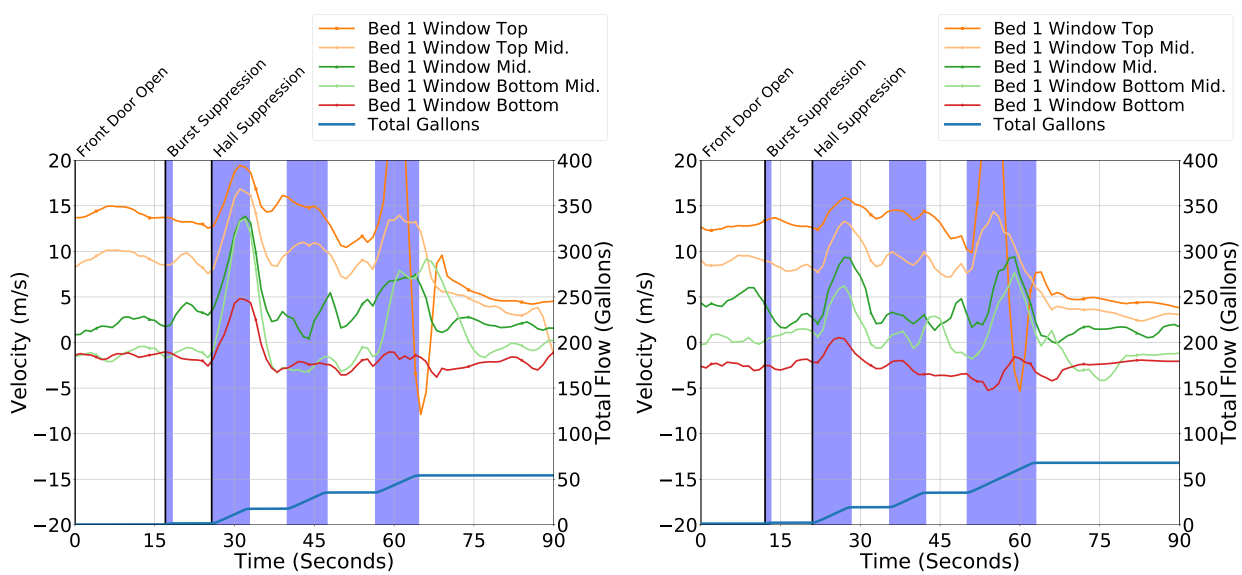


Figure 6.27: Gas velocities at the Fire Room Window for the shutdown and move interior attacks with one room of fire and a single window vent. Experiment 8 is left and Experiment 10 is right. The blue shaded areas represent where water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

At the front door, on the initial flow, the velocity at the front door became all inflow, or a uni-directional vent, flowing into the structure. Once the line is shut down to move forward, the door vent became bi-directional again with air flowing in at the bottom and smoke out at the top. This was noted at all points when the line was opened.

Similarly, at the start of the hall, each time the line was opened the gas velocities became uni-directional down the hallway towards the fire room. Once the line was shutdown, the flow resumed with inflow at the bottom and outflow at the top.

The flow out the bedroom window increased the first time the line was open, but subsequent water applications did not produce the same changes. Once the line reached the fire room, the water stream hit the velocity probes, resulting in inaccurate readings.

During interior suppression, it is apparent water application has the potential to impact the flow of products of combustion. Applying water down the hallway changed the velocity to be completely in the direction of water application. Once the line is shutdown the flow returns to the conditions prior to application. If the fire is knocked down (temperatures reduced), the magnitude of the velocity changes however the direction remains the same. The flow and move case was not as effective at maintaining the directional change of gas flow, potentially due to the difficulty in maintaining the nozzle pattern while moving down the hallway. The shutdown and move case changed the velocity each time the nozzle was opened, potentially because the suppression crew was able to maintain a better application pattern in a fixed position.

6.5.2 Exterior

During the exterior suppression tactics, the velocity probes at the fire room window, the velocity probes at the start of the hallway, and when open, the velocity probes at the front door, show the impact of exterior water application on the flow of productions of combustion.

Figures 6.28, 6.29, and 6.30 shows the flows at the front door, start of the hallway, and bedroom window for the single room of fire and single open window ventilation cases where exterior water application. For top row, Experiments 18 and 20 respectively, the front door was closed until after the water was applied through the window. The bottom image, Experiment 21 had the front door open at the time of the application.

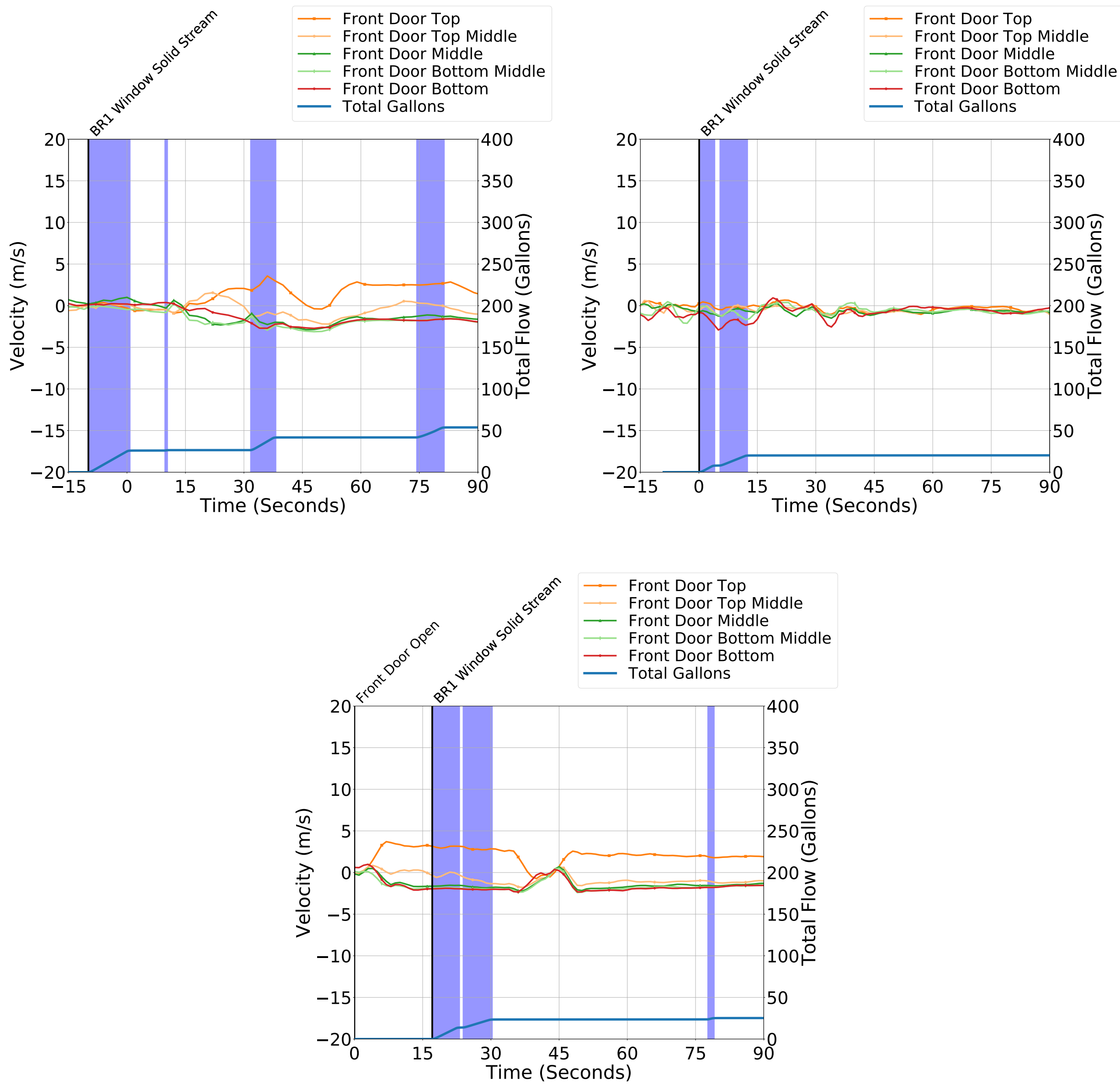


Figure 6.28: Gas velocities at the front door for exterior water application with one room of fire and a single window vent; Experiment 18 (left) and experiment 20 (right) and Experiment 21 (bottom). The blue shaded areas represent where water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

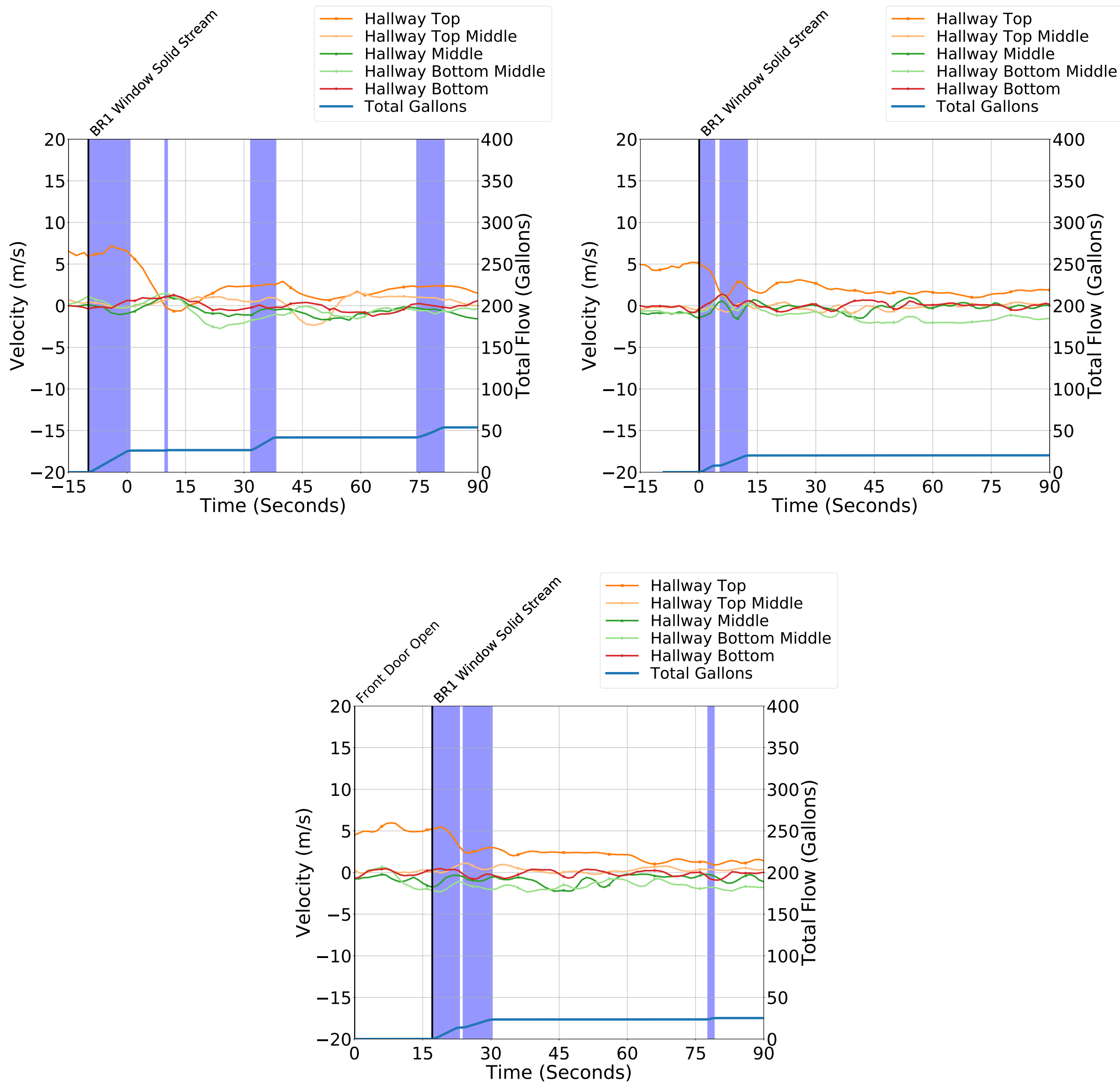


Figure 6.29: Gas velocities at the start of the hall for exterior water application with one room of fire and a single window vent; Experiment 18 (left), Experiment 20 (right) and Experiment 21 (bottom). The blue shaded areas represent where water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

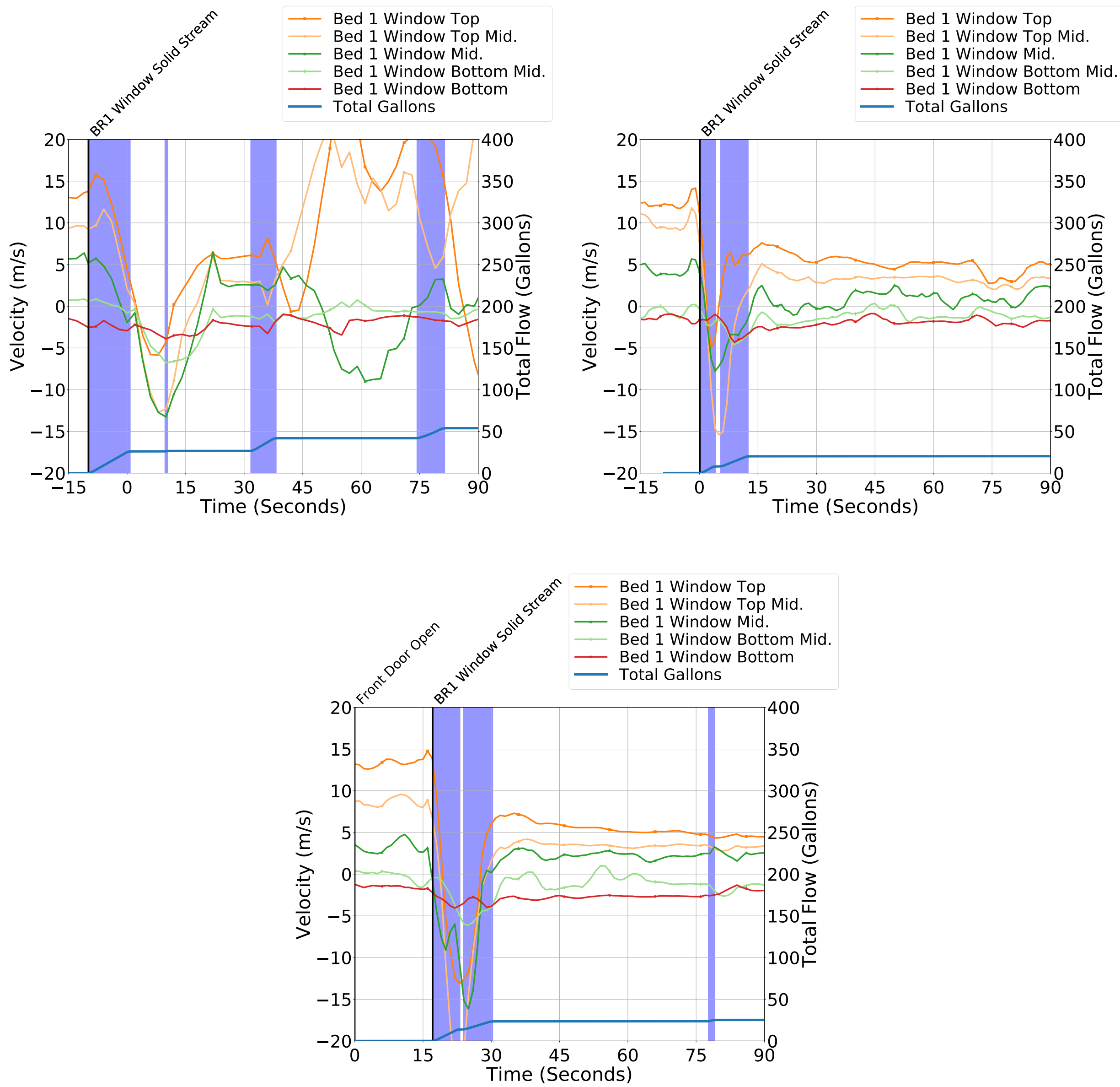


Figure 6.30: Gas velocities at the fire room window for exterior water application with one room of fire and a single window vent; Experiment 18 (left), Experiment 20 (right) and Experiment 21 (bottom). The blue shaded areas represent where water was flowing from the hose stream. Charts begin 15 seconds prior to the start of water flow and continue for 75 seconds after the water flow started.

The front door was closed for the first two Experiments, 18 and 20 and yielded no change to the flow at the door from water application. In the third Experiment, 21, the front door was open when water was applied. The flow at the top middle probe went from approximately 0 to an inflow of 1.5 m/s. This indicates more air being drawn in when water flow occurred in the window. Following the water flow, the probes were moved to allow for the suppression crew to enter which is the return to 0 for several seconds. When the probes were put back in place the gas velocities were of the same magnitude as they were before they were moved.

At the start of the hallway the application of water decreased the velocity of the gases at the top of the hallway from 5 m/s to 2.5 m/s indicating less products of combustion were flowing towards the door immediately following water application.

At the window the water was applied from, the flow of gases went from a bi-directional vent with inflow only on the bottom probe and outflow on the upper four probes to complete inflow. This was due to both contraction caused by the cooling of the gases and the air entrainment in the stream entering the window.

When the end of the hallway values are evaluated with the window values it becomes apparent that entrainment is not the predominant reason for inflow in the window. The lack of increased flow at the start of the hallway even when the front door is open (creating a flow path), indicates the predominant mechanism of flow change was due to the contraction from cooling gases. This is only applicable when a straight stream or solid stream are used.

Figure 6.31 shows the change in velocity at the Bedroom 1 doorway and the start of the hallway when a fog stream is used on the exterior window. The fog stream in the window is capable of pushing products of combustion into the hallway. However further down the hallway at the start of the hall, the fog suppression has an opposite effect, and it limits the flow into the living room.

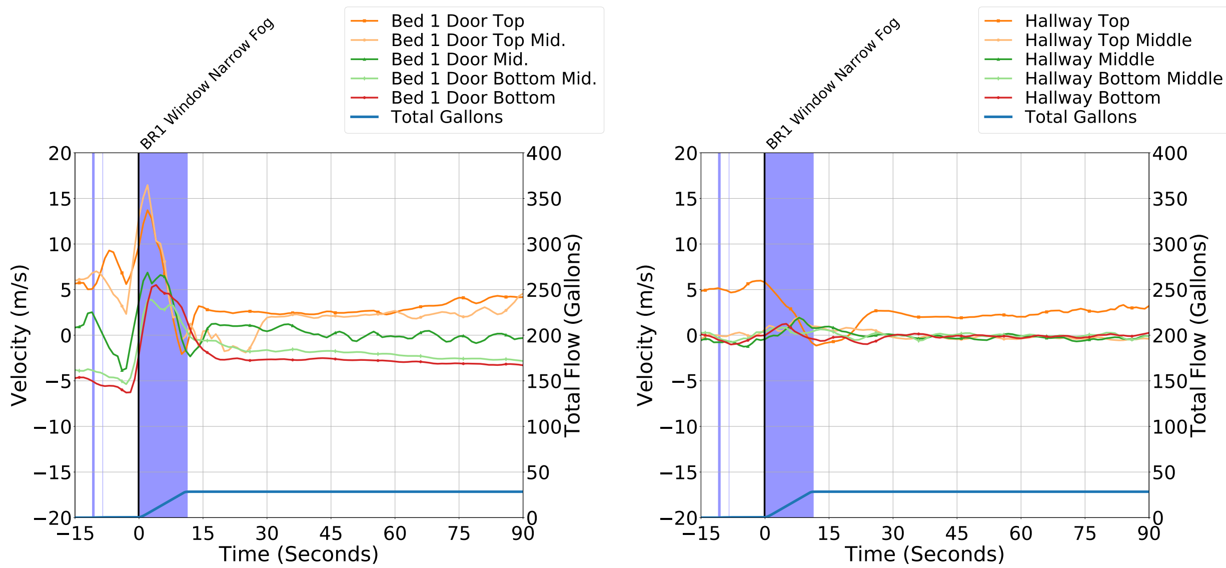


Figure 6.31: Gas velocities at the fire room door (left) and start of hall (right) for exterior water application with a fog stream with one room of fire and a single window vent. The front door is closed. The blue shaded areas represent where water was flowing from the hose stream.

Figure 6.32 shows the change in velocity at the Bedroom 2 doorway (across from the fire room) and the start of the hallway when a straight stream is used on the fire room window. Immediately following water application, the velocity of the products of combustion flowing into Bedroom 2 decreases (negative flow is into room). Additionally, the products flowing at the start of the hall decreases most likely due to the suppression of the fire.

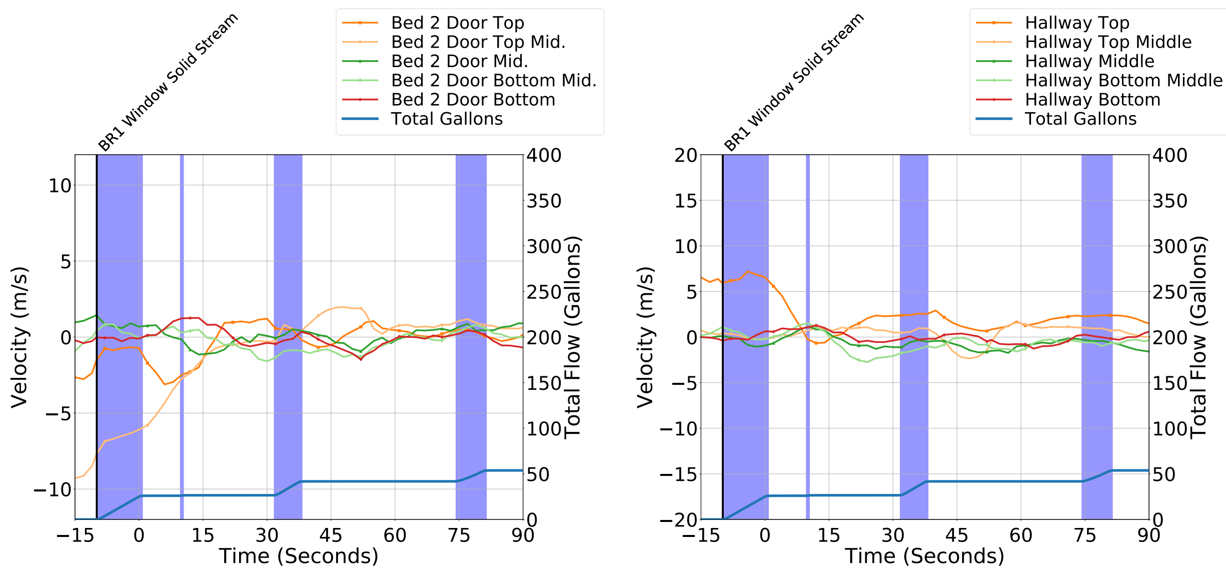


Figure 6.32: Gas velocities at room across from the fire room (left) and the start of hall (right) for exterior water application with straight stream with one room of fire and a single window vent. The front door is closed. The blue shaded areas represent where water was flowing from the hose stream.

The application of water from the exterior has the potential to alter the flow of the products of combustion. When a solid stream or straight stream are utilized, the flow from the fire room to the remainder of the structure is minimal.

6.6 Impact of Placing Nozzle Through Window on Regrowth

During all experiments that used an exterior fire attack method, an interior suppression was performed after the exterior suppression event(s) to completely extinguish the fire. In every one of these experiments, the temperature 7 ft above the floor in the fire room began to increase in the time between the end of exterior suppression and start of interior suppression, indicating the exterior attack hadn't fully extinguished the fire and that it was beginning to regrow. The fire "regrowth intensity" during this period was quantified for each applicable experiment as the difference between the maximum and minimum temperature 7 ft above the floor in the fire room during the period divided by the total duration of the period.

Experiments 18 and 20 began with an exterior attack through the window of Bedroom 1, followed by an interior suppression to completely extinguish the fire. Both experiments contained the 'Single Vent' configuration and used a smooth bore nozzle to flow water. The main difference between Experiments 18 and 20 was that towards the end of the initial suppression event during Experiment 20, the nozzle was advanced forward through the window opening, and water was applied in a "O" pattern with the nozzle's bale half-closed, putting water directly on the contents. During Experiment 18, however, the nozzle was aimed at the ceiling of Bedroom 1 for the entire exterior attack. Comparing the fire regrowth intensity during the two experiments, the rate of temperature increase during the fire regrowth period for Experiment 20 was 1.0 °F/sec less than the rate of temperature increase during the regrowth period for Experiment 18.

Experiment 24 used the 'Two Vent' configuration, which contained two fire rooms: Bedroom 1 and Bedroom 2. The initial suppression event performed during Experiment 24 was an exterior attack through the window of Bedroom 1, followed by an exterior attack through the window of Bedroom 2, and a final interior suppression to fully extinguish the fire. A combination nozzle was used to flow water in a straight stream pattern. Towards the end of each exterior suppression event, the nozzle was advanced forward through the window opening, and water was applied as a narrow fog in a "O" pattern putting water directly on the contents. Two fire regrowth intensities were calculated for Experiment 24—one for each fire room. The initial suppression event performed during Experiment 27 was an exterior attack through the window of Bedroom 4, the fire room, followed by an interior suppression to completely extinguish the fire. A combination nozzle was used to flow water in a straight stream pattern during Experiment 27, and the exterior attack did not include water application in the "O", pattern on the contents through the window. Looking at Table 6.6, the fire regrowth intensity for each fire room in Experiment 24, was much less than the regrowth intensity from Experiment 27.

Table 6.6: Fire Regrowth Intensity during Experiments 18, 20, 24, and 27

Experiment	Fire Room	Regrowth Period Duration (sec)	Regrowth Intensity (°F/sec)
18	Bedroom 1	32	5.3
20	Bedroom 1	89	4.3
24	Bedroom 1	88	2.2
24	Bedroom 2	69	0.4
27	Bedroom 4	23	22.4

Overall, the temperature rise during the time between the end of the exterior attack and start of interior suppression occurred at a slower rate and was less drastic for experiments that included placing the nozzle through the window and moving it in an "O" towards the end of exterior suppression compared to experiments that did not involve this step. Using the "O" pattern aimed at the contents allowed water to reach a larger surface area of the fuel compared to flowing water exclusively with the nozzle aimed at the ceiling of the fire room.

6.7 Impact of Door Control

Controlling the access door was a tactical consideration from the DHS-2010 'Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes.' When gaining access, the open front door provided oxygen to the ventilation-limited fire, causing the fire to grow and spread [14]. To access the impact door control had a on a bedroom fire with a long hallway, four experiments were conducted: two with the bedroom window closed (No Vent) and two with the bedroom window open (Single Vent). In each case velocity of the gases were measured at the start of the hallway to determine if additional flow was moving towards the fire room prior to suppression activities commencing.

6.7.1 No Vent

To evaluate the impact of door control, Experiment 3, which included door control, is compared to Experiment 6, where no door control was provided. Figure 6.33 below shows the gas velocity at the start of the hallway.

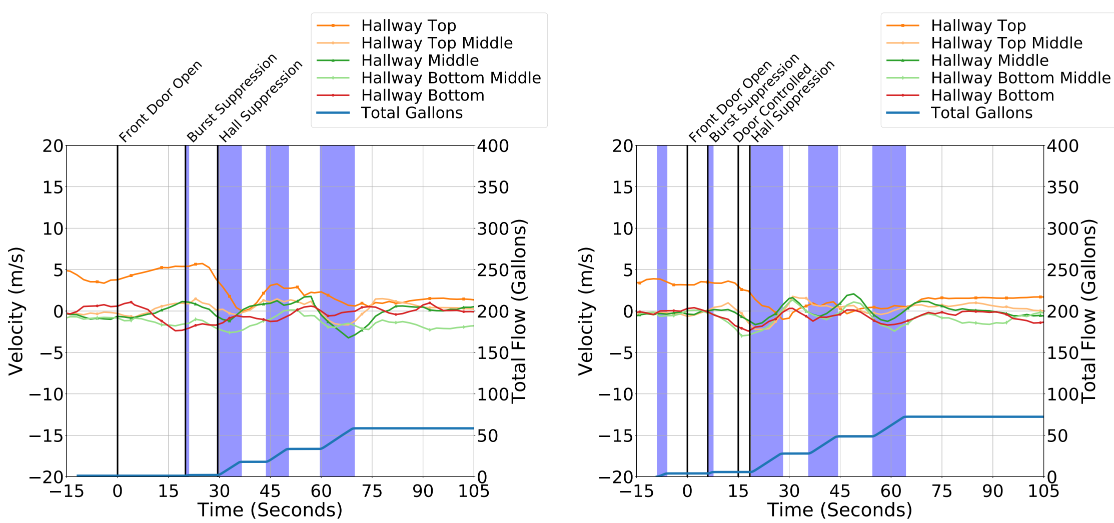


Figure 6.33: Start of hall flow with no door control Experiment 6 (left), with door control Experiment 3 (right) for interior attack. The blue shaded areas represent where water was flowing from the hose stream. Charts start 15 seconds prior to the tactic is started and continue until 105 seconds after the door was opened.

The use of door control had limited impact on the effectiveness of the tactic when no additional openings were provided, and the hose stream was used to seal the hallway preventing the ambient air from reaching the fire room.

6.7.2 Single Window Vent

To evaluate the impact door control had on two rooms of fire with ventilation opposite the suppression crew, Experiment 14 was conducted without door control and Experiment 15 included door control. Figure 6.34 shows the velocity at the start of the hallway during the two experiments.

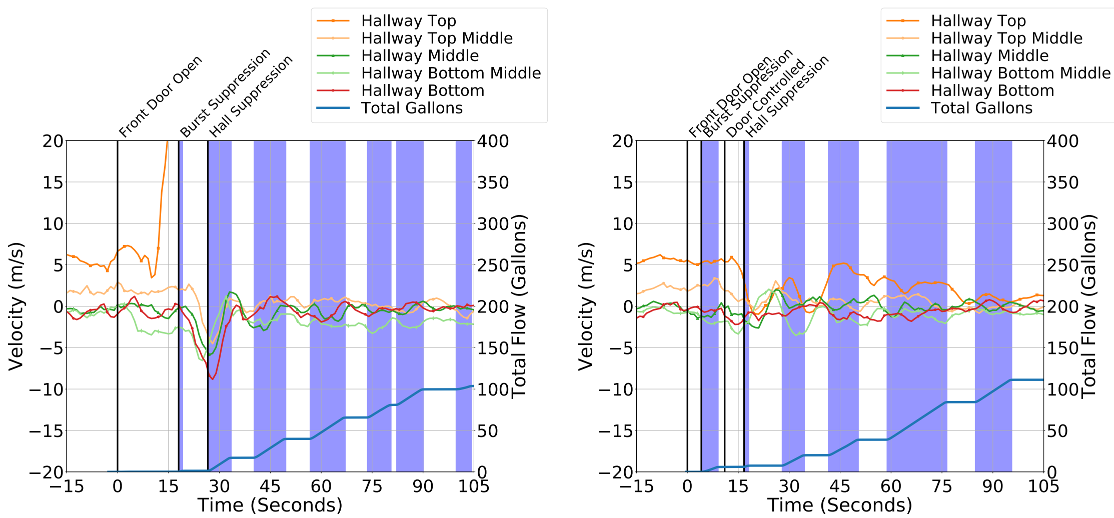


Figure 6.34: Start of hall flow with no door control Experiment 14 (left), with door control Experiment 15 (right) for interior suppression with the window venting prior to initiating the tactic. The blue shaded areas represent where water was flowing from the hose stream. Charts start 15 seconds prior to the tactic is started and continue until 105 seconds after the door was opened.

When two rooms of fire were opposite the suppression crew, the use of door control had more effect on the flow. The velocity of air being drawing towards the fire (the bottom four velocity measurements) in Experiment 14 were significantly more than in Experiment 15. Once the line was opened down the hallway, it sealed the hallway much like the no vent opposite case, and negated the flow. This illustrates how door control is a potential viable tactic to limit the air drawn towards the fire until the suppression crew can begin flowing water from a position between the entry door at the fire.

6.8 Flowing While Moving vs. Shutting Down to Move

There were two methods of approach to the fire. The first, titled ‘flow and move’, involved flowing the hose line while moving down the hallway towards the fire room. The second, titled ‘shutdown and move’, involved flowing the nozzle from a fixed position, shutting it down, moving up to the next position, flowing again, shutting it down and moving to the next position until the crew reached the fire room. This section will compare these two tactics as they relate to temperatures in the approach path, temperatures in the fire room, and gas velocities in the hallway for the three ventilation cases tested.

6.8.1 Approach Temperatures

The single room fires with no ventilation as illustrated in Figure 6.6 were interior attacks with no ventilation opposite. Figure 6.35 shows the comparison between the "flow and move" method and "shutdown and move" method. With no ventilation provided opposite the suppression crew, the "shutdown and move" method results in temperatures rebounding in the upper level of the hallway when the line is shut down as the suppression crew makes their way down the hallway. This is not seen in the "flow and move" method as the hose stream is continuously cooling as the crew makes their way down the hallway.

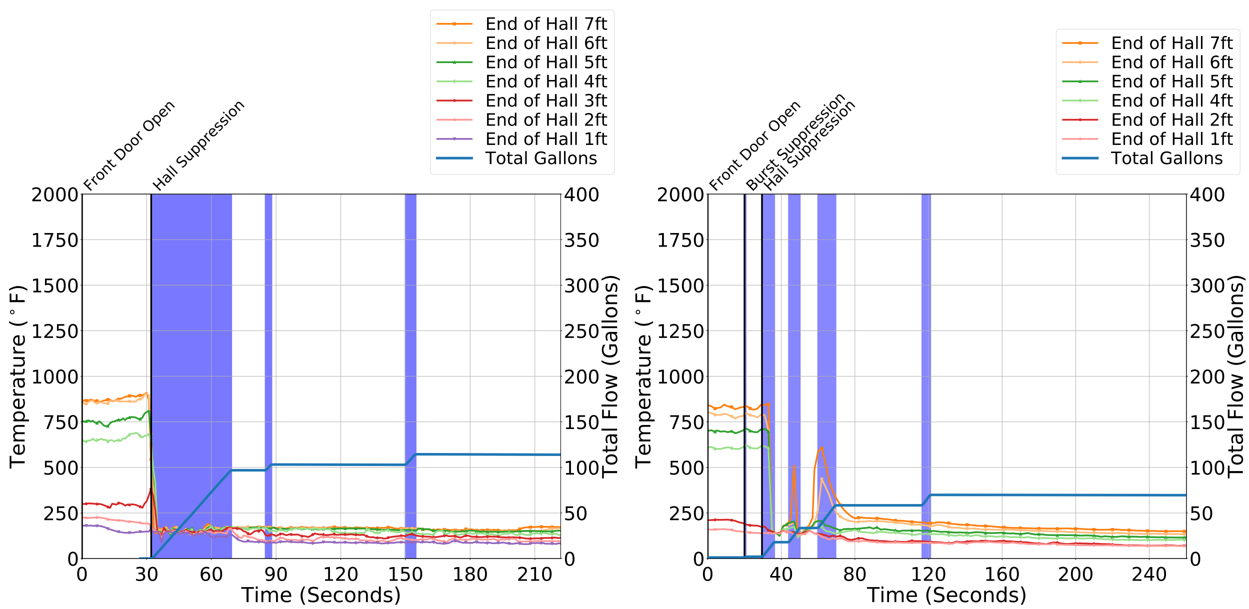


Figure 6.35: End of hallway temperatures (3TC) for the two attack methods used in the single room of fire with no ventilation. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 2 and the right shows the "shutdown and move" method from Experiment 6.

Ventilation provided opposite the suppression crew, has little impact on the "flow and move' versus the "shutdown and move" methods, as seen in Figure 6.36 for the single room fire and Figure 6.37 for the two rooms of fire. The same temperature rebounding occurs in the "shutdown and move" case, it is again not seen in the "flow and move" case.

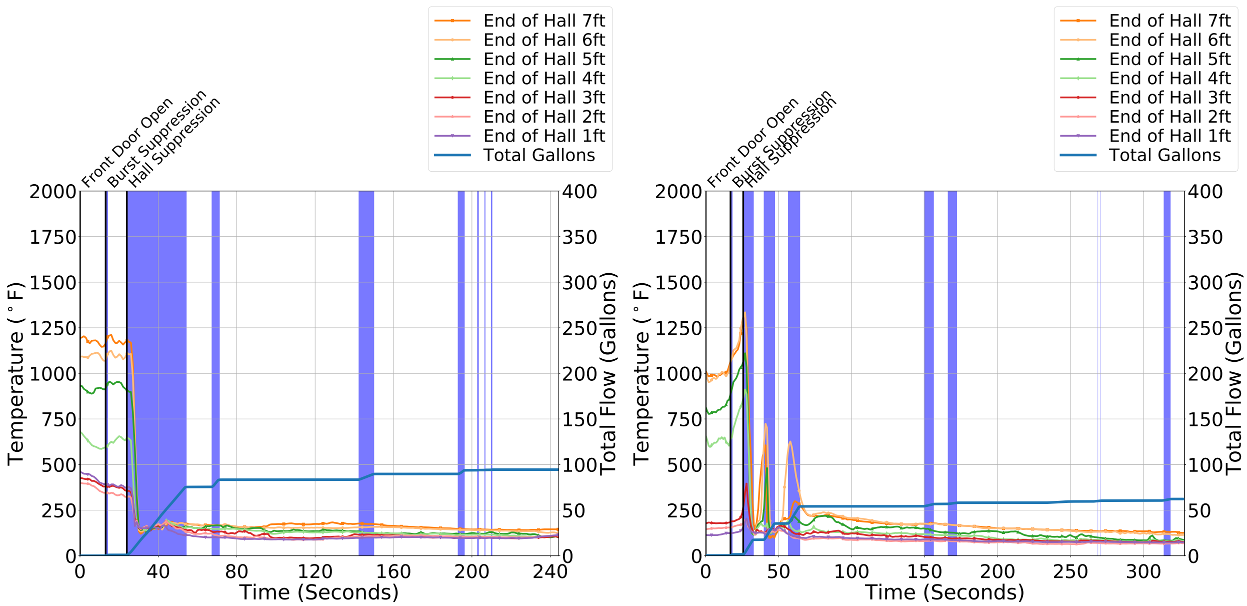


Figure 6.36: End of hallway temperatures (3TC) for the two attack methods used in the single room of fire with ventilation opposite the suppression crew. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 7 and the right shows the "shutdown and move" method from Experiment 8.

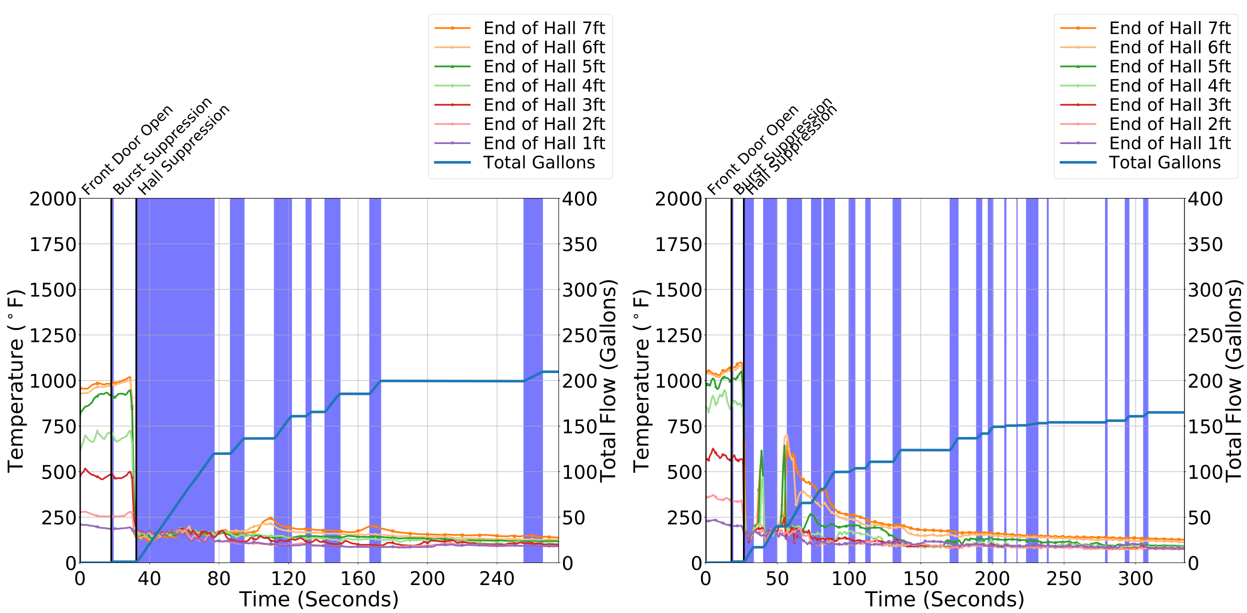


Figure 6.37: End of hallway temperatures (3TC) for the two attack methods used in the two rooms of fire with two windows of ventilation opposite the suppression crew. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 13 and the right shows the "shutdown and move" method from Experiment 14.

6.8.2 Fire Room Temperatures

The ultimate goal of any method of fire attack is to extinguish the fire in the fire compartment. When comparing the "flow and move" method and "shutdown and move" methods it is important to note the effect on the fire room during approach. Figure 6.38 shows the two methods and their effect on the fire room temperatures. In the "flow and move" case, initially the water has no impact on the fire compartment as it is not physically possible for water to enter the compartment from the position the crew began to flow water. As the crew advanced down the hallway, water begins to enter the compartment and effect the fire. It is not until the crew reaches the compartment that greatest impact occurs. For the "shutdown and move" case it is more pronounced as neither the first nor second position in the hall resulted in temperature reduction in the fire room. It was not until the crew was at the end of the hall flowing into the fire room that the water had an impact on temperatures.

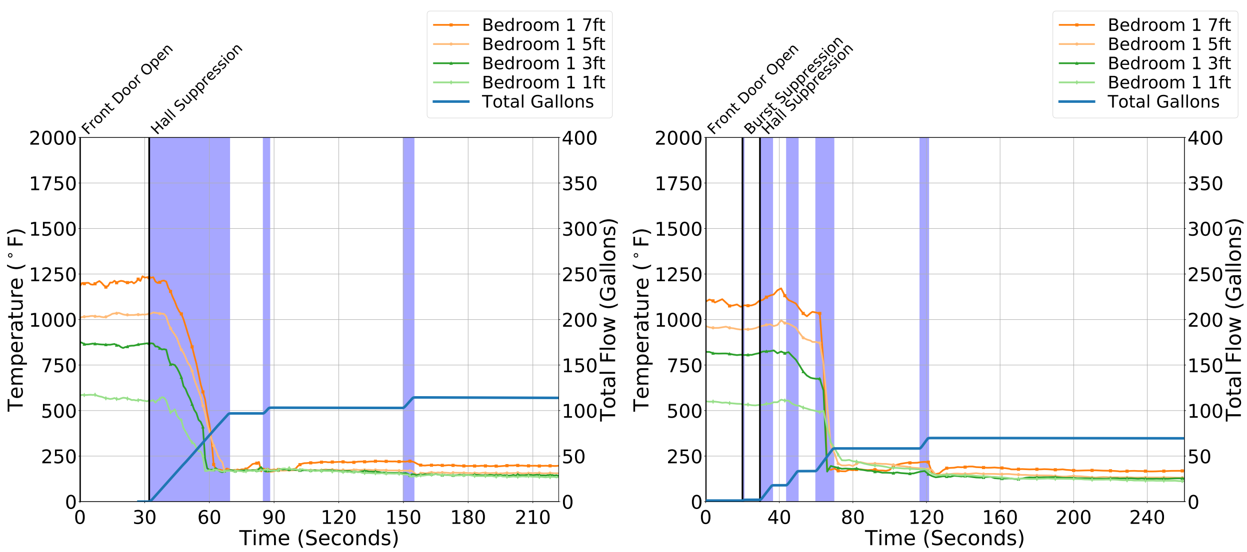


Figure 6.38: Fire room (Bedroom 1) temperatures (1TC) for the two attack methods used in the single room of fire with no ventilation. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 2 and the right shows the "shutdown and move" method from Experiment 6.

Providing a vent opposite the suppression crew does not change the effect of the methods on the fire room (Figure 6.39). The water being directed down the hall in both the "flow and move" and "shutdown and move" cases cannot impact the fire room from the entrance to the hallway. It is not until the crew makes it to the midpoint of the hallway that water can enter the room and begin to have an effect. It isn't until the crew reaches the fire room and is able to direct the stream into the compartment that the temperatures drop significantly.

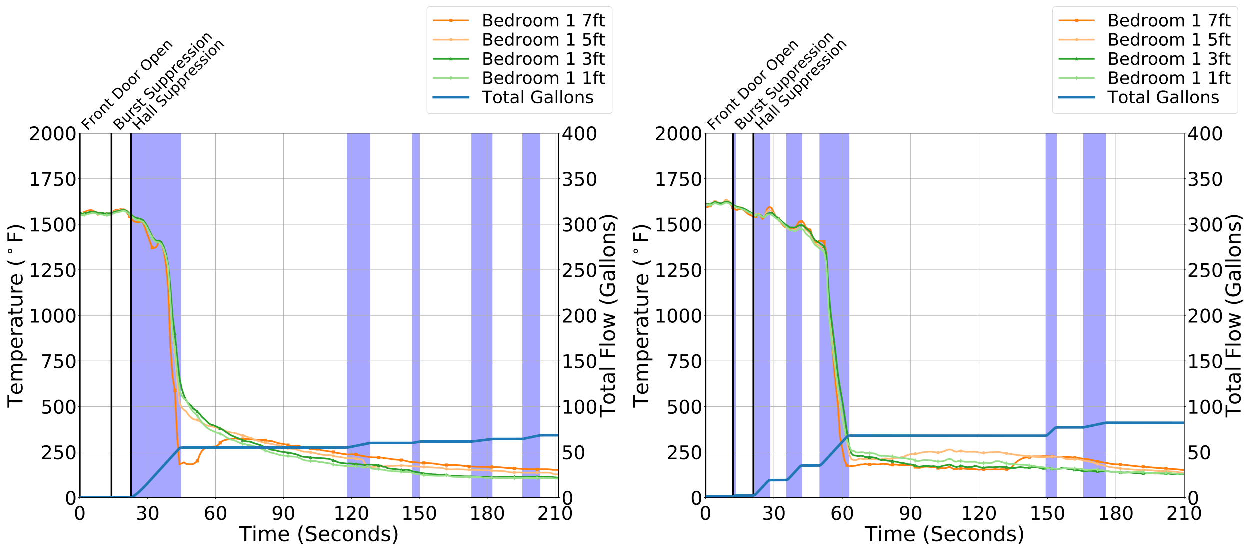


Figure 6.39: Fire room (Bedroom 1) temperatures (1TC) for the two attack methods used in the single room of fire with a window vent opposite the suppression crew. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 9 and the right shows the "shutdown and move" method from Experiment 10.

With the two rooms of fire with two window vents opposite as seen in Figure 6.40 the additional energy being released from the fire results in more difficulty in cooling the fire compartment.

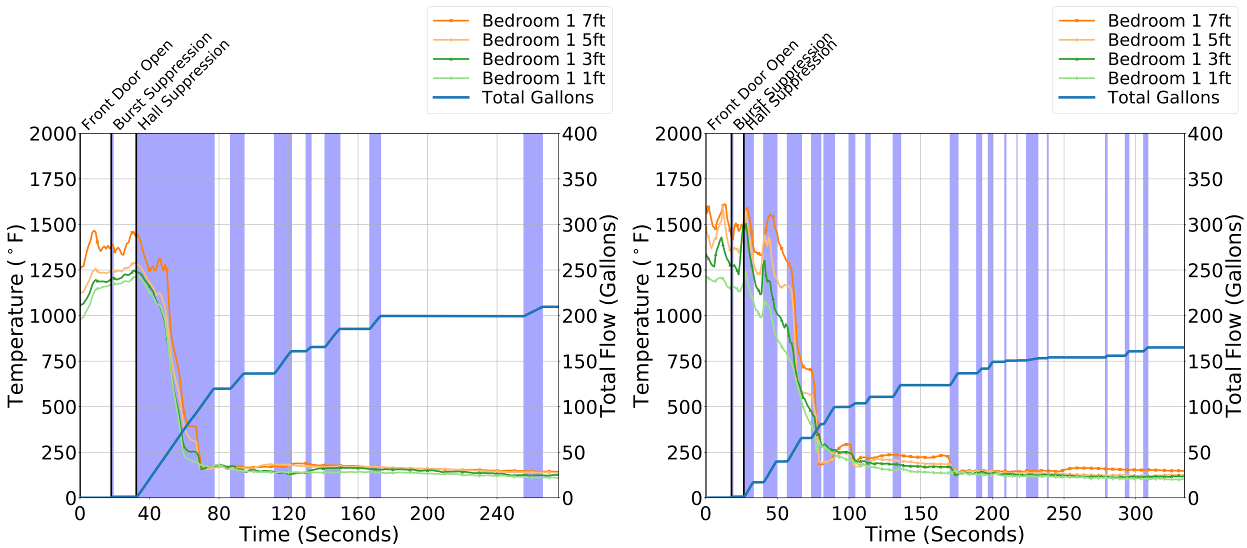


Figure 6.40: Fire room (Bedroom 1) temperatures (1TC) for the two attack methods used in the single room of fire with a window vent opposite the suppression crew. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 13 and the right shows the "shutdown and move" method from Experiment 14.

6.8.3 Gas Velocity

Examining the air movement at the start of the hallway for the two cases illustrates the ability of the hose stream to move products of combustion away from the nozzle crew and draw air in behind them as the make their way down the hallway. For the case with no ventilation opposite the advancing suppression crew, Figure 6.41 shows that the gas velocity at the top of the hallway goes from approximately 5 m/s out toward the front door to roughly 0 m/s on the initial flow, and the values of the lower gas velocity probes go from flowing down the hallway toward the fire to 0 m/s.

As the crew advances down the hallway in the "flow and move" method, all velocities maintain a flow near 0 m/s until the nozzle is shut down. The flow at the top of the opening returns to about 1 m/s as the products of combustion seek the low pressure at the front door. With the "shutdown and move" case, as the crew shutdown the nozzle to move the gas velocities return in between flows to values of about 2.5 m/s, or half the initial velocity. Once the crew reaches the fire room and conducts the last flow, the gas velocity at the top of the door returns to 1 m/s as the combustion products seek the low pressure much like the "flow and move" case.

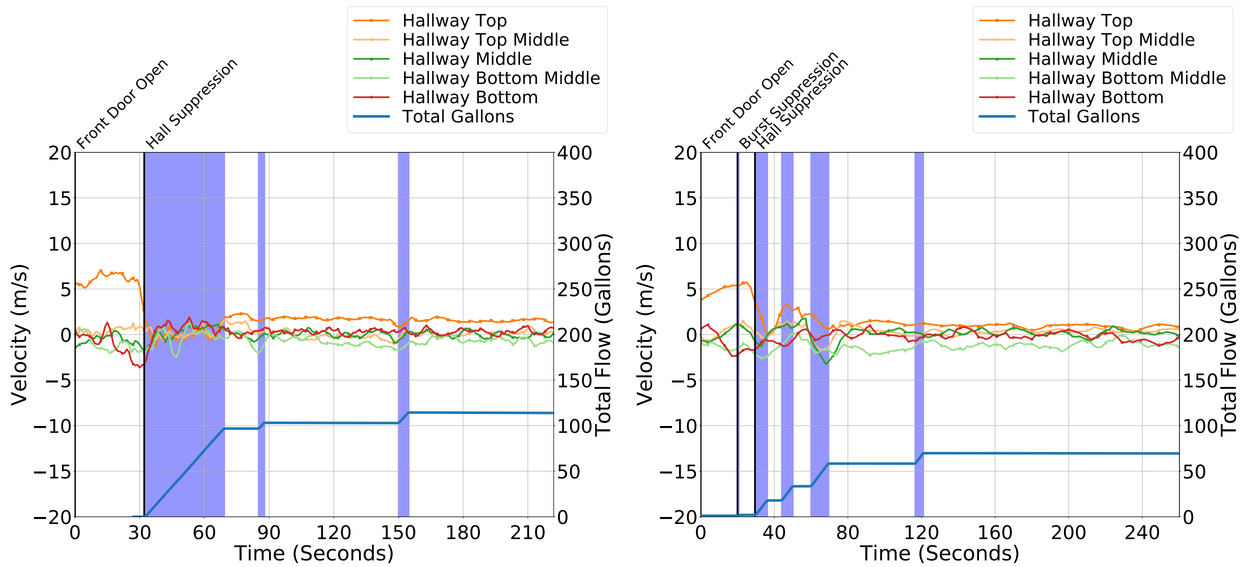


Figure 6.41: Gas velocity at the start of hallway (6BDP) for the "flow and move" method from Experiment 2 (left) and "shutdown and move" method from Experiment 6 (right) with the single room of fire with no ventilation. The blue shaded areas represent water flow from the hose stream.

Providing ventilation ahead of the nozzle crew changes the ability of the hose stream to move the products of combustion, as seen in Figure 6.42. The initial water flow now changes the velocity across the entire hallway entrance to be down the hallway towards the fire room. This occurs for the "flow and move" method and the "shutdown and move" method. When the crew uses the flow and move tactic to advance, the velocity trends toward to zero as they advance. The velocity at the top of the hallways stays near zero until the crew makes it approximately half way down the hall where it returns to 1 m/s. With the "shutdown and move" case, as soon as the line shuts down the flow resumes towards the low pressure at the front door. When the nozzle is opened half way down the hallway the flow goes unidirectionally down the hallway towards the fire again until the nozzle shuts down. This happens at all points of flow with the "shutdown and move" case.

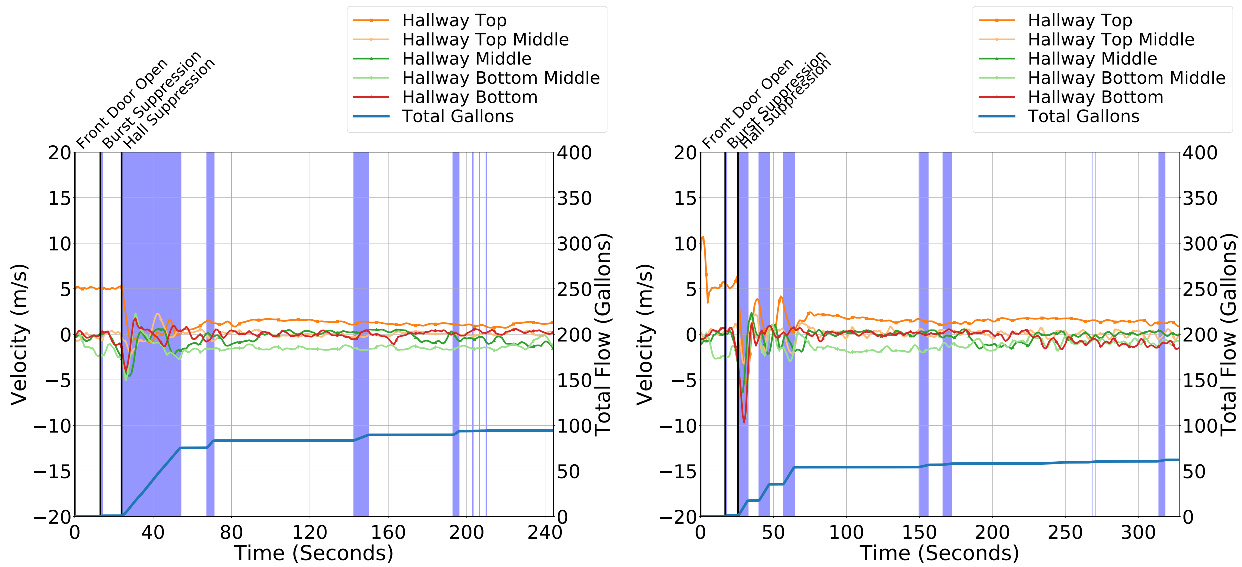


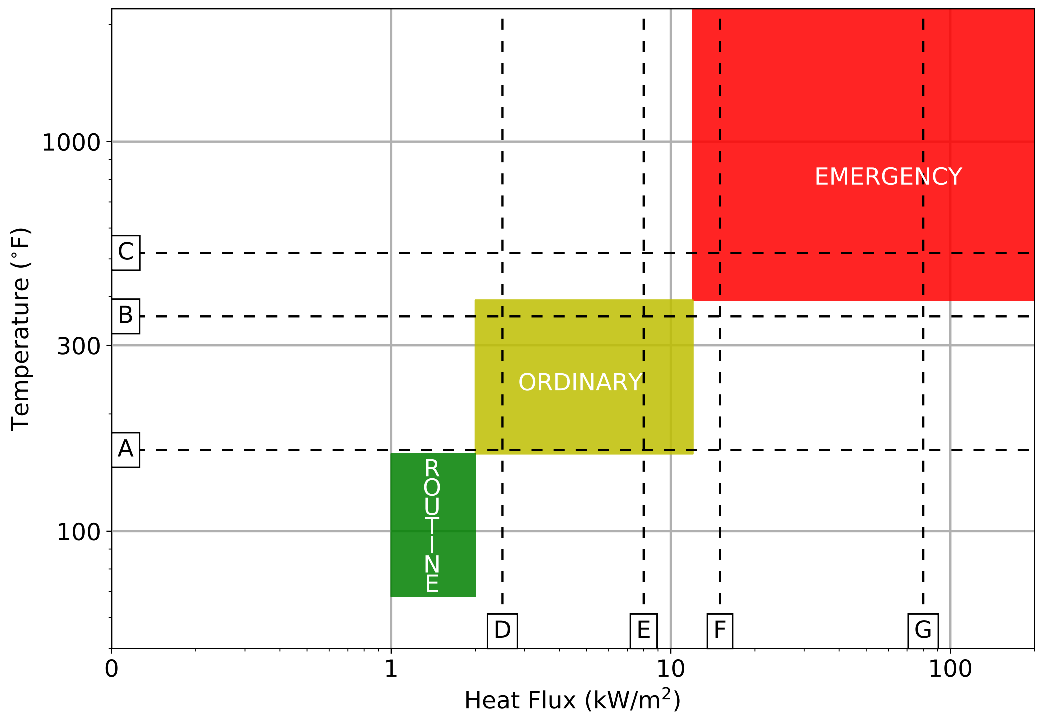
Figure 6.42: Gas velocity at the start of hallway (6BDP) for the "flow and move" method from Experiment 7 (left) and "shutdown and move" method from Experiment 8 (right) with the single room of fire with a single window vent opposite the suppression crew. The blue shaded areas represent where water was flowing from the hose stream.

6.9 Need to Cool While Operating on in the Interior

Traditionally, firefighters have been taught that there are negative consequences to applying water prior to reaching the fire compartment [6–9]. This, combined with training fires that do not cause hazardous thermal scenarios lead to firefighters believe that water application down a hall; prior to advancing is not necessary. The structural turnout gear will provide enough protection to make it to the compartment before applying water. To evaluate this instrumentation was placed outside the fire compartment and at various places down the hallway.

Utech developed three thermal classes for environments found inside the structure. These classes combined temperature (convective) and heat flux (radiative) to develop zones quantifying the hazard thermal energy poses to firefighters in structural gear. The routine zone represents those areas were structural turnout gear are not necessary for thermal protection. The ordinary zone was intended to be a thermal classification where a firefighter in full protective equipment could remain for the duration of their air supply. The emergency zone identified a zone in which a fully-encapsulated firefighter could only remain for under a minute, and the upper range, only a few seconds [31].

The thermal classes proposed by Utech do not account for all the combinations of temperature and heat flux found in structure fires. However when the classes are compared to the failure points of the modern fire protective ensemble in Figure 6.43 the independent temperature and heat flux criteria can be shown to encompass similar hazard zones. Thus for the purpose of this evaluation in addition to the thermal classes proposed by Utech, the corresponding independent temperature and heat flux will be considered similar thermal hazards to the combined values.



A	161.6°F (Temperature at which skin is instantly destroyed [35])
B	356°F (Mean temperature of hole formation in SCBA facepiece lens [34])
C	518°F (Mean temperature of crack formation in SCBA facepiece lens [34])
D	2.5kW/m^2 (Typical firefighter exposure and working environment [36])
E	8 kW/m^2 (Minimum heat flux exposure where lens failure was noted in less than 20 minutes [34])
F	15 kW/m^2 (SCBA facepiece lens failure occurs between 1.5 and 4 minutes [34])
G	80 kW/m^2 (Heat flux which PPE ensemble is exposed to during Thermal Performance Test (TPP) [32])

Figure 6.43: Modern PPE Performance Comparison with Utech Thermal Classes

Figure 6.44 shows the thermal exposure (temperature vs. heat flux) for the three experiments where suppression was delayed to evaluate the conditions had suppression not occurred, plotted against three thermal zones defined by Utech. Each point represents an average heat flux and temperature for which the suppression crew would have been exposed while in each of the five positions.

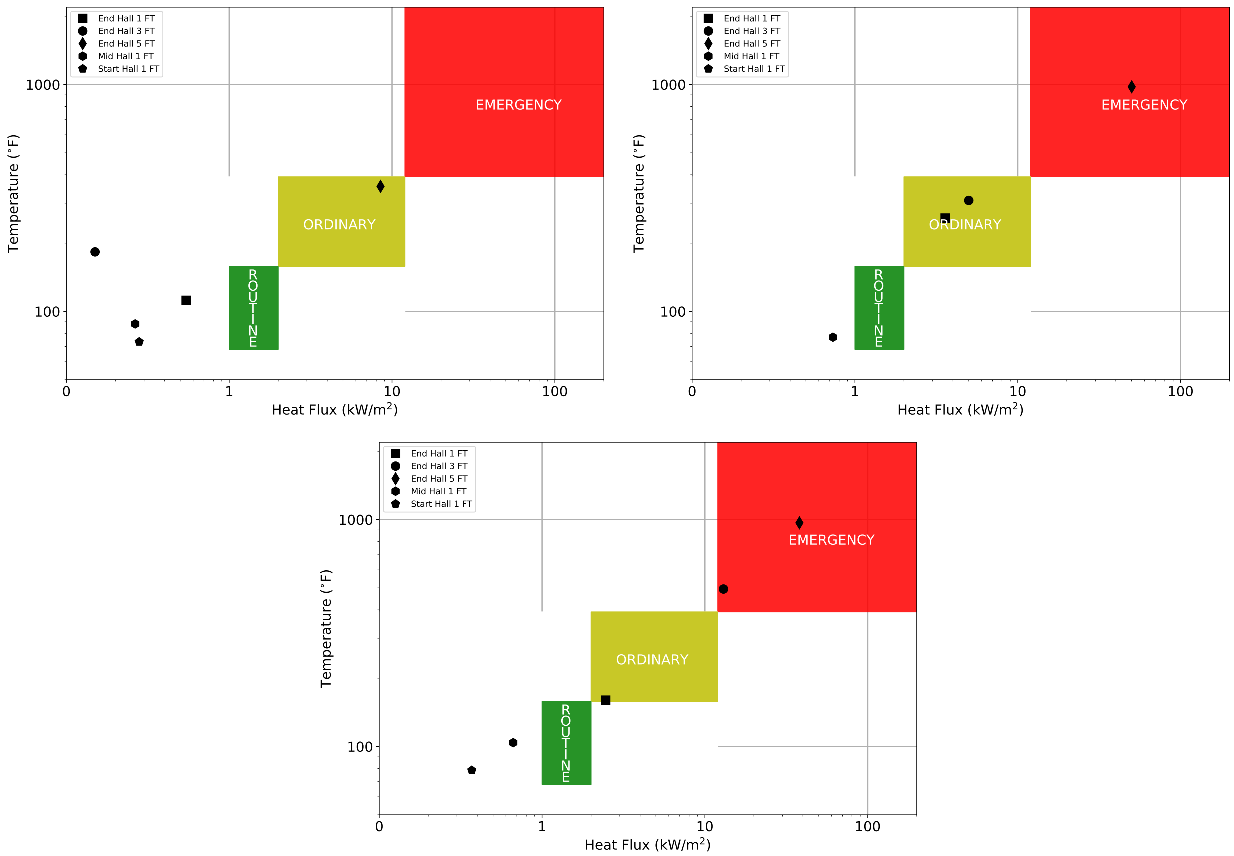


Figure 6.44: Temperature and heat flux during the 60 second period of interior suppression where suppression was delayed as compared to the thermal classes Proposed by Utech. Upper left is Experiment 1 - no ventilation, upper right is Experiment 12 - one vent opposite the suppression crew, and the bottom is Experiment 14 - two rooms of fire with a vent in each. The lightly shaded areas represent areas outside of Utech's thermal classes but still2 a similar thermal hazard.

The end of the hallway falls in the most severe range of the ordinary class for the no vent case (Experiment 1) and in the emergency range for the single vent (Experiment 12) and two vent (Experiment 17) experiments, indicating a firefighter would have less than 1 minute to suppress the fire once they reached the end of the hallway before receiving a burn injury. Although a more experienced firefighter may be able to achieve this, any occurrence which either delayed or prevented suppression would have resulted in a burn injury. Additionally, the emergency zone is an exposure that would likely damage the firefighters protective equipment, even if injury did not occur.

In contrast if water is applied as crews are operating on the interior the thermal insult is reduced. Figure 6.45 shows the temperature and heat flux at the end of hall 1 ft, 3 ft and 5 ft elevations along with the mid hall and start hall at 1 ft as compared to the thermal classes proposed by Utech [31]. The area at the end of the hallway outside the fire rooms is in the emergency zone prior to water application (left column), indicating a firefighter could not advance down the hallway to the fire rooms without applying water. After water application, temperatures and heat fluxes are reduced to the ordinary range making advancement down the hallway possible without significant injury.

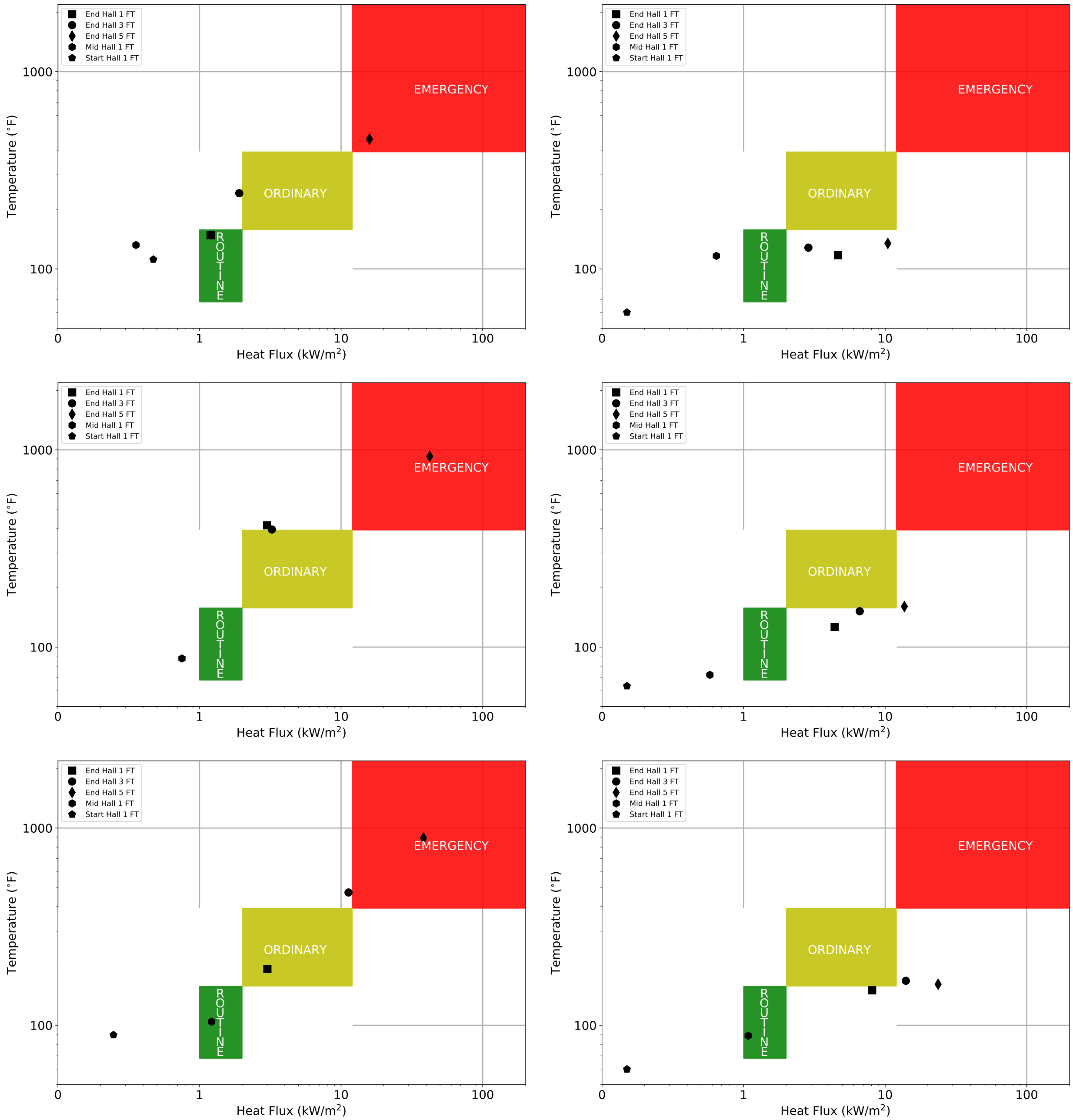


Figure 6.45: Temperature and heat flux 10 seconds prior to interior suppression (left column) compared to 30 seconds after hall suppression (right column) for no vent case - Experiment 4 (top row), single vent case - Experiment 7 (middle row) and two vent case (bottom row). Values are compared to Thermal Classes Proposed by Utech [31]. The lightly shaded areas represent areas outside of Utech's thermal classes but still a similar thermal hazard.

Additionally if water is applied via a transitional attack, the thermal insult is also reduced. Figure 6.46 shows the temperature and heat flux at the end of hall 1 ft, 3 ft and 5 ft elevations along with the mid hall and start hall at 1 ft as compared to the thermal classes proposed by Utech [31]. The area at the end of the hallway outside the fire rooms is in the emergency zone prior to the initial water application during the transitional attack (left column), indicating a firefighter could not advance down the hallway to the fire rooms without sustaining injury. After the initial water application, temperatures and heat fluxes are reduced to the ordinary range making advancement down the hallway possible without significant injury.

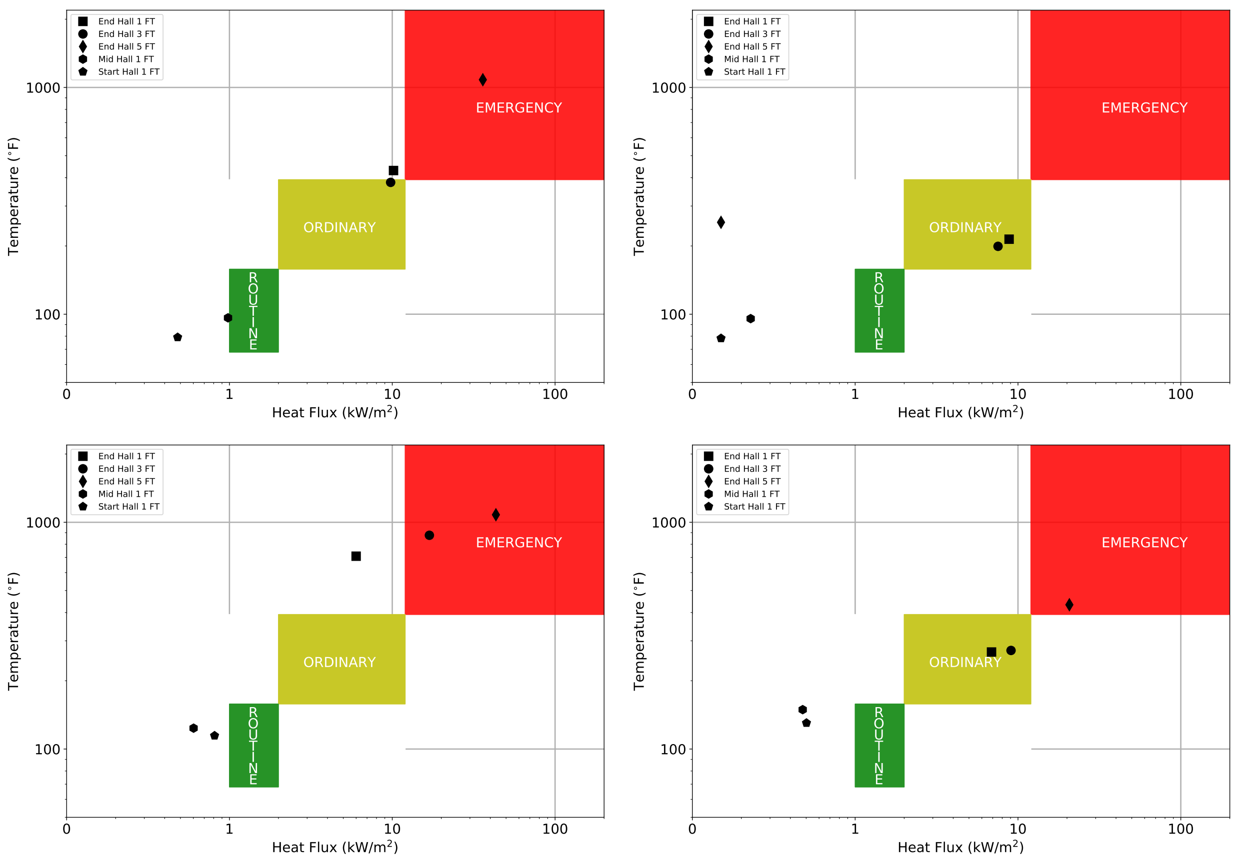


Figure 6.46: Temperature and Heat flux 10 seconds prior to the initial water application from transitional attack (left column) compared to 30 seconds after the initial suppression suppression (right column) for Single Vent Case - Experiment 7 (top row) and Two Vent Case (bottom row). Values are compared to Thermal Classes Proposed by Utech [31]. The lightly shaded areas represent areas outside of Utech's thermal classes but still thermal hazard, arguably in the same thermal class.

6.10 Timing Analysis

The full-scale fire experiments incorporated fire department interventions which were scripted to mimic pre-determined tactics and fire ground actions. Input from the fire service technical panel was obtained to determine what fire ground actions were pertinent to the study and how each of the attack methods should be executed. It should be noted that the experiments were not designed to study timing; however, through an analysis of experiment video, the time to complete various tactics and reach certain locations within the structure can be found. During the testing, there were two pre-determined times in which actions would be dictated. The first was the initial fire ground action performed: either window suppression for an exterior attack or door open and read for interior attack. After ignition, this initial action was the first to occur and was determined based on conditions within the structure. The overarching purpose of the study is to determine the impact of suppression tactics on victims and firefighters alike. Therefore, the suppression tactics during each experiment needed to be performed on similar fires with regards to fire growth and behavior in the fire room and on approach. Once the initial action was called for, the firefighters conducted actions and suppression tactics as prescribed. The tactics took as long as they needed to with no further dictation of time. Once the tactic was completed to the point the fire was deemed "under control", the second and final pre-determined time was seen. The firefighters were instructed to pause for approximately 1 minute after the fire was "under control" to determine the effectiveness of a given suppression tactic.

It should also be noted that the fire ground actions were performed under ideal conditions. The hoseline was pre-deployed and charged prior to the beginning of the experiment. The surface for the hoseline advancement, on both the exterior and interior of the structure, was flat and smooth with no obstructions in the path of travel. Additionally, staffing on the handline was adequate to ensure that the hoseline advancement and subsequent execution of the suppression tactic was not hindered by outside factors.

Once the experiments were complete, video analysis was completed to determine the time it took to carry out different fire ground actions. This included the following: time to complete a given suppression tactic, travel time of firefighters for both the exterior and interior of the structure, and the time to reach various victim locations. Once inside the structure, the firefighter's path of travel while advancing the hoseline took them past victim packages 4 and 1. Victim package 4 was located to the right of the start of the hallway, inside the living room and was reached first by the advancing hose crew. Victim package 1 was located at the end of the hallway, just outside of Bedroom 2. Figure 6.47 shows these locations with reference to the structure and path of advancement.

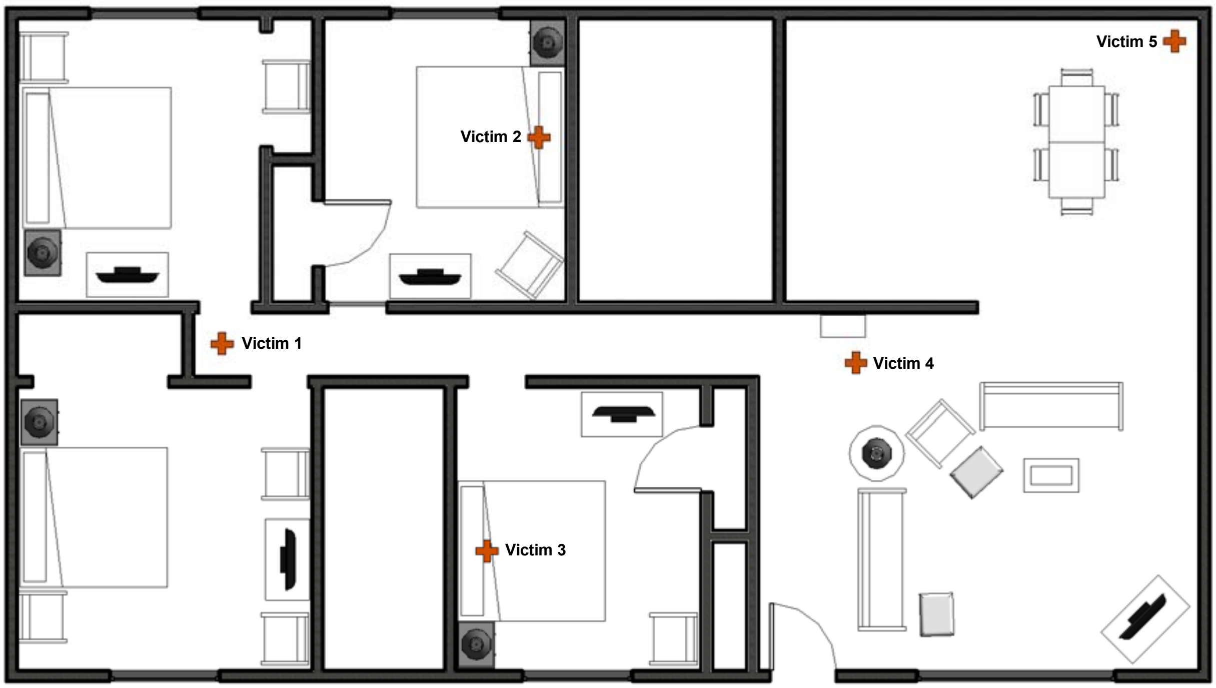


Figure 6.47: Victim Locations

The tables below show the various times separated by attack type and ventilation configuration: Interior shutdown and move (no vent, singlevent, two vent), interior flow and move (no vnt, single vent, two vent), and exterior (transitional) with single and two vent cases. The description of how the times were derived is as follows:

1. Exterior flow [min:sec] - Total flow time for exterior attack, start of initial knock down to end of respective "O" pattern through the window.
2. Exterior travel [min:sec] - Total suppression crew movement time exterior of the structure in transitional attack, starting at window 1 location and ending at the front door entrance location.
3. Door read [min:sec] - Total time spent assessing the fire growth from the front door, starting at door open and ending at entrance to the structure. For the interior attack methods this was a pause at the doorway. For the transitional attack methods, this was done while the line was re-positioned.
4. Interior flow [min:sec] - Total flow time for interior attack, starting at initial flow (beginning of the hallway) and ending at final flow (end of hallway).

5. Interior travel [min:sec] - Total suppression crew movement time interior of the structure, starting at the beginning of the hallway location ending at the end of the hallway location.

6. Victim 4 [min:sec] - Total time the suppression crew took to reach the location of Victim 4, from initial attack to location of Victim 4.

7. Victim 1 [min:sec] - Total time the suppression crew took to reach the location of Victim 1, from initial attack to location of Victim 1.

8. Tactic time [min:sec] - Total time from initial intervention (exterior or interior flow) to final intervention (final flow or end of hallway location).

Table 6.7: Summary of Tactic Times for Interior Shutdown and Move Attack with No Vent Ventilation Configuration (Time, [min:sec])

Exp	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
1	N/A	N/A	N/A	18:33	19:32	N/A
3	N/A	00:47	00:41	00:12	00:54	01:04
5	00:12	00:41	00:32	00:21	00:59	01:00
6	00:14	00:40	00:32	00:23	01:00	00:54

Table 6.8: Summary of Tactic Times for Interior Shutdown and Move Attack with Single Vent Ventilation Configuration (Time, [min:sec])

Exp	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
8	00:13	00:39	00:32	00:28	00:58	00:53
10	00:11	00:41	00:32	00:20	00:55	00:56

Table 6.9: Summary of Tactic Times for Interior Shutdown and Move Attack with Two Vent Ventilation Configuration (Time, [min:sec])

Exp	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
14	00:13	00:41	00:34	00:21	00:55	00:53
15	N/A	00:48	00:40	00:20	00:52	01:04

Table 6.10: Summary of Tactic Times for Interior Flow and Move Attack with No Vent Ventilation Configuration (Time, [min:sec])

Exp	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
2	00:12	00:36	00:33	00:22	01:19	00:56
4	00:12	00:34	00:25	00:20	00:54	00:52

Table 6.11: Summary of Tactic Times for Interior Flow and Move Attack with Single Vent Ventilation Configuration (Time, [min:sec])

Exp	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
7	00:11	00:32	00:22	00:16	00:40	00:49
9	00:11	00:22	00:19	00:21	00:42	00:37
11	00:10	00:29	00:23	00:22	00:45	00:47
12	N/A	N/A	N/A	07:39	08:14	N/A

Table 6.12: Summary of Tactic Times for Interior Flow and Move Attack with Two Vent Ventilation Configuration (Time, [min:sec])

Exp	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
13	00:11	00:42	00:32	00:25	00:57	01:03
16	00:10	00:38	00:26	00:19	00:45	00:54
17	N/A	N/A	N/A	05:12	05:35	N/A

Table 6.13: Summary of Tactic Times for Transitional Attack with Single Vent Ventilation Configuration(Time, [min:sec])

Exp.	Tactic	Exterior Flow	Exterior Travel	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
18	No Additional Water	00:10	00:07	00:07	00:06	00:15	00:27	00:46	00:48
19	Fog Additional Water Delayed	00:11 Fog 00:18 Stright Stream	00:21	N/A	N/A	N/A	03:54	04:10	N/A
20	Additional Water	00:13	00:29	00:12	N/A	00:14	00:49	01:02	01:00
21	Additional Water	00:14	00:07	00:40	N/A	00:14	00:47	01:01	00:40
22	Additional Water	00:22	00:07	00:04	00:47	00:43	00:36	01:17	01:29

Table 6.14: Summary of Tactic Times for Transitional Attack with Two Vent Ventilation Configuration(Time, [min:sec])

Exp.	Tactic	Exterior Flow	Exterior Travel	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
23	Occlude Opening 1 Window	00:16	00:08	00:07	01:01	00:35	00:36	01:07	01:35
24	Additional Water Both Rooms	00:43	00:18	00:13	N/A	00:14	01:42	01:11	01:22

The average times for the interior "shutdown and move" experiments are shown in Table 6.15. It should be noted that these averages do not include Experiment 1 with delayed intervention.

Table 6.15: Average Tactic Times for Interior Shutdown and Move Attack (Time min:sec)

Ventilation Configuration	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
No Vent	00:12	00:36	00:29	00:21	00:67	00:54
Single Vent	00:11	00:28	00:21	00:20	00:42	00:44
Two Vent	00:11	00:40	00:34	00:22	00:51	00:59

The average times for the interior "flow and move" experiments are shown in Table 6.16. It should be noted that these averages do not include Experiments 12 or 17 with delayed intervention.

Table 6.16: Average Tactic Times for Interior Flow and Move Attack (Time min:sec)

Ventilation Configuration	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
No Vent	00:13	00:43	00:35	00:19	00:58	00:59
Single Vent	00:12	00:40	00:32	00:24	00:57	00:55
Two Vent	00:13	00:45	00:37	00:21	00:54	00:59

The average times for the transitional experiments are shown in Table 6.17. It should be noted that these averages do not include Experiment 19 with delayed intervention.

Table 6.17: Average Tactic Times for Transitional Attack (Time min:sec)

Ventilation Configuration	Exterior Flow	Exterior Travel	Door Read	Interior Flow	Interior Travel	Victim 4	Victim 1	Tactic Time
Single Vent	00:12	00:15	00:20	00:02	00:15	00:41	00:56	00:49
Two Vent	00:27	00:11	00:08	00:54	00:31	00:58	01:12	01:29

6.11 Impact of Water Usage

The amount of water used during each suppression tactic was measured from the start of the experiment until the fire was extinguished. Some hot spots remained, however no visible flame or smoldering existed. Figure 6.48 illustrates the water used in all experiments. The average water used varied from as little as 30.6 gallons in a single room exterior attack to as much as 257.2 gallons in a two-room interior attack.

During these experiments most of the water flow was scripted with leeway given based on conditions experienced by the nozzle firefighter, so the intent of this section is not to propose that a particular type of attack is more efficient. The intent is to highlight that transitional attack or interior attack utilizing the reach of your stream to cool while advancing toward and into the fire rooms, was successful with a relatively low amount of total water used.

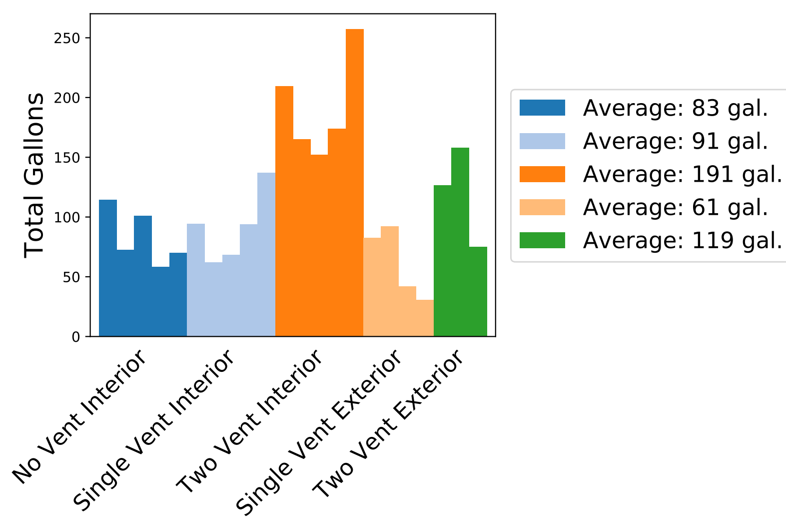


Figure 6.48: Water flow during all experiments grouped by ventilation type and attack method.

In the single-room interior attacks, the water usage did not vary with additional ventilation. The majority of the water was utilized in cooling the environment as the suppression crew approached the fire from the living room area, thus regardless of if the window was open or closed a similar amount of water was used. When a second room was involved in fire the amount of water used more than doubled. The charts in Figure 6.49 break up the water used by ventilation configuration and attack method.

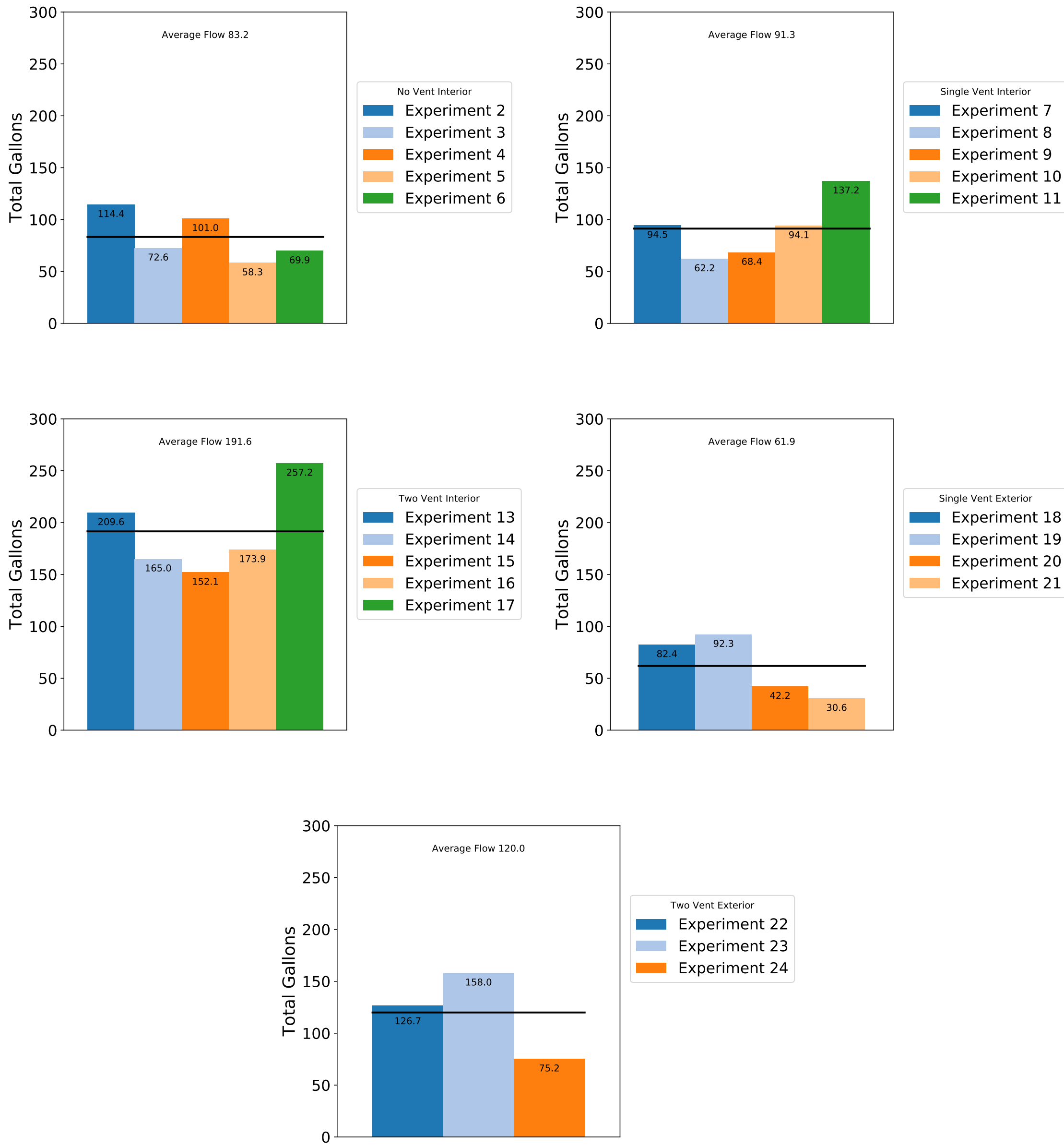


Figure 6.49: Water usage during suppression. Upper left is no-ventilation configuration interior attack, upper right is a single bedroom window open with a single room of fire interior attack, middle left is two bedroom open windows with two rooms of fire interior attack, middle right is a single bedroom window open with a single room of fire exterior attack, bottom center is two bedroom windows open with two rooms of fire exterior attack

The interior suppression tactics utilized some water for cooling the approach to the fire. To provide a direct comparison Figure 6.50 shows the comparison of the amount of water used on a single room fire from both the window and the door. The door values are adjusted to remove the water used for the cooling during the approach, which was necessary for advancement but did not contribute directly to suppression. For the doorway, the total flow was calculated from the point the crew was capable of directing water into the fire room until the completion of the experiment. For the window, the crew did not utilize water while approaching the fire thus all water usage was accounted for. In order to provide an accurate comparison, only single room fires with an open window were utilized. Additionally, the point where water was capable of entering the room during a "flow and move" approach was not possible thus only "shutdown and moved" approaches were utilized.

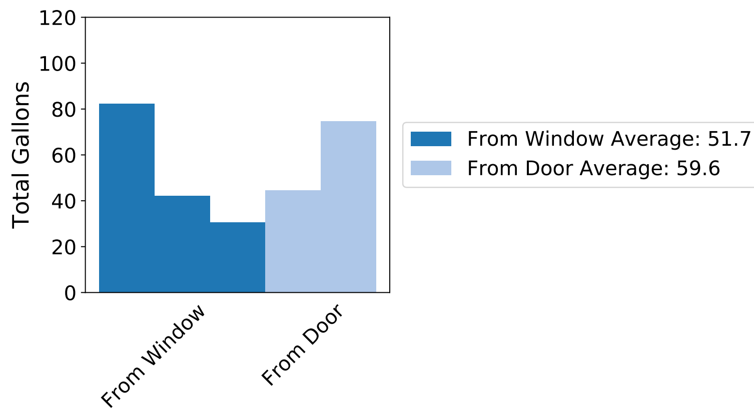


Figure 6.50: Water usage comparison for a single room fire where the door way suppression is adjusted to account for cooling during the approach not contributing to suppression.

As expected, adjusting the interior tactic water usage as described above results in an average usage of 51.7 gallons for the window and 59.6 gallons in the doorway. When taking into account the accuracy of the measurement device these two values can be considered the same.

6.12 Large Volume Gas Cooling

In order to analyze the effect of gas cooling in a large space under challenging conditions the interior walls of the structure were removed with the exception of the master bedroom wall separating the master bedroom from the rest of the structure. The open floor plan allowed for the analysis of gas cooling as a result of indirect attack, when the fire cannot be accessed with the hose stream without crawling into the structure through the flow path. Four different application methods 'pulse', 'long pulse', 'sweeping pulse' and 'narrow fog sweep' were utilized at two different flow rates, 95 gpm at 100 psi and 150 gpm at 100 psi. Table 6.18 lists the application techniques, flow rate, and average flow for each of the methods and flows used.

Pulse techniques were not used during the fire attack experiments as other variables were chosen to examine. Further research is needed to examine these techniques and different types of tools used to implement these techniques.

Table 6.18: Gas Cooling Application Techniques

Technique	Flow Rate (gpm)	Average Flow (Gallons)
Pulse	95	0.87
Long Pulse	95	1.68
Sweeping Pulse	95	5.83
Narrow Fog Sweep	95	6.98
Pulse	150	0.52
Long Pulse	150	2.95
Sweeping Pulse	150	9.73
Narrow Fog Sweep	150	8.16

6.12.1 Pulse

A common technique used for gas cooling while approaching a fire is the short pulse. The combination nozzle is set to a wide fog pattern and the nozzle is open and closed rapidly, remaining open for less than 1 second. Figure 6.51 shows the effect of the gas temperatures in the area of the suppression crew when a utilizing a pulse technique with a 95 gpm nozzle. With less than a gallon of water, even in a wide fog pattern, had little to no effect on temperature near the approach crew. The fire compartment is also un-effected.

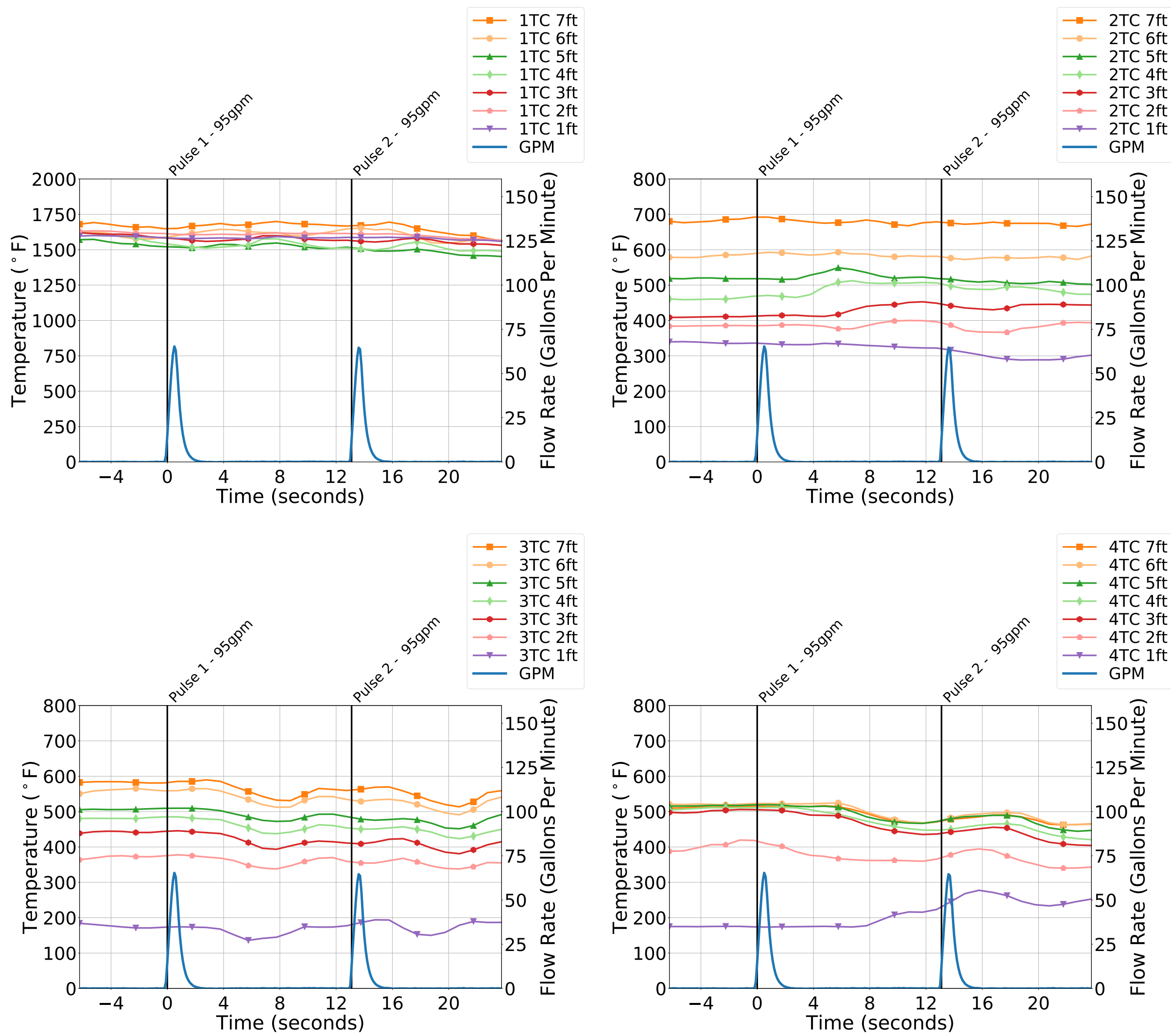


Figure 6.51: Effectiveness of 'pulse' technique using 95 gpm nozzle at gas cooling. Upper left is fire compartment, upper left is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

Increasing the flow rate of the nozzle has does not change the impact of the tactic as the water flow is still less than 1 gallon. Figure 6.52 shows the temperatures both near the suppression crew and in the fire compartment remain unchanged.

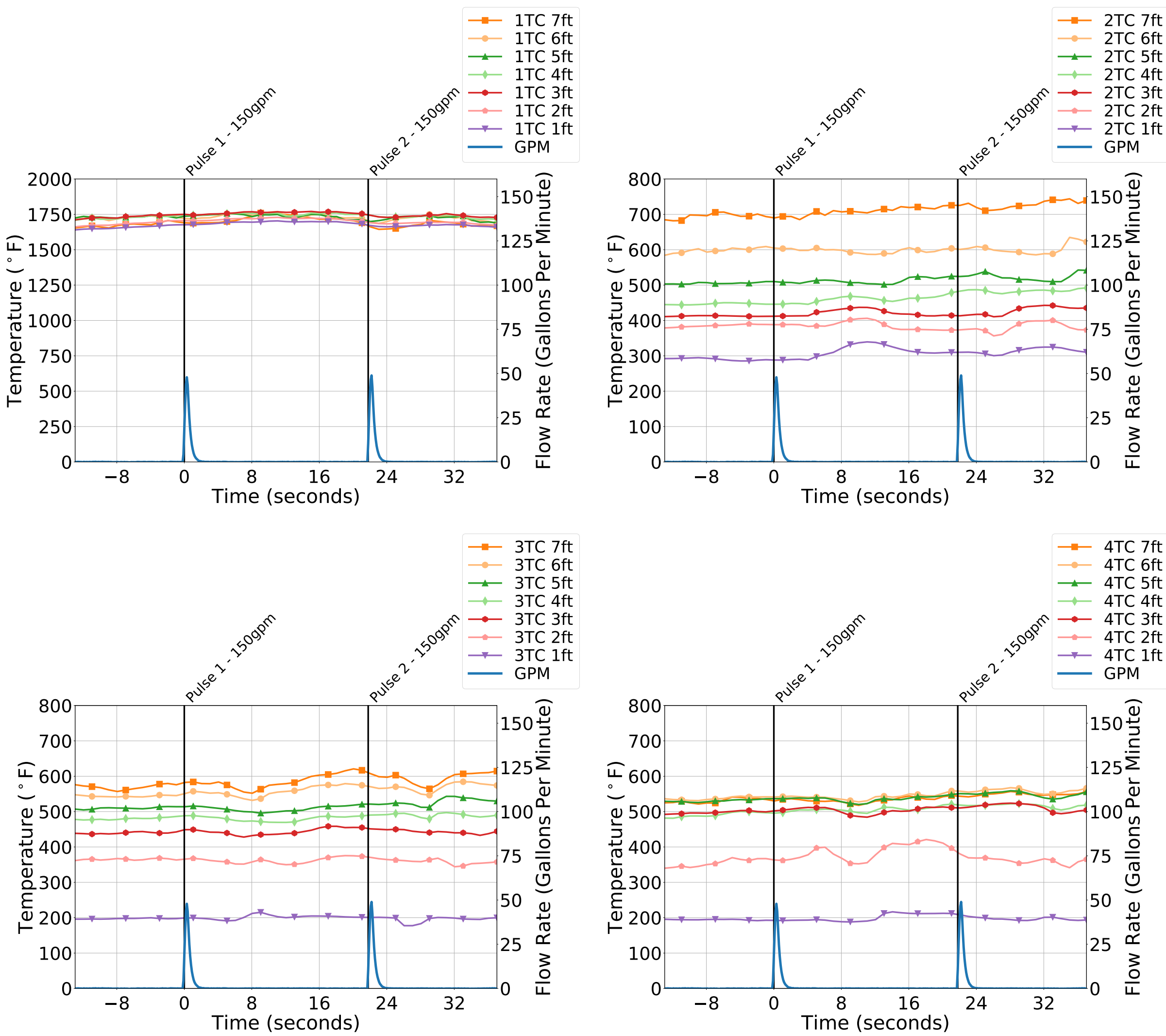


Figure 6.52: Effectiveness of ‘pulse’ technique using 150 gpm nozzle at gas cooling. Upper left is fire compartment, upper left is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

6.12.2 Long Pulse

Increasing the length of the pulse to increase the total flow by a factor of two had a slight effect on the effectiveness of the cooling. Figure 6.53 shows the effect of the gas temperatures in the area of the suppression crew when a utilizing a long pulse technique with a 95 gpm nozzle. Increasing the duration of the pulse and the total flow to 1.68 gallons is capable of decreasing the temperature by less than 100 °F. The temperature rebounds within 15 seconds of the decrease back to the level prior to application.

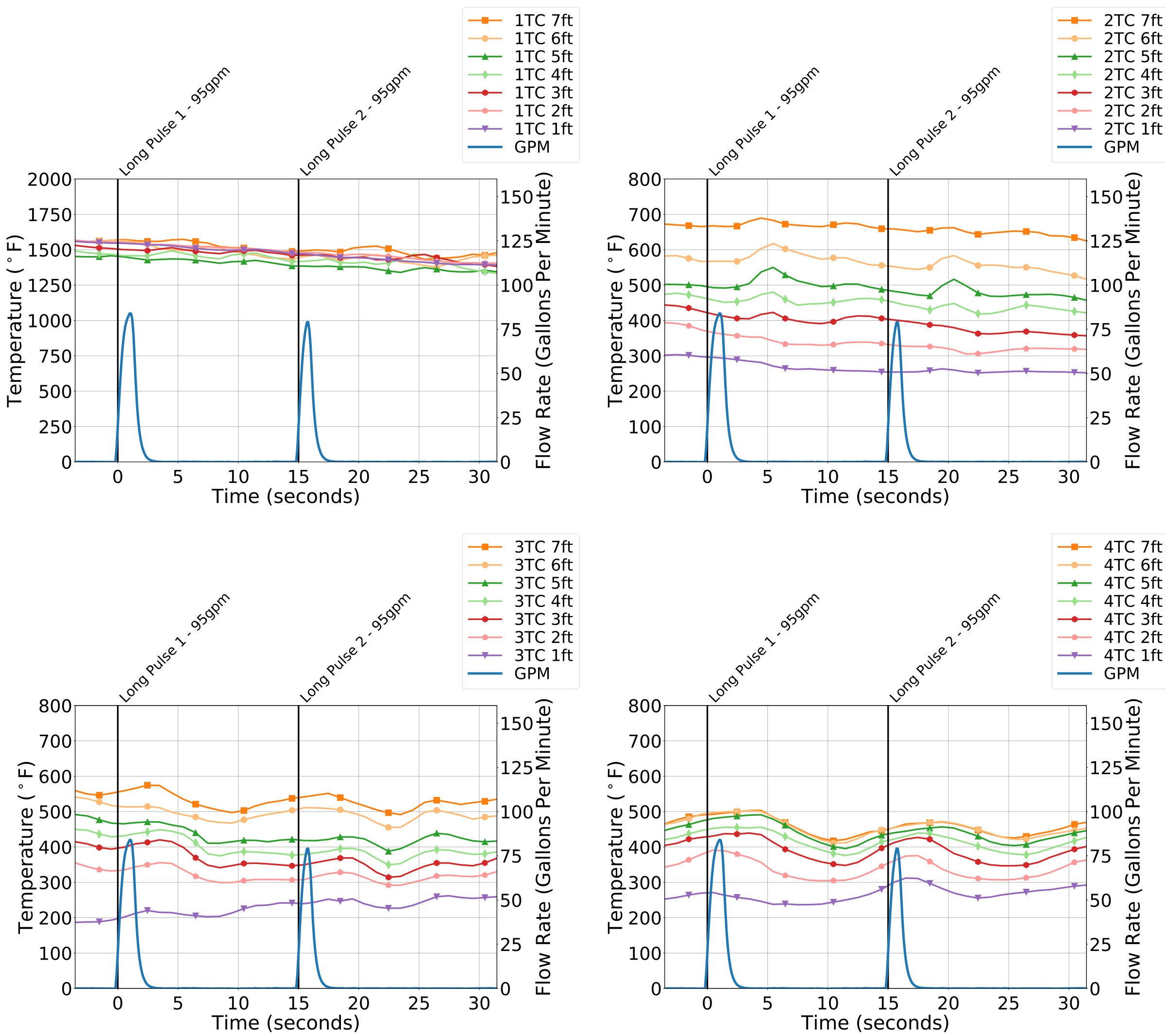


Figure 6.53: Effectiveness of 'long pulse' technique using 95 gpm nozzle at gas cooling. Upper left is fire compartment, upper left is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

As shown in Figure 6.54, increasing the flow rate to 150 gpm increases the cooling effectiveness however the temperatures rebound within 15 seconds of application.

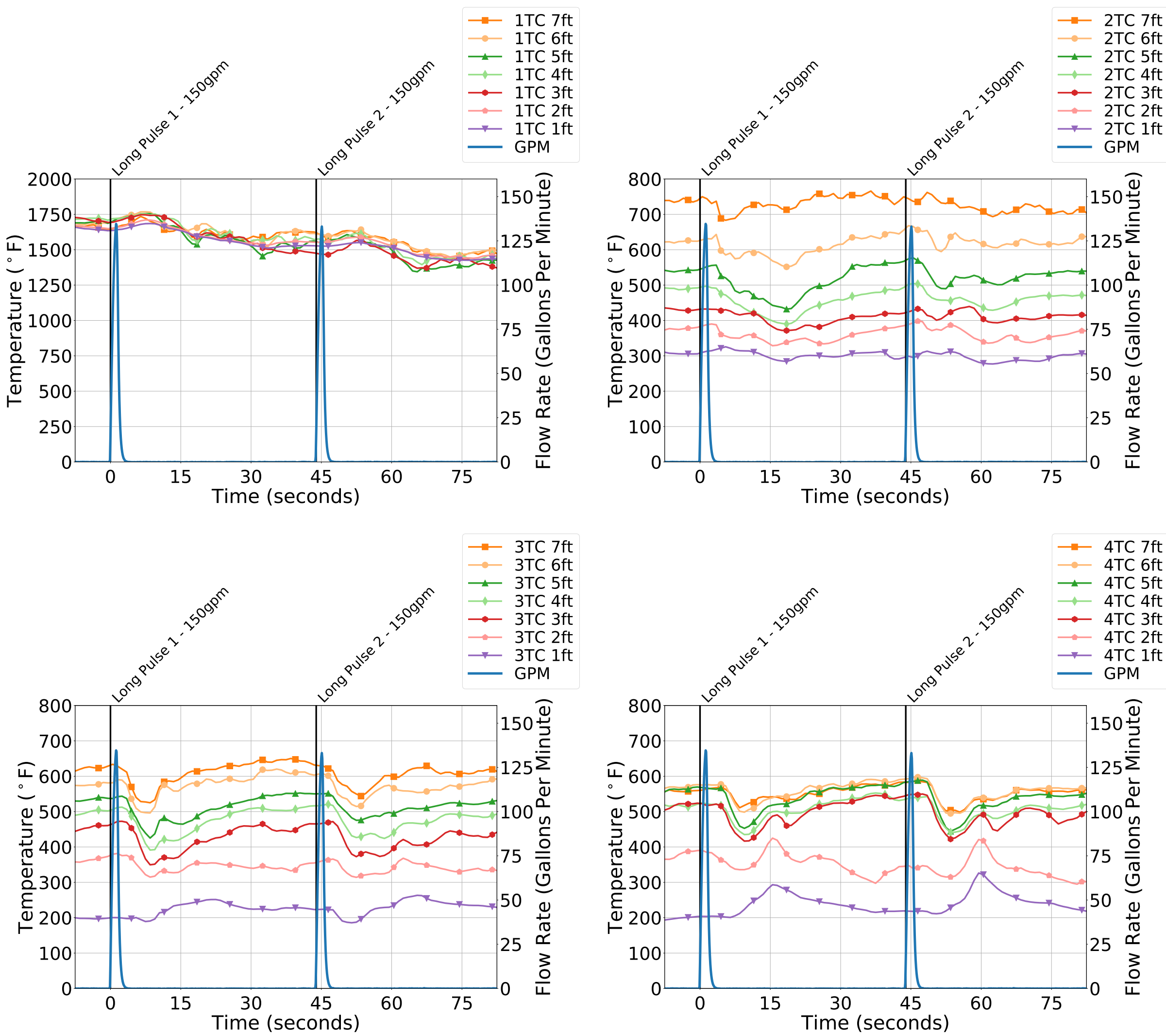


Figure 6.54: Effectiveness of 'long pulse' technique using 150 gpm nozzle at gas cooling. Upper left is fire compartment, upper left is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

6.12.3 Sweeping Pulse

To increase the volume of water and the application location a longer pulse, moved horizontal from right to left in the space in a sweeping motion was used. Figure 6.55 shows the impact of the sweeping pulse on the temperatures in fire compartment and the area around the suppression crew. The sweeping pulse has a more significant impact on the temperatures with temperatures in the fire compartment reacting due to the mixing and more significant cooling in the area of the suppression crew. Although the cooling is more significant than the pulse and long pulse the temperatures still return to the state they were prior to water application within 15 seconds.

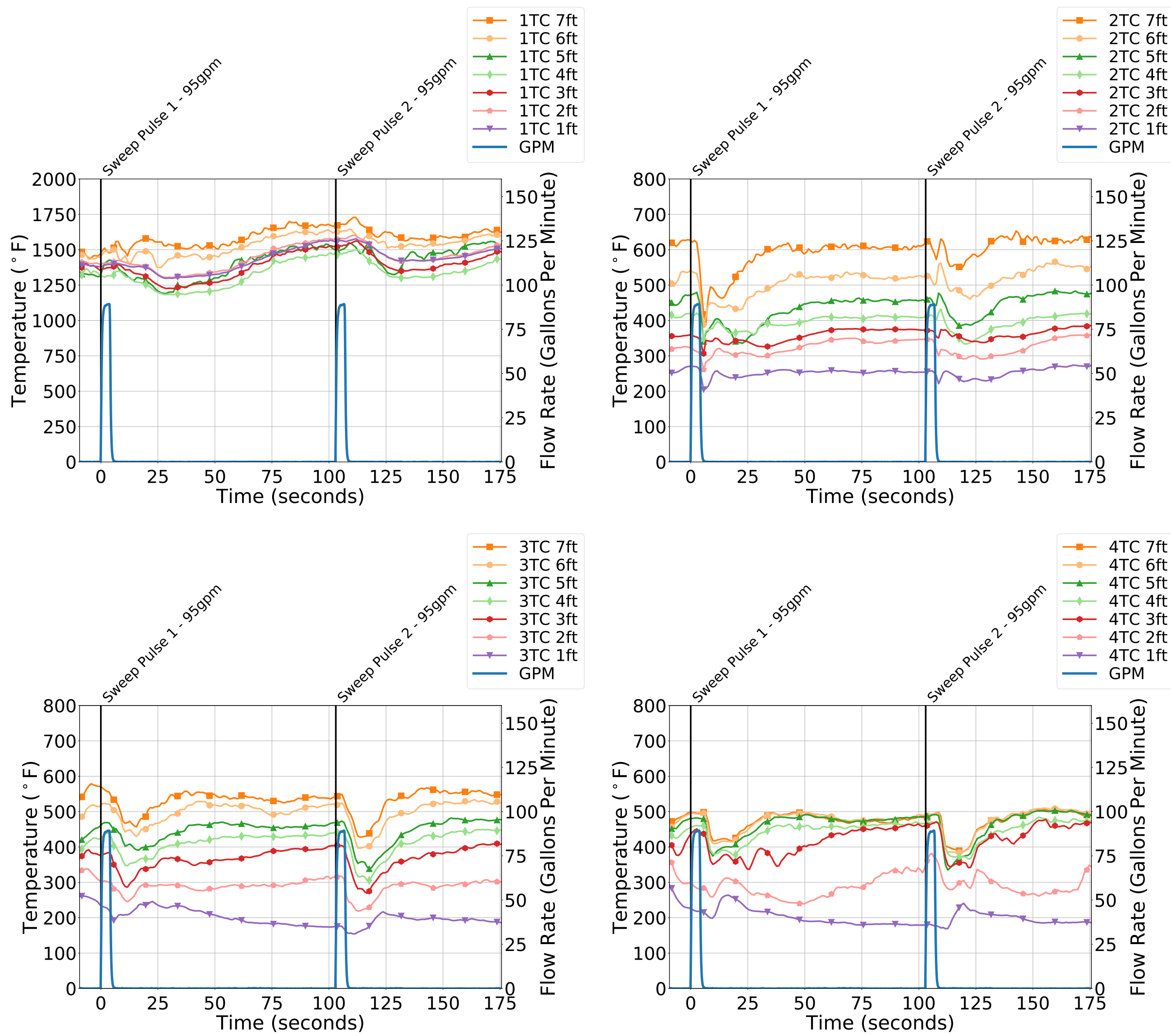


Figure 6.55: Effectiveness of 'sweeping pulse' technique using 95 gpm nozzle at gas cooling. Upper left is fire compartment, upper right is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

As shown in Figure 6.56, increasing the flow rate to 150 gpm increases further increases the cooling however the temperatures rebound within 15 seconds.

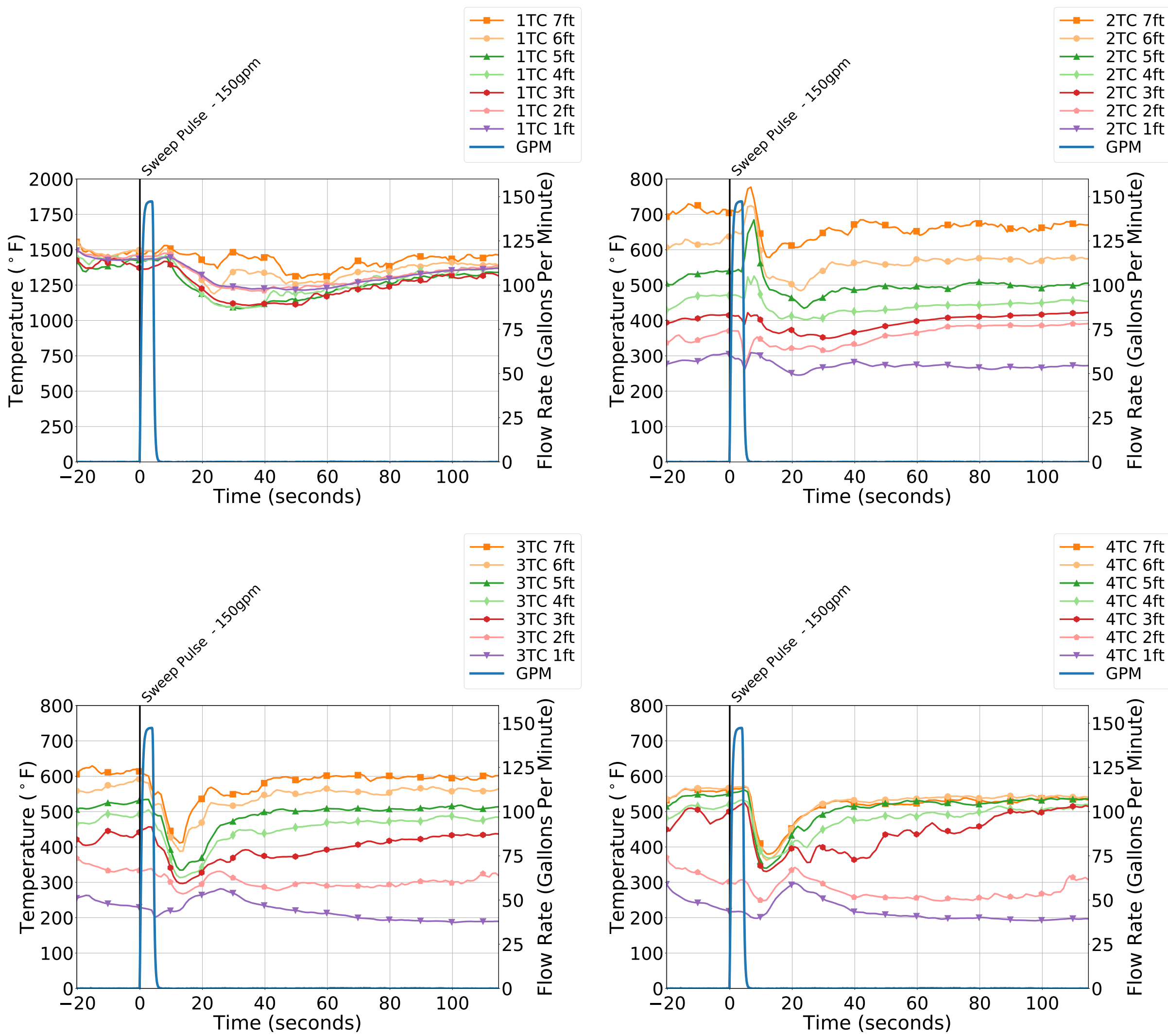


Figure 6.56: Effectiveness of ‘sweeping pulse’ technique using 150 gpm nozzle at gas cooling. Upper left is fire compartment, upper right is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

6.12.4 Narrow Fog Sweep

Adjusting the pattern to a narrow fog from the wide fog pattern will increase the reach of the stream. Figure 6.57 shows the impact of the narrow fog sweep on the temperatures in fire compartment and the area around the suppression crew. Increasing the reach of the stream over the pulse, long pulse and sweeping pulse has even more impact on the temperature reduction and temperatures take longer to rebound, approximately 20 seconds after application.

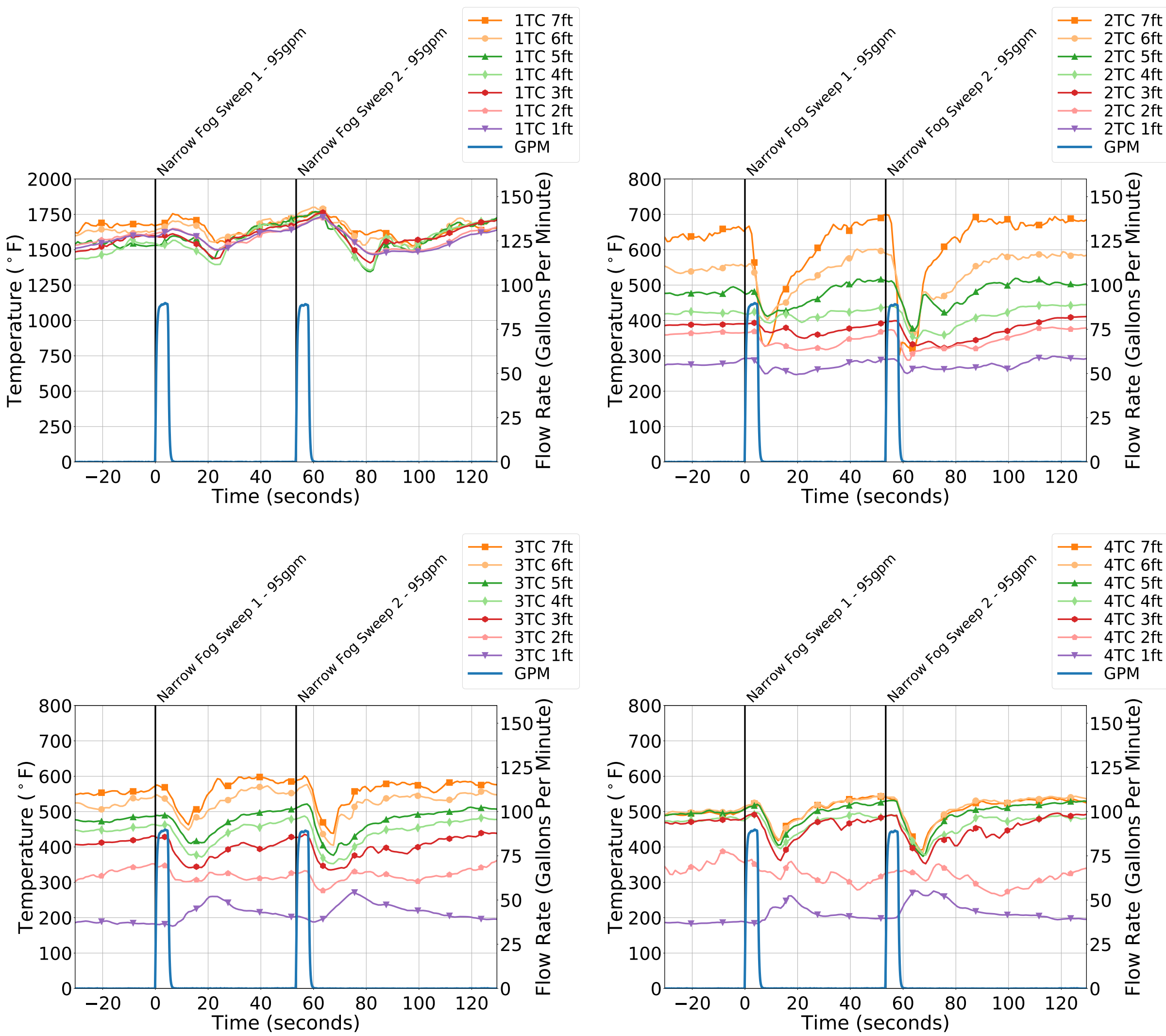


Figure 6.57: Effectiveness of ‘narrow fog sweep’ technique using 95 gpm nozzle at gas cooling. Upper left is fire compartment, upper right is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

As shown in Figure 6.58 increasing the flow rate to 150 gpm significantly increases the cooling and it increases the time to it takes the temperature to rebound from 20 seconds to 30 seconds.

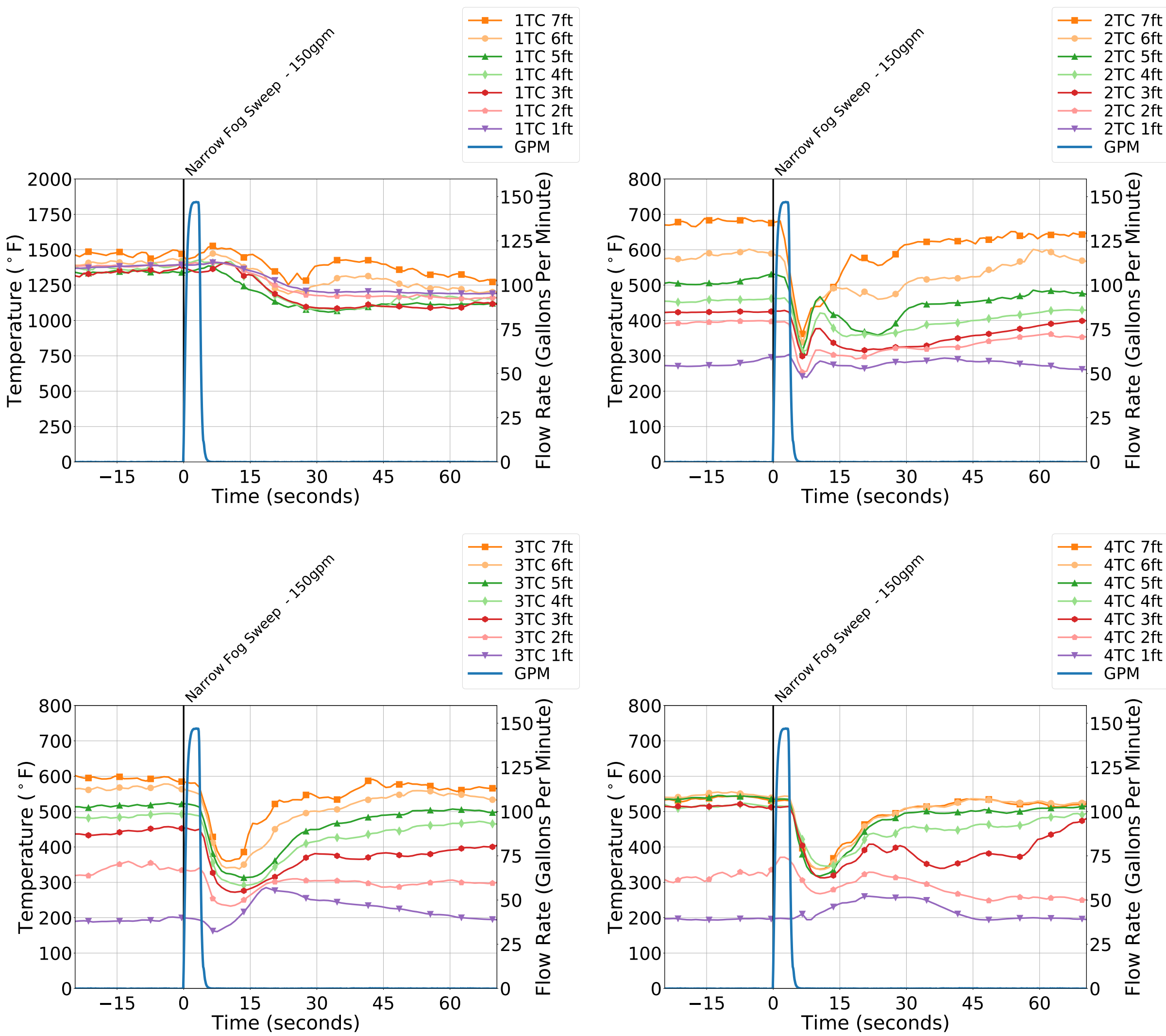


Figure 6.58: Effectiveness of 'narrow fog sweep' technique using 150 gpm nozzle at gas cooling. Upper left is fire compartment, upper right is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

6.12.5 Straight Stream

To compare the cooling tactics to the approach tactics used in the hallway, suppression experiments using the same 'wall, ceiling, wall' technique was used, directed as much as possible towards the fire compartment with the 150 gpm setting. Figure 6.59 shows the impact of the narrow fog sweep on the temperatures in fire compartment and the area around the suppression crew. The "wall ceiling wall" technique has the most effect on gas temperatures in the area it was applied. It also has a slight effect on temperatures in the fire compartment. It also increases the time it takes the temperatures to rebound over the other gas cooling techniques, to approximately 50 seconds.

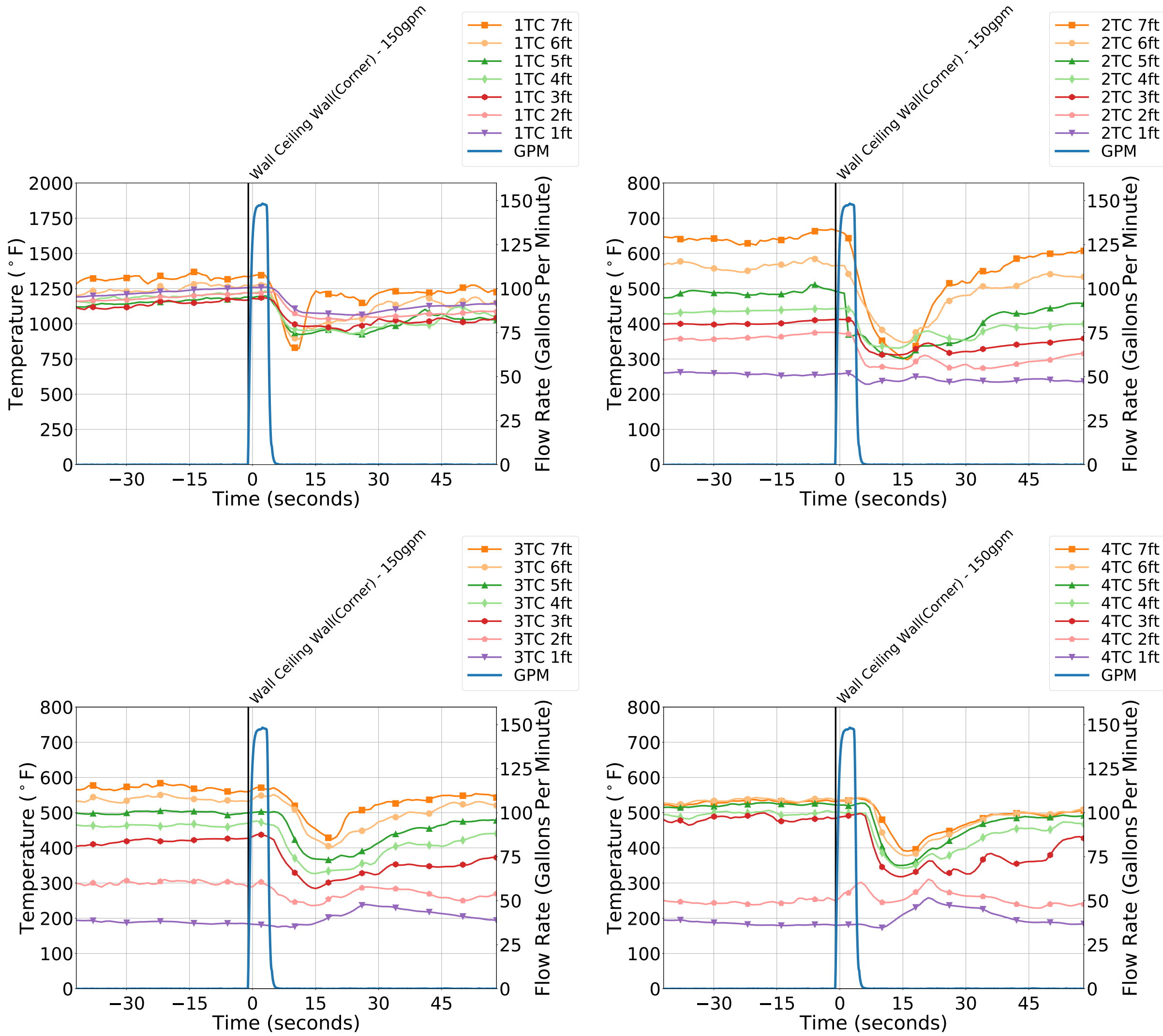


Figure 6.59: Effectiveness of 'wall, ceiling, wall' technique using 150 gpm nozzle at gas cooling. Upper left is fire compartment, upper right is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team.

6.13 Thermal Imager Use

Thermal imagers can provide visibility to a fire attack crew, assist them in navigating the structure and looking for victims and improve crew accountability. Based on the visual data collected from these experiments comments can be made regarding the navigation and accountability.

Each of the experiments had two "fire department" thermal imagers installed in the structure. One of the thermal imagers was installed near floor level, to the right side of the front door. This provided a view of the path from the front door to the opening to the hallway to the bedrooms (fire rooms) on the left side of the view. The other thermal imager was positioned near the floor with a view down the hallway looking toward the bedrooms.

During several of the experiments, a third hand-held thermal imagers was carried in to the structure by one of the firefighters. This thermal imager was used to guide the attack crew as needed and then used to find “hot spots after the initial knockdown.

Both of the thermal imagers installed in the structure were paired with a standard video camera. The purpose was to demonstrate what the firefighters could see with and without a thermal imager.

6.13.1 Thermal imagers provide improved visibility in heavy smoke conditions.

The fires had reached the fully developed stage at the point of firefighter entry. As a result, once the firefighters entered the building they had no visibility and had to feel their way as they advanced the hose line into the house.

In Figures 6.60 and 6.61, the only opening to the exterior was the front door. The front door served as both the air intake and smoke exhaust for the structure. The images from the front door Figure 6.60 and the hallway Figure 6.61 were captured at the same time.

Figure 6.60: Bedroom window closed configuration. The images are frame captures from the standard video on the left and the thermal imager on the right. While air flowing through the lower part of the doorway has provided a small amount of visibility just inside the doorway, the back-up firefighter on the hose line is only visible in the thermal imager view.

Figure 6.61: Bedroom window closed configuration. The images are frame captures from the standard video on the left and the thermal imager on the right. The firefighter with the nozzle has advanced to the entry point of the hall way. The firefighter can be seen in the thermal imager view on the right. The smoke has obscured the view of the firefighter in the standard video.

Figures 6.62 and 6.63 show similar views as Figures 6.60 and 6.61. The difference in the ventilation configuration is that the window in Bedroom 1 was open and the front door was opened a few seconds before the attack crew makes entry. The vent in the fire room allowed the fire to flashover and burn with an increased heat release rate relative to the previous case with the window closed. The result was additional air was moving in through the front door, which provided improved visibility near the floor by the doorway but it did not improve the visibility of the firefighters.

Figure 6.62: Bedroom window open configuration. The images are frame captures from the standard video on the left and the thermal imager on the right. Notice how more of the back-up firefighter can be seen in the visual image compared to the visual image in Figure 6.60.

Figure 6.63: Bedroom window open configuration. The images are frame captures from the standard video on the left and the thermal imager on the right. The firefighter with the nozzle has advanced to the entry point of the hall way. The firefighter can be seen in the thermal imager view on the right. The smoke has obscured the view of the firefighter in the standard video. The open doorway is toward the left side of the standard video image.

The third type of ventilation configuration had two open windows, one in each fire room at the end of the hallway and the open front door. Both bedroom windows were open and the front door was opened a few seconds before the attack crew made entry. The window vents in the fire rooms allowed the fire to flashover and burn with an increased heat release rate relative to the previous case with only one bedroom on fire. The result was additional air was moving in through the front door which provided improved visibility near the floor by the doorway but it did not improve the visibility of the firefighters. This is shown in Figures 6.64 and 6.65.

Figure 6.64: Bedroom windows open configuration. The images are frame captures from the standard video on the left and the thermal imager on the right. Notice how more of the back-up firefighter can be seen in the visual image compared to the visual image in Figure 6.60.

Figure 6.65: Bedroom windows open configuration. The images are frame captures from the standard video on the left and the thermal imager on the right. The firefighter with the nozzle has advanced to the entry point of the hall way. The firefighter can be seen in the thermal imager view on the right. The smoke has obscured the view of the firefighter in the standard video.

As shown in the figures above, the thermal imager provided a clear view of the firefighters as well as the position of the hot gas layer and cooler gas layer interface. Furnishings and the interior walls, ceiling and floors could also be seen to assist firefighters in navigating in navigating.

In addition, thermal imagers can be used to look for thermal contrasts, heat signatures and the convective flow of soot-laden gases.

Thermal imagers nay be used to see radiant heat which may assist the attack crew in finding the seat of the fire.

Thermal imagers can be utilized to aid in the search for victims within the structure, keeping in mind that the victim may appear “white” in a room in which the victim would be the hottest object and “black” in a room in which the victim is the coolest. The victim may also not be visible at all if the victim is the same temperature as the surrounding objects.

6.13.2 Thermal Imager Limitations

As outlined within *NFPA 1408: Standard for Training Fire Service Personnel in the Operation, Care, Use, and Maintenance of Thermal Imagers*, all personnel using thermal imagers must understand their use and limitations [56]. Thermal imagers are designed to detect radiant thermal energy emitted from solid surfaces, particulates, and some gases utilizing a constant emissivity value. Emissivity is defined as the ratio of the energy radiated from a material’s surface to that of a blackbody, or perfect emitter, at the same temperature. The emissivity of the surfaces and gases radiating energy during a fire affect the thermal imager‘s ability to determine the actual temperature and can be misleading to the firefighters utilizing the device. As the emissivity value of radiating objects within a fire diverge from the imager‘s constant value, the temperature readout becomes more and more inaccurate.

Further, the sensors in the thermal imagers are designed for a range of wavelengths which allow them to “see” though a variety of hot gases and vapors. As a result if the thermal imager is aimed at a hot wall, it will display an estimated temperature of that hot wall based on the radiant heat flux being emitted from the wall and the assumed emissivity. If gases of a higher temperature are located between the wall and the thermal imager, it is possible that the thermal imager will not “see” them. As a result, a firefighter could be in contact with gas temperatures that are hotter than those displayed by the thermal imager.

For the reasons above, thermal imagers are considered unreliable thermometers.

Below are several examples from four different experiments which represent the three different ventilation configurations: Bedroom 1 (fire room) window closed (Experiment 1 & 19), Bedroom 1 (fire room) window open (Experiment 12), and Bedroom 1 & 2 (both fire rooms) with windows open (Experiment 17).

Each of the examples are presented a pair of charts, one from each imager where the readout from the thermal imager display is compared to a temperature measurements from the thermocouple arrays that are located at those two positions.

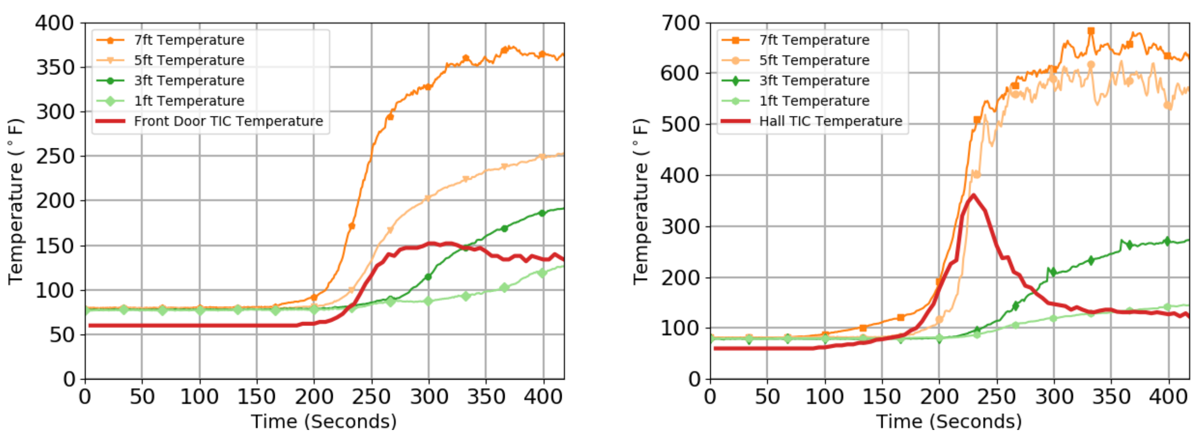


Figure 6.66: Comparison of thermal imager temperature read out to the actual compartment temperatures. Thermal imager from the door location is left and thermal imager from the hallway location is right. The thermocouple temperatures from the adjacent arrays are shown at 7, 5, 3, and 1 ft above the floor (AF). (Experiment 1)

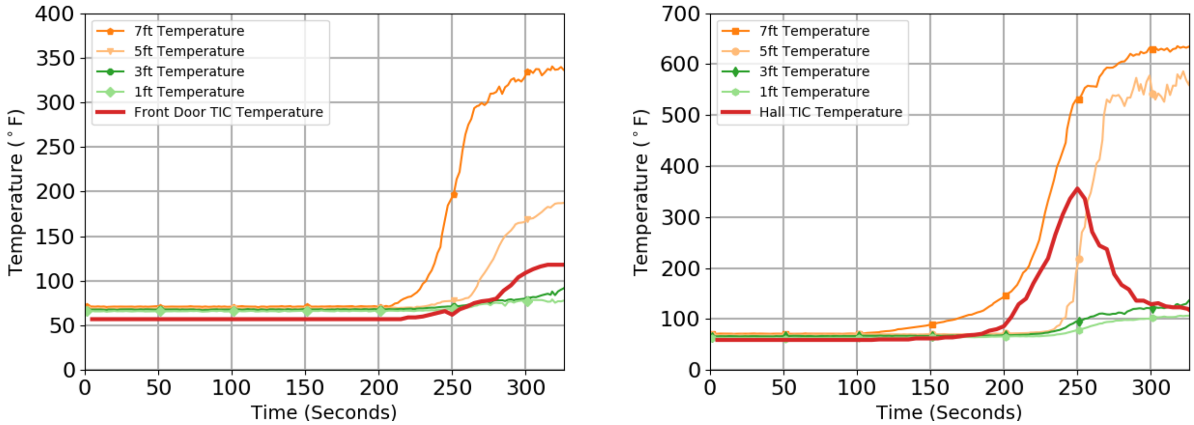


Figure 6.67: Comparison of thermal imager temperature read out to the actual compartment temperatures. Thermal imager from the door location is left and thermal imager from the hallway location is right. The thermocouple temperatures from the adjacent arrays are shown at 7, 5, 3, and 1 ft above the floor (AF). (Experiment 12)

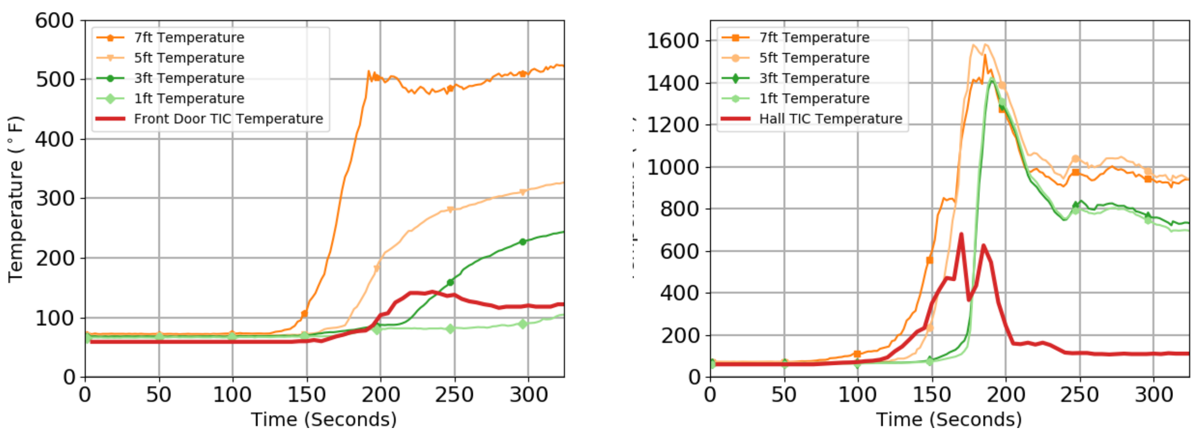


Figure 6.68: Comparison of thermal imager temperature read out to the actual compartment temperatures. Thermal imager from the door location is left and thermal imager from the hallway location is right. The thermocouple temperatures from the adjacent arrays are shown at 7, 5, 3, and 1 ft above the floor (AF). (Experiment 17)

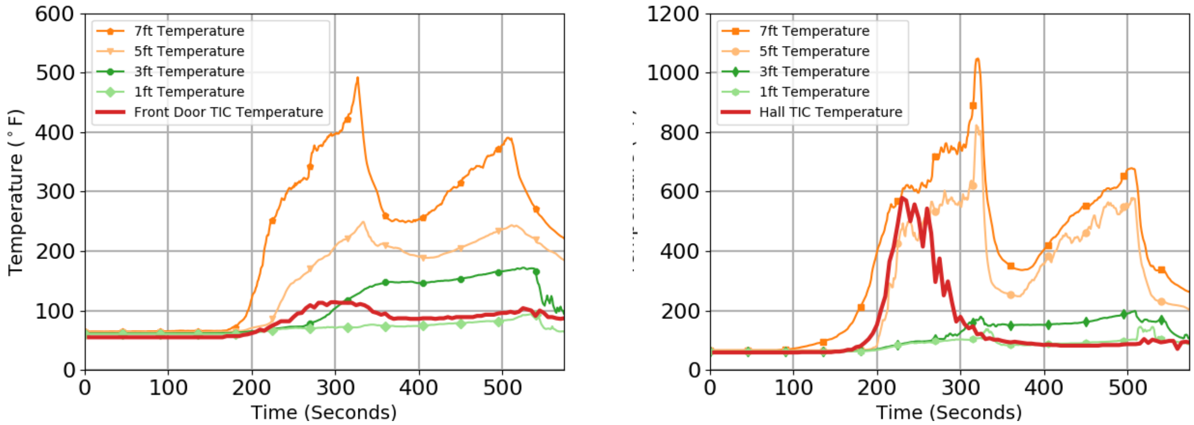


Figure 6.69: Comparison of thermal imager temperature read out to the actual compartment temperatures. Thermal imager from the door location is left and thermal imager from the hallway location is right. The thermocouple temperatures from the adjacent arrays are shown at 7, 5, 3, and 1 ft above the floor (AF). (Experiment 19)

In each of the scenarios, the thermal imager indicated temperatures similar to the thermocouple measuring the gas temperature early on in the experiment. As time progressed the temperature recorded on the imager diverged significantly from that of the gas temperature.

7 Tactical Considerations

In this section, the results of all the experiments are discussed to develop relationships to tactics on the fire ground as they may impact the safety of the fire service. The topics examined in this section were developed with the project's technical panel. The application of the findings discussed in this section to the fire scene depend upon many factors such as (i) building structure and geometry; (ii) capabilities and resources available to the first responding fire department; and (iii) availability of mutual aid. In addition, the tactical considerations provided should be viewed as concepts for the responding fire service personnel to consider at the fire scene. There is no silver bullet tactic for structure fires, and these considerations are meant to increase the knowledge of the fire service and to be incorporated into training and procedures, if deemed applicable.

In these experiments, interior fire attack was implemented and measured for the first time and addition transitional fire attacks were conducted with more measurements than ever before. In every experiment, the fire went out and no one was injured, but that should not be a surprise to the fire service as tactics like these are executed successfully everyday. With all of the measurements made during these experiments as well as the vast experience of the technical panel, several consistent themes emerge which may be helpful to the fire service. Each of these themes is packaged as a tactical consideration with supporting text and visuals. Each one can also be traced back to the analysis section for more scientific support. Each of these considerations can have limitations so it is important that they are interpreted in the proper context.

These experiments were conducted in an average-sized, one-story single family detached house without the ability for fire extension into the structure. Additional interpretation will be required to expand these considerations to a two-story house with and advanced fire in the void spaces. It may be possible for some of the considerations but not all. Prior to the start of simulated fire service intervention, the hose lines were laid out and charged, proper pressure was applied to the line, there were no kinks, and the crews had donned all of their equipment to attack the fire. In the street, the fire service has to do all of these things; the faster and more efficient they are done the faster the tactics can be executed.

The fire was permitted to develop until it was ventilation-limited and similar for every experiment. In the street, fires could be more or less advanced and have different ventilation configurations. In these experiments, we had 3 firefighters deploy the 1 3/4 in hose line with additional resources as needed to execute the tactics examined. A single hose line was utilized, repositioned when necessary to accomplish multiple water applications. In the street, resources can limit the tactical options as well as the timeline in which they are executed.

These experiments attempted to replicate as close to ideal versions of the tactics they were examining, crews knew where the fire was, the layout of the house, what obstacles were in their way and executed the same way many times with a lot of practice. In the street, highly-trained and efficient firefighters come up against unknowns on the fire ground and they adapt the best they can.

There are a lot of variables during the fires that are responded to across the world every day that vary from these experiments. Examine these tactical considerations through the lens of your own experience, and apply them appropriately and in the right context where applicable to your local system. The goal is that if the fire service understands fire dynamics and they understand the benefits and limitations of their tactics, then good decisions will be made on the fire ground that result in the best possible outcome for the mission of the fire service: life safety (civilian and firefighters), property conservation, and incident stabilization.

7.1 Interior Suppression With Only Smoke Showing.

When arriving on a residential structure fire where there is smoke showing, determining the location and extent of the fire is an important part of the initial size-up and often step one to developing an initial action plan. When the fire is not venting out an opening, determining the location can be difficult. In this instance an interior attack may be the most effective way to locate, confine, and suppress the fire. Figure 7.1 below shows an example of how difficult determining the exact location of the fire may be. Although the side 'B/C' window shows dark black smoke, the fire is actually located in the 'A/B' corner bedroom. The smoke color/velocity venting from around openings can sometimes be driven more by the size of the gap it is venting from and less about its proximity to the fire.

Figure 7.1: Example of no fire showing with no open vents on a residential structure. Side A (left) has a front door and A/B corner window with smoke showing. Side C (right) shows darker smoke showing from the B/C corner. The fire is located in Bedroom 1 in the A/B corner of the structure.

In this scenario, committing a suppression crew to the front door with a hoseline to locate and suppress the fire may be the most effective tactic. If this tactic is chosen further considerations should include; door control as identified by Kerber in 2013 [57]: the amount of air entrained in your stream [2]; the effects of flowing while moving versus shutting down to move (Section 7.14); the importance of using your stream to cool as you approach the fire (Section 7.15); and what effect that stream has on the flow paths within the structure (Section 7.9).

When conducting an interior attack, the suppression crew should cool as they advance. If the intent is to achieve the greatest reach, while limiting the air entrainment, a smooth bore nozzle or combination nozzle set to straight stream should be utilized. If the intent is to move products of combustion ahead of their position, the crew should consistently move the nozzle in a pattern ('O', 'T', 'Z', 'n'), the faster the nozzle is moved the more it will move products ahead of the crew. If a combination nozzle is being used, the most air entrainment will be achieved on a narrow fog moved in an 'O' pattern.

If at any time flames are visible, the suppression crew should apply water to them immediately to prevent rollover/flashover. Once they reach the fire compartment, applying a steep angle stream off the ceiling will coat the most surfaces in the room, providing the most cooling [1]. After applying water at a steep angle, the stream should be transitioned down to apply water to the contents in the room. If at any time flames are visible, the suppression crew should apply water to them. After checking the integrity of the floor, they should enter the compartment for final suppression. This sequence of steep angle followed by content suppression rapidly cooled the space to a level which allows firefighters in full protective clothing to enter the compartment.

Note: In this study utilizing a narrow fog pattern in a flow and move technique, during an interior attack with no ventilation opposite the attack crew was purposely omitted due to safety concerns for the suppression crew. Entraining a large amount of air towards a fire with no ventilation opposite could create a high pressure near the fire compartment with no exhaust. This high pressure would seek the low pressure behind the attack crew and could potentially have resulted in a rapid-fire event. Previous experiments using interior suppression controlled from the exterior resulted in hazardous conditions where firefighters would have been located. This topic requires further research to fully understand.

7.2 Transitional Attack With Fire Showing Near the Entry Point.

Once a tactical fire suppression plan is chosen, one of the first decisions is where to stretch the hoseline. When there's fire venting from the A side, near the entry door, with no other openings on the structure, it's easy to determine the location of the fire. In this scenario, a transitional attack may be the most effective way to knock-back confine, and suppress the fire. Figure 7.2 shows this scenario from Experiment 26. The fire is venting from the side A window near the door, no other vents are open, and the neutral plane is above the sill of the window. The lack of additional vents and neutral plane position indicate the seat of the fire is located in that compartment.

Figure 7.2: Example of fire showing from a side A window, adjacent to the front door on a residential structure.

A transitional attack on the fire venting from the window followed by immediate advancement to the interior may be the most effective method to knock back, confine, and suppress the fire. If this tactic is chosen, further considerations should include water mapping and air entrainment as identified by UL FSRI [1,2]; applying water off the ceiling at a steep angle, using a solid or straight stream in a fixed position (Section 7.9); the importance of following the initial flow with immediate advancement to the interior (Section 7.11); water application did not produce a noticeable increase in steam expansion or moisture for victims during these experiements (Sections 7.12 & 7.13: and the fact that you don't need a considerable amount of water to knock back the fire (Section 7.8).

When a transitional attack is chosen, the most effective method of initial water application to coat the most surfaces thus providing the most cooling is as steep an angle as possible off the ceiling, keeping the nozzle as steady as possible. The nozzle firefighter should be constantly evaluating the effectiveness of the water application, looking for indications it is having an effect. The flames in the gas layer should begin to extinguish within seconds. If no effect is noted, the nozzle should be directed in a different location or possibly off the top of the window to coat surfaces. Once the gases have been cooled enough to no longer have fire venting out the window, the nozzle can be shut down to evaluate conditions. There is no specific time limit or suggested flow time, as the time required for cooling should be based on conditions. If the water application is no longer showing signs of effective cooling, the application angle should be adjusted. If the initial water application is not positively impacting the conditions (Figure 7.3) the crew should shut down and immediately conduct an interior attack.

Figure 7.3: Example of the improved conditions from the initial water application during a transition attack using a smooth bore nozzle at a steep angle directed off the ceiling (Experiment 18). Sequence of images is the first three seconds after initial water application. The moment suppression starts (top left), 1 second after suppression starts (top right), 2 seconds after suppression starts (bottom left), and 3 seconds after suppression starts (bottom right).

Once the gases have been cooled and the nozzle shut down, the nozzle firefighter should apply water to any visible flame in the compartment. If visibility is limited, a half bale (smooth bore nozzle) or narrow fog (combination nozzle) should be applied through the window in a wide 'O' pattern to coat the most surfaces. Care should be taken to limit air entrainment by ensuring the nozzle is placed inside the window. If the suppression crew cannot apply water directly, due to an obstruction near the opening or the elevation of the window (second floor fire), or if tactic is ineffective, they should rapidly transition to the interior once the gases are cooled. While relocating the line to the front door the crew should pay attention to the conditions at the front door, evaluating for conditions which indicate the transitional attack was not effective.

Consideration should be given to the line used for final interior suppression. The crew should utilize the most rapid method of transitioning. In some instances, this will be by relocating the initial attack line to the interior, in others it may be deploying an additional line for interior suppression. If more than one crew is available, consideration should be given to conducting simultaneous exterior application and interior advancement. The initial application of water during the transitional attack was shown to reduce not only the fire room temperature but temperatures in adjacent spaces as well.

Any interior portion of a transitional attack should advance to the fire compartment as fast as possible, applying water as conditions warrant. Once at the fire compartment a short pause is needed to determine if gases are once again burning or if visibility is limited. If so, they should apply a steep angle off the ceiling to coat the most surfaces. If flames are visible the crew should apply water to any visible fire in the compartment. If there is no visible fire in the compartment. The crew should check the integrity of the floor, then enter the compartment for final suppression.

7.3 Fire Showing Remote from Primary Entry Point.

The tactical choice of where to deploy the initial attack line may have less to do with the proximity of the venting fire to the entry point and more to do with all the other variables on the fire scene. Figure 7.4 shows an example of fire showing remote from the primary entry point (front door). In this example there are no other ventilation points indicating the fire is located in a room on the ‘C’ side of the structure. The structure is also in the out in the open with no obstructions to attack line deployment and the front door does not require forcible entry.

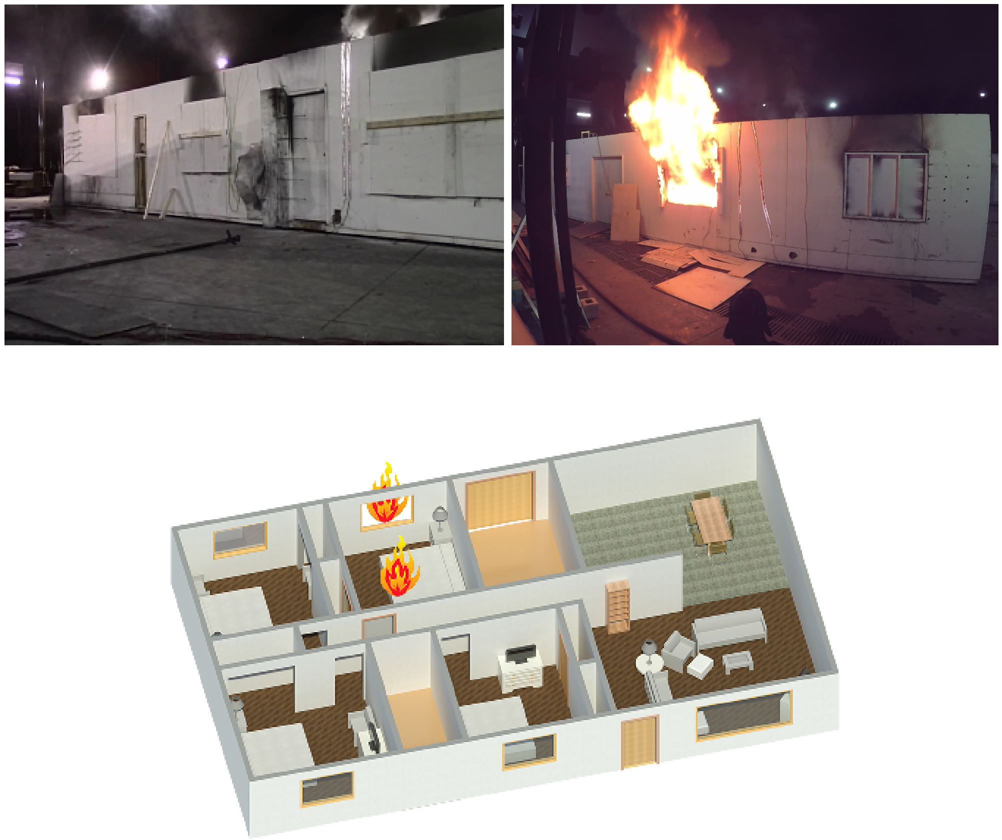


Figure 7.4: Example of a ranch style structure with fire showing from a Side ’C’ window (right) remote from the primary entry point on side ’A’ (left). An isometric showing the interior (bottom) provides the potential line advancement path on the interior.

For a room and contents fire, the most important timing piece is the initial application of water into the compartment, to cool the compartment and knock back the fire prior to it extending outside the compartment. If that can be achieved faster by conducting an interior attack through the front door, then that is the most effective tactical choice. If it can be achieved faster by deploying the line to side ‘C’, then that is the most effective tactical choice.

Adding in items such as vehicles, fences, porches, adjacent structures, changes in grade, landscaping can change significantly impact the deployment of the line. Additionally, deploying the line for an interior attack can encounter obstacles such as a locked front door(s), hording conditions, divided up interiors, or complex floor plans which can delay the advancement to the fire compartment.

Resources available on scene and time for additional resources to arrive should also be considered in this scenario. If staffing allows, two hoselines can be deployed and multiple operations can happen simultaneously to speed up time to water on the fire and allow firefighters inside to conduct searches and ensure the fire is suppressed.

The time to accomplish these different tactics is much more dependent on the individual conditions on each fire ground. The tactical choice of an interior or transitional attack should be about timing to get water into the compartment. Once initial water is applied into the compartment, the next tactical choice is how to most effectively get into the compartment to complete suppression. This too has many variables which are different on every fire. Some fires you may be able to approach the side 'C' window and apply water to the burning contents through the window, however on others you may not. Similarly, for interior attack, some fires you can rapidly advance to the compartment after using the reach of your stream, other times conditions on the interior prevent you from making rapid entry into the compartment. All of these factors should be considered together when making the choice on where to initially deploy the primary attack line.

7.4 There Can Be Survivable Spaces on Arrival at a Single Family Residential Home.

When occupants become trapped in a structure fire, the number one priority for the arriving fire crews is rescue. An emphasis is often placed on the risk profile of a given scenario. The larger the benefit, the larger the risk which can be considered. Understanding the potential for a victim to survive a given environment is important to determining the potential benefit. If a victim can survive the environment, risking crews on an interior search prior to fire control is of greater benefit than if no survivable spaces exist.

Two things impact the survivability of a given space in the structure: the proximity to the fire and the elevation in the space. The proximity to the fire compartment relates to the thermal exposure where the elevation in the space relates to the exposure to toxic gases and thermal exposure.

An occupant inside the compartment of origin would not have survived to the point of fire department intervention in any of the experiments. All of the experiments had the potential for flashover prior to fire department intervention. Occupants just outside the compartment of origin (hallway of the bedroom fire) were exposed to levels which exceeded the survivability threshold base on thermal exposure. Figure 7.5 illustrates the thermal exposure calculated in the form of fractional effective dose where a value of 1.0 represents a fatal does for 50% of the population (LD_{50}. Victim 1, which was closest to the fire received the highest dose where Victim 5 was further from the origin and received the lowest dose. In general, the higher the FED, the less chance of survival.

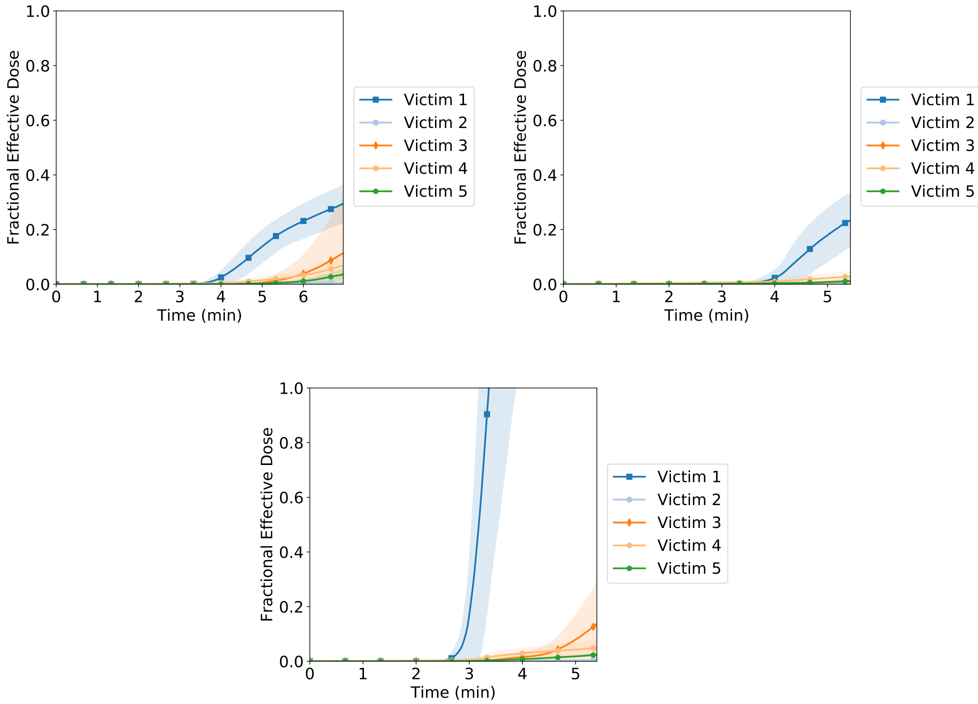


Figure 7.5: Fractional effective dose (FED) of thermal exposure based on total flux to the surface. Top left is the no ventilation case, top right is the single vent with a single room of fire case and bottom is the two rooms of fire with two vent case. The shaded areas represent the various +/- one standard deviation for the average value recorded.

When the toxic gas exposure is concerned, the elevation in the space is the larger component. Victim 3 was located on the bed in the bedroom down the hall from the fire room, yet because of the elevation in all three ventilation cases received the largest dose. Similar to the thermal dose, a lethal dose would be a FED of 3.0 representing a LC_{50}. The higher the FED, the less chance of survival.

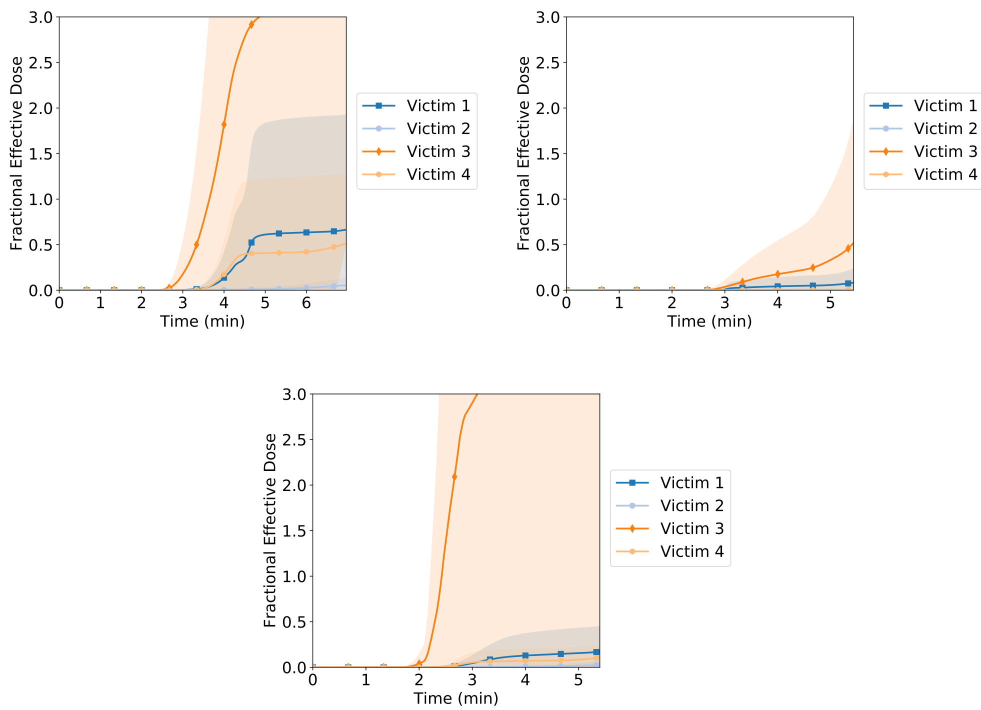


Figure 7.6: Fractional effective dose (FED) of toxic gas exposure based on CO, CO_2 and O_2. Top left is the no ventilation case, top right is the single vent with a single room of fire case and bottom is the two rooms of fire with two vent case. The shaded areas represent the various +/- one standard deviation for the average value recorded.

When developing a risk profile for a given scenario, identifying the survivable spaces is important. Areas further from the compartment of origin and low in the space have the best chance of survival. Areas closest to the fire and high in the space have the least chance of survival.

Figure 7.7: Victim Locations

Table 7.1: Time to Fatal FED (Minutes) - Delayed Intervention

Experiment	Victim	Time to Fatal FED (minutes:seconds)	Driving Factor
No Vent	Victim 1	8:10	Toxic Gases
	Victim 2	NFD	NFD
	Victim 3	6:58	Toxic Gases
	Victim 4	NFD	NFD
	Victim 5	NFD	NFD
Single Vent	Victim 1	6:30	Toxic Gases
	Victim 2	NFD	NFD
	Victim 3	5:14	Toxic Gases
	Victim 4	NFD	NFD
	Victim 5	NFD	NFD
Two Vent	Victim 1	3:08	Total Flux
	Victim 2	NFD	NFD
	Victim 3	3:06	Toxic Gases
	Victim 4	NFD	NFD
	Victim 5	NFD	NFD

NFD - No Fatal Dose Received

The time it takes to reach a fatal dose of toxic gases or total heat flux is often short as compared to the response times of fire departments. Immediate intervention, involving suppression and ventilation is necessary to increase the survivability of all spaces in the structure.

7.5 Fire Attack and Search & Rescue Can Occur Simultaneously

Although survivable spaces exist at the time of fire department arrival (Section 7.4, 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.

Removing any potential victim from the hazardous atmosphere as soon as possible after arrival is essential to minimizing the Fractional Effective Dose (FED), therefore increasing their chance of survival. FED is defined as the dose received in a given time divided by the effective dose required for a desired endpoint, whether it be incapacitation or death. As the FED is a function of the time a victim is exposed to the hazard (whether it be heat flux or fire gases), the earlier into an incident that the victim is removed from the atmosphere, the less FED they have been exposed to and the greater their chances for survival. Finding them is the first step to removing them, and therefore searches need to start as soon as possible.

Figure 7.8: Thermal conditions before (left) and after (right) water application down the hallway during an interior suppression tactic. Color conditions represent operating zones per Utech [31] where green is routine, yellow is ordinary, and red is emergency. (Experiment 7)

In the scenario in Figure 7.8, a room and contents fire is located at the end of a long hallway. Prior to water application, Figure 7.8 (left) shows the end of the hallway near the fire compartment from floor to ceiling is in the emergency operating range (red) of structural turnout gear as proposed by Utech [31], where a firefighter in full protective gear could only occupy the space for a matter of seconds. This cuts off a search crew from reaching Bedroom 2. The closed door to bedroom 3 makes the space survivable and occupiable for the firefighter, however accessing it from the interior (opening the door) has the potential to reduce the survivability of the space. The middle of the hallway below the 3 ft level is in the ordinary operating rage (yellow) where the firefighter could occupy the space for a matter of minutes, allowing the search crew access to Bedroom 4. The remainder of the structure below 3 ft is in the routine operating range (green) where a firefighter could search prior to water application. Once water is applied down the hallway as the crew advances toward the fire compartment Figure 7.8 (right) the conditions in the hallway go from the ordinary (yellow) and emergency (red) operating ranges to the routine range (green). A search crew could follow the advancing attack crew, accessing and searching the bedrooms off the hallway as the crews advance.

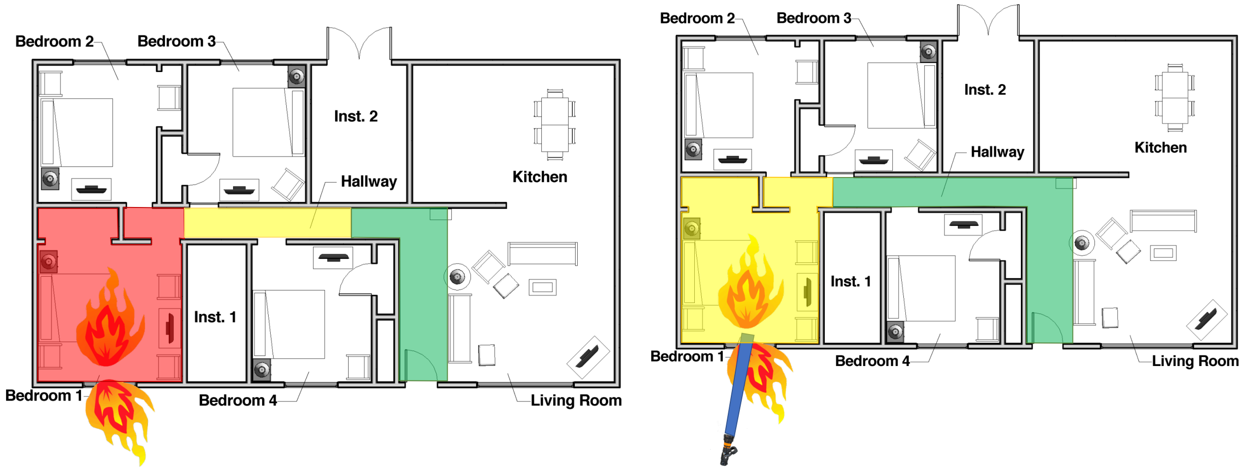


Figure 7.9: Thermal conditions before (left) and after (right) water application through the fire room window during a transitional suppression tactic. Color conditions represent operating zones per Utech [31] where green is routine, yellow is ordinary, and red is emergency. (Experiment 18)

The conditions prior to water application in Figure 7.9 (left) are the same for the transitional attack. A search crew would not safely be able to enter the emergency (red) zones and although the bedrooms off the emergency zones would most likely not be as significant a hazard, accessing them would not be possible without potential significant injury. Once water is applied through the window directly into the compartment in a transitional attack [Figure 7.9 (right)], it not only effects the fire room but the adjacent spaces as well. The fire is no longer transferring heat energy to these spaces and they cool to the ordinary (yellow) and routine (green) operating range of the structural gear.

7.6 Search Consideration: Closed Doors Significantly Increase Occupant Survivability

A victim located in a bedroom during a search with a closed door between them and the fire has a much higher likelihood of survivability than a victim with an open bedroom door. In every experiment, a victim in the closed bedroom would survive through the length of the experiment, including simulated fire department operations. In the same room with an open bedroom door this is not the case. In Experiment 1 a fire was ignited in Bedroom 1 with the door to Bedroom 3 left open with a simulated victim (Victim 2) on the bed. The same scenario was conducted 4 additional times with the door to Bedroom 3 closed prior to ignition (Experiments 2, 4, 5 and 6). With the bedroom door open, the victim would have exceeded survivability thresholds at approximately 7 minutes due to toxic gases and 9 minutes due to heat flux. With the bedroom door closed the victim remained well below the survivability thresholds through fire extinguishment, Figure 7.10. Comparing visibility at 6 minutes after ignition, it is obvious the difference a closed door makes, Figure 7.11.

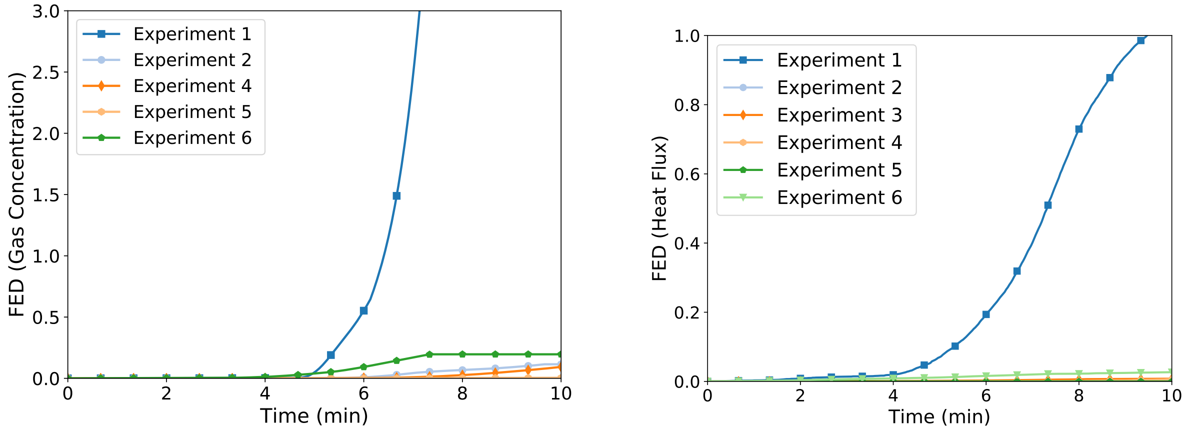


Figure 7.10: Survivability thresholds, toxic gases (left) and heat flux (right) for the no vent Victim 2 for Experiments 1 - 6.

When searching and you encounter a closed door it is important to consider the environment you are in and the environment on the other side of the door that a potential trapped occupant is in. That door could be the barrier between a survivable atmosphere and a non-survivable atmosphere as the victim is not wearing an SCBA and turnout gear. Waiting for fire attack to take place or quickly entering the room and closing the door behind you could increase the chances of a successful rescue.

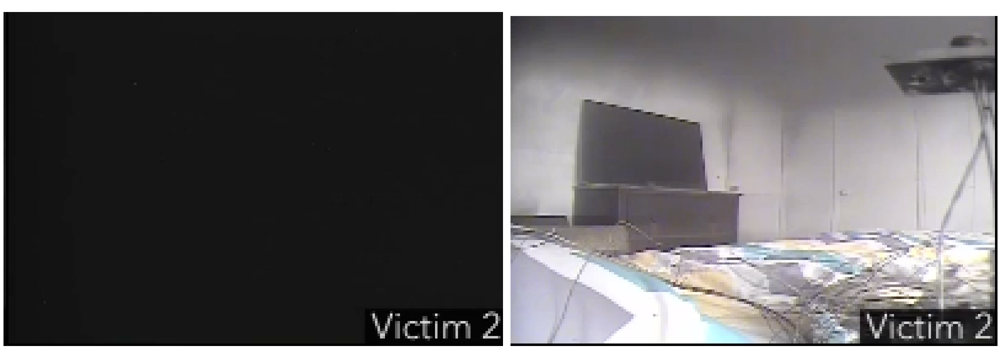


Figure 7.11: Visibility at Victim 2 at 6 min for open door (left) and closed door (right). (Experiment 1 & 2)

Consistent conclusions and tactical considerations can be found in previous studies on Horizontal Ventilation [13], Vertical Ventilation [57], Governor's Island Research and others found at www.ULfirefightersafety.org. Additionally, a public safety education campaign that highlights the importance of the public closing doors and tools the fire service can use to support that education can be found at www.CloseYourDoor.org.

7.7 Water in the Fire Compartment Matters, and so does Timing

Effective application of water, whether from the interior doorway or from the exterior window, into the fire compartment has a positive impact. The heat release rate of the fire is reduced, temperatures both near and remote from the fire are reduced, and the rate at which toxic gases are produced slows making tactical ventilation effective. With all else being equal, the tactical choice on where to apply water from should be based more on the time it takes to knock back the fire and less on the position the water is being applied from.

To have an impact on the fire, water must be applied to the compartment of origin. Figure 7.12 shows the fire room temperature for an interior suppression where the suppression crew needs to apply water down the hallway before they can move down the hallway. They may need to move down the hallway before water enters the compartment and reduces temperatures to a point where a firefighter could occupy the compartment in full protective gear (400°F). This is compared to a transitional attack where water can be applied directly into the compartment from the exterior. Each is effective at reducing temperatures; the hallway attack takes slightly longer (30 seconds vs. 15 seconds) to reduce temperatures. The sooner the stream enters the compartment, the sooner the temperatures are reduced. This is largely due to hose streams being limited to line of sight. A fire service hose stream does not bounce off of surfaces [1], nor can it make turns around corners. In order to apply water to a compartment, the crew must under normal visibility be able to see into the compartment.

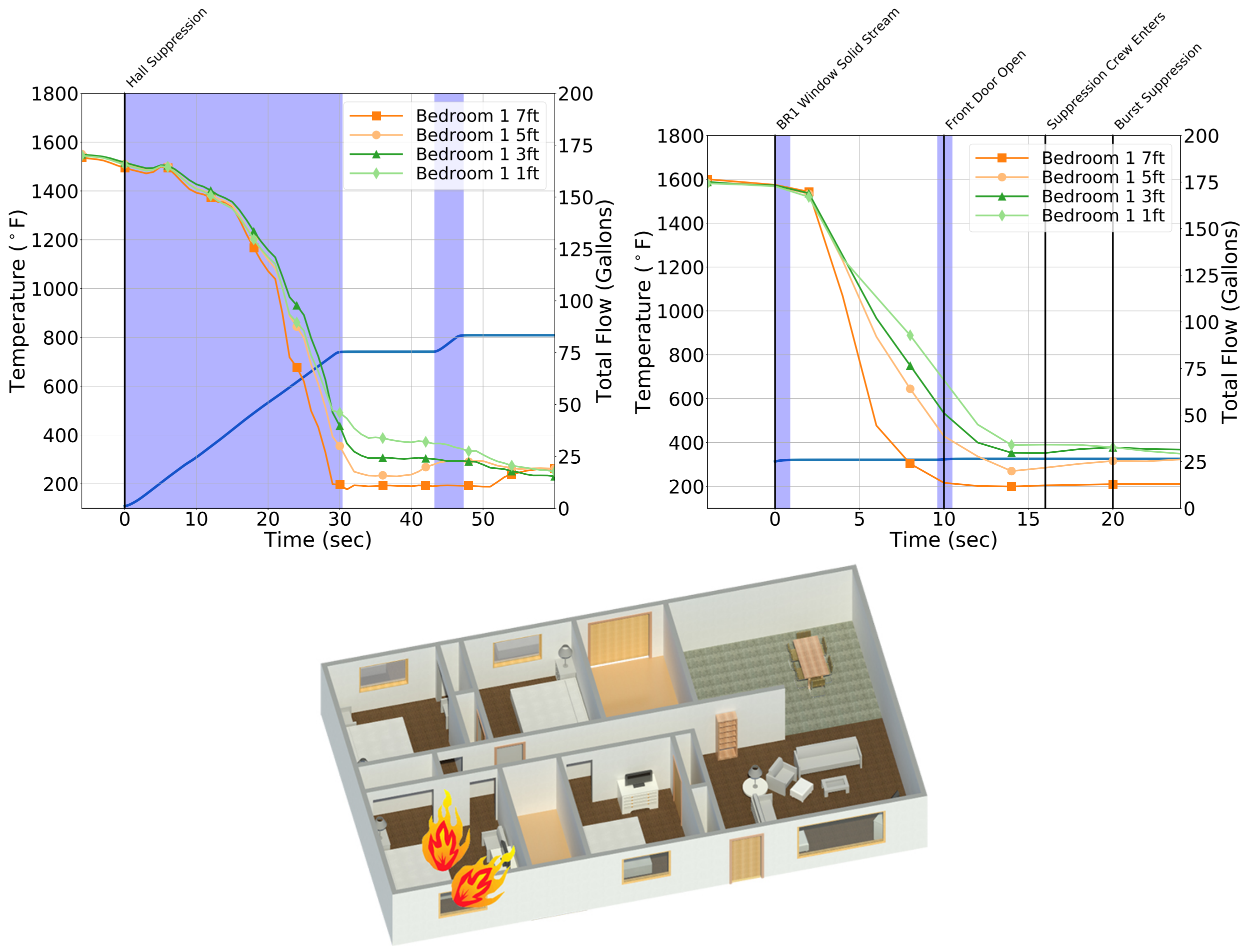


Figure 7.12: Fire room temperatures Experiment 7 - Interior (left), Experiments 18 - Transitional (right). The blue shaded areas represent water flow from the hose stream. The layout of the structure (bottom) prevents water application into the room without advancing down the hallway.

When choosing an interior attack, advancing to the seat of the fire without applying water, even in full protective gear, significantly increases the potential for injury. Using the reach of the stream while advancing to cool the environment around and ahead of your position only has a positive impact on the environment for both firefighters and potential occupants. Applying water while moving, and moving the nozzle in a pattern had the most positive effect on the area around and ahead of the advancing hose crew. Once at the door to the compartment, where a lack of visibility limits the ability to determine the exact location of flames, a steep angle off the ceiling using a solid or straight stream will coat the most surfaces (walls, ceiling, floor) and provide the best protection prior to entering the compartment.

The most effective initial application method from outside the compartment, to coat the most surfaces (ceiling, walls, floor) in the room, was found to be a solid stream or straight stream at steep angle off the ceiling [1]. When applying water from the exterior through a window, the straight or solid stream, in a fixed position was shown to have the least air entrainment [2] and thus least impact on the existing flow paths within the structure. When applying this to a window or door on the fire ground, this would be a straight stream or solid stream, directed from as close as possible directed at as steep an angle as possible. In some instances, there will be obstructions to steep angle application such as landscaping or potential building outcroppings. This will not completely negate the effect of the tactic as a whole, it will however reduce the amount of surfaces coated, which in turn will require more time for the cooling to take effect. If the stream is no longer having a visual effect on the fire (extinguishing flames), repositioning the line, directing the stream off the top of the window frame (also called the bottom of the window header or lintel), or using a half-bale technique are all options to increase effectiveness [1].

Figure 7.13: Exterior water application using a steep angle off the ceiling.

"Knock back" is only a portion of the fire extinguishment. Although "knock back" is capable cooling the environment in the structure, reducing the rate of combustion and therefore reducing the creation of products of combustion, it is not full extinguishment. In order to ensure the fire is completely extinguished a crew must enter the compartment and apply water under and behind all objects in the room. The application of water behind and under obstructions should be a priority immediately following "knock back".

7.8 If You Can Get Water to Where it Needs to Go, You Don't Need Much.

When dealing with a room and contents fire, the energy release rate is limited by the available oxygen (ventilation - limited) [13,14]. It does not take a large amount of water to absorb the energy being released and knock back the fire. Although less is not necessarily better, when a water supply has not been established, or in areas where no municipal supply exists, water application should not be delayed to establish a water supply. Even a 500-gallon supply tank can be sufficient to knock back two rooms of fire, if the attack crew can get the water where it needs to go.

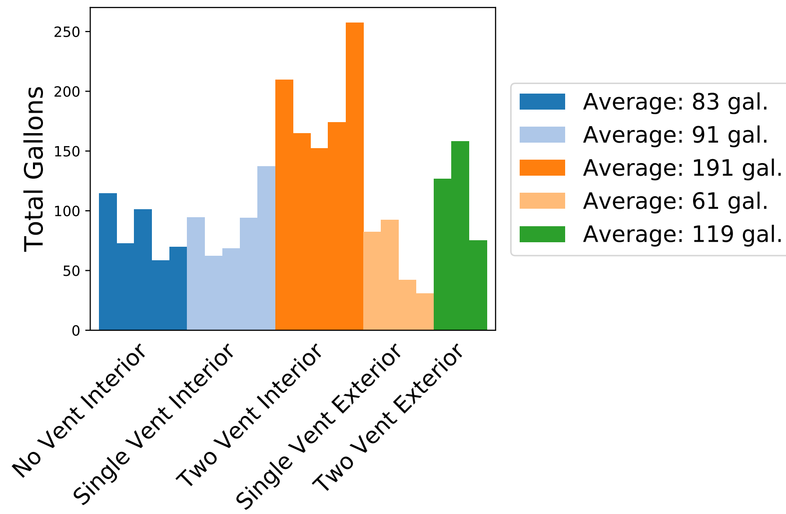


Figure 7.14: Water flow during all experiments grouped by ventilation type and attack method.

During the 25 suppression experiments conducted, using a 1 3/4 in hand line flowing 150 gpm-165 gpm, the most water utilized for initial knock-back and suppression was less than 250 gallons. When attacking a single room and contents fire, in a residential structure, knock back and initial suppression is often possible with less than 100 gallons, in some instances less than 75 gallons. Even flowing while moving to the compartment of origin did not result in utilizing more water than available in a 500-gallon supply tank.

It is important to note in both the transitional and interior attacks, the suppression crew utilized a sequence of cooling the gases followed by cooling the surfaces of the fuel. This provided the most efficient use of the water. A steep angle off the ceiling (used from both the window and doorway) cooled the gases rapidly. This was followed by directing the stream to the contents. In the interior attack after the initial steep angle the stream was moved down to the contents. In the transitional attack this was done by placing the nozzle in the window at a half-bale and applying water to as many surfaces as possible in an 'O' pattern. This cooled the surfaces of the fuel, resulting in full knock down. If the surface of the fuel was not sufficiently cooled/extinguished the fire could re-grow, resulting in the need for more water.

Keep in mind, using less water does not relate to more effective suppression. In instances where an interior suppression is chosen, more water used on the approach to the fire relates directly to more tenable conditions for potential trapped occupants and suppression crews (Section 7.15). Keep in mind, during these experiments most of the water flow was scripted with leeway given based on conditions experienced by the nozzle firefighter, so the intent of this section is not to propose that a particular type of attack is more efficient. The intent is to highlight that, even at high flow rates (150 gpm to 165 gpm), both transitional attack and interior attack using the reach of your stream to cool as you advance do not require much water to improve conditions.

This study focused on controlling and suppressing a room and contents fire through the use of a primary attack line with an established water supply. The content fires required some overhaul as contents were removed however this water was not measured. Additional water, not accounted for in the measurement, would be required for overhaul of the contents as well as structural overhaul if the fire had penetrated into the structure. Although the flow can typically be reduced when utilizing water during overhaul, this necessary step would require water flow above and beyond what was measured.

The multitude of potential variables on the fire ground will often complicate operations more than the scenarios tested. Establishing a water supply and deploying a backup hand line are two critical steps to help provide a safety factor to the operations on the fire ground in the event the primary attack line encounters difficulty applying water directly where it needs to go.

7.9 Water Flow Can Impact Flow Path.

Flow path is the volume between the air inlet and the exhaust outlet in a structure fire, where fresh air is flowing towards the base of the fire (low pressure) and products of combustion are flowing away from the fire (high pressure). Figure 7.15 shows an example of flow path in a single compartment where the left image is a single flow path, in the door low and out the door high; and the right image is multiple flow paths, one in the door low and out the door high and one in the door low and out the window.

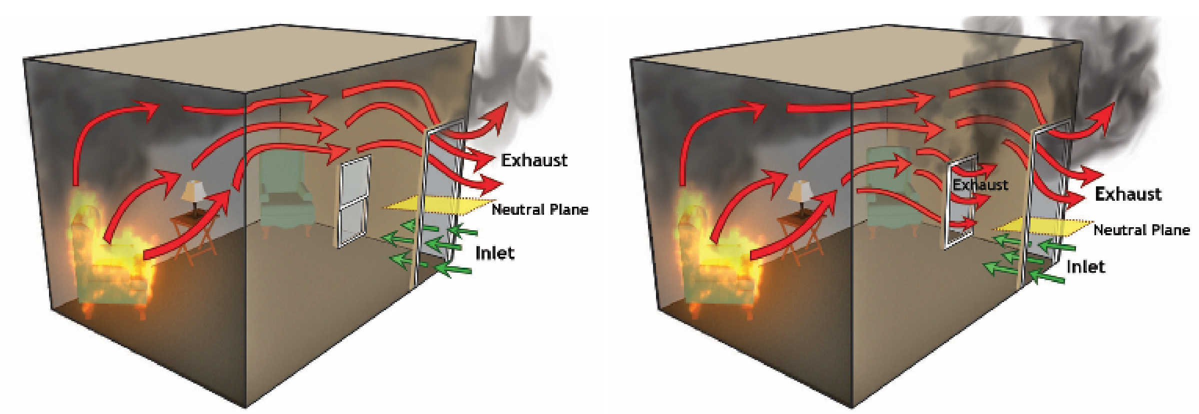


Figure 7.15: Examples of flow path in a compartment, a single flow path (left) and multiple flow paths (right).

Fire service hose streams have the ability to entrain air and thus create flow [2]. This entrainment has the potential to alter the flow path during both interior and exterior suppression tactics.

During an interior attack, applying water down the hallway, without a vent opposite, in a method which entrains air can alter the flow path such that the hot gases are no longer flowing over the heads of the firefighters as they advance. Figure 7.16 shows the ability of an advancing hose team to stop the flow of hot gases down the hallway as they advance with a "flow & move" technique. It also blocks the fresh air being entrained down the hallway, limiting growth due to the additional oxygen, however preventing fresh air from reaching the bedrooms ahead of the hose team.

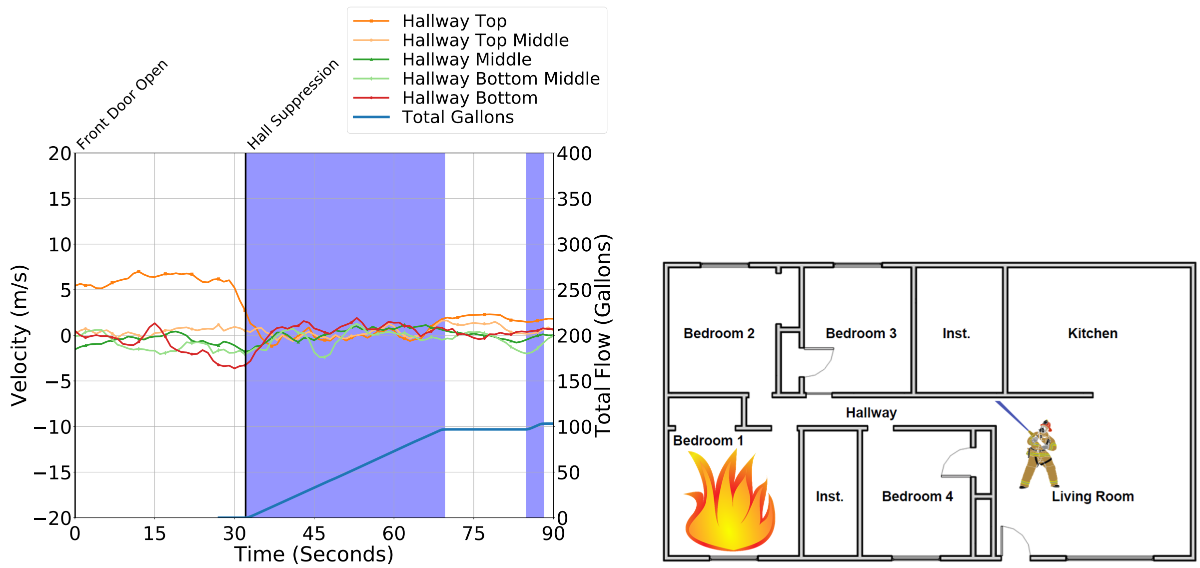


Figure 7.16: Effect of flowing while moving on the gas velocity in the hallway (left), and floor plan (right) during an interior suppression with no vent opposite (Experiment 2). Negative flow is flow towards the fire compartment, positive flow is towards the front door. The blue shaded area represents when water is flowing.

When advancing during an interior attack with a vent opposite, the entrainment was not only capable of stopping the flow at the hallway, it was capable of re-directing the flow ahead of the advancing suppression crew. Figure 7.17 shows the flow at the start of the hallway (left), front door (right) and fire room (bottom). When the hallway suppression starts, it re-directs the gases flowing towards the front door back towards the fire room. It also reverses the flow at the top of the front door. However, the pressure created by the fire cannot be overcome by the hose stream. The flow at the fire room door decreases slightly on initial flow and it is not until the crew reaches the doorway and applies water in the room that the flow reverses. Once the line is shut down, the flow returns to bi-directional at all three locations.

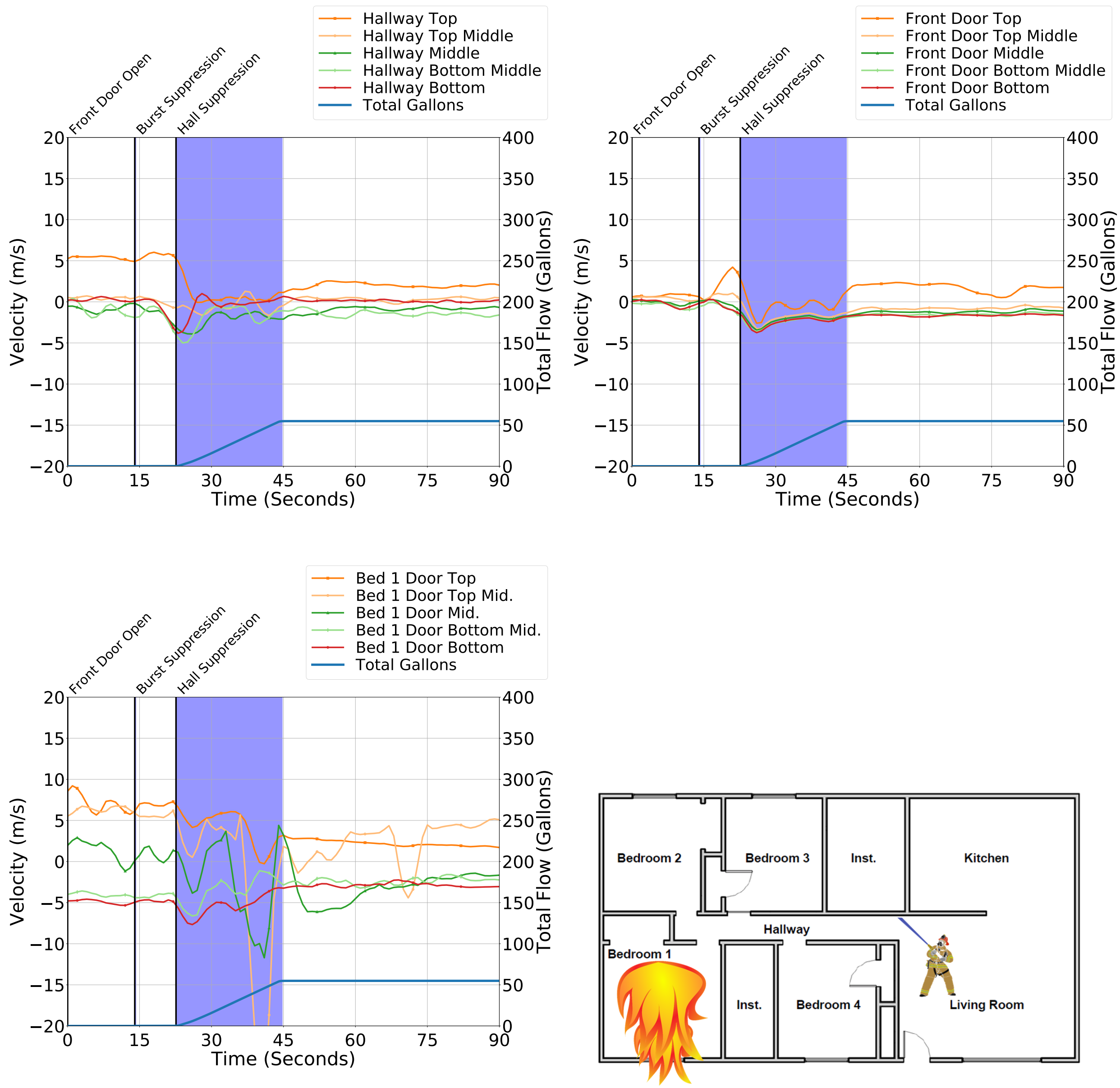


Figure 7.17: Effect of flowing while moving on the gas velocity in the hallway (top left) and front door (top right), fire room (bottom left) and floor plan (bottom right) during an interior suppression where a vent is opposite the suppression crew (Experiment 9). Negative flow is flow towards the fire compartment, positive flow is towards the front door. The blue shaded area represents when water is flowing.

Water application from the exterior also entrains air. A narrow fog stream moved in an ‘O’ pattern was shown to entrain as much air as a positive pressure fan [2]. When this same technique is used during an exterior attack it has the potential to block the vent and re-direct the flow path to the interior, much like a positive pressure fan would. When a straight stream or solid stream is utilized in a fixed position, there is limited impact on the flow path.

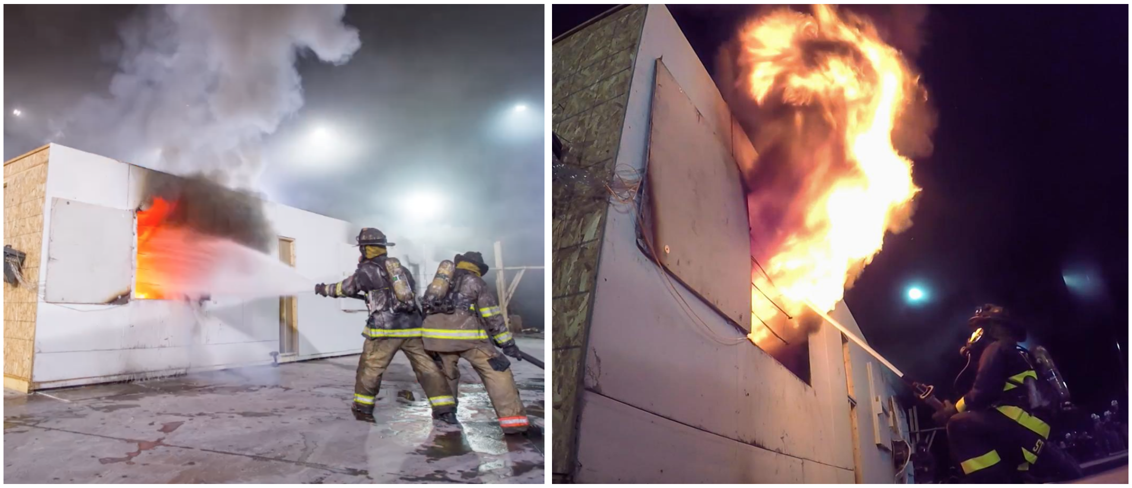


Figure 7.18: Examples of the potential to change the flow path based on the application of water from the exterior. The narrow fog (left) blocks the opening and entrains air increasing the pressure in the room, the solid stream (right) does not affect the flow path.

7.10 Suppression Operations, Both Interior and Transitional, Did Not Increase Potential Burn Injuries to Occupants

When arriving at a residential structure fire, assessing the impact of your tactical decisions may have on occupants trapped inside the structure requires a knowledge of how these tactical decisions effect occupant survivability. The potential negative consequences of water application are highlighted throughout fire service literature and training manuals [6]. These negative consequences focus on the impact to a victim located immediately outside the fire compartment. In this study, instrumentation was located immediately outside the compartment to assess the potential impacts of the various tactics chosen. Additionally, victims were located in adjacent bedrooms outside the flow path, in the path of travel of the approaching hose crew and at the opposite corner of the structure from the fire compartment.

Figure 7.19: Simulated Victim Locations Within the Structure

No potential burn injuries were observed at the victims located remote from the fire (Victim 4 and Victim 5) and at the victim located behind a closed door (Victim 2). The victim immediately outside the fire compartments (Victim 1) and the victim in the adjacent bedroom on the bed (Victim 3) both had potential burn injuries.

When fire department intervention was delayed, these locations received third and fourth degree burns during the longer duration exposures. Table 7.2 shows the potential injury to unprotected skin when suppression is delayed. The distance from the fire to Victim 3, along with the location being outside the flow path, reduced the potential injuries to first degree burns. However, this location received lethal doses of toxic gases in 5 minutes and 14 seconds with the Bedroom 1 fire with the bedroom window open and 3 minutes and 6 seconds for the Bedroom 1 & 2 fires with Bedroom 1 & 2 windows open (Section 7.4).

Table 7.2: Potential Burn Injury - No Fire Department Intervention

Test Type	Victim 1	Victim 3	Time from Ignition
Bedroom 1 Fire - No Vents	4th degree	3rd degree	27:49
Bedroom 1 Fire - Bedroom Window Open	3rd degree	1st degree	13:45
Bedroom 1 & 2 Fire - Bedroom 1 & 2 Window Open	3rd degree	1st degree	10:42

When fire department intervention occurred, regardless of the tactic chosen, the majority of the time the injury did not escalate from one degree of injury to the next. With the wide range of criteria for burn injuries, it is possible the damage still increased without escalating to the next degree of burn. Additionally, it is possible that only a slight increase of damage occurred; however, because the starting point was on the transition point from one degree to the next, the potential injury increased from one degree to the next.

Table 7.3: Burn Injury Summary Based on Necrosis Depth

		Location 1		Location 3	
Test Type	Suppression Tactic	Pre-Water	Post-Water	Pre-Water	Post-Water
No Vent	Interior	(1) no damage (4) 1^{st} degree	(1) no damage (4) 1^{st} degree	(2) no damage (2) 1^{st} degree (1) 2^{nd} degree	(1) no damagee (3) 1^{st} degre (1) 2^{nd} degree
Single Vent	Interior	(3) 1^{st} degree (2) 2^{nd} degree	(2) 1^{st} degree (3) 2^{nd} degree	(5) no damage	(5) no damage
	Transitional	(3) 1^{st} degree (1) 2^{nd} degree	(3) 1^{st} degree (2) 2^{nd} degree	(4) no damge	(4) no damage (3) 1^{st} degree
Two Vent	Interior	(2) 2^{nd} degree (2) 3^{rd} degree	(4) 3^{rd} degree	(1) no damage (3) 1^{st} degree	(3) 1^{st} degree (1) 2^{nd} degree
	Transitional	(3) 3^{rd} degree	(3) 3^{rd} degree	(2) no damage (1) 1^{st} degree	(1) no damage (2) 1^{st} degree

* (x) denotes number of tests where that type of burn injury was noted.

When Table 7.3 is compared to Table 7.2, the impact of fire department intervention is evident as the injuries are not as severe when the fire department intervened. The two rooms of fire with two vents is the exception. The size of the fire resulted in significant burn injuries prior to fire department intervention which were the same as the cases where fire department intervention was delayed.

7.11 Speed of Transition is the Enemy of Re-Growth

As with the initial water application, the method used for final suppression should be based on the time it takes to perform the tactic. During an exterior attack and often some interior attacks, for example hording conditions, it is often difficult to apply water under or behind obstructions such as beds, dressers, chairs and sofas. After an initial water application from the exterior, if flames are visible the crew should attempt to place the nozzle in the ventilation opening and suppress the flames. If there are no obstructions, placing the nozzle through the opening on a half-open bale or narrow fog and moving it in two or three large circles will cool as many surfaces as possible.

When the fire is located on the floors above the exterior grade level, the nozzle cannot be placed in the opening. In this instance, following the initial full-bale steep angle application, with a steep angle half-bale application for 5-10 seconds will result in the most effective surface cooling [1]. However, extended exterior application should not take precedence over the transition to the interior for final suppression.

During any type of suppression method, after cooling all surfaces that can be cooled from that position, the crew should rapidly relocate to a position which allows for complete extinguishment (most often the interior of the compartment). The door, which provides the fastest, most direct path to that location, should be utilized to limit the time between the last water application and final suppression.

After the initial water application in a transitional attack, it is possible the fire will still be located under and behind objects which will cause the room to re-grow while the crew positions for final suppression. Figure 7.20 shows five second increments prior to, during, and after the initial water application during a transitional attack.

Figure 7.20: Image sequence of transitional attack from 10 seconds prior to water application (top left) through suppression 40 seconds after initial suppression (bottom right).

Although visually the re-growth appears severe, the temperatures inside the fire compartment and in the hallway directly outside the fire compartment (Figure 7.21) do not show a significant increase in the 40 seconds it takes the suppression crew to transition from the initial exterior suppression to room suppression on the interior. The initial water application took temperatures at the 3 ft level immediately outside the fire compartment from 500 °F to under 250 °F, allowing the suppression crew to move directly to the interior doorway an limiting the need for additional water flow.

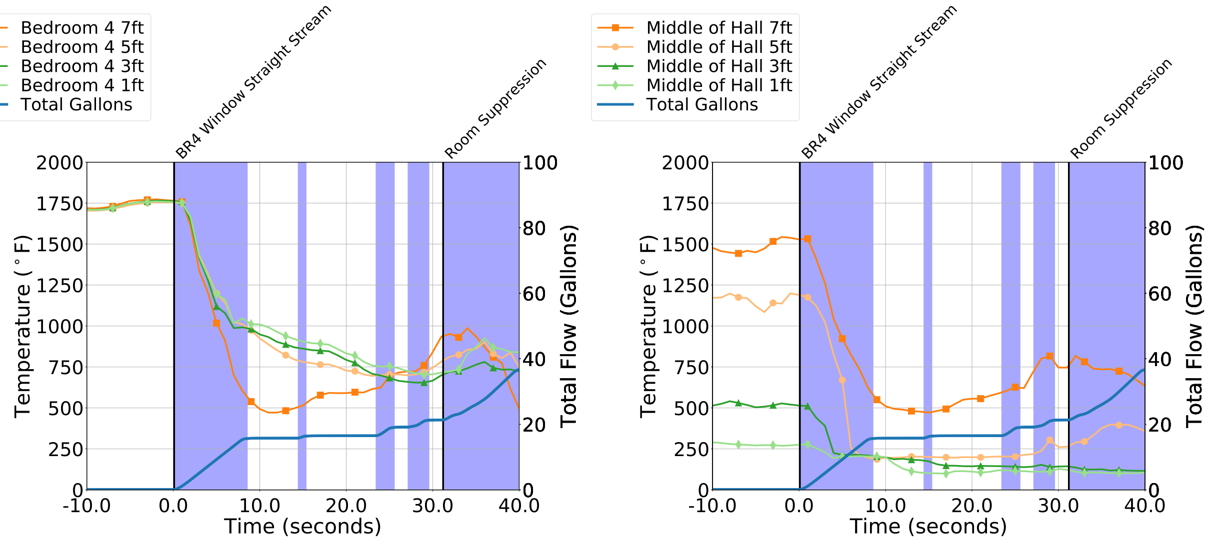


Figure 7.21: Temperatures in the fire room (left) and hallway outside the fire room (right) for transitional attack from 10 seconds prior to water application, through room suppression 40 seconds after initial suppression.

When a transitional attack is chosen and a single hose line is going to be utilized to complete the tactic, the crew should understand the importance of rapidly relocating the hoseline from its exterior position after the initial knock-back to the interior for complete suppression. The faster this can be accomplished, the less the temperatures will rebound. If regrowth is a significant concern, and resources permit, maintaining the initial suppression crew on the exterior position while a second hoseline and crew complete the interior suppression is an option to limit the re-growth.

As with any suppression operation, during a transitional attack the suppression crew needs to constantly monitor conditions. Anytime an additional vent is made, there is the potential the additional oxygen could cause a ventilation-limited fire inside the structure to grow. Once the initial water application is complete, it may be advantageous to open the front door as the crew approaches with the relocated line, evaluating for a change in conditions when the door is opened as they are relocating the line to both evaluate conditions and speed up the time it takes to get to the interior.

7.12 Water Converted to Steam Expands, Hot Gases Cooled Rapidly Contract.

As water is heated from a liquid to a gas (evaporation), it expands 1,700 times. This is often referred to in the fire service as ‘steam expansion’ and the value is referenced in almost all fire service training manuals [6,9]. Depending on the reference this can be seen as a positive or negative effect of applying water to a fire. When looked at in a positive way, steam expansion conceptually can displace the oxygen in the compartment, smothering the fire. On the negative side, conceptually this expansion could create pressure which in turn would move hot gases towards areas where potential occupants may be trapped.

During fire suppression the conceptual effects of ‘steam expansion’ are not seen when water is applied to a flashed-over compartment with gypsum walls. As the ‘steam expansion’ is occurring, the gases inside the compartment are also being rapidly cooled from a temperature exceeding 1,500 °F to below 300°F, a reduction of approximately 1,200 °F. The energy in the hot gases is transferred to the water, creating steam, which results in expansion. The transfer of energy causes the gases to cool rapidly, which causes them to contract. The gases contract more than the water expands; in the end, the net effect is contraction.

Figure 7.22 shows that as the room is cooled, temperatures reduce from over 1,500 °F to below 300 °F (green line on right axis) and as the room is cooling the average velocity at the window and doorway go from outflow (positive) to inflow (negative). Although only occurring for a few seconds, this demonstrates the net effect being contraction due to cooling rather than expansion due to conversion of water to steam.

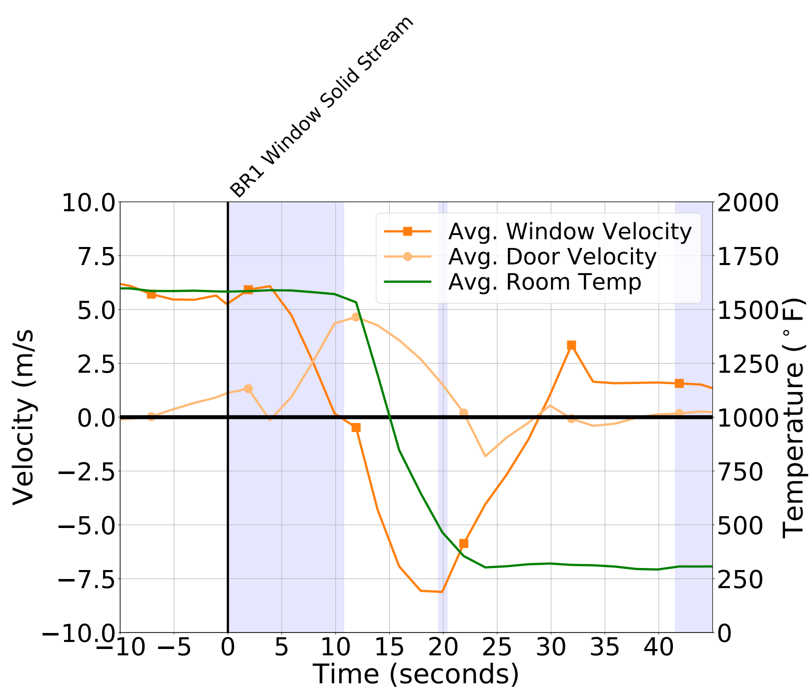


Figure 7.22: The net effect of applying water to a flashed over compartment where cooling gases causes contraction (Experiment 18). The left axis is the gas velocity at the door and window. The right axis is the temperature of the average temperature of the fire room.

In the example above, the line is operated for approximately 11 seconds, with a total flow of 26 gallons as recorded from the flow meter. One gallon of water takes up 0.13 ft^3 of space. The 26 gallons utilized would take up 3.48 ft^3 as liquid water and when converted to steam (3.48 ft^3 x 1,700), would take up 5,909 ft^3 of space. The room was approximately 1350 ft^3 and the house was approximately 8500 ft^3 when the dead space for walls is removed. Thus, if all the water was converted to steam and expanded, the entire room and 70% of the house would have been filled with steam. All the water was not converted to steam; however, some most likely was and this created expansion. At the same time the gases contracted as they were cooled balancing out and most likely negating the expansion.

7.13 Water Vapor is a Bi-Product of Combustion, Suppression Water is not Drastically Increasing Water Vapor in the Environment

In the presence of oxygen, fuel provided with sufficient heat results in combustion. As seen in Equation 7.1 the complete combustion of methane (CH_4) results in the products of carbon dioxide (CO_2) and water vapor(H_2O) also known as steam.

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O \tag{7.1}$$

Although in a house fire fuels are more complex than methane, and sufficient oxygen does not exist for complete combustion, CO_2 and H_2O are still a portion of the bi-products of combustion. In the fire service the products of combustion are generalized as the term smoke. Smoke contains things such as soot, carbon monoxide, carbon dioxide, hydrogen cyanide and water vapor among many other substances. The water vapor created by the combustion reaction is not trivial. Table 7.4 shows the moisture content of the air at ignition, 5 seconds prior to water application, 60 seconds after water application along with the peak measured during the experiment.

Table 7.4: Summary of Water Vapor Measurements in Percent Water Concentration by Volume. (Change in Percentage from Ignition)

Experiment	Concentration at Ignition	Concentration 5 seconds Prior to Suppression (% Change)	Concentration 60 Seconds After Application (% Change)	Peak Concentration (% Change)
No Vent - 1 ft				
4	1.65	N/A (N/A)	N/A (N/A)	4.10 (2.45)
6	1.09	4.40 (3.32)	4.39 (3.30)	4.94 (3.85)
Average	1.37	4.40 (3.32)	4.39 (3.30)	4.52 (3.15)
Single Vent - 1 ft				
18	0.85	1.07 (0.22)	1.73 (0.88)	1.95 (1.09)
19	1.23	1.14 (-0.08)	1.86 (0.63)	4.01 (2.78)
Average	1.04	1.11 (0.07)	1.8 (0.76)	2.98 (1.94)
Single Vent - 3 ft				
20	1.94	2.36 (0.42)	4.55 (2.62)	6.36 (4.42)
Single Vent - 5 ft				
7	1.61	2.61 (1.00)	N/A (N/A)	4.91 (3.30)
10	2.06	6.07 (4.00)	6.99 (4.92)	11.9 (9.84)
11	1.70	N/A (N/A)	6.73 (5.03)	7.25 (5.54)
21	2.26	5.18 (2.92)	6.15 (3.88)	9.41 (7.15)
Average	1.91	4.62 (2.64)	6.62 (4.61)	8.37 (6.46)
Two Vent - 1 ft				
16	1.53	3.37 (1.85)	3.57 (2.04)	3.99 (2.46)
Two Vent - 3 ft				
13	1.62	N/A (N/A)	N/A (N/A)	5.97 (4.35)

As the moisture was measured at higher elevations in the space, more moisture was detected. Even prior to suppression, at elevations in the smoke layer (5 ft), water vapor increased by a factor of 2.

When the measurement was taken at the 1 ft level there was limited increase in moisture content between 5 seconds prior to suppression and 60 seconds after suppression. At the higher elevations in the space (in the smoke layer) the moisture would increase between approximately 2% by volume during the period between 5 seconds prior to and 60 seconds after suppression however it would increase by a similar amount from ignition until the time of 5 seconds prior to suppression.

This suggests that at the 1 ft level in a bedroom outside the flow path, where water is not applied in the room, moisture content is not increasing during suppression activities. At the higher elevations, moisture content is increasing however it is not possible to determine whether the increase is due to the application of water or due to transport time for the products of combustion to reach the location of the sensor. With no appreciable increase in moisture content at the 1 ft level even after suppression, it is not possible the suppression is causing a victim further damage due to steam.

7.14 Flow vs. Shutdown

Hoseline advancement techniques differ from department to department, however generally two types of advancement were found through a poll of the project technical panel. The first method was titled "flow and move" and involved getting in a position to approach the fire down a hallway and flowing the hoseline while moving down the hallway towards the seat of the fire. The second method was titled "shutdown and move" and involved shutting off the hoseline at the bale to allow the advancing suppression crew to move closer to the seat of the fire. Although this may be a tactical choice based on crew size, experience, and training, the approaches differ in how they affect the environment around and ahead of the suppression crew.

When flowing and moving, there is a constant cooling effect for the hoseline, both around and ahead of the advancing hose crew. When the line is shutdown to move forward the cooling effect is no longer present, and temperatures begin to re-bound ahead and around the advancing crew. The temperature re-bound occurs mostly over the head of the advancing crew. If the hoseline is operated again within 10-15 seconds, the rebound never reaches the temperature prior to suppression. Although structural protective gear will prevent the advancing crew from feeling a change in the environment, elevated temperatures return. If the hoseline was not operated again, the temperature would rebound to the level prior to suppression.

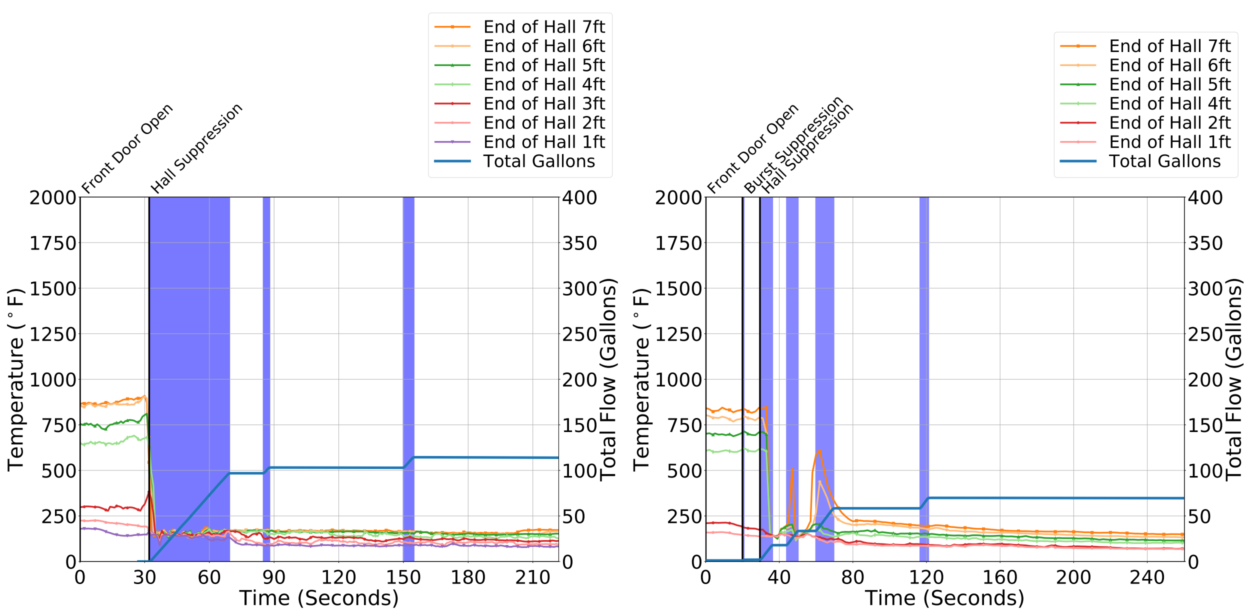


Figure 7.23: End of hallway temperatures (3TC) for the two attack methods used in the single room of fire with no ventilation. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 2 and the right shows the "shutdown and move" method from Experiment 6.

The ability of the hoseline to influence the flow ahead of the suppression crew did not differ greatly between the two tactics. The line was capable of preventing flow over the head of the advancing suppression crew while it was operating; however, once shut down the flow returned, but not at the previous level and was halted again once the line was opened again.

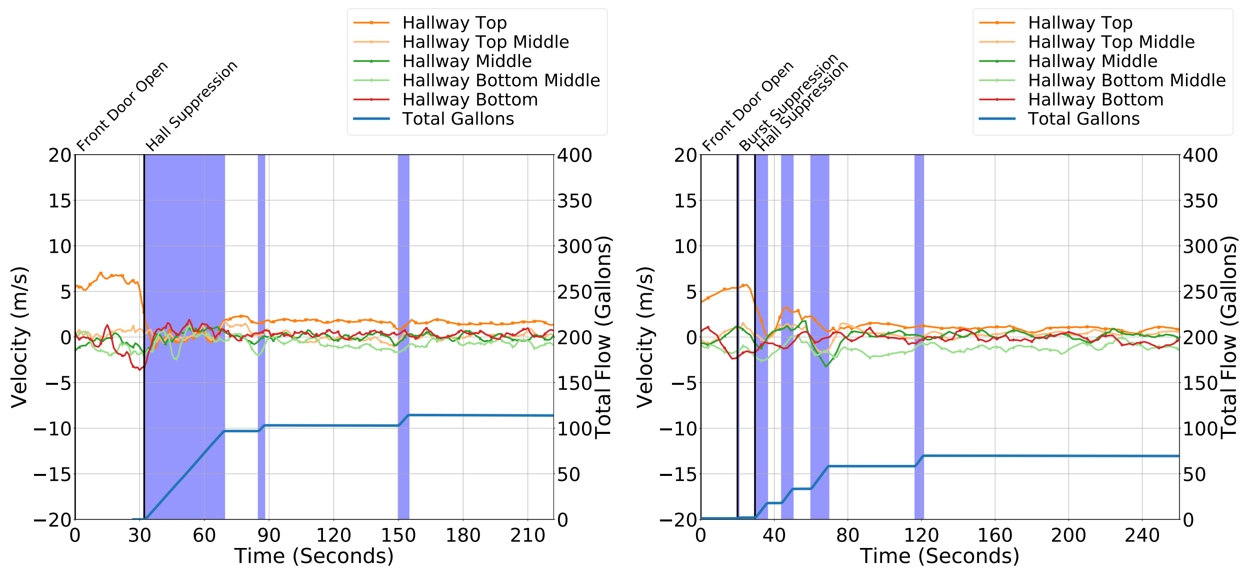


Figure 7.24: Gas velocity at the entrance to the hallway (6BDP) for the "flow and move method" from Experiment 2 (left) and "shutdown and move" method from Experiment 6 (right) with the single room of fire with no ventilation. The blue shaded areas represent water flow from the hose stream.

Additionally, neither tactic was able to make an impact on the fire compartment ahead of the suppression crew until the crew could apply water into the compartment.

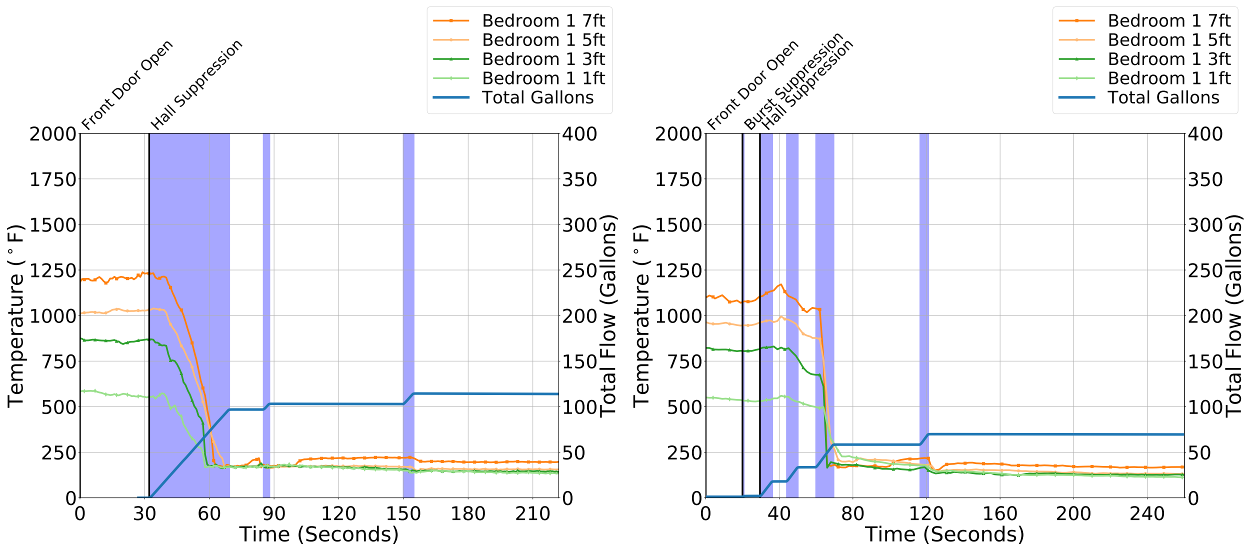


Figure 7.25: Fire room (Bedroom 1) temperatures (1TC) for the two attack methods used in the single room of fire with no ventilation. The blue shaded areas represent water flow from the hose stream. The left shows a "flow and move" method from Experiment 2 and the right shows the "shutdown and move" method from Experiment 6.

The choice of hoseline advancement technique may be more dependent to the experience of the nozzle firefighter or staffing of the advancement crew and less on the differences the techniques have on the environment on the approach to the fire.

7.15 You Should Cool as You Advance.

The concepts that structural protective gear will protect a firefighter as they advance to the compartment of origin without applying water and that applying water prior to reaching the compartment will have negative consequences does not fit with what is known about modern fuel loads and fire development. Additionally, the thought that a suppression crew must be in the compartment before applying water is just not practical. The compartment of origin becomes untenable for firefighters in full protective gear once it reaches flashover. All bedroom fires reached flash over well before the initial fire department actions were performed. Often flashover is occurring within 4-4.5 minutes of ignition. Entering the compartment before applying water would have resulted in significant injury, if not death, to any firefighter even in=f they were wearing full protective gear.

To illustrate this concept the fire compartment and path of approach are classified according to the thermal operating zones described by Utech where the routine zone (green) is approximately to ambient conditions, not necessarily requiring any thermal protection. The ordinary zone (yellow) is more of a thermal threat where firefighters would be able to function for 10-20 minutes at a time in full PPE. The Emergency zone (red) is an environment dangerous to a firefighter even with full PPE, where a firefighter's PPE would only be able to withstand an exposure on the order of a few seconds.

Figure 7.26: Thermal conditions during the three ventilation configurations, no vent Experiment 1 (left), single vent Experiment 12 (right) and two vent, Experiment 17 (bottom) just prior to hall suppression crew arrival time. Color conditions represent operating zones per Utech [31] where green is routine, yellow is ordinary, and red is emergency.

When interior attack was chosen over applying water through the venting 'A' side window, conditions outside the compartment were just as severe as a flashed-over compartment in terms of thermal assault to firefighters (Figure 7.26). The heat flux and temperature fall within the emergency range of their structural turnout gear, where injury is likely and the gear's ability to protect the firefighter is decreased or non-existent. For the single vent and two vent configurations tested, even halfway down the hallway the heat flux and temperature exceeded the ordinary operating range of structural turnout gear.

When conducting an interior attack, the suppression crew should cool as they advance. The effect of this is shown in Figure 7.27 where water application during advancement down the hallway reduces the thermal threat to firefighters in full PPE to a level where injury is less likely. Utilizing a smooth bore nozzle or combination nozzle set to straight stream will achieve the greatest reach while limiting the air movement. As the crew advances toward the fire they should cool, either using a "flow and move" technique or a "shutdown and move" technique. If they intend to move products of combustion ahead of their position, they should consistently move the nozzle in a pattern ('O', 'T', 'Z', 'n'), keeping in mind that the faster the nozzle is moved the more it will move products ahead of the crew. If at any time flames are visible, the suppression crew should apply water to them immediately to prevent rollover/flashover. Once they reach the fire compartment, applying a steep angle stream off the ceiling will coat most surfaces in the room, providing the most cooling. If flames are visible, the suppression crew should apply water to them. After checking the integrity of the floor, they should enter the compartment for final suppression.

Figure 7.27: Thermal conditions during the three ventilation configurations, no vent Experiment 4 (left), single vent Experiment 7 (right) and two vent, Experiment 13 (bottom) 10 seconds after hallway suppression while conducting an interior attack. Color conditions represent operating zones per Utech [31] where green is routine, yellow is ordinary, and red is emergency.

The transitional attack on a single room of fire was just as effective at cooling the approach to the fire compartment as applying water application down the hallway; both allow the suppression crew to rapidly advance to the compartment for final extinguishment. Additionally, it knocked back the room of fire where the initial water application is applied to reduce temperatures in that room (Figure 7.28).

Figure 7.28: Thermal conditions during the two ventilation configurations, single vent Experiment 18 (left), two vent Experiment 22 (right) 10 seconds after initial exterior suppression while conducting a transitional attack. Color conditions represent operating zones per Utech [31] where green is routine, yellow is ordinary, and red is emergency.

7.16 Understanding the Limitations of a Thermal Imaging Camera Can Increase its Effectiveness

As outlined within *NFPA 1408: Standard for Training Fire Service Personnel in the Operation, Care, Use, and Maintenance of Thermal Imagers*, all personnel using thermal imagers must understand their use and limitations [56]. Thermal imagers are designed to detect radiant thermal energy emitted from solid surfaces, particulates, and some gases utilizing a constant emissivity value. Emissivity is defined as the ratio of the energy radiated from a material's surface to that of a blackbody, or perfect emitter, at the same temperature. The emissivity of the surfaces and gases radiating energy during a fire affect the thermal imager's ability to determine the actual temperature and can be misleading to firefighters utilizing the device. As the emissivity value of radiating objects within a fire diverge from the imager's constant value, the temperature readout becomes more and more inaccurate.

Further, the sensors in thermal imagers are designed to recieve a range of wavelengths which allow them to "see" through a variety of hot gases; however, at times the gases are so optically thick (opaque) that even these wavelengths cannot penetrate them. It is possible the the temperature reading on the thermal imager is reading the temperature of the smoke as far as it can practically penetrate through with its range of wavelengths. The actual temperature of the smoke behind those optically-thick gases may be significantly higher.

For the reasons outlined above, thermal imagers are considered unreliable thermometers.

Below is an example from a single room of fire (Bedroom 1) with no ventilation (Experiment 1). Figure 7.29 shows the thermal imagers temperature readout as compared to the gas temperature recorded where the thermal imagers temperature measrument zone was directed, along with a floor plan showing the location of the imagers. Early in the experiment the imager does a fairly reliable job of showing the gas temperatures; however, after 200 seconds in the hallway (top right) and 250 seconds at the front door (top left) the temperature readout of the imager no longer accurately represents the temperature of the gases. At the time of fire department intervention at just over 300 seconds, the gas temperatures at the end of the hallway are in excess of 600°F while the imager is recording just over 150$^{c}\circ$F. Similarly, the gas temperature at the doorway is recorded in excess of 500° at the ceiling while the imager records at just over 100°F.

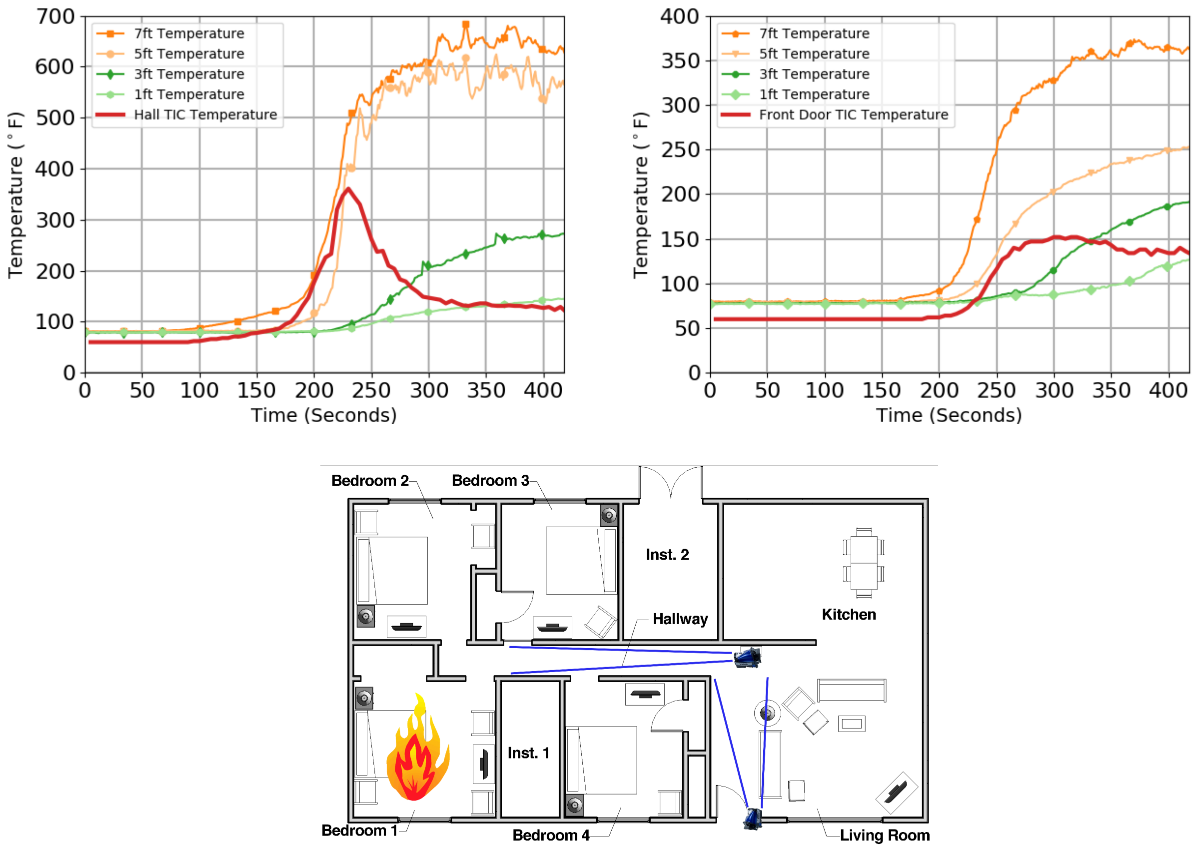


Figure 7.29: Comparison of thermal imager temperature readout to the actual compartment temperatures in a single room of fire with no ventilation (Experiment 1). Thermal imager from the hall location (top left) and doorway location (top right), and floor plan with imager field of view (bottom).

Thermal imaging cameras should not be used as a 'go', 'no go' indicator strictly based on the temperature readout. Depending on the optical density of the smoke and the emissivity of the object the imager is pointed at, impact the ability of the imager to accurately report the temperature. The actual temperature in the hot gas layer may be 5 to 6 times or more than the readout indicates.

7.17 A Short Burst Cannot Tell You Gas Temperature

Firefighters operating as a fire attack team use all of their senses as part of an ongoing size-up when entering a structure fire with zero visibility. A common fire service tactic is to, once inside the doorway, quickly open and close the nozzle to direct a stream of water at the ceiling. This allows the firefighter to âĂIJcheck for returnâĂİ or cool the environment prior to advancing. In this study we refer to this action as âĂIJburst suppressionâĂİ. âĂIJChecking for returnâĂİ does not work as has been previously taught and is not a reliable indicator of tenability in the compartment.

When "checking for return" it is important to know where your water goes. In the water mapping experiments, you can see that flow from a nozzle will hit a surface and the momentum will carry most of the water along the ceiling to the walls. Water directed over your head will not simply bounce off the ceiling and return. Additionally, when the flow is directed into a hot gas layer, the large droplets produced by the nozzles utilized in these experiments were not fully consumed in the overhead and much of the flow returned to the ground, via the walls. Regardless of how hot the gases were, water still returned to the floor.

Figure 7.30: Thermal imager views of the two patterns utilized during burst suppression smooth bore (left) and narrow fog (right).

To examine the cooling effects of the environment by burst suppression, we analyzed the temperatures in the flow path between the front door and the start of the hallway. At 3 ft above the floor, where the firefighters are operating, the temperatures decreased an average of 20% immediately after burst suppression (starting temperatures averaged 160°F). This decrease is a combination of cooling from the water flow and the cool air being entrained by the fire. However, temperature rebounded within seconds and the cooling was not sustained. At 7 ft, above the firefighters' heads, the temperatures averaged 360°F and decreased an average of 10% after burst suppression and also recovered within seconds. There was no impact on temperatures in the hallway and the firefighters did not report feeling any change in thermal conditions as a result of the burst suppression.

While lasting cooling did not occur, using the short burst of water, there are other potential benefits of flowing once inside the structure when you have zero visibility: to wet walls and ceilings to potentially slow down ignition of the gases and wall linings in the room; and to hear water hitting walls and ceilings to get an approximate size of the space when there is no thermal imaging camera available. This can be important in the case of vaulted ceilings to let the crew know that there is potentially a high volume of unburned smoke over their position.

7.18 Large Volume Gas Cooling Requires a Large Volume of Water

Although small droplets of water theoretically will provide the most effective cooling of hot fire gases in a large volume, using a combination nozzle on a wide fog setting providing pulses was not effective. Most likely this is due to a combination of the droplets being too large, the gases not being hot enough to take advantage of the cooling before the droplets fall to the floor out of the hot gas layer, or the gases are replaced too quickly due to the exhaust flow out of the open door.

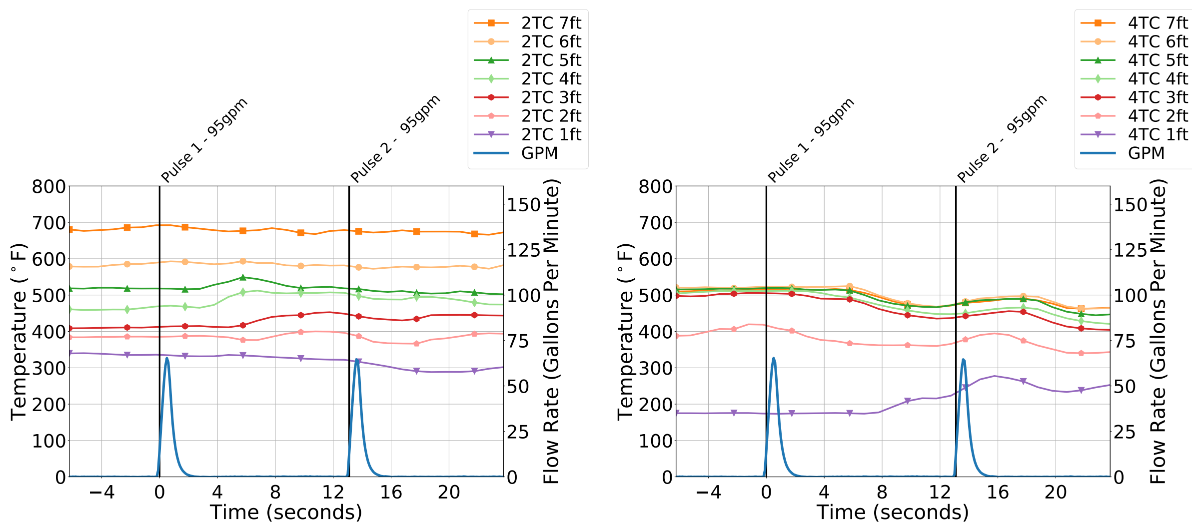


Figure 7.31: Effectiveness of ‘pulse’ technique at gas cooling using 95 gpm nozzle. Left center of doorway (left), right center of doorway (right). (Experiment 25)

The effectiveness of the cooling increased as both the flow rate and the ability of the stream to penetrate further and reach more surfaces increased. The most effective method at reducing temperatures and maintaining them lower the longest was the straight-stream pattern at 150 gpm flowing in a ‘wall, ceiling, wall’ pattern toward the fire compartment.

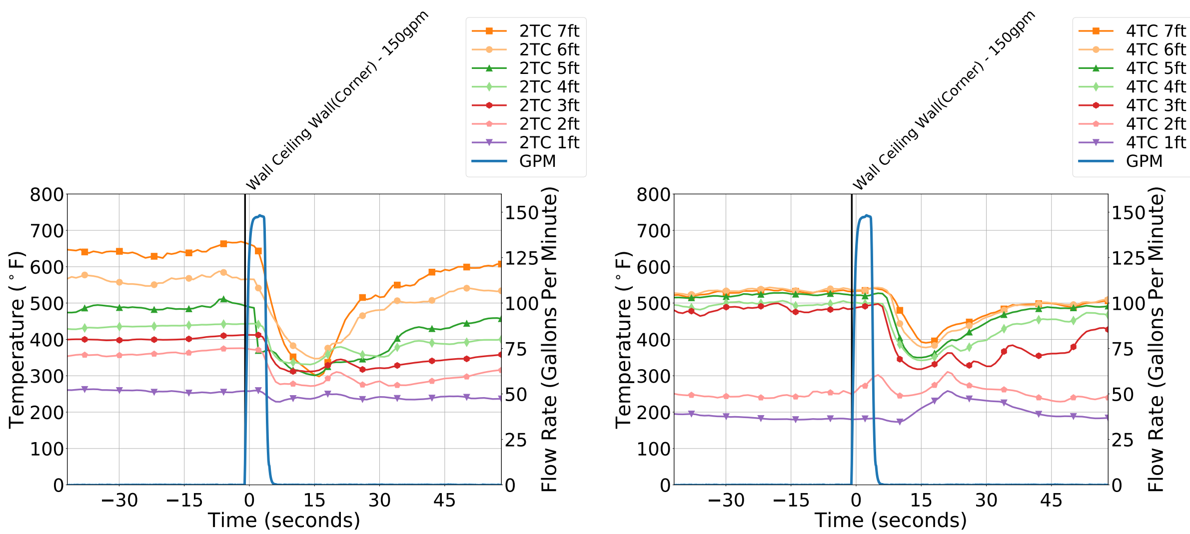


Figure 7.32: Effectiveness of ‘wall, ceiling, wall’ technique using 150 gpm nozzle at gas cooling. Upper left is fire compartment, upper left is left center of doorway, lower left is right center of doorway and lower right is just to the right of the advancing hose team. (Experiment 25)

It is important to note that water could not be applied directly into the fire compartment and the volume used was significantly larger than a standard residential room (all of the interior walls had been removed). This would represent the most challenging scenario to cool the gases as they would be replaced rapidly by the constant fire source with a flow path through the compartment out the open door. Future research should be done on the tactics used above to evaluate the effectiveness. In addition, future research should be done on residential-sizeed rooms; tactics such as door control, and high-pressure, low-flow nozzles.

8 Future Research Needs

Although this report covered the potential manual fire suppression methods in residential structures, other methods exist which may be more or less effective. Methods utilized in other countries, specifically involving different pressure and flow rates for hose streams should be evaluated against the methods tested to understand if any additional considerations can be developed. Gas cooling utilizing low-flow, high-pressure hose streams should be evaluated against the low-pressure, high-flow streams utilized in this study for effectiveness and safety provided while cooling the environment on approach. Of specific interest is the method of utilizing a low flow fog nozzle to cool a fire venting from a window, the thermal impact on the firefighter conducting the operation and the fire dynamics of the suppression tactic.

Additionally, this work only looked at single-story residential structures. Some of the considerations can easily be extrapolated to larger, multi-story single family homes, however others will require further research to understand their implications in larger multi-story structures. Although the fires represented a realistic scenario found in modern residential construction, they were only content fires. Additional work should be done to examine the impact of fires which extend beyond the contents to the structure itself.

Finally, this work looked at the potential impact of two different suppression methods on trapped occupants; however, it did not evaluate the methods of locating and removing those occupants. Further research needs to be conducted on fire department search and rescue, preferably in close coordination which fire suppression. Tactics such as Vent Enter Isolate Search (VEIS) should be evaluated for areas of the structure which were not accessible due to the thermal conditions on approach to those areas. Although the measurement techniques developed took steps to better understand the moisture and thermal injury potential, further research should be considered to enhance the measurements, by utilizing them in more places within the environment.

Definition List

The definitions below are included to help provide context to the reader. It should be understood the fire service across the United States often has slightly different meanings for the same word. Additionally, some areas have completely different meanings for the same word or phrase, thus several definitions may be included for a single word or phrase.

Atmospheric Pressure

The pressure of the weight of air on the surface of the earth, approximately 14.7 pounds per square inch (psia) (101 kPa absolute) at sea level.

Bi-directional vent

A building opening that serves as both as an intake and exhaust vent of a flow path at the same time.

Broken Stream

A stream of water that has been broken into coarsely divided drops; usually created by the rapid movement of a nozzle.

Burning Rate

See Heat Release Rate (HRR).

Calorie

The amount of heat necessary to raise 1 gram of water 1 °C at the pressure of 1 atmosphere and temperature of 15 °C; a calorie is 4.184 joules, and there are 252.15 calories in a British thermal unit (Btu).

Combustion

A chemical process of oxidation that occurs at a rate fast enough to produce heat and usually light in the form of either a glow or flame.

Combustion Products

The heat, gases, volatilized liquids and solids, particulate matter, and ash generated by combustion.

Compartment

A room or are that is subdivided from other areas of the structure.

Conduction

Heat transfer to another body or within a body by direct contact.

Convection

Heat transfer by circulation within a medium such as a gas or a liquid.

Direct Attack

Attack method that involves the discharge of water or a foam stream directly onto the burning fuel.

Firefighting operations involving the application of extinguishing agents directly onto the burning fuel.

Differential Pressure

The difference between pressures at different points along a flow path. The pressure difference creates the flow of gases or fluids from an area of higher pressure to an area of lower pressure.

Extinguishment

A state of non-fire growth.

To completely stop the combustion process.

Fire

A rapid oxidation process, which is a gas-phase chemical reaction resulting in the evolution of light and heat in varying intensities.

Fire Attack

See Fire Suppression

Fire Control

Limiting the size of the fire so as to decrease the heat release rate and prevent fire spread to adjacent combustibles, while reducing fire gas temperatures.

Fire Dynamics

The detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior.

Fire Gases

Smoke, products of combustion and pyrolyzates, and gaseous fuels that are present and could ignite and increase the size and intensity of the fire.

Fire Science

The body of knowledge concerning the study of fire and related subjects (such as combustion, flame, products of combustion, heat release, heat transfer, fire and explosion chemistry, fire and explosion dynamics, thermodynamics, kinetics, fluid mechanics, fire safety) and their interaction with people, structures, and the environment.

Fire Spread

The movement of fire from one place to another.

Fire Suppression

The activities involved in controlling and extinguishing fire.

Flame

A body or stream of gaseous material involved in the combustion process and emitting radiant energy at specific wavelength bands determined by the combustion chemistry of the fuel. In most cases, some portion of the emitted radiant energy is visible to the human eye.

Flameover

The condition where unburned fuel from a fire has accumulated in the ceiling layer to a sufficient concentration (i.e., at or above the lower flammable limit) that it ignites and burns; can occur without ignition of, or prior to, the ignition of other fuels separate from the origin.

Flammable

Capable of burning with a flame.

Flashover

A rapid transition from the growth stage to the fully developed stage.

A transition stage in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space.

A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in near full room involvement.

Flow Path

Composed of at least one inlet opening, one exhaust opening, and the connecting volume between the openings. The direction of the flow is determined by difference in pressure. Heat and smoke in a high-pressure area will flow toward areas of lower pressure.

The volume in a structure between an inlet and an outlet that allows the movement of heat and smoke from the higher pressure within the fire area toward the lower pressure areas accessible via doorways, halls, stairs, and window openings.

The area(s) within a structure where heat, smoke and air flows from an area of higher pressure to lower pressure. It is composed of at least one intake vent, one exhaust vent and the connecting volume between the vents.

Fuel

A material that will maintain combustion under specified environmental conditions.

Fuel-Limited Fire

(Fuel-Controlled) A fire with adequate oxygen in which the heat release rate and growth rate are determined by the characteristics of the fuel, such as quantity and geometry.

A fire that has sufficient oxygen for fire growth but has a limited amount of fuel available for burning.

A fire that has a heat release rate that is controlled by the material burning.

A fire in which the heat release rate and growth rate are controlled by the characteristics of the fuel, such as combustibility, quantity and geometry, and in which adequate air for combustion is available.

Fuel Load

The total quantity of combustible contents of a building, space, or fire area, including interior finish and trim, prior to ignition.

Gas

The physical state of a substance that has no shape or volume of its own and will expand to take the shape and volume of the container or enclosure it occupies.

Half Bale

Using the broken stream of the nozzle to get water into the fire room above grade level. This is a secondary water application method for the exterior portion of transitional attack.

Heat

A form of energy characterized by vibration of molecules and capable of initiating and supporting chemical changes and changes of state.

Heat Flux

The measure of the rate of heat transfer to a surface, expressed in kilowatts/m^2, kilojoules/m^2*sec, or Btu/ft^2*sec.

Heat Release Rate (HRR)

The rate at which heat energy is generated by burning.

Indirect Attack

Form of fire attack that involves directing fire streams toward the ceiling of a compartment in order to generate a large amount of steam in order to cool the compartment. Converting the water to steam displaces oxygen, absorbs the heat of the fire, and cools the hot has layer sufficiently for firefighters to safely enter and make a direct attack on the fire.

Firefighting operations involving the application of extinguishing agents to reduce the build-up of heat released from a fire without applying the agent directly onto the burning fuel.

Firefighting operations involving the application of extinguishing agents to reduce the buildup of heat released from a fire without applying the agent directly onto the burning fuel.

Interior Attack

A fire attack where the application of water occurs on the interior utilizing a hoseline to cool adjoining spaces and extinguish the fire.

Ignition

The process of initiating self-sustained combustion.

Immediate Dangerous to Life and Health (IDLH)

Any condition that would pose an immediate or delayed threat to life or irreversible adverse health effects.

Jargon

The specialized or technical language of a trade, profession, or similar group.

Joule

The preferred SI unit of heat, energy, or work. A joule is the heat produced when one ampere is passed through a resistance of one ohm for one second, or it is the work required to move a distance of one meter against a force of one newton. There are 4.184 joules in a calorie, and 1055 joules in a British thermal unit (Btu). A watt is a joule/second.

Kilowatt

A measurement of energy release rate. A kilowatt is 1000 watts. A watt is a joule/second.

Knock Back

A state of partial fire extinguishment which will allow for fire regrow in a short period of time without additional intervention.

Knock Down

A state of partial fire extinguishment that is close to full extinguishment and where regrowth is unlikely.

Neutral Plane

The interface or level of zero differential pressure at a compartment vent, such as a door or window, between the higher pressure hot gas flowing out of a fire compartment and the lower pressure cooler air flowing into the compartment.

Oxygen Deficiency

Insufficiency of oxygen to support combustion.

Positive Pressure Ventilation

The utilization of powered blowers or fans, post-fire control, to exhaust heat and smoke from the fire area.

Pressure

Pressure is a measure of force per unit area exerted on a surface at 90 degrees to that surface. Values for pressure may be given in pounds per square inch (psi) or Pascals (Pa) The earth is surrounded by an atmosphere made up of approximately 78% nitrogen, 21% oxygen and 1% of other gases. The weight of these gases on the earth creates a force of 14.7 pounds per square inch (psi) at sea level. This is referred to as Atmospheric pressure. Pressure in the fire service is typically referenced in the units of pounds per square inch or PSI, as this is the standard pressure unit for many of the pump panel gauges on an engine. The pressure shown on the pump panel gauge is actually measured relative to the atmospheric pressure. In other words, 50 psi is really 50 psi over the atmospheric pressure. This type of pressure measurement is referred to as psi gauge or psig. The pressure developed by the fire or by a fan is the measured pressure over and above the atmospheric pressure. Fires create pressure that push smoke and gases throughout a room or structure. The pressures are very small, on the order of one thousandth of a psi. Therefore it is best to use a different unit for measuring pressure. This unit is called a Pascal. When it is written, it is abbreviated as Pa. 101,325 Pa equals 14.7 psi. Or 1 Pa equals 0.00015 psi.

Products of Combustion

See Combustion Products.

Pyrolysis

A process in which material is decomposed, or broken down, into simpler molecular compounds by the effects of heat alone; pyrolysis often precedes combustion.

Radiant Heat

Heat energy carried by electromagnetic waves that are longer than light waves and shorter than radio waves; radiant heat (electromagnetic radiation) increases the sensible temperature of any substance capable of absorbing the radiation, especially solid and opaque objects.

Radiation

Heat transfer by way of electromagnetic energy.

Rate of Heat Release

See Heat Release Rate (HRR).

Risk

The degree of peril; the possible harm that might occur that is represented by the statistical probability or quantitative estimate of the frequency or severity of injury or loss.

Rollover

See Flameover.

Size-up

Ongoing evaluation of influential factors at the scene of an incident.

The observation and evaluation of existing factors that are used to develop objectives, strategy, and tactics for fire suppression.

The observation and evaluation of existing factors in order to develop objectives, strategies, and tactics for fire suppression.

Smoke

The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass.

Soot

Black particles of carbon produced in a flame.

Steam conversion

The physical event where water is delivered to the heat of a fire and the water is converted from a liquid to a vapor in the form of steam.

Temperature

The degree of sensible heat of a body as measured by a thermometer or similar instrument.

Transitional Attack

A fire attack where the application of water starts on the exterior to cool the fire area for a period and then repositioned to the interior for final suppression.

Under Control

A term used to describe when visible and audible signs of combustion are absent from the environment.

Uni-directional vent

A building opening that serves as either an intake or an exhaust vent of a flow path at a given point in time.

Vent

An opening for the passage of, or dissipation of, fluids, such as smoke, gases, and heat.

Ventilation

Circulation of air in any space by natural wind or convection or by fans blowing air into or exhausting air out of a building; a fire-fighting operation of removing smoke, gases and heat from the structure by natural or mechanical methods.

Ventilation-Limited Fire

A fire in which the heat release rate or growth is controlled by the amount of air (oxygen) available to the fire.

(Ventilation-Controlled) A fire with limited ventilation in which the heat-release rate or growth is limited by the amount of oxygen available to the fire.

A fire in an enclosed building that is restricted because there is insufficient oxygen available for the fire to burn as rapidly as it would with an unlimited supply of oxygen.

A fire where every object in the fire compartment is fully involved in fire and the heat release rate depends on the airflow through the openings to the fire compartment.

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Appendices

Appendix A   Test Fixture Drawings

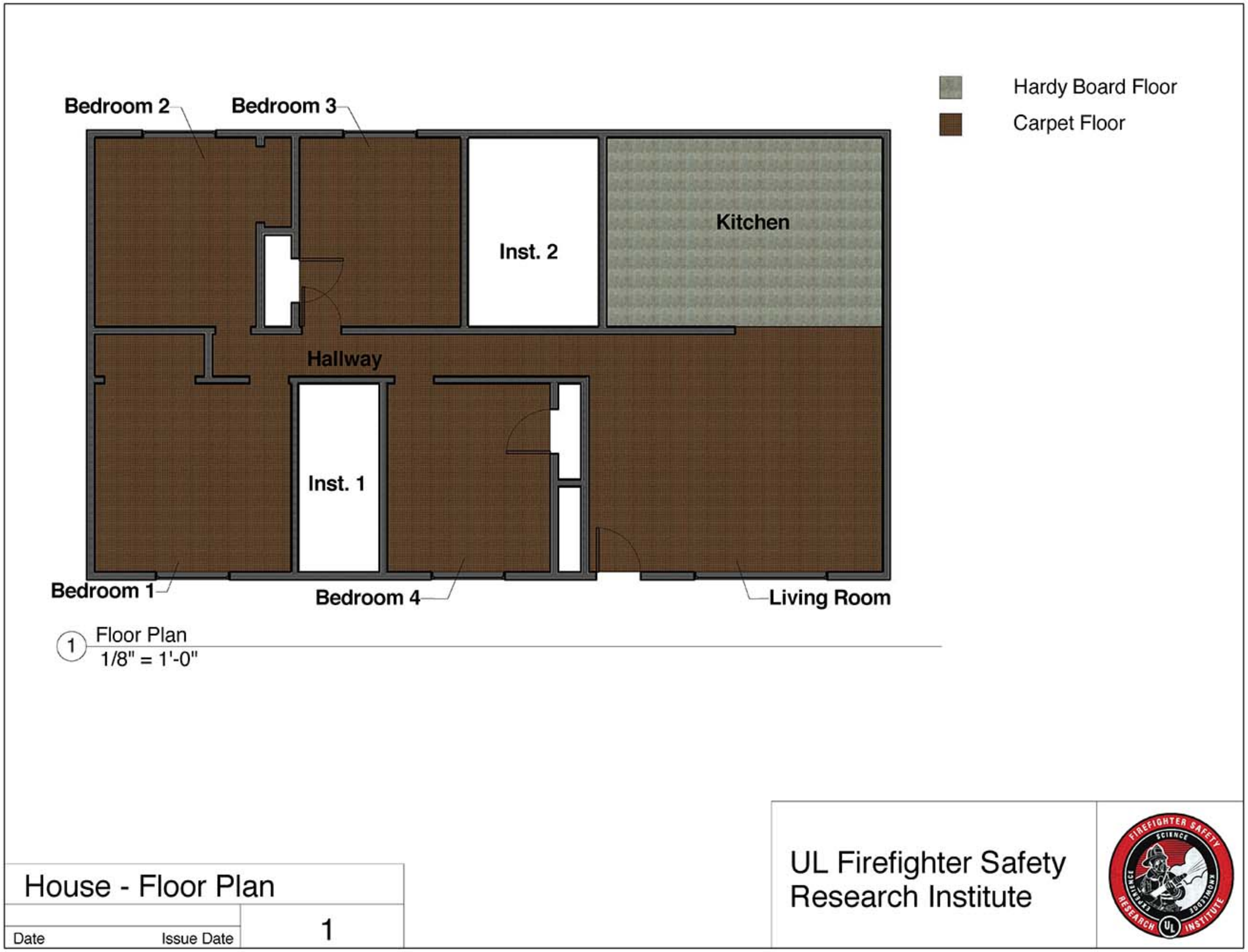


Figure A.1: Test Fixture Floor Plan

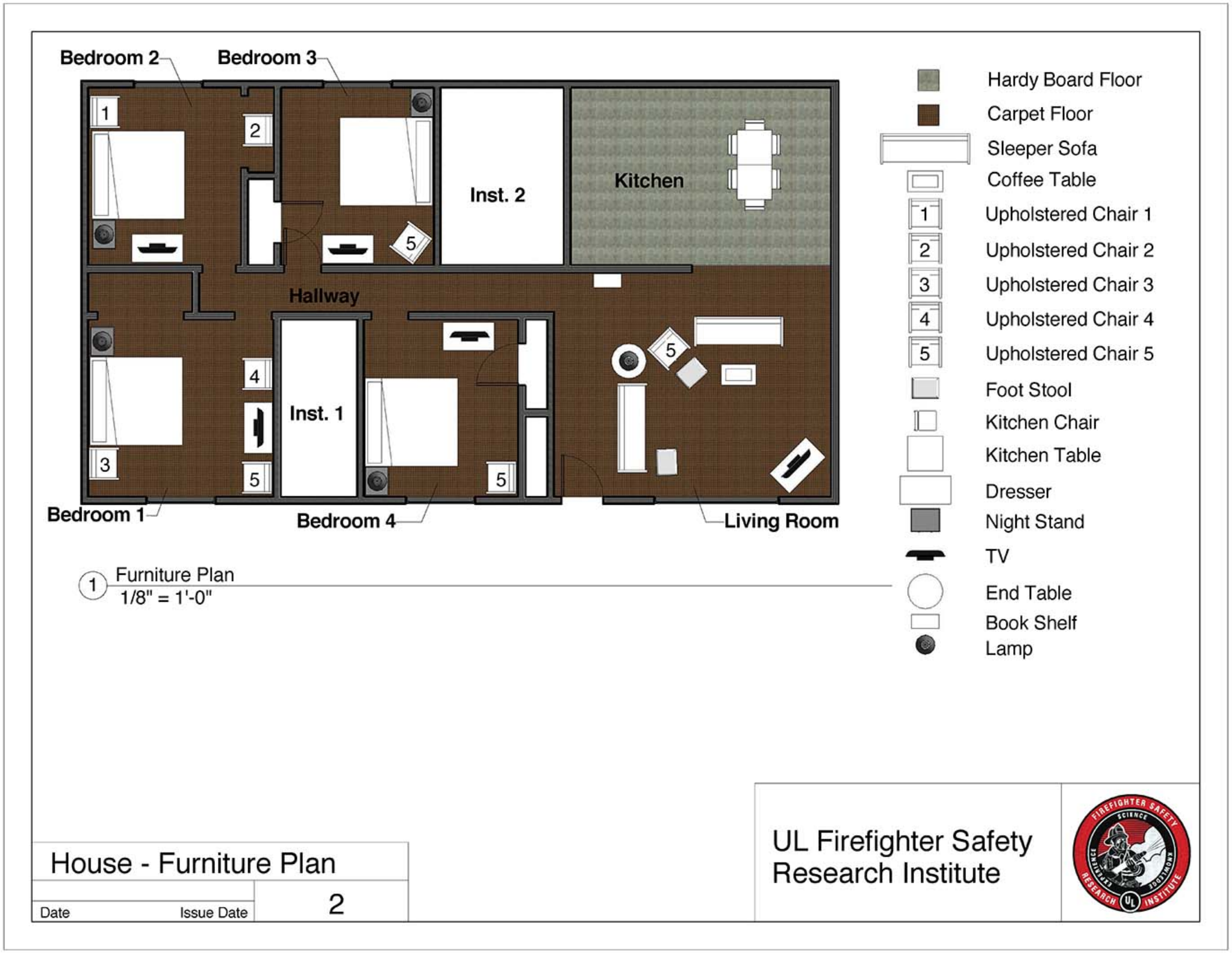
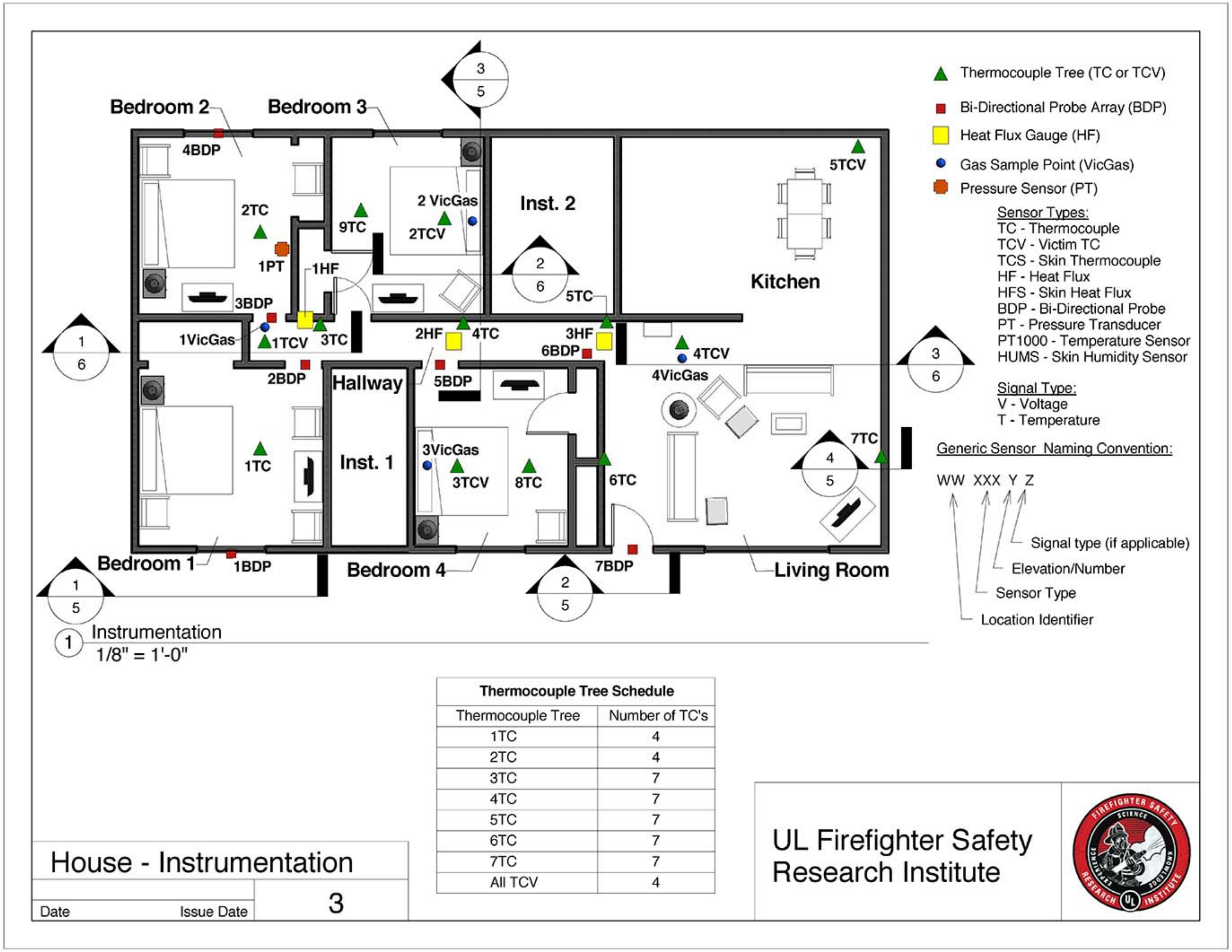


Figure A.2: Test Fixture Furniture Plan

Figure A.3: Test Fixture Furniture Images



Thermocouple Tree Schedule	
Thermocouple Tree	Number of TC's
1TC	4
2TC	4
3TC	7
4TC	7
5TC	7
6TC	7
7TC	7
All TCV	4

Figure A.4: Instrumentation Plan

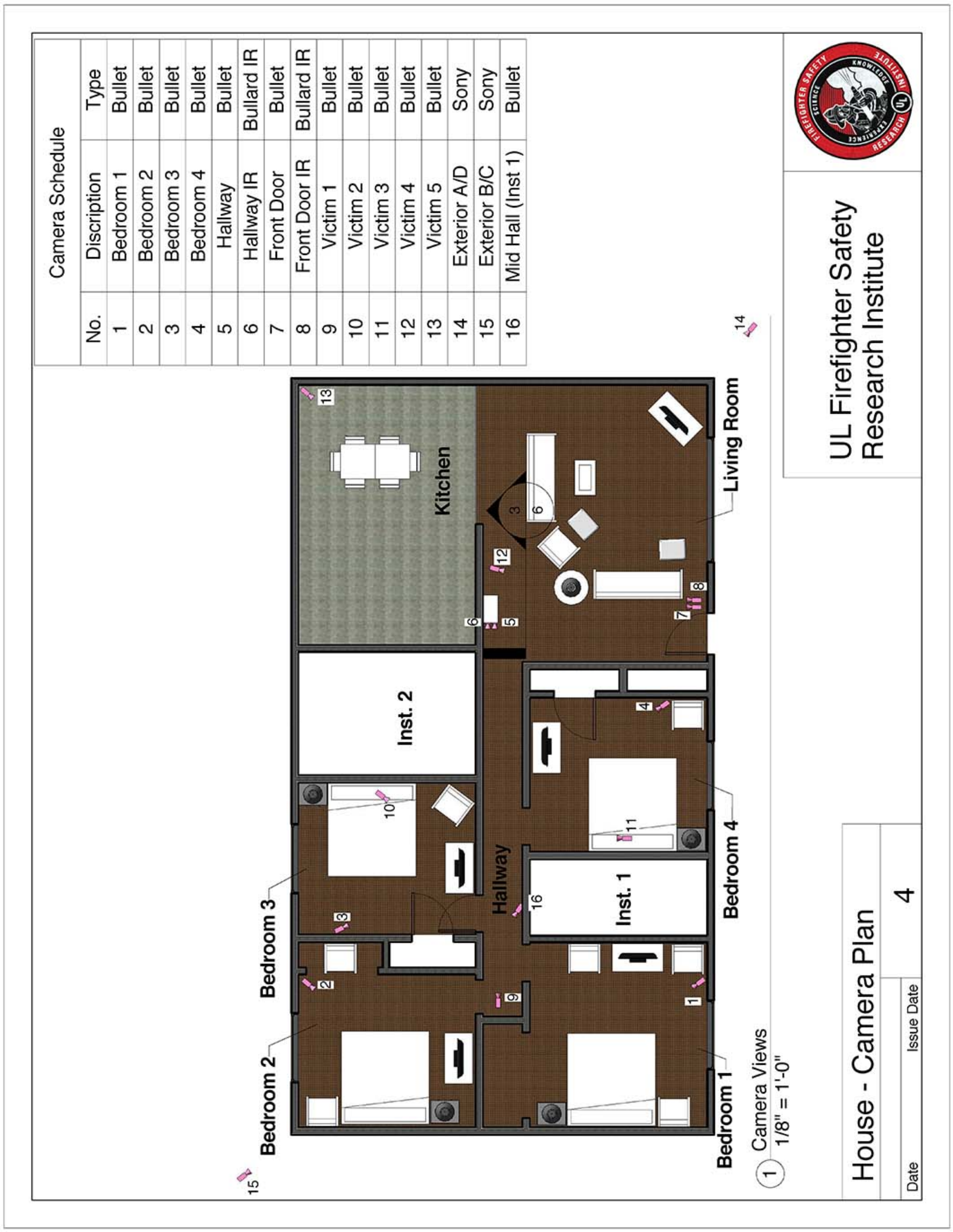


Figure A.5: Camera Plan

Appendix B Detailed Fuel Load Specifications

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)	Material
King Mattress	79.0	71.0	10.0	76.0	52% Polyurethane Foam, 30%, Blended Cotton Batting, & 18% Polyester Fiber Batting
King Box Spring	78.0	35.0	7.0	46.0	59% Fiber Pad, 41% Blended Cotton Batting & Wood Frame
King Headboard	78.0	24.0	1.0	54.0	Medium Density Fiberboard
Pillow	23.5	17.0	4.0	1.5	Filling - All Polyester, Cover - 100% Cotton
Comforter	104.0	92.0	1.0	4.6	Cover - 100% Polyester, Fill - 100% Polyester
Mattress Topper 4 in	78.0	75.0	3.9	16.0	Viscoelastic Polyurethane Foam Pad 100%
Night Stand	18.0	27.0	23.4	60.0	Solid Wood
Dresser	22.1	36.0	34.25	120.0	Wood & Plywood
Curtain (Small)	39.0	73.0	0.1	4.5	Flame Retardant & Synthetic Fibers
Sofa Chair (Yellow/Green)	31.3	31.0	39.0	54.0	Polyester Fiber 75%, Polyurethane Foam 25%, Pillow - Polyurethane Foam 90%, Polyester Batting 10%
Sofa Chair (Red Lines)	34.5	34.0	32.0	63.0	Urethane Foam 100%
Sofa Chair (Red Swirl)	34.0	34.0	32.0	70.0	Blended Cotton Felt 100%, Cushion, Polyurethane Foam 100%
Sofa Chair (Red Diamond)	35.0	35.0	34.0	69.0	Polyurethane Foam (Blended Cotton or, Polyester when used is less than 10%)

Table B.1: Bedroom Fuel Load Information

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)	Material
Curtain (Large)	107.0	73.0	0.1	13.7	Flame Retardant & Synthetic Fibers
Mattress Topper 5 in	77.5	76.3	4.6	20.1	Urethane Foam
Kitchen Table	52.0	26.0	24.5	29.1	Particleboard & Wood
Straight Chair (Pink)	18.0	19.0	33.0	15.2	Wood & Upholstery
Straight Chair (Blue)	19.0	19.0	38.9	14.9	Wood & Upholstery
Bookcase	11.5	24.6	71.3	46.0	Particleboard
TV Stand	22.1	36.0	34.3	120.0	Wood & Plywood
Sofa	35.0	77.0	30.5	255.0	Polyurethane Foam 50%, Polyester Fiber 50%,& Wood Frame
Sofa Chair (Striped)	33.0	35.0	33.5	65.0	Polyurethane Foam 75% Polyester Fiber 25%
Ottoman	19.8	25.5	16.0	21.3	Upholstery
Coffee Table	30.0	18.0	18.3	24.4	Particleboard & Wood
End Table	24.3	24.3	22.1	32.1	Solid Wood
Table Lamp Base	5.8	5.3	31.3	5.9	Glass, Metal
Table Lame Shade	14.4	14.4			Cloth Shade

Table B.2: Kitchen and Living Room Fuel Load Information

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)	Material
Bedroom 1 Carpet (Room)	13.3	12.8	0.4	47.6	Polyester 100%
Bedroom 1 Carpet (Closet)	7.5	2.9	0.4	6.0	Polyester 100%
Bedroom 1 Carpet Padding (Room)	13.3	12.8		27.2	
Bedroom 1 Carpet Padding (Closet)	7.5	2.9		3.4	
Bedroom 2 Carpet (Room)	11.0	12.8	0.4	39.3	Polyester 100%
Bedroom 2 Carpet (Closet)	6.1	1.9	0.4	3.2	Polyester 100%
Bedroom 2 Carpet Padding (Room)	11.0	12.8		22.4	
Bedroom 2 Carpet Padding (Closet)	6.1	1.9		1.8	
Bedroom 3 Carpet	11.0	12.8	0.4	39.3	Polyester 100%
Bedroom 3 Carpet Padding	11.0	12.8		22.4	
Bedroom 4 Carpet	11.1	12.8	0.4	39.6	Polyester 100%
Bedroom 4 Carpet Padding	11.1	12.8		22.6	
Kitchen Carpet	12.8	18.8	0.4	67.1	Polyester 100%
Kitchen Carpet Padding	12.8	18.8		38.3	
Living Room Carpet	16.1	19.1	0.4	85.5	Polyester 100%
Living Room Carpet Padding	16.1	19.1		49.5	

Table B.3: Carpet and Padding Fuel Load Information

Appendix C One-Dimensional Heat Diffusion Model

In order to predict the pig skin temperature from heat flux gage measurements, a one-dimensional heat diffusion model outlined in Equations C.1-C.4 was implemented.

$$\alpha \frac{d^2T(x,t)}{dx^2} = \frac{dT(x,t)}{dt} \tag{C.1}$$

$$-k\frac{dT(0,t)}{dx} = \dot{q}"(t) \tag{C.2}$$

$$T(L,t) = 310 \tag{C.3}$$

$$T(x,0) = T_{initial} \tag{C.4}$$

Where α is thermal diffusivity

T is the temperature
x is the spatial coordinate
t is the time coordinate
k is the thermal conductivity of the siding
$\dot{q}"(t)$ is the heat flux data from experiments
L is the thickness of the pig skin and neopren
$T_{initial}$ is the initial surface temperature

In solving these equations, it is assumed that the water bath maintains the core temperature of 37°C, and the top surface boundary condition with $\dot{q}"(t)$ coming from the measured heat flux values. These equations are discretized and solved using an implicit solution with $\Delta x = 0.1mm$ and $\Delta t = 0.1s$. The thermal properties used for skin were: density = 1000 kg/m^3, heat capacity = 3200 $J/(kgK)$, and thermal conductivity = 0.21 $W/(mK)$. Unfortunately, moisture interaction with the heat flux sensor results in the predicted temperature deviating significantly from those measured on the skin surface, particularly after water application. Thus, it was found that using the heat flux gage to predict skin damage was unreliable.

However, implementing the 1-D model outlined in Equations C.1-C.4 in reverse, the apparent heat flux can be estimated from the measured skin temperatures in the SBA packages. Using an iterative scheme, heat flux is incremented by ± 20 W/m^2 in the model and the surface temperature is compared to experimental measurements until it agrees to within ± 0.2 °C This heat flux estimation scheme has been validated against laboratory calibration experiments in an environmental chamber showing good agreement for radiation and convection dominated conditions

Further details on the model can be found in [58].

Appendix D Blood Perfusion & Skin Damage Model

The current, pig skin temperature data provides an estimate of the temperature response for dead skin. However, this fails to account for one of the key cooling mechanisms of live skin, which is blood perfusion, i.e. the impact of blood flowing through the skin and removing (or providing) heat. In order to account for blood perfusion, the 1-D heat diffusion must be modified slightly. With the ability to estimate heat flux to the skin surface accurately, equation C.1 can be updated to include an additional term as shown in D.1.

$$\alpha \frac{d^2T(x,t)}{dx^2} + \frac{C_B G_B (T_B - T(x,t))}{C} = \frac{dT(x,t)}{dt} \tag{D.1}$$

Where C_B is the volumetric specific heat of blood

G_B is the blood perfusion rate
C is the volumetric specific heat of skin
T_B is the blood temperature

To account for the effect of tissue damage, an Arrhenius integral formulation is used to define the damage (necrosis), $\theta(x)$ D.2, which is then used to adjust the blood perfusion rate D.3 [59, 60]:

$$0(x) = \int_0^t A exp(-\frac{\Delta E}{RT(x,t)})dt \tag{D.2}$$

$$G_B(\theta) = \begin{cases} (1 + 25\theta - 260\theta^2)G_{BO}, & 0 < \theta \leq 0.1 \\ (1-\theta)G_{BO}, & 0.1 < \theta \leq 1 \\ 0, & \theta > 1 \end{cases} \tag{D.3}$$

Equation D.2 is identical to the Henriques equation proposed by Stoll et al. Second degree burn occurs when the skin depth is between the epidermis and dermis and θ is equal to one. A third degree burn occurs when θ is equal to one at a depth between the dermis and subcutaneous layers [49]. Information from burn models regarding thresholds of time and temperature for injury will help set parameters for future experiments to be performed.

Further details on the use of pig skin surface temperatures to measure heat flux and the use of the blood perfusion model can be found in [58].

Appendix E   Experimental Results

E.1 Experiment 1 Data

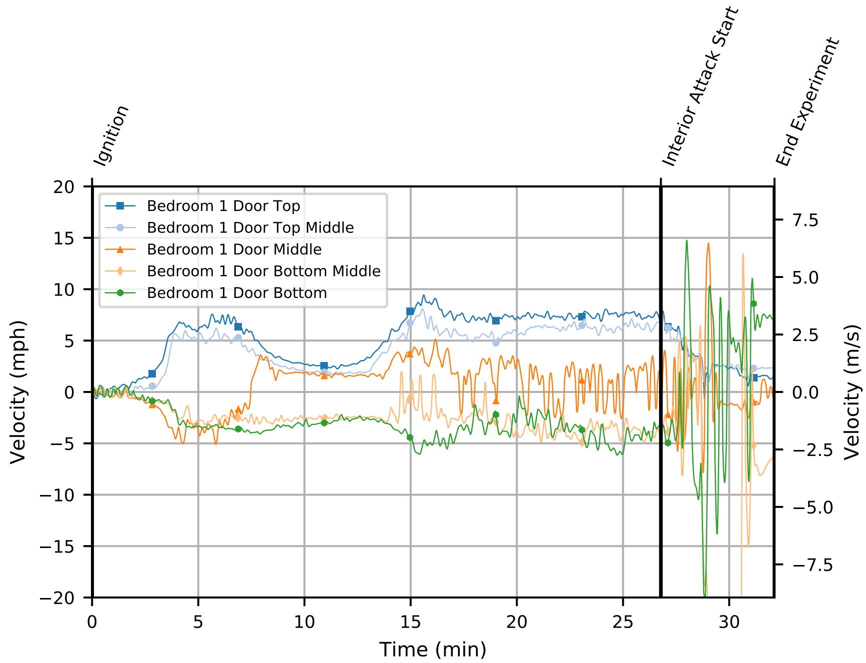


Figure E.1: Experiment 1 - Bedroom 1 Door

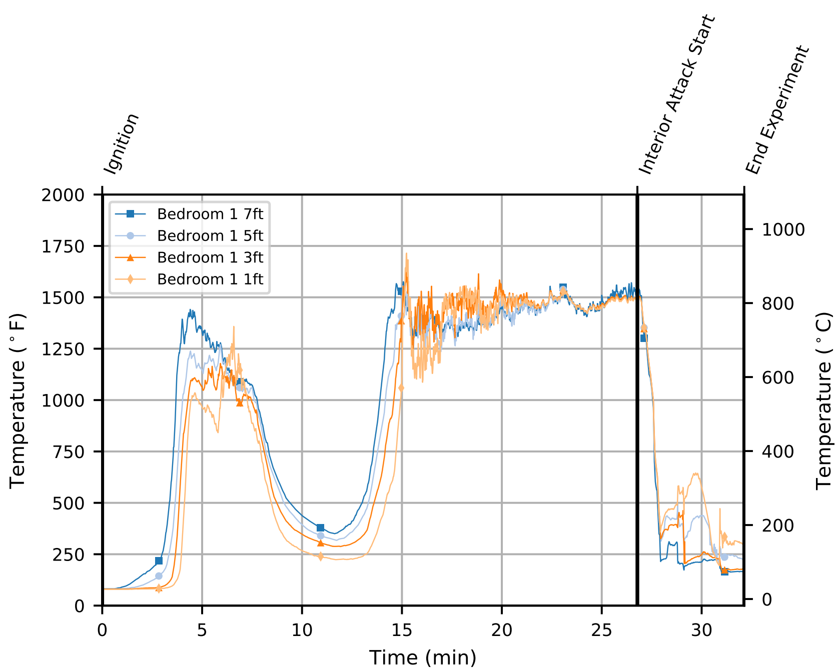


Figure E.2: Experiment 1 - Bedroom 1 Temps

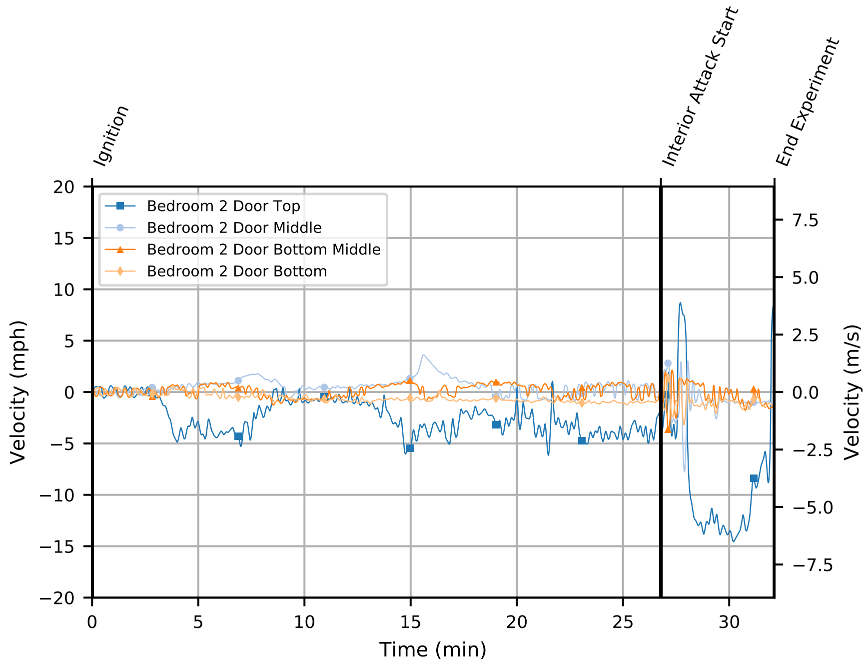


Figure E.3: Experiment 1 - Bedroom 2 Door

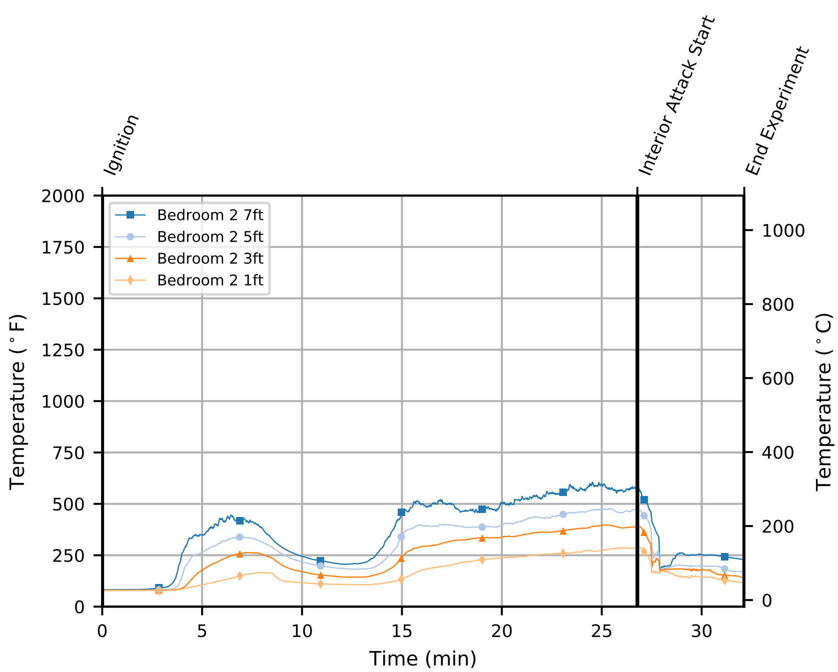


Figure E.4: Experiment 1 - Bedroom 2 Temps

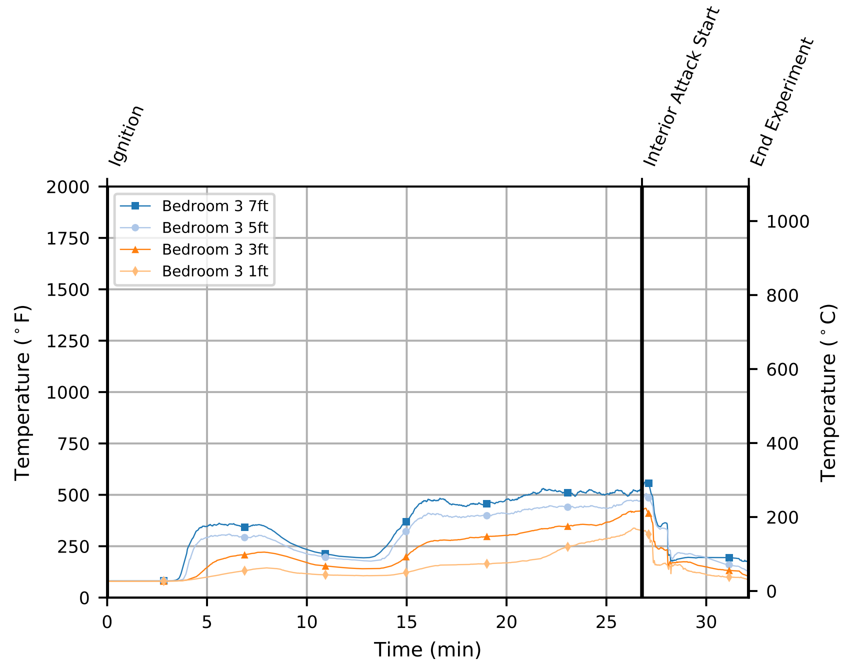


Figure E.5: Experiment 1 - Bedroom 3 Temps

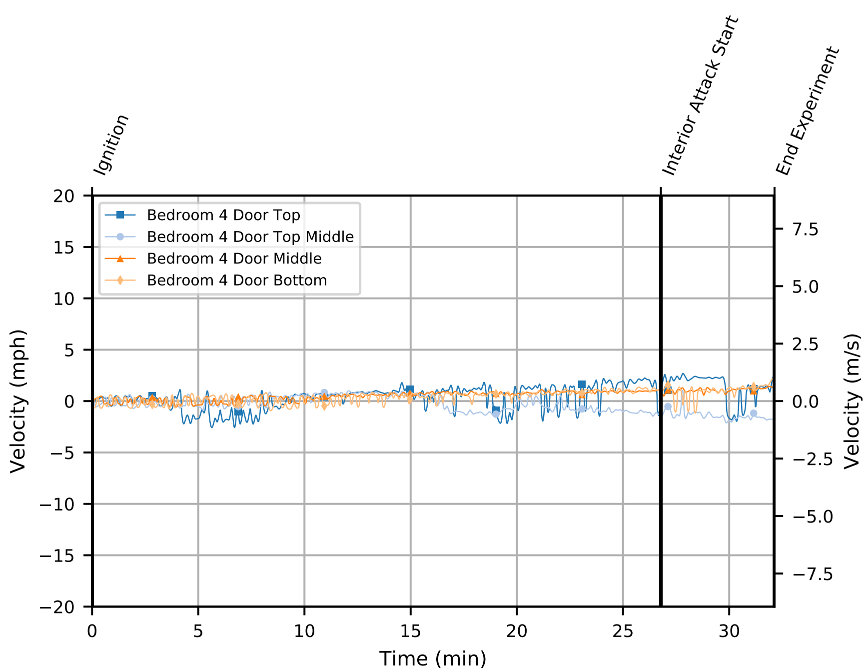


Figure E.6: Experiment 1 - Bedroom 4 Door

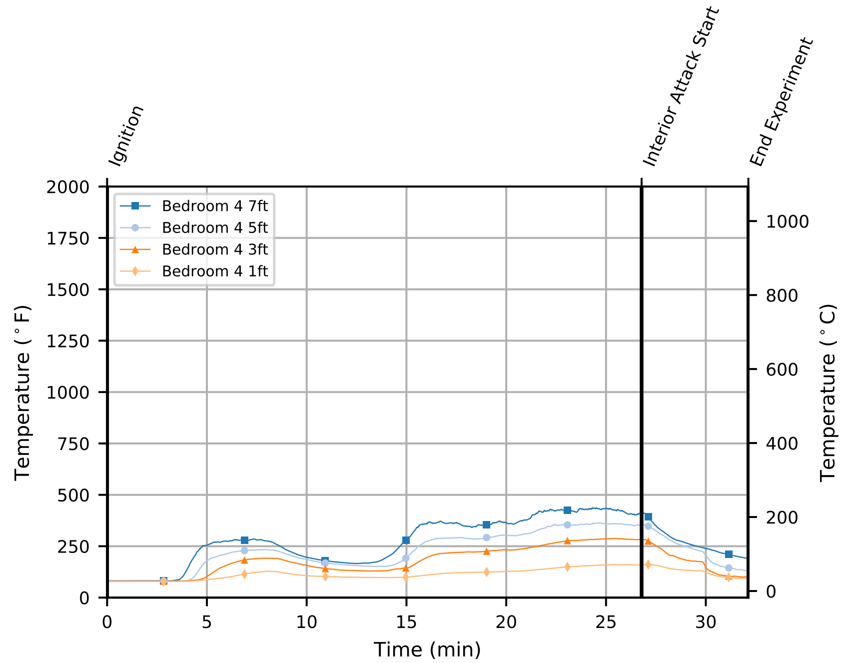


Figure E.7: Experiment 1 - Bedroom 4 Temps

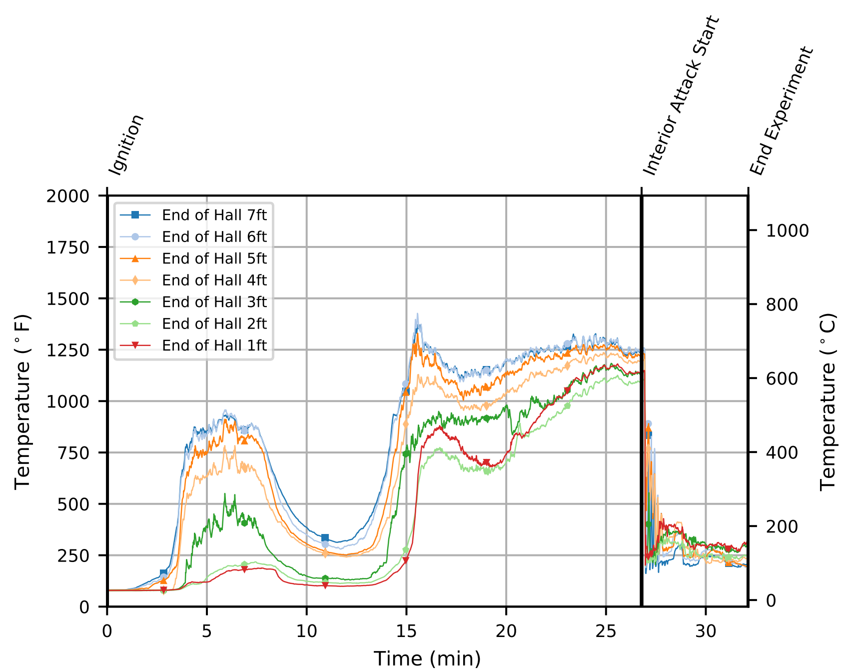


Figure E.8: Experiment 1 - End Hall Temps

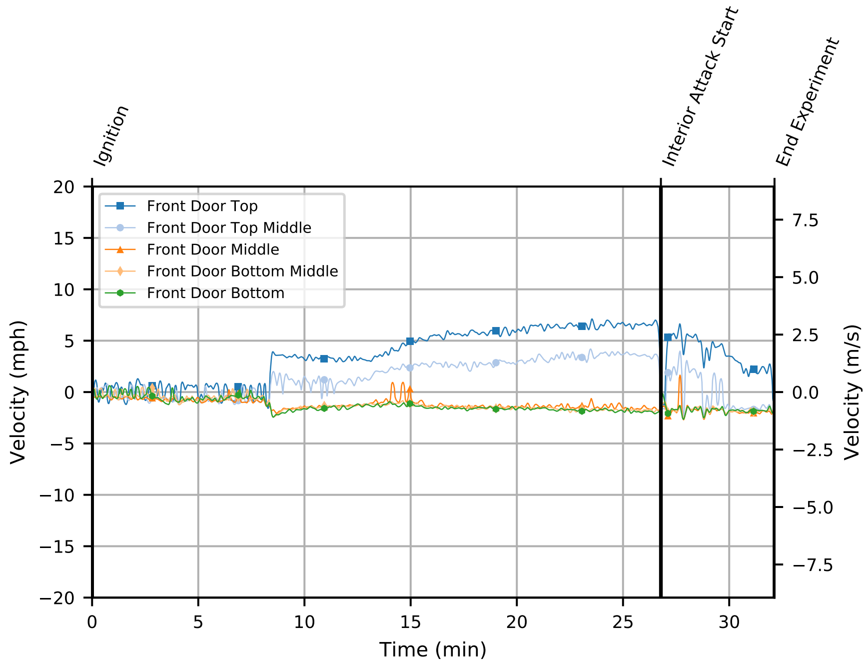


Figure E.9: Experiment 1 - Front Door Flow

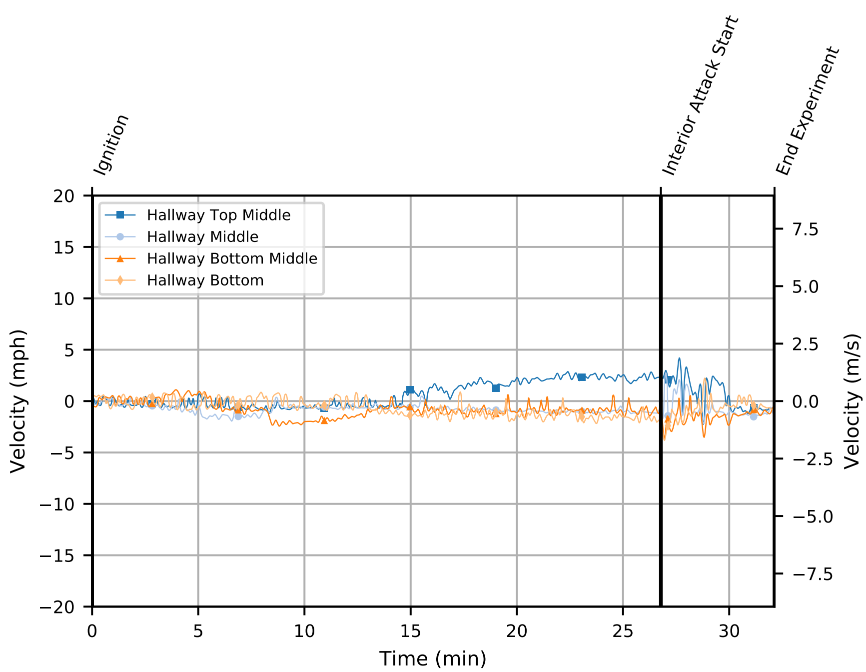


Figure E.10: Experiment 1 - Hallway Flow

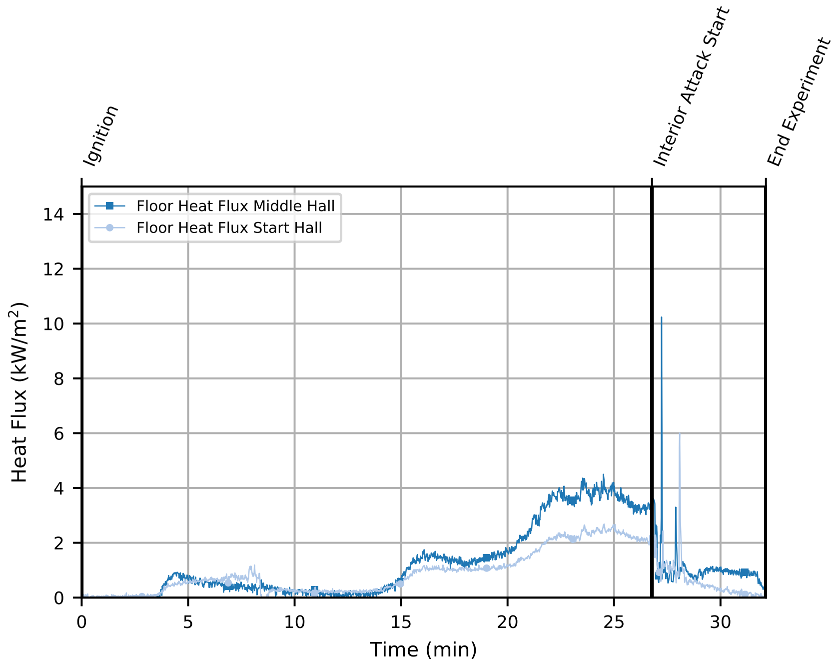


Figure E.11: Experiment 1 - Heat Flux Floor

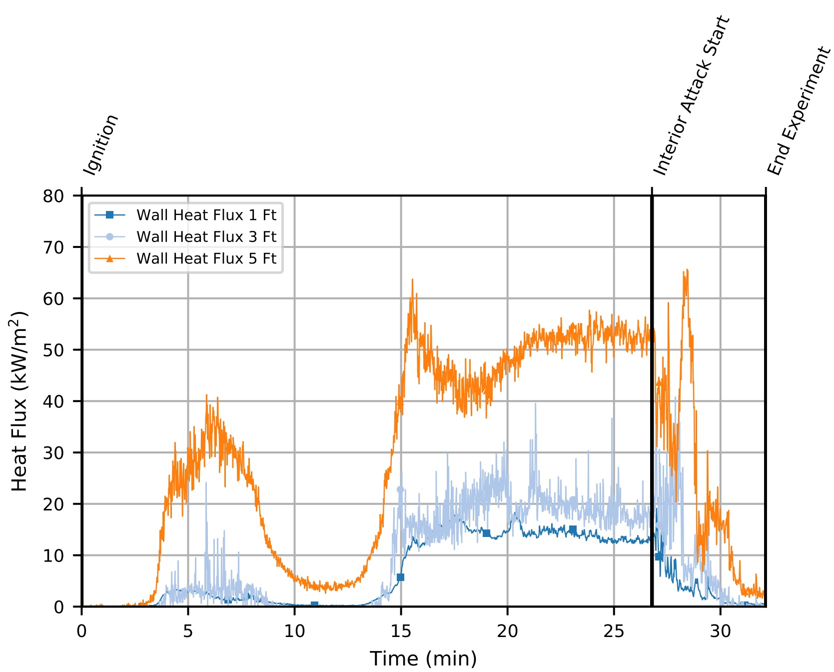


Figure E.12: Experiment 1 - Heat Flux Wall

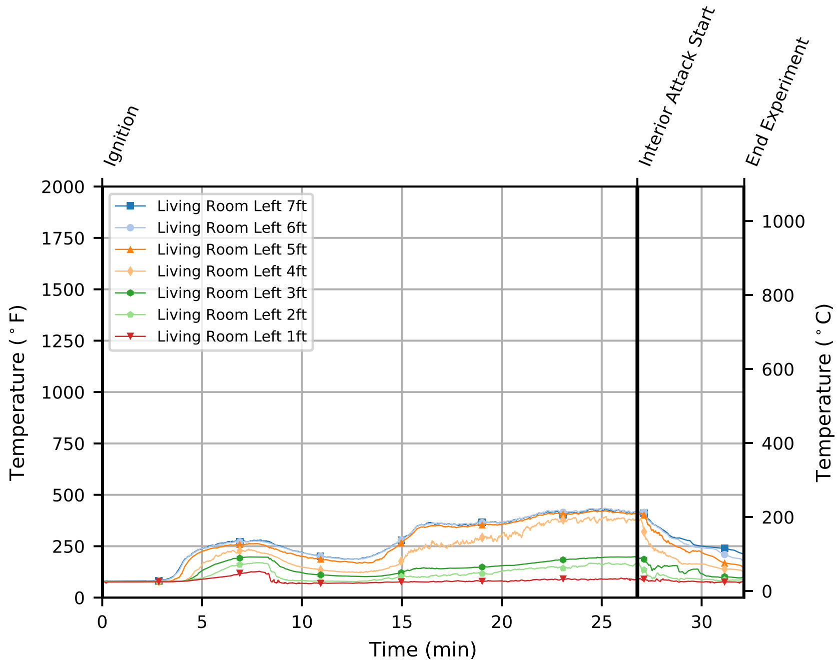


Figure E.13: Experiment 1 - Living Room Left Temps

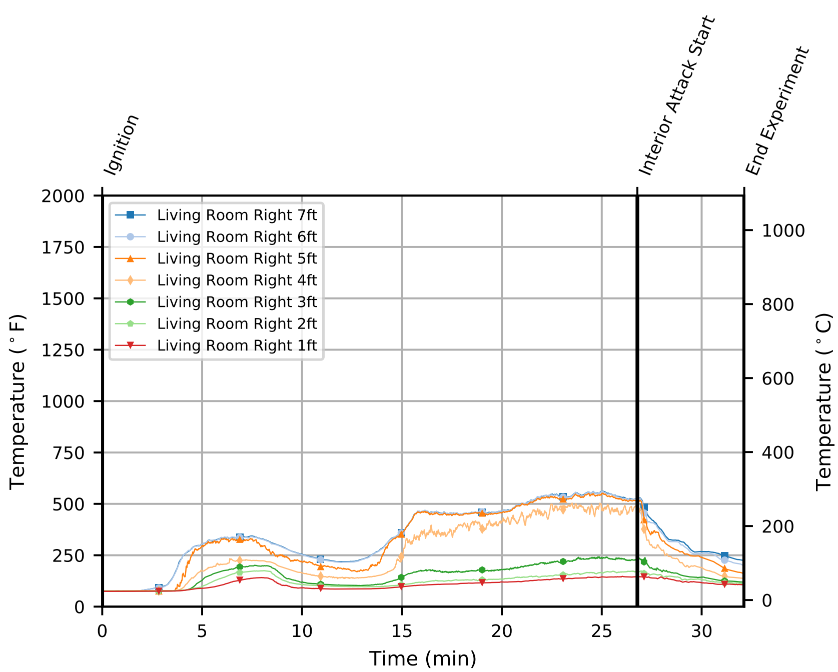


Figure E.14: Experiment 1 - Living Room Right Temps

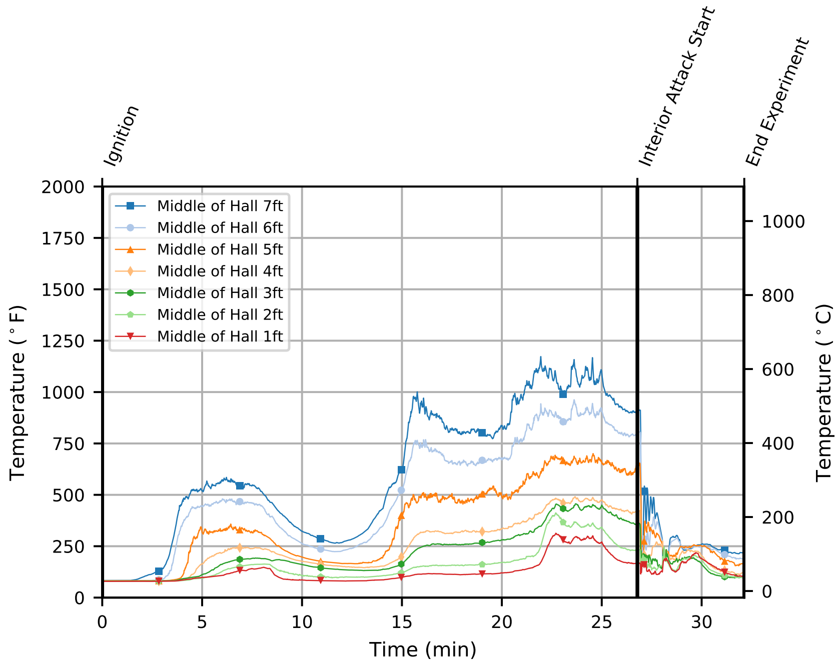


Figure E.15: Experiment 1 - Middle Hall Temps

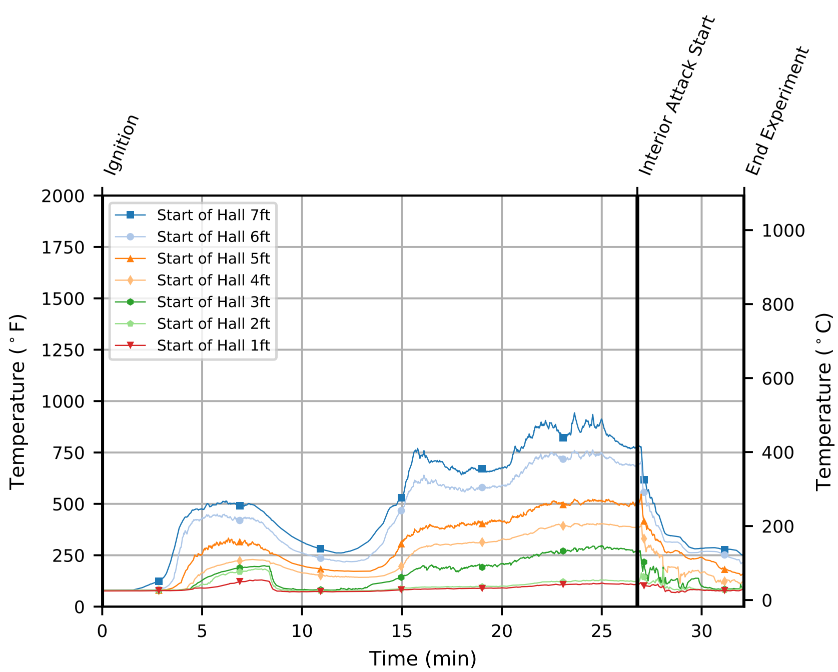


Figure E.16: Experiment 1 - Start Hall Temps

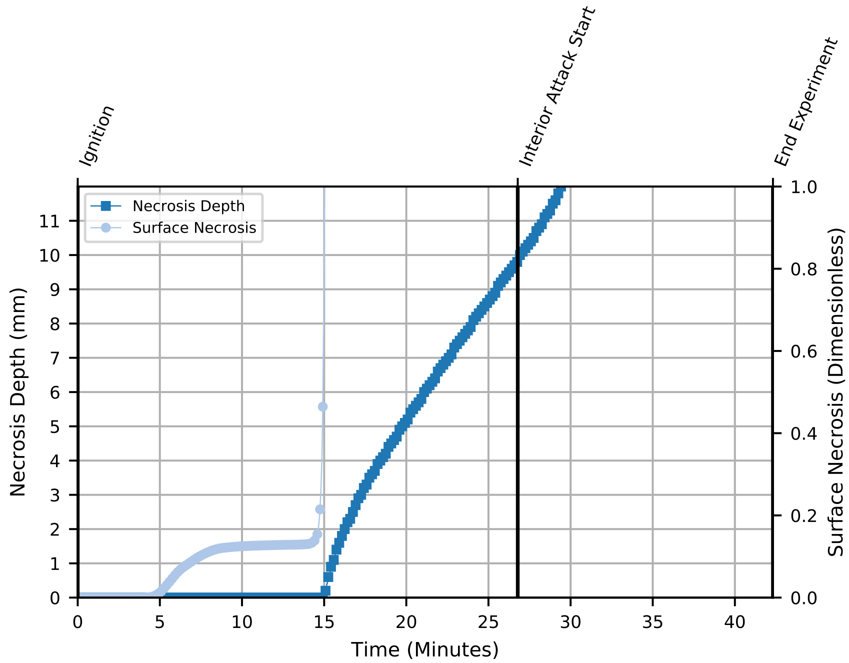


Figure E.17: Experiment 1 - Vic 1 Necrosis Depth

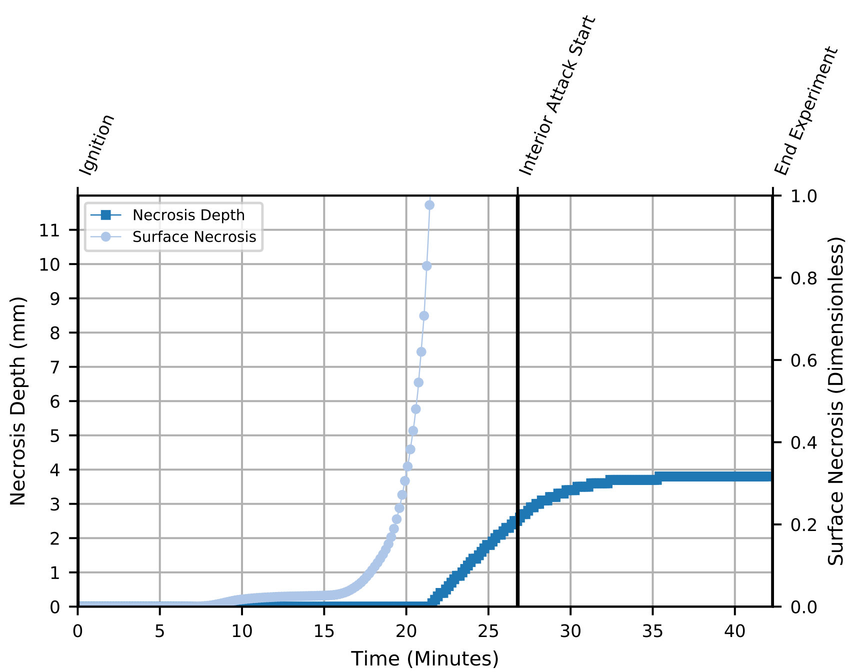


Figure E.18: Experiment 1 - Vic 3 Necrosis Depth

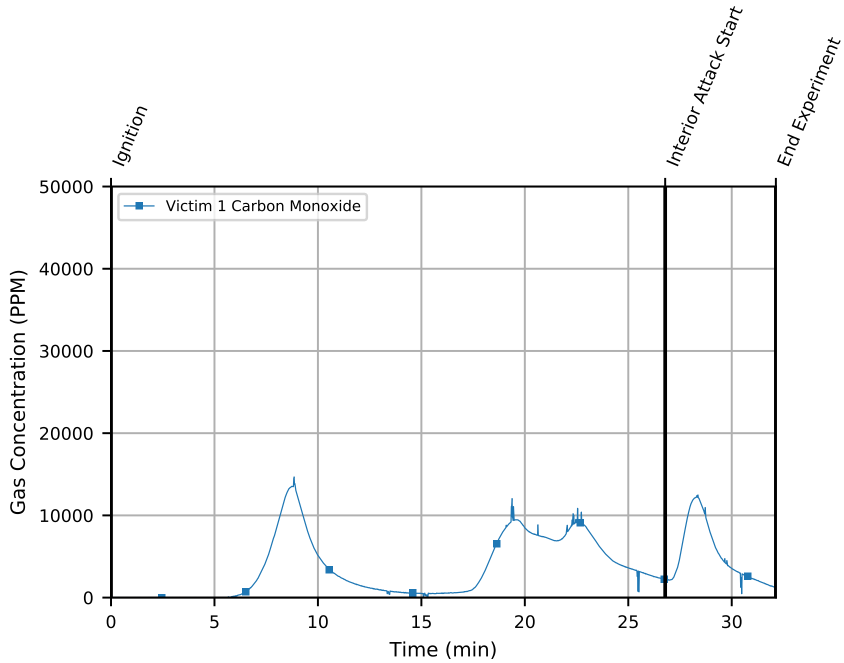


Figure E.19: Experiment 1 - Victim 1 Carbon Monoxide

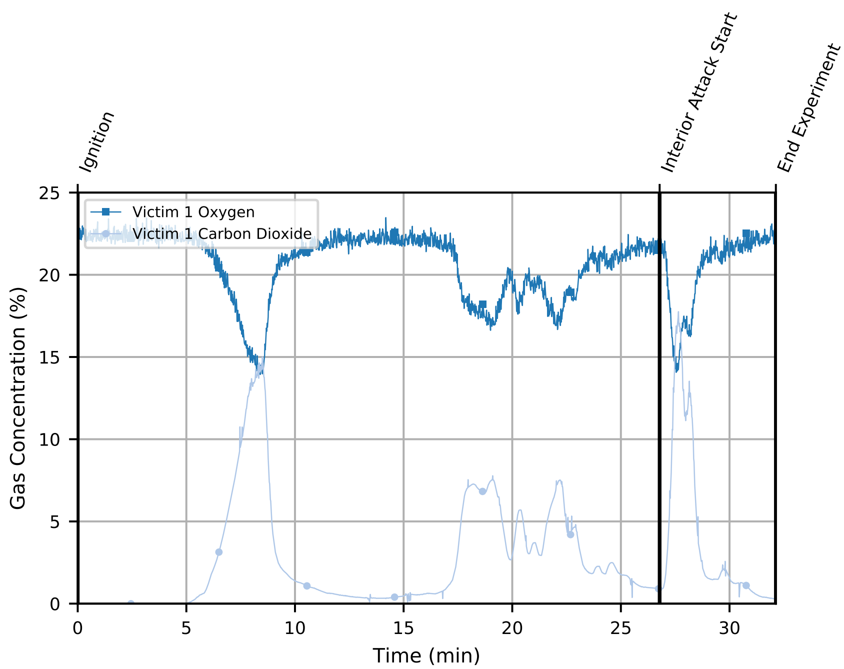


Figure E.20: Experiment 1 - Victim 1 Gas

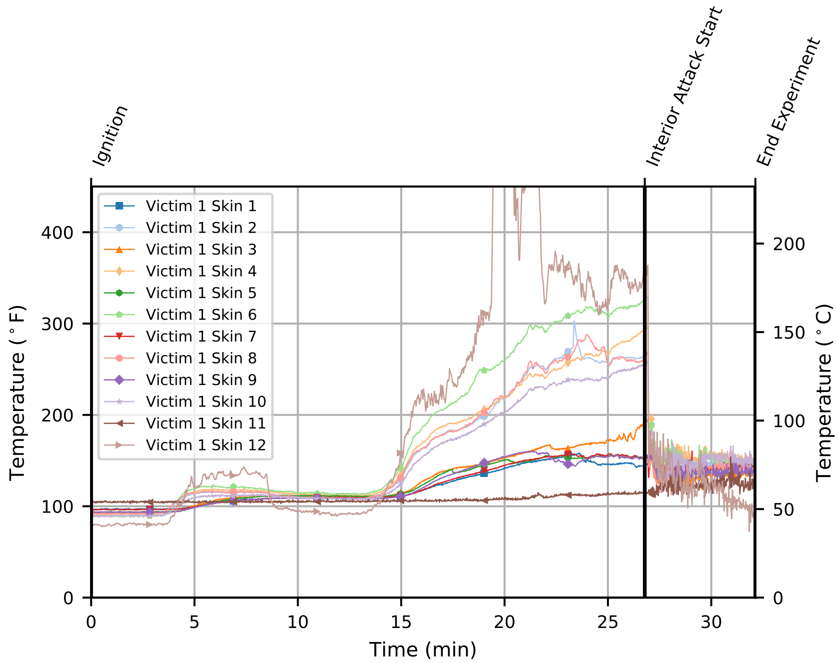


Figure E.21: Experiment 1 - Victim 1 Skin Temps

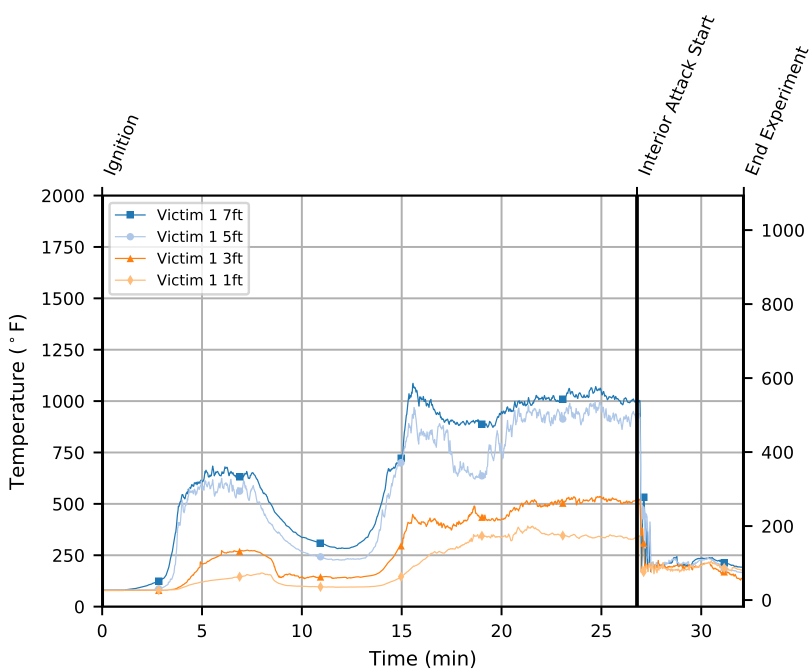


Figure E.22: Experiment 1 - Victim 1 Temps

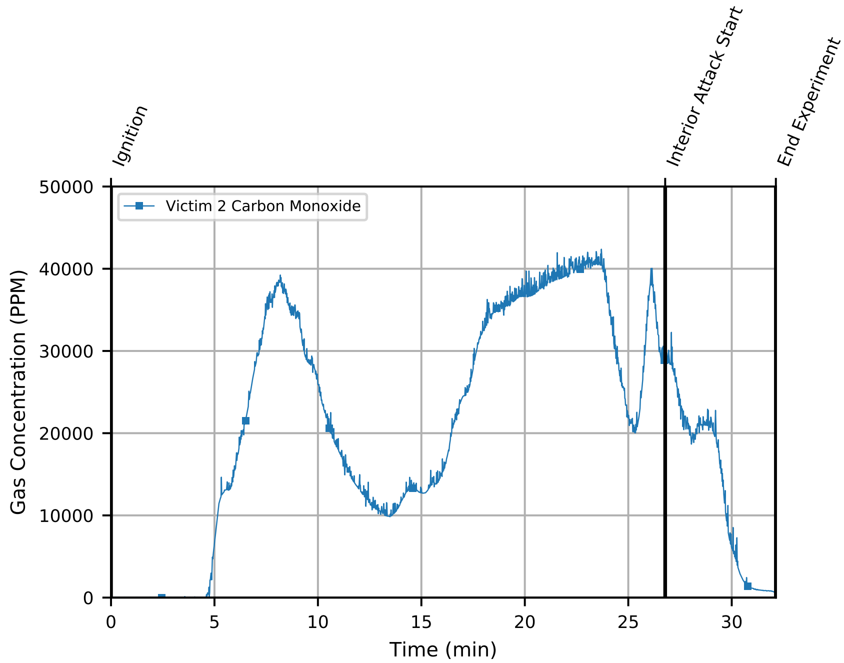


Figure E.23: Experiment 1 - Victim 2 Carbon Monoxide

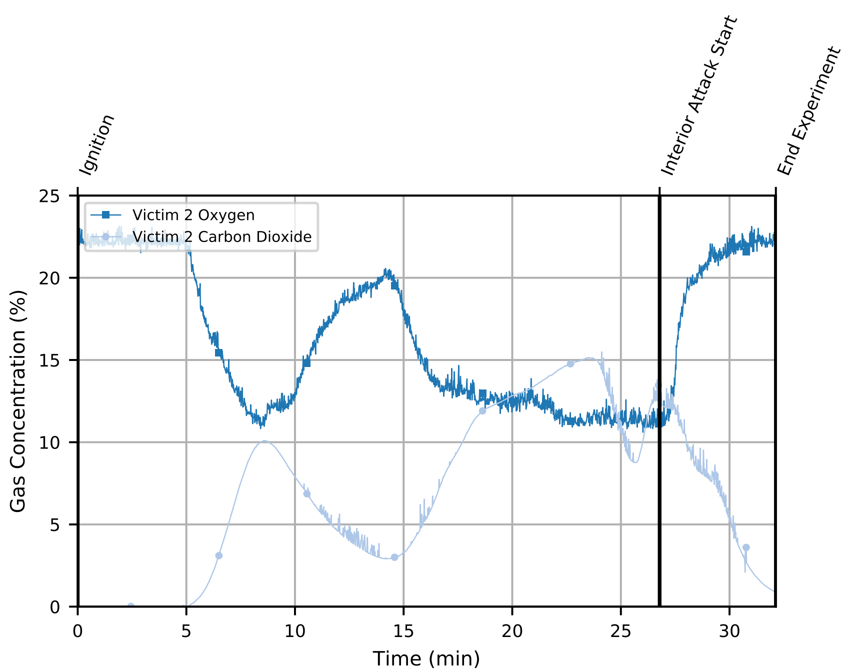


Figure E.24: Experiment 1 - Victim 2 Gas

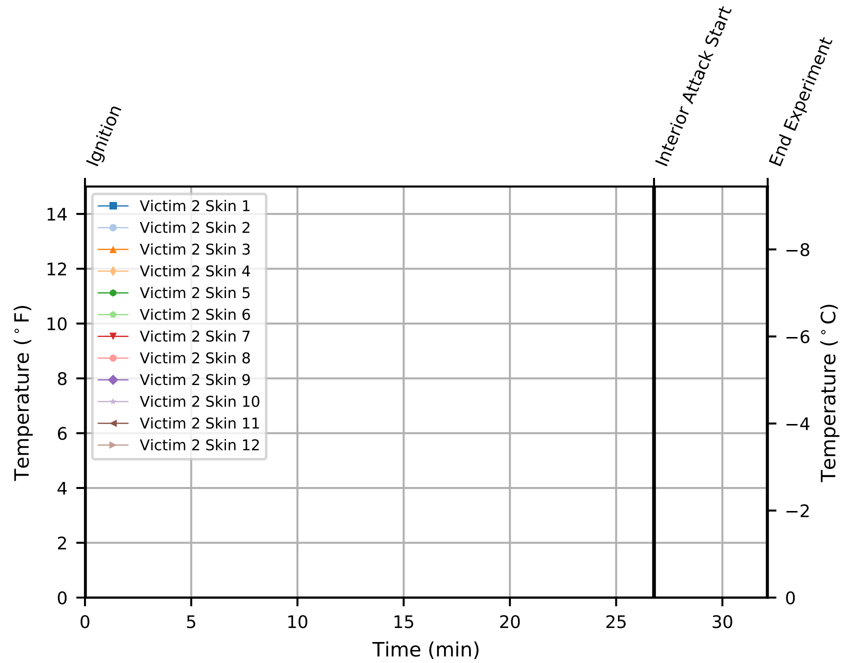


Figure E.25: Experiment 1 - Victim 2 Skin Temps

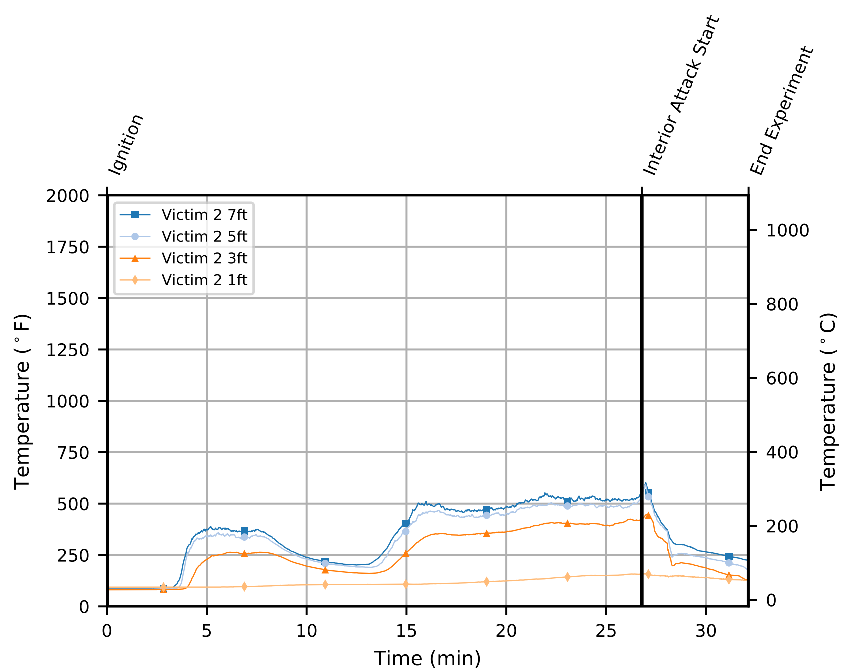


Figure E.26: Experiment 1 - Victim 2 Temps

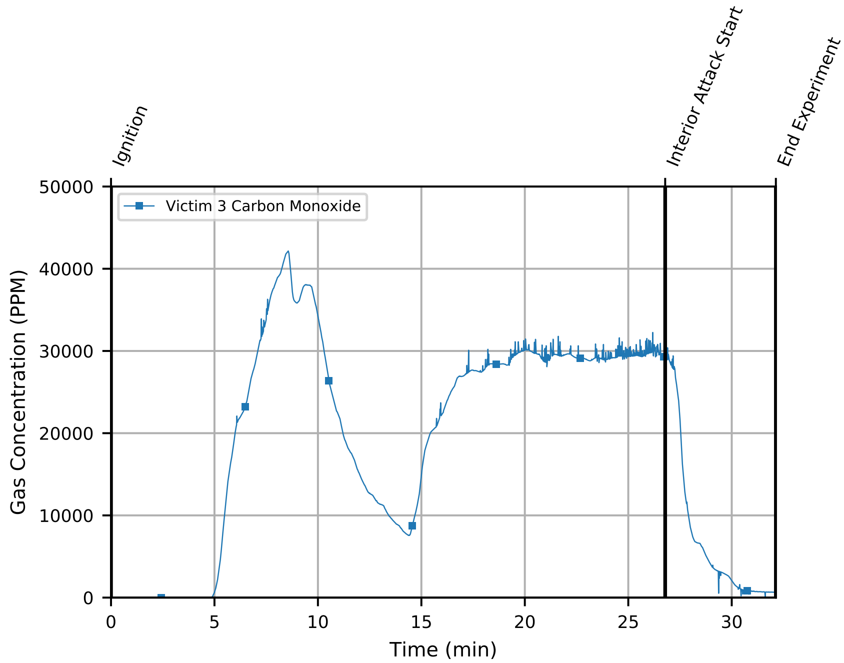


Figure E.27: Experiment 1 - Victim 3 Carbon Monoxide

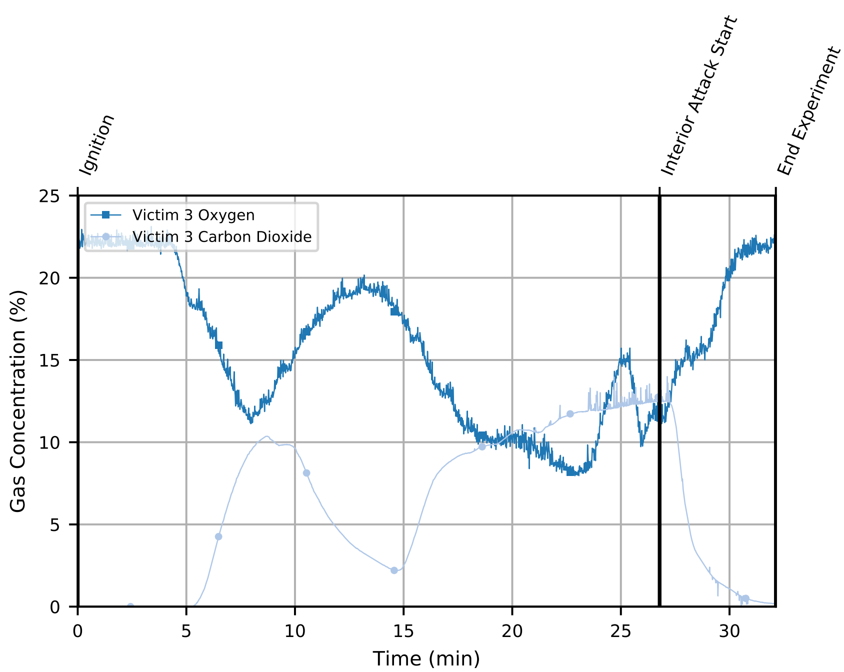


Figure E.28: Experiment 1 - Victim 3 Gas

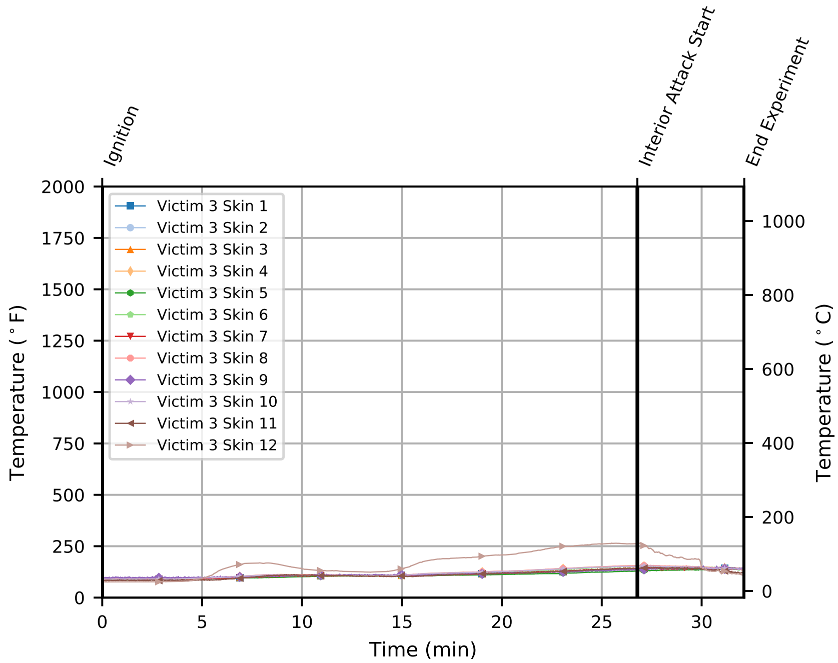


Figure E.29: Experiment 1 - Victim 3 Skin Temps

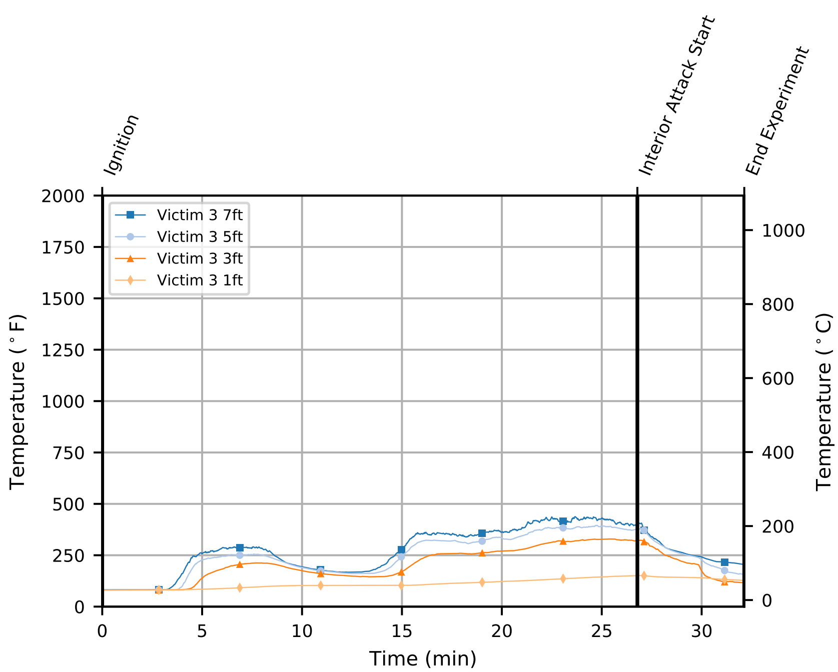


Figure E.30: Experiment 1 - Victim 3 Temps

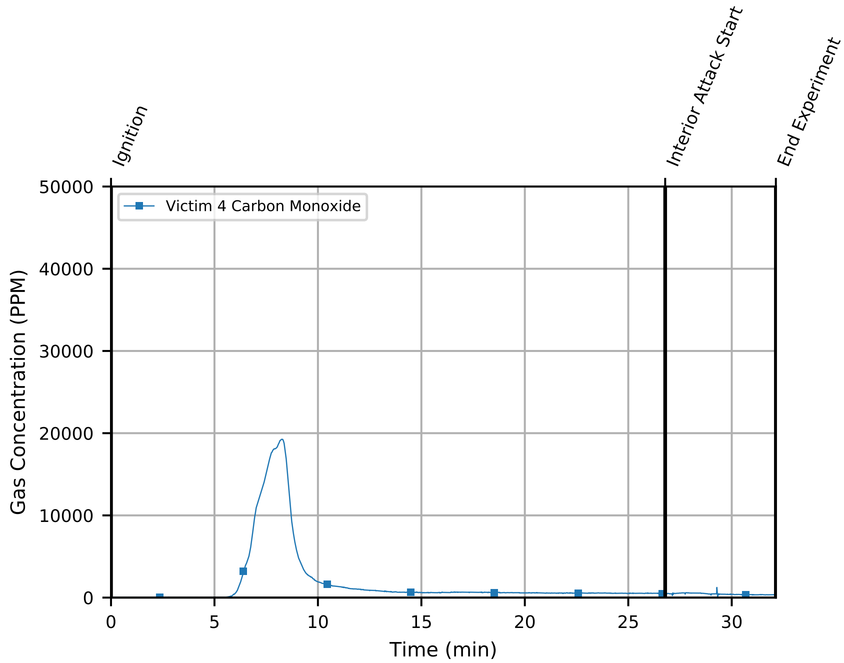


Figure E.31: Experiment 1 - Victim 4 Carbon Monoxide

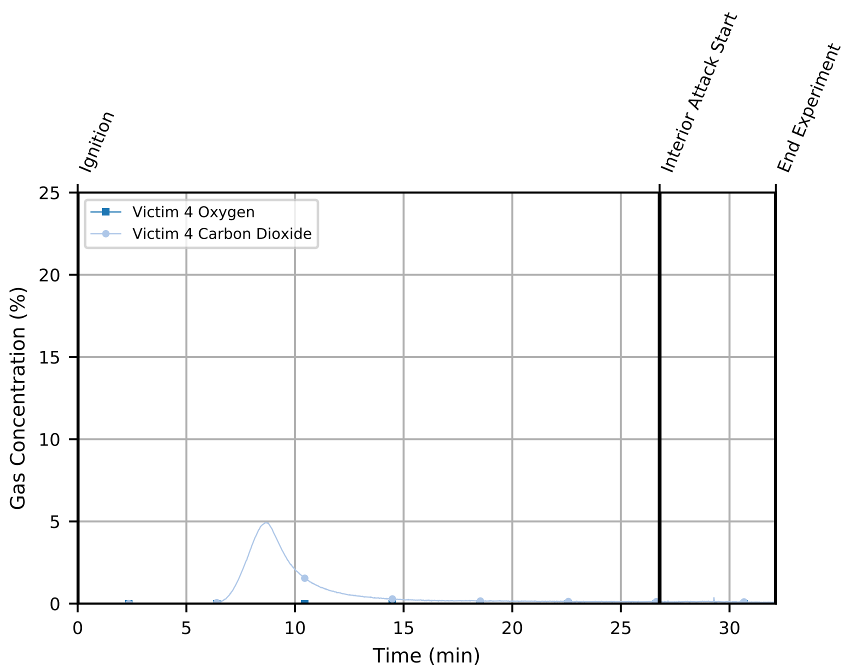


Figure E.32: Experiment 1 - Victim 4 Gas

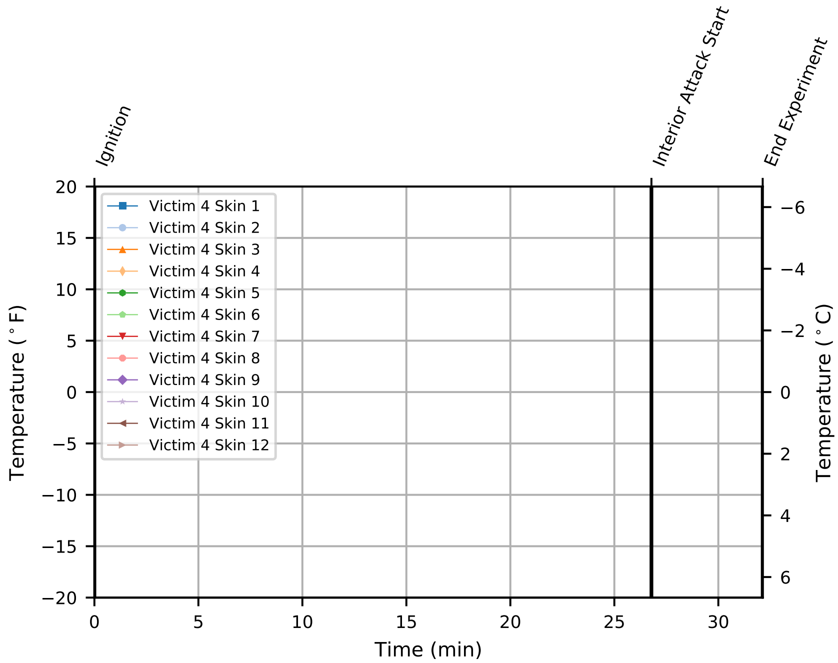


Figure E.33: Experiment 1 - Victim 4 Skin Temps

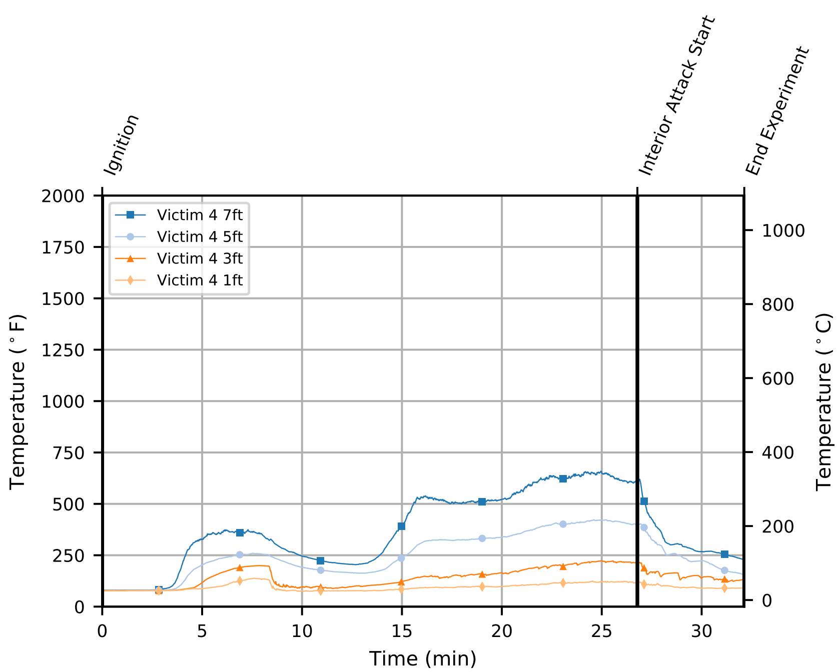


Figure E.34: Experiment 1 - Victim 4 Temps

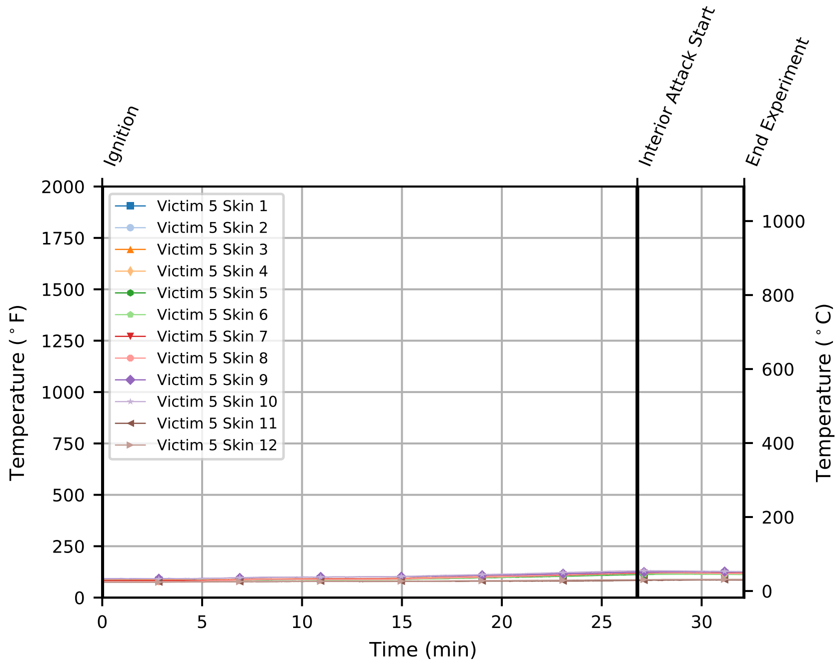


Figure E.35: Experiment 1 - Victim 5 Skin Temps

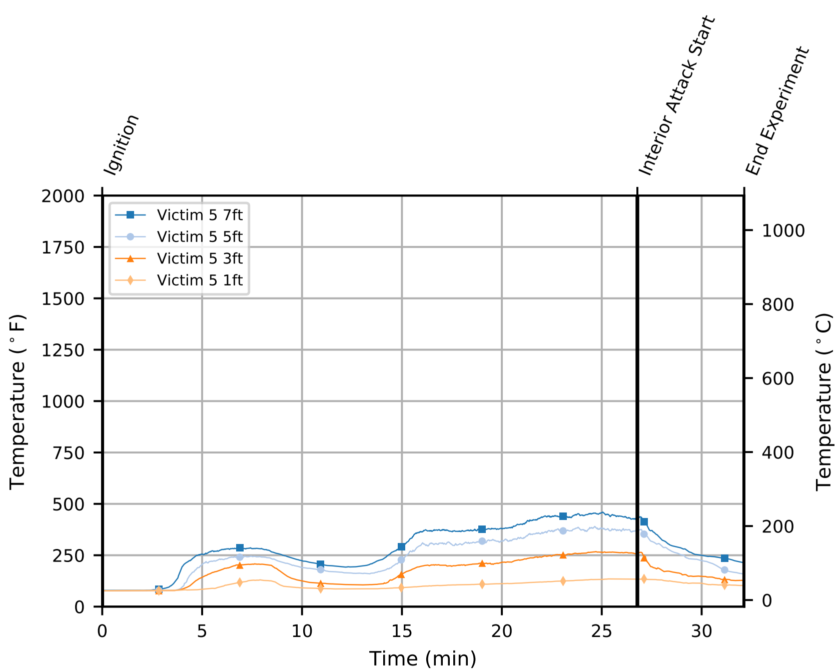


Figure E.36: Experiment 1 - Victim 5 Temps

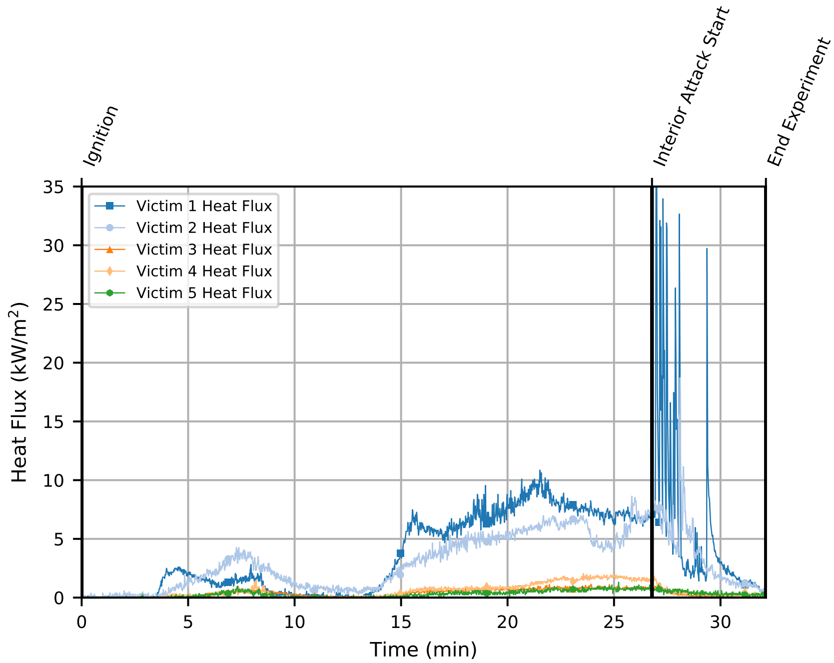


Figure E.37: Experiment 1 - Victim Heat Flux

E.2 Experiment 2 Data

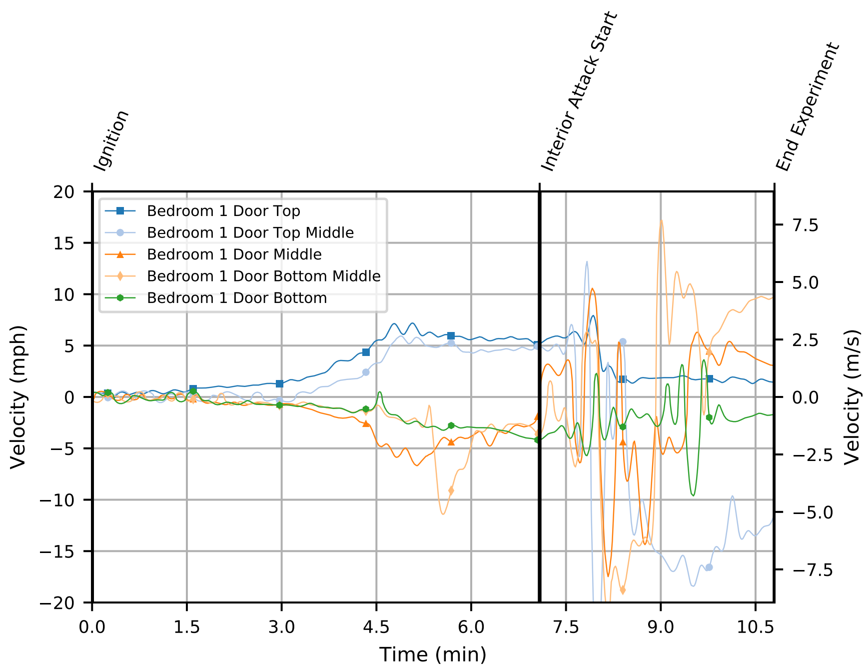


Figure E.38: Experiment 2 - Bedroom 1 Door

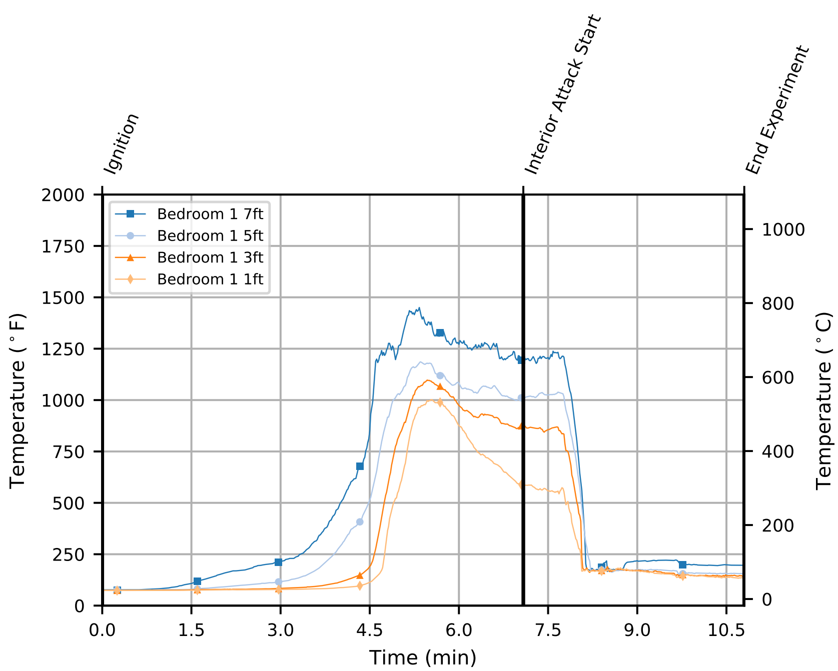


Figure E.39: Experiment 2 - Bedroom 1 Temps

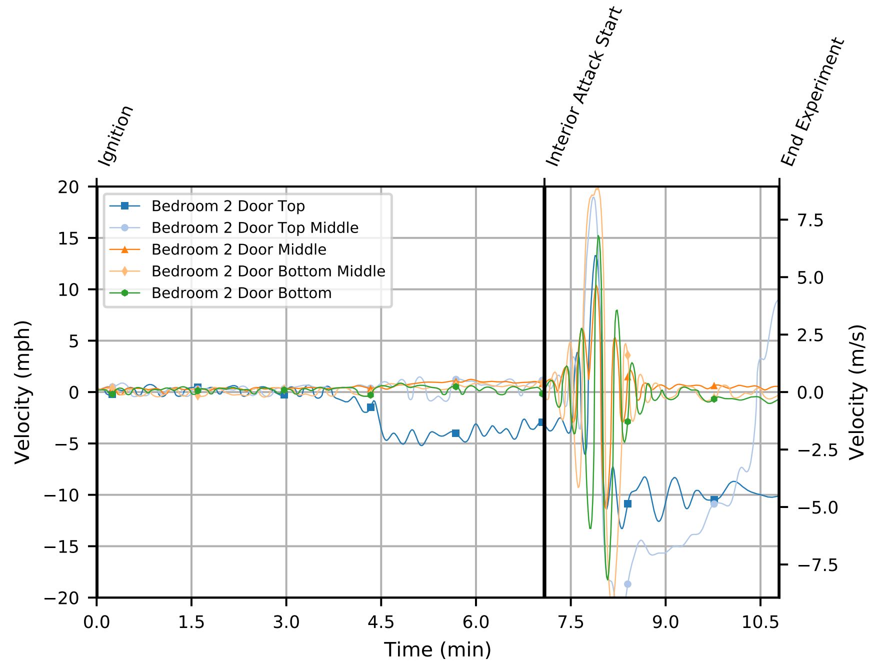


Figure E.40: Experiment 2 - Bedroom 2 Door

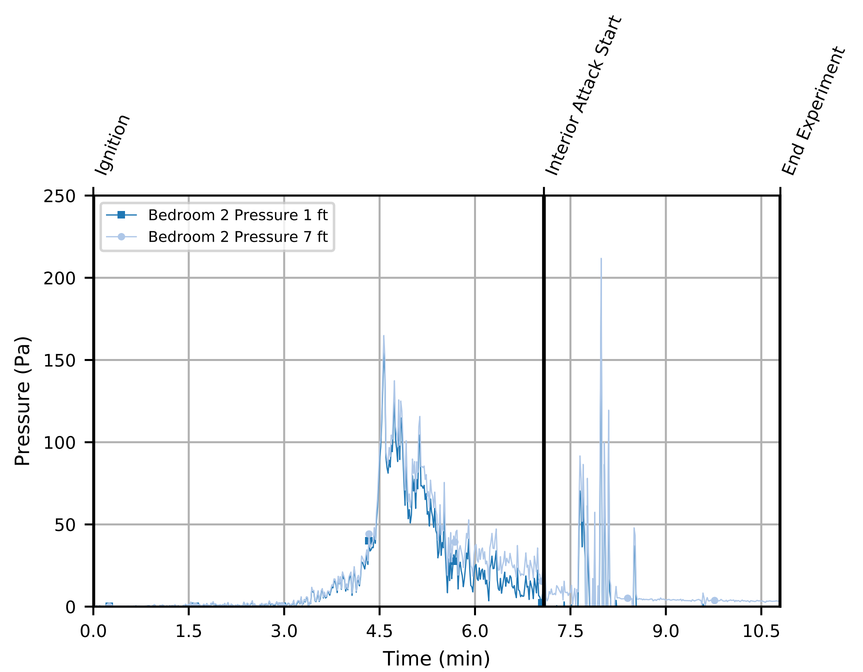


Figure E.41: Experiment 2 - Bedroom 2 Pressure

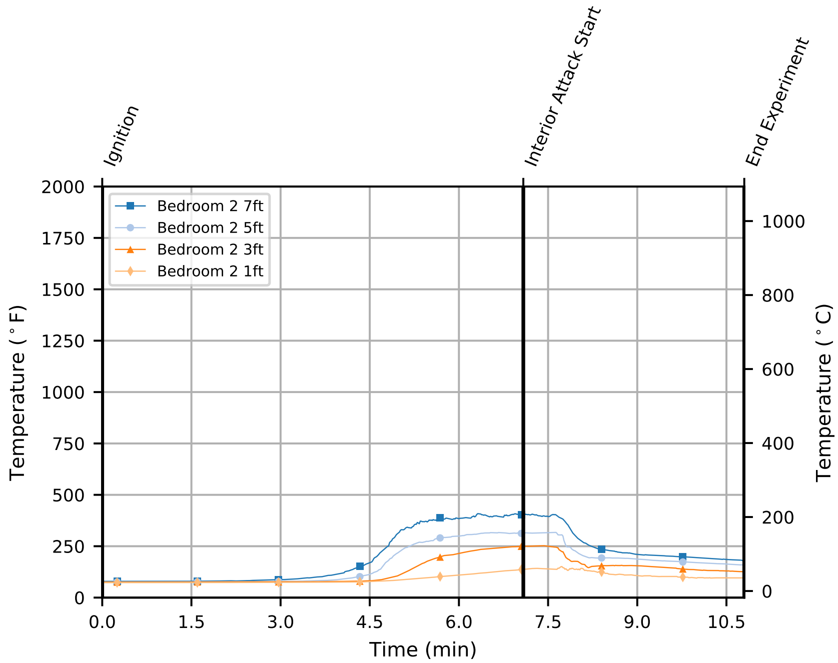


Figure E.42: Experiment 2 - Bedroom 2 Temps

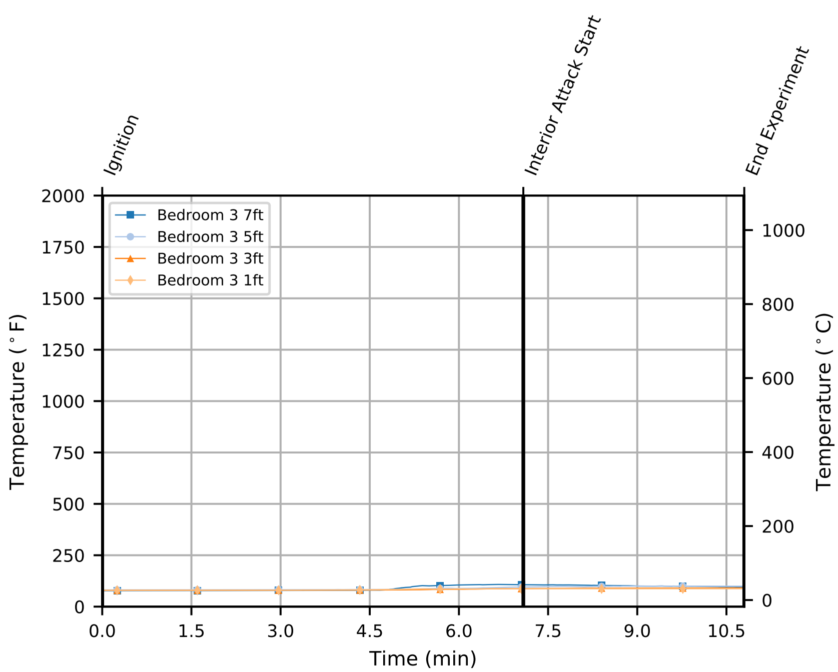


Figure E.43: Experiment 2 - Bedroom 3 Temps

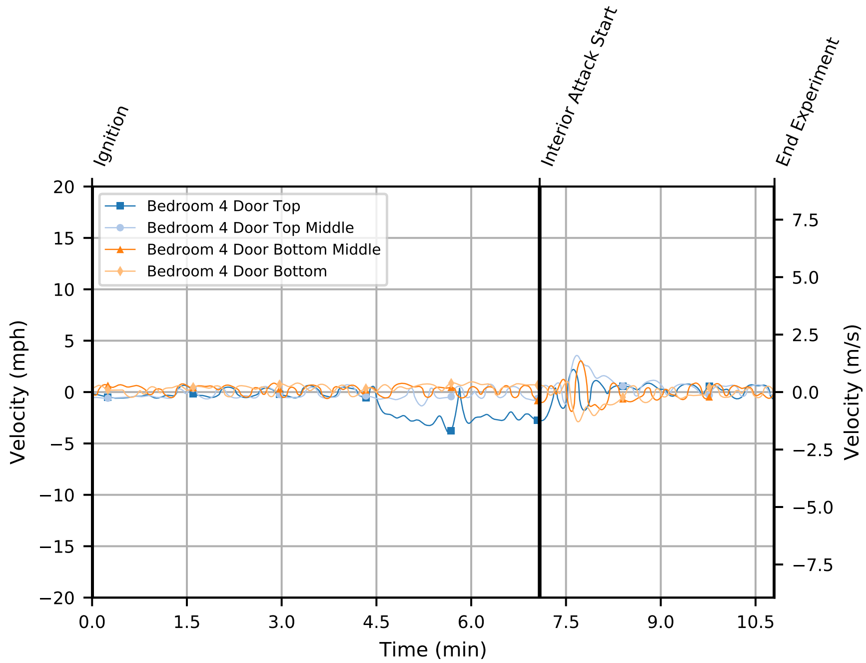


Figure E.44: Experiment 2 - Bedroom 4 Door

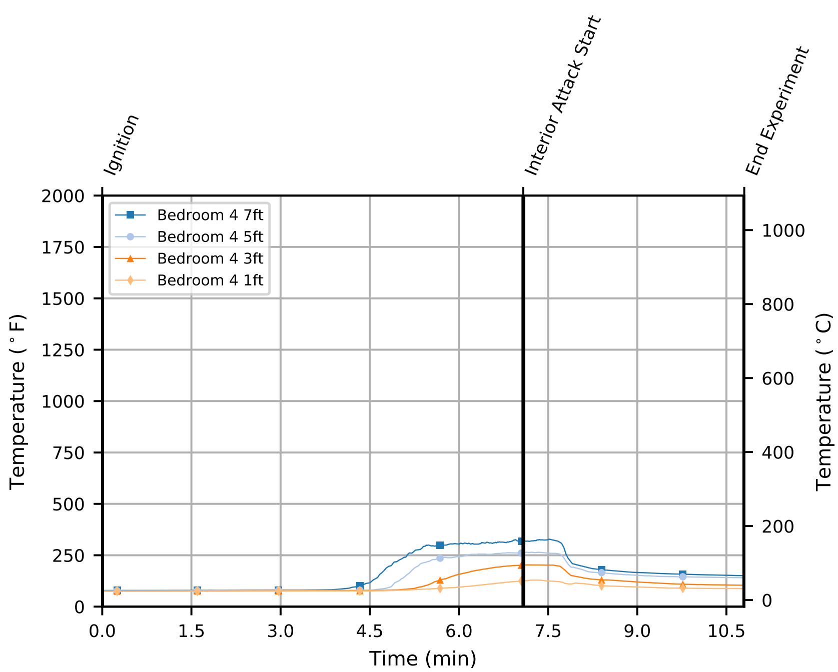


Figure E.45: Experiment 2 - Bedroom 4 Temps

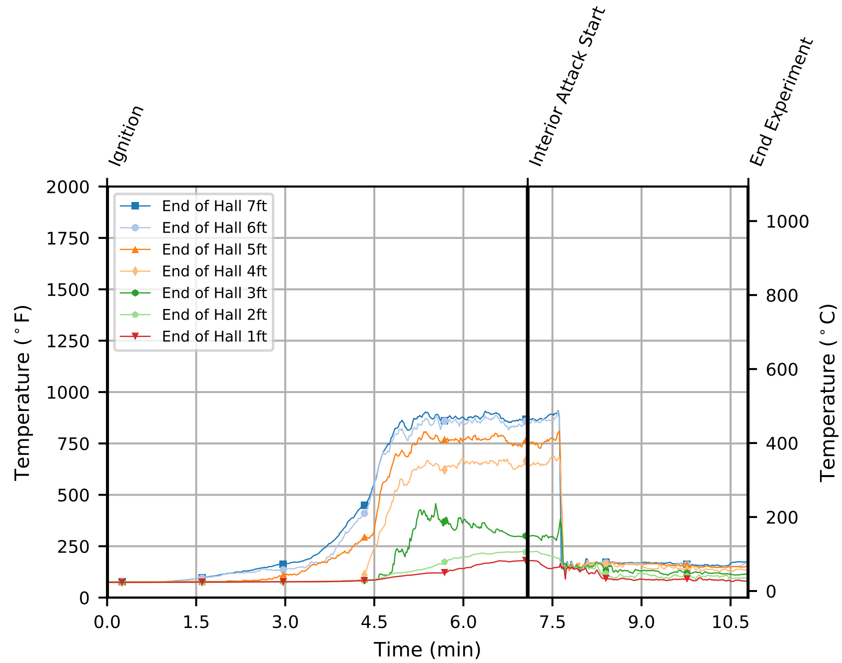


Figure E.46: Experiment 2 - End Hall Temps

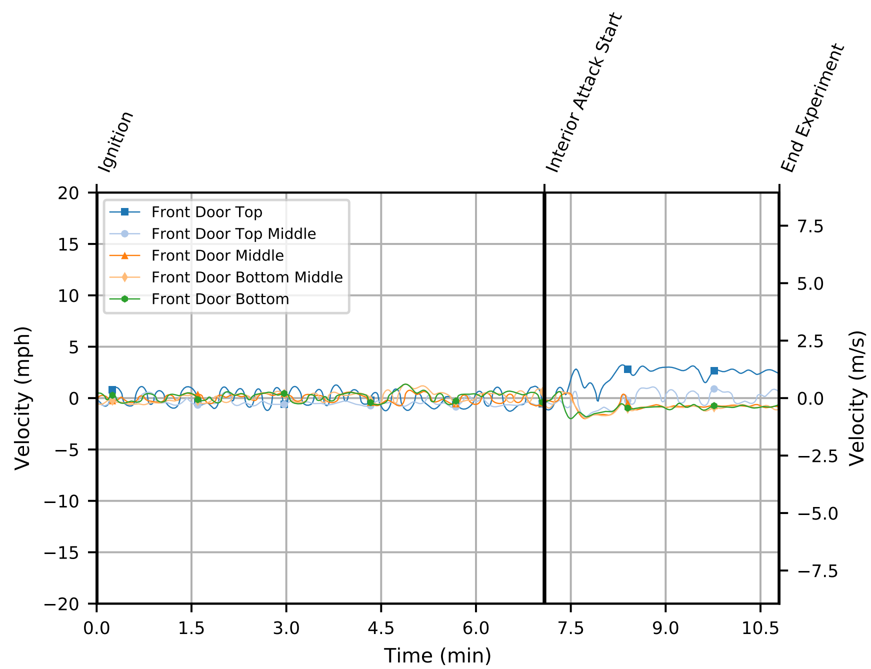


Figure E.47: Experiment 2 - Front Door Flow

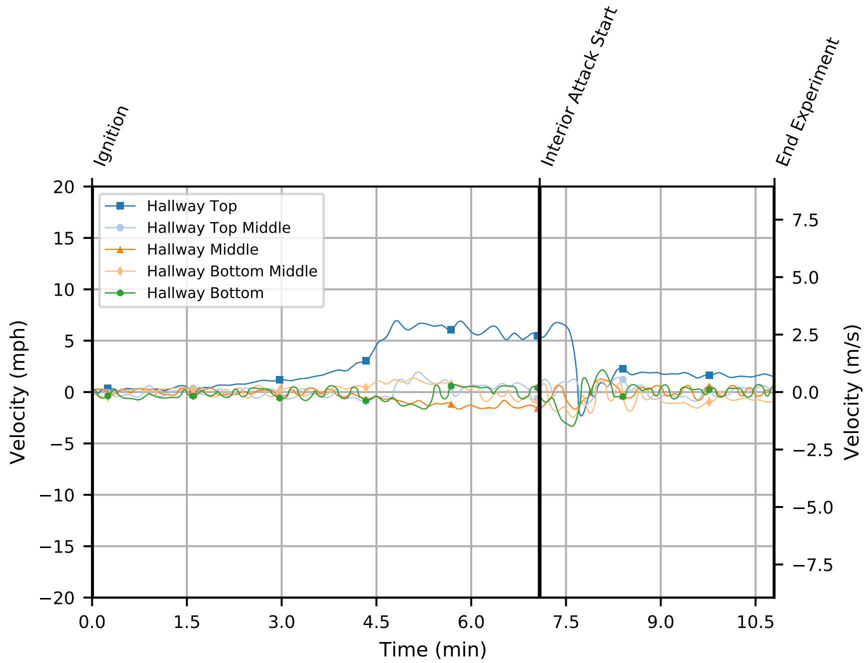


Figure E.48: Experiment 2 - Hallway Flow

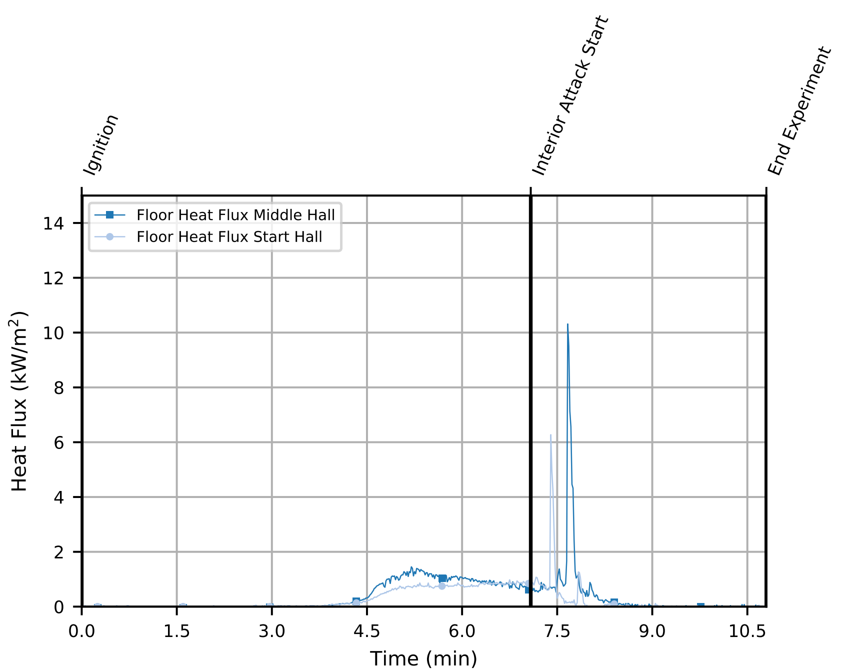


Figure E.49: Experiment 2 - Heat Flux Floor

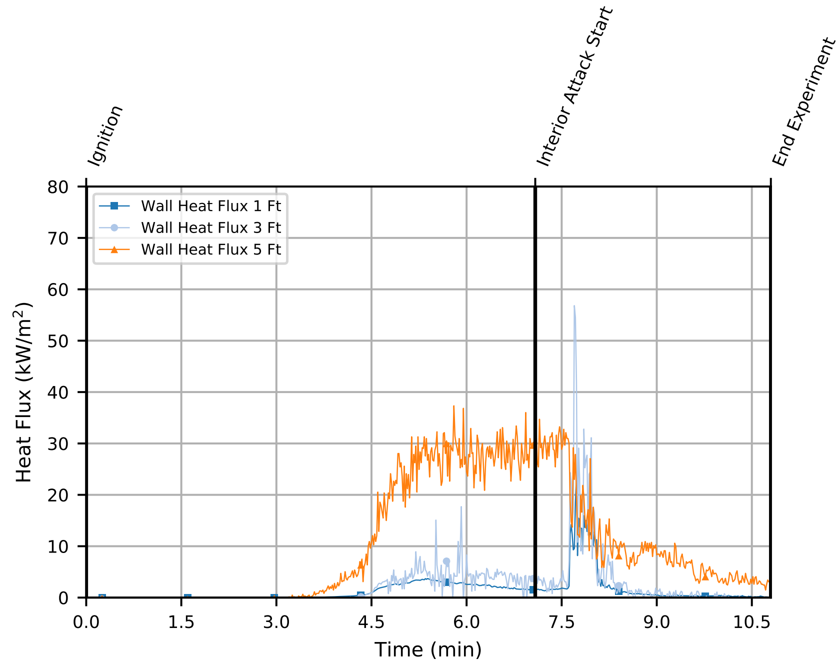


Figure E.50: Experiment 2 - Heat Flux Wall

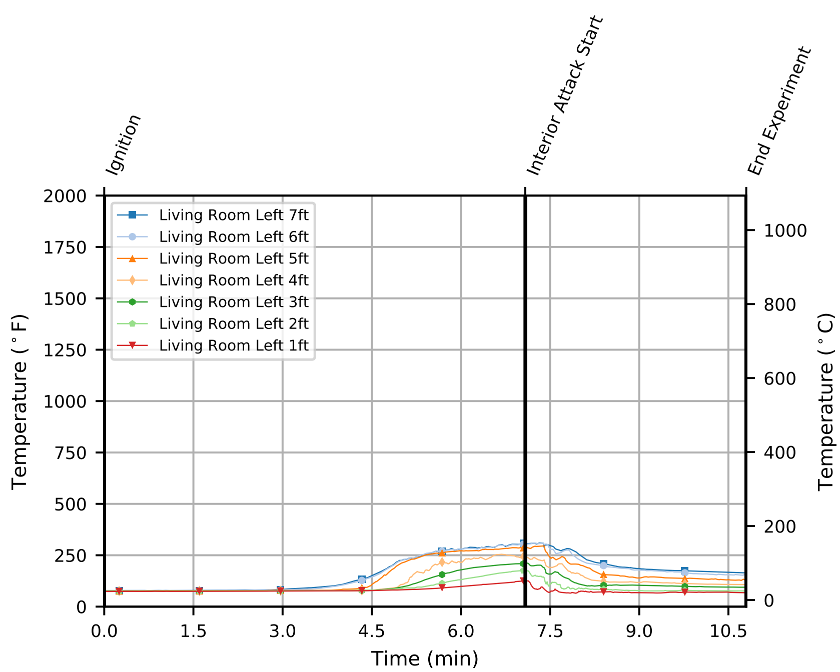


Figure E.51: Experiment 2 - Living Room Left Temps

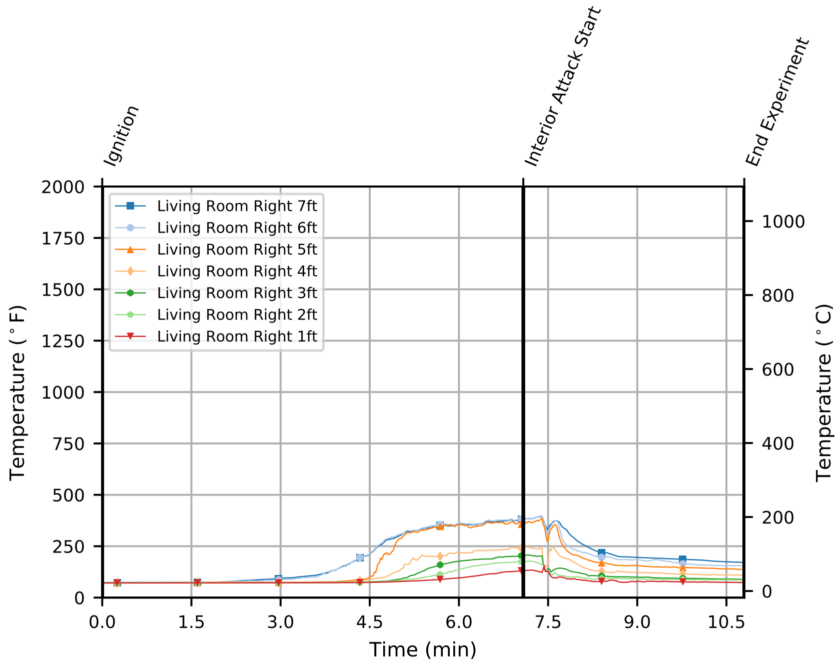


Figure E.52: Experiment 2 - Living Room Right Temps

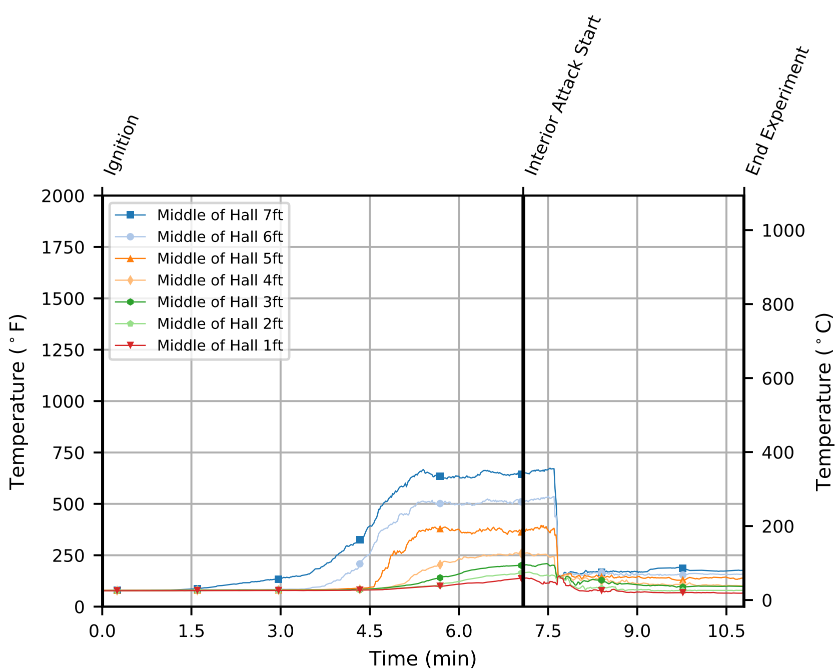


Figure E.53: Experiment 2 - Middle Hall Temps

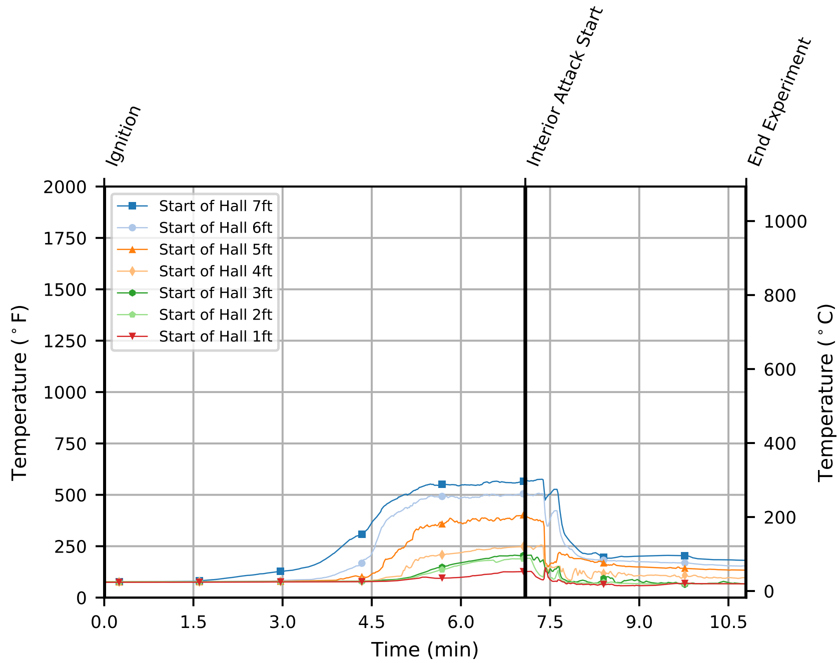


Figure E.54: Experiment 2 - Start Hall Temps

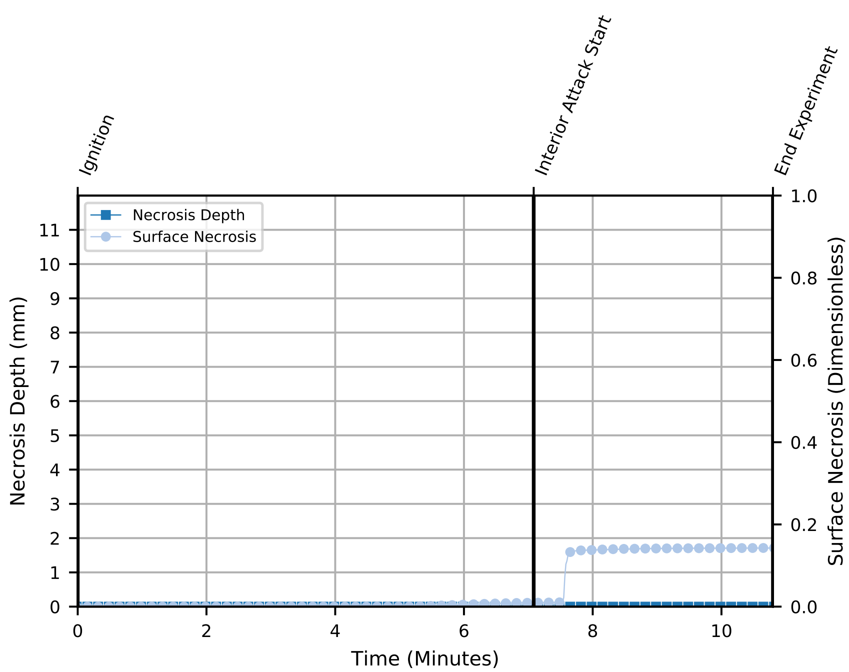


Figure E.55: Experiment 2 - Vic 1 Necrosis Depth

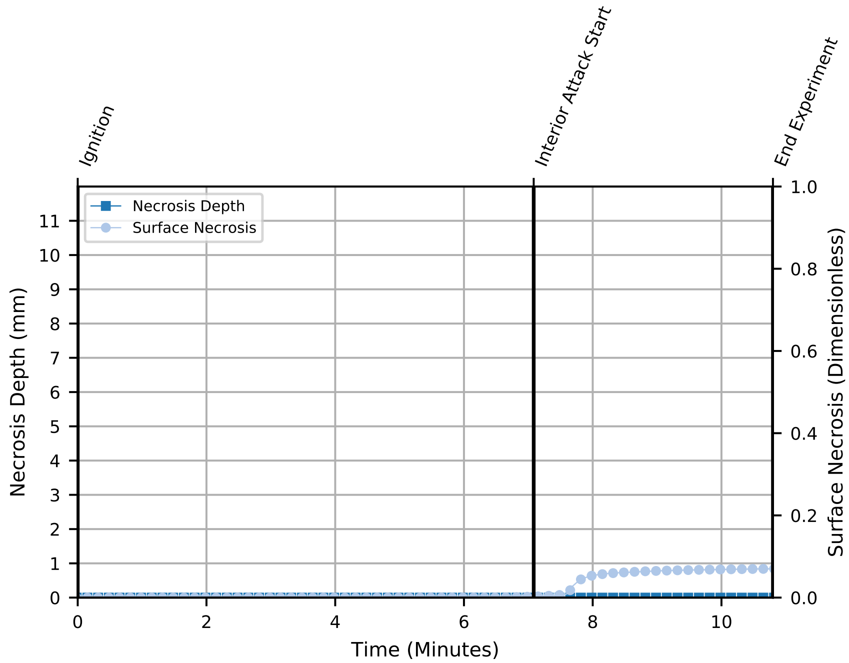


Figure E.56: Experiment 2 - Vic 3 Necrosis Depth

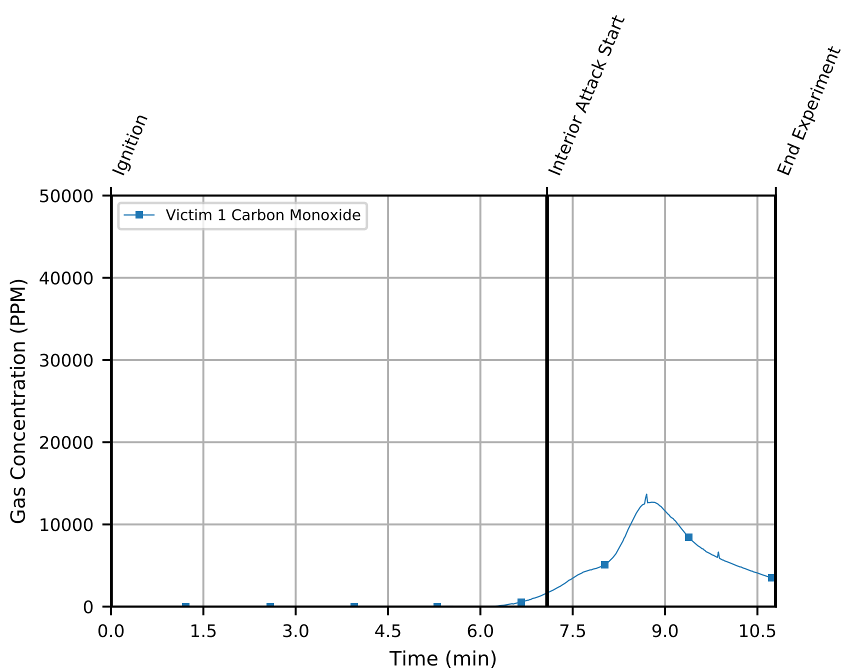


Figure E.57: Experiment 2 - Victim 1 Carbon Monoxide

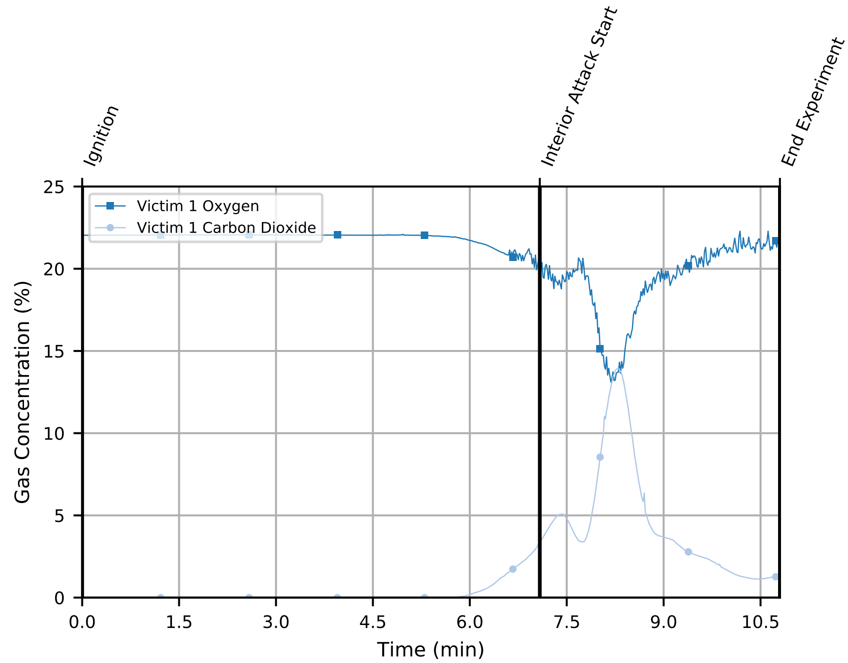


Figure E.58: Experiment 2 - Victim 1 Gas

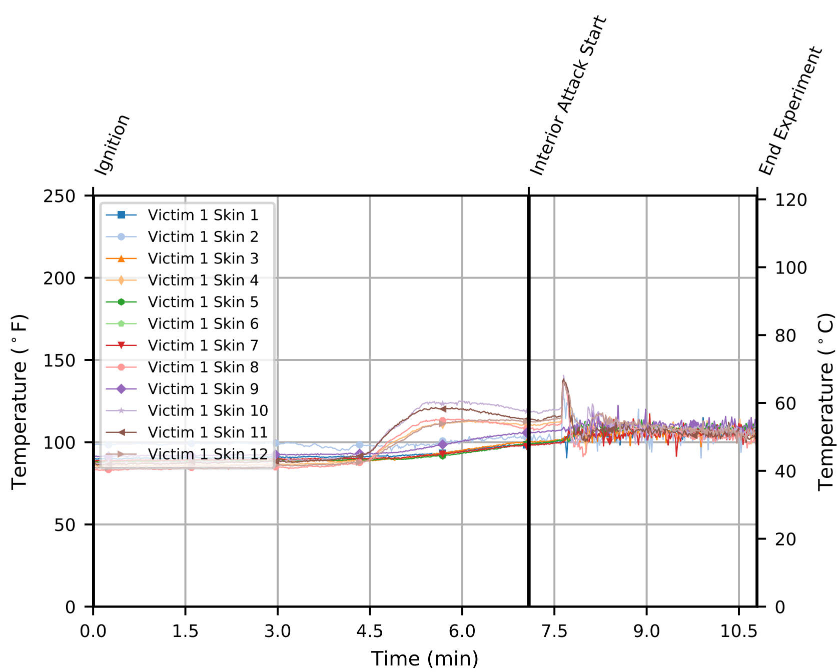


Figure E.59: Experiment 2 - Victim 1 Skin Temps

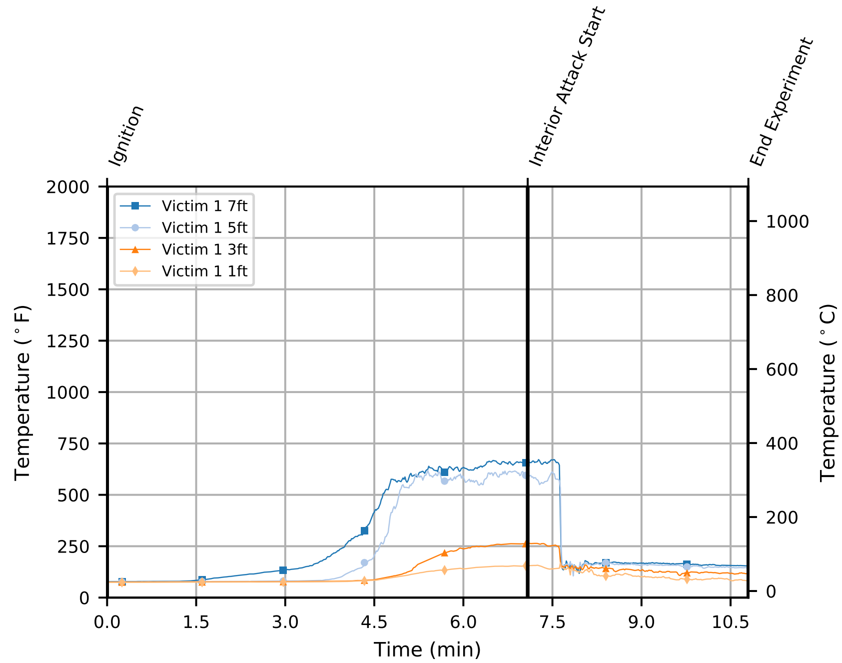


Figure E.60: Experiment 2 - Victim 1 Temps

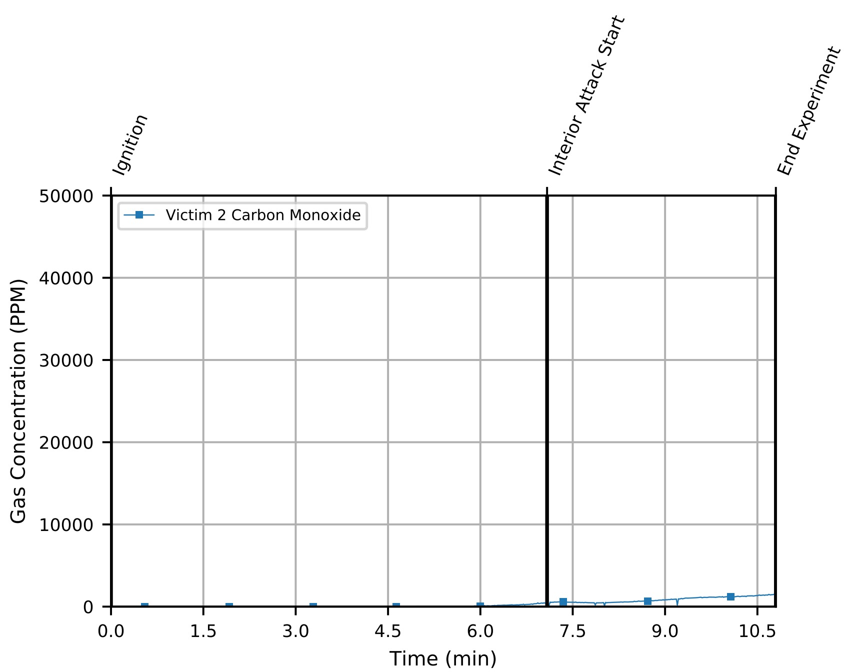


Figure E.61: Experiment 2 - Victim 2 Carbon Monoxide

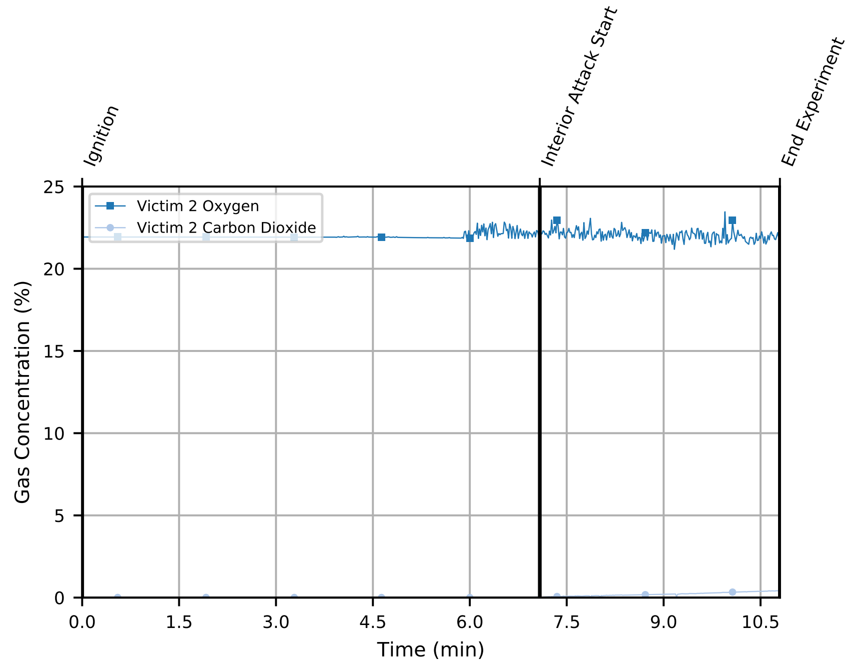


Figure E.62: Experiment 2 - Victim 2 Gas

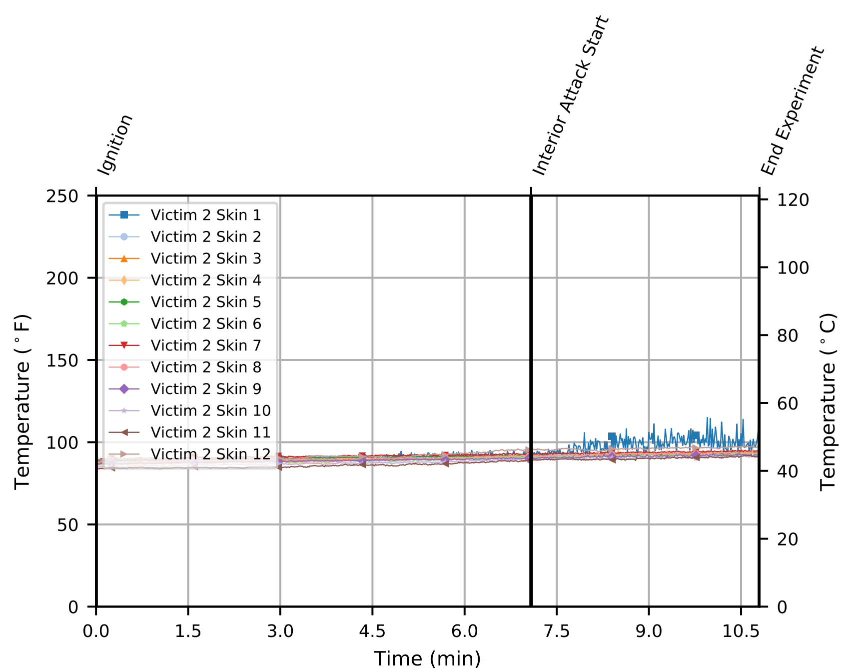


Figure E.63: Experiment 2 - Victim 2 Skin Temps

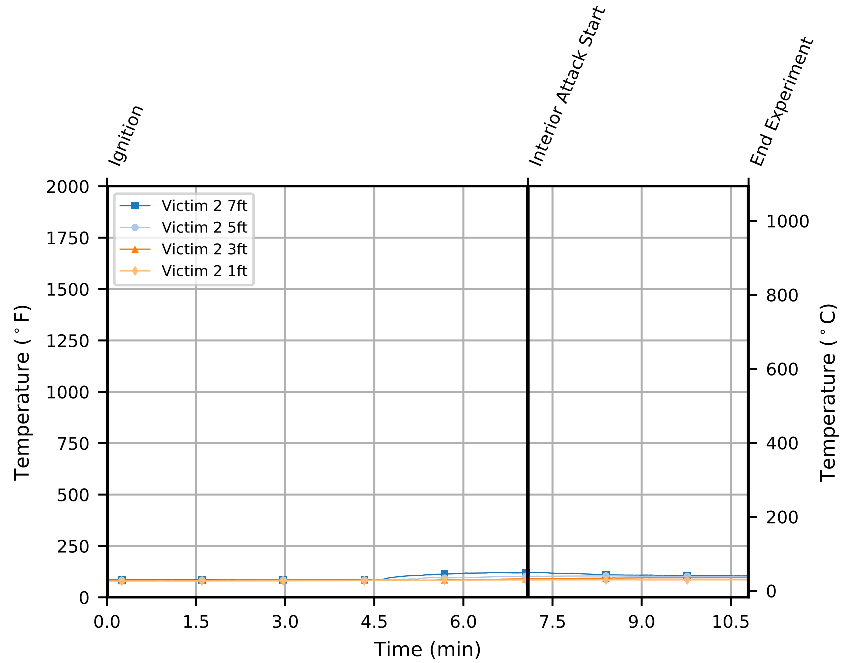


Figure E.64: Experiment 2 - Victim 2 Temps

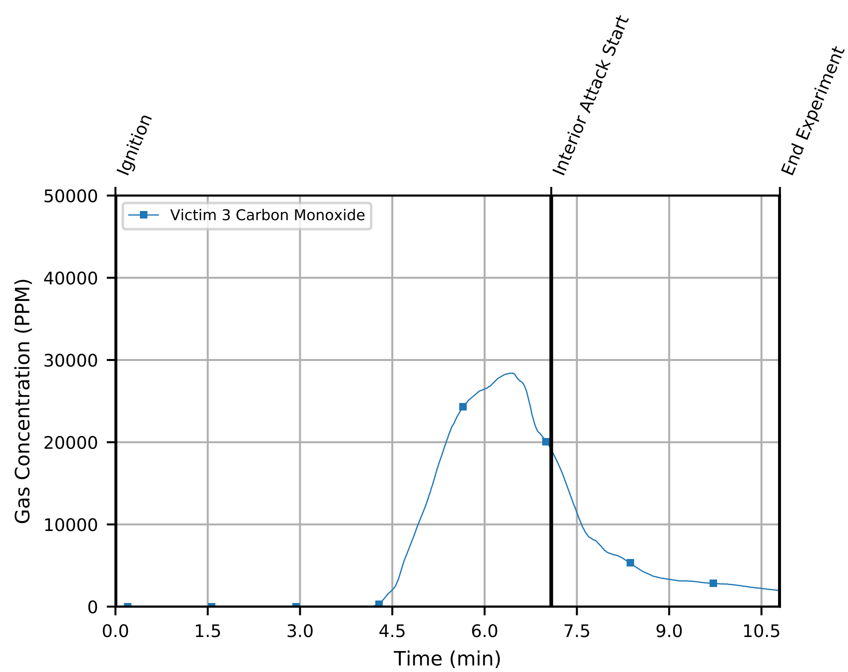


Figure E.65: Experiment 2 - Victim 3 Carbon Monoxide

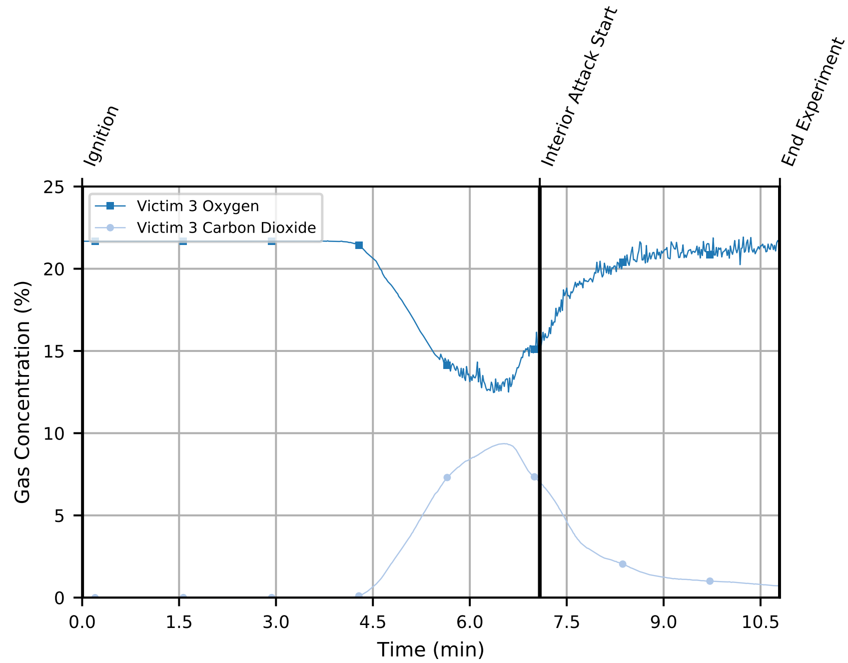


Figure E.66: Experiment 2 - Victim 3 Gas

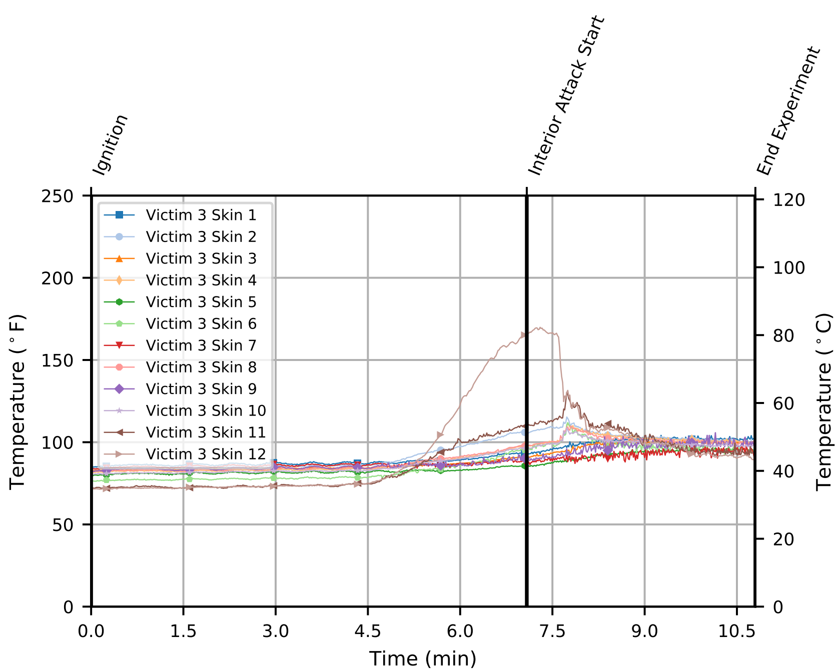


Figure E.67: Experiment 2 - Victim 3 Skin Temps

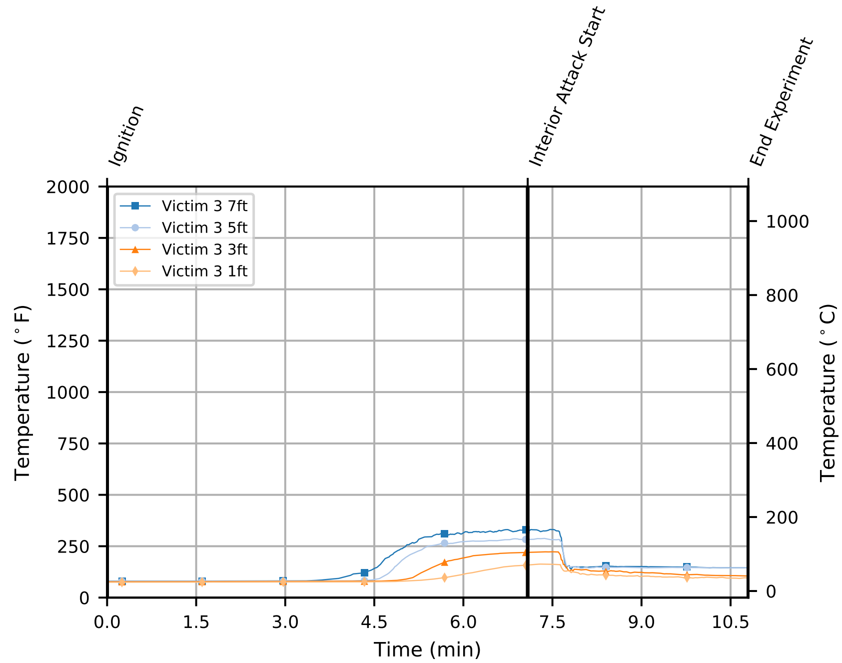


Figure E.68: Experiment 2 - Victim 3 Temps

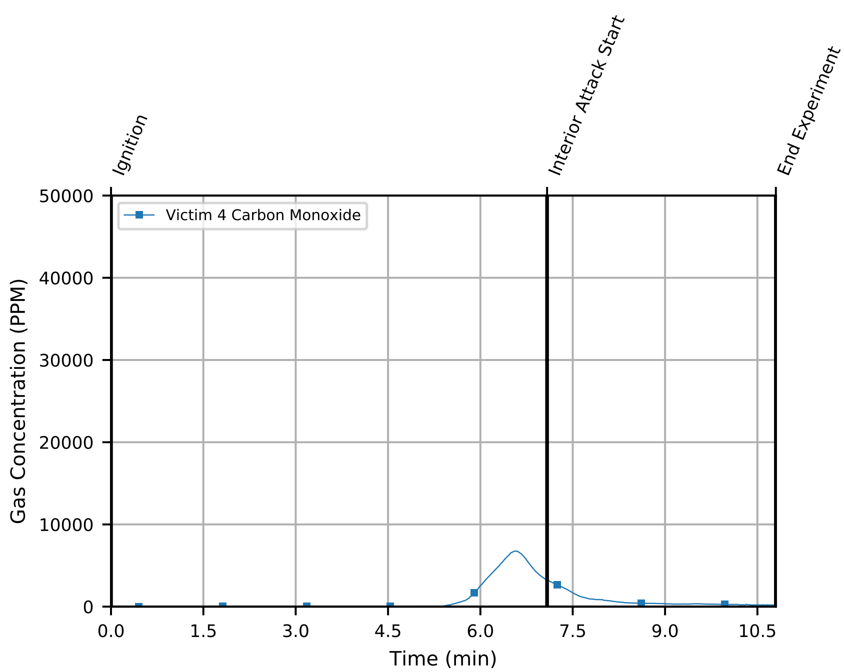


Figure E.69: Experiment 2 - Victim 4 Carbon Monoxide

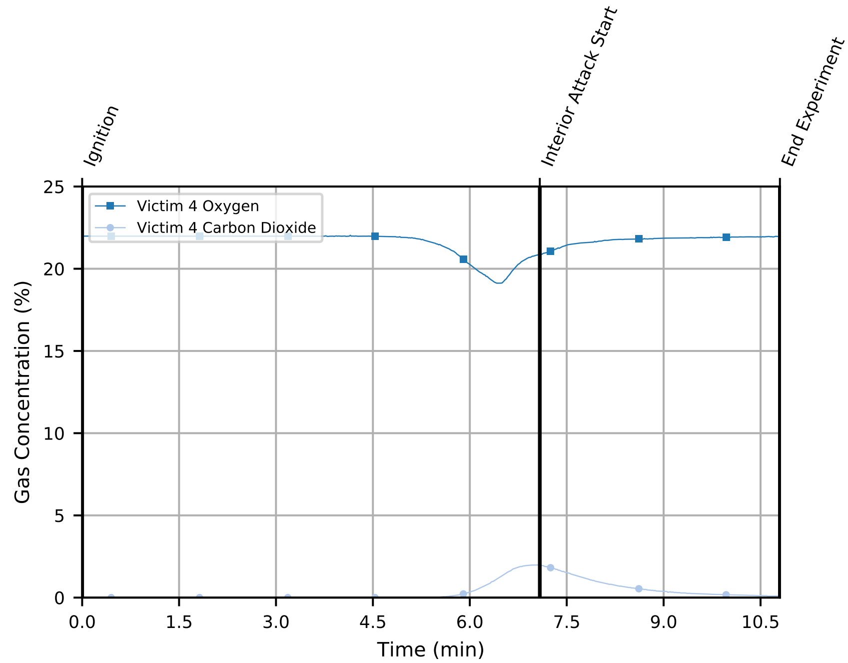


Figure E.70: Experiment 2 - Victim 4 Gas

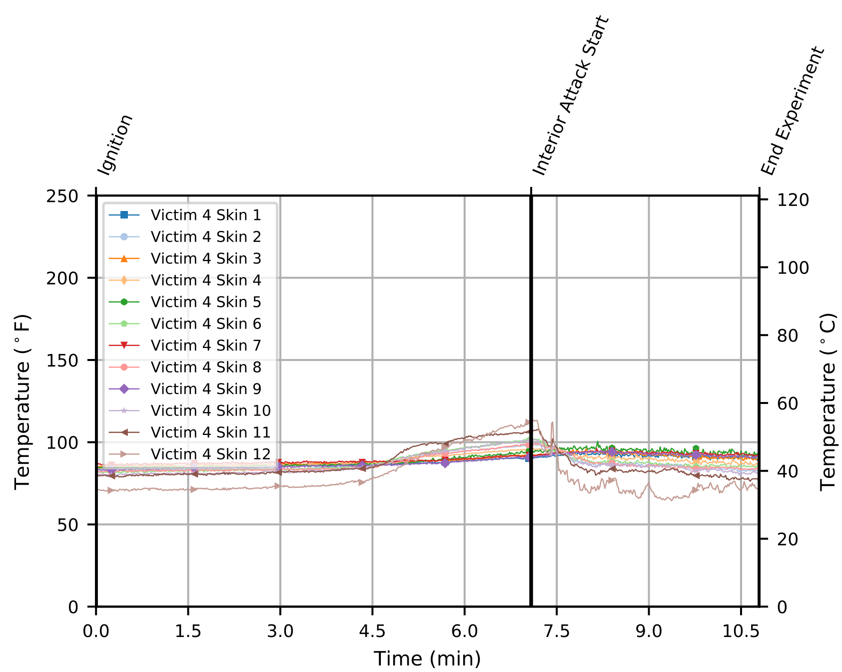


Figure E.71: Experiment 2 - Victim 4 Skin Temps

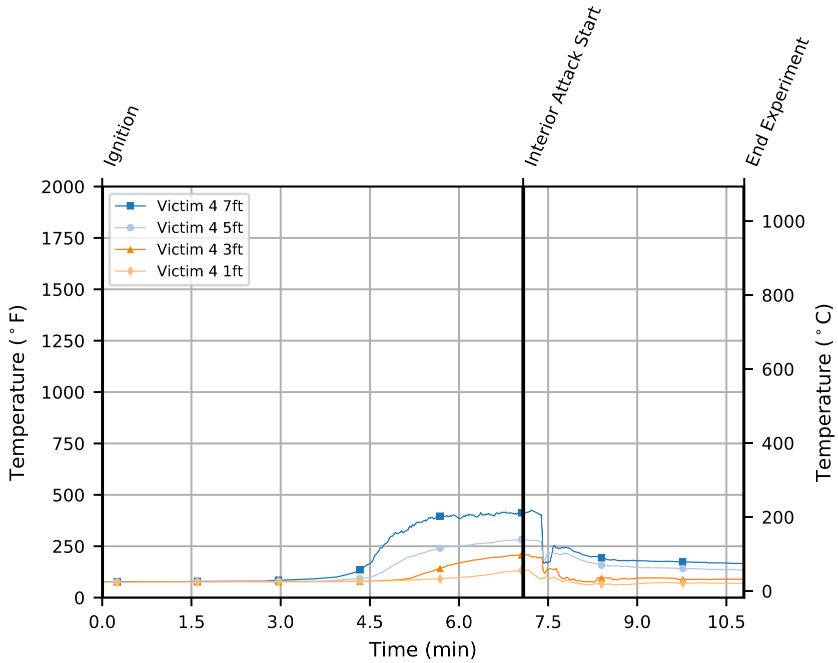


Figure E.72: Experiment 2 - Victim 4 Temps

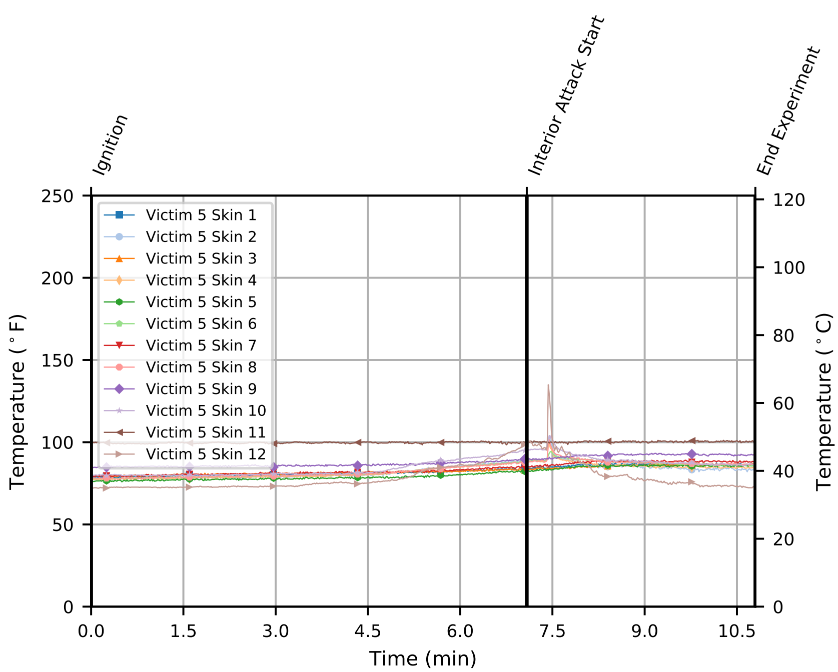


Figure E.73: Experiment 2 - Victim 5 Skin Temps

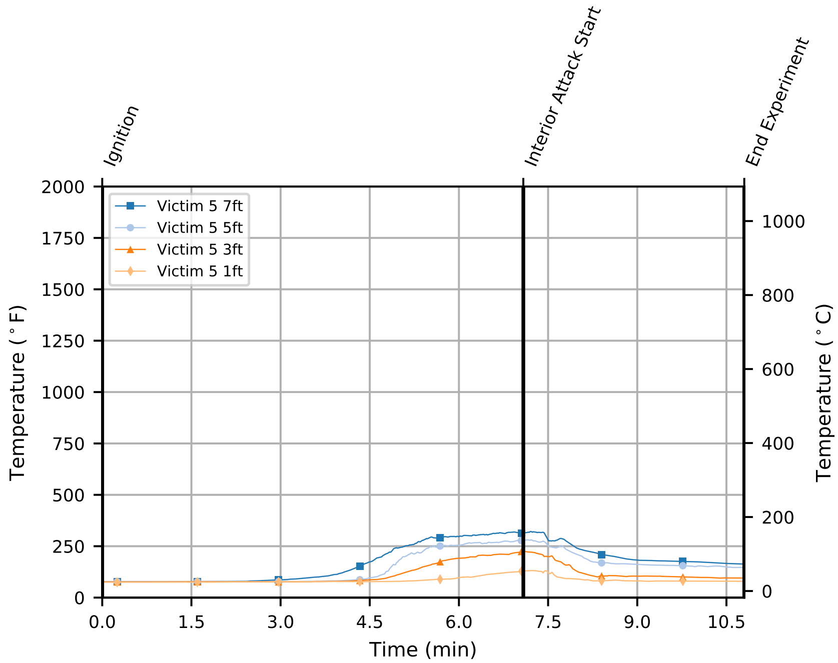


Figure E.74: Experiment 2 - Victim 5 Temps

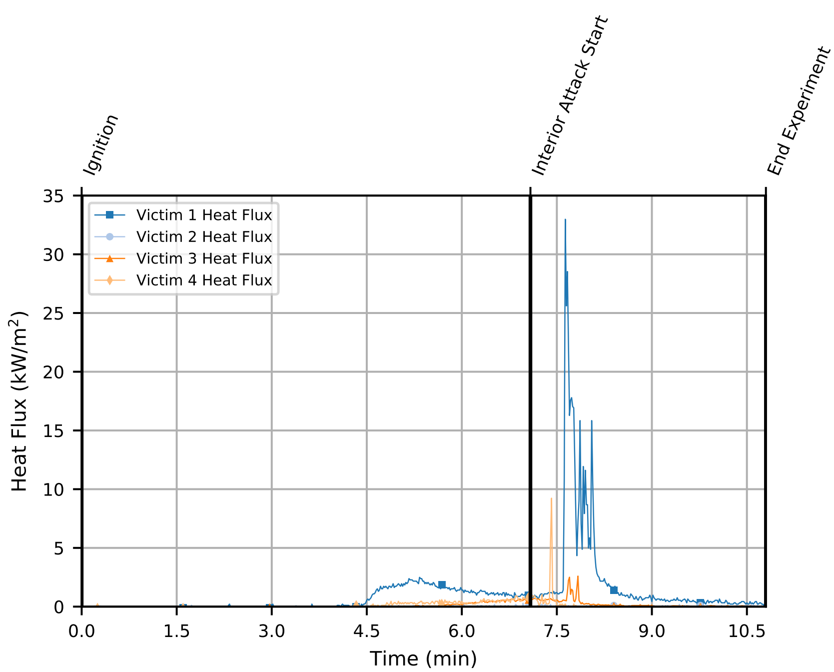


Figure E.75: Experiment 2 - Victim Heat Flux

E.3 Experiment 3 Data

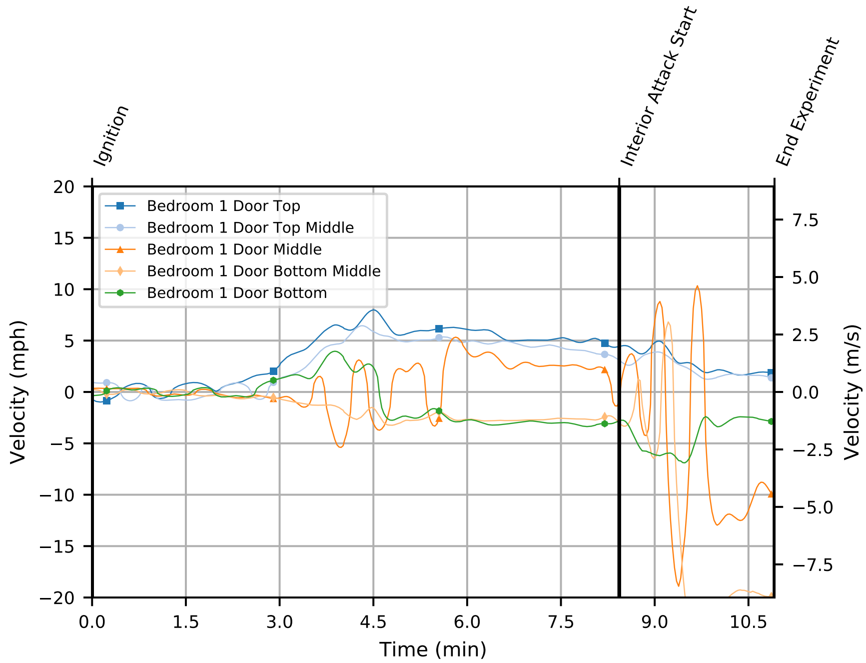


Figure E.76: Experiment 3 - Bedroom 1 Door

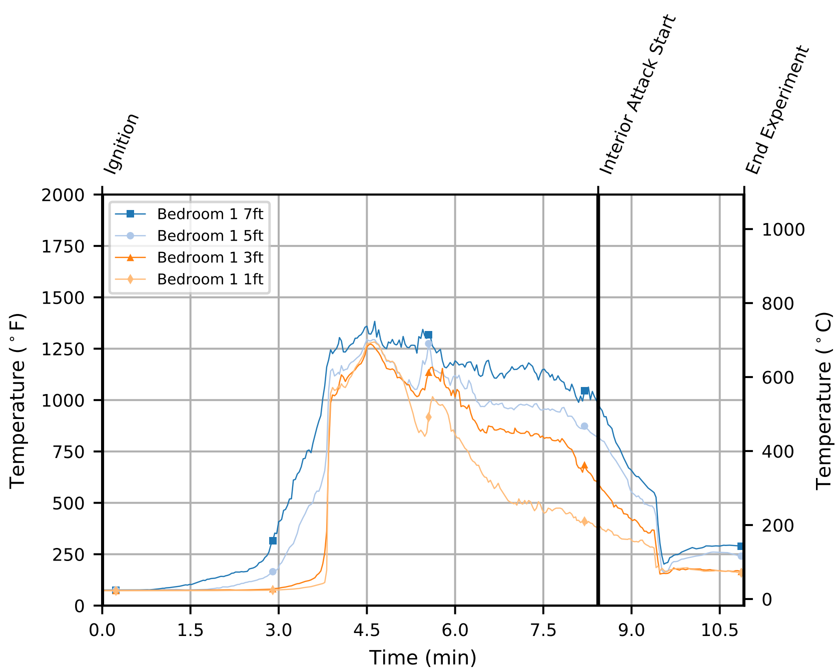


Figure E.77: Experiment 3 - Bedroom 1 Temps

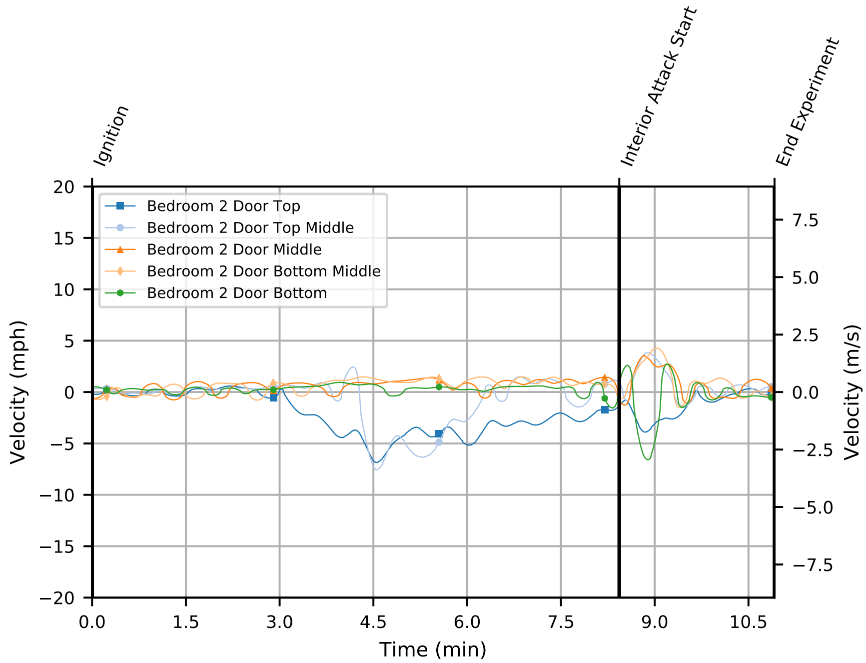


Figure E.78: Experiment 3 - Bedroom 2 Door

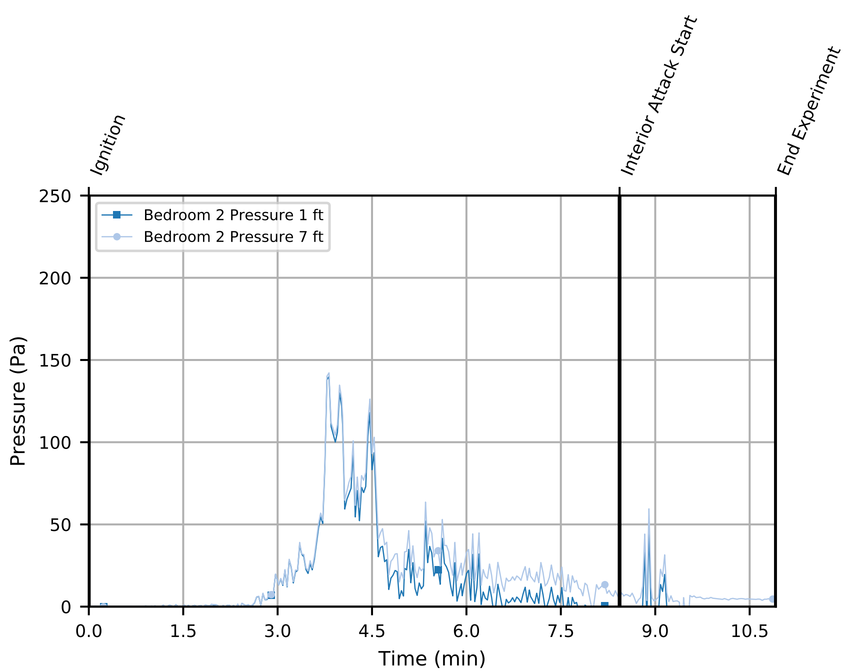


Figure E.79: Experiment 3 - Bedroom 2 Pressure

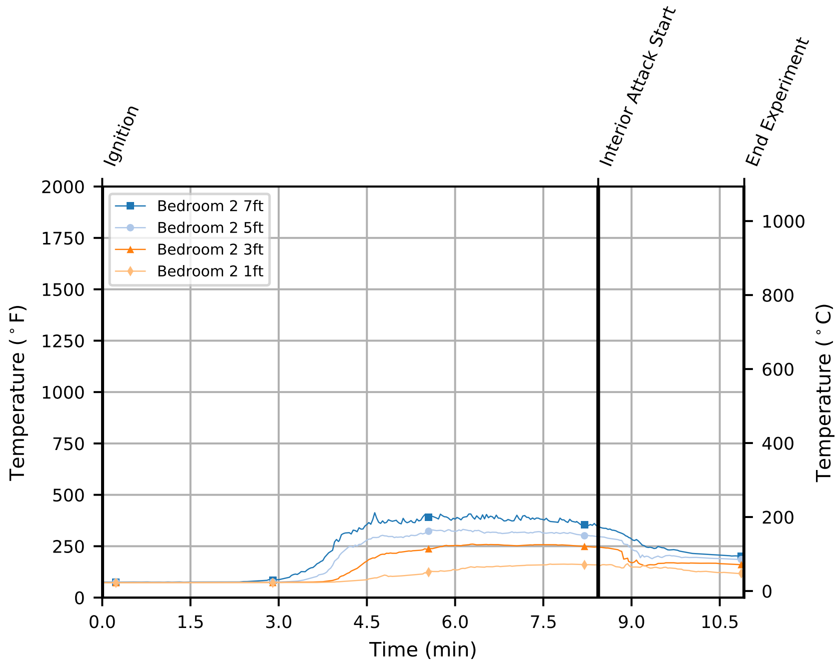


Figure E.80: Experiment 3 - Bedroom 2 Temps

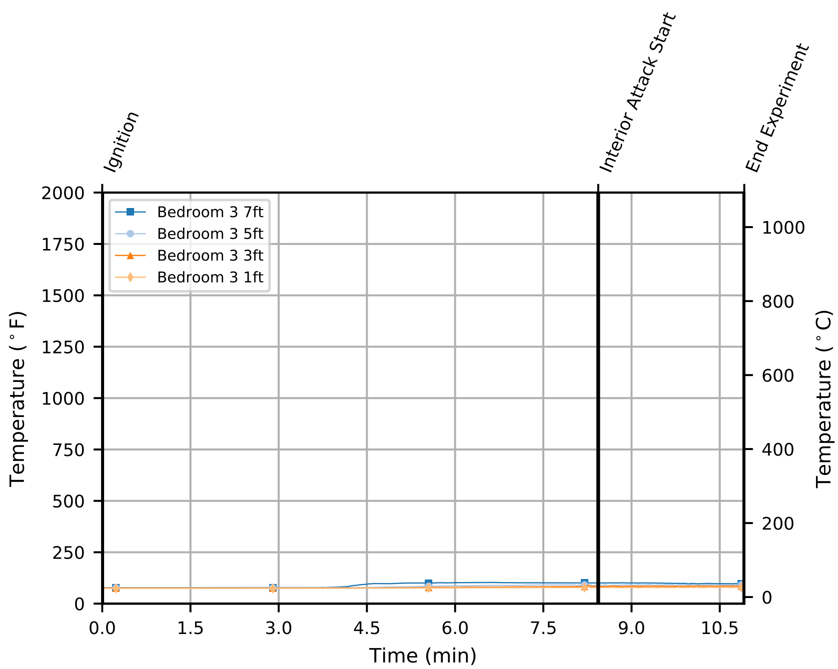


Figure E.81: Experiment 3 - Bedroom 3 Temps

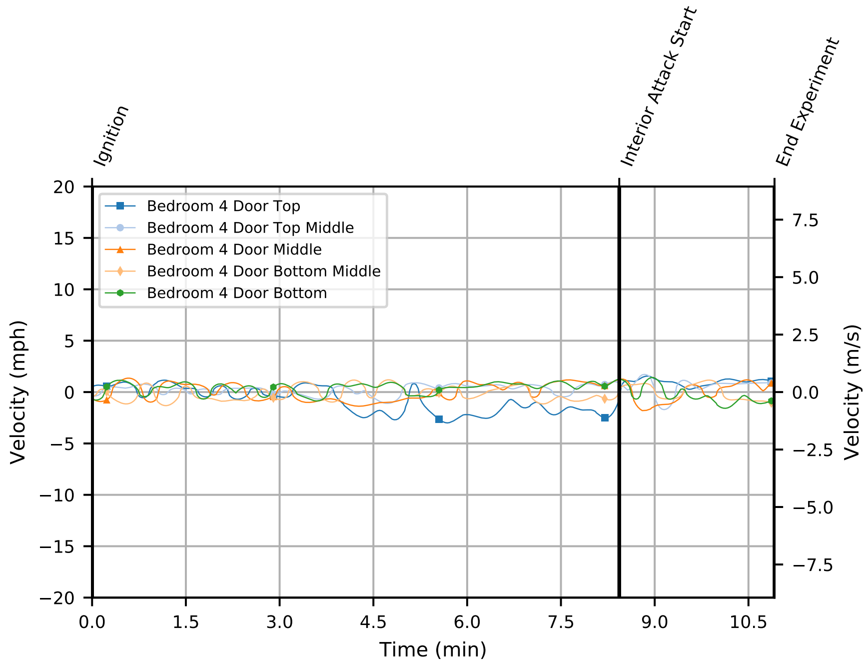


Figure E.82: Experiment 3 - Bedroom 4 Door

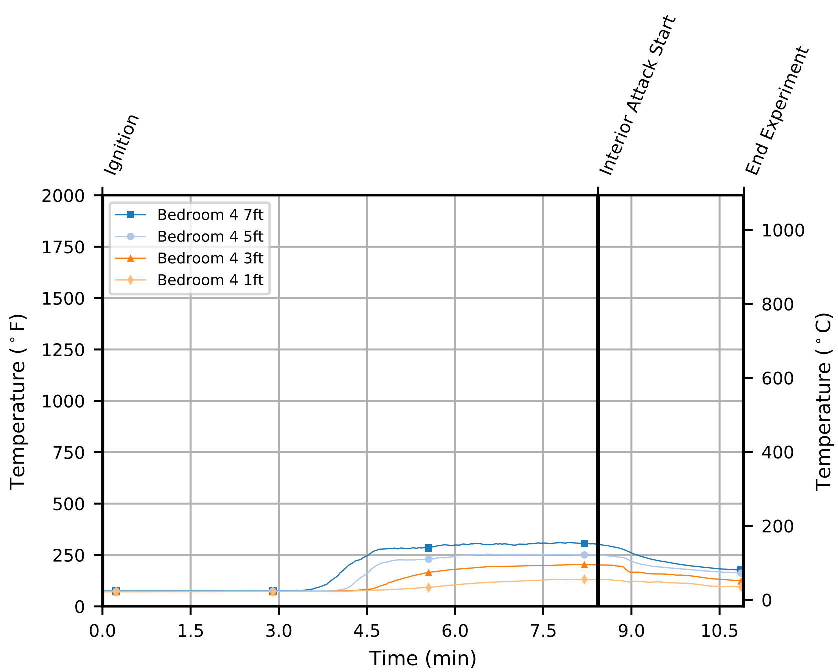


Figure E.83: Experiment 3 - Bedroom 4 Temps

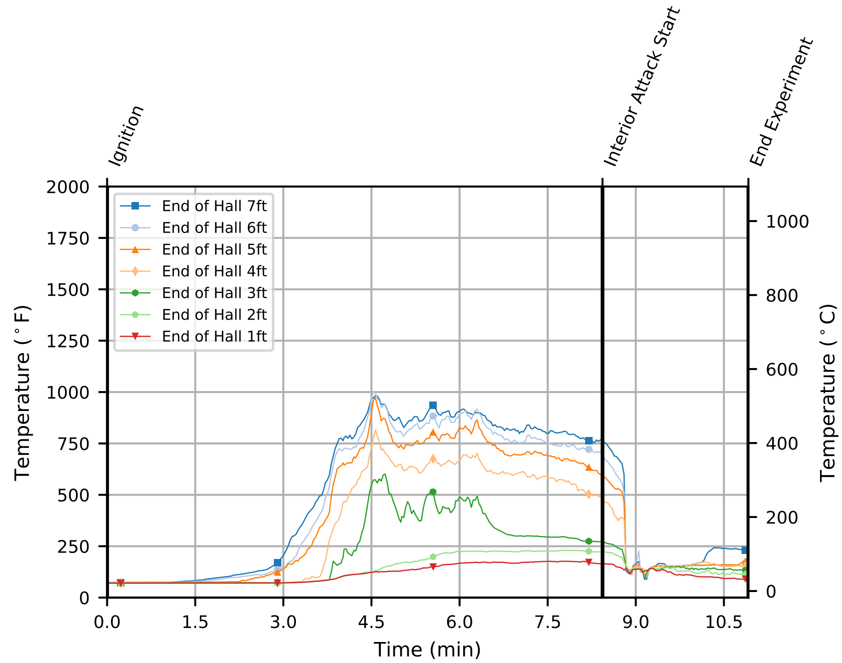


Figure E.84: Experiment 3 - End Hall Temps

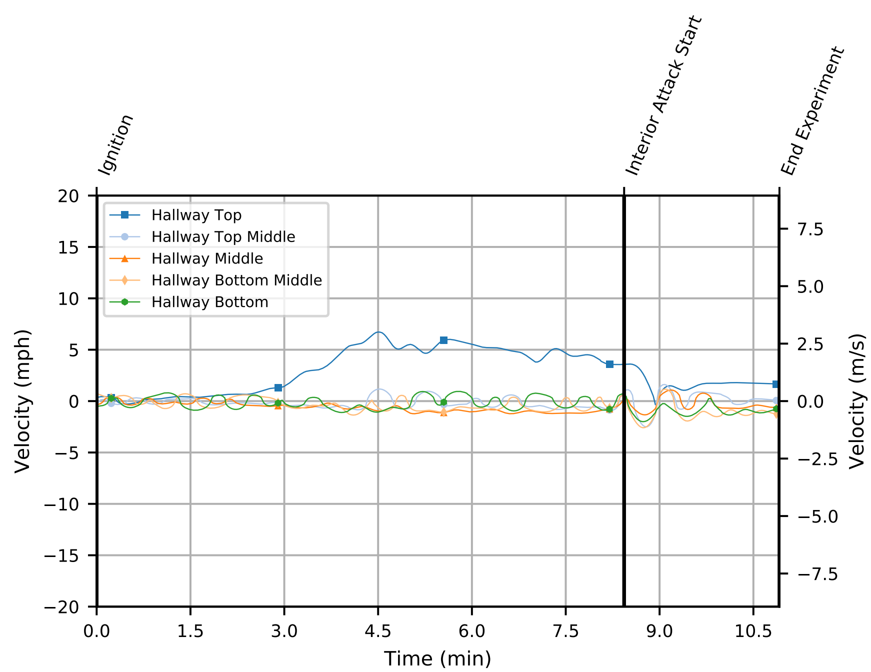


Figure E.85: Experiment 3 - Hallway Flow

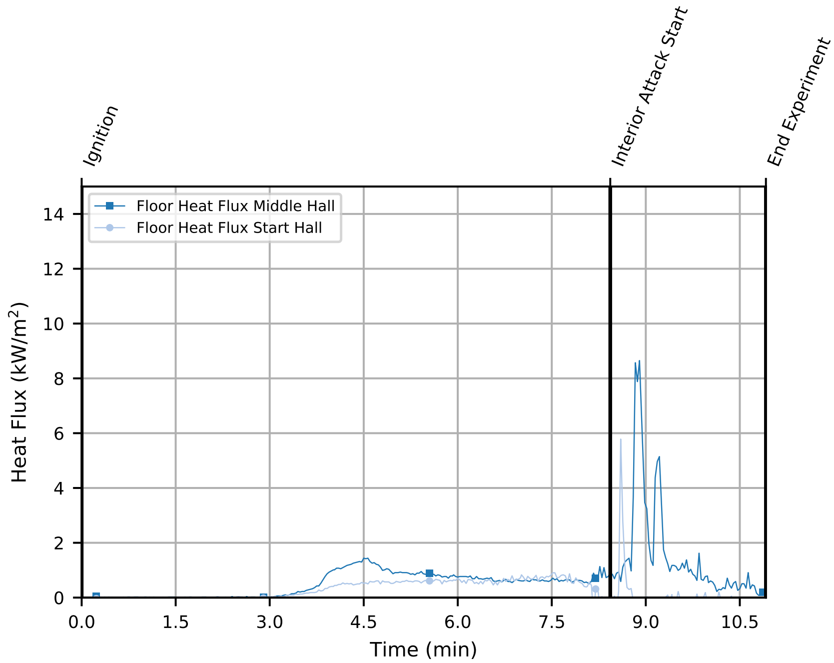


Figure E.86: Experiment 3 - Heat Flux Floor

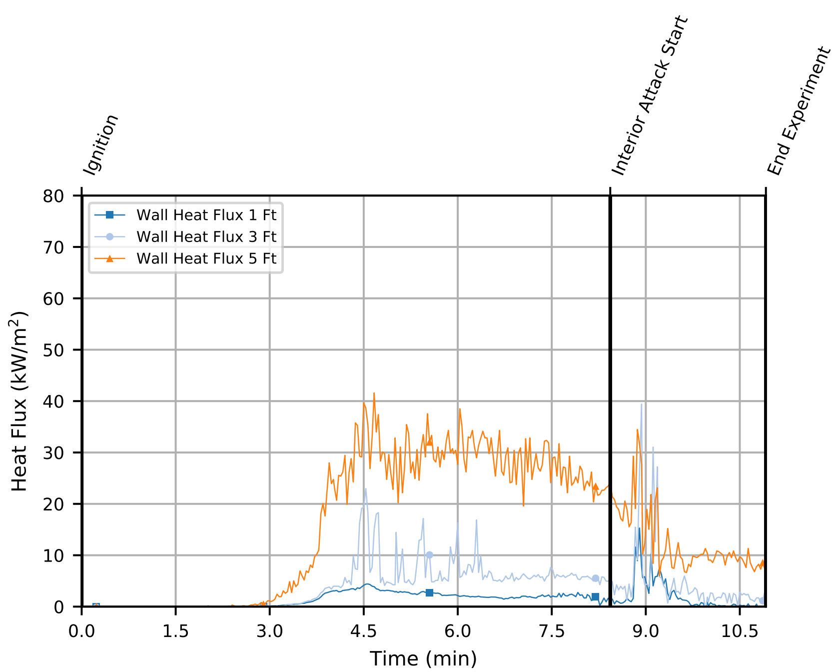


Figure E.87: Experiment 3 - Heat Flux Wall

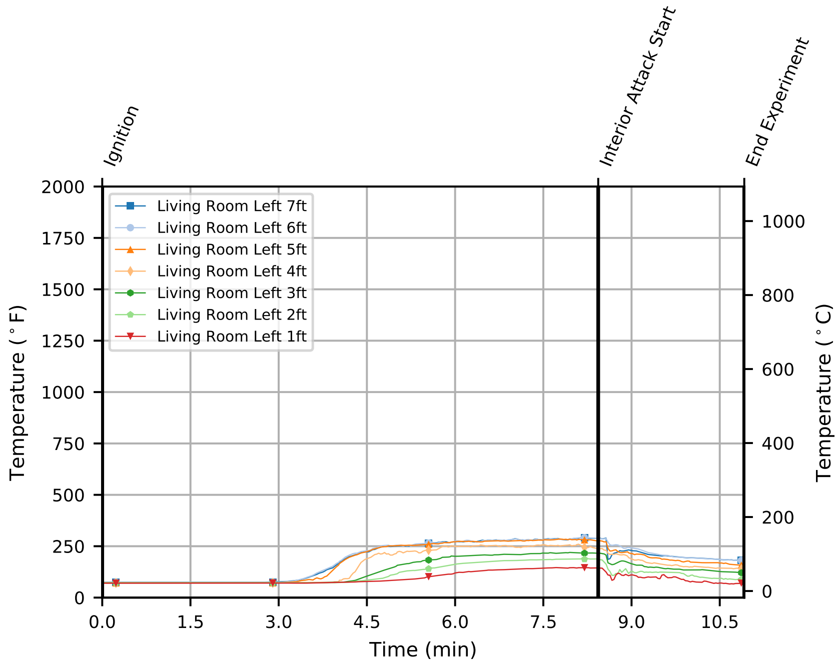


Figure E.88: Experiment 3 - Living Room Left Temps

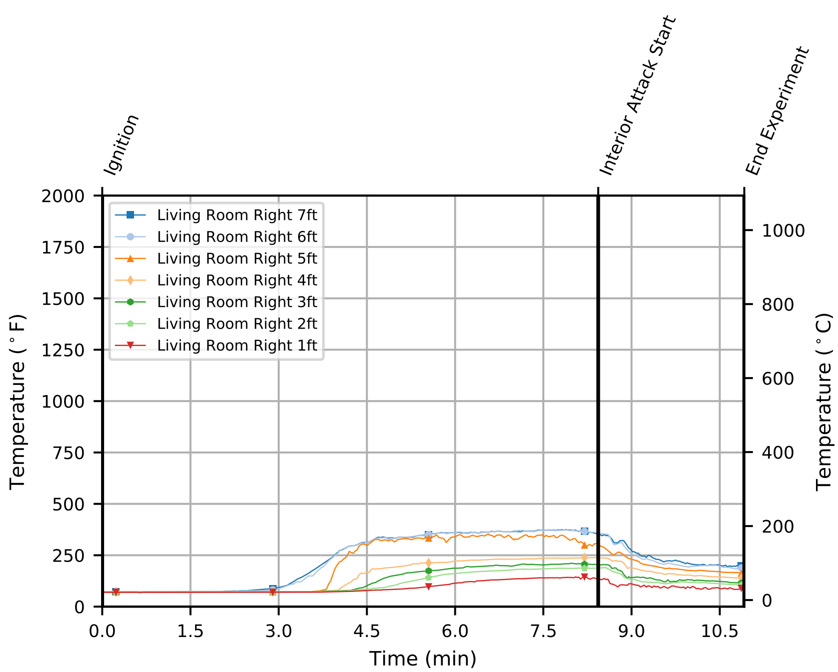


Figure E.89: Experiment 3 - Living Room Right Temps

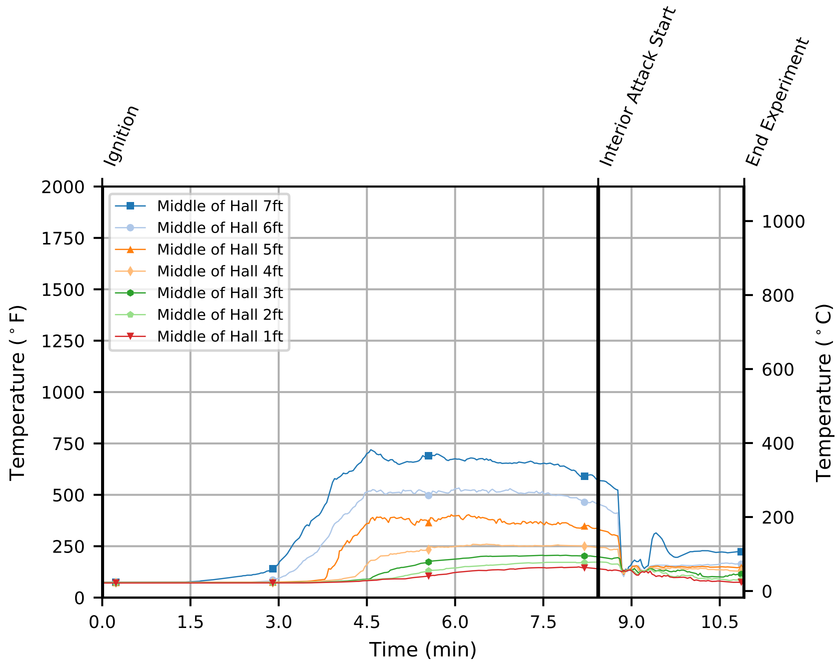


Figure E.90: Experiment 3 - Middle Hall Temps

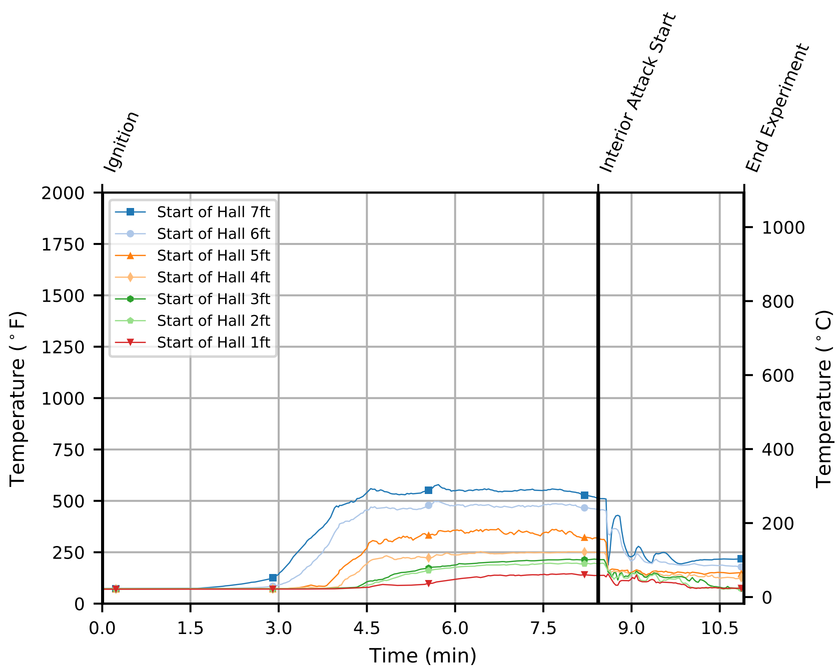


Figure E.91: Experiment 3 - Start Hall Temps

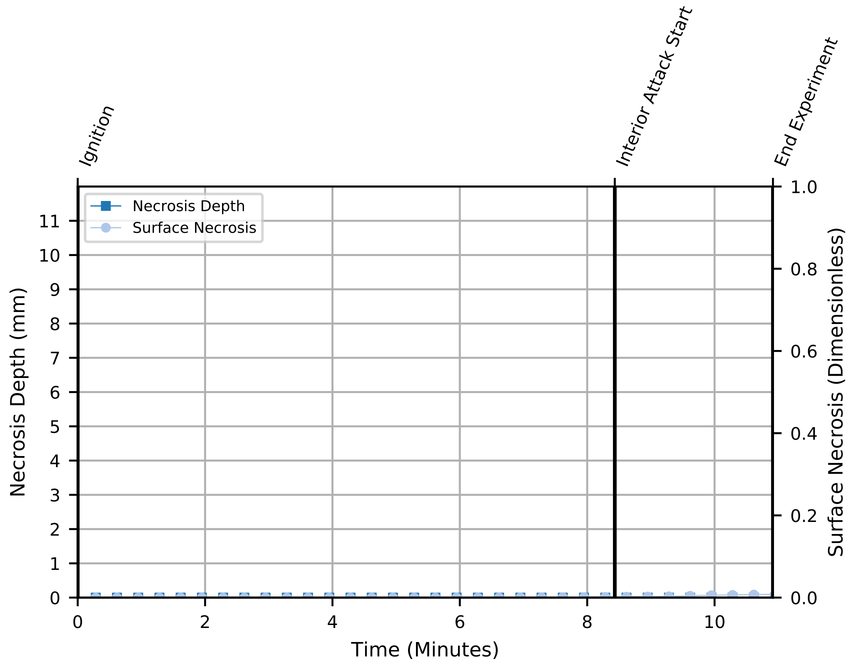


Figure E.92: Experiment 3 - Vic 1 Necrosis Depth

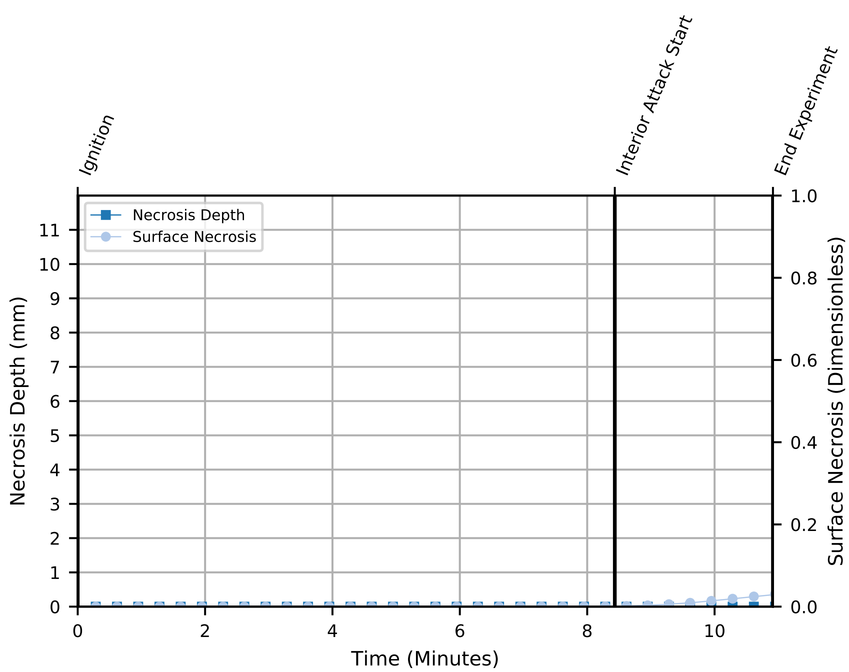


Figure E.93: Experiment 3 - Vic 3 Necrosis Depth

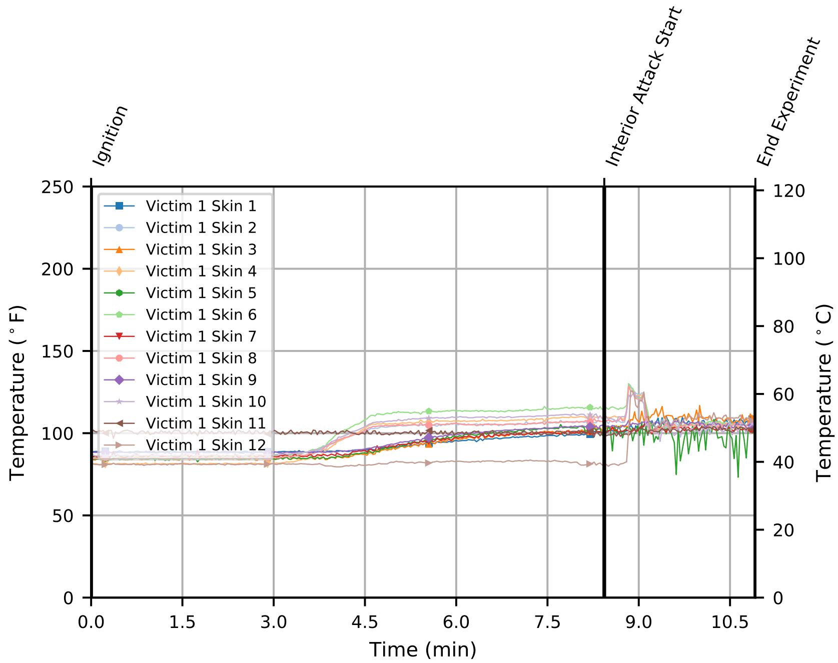


Figure E.94: Experiment 3 - Victim 1 Skin Temps

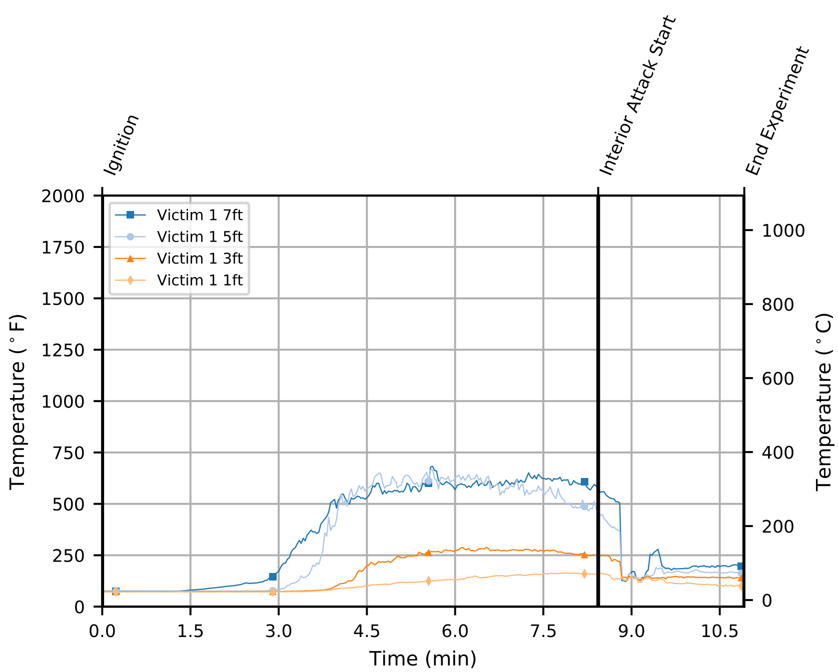


Figure E.95: Experiment 3 - Victim 1 Temps

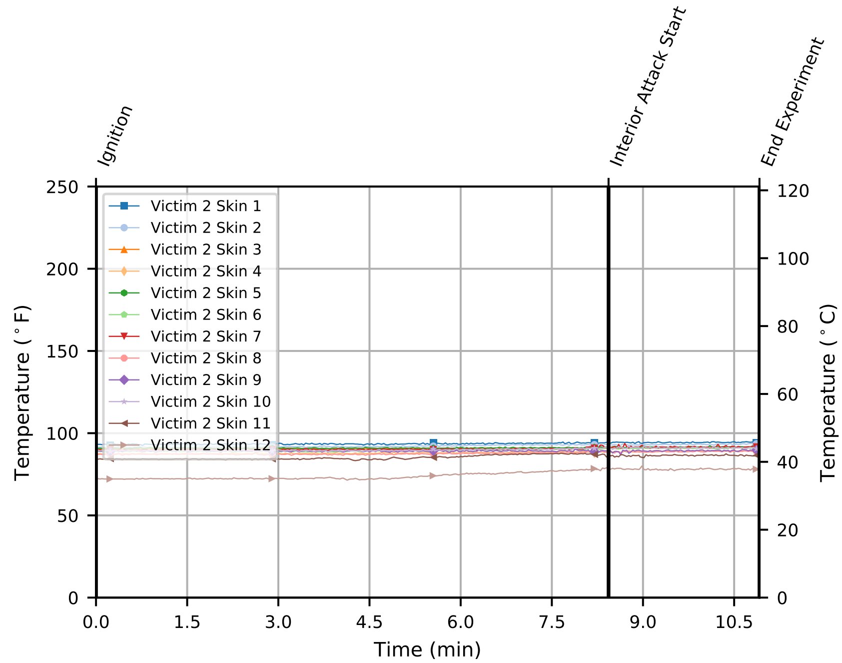


Figure E.96: Experiment 3 - Victim 2 Skin Temps

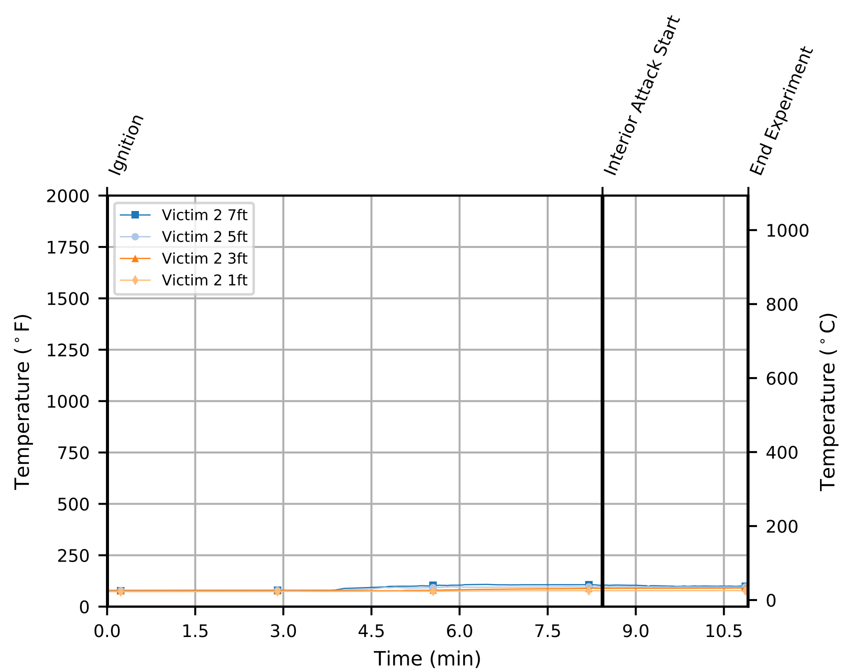


Figure E.97: Experiment 3 - Victim 2 Temps

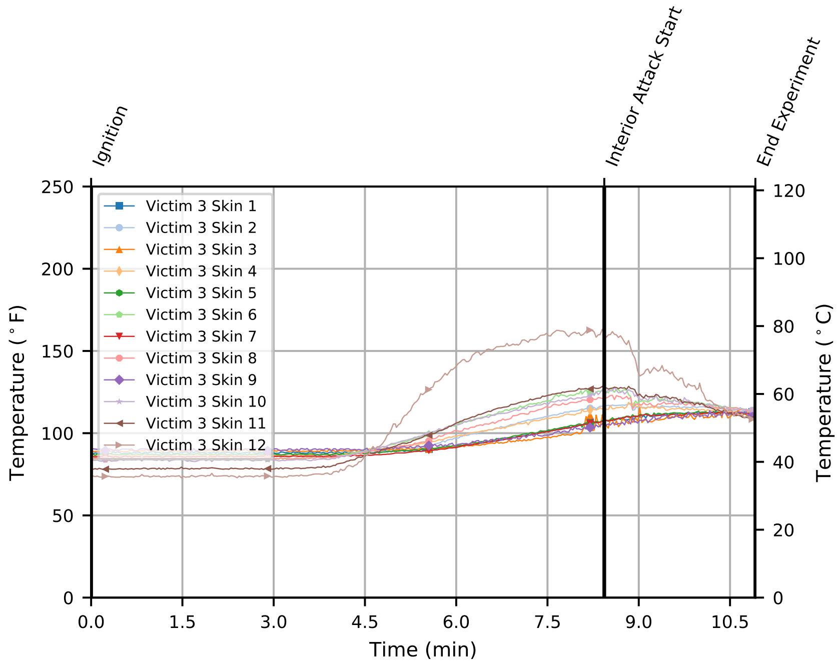


Figure E.98: Experiment 3 - Victim 3 Skin Temps

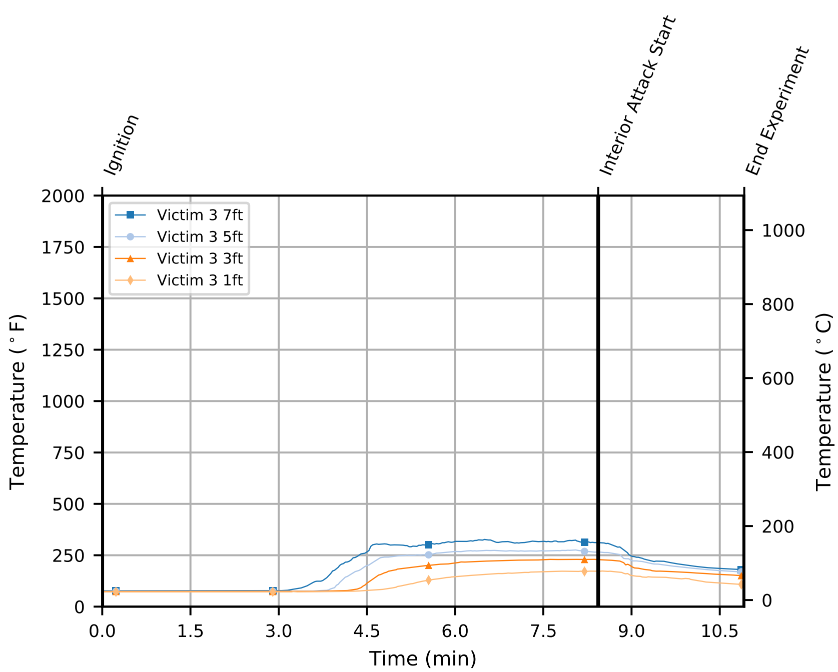


Figure E.99: Experiment 3 - Victim 3 Temps

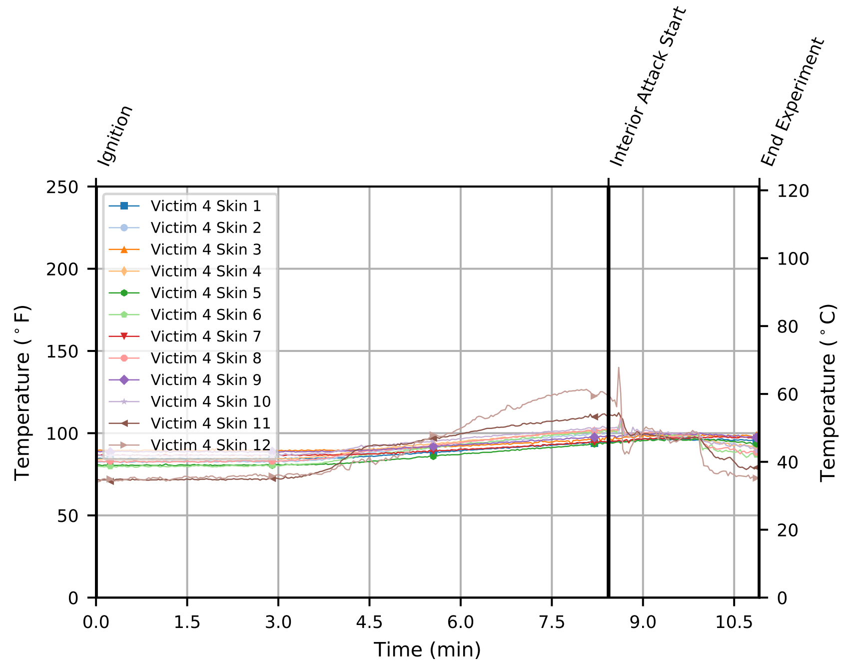


Figure E.100: Experiment 3 - Victim 4 Skin Temps

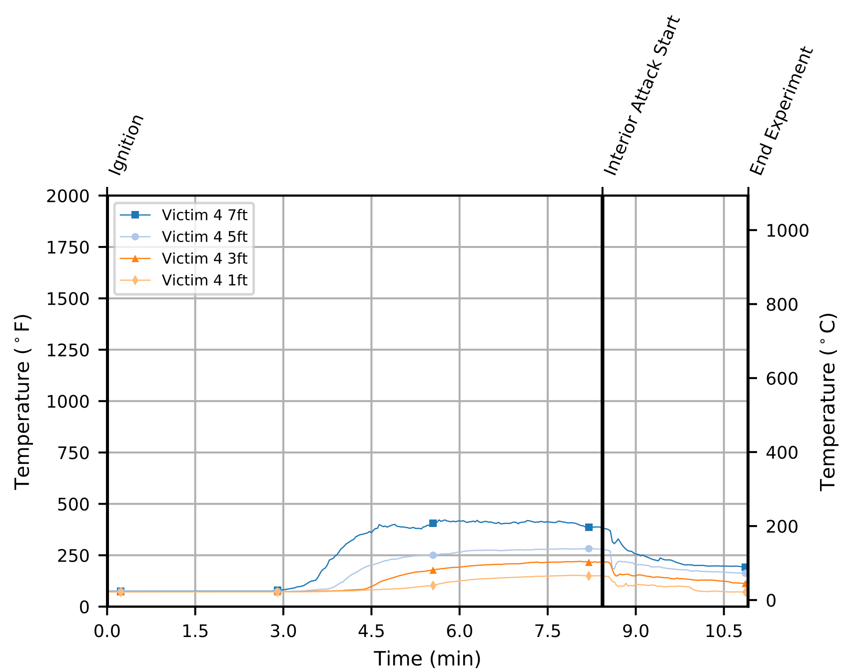


Figure E.101: Experiment 3 - Victim 4 Temps

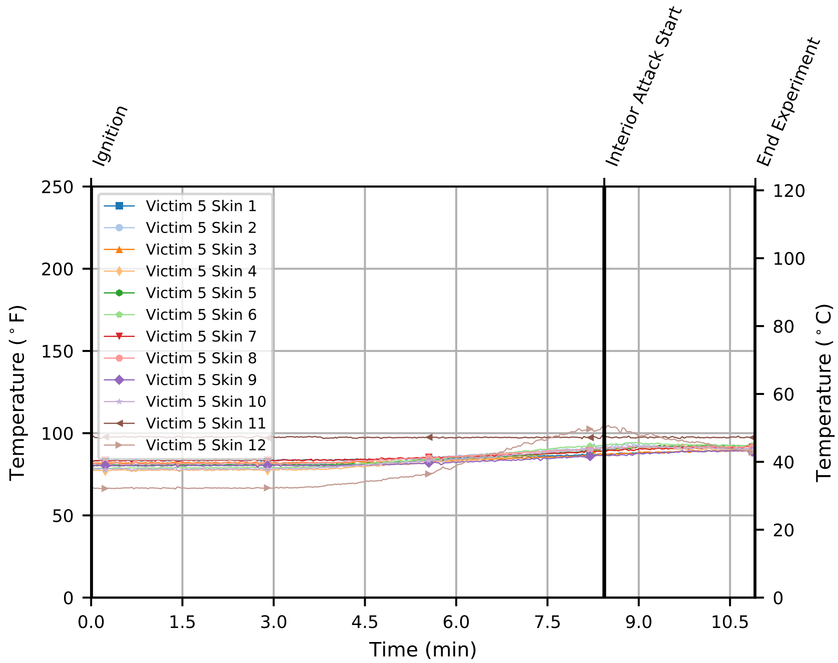


Figure E.102: Experiment 3 - Victim 5 Skin Temps

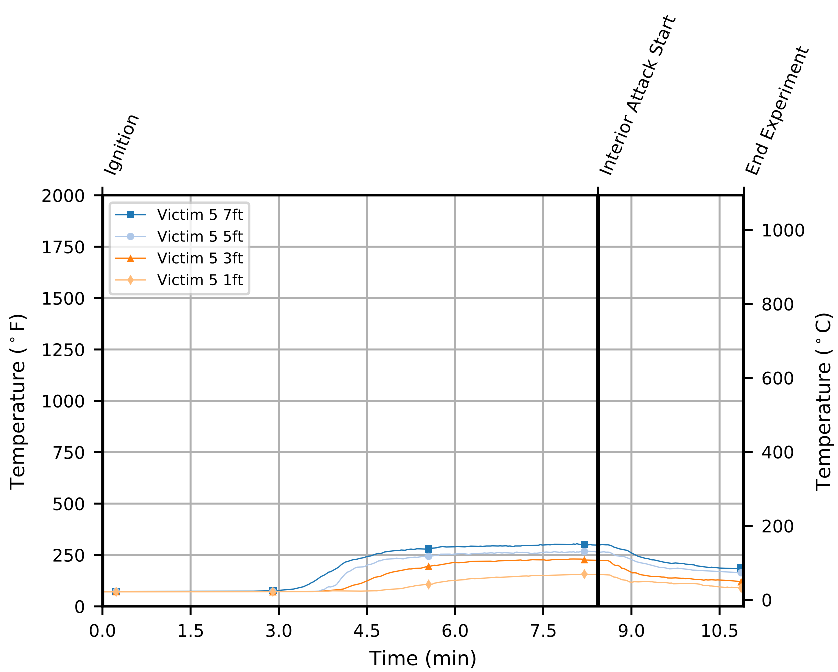


Figure E.103: Experiment 3 - Victim 5 Temps

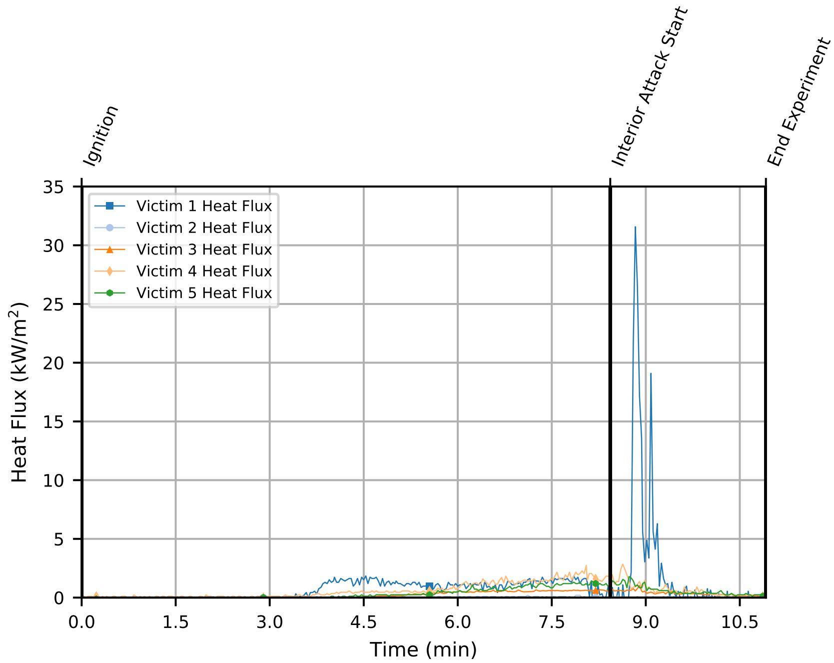


Figure E.104: Experiment 3 - Victim Heat Flux

E.4 Experiment 4 Data

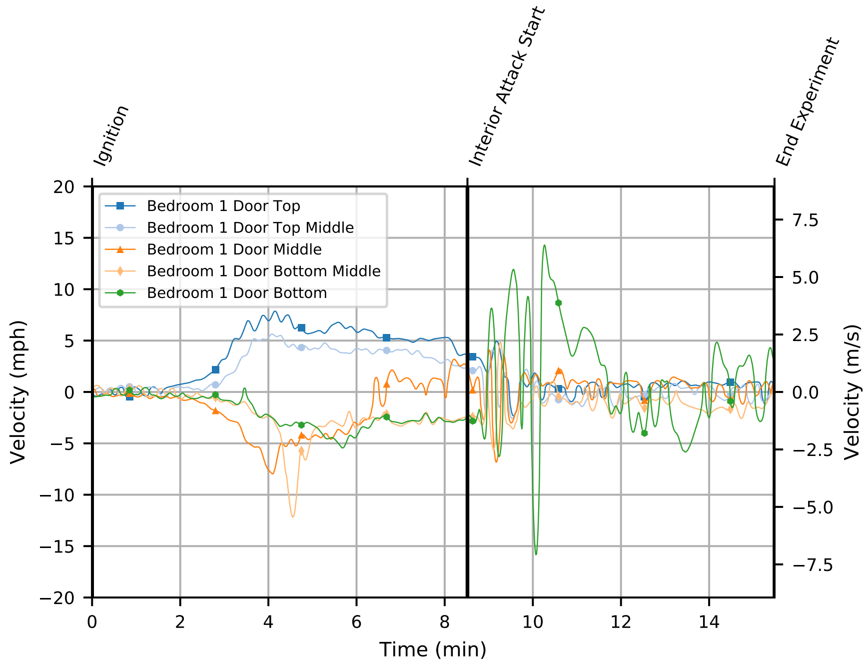


Figure E.105: Experiment 4 - Bedroom 1 Door

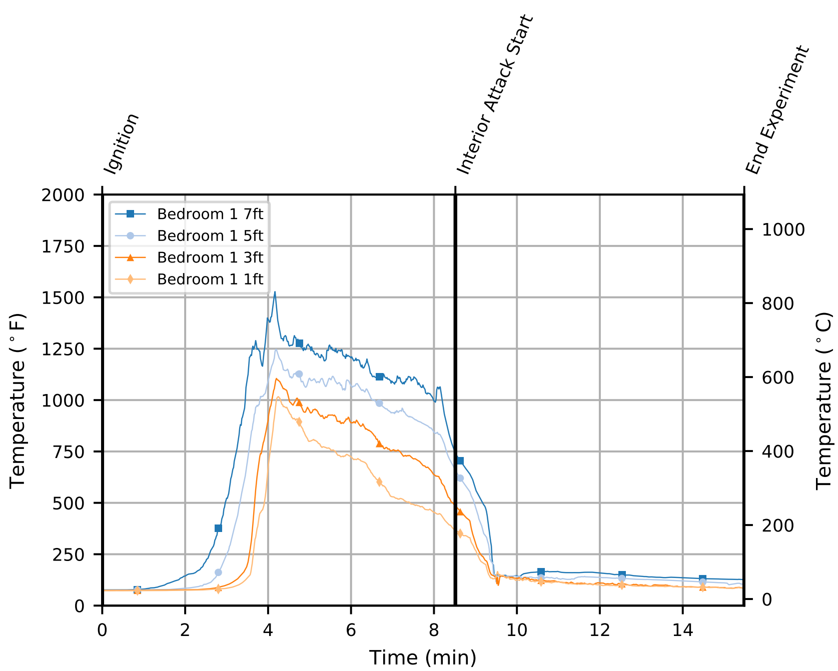


Figure E.106: Experiment 4 - Bedroom 1 Temps

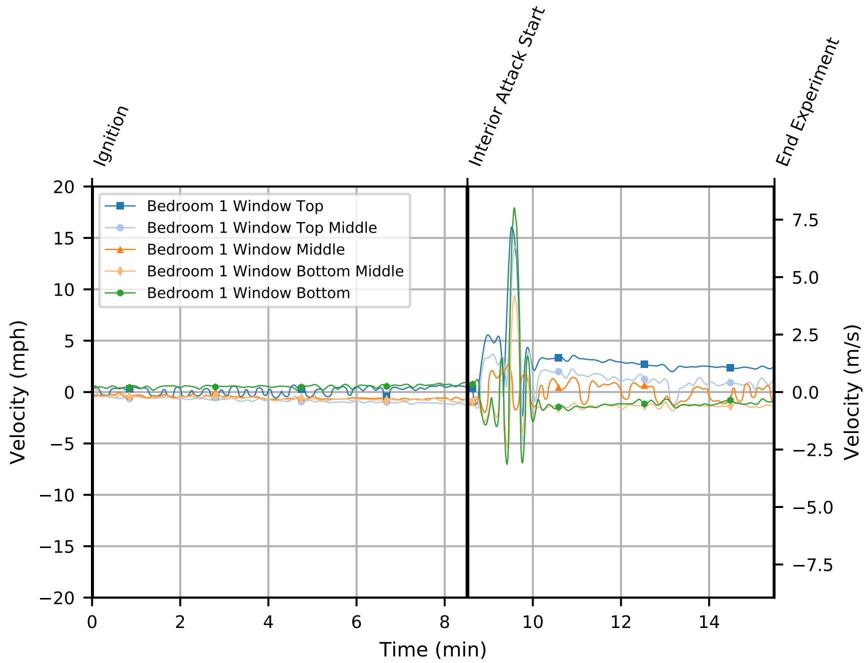


Figure E.107: Experiment 4 - Bedroom 1 Window

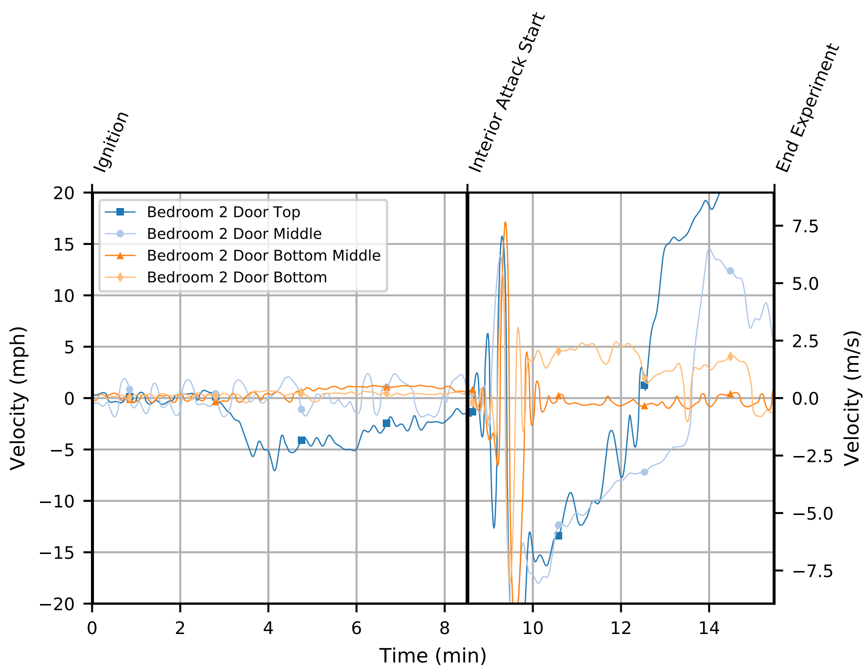


Figure E.108: Experiment 4 - Bedroom 2 Door

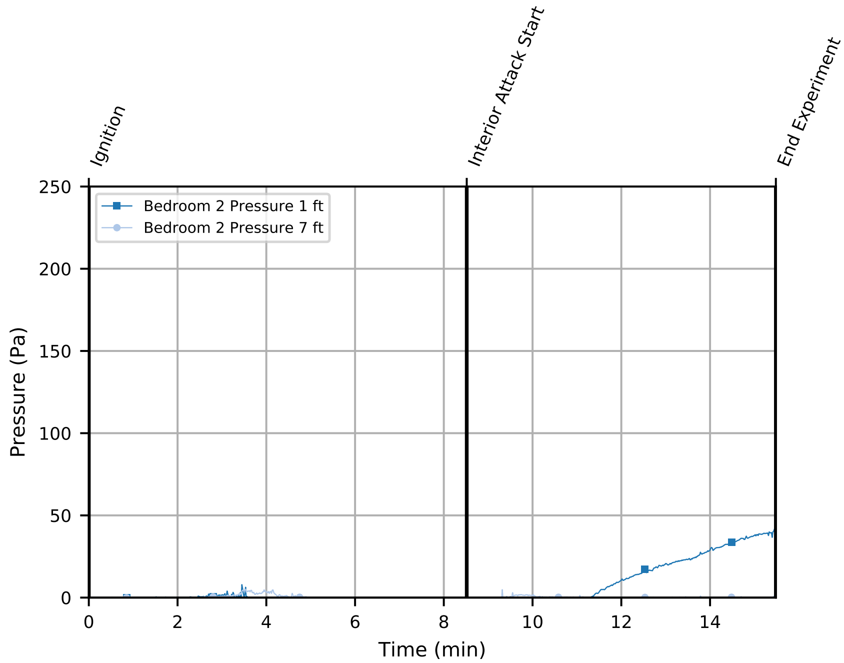


Figure E.109: Experiment 4 - Bedroom 2 Pressure

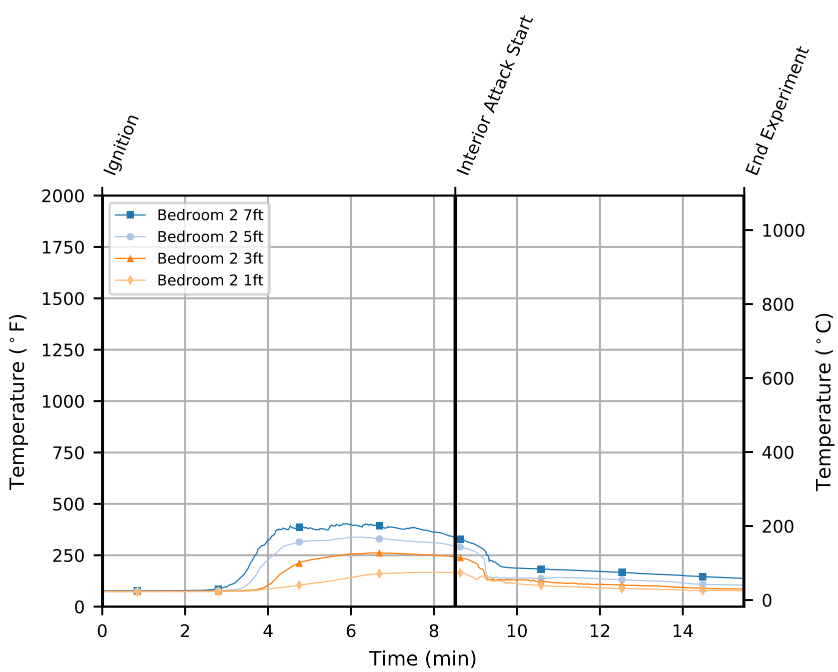


Figure E.110: Experiment 4 - Bedroom 2 Temps

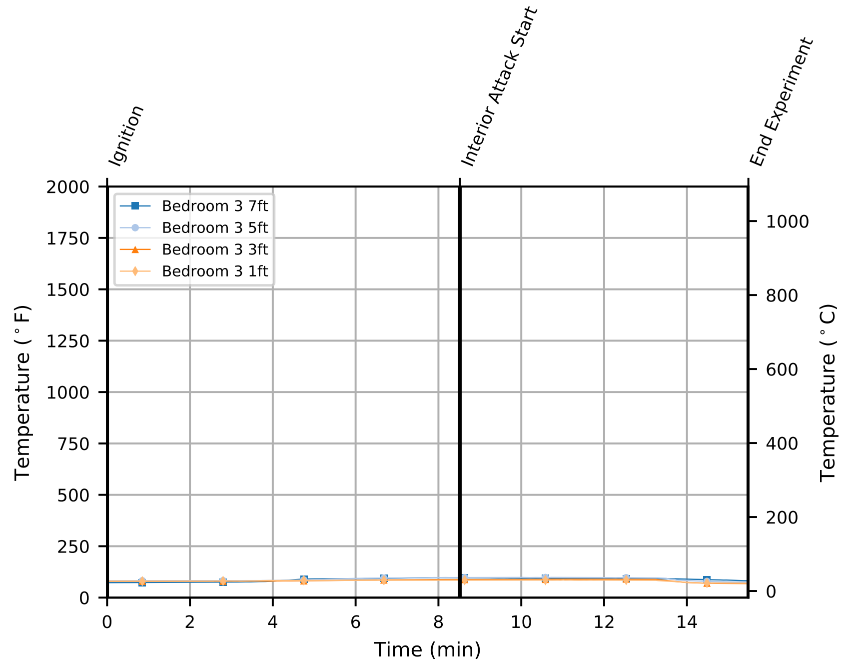


Figure E.111: Experiment 4 - Bedroom 3 Temps

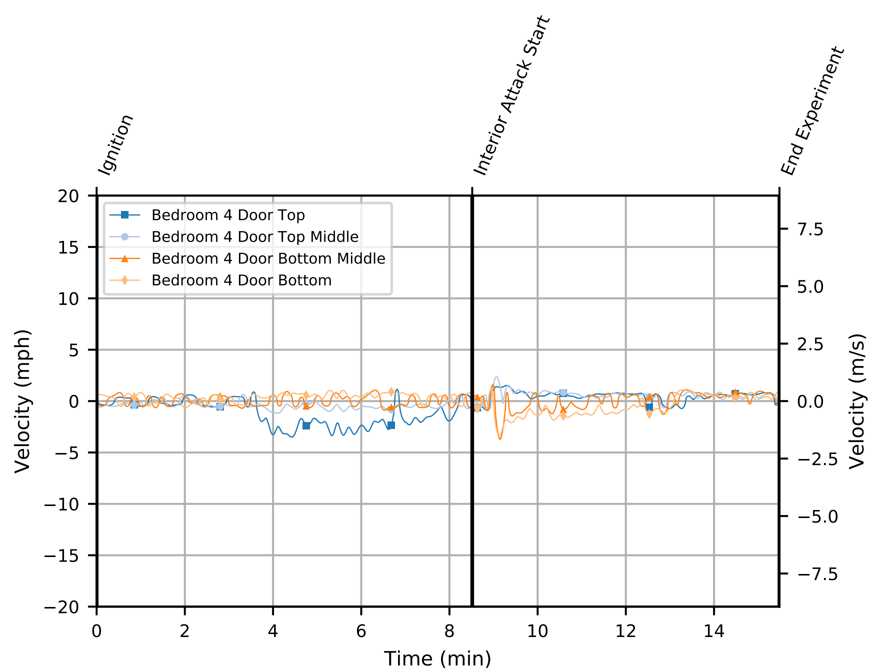


Figure E.112: Experiment 4 - Bedroom 4 Door

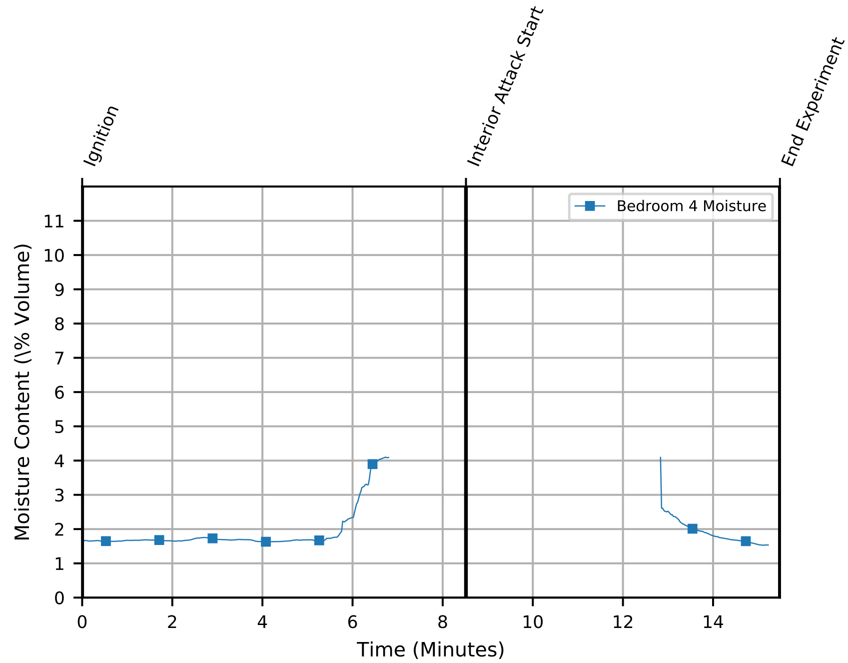


Figure E.113: Experiment 4 - Bedroom 4 Moisture

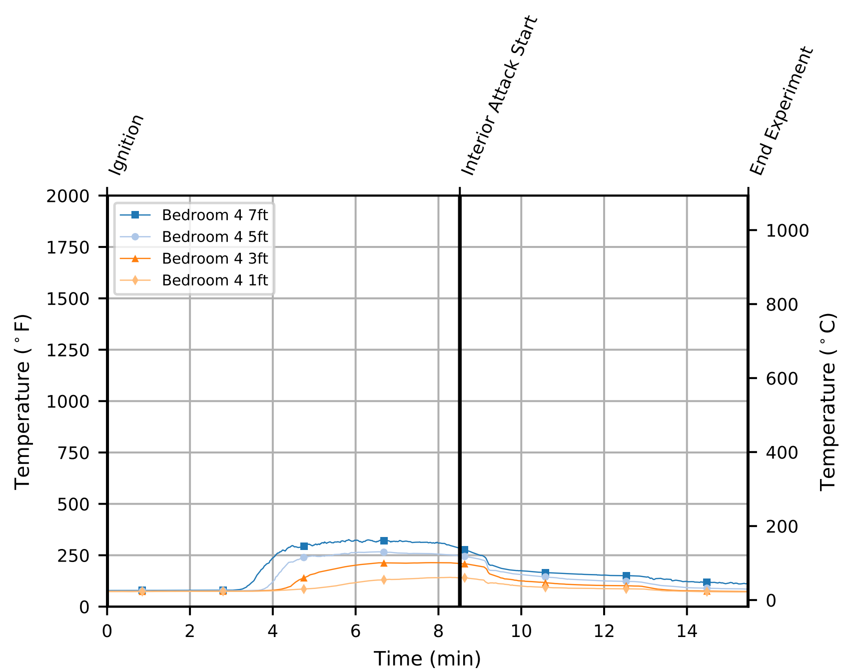


Figure E.114: Experiment 4 - Bedroom 4 Temps

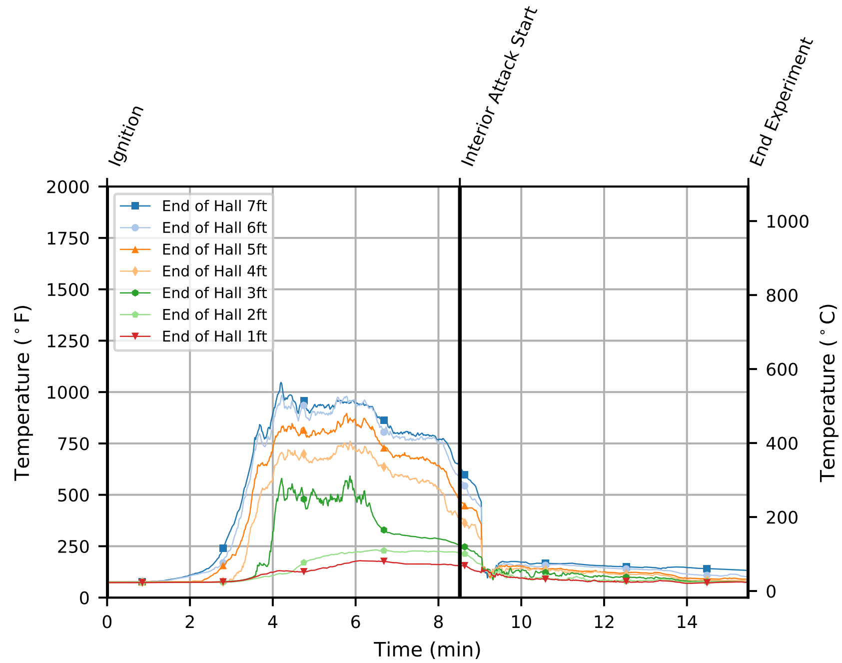


Figure E.115: Experiment 4 - End Hall Temps

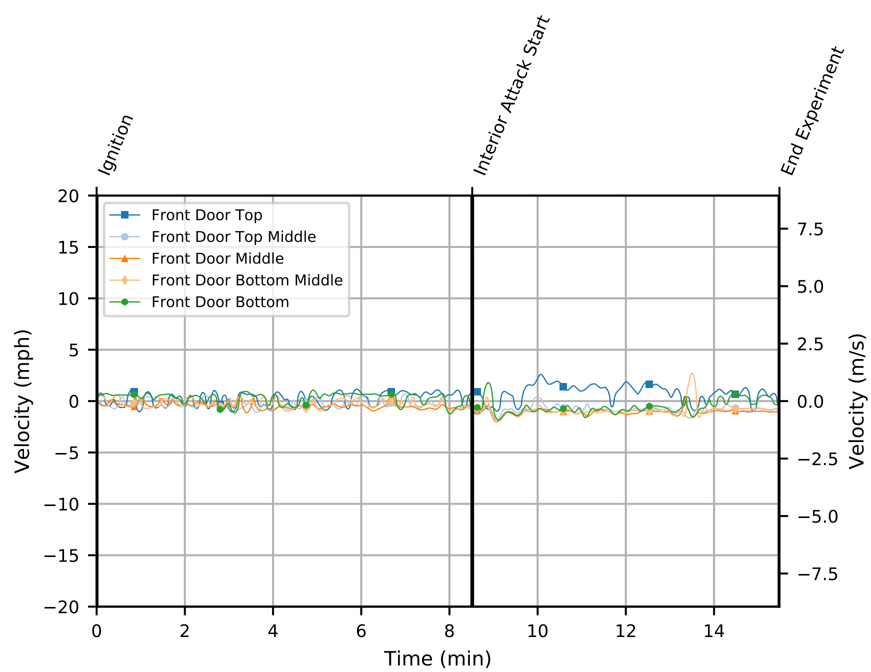


Figure E.116: Experiment 4 - Front Door Flow

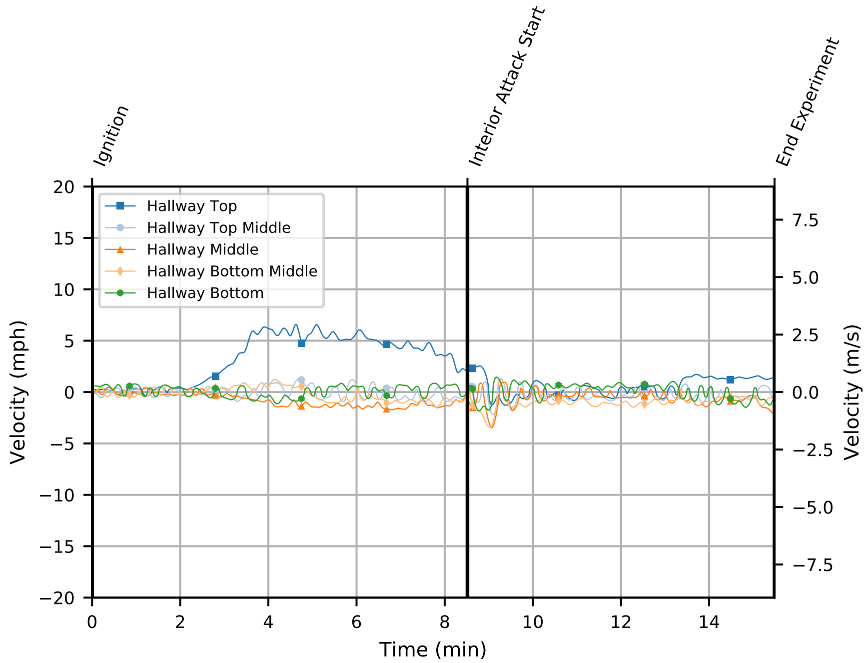


Figure E.117: Experiment 4 - Hallway Flow

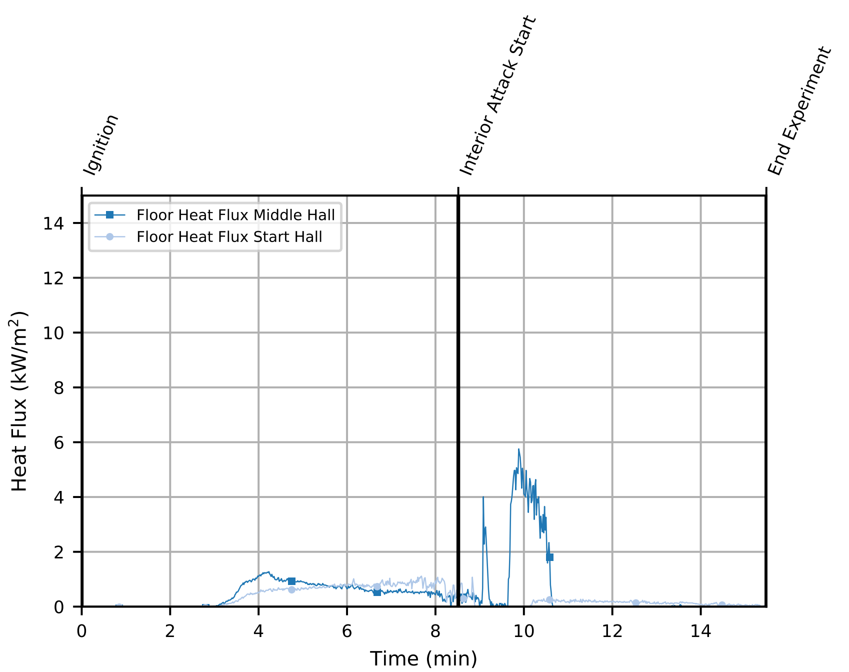


Figure E.118: Experiment 4 - Heat Flux Floor

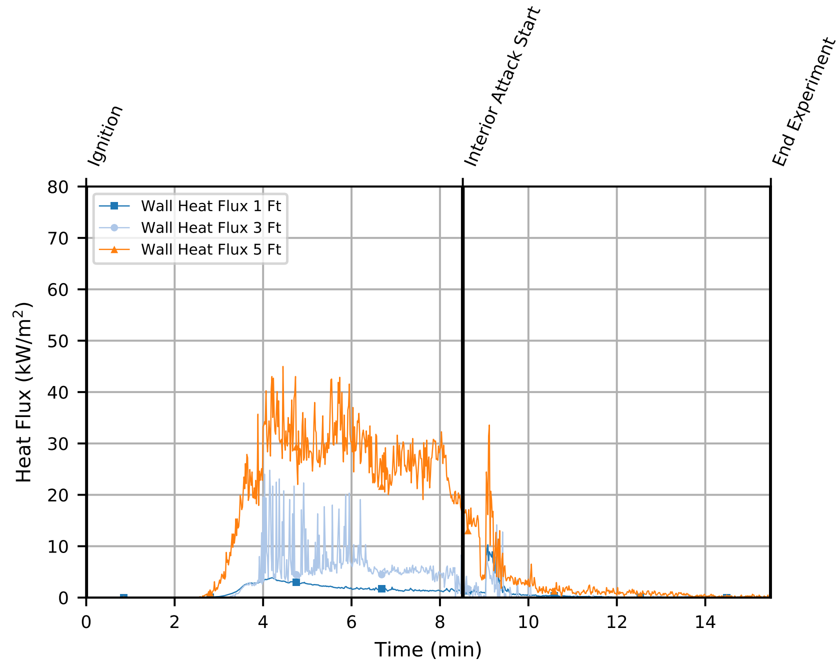


Figure E.119: Experiment 4 - Heat Flux Wall

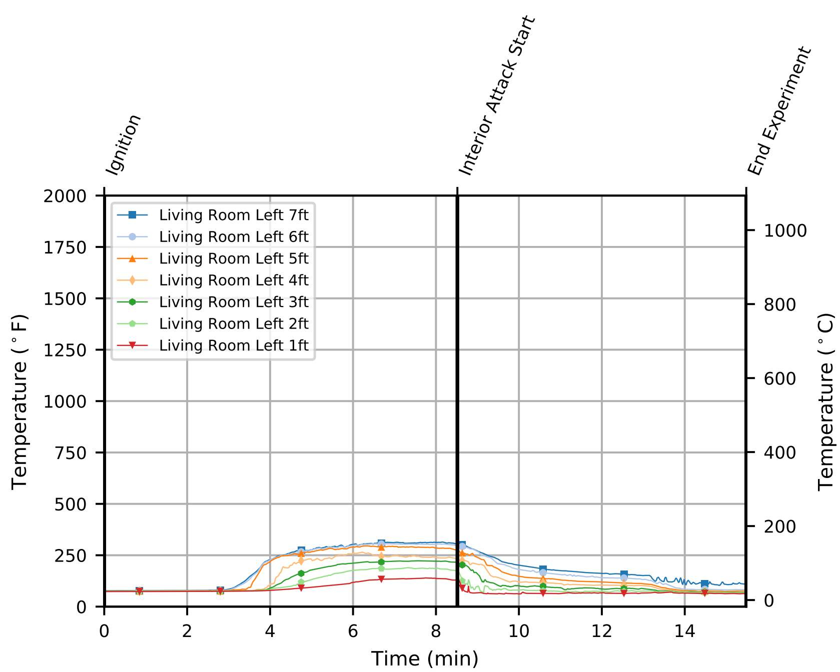


Figure E.120: Experiment 4 - Living Room Left Temps

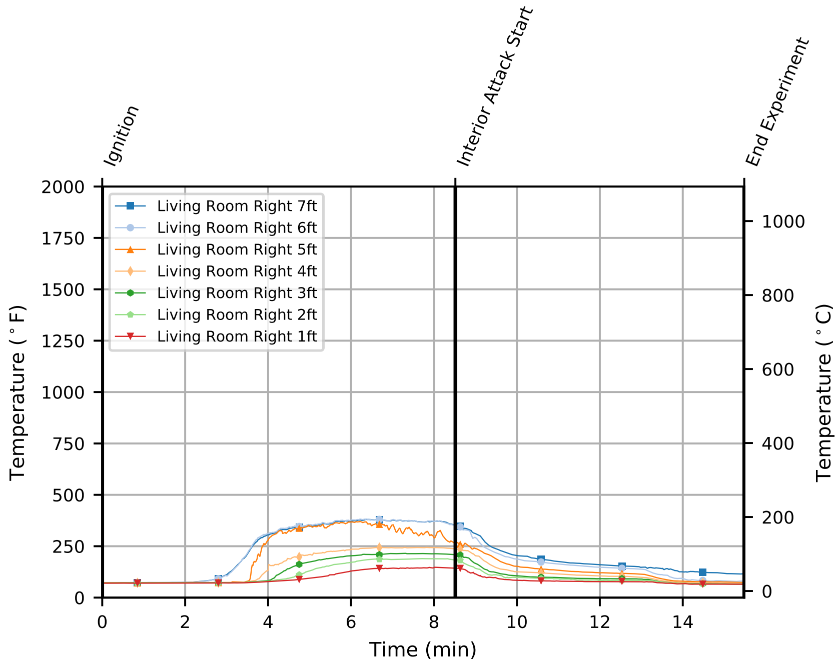


Figure E.121: Experiment 4 - Living Room Right Temps

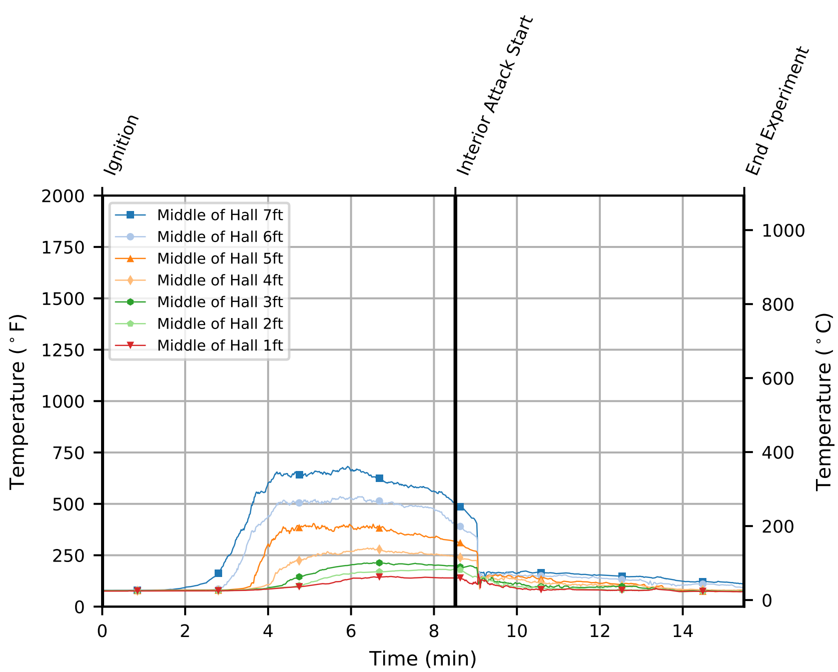


Figure E.122: Experiment 4 - Middle Hall Temps

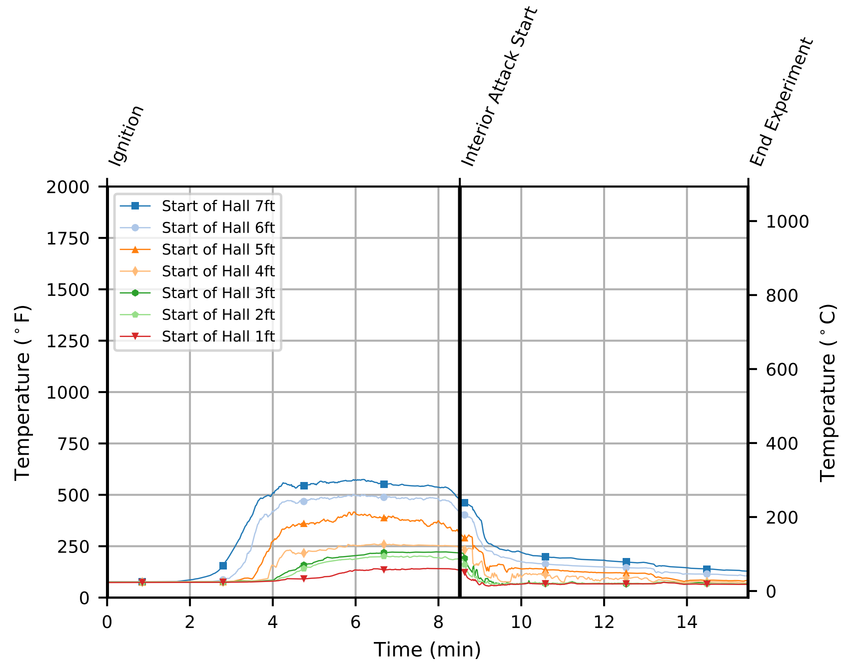


Figure E.123: Experiment 4 - Start Hall Temps

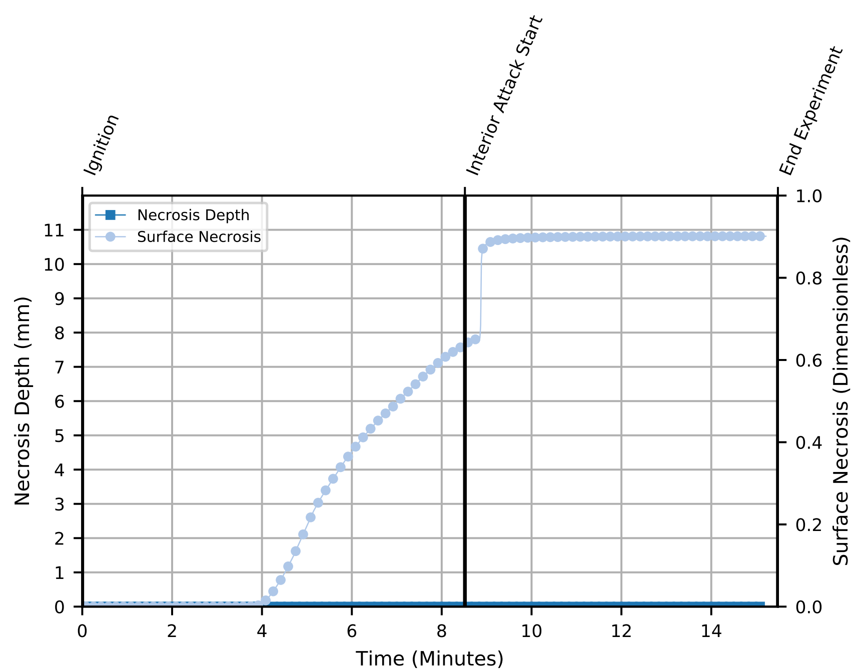


Figure E.124: Experiment 4 - Vic 1 Necrosis Depth

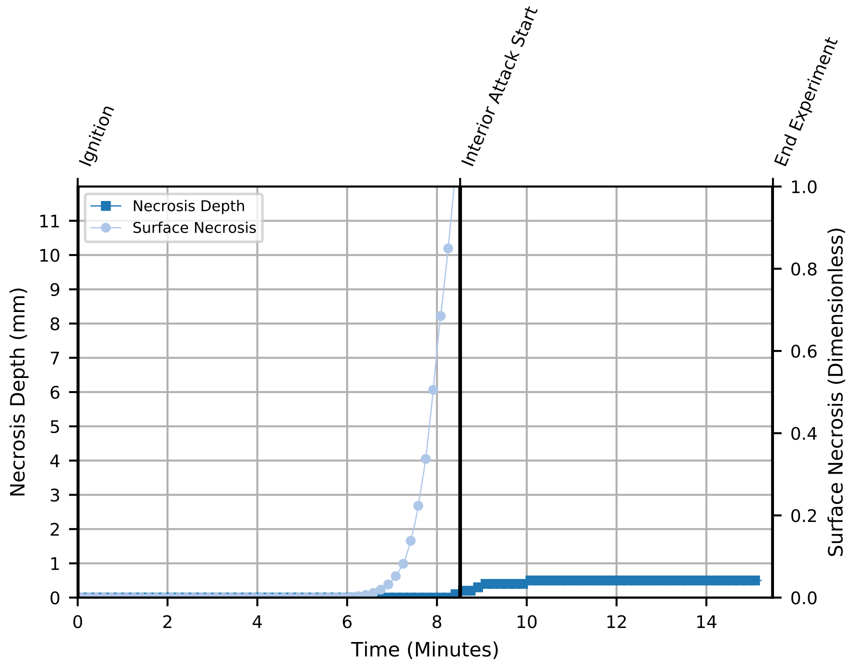


Figure E.125: Experiment 4 - Vic 3 Necrosis Depth

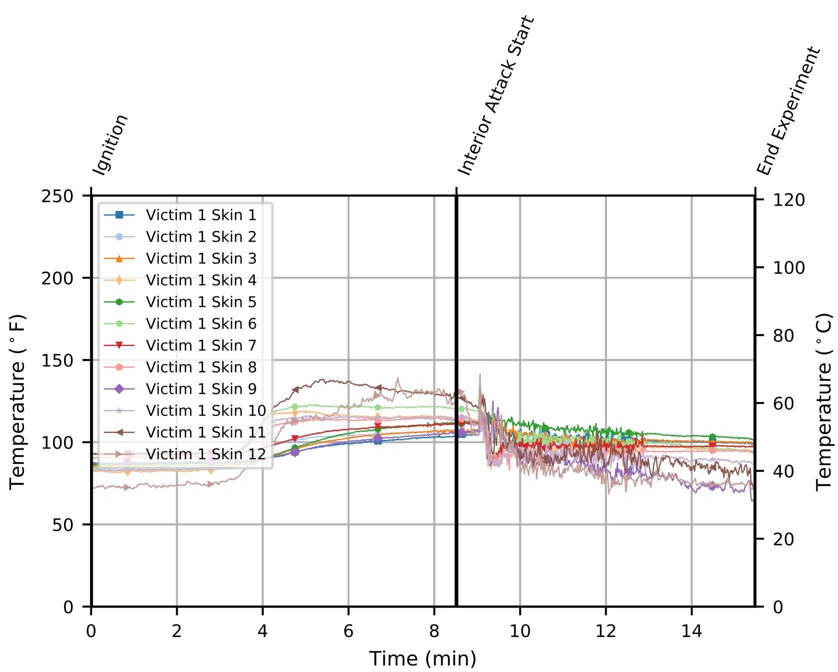


Figure E.126: Experiment 4 - Victim 1 Skin Temps

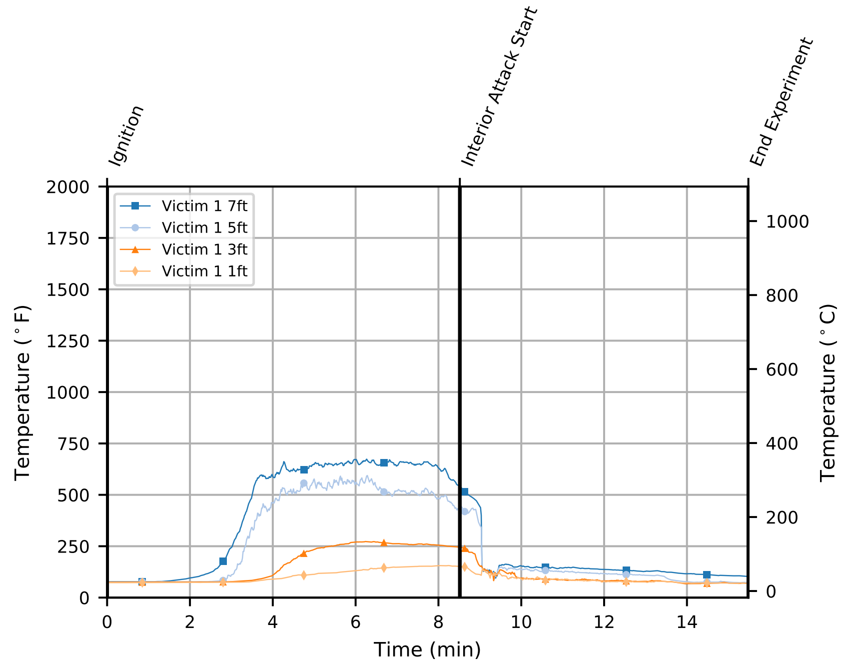


Figure E.127: Experiment 4 - Victim 1 Temps

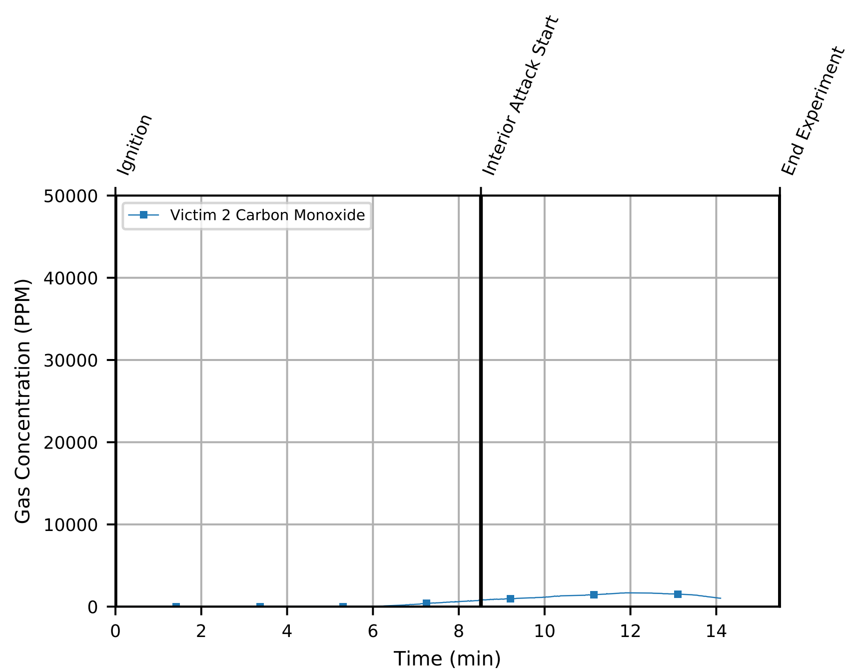


Figure E.128: Experiment 4 - Victim 2 Carbon Monoxide

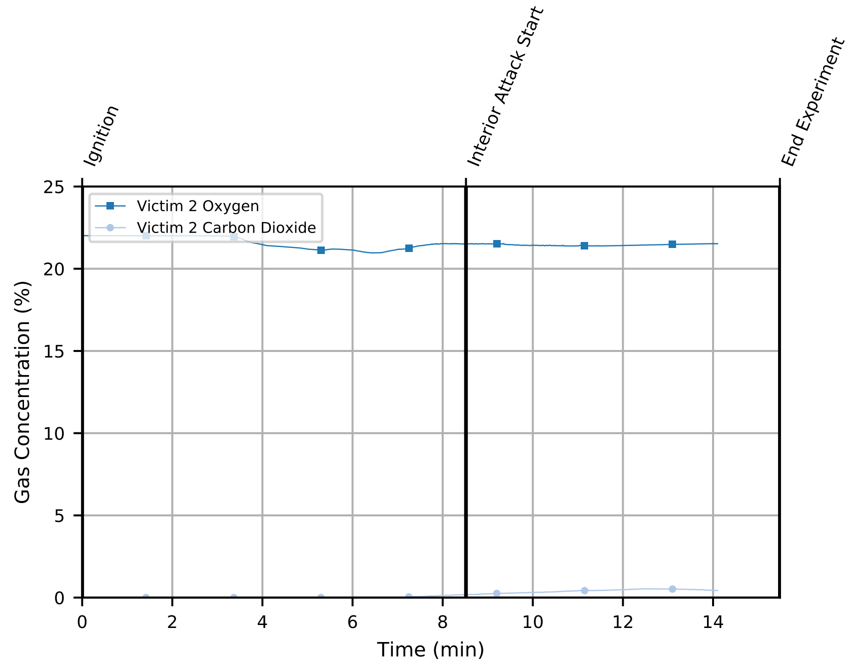


Figure E.129: Experiment 4 - Victim 2 Gas

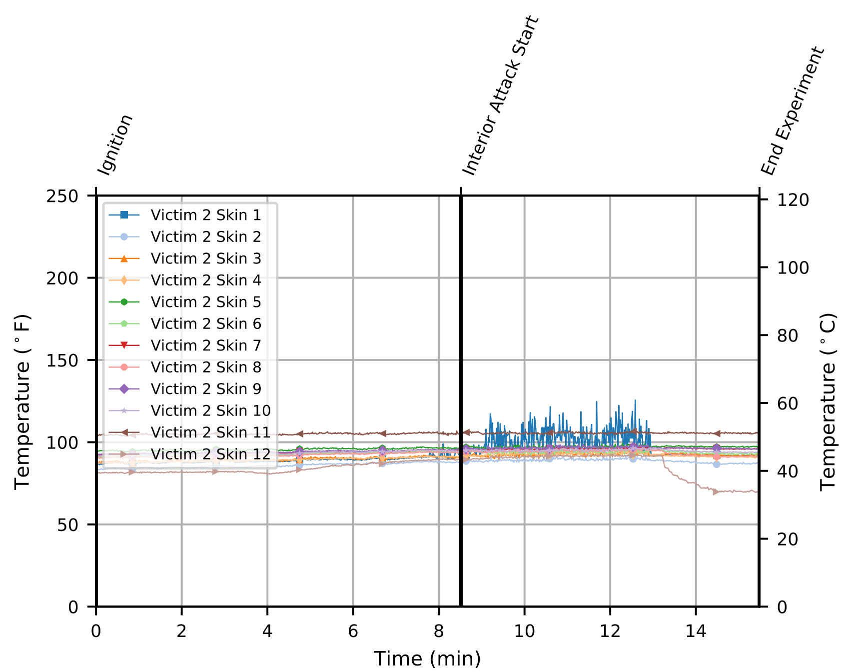


Figure E.130: Experiment 4 - Victim 2 Skin Temps

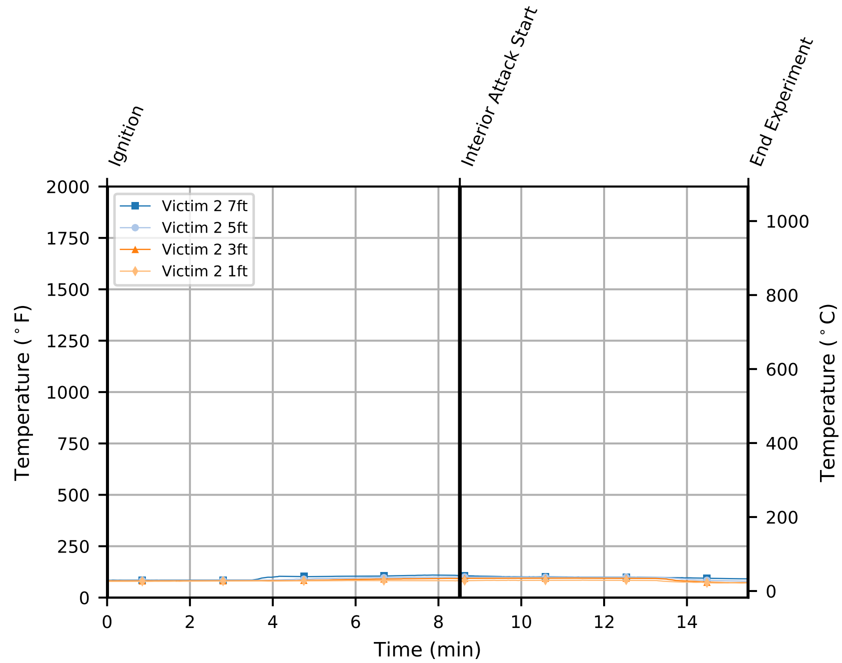


Figure E.131: Experiment 4 - Victim 2 Temps

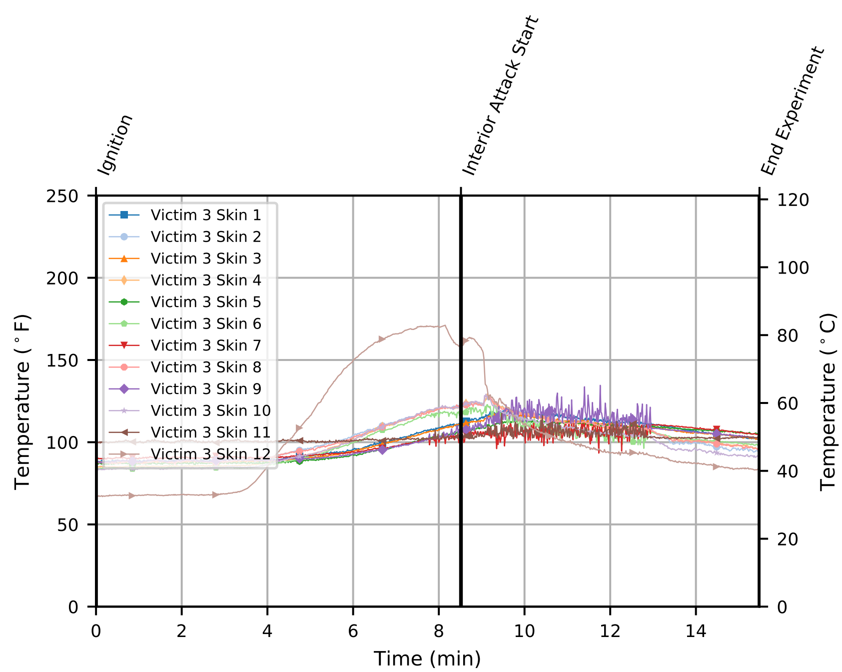


Figure E.132: Experiment 4 - Victim 3 Skin Temps

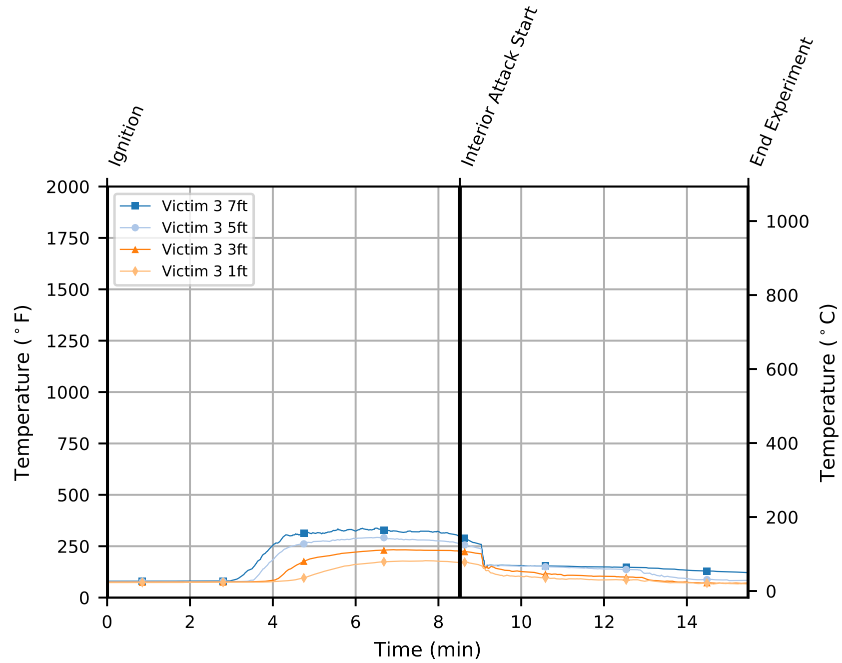


Figure E.133: Experiment 4 - Victim 3 Temps

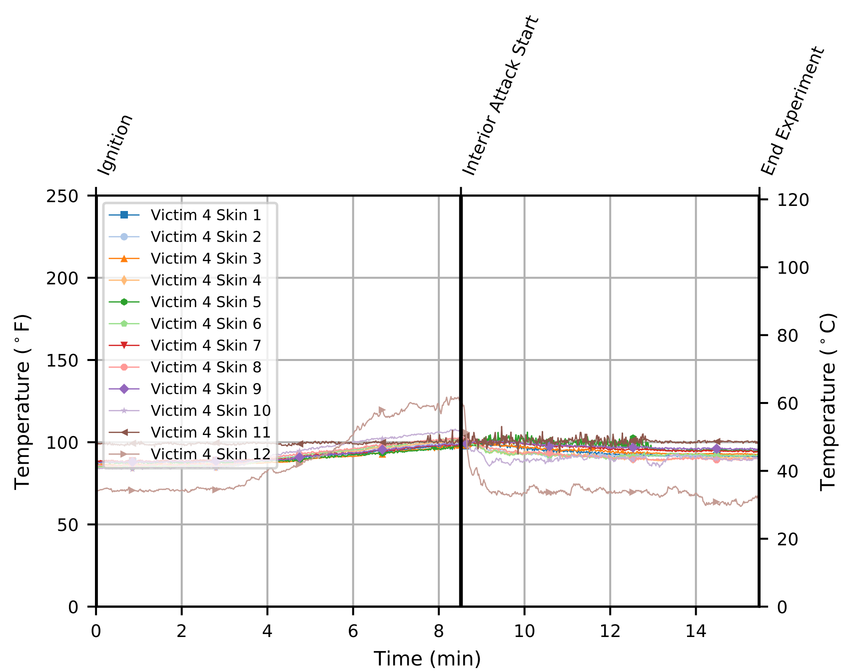


Figure E.134: Experiment 4 - Victim 4 Skin Temps

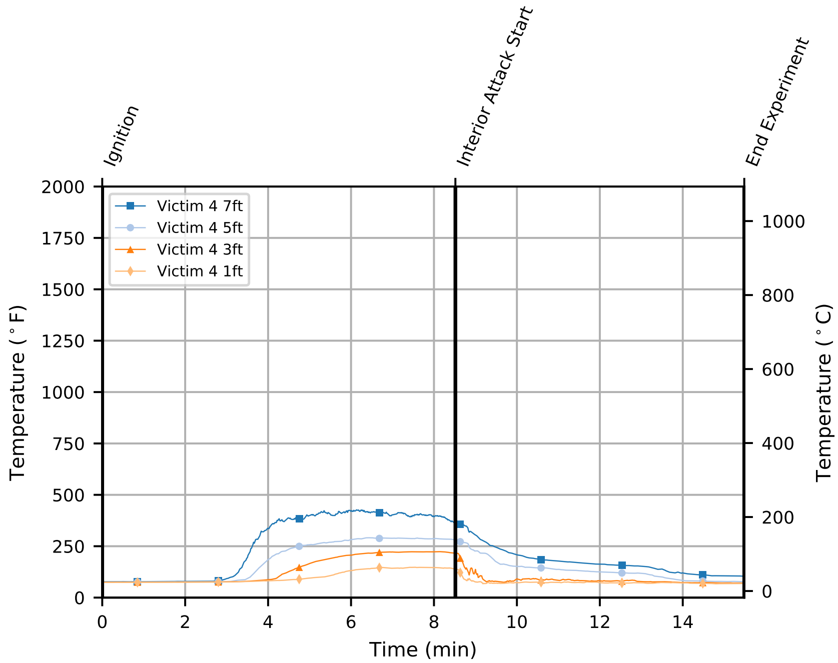


Figure E.135: Experiment 4 - Victim 4 Temps

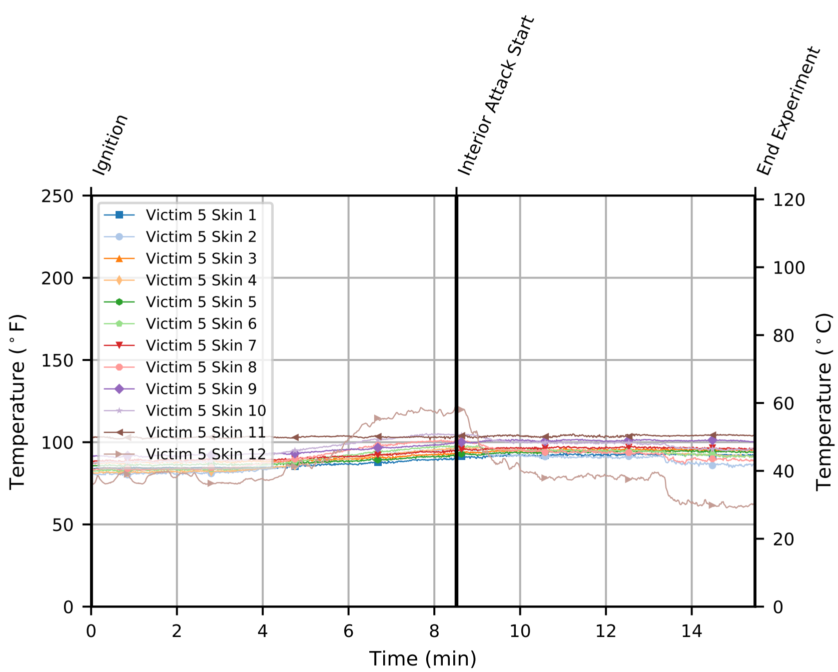


Figure E.136: Experiment 4 - Victim 5 Skin Temps

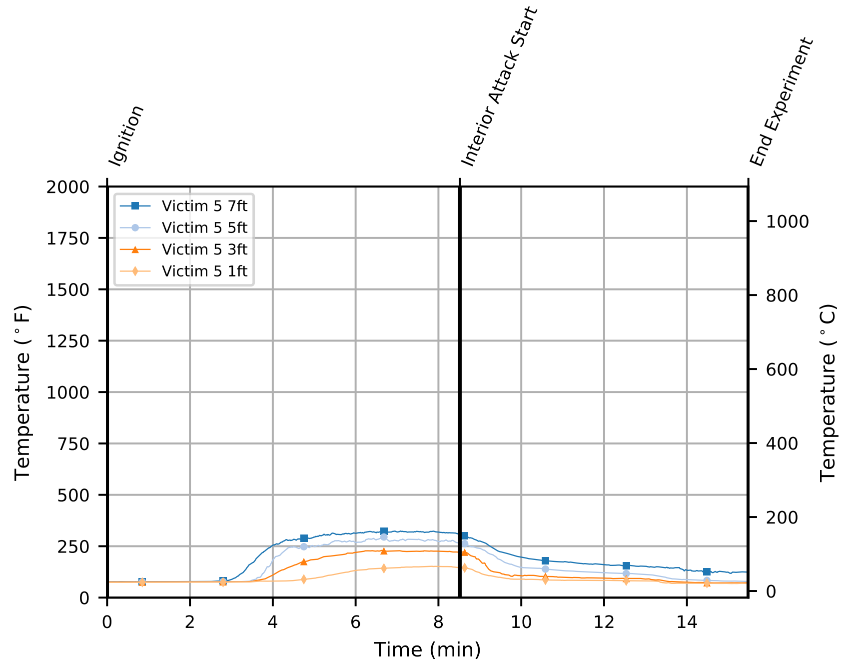


Figure E.137: Experiment 4 - Victim 5 Temps

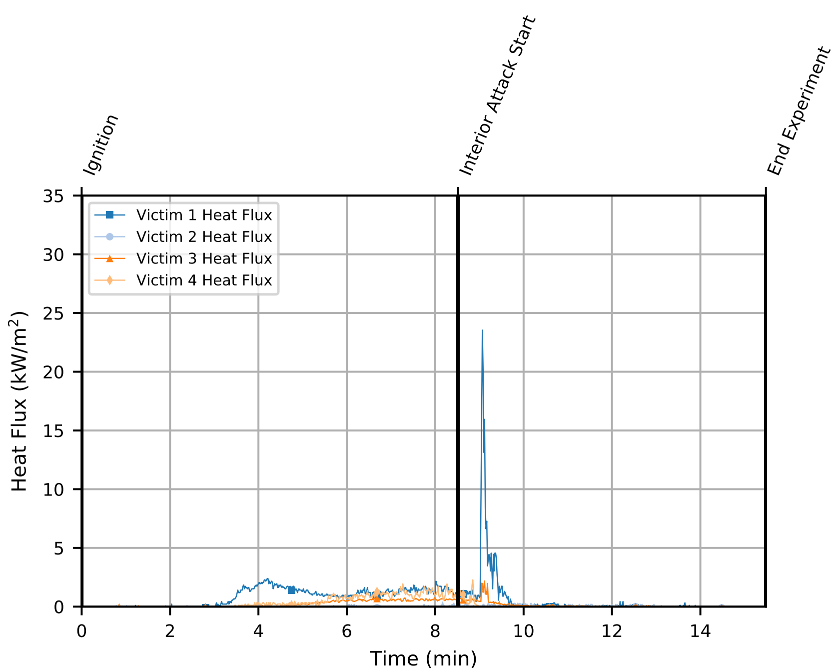


Figure E.138: Experiment 4 - Victim Heat Flux

E.5 Experiment 5 Data

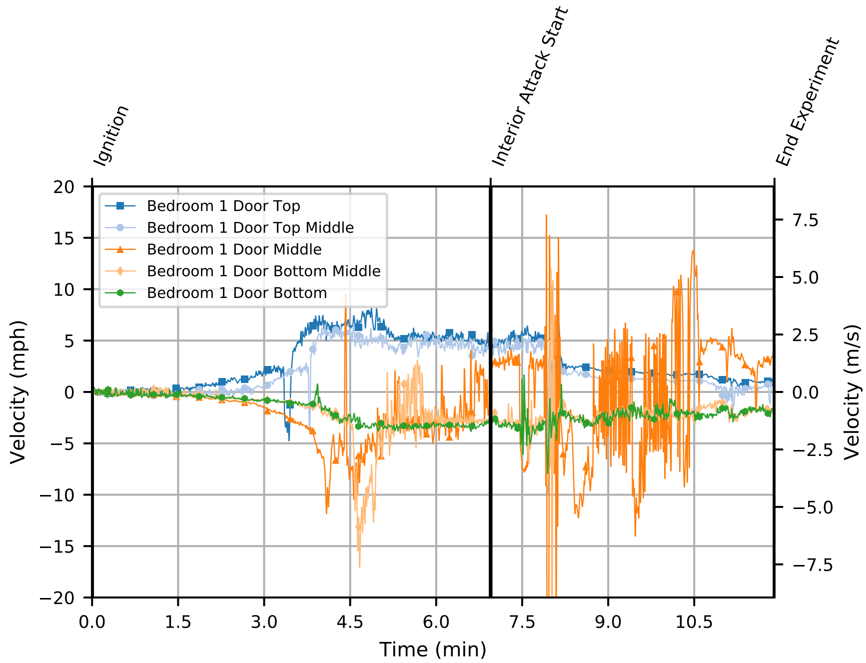


Figure E.139: Experiment 5 - Bedroom 1 Door

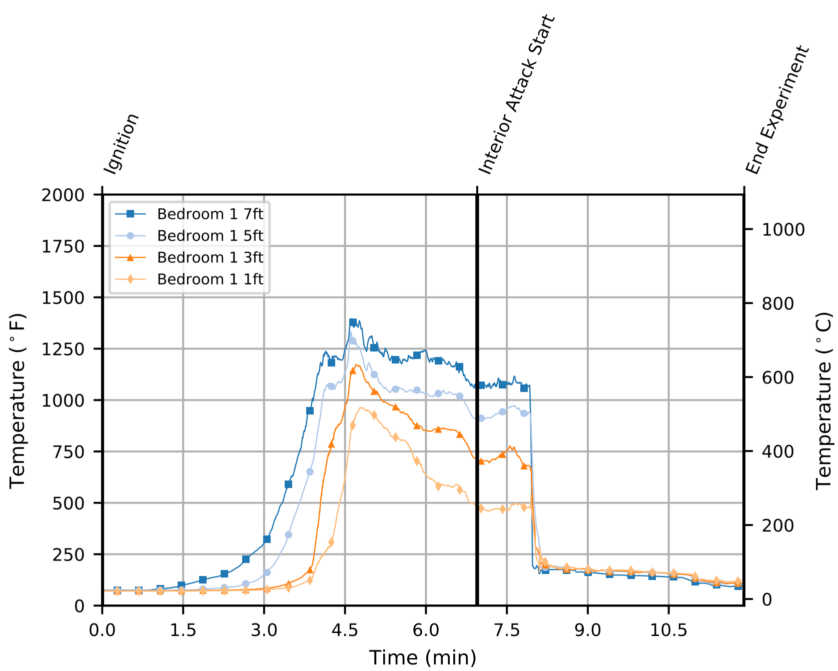


Figure E.140: Experiment 5 - Bedroom 1 Temps

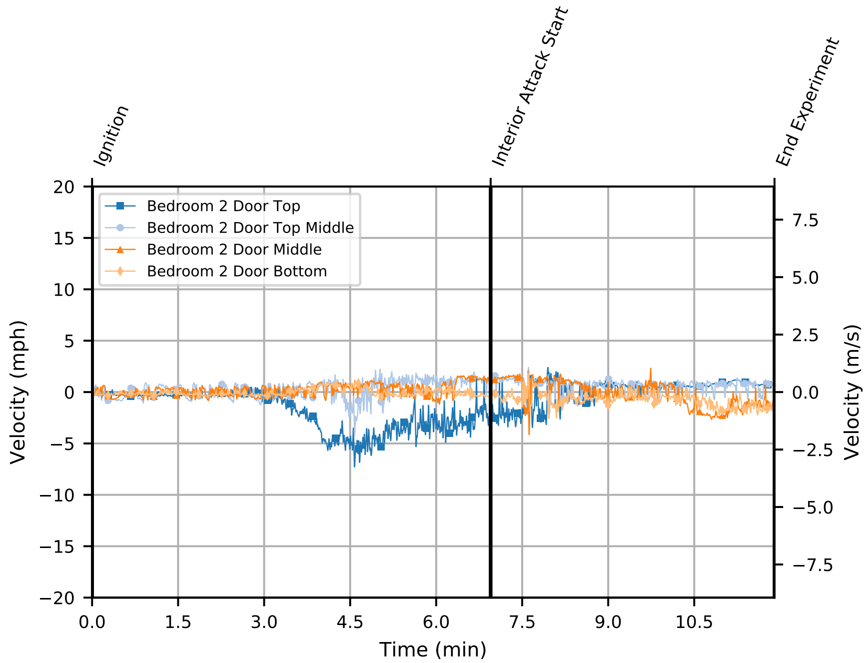


Figure E.141: Experiment 5 - Bedroom 2 Door

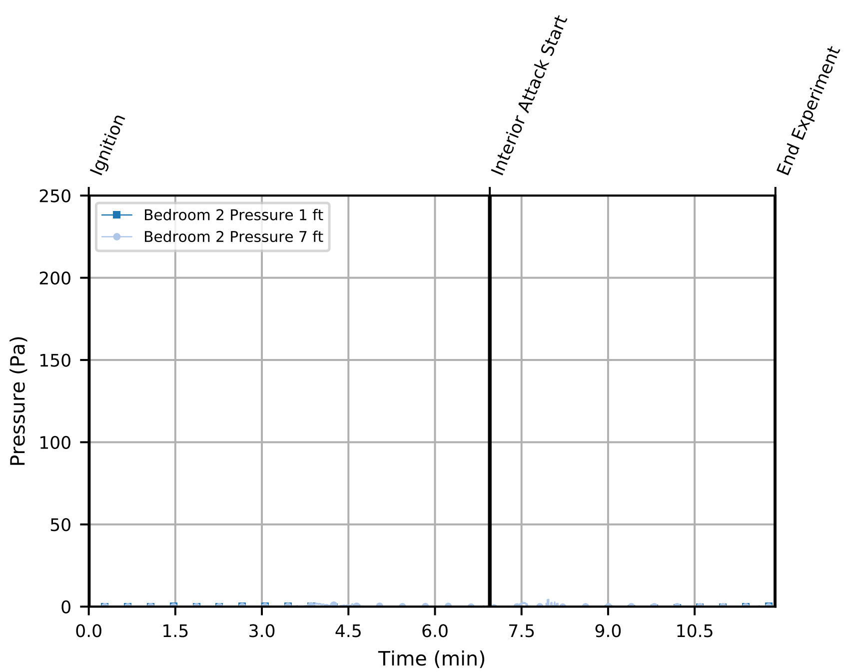


Figure E.142: Experiment 5 - Bedroom 2 Pressure

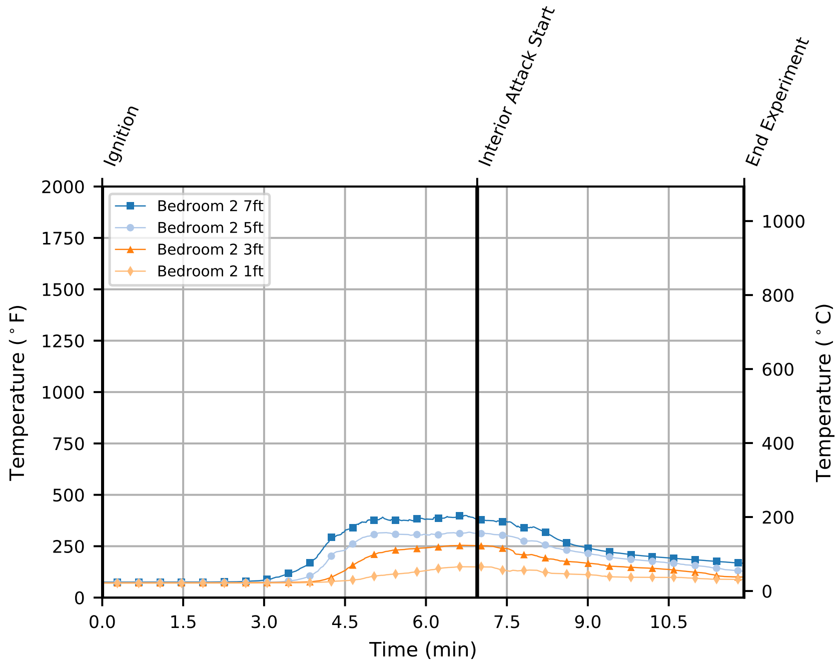


Figure E.143: Experiment 5 - Bedroom 2 Temps

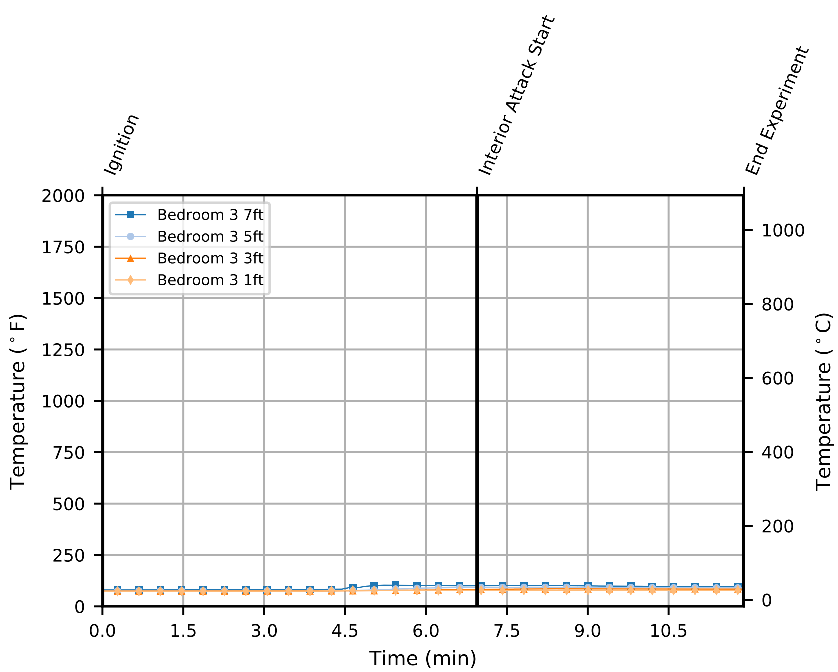


Figure E.144: Experiment 5 - Bedroom 3 Temps

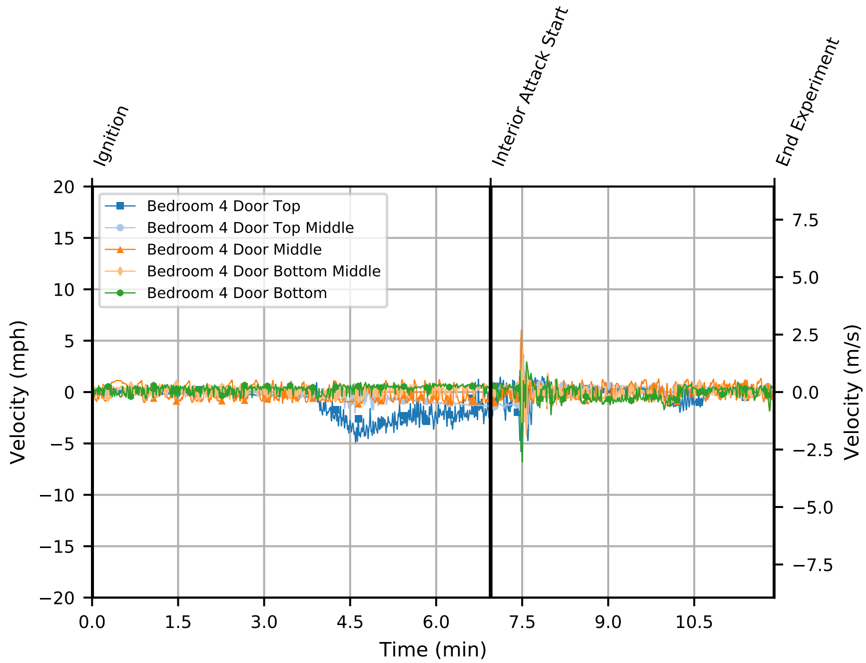


Figure E.145: Experiment 5 - Bedroom 4 Door

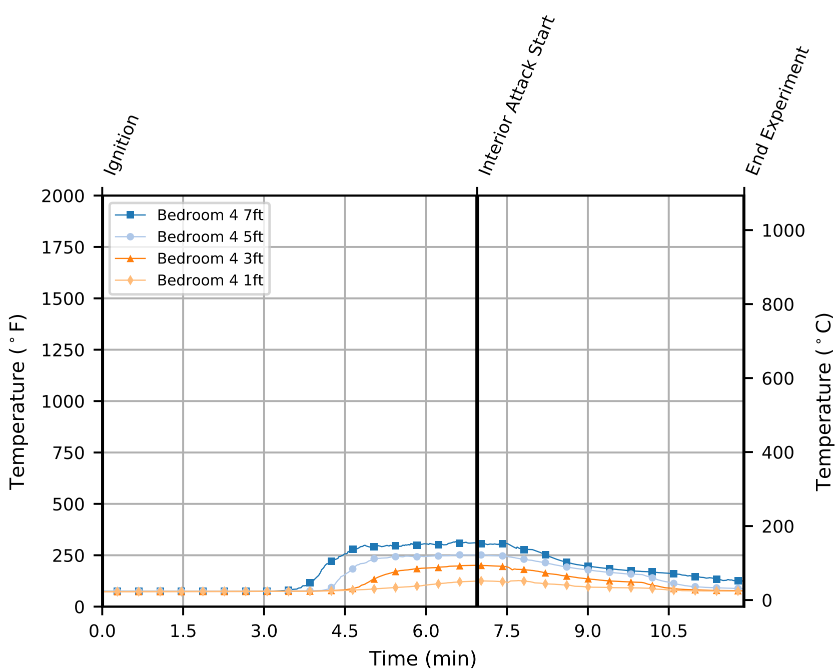


Figure E.146: Experiment 5 - Bedroom 4 Temps

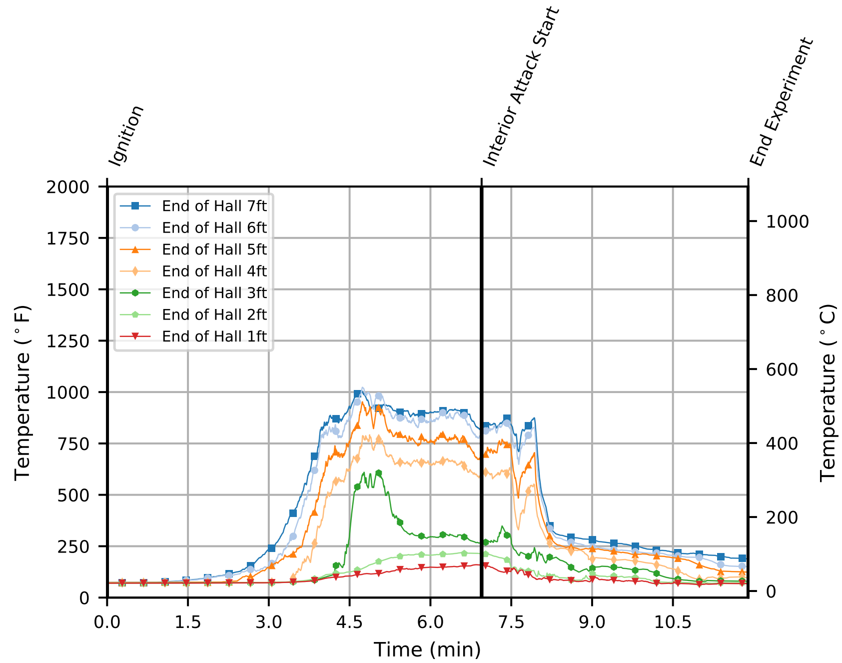


Figure E.147: Experiment 5 - End Hall Temps

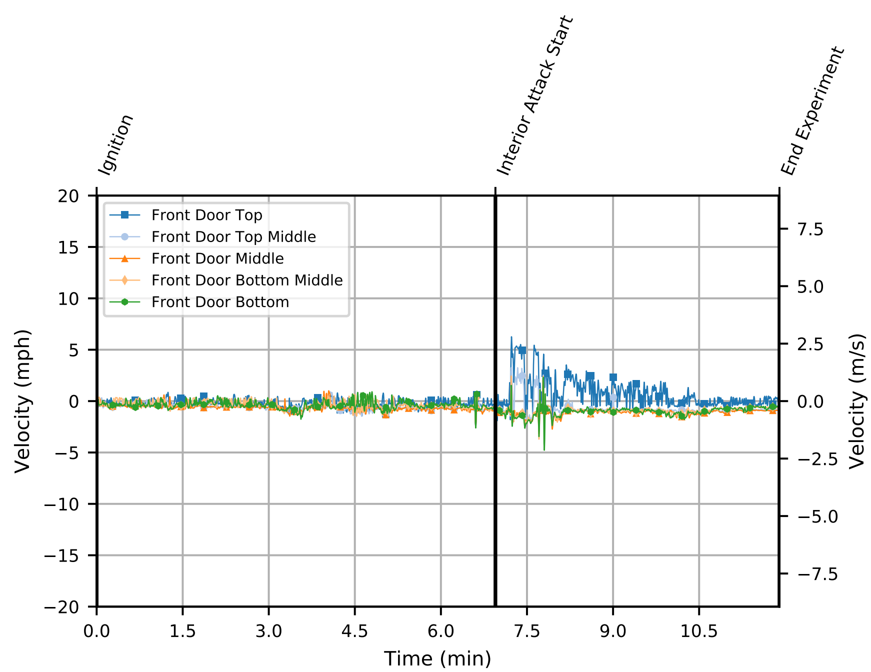


Figure E.148: Experiment 5 - Front Door Flow

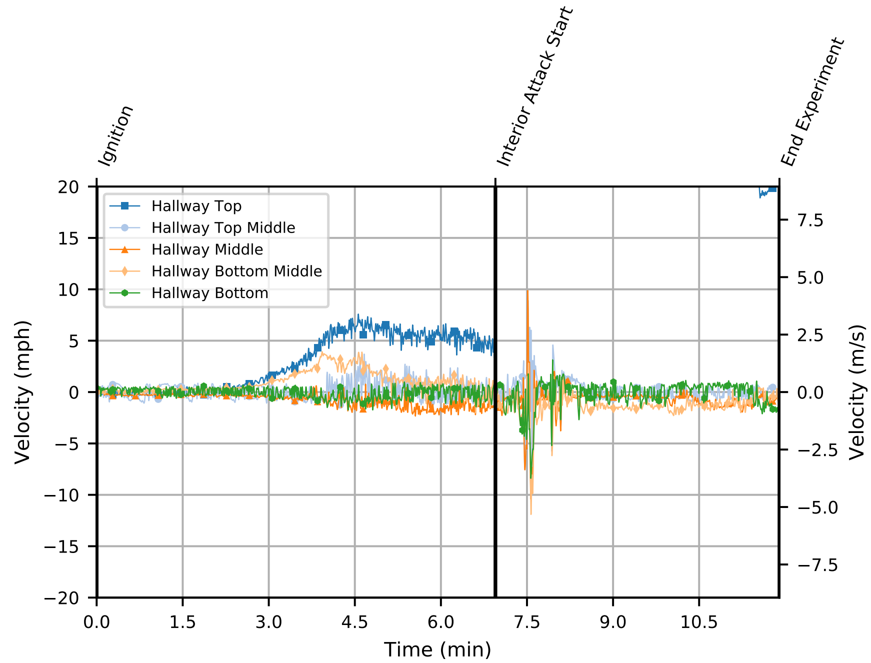


Figure E.149: Experiment 5 - Hallway Flow

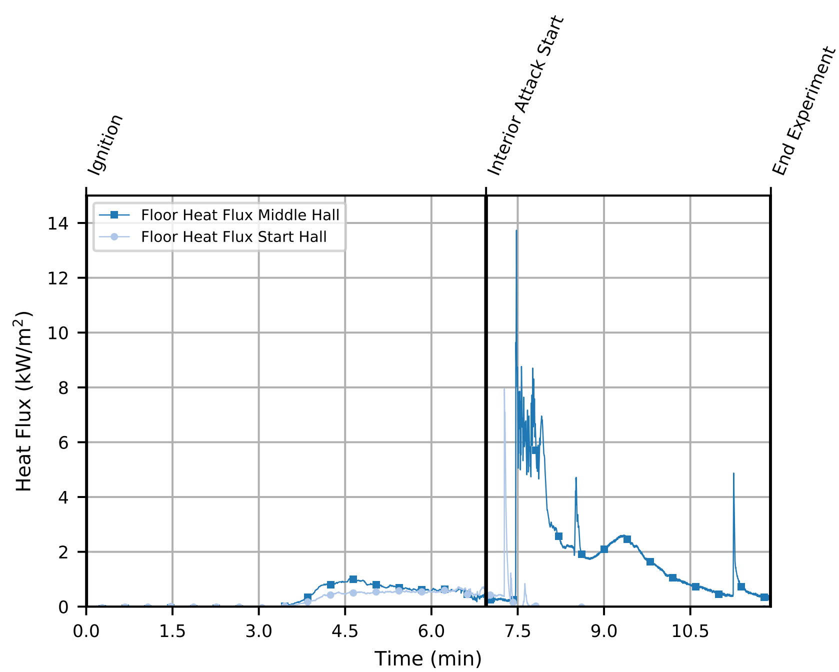


Figure E.150: Experiment 5 - Heat Flux Floor

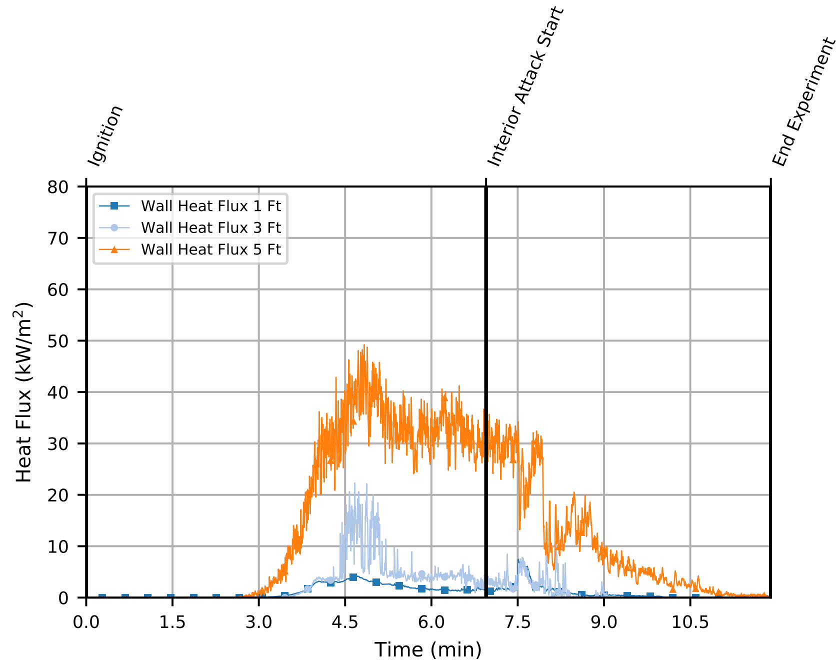


Figure E.151: Experiment 5 - Heat Flux Wall

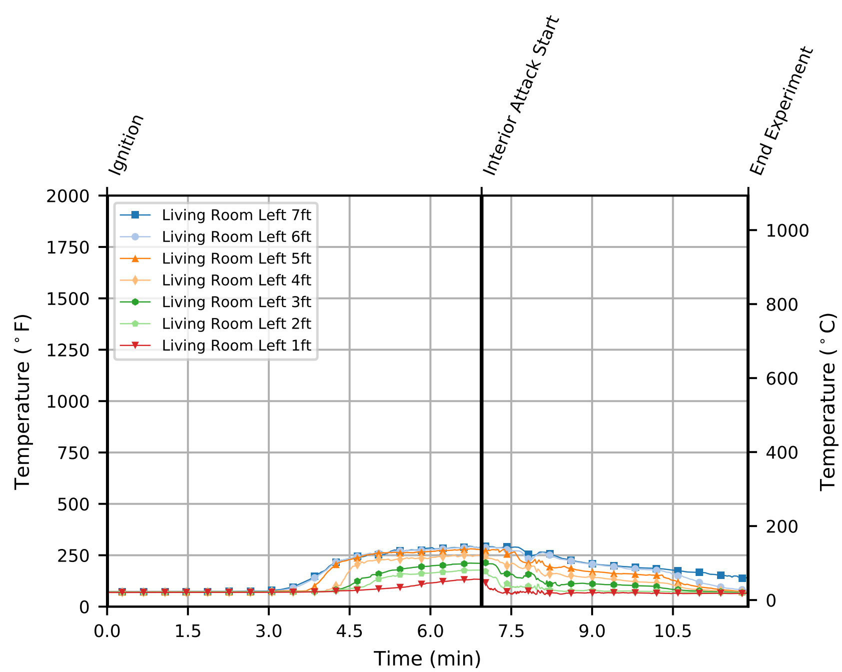


Figure E.152: Experiment 5 - Living Room Left Temps

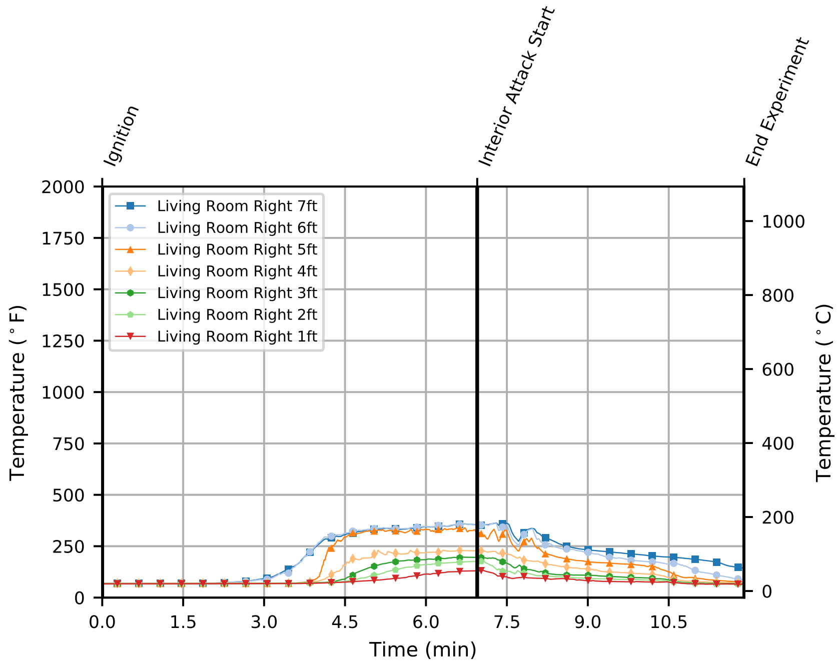


Figure E.153: Experiment 5 - Living Room Right Temps

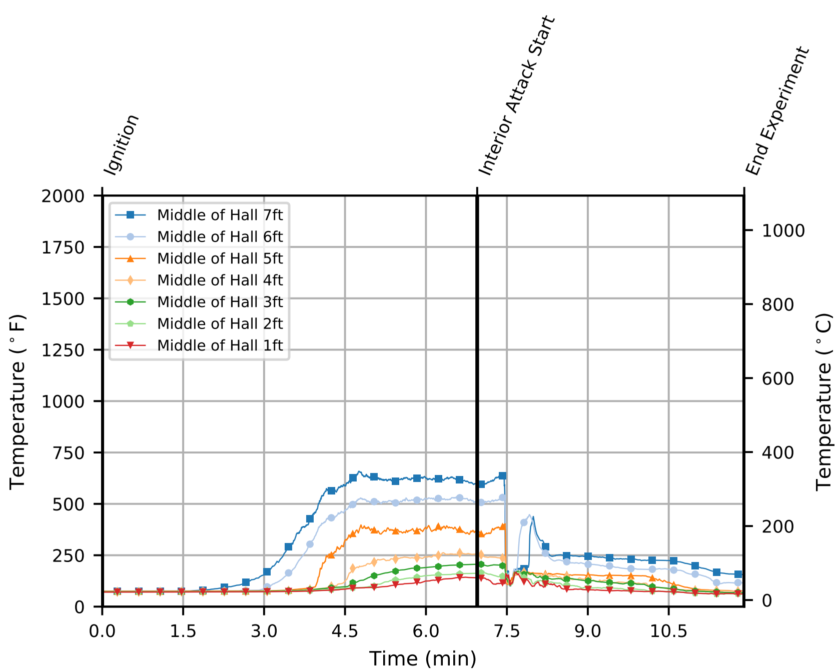


Figure E.154: Experiment 5 - Middle Hall Temps

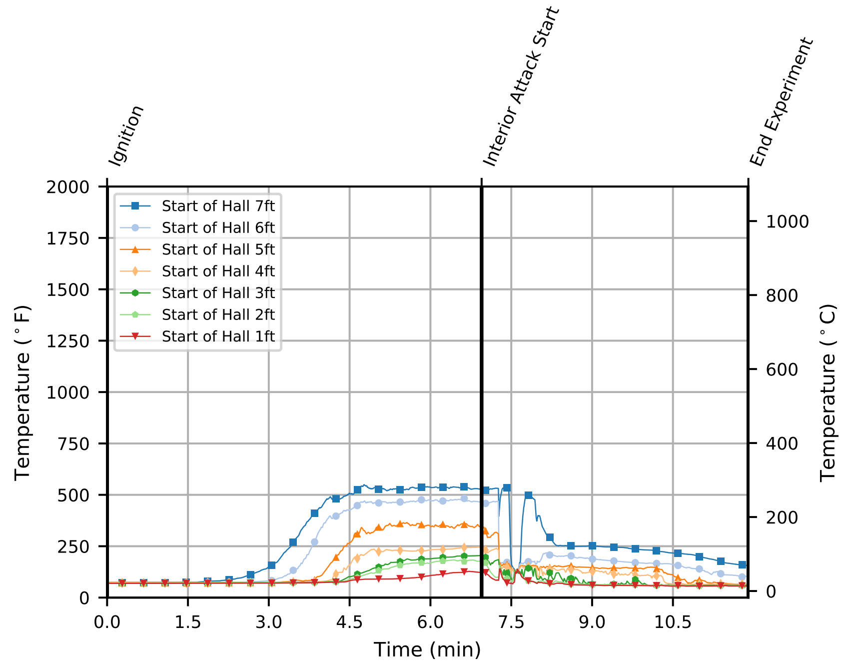


Figure E.155: Experiment 5 - Start Hall Temps

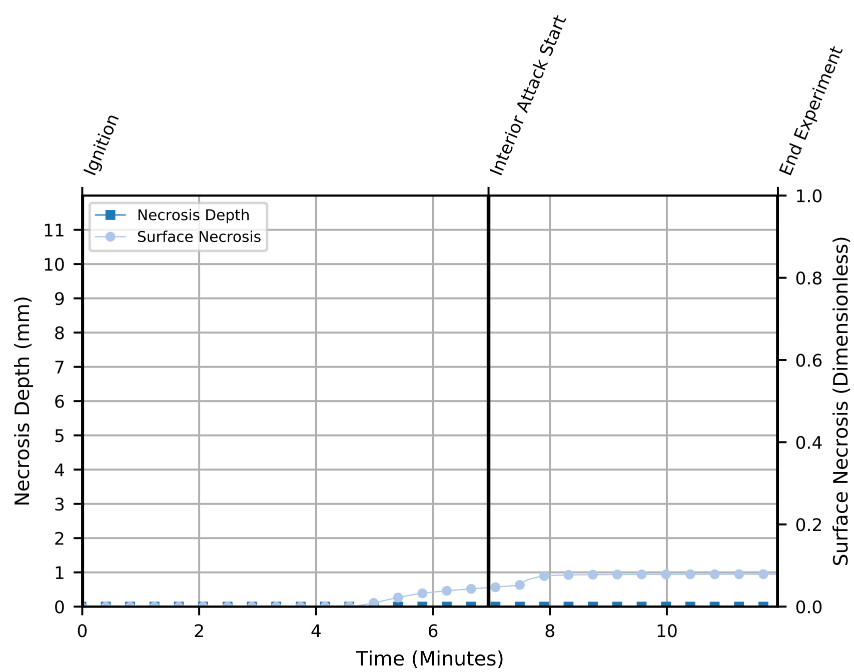


Figure E.156: Experiment 5 - Vic 1 Necrosis Depth

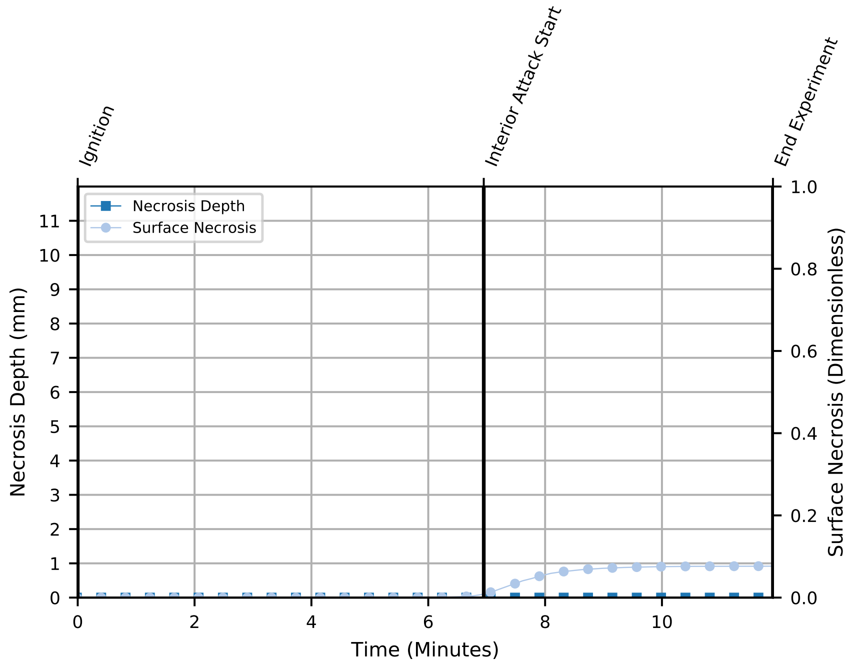


Figure E.157: Experiment 5 - Vic 3 Necrosis Depth

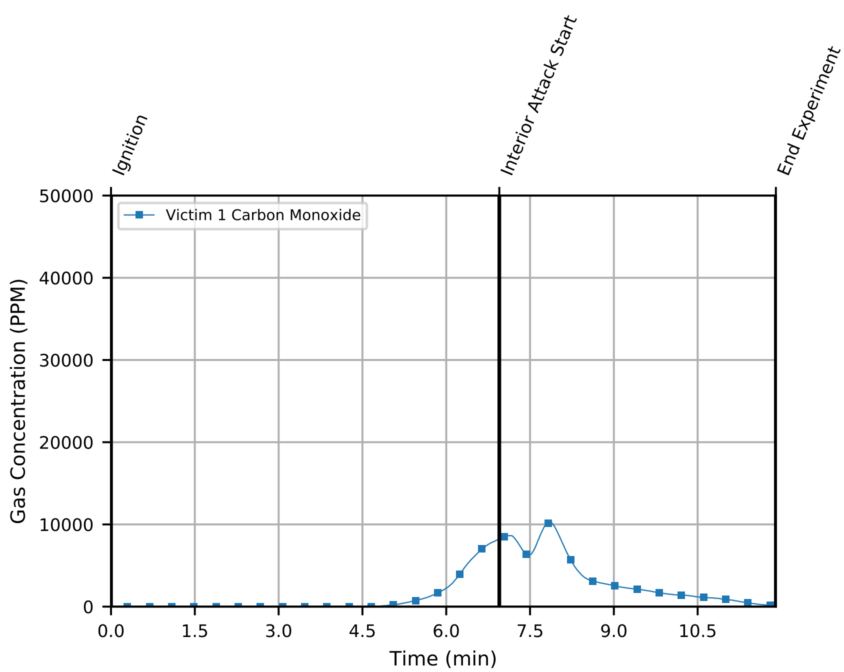


Figure E.158: Experiment 5 - Victim 1 Carbon Monoxide

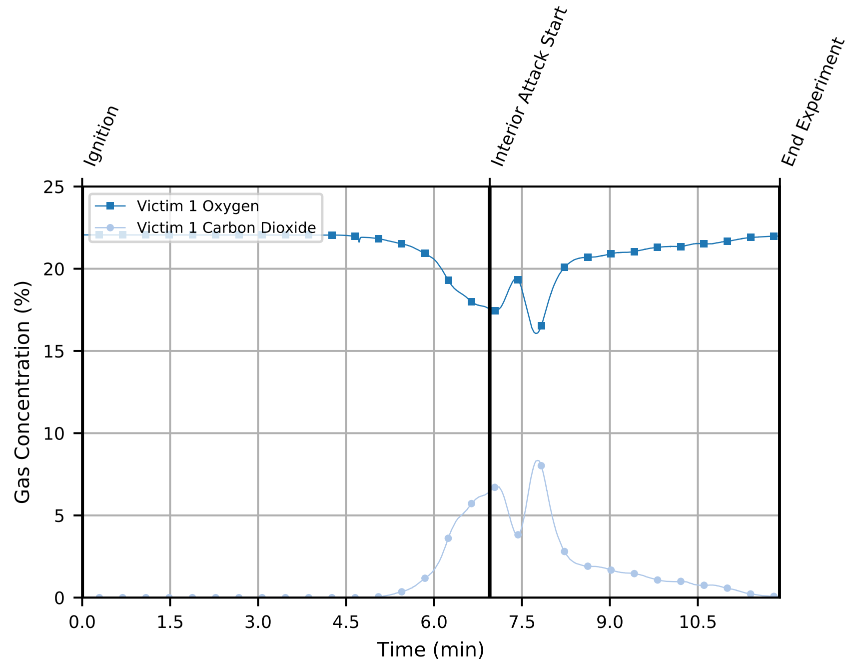


Figure E.159: Experiment 5 - Victim 1 Gas

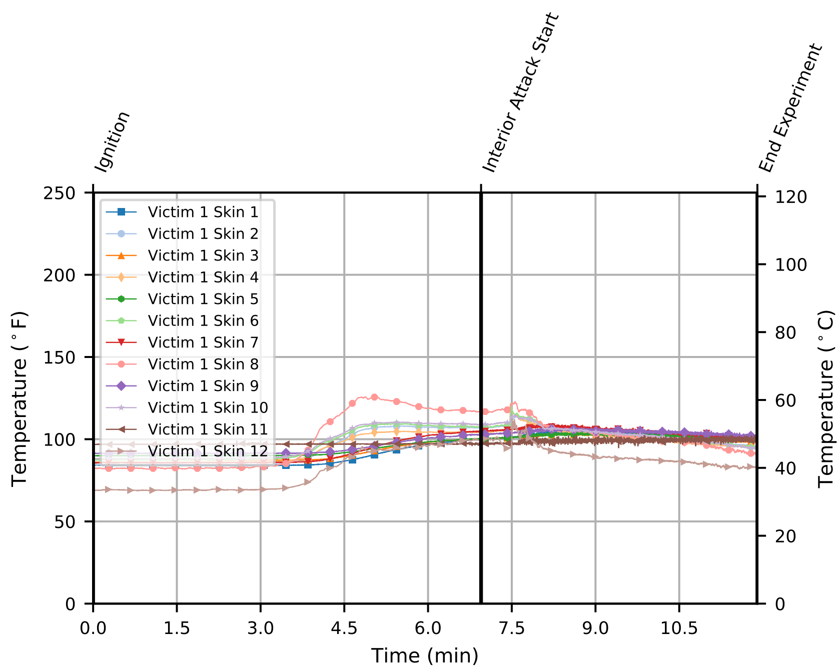


Figure E.160: Experiment 5 - Victim 1 Skin Temps

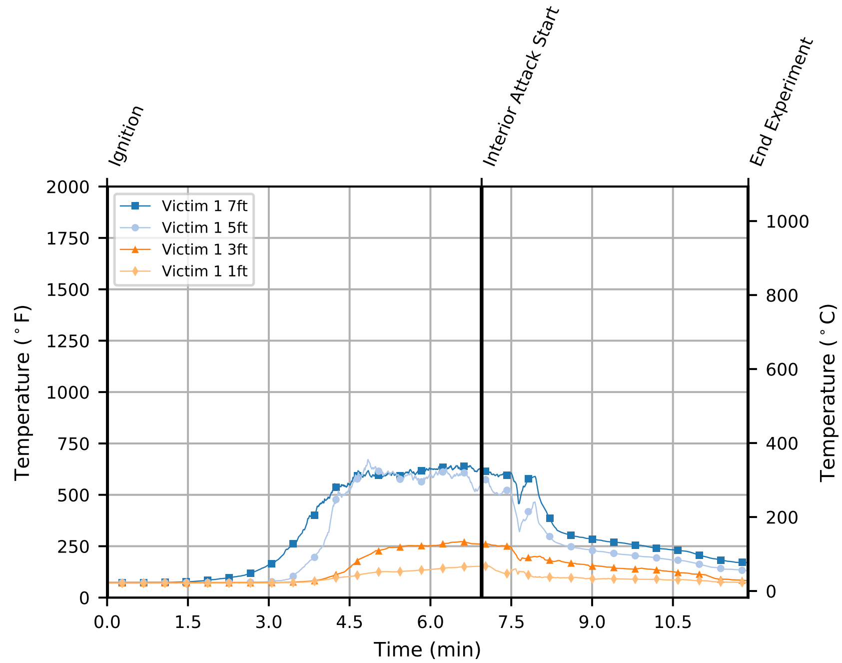


Figure E.161: Experiment 5 - Victim 1 Temps

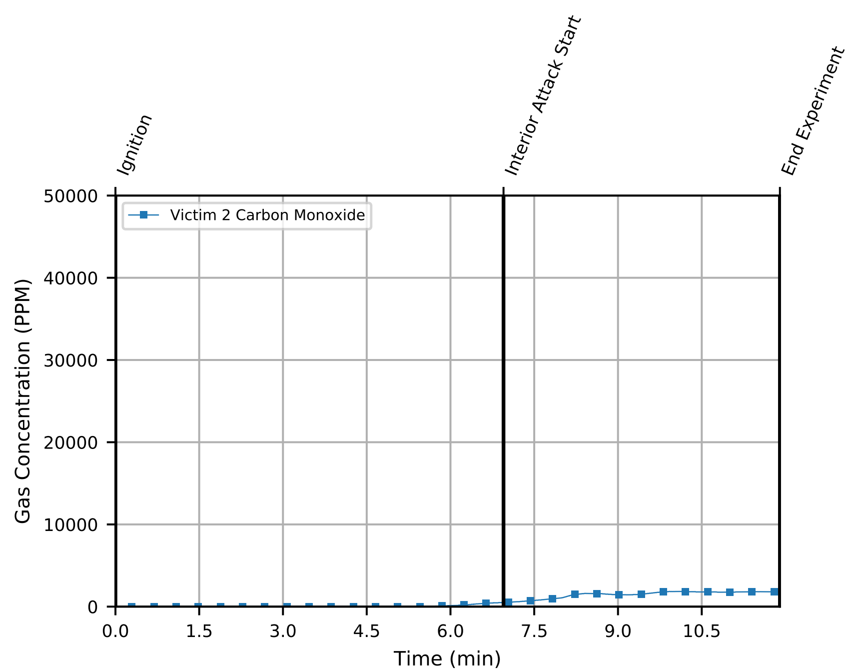


Figure E.162: Experiment 5 - Victim 2 Carbon Monoxide

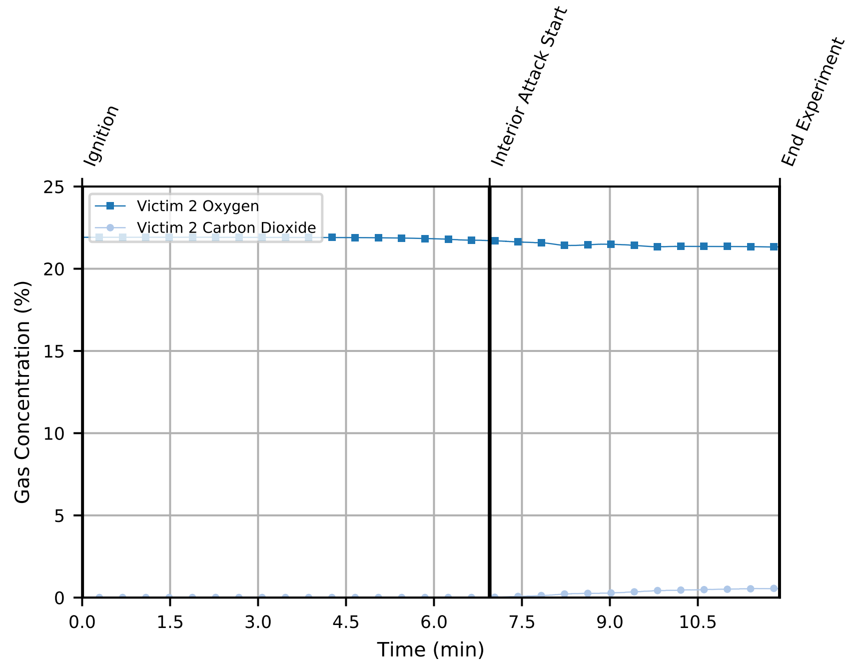


Figure E.163: Experiment 5 - Victim 2 Gas

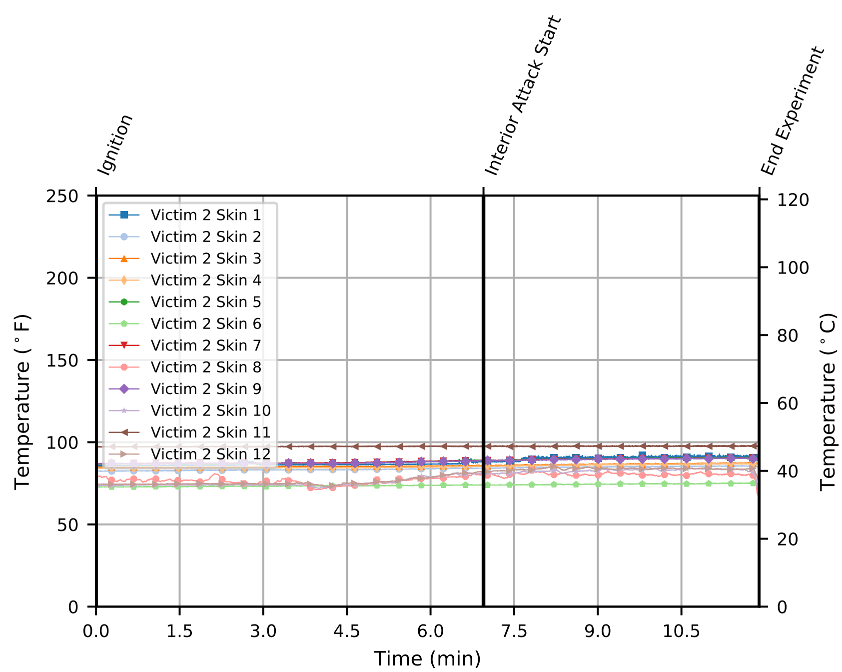


Figure E.164: Experiment 5 - Victim 2 Skin Temps

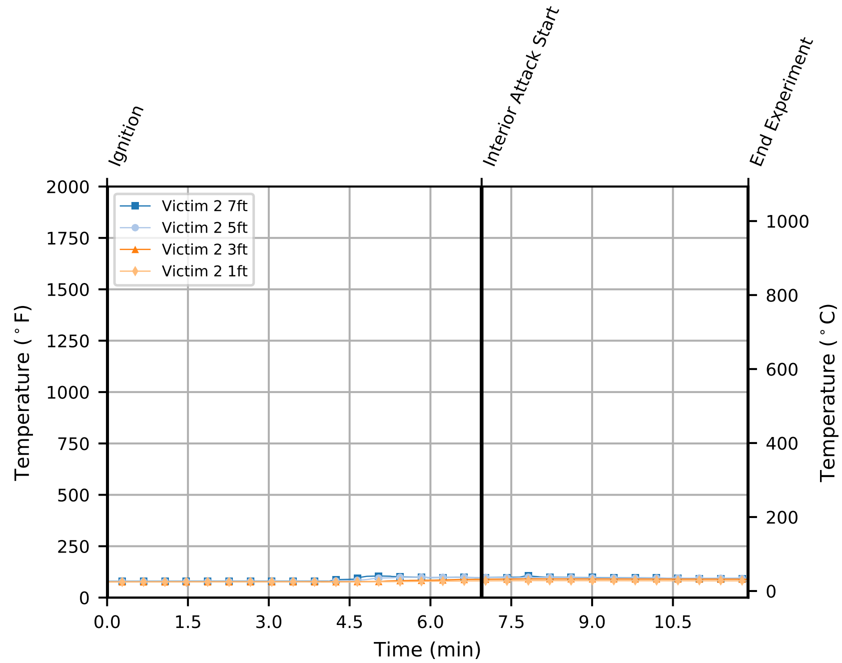


Figure E.165: Experiment 5 - Victim 2 Temps

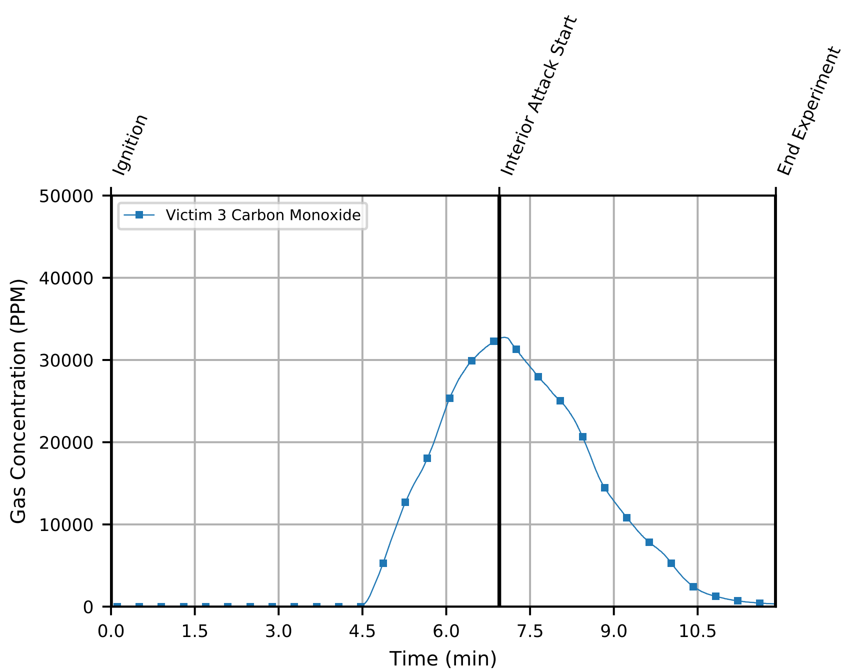


Figure E.166: Experiment 5 - Victim 3 Carbon Monoxide

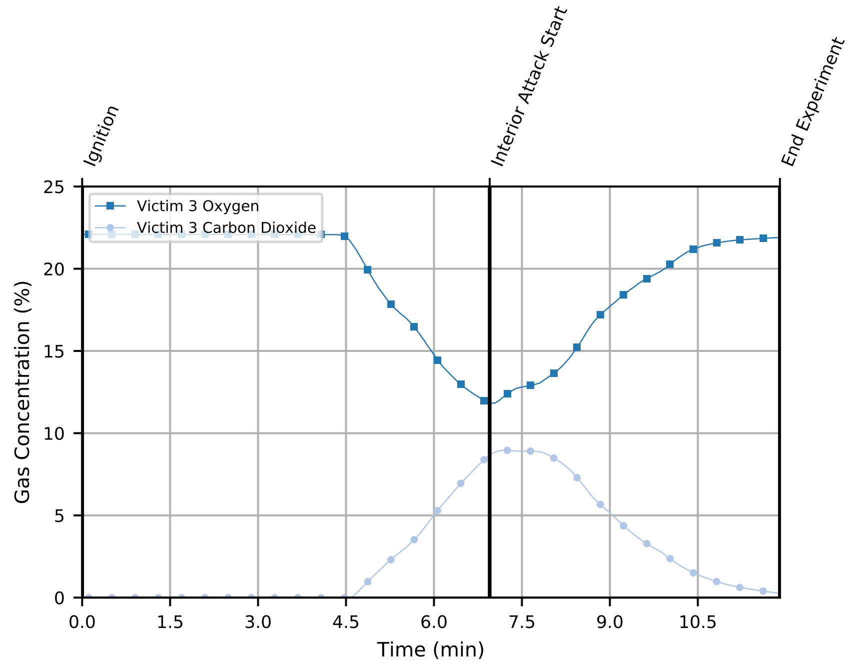


Figure E.167: Experiment 5 - Victim 3 Gas

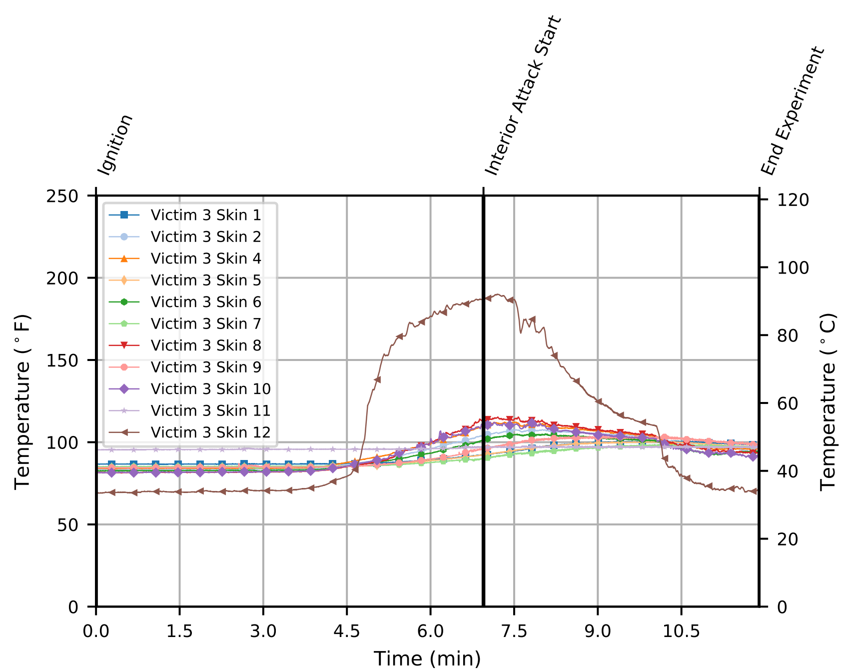


Figure E.168: Experiment 5 - Victim 3 Skin Temps

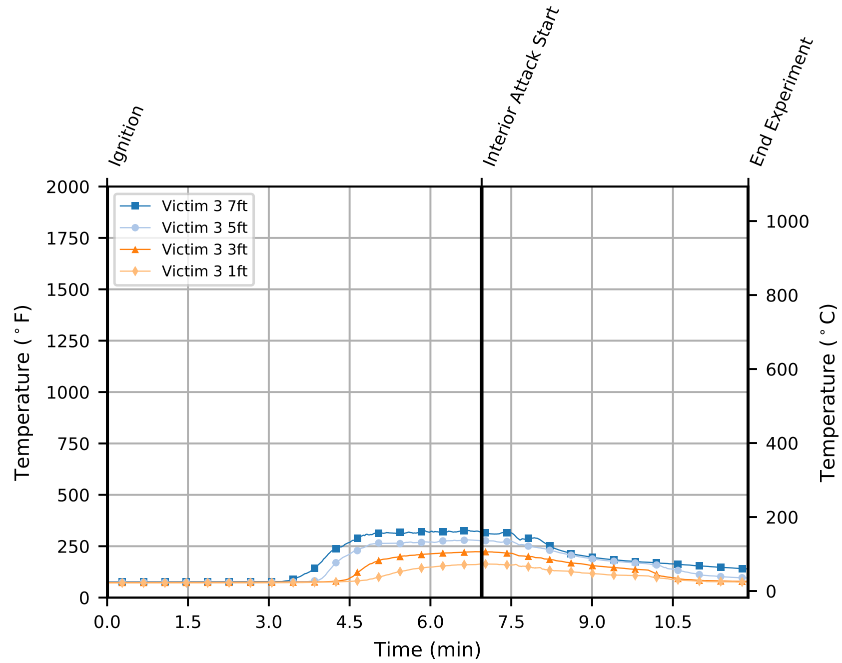


Figure E.169: Experiment 5 - Victim 3 Temps

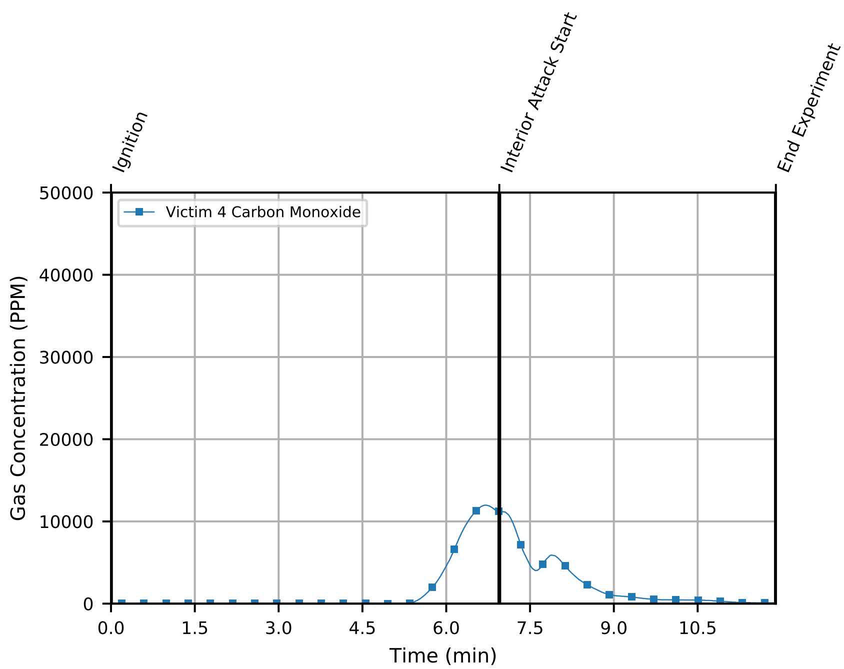


Figure E.170: Experiment 5 - Victim 4 Carbon Monoxide

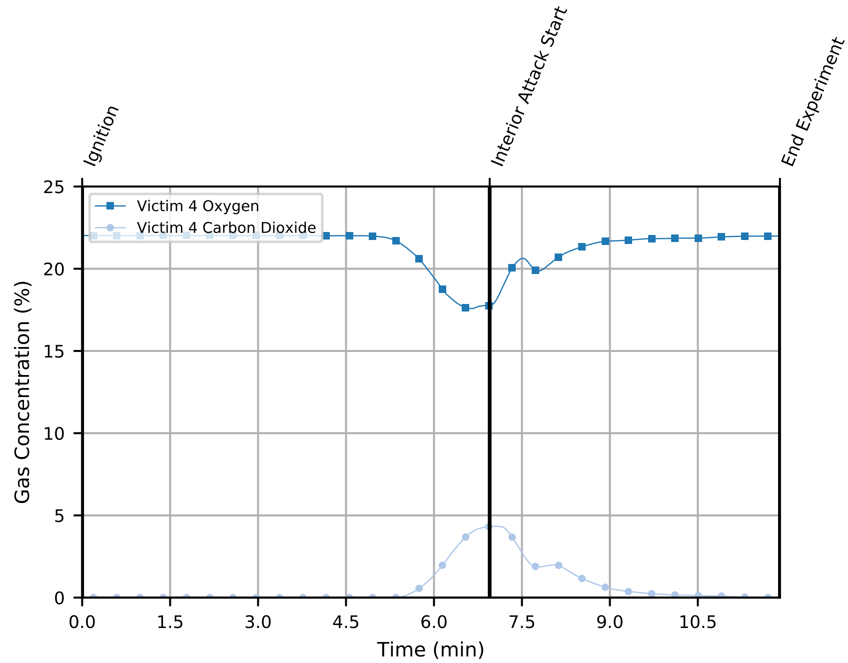


Figure E.171: Experiment 5 - Victim 4 Gas

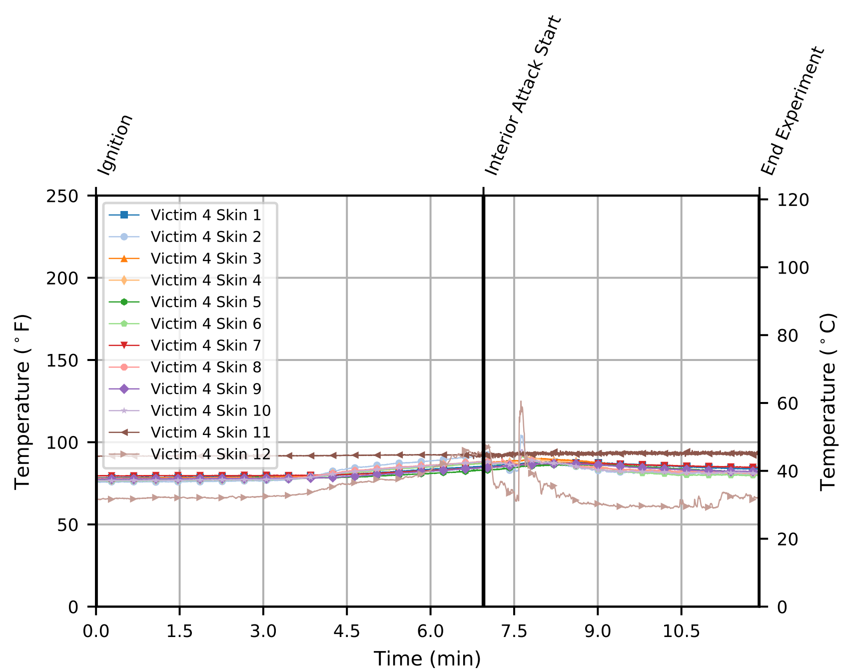


Figure E.172: Experiment 5 - Victim 4 Skin Temps

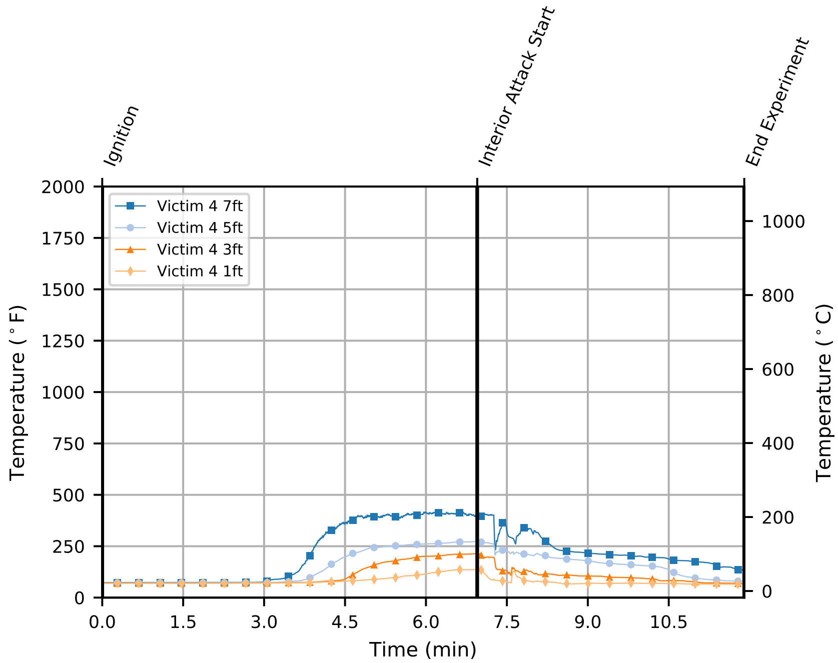


Figure E.173: Experiment 5 - Victim 4 Temps

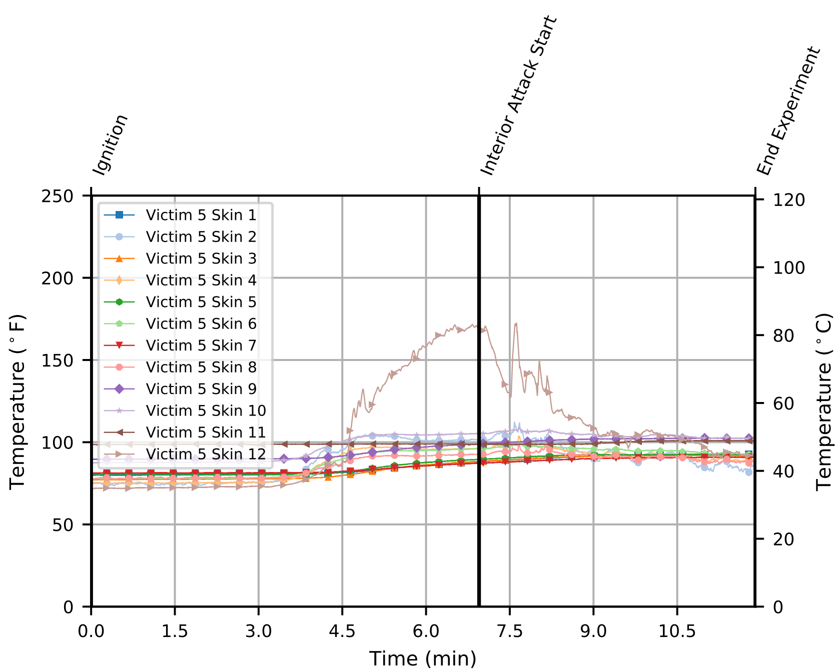


Figure E.174: Experiment 5 - Victim 5 Skin Temps

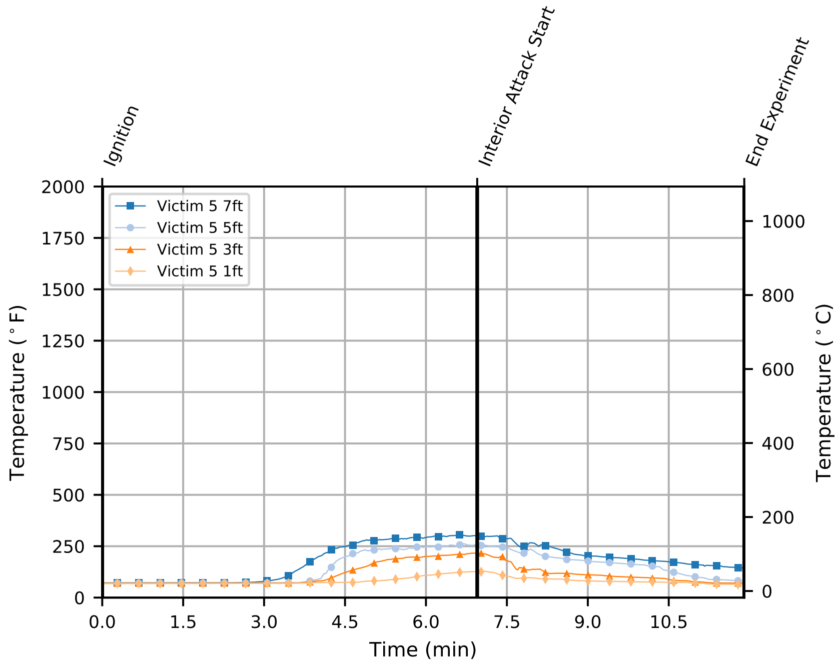


Figure E.175: Experiment 5 - Victim 5 Temps

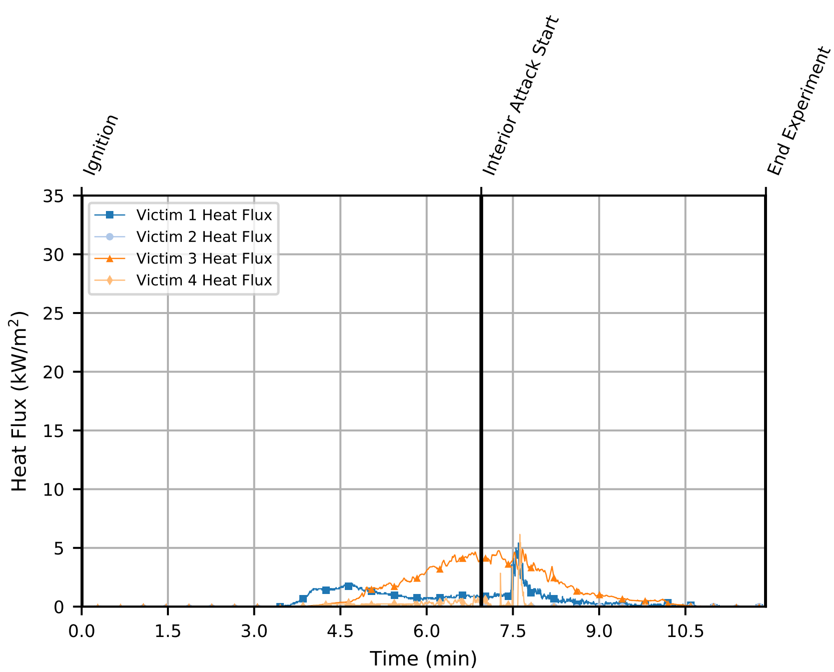


Figure E.176: Experiment 5 - Victim Heat Flux

E.6 Experiment 6 Data

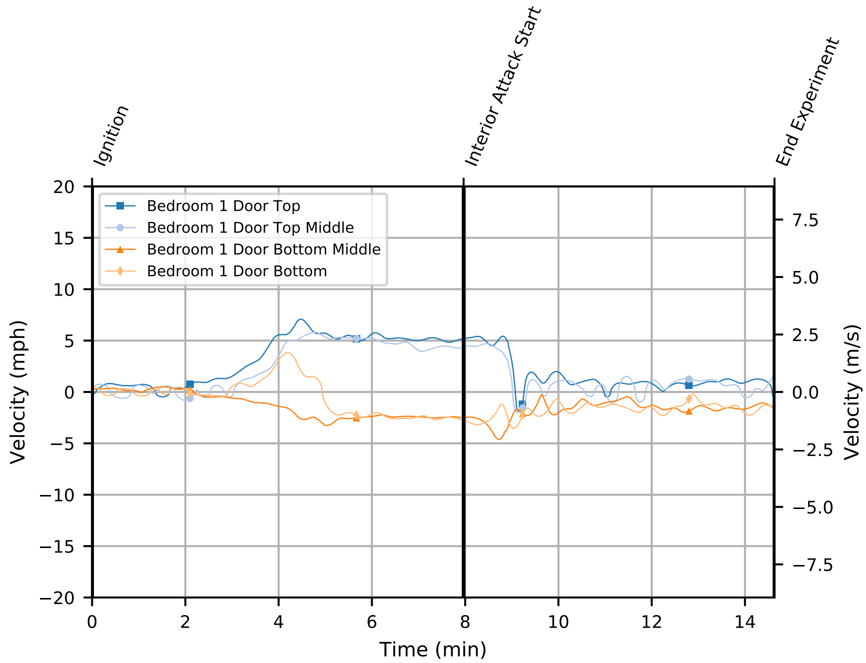


Figure E.177: Experiment 6 - Bedroom 1 Door

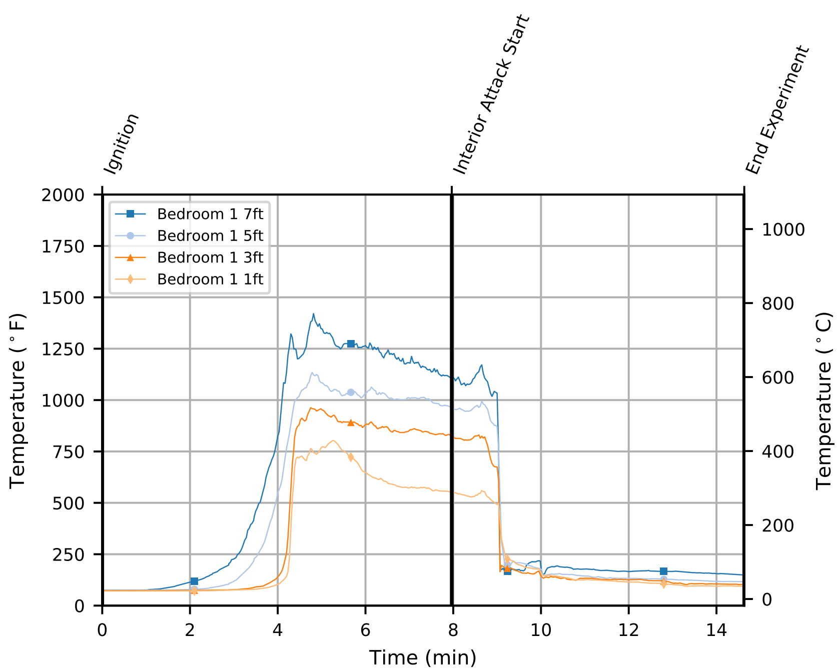


Figure E.178: Experiment 6 - Bedroom 1 Temps

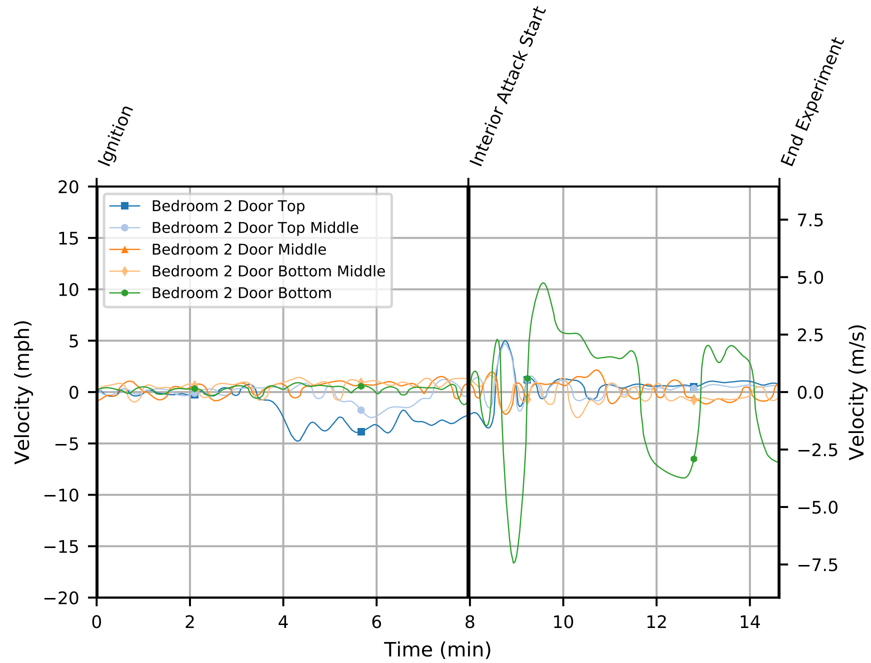


Figure E.179: Experiment 6 - Bedroom 2 Door

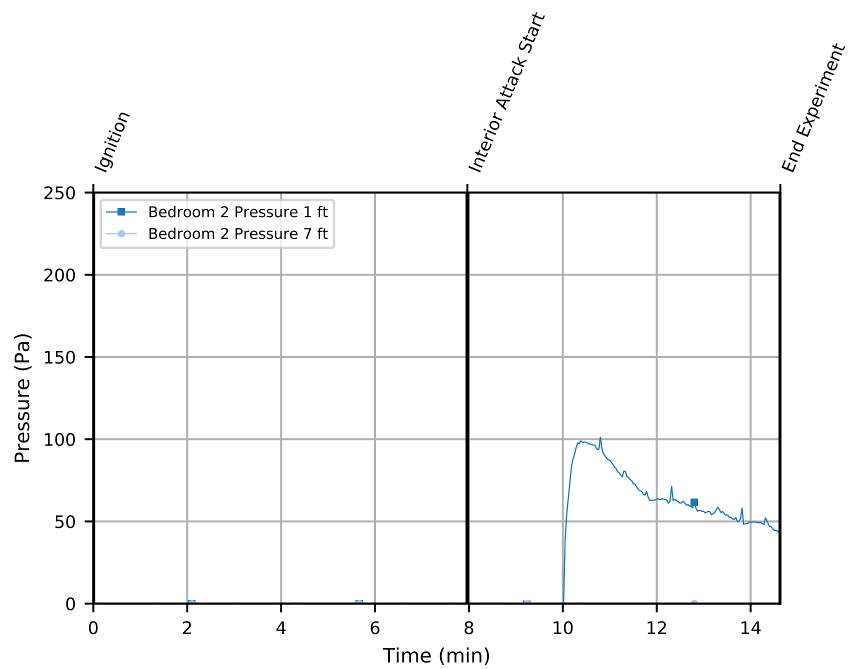


Figure E.180: Experiment 6 - Bedroom 2 Pressure

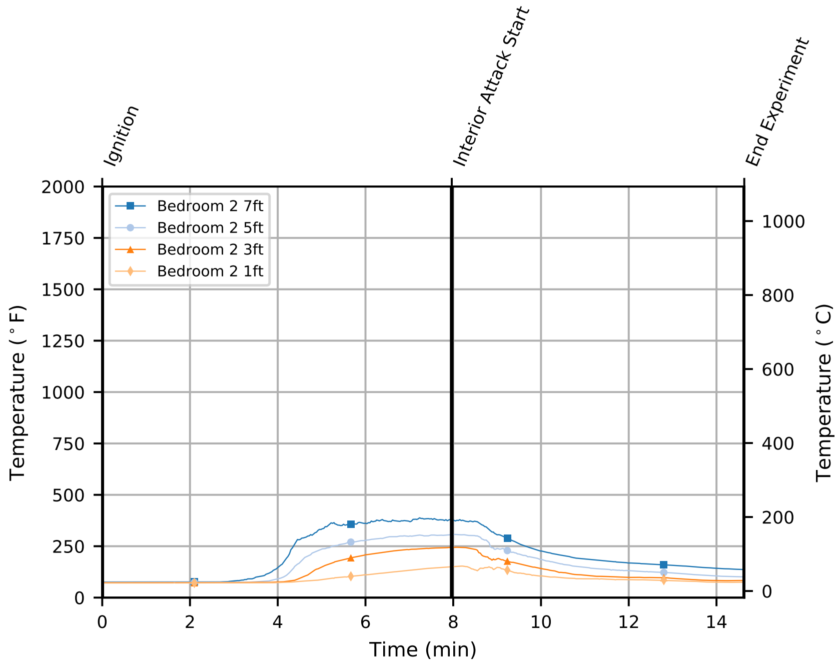


Figure E.181: Experiment 6 - Bedroom 2 Temps

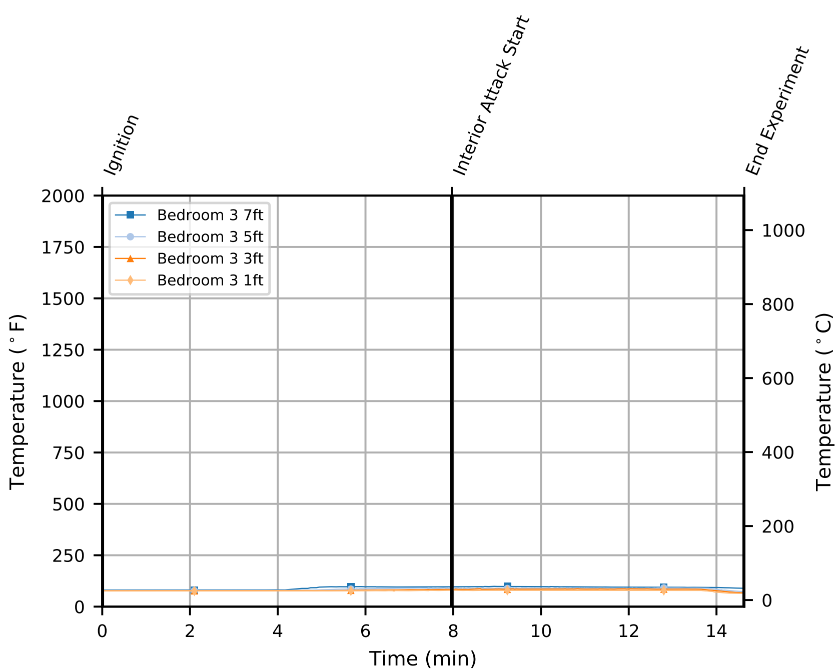


Figure E.182: Experiment 6 - Bedroom 3 Temps

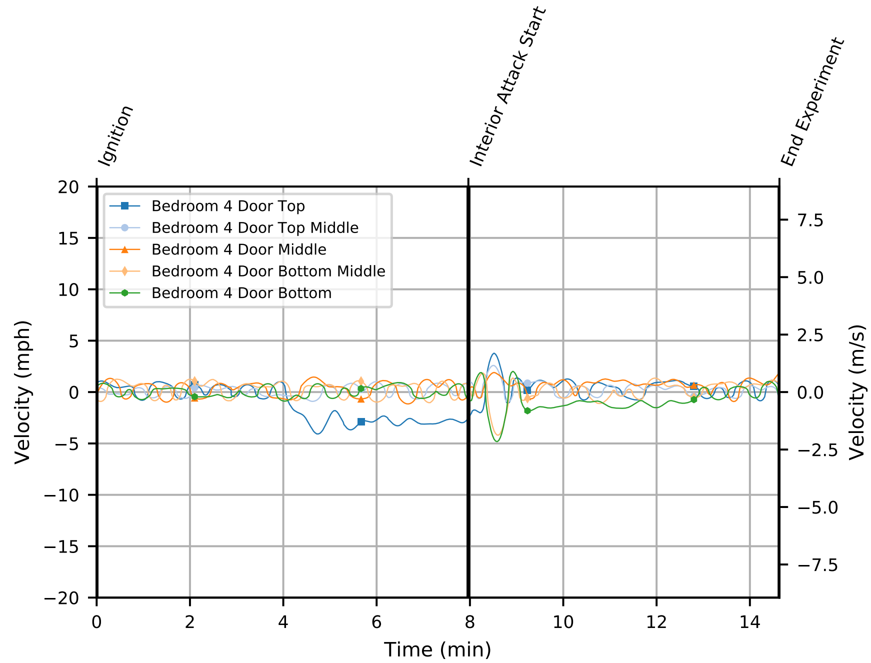


Figure E.183: Experiment 6 - Bedroom 4 Door

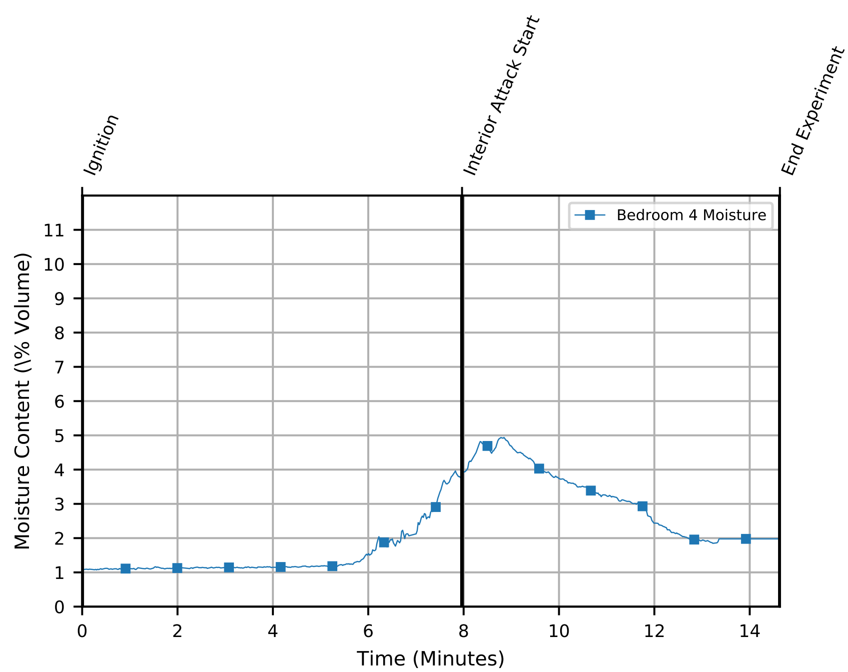


Figure E.184: Experiment 6 - Bedroom 4 Moisture

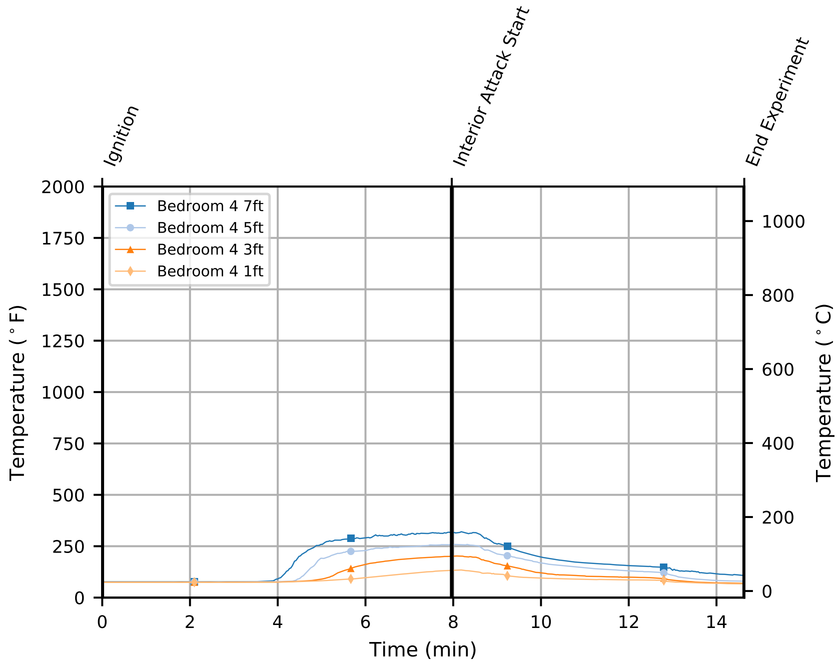


Figure E.185: Experiment 6 - Bedroom 4 Temps

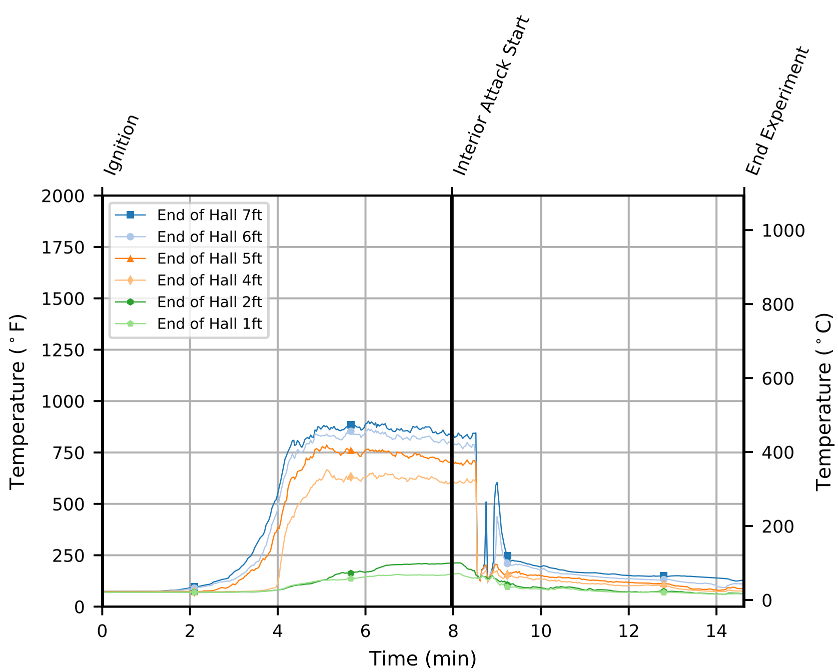


Figure E.186: Experiment 6 - End Hall Temps

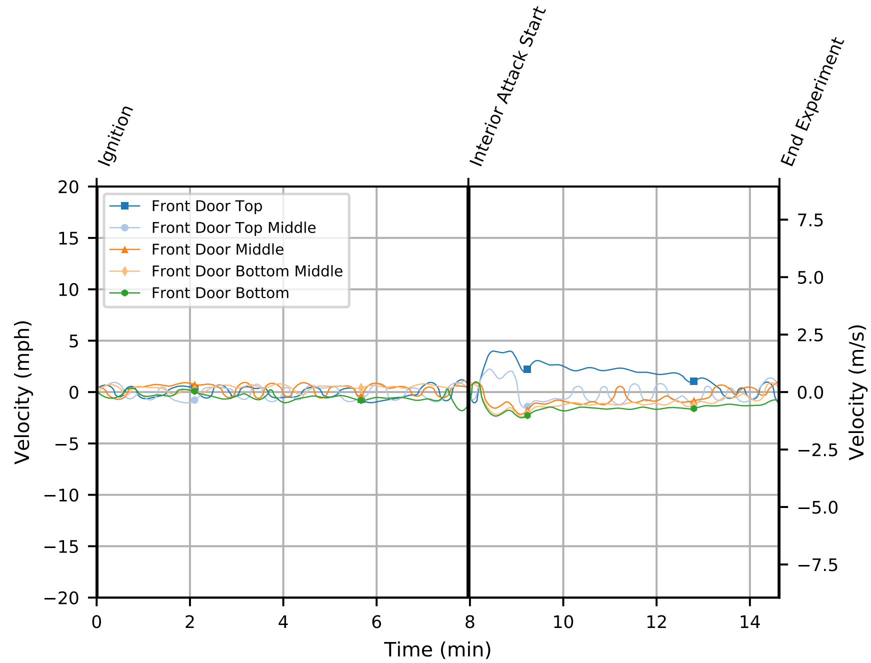


Figure E.187: Experiment 6 - Front Door Flow

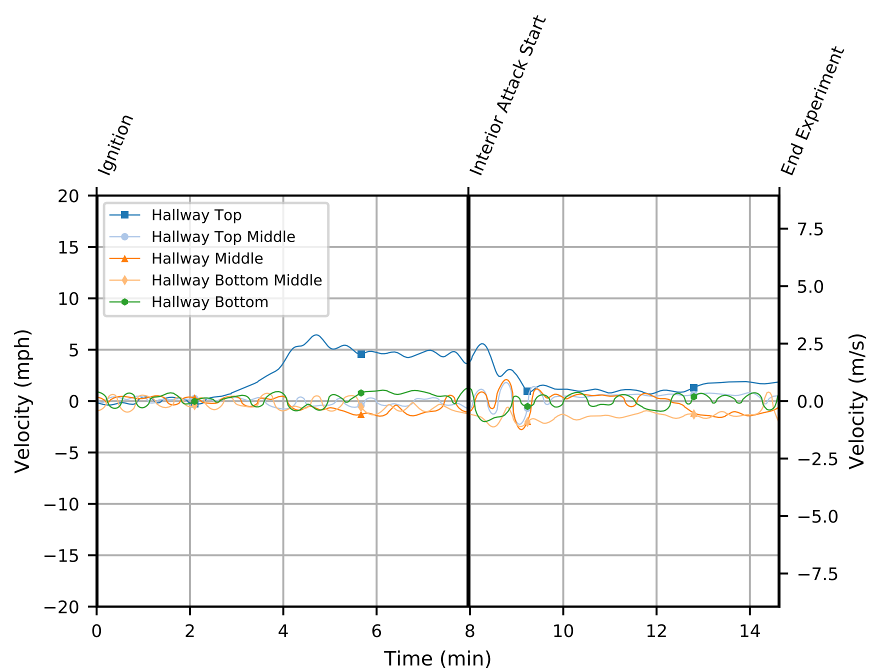


Figure E.188: Experiment 6 - Hallway Flow

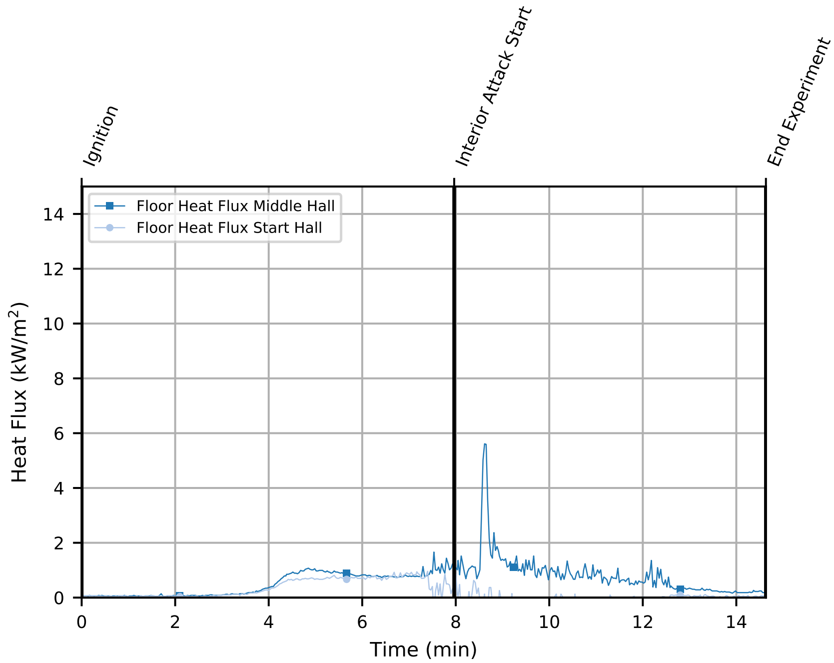


Figure E.189: Experiment 6 - Heat Flux Floor

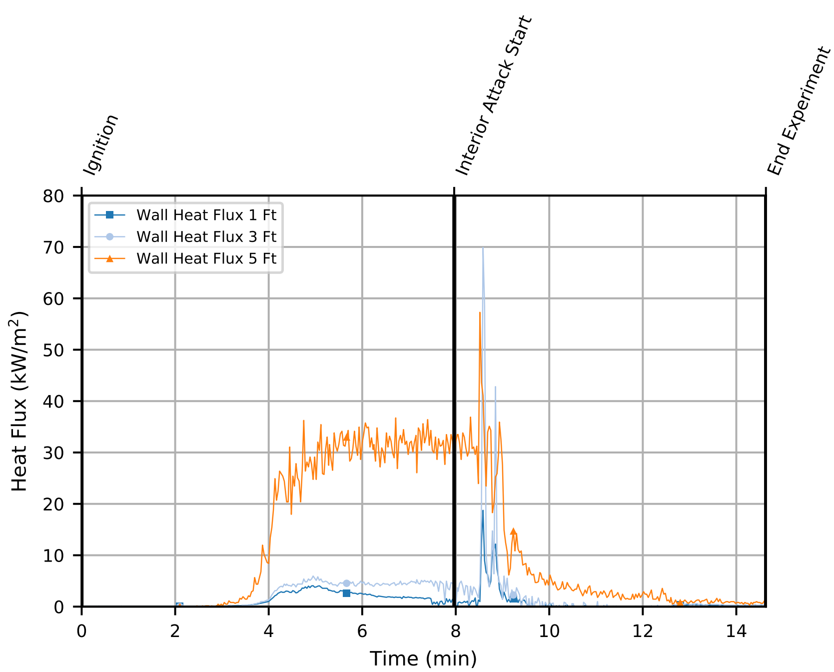


Figure E.190: Experiment 6 - Heat Flux Wall

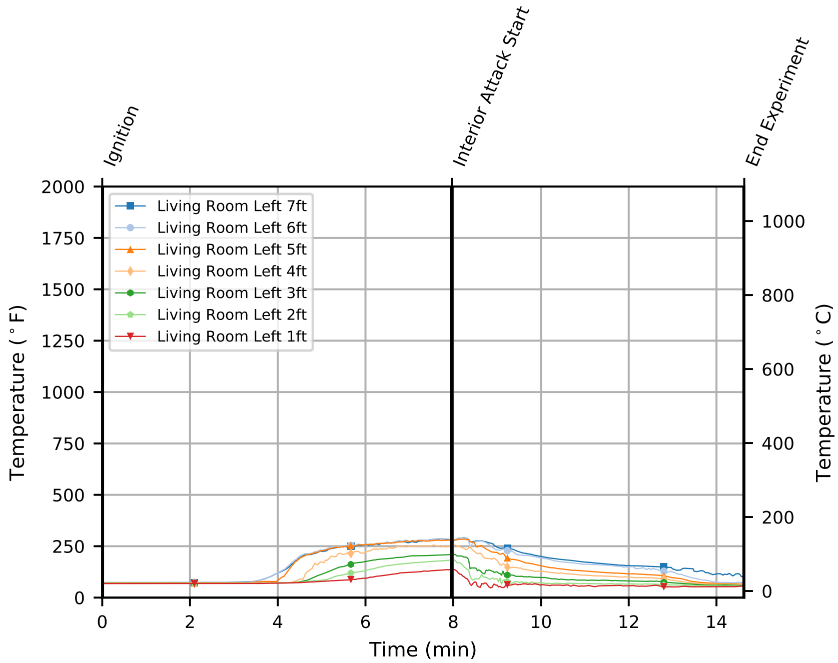


Figure E.191: Experiment 6 - Living Room Left Temps

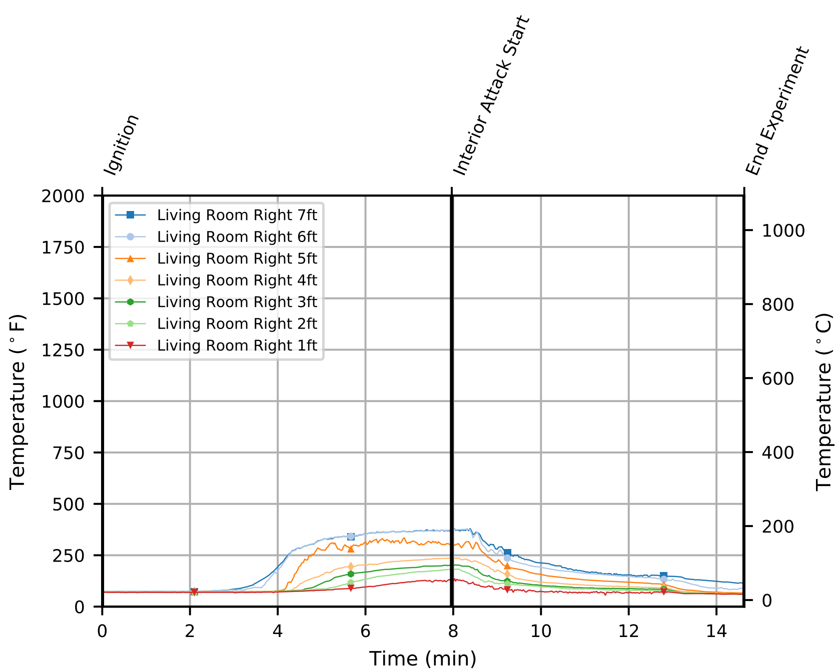


Figure E.192: Experiment 6 - Living Room Right Temps

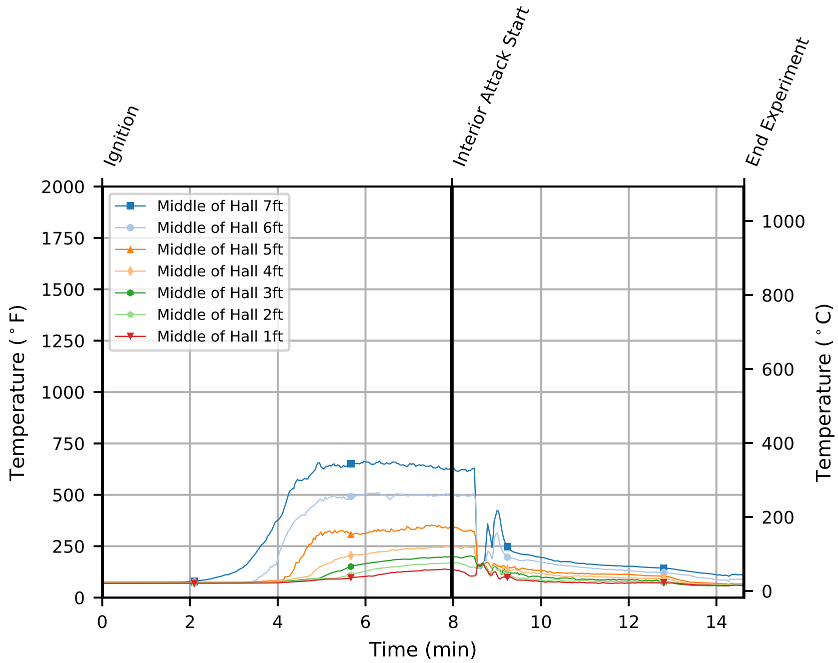


Figure E.193: Experiment 6 - Middle Hall Temps

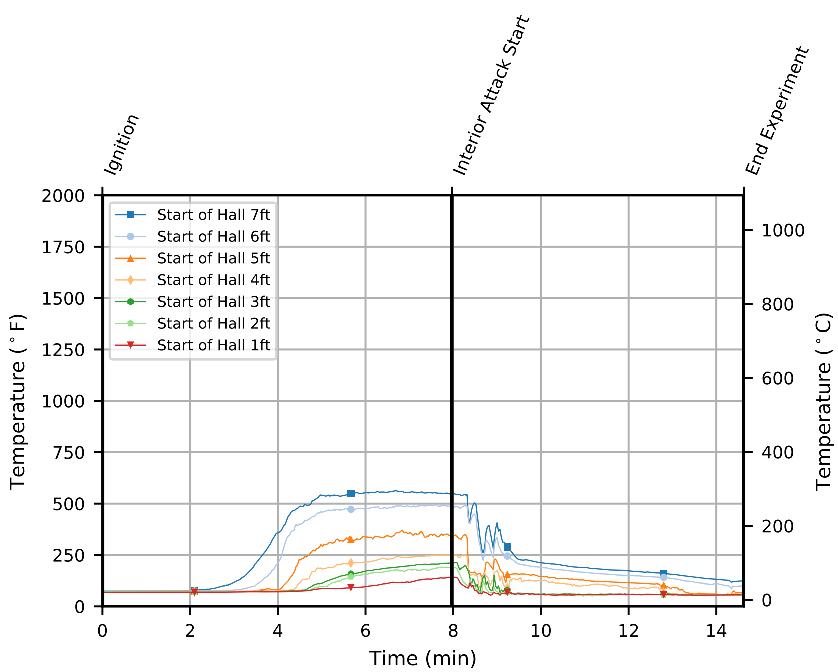


Figure E.194: Experiment 6 - Start Hall Temps

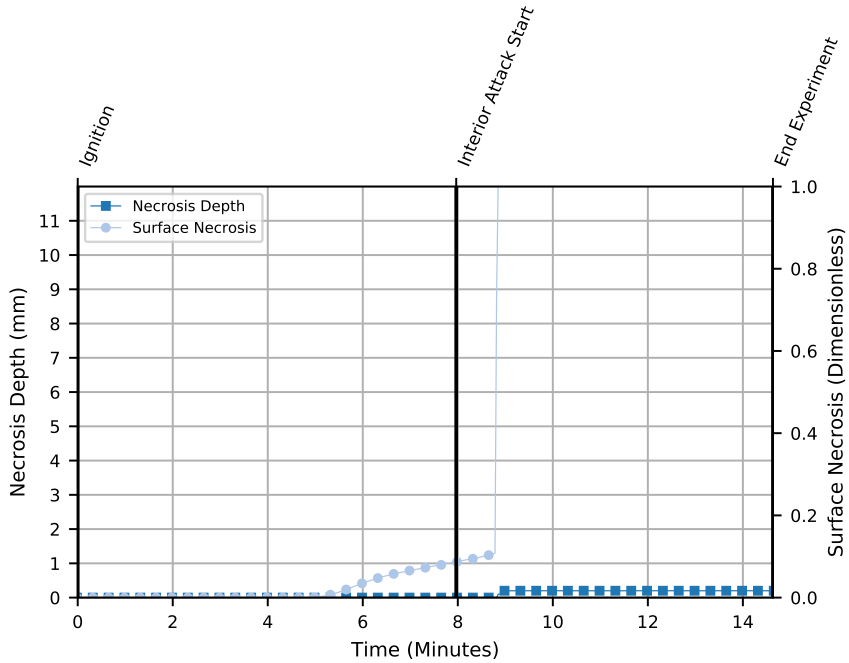


Figure E.195: Experiment 6 - Vic 1 Necrosis Depth

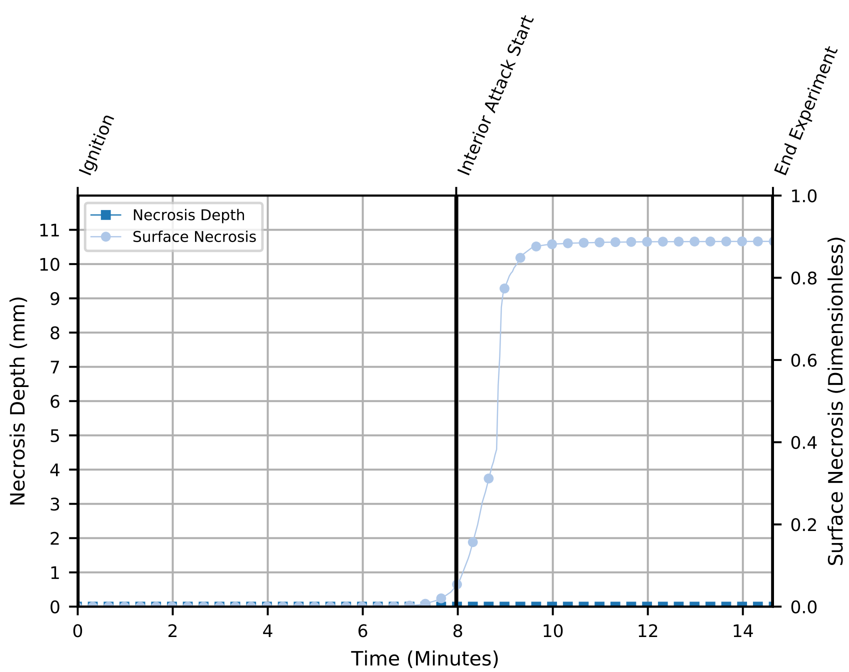


Figure E.196: Experiment 6 - Vic 3 Necrosis Depth

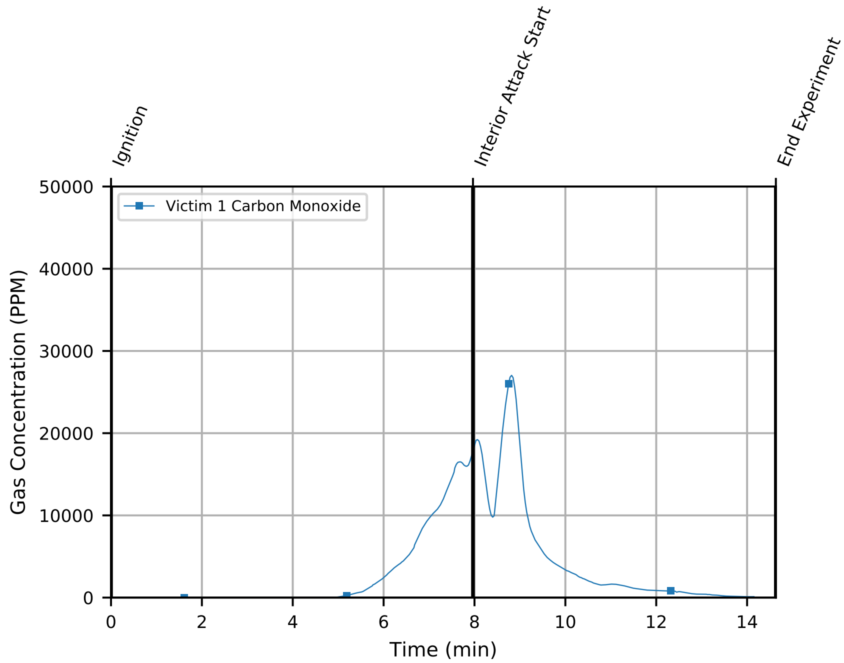


Figure E.197: Experiment 6 - Victim 1 Carbon Monoxide

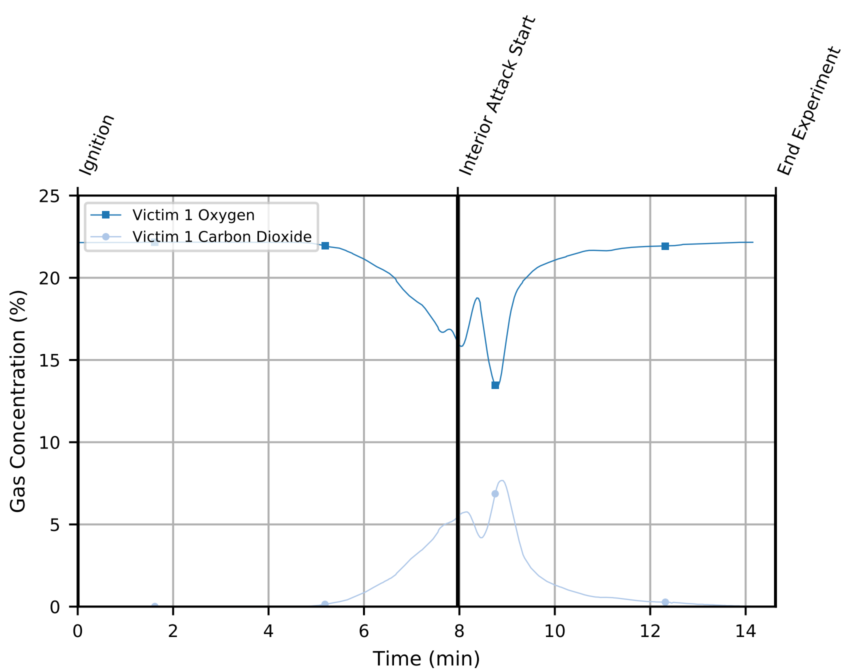


Figure E.198: Experiment 6 - Victim 1 Gas

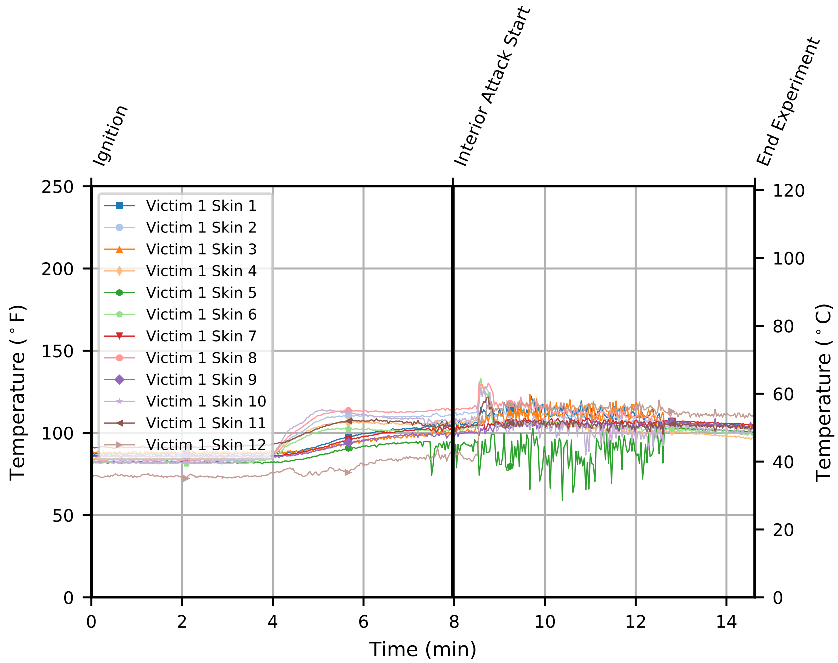


Figure E.199: Experiment 6 - Victim 1 Skin Temps

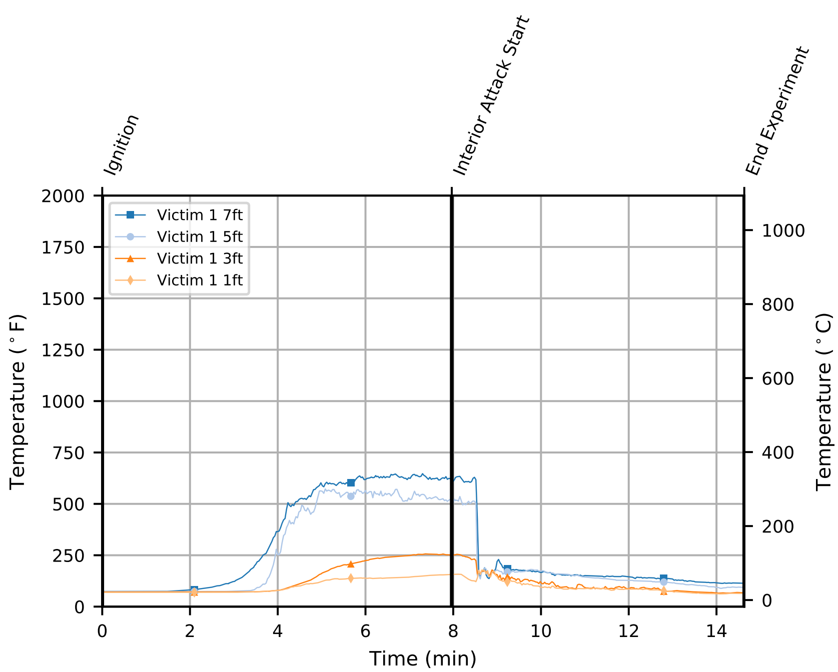


Figure E.200: Experiment 6 - Victim 1 Temps

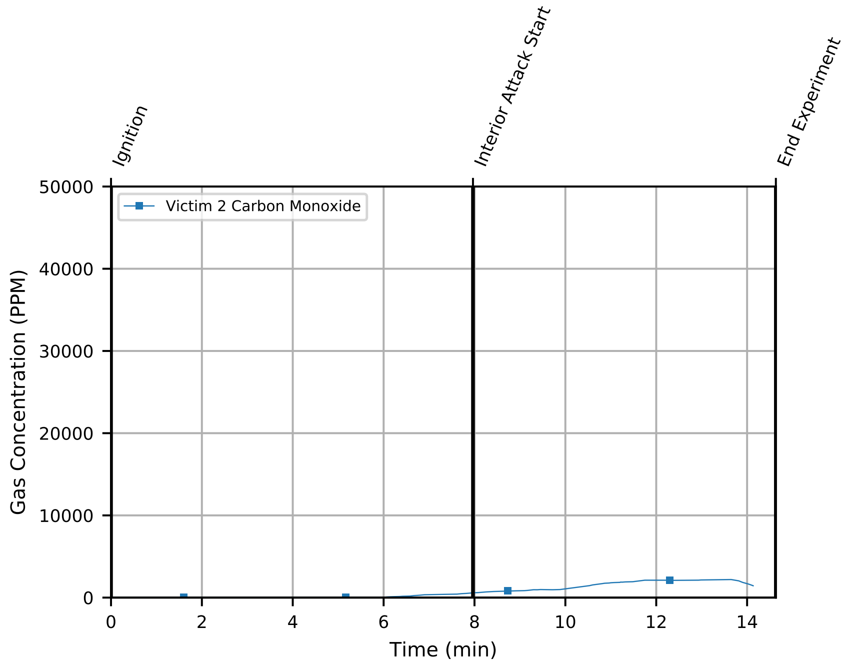


Figure E.201: Experiment 6 - Victim 2 Carbon Monoxide

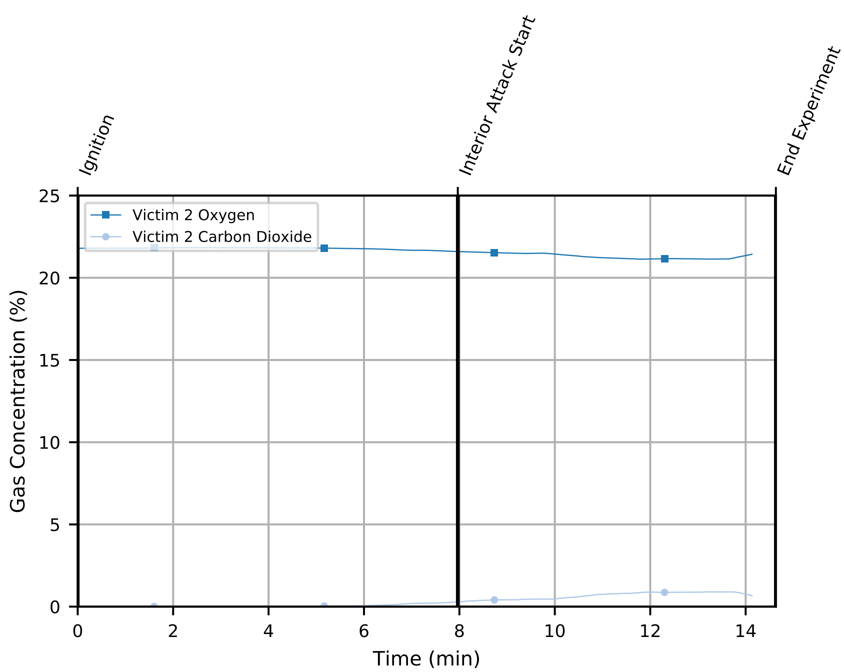


Figure E.202: Experiment 6 - Victim 2 Gas

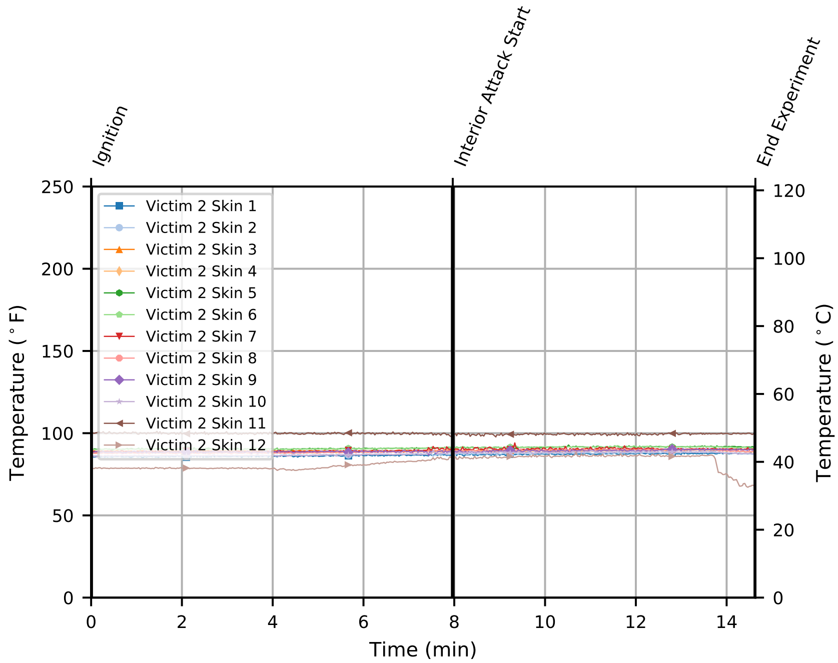


Figure E.203: Experiment 6 - Victim 2 Skin Temps

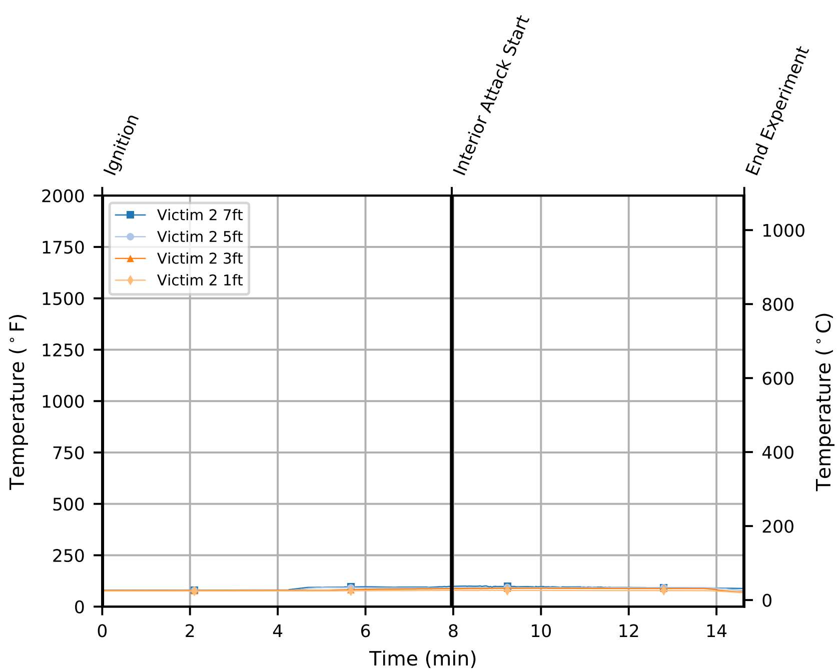


Figure E.204: Experiment 6 - Victim 2 Temps

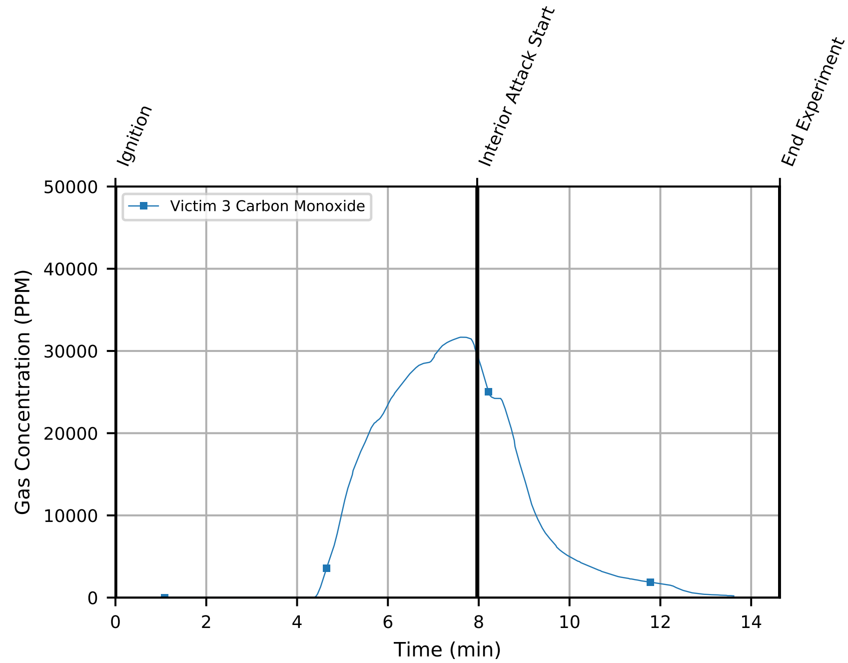


Figure E.205: Experiment 6 - Victim 3 Carbon Monoxide

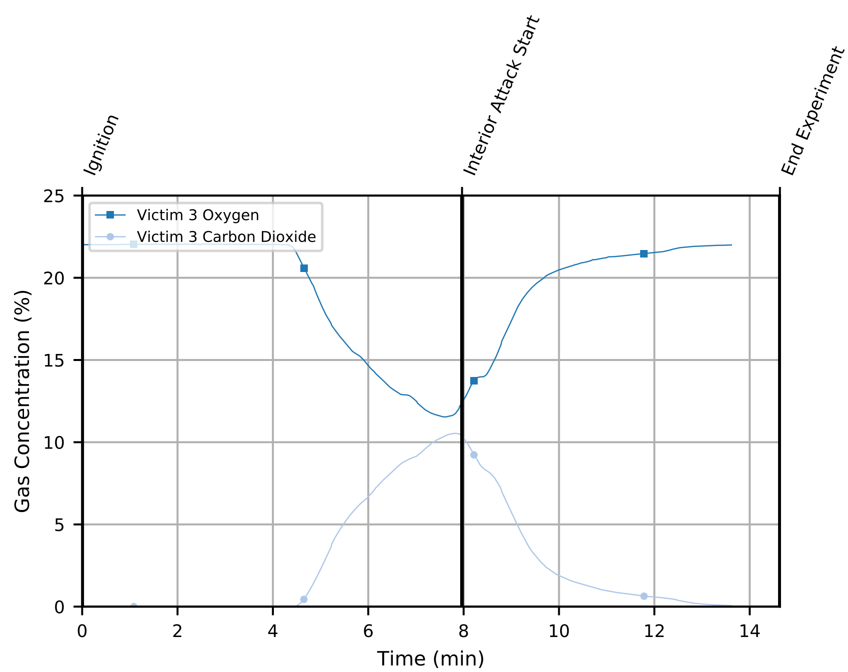


Figure E.206: Experiment 6 - Victim 3 Gas

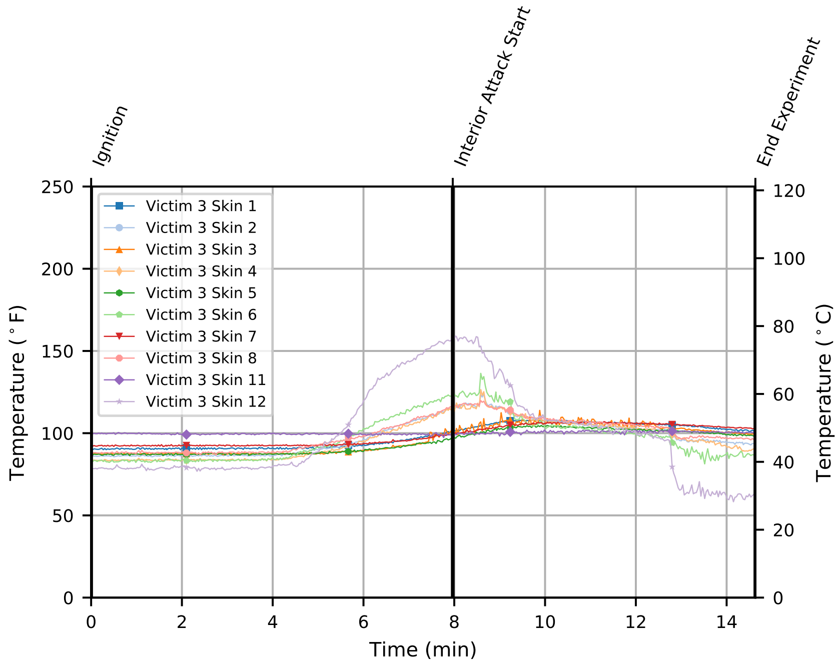


Figure E.207: Experiment 6 - Victim 3 Skin Temps

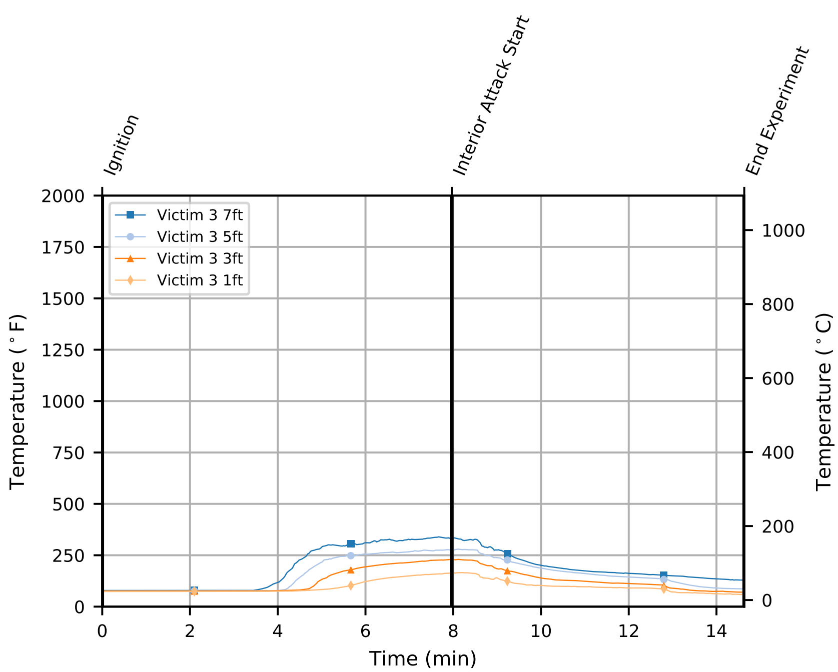


Figure E.208: Experiment 6 - Victim 3 Temps

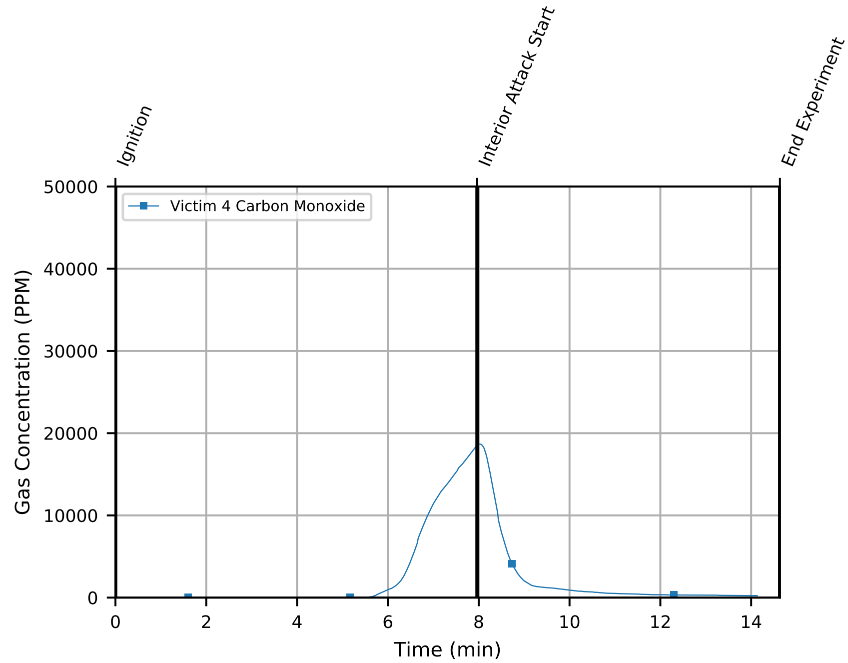


Figure E.209: Experiment 6 - Victim 4 Carbon Monoxide

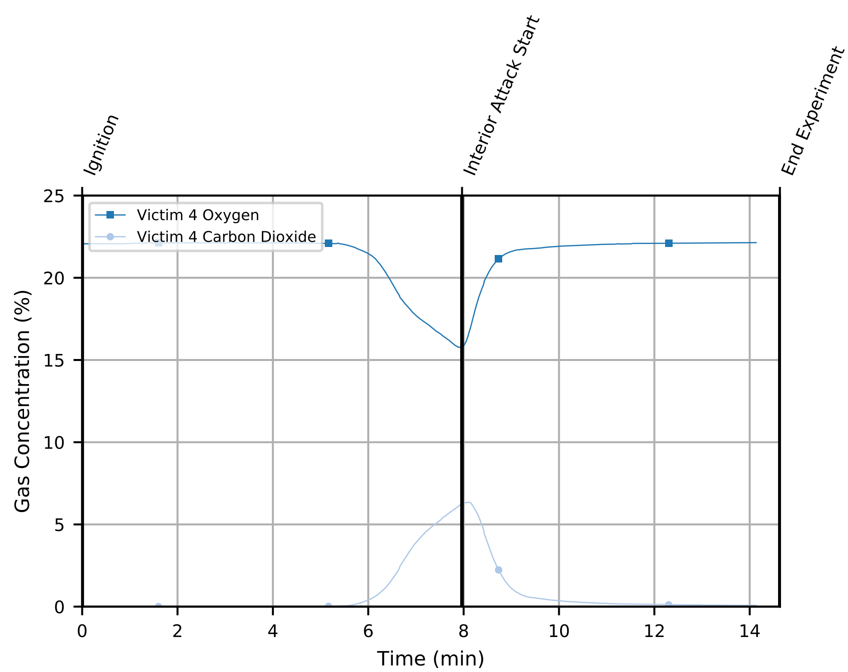


Figure E.210: Experiment 6 - Victim 4 Gas

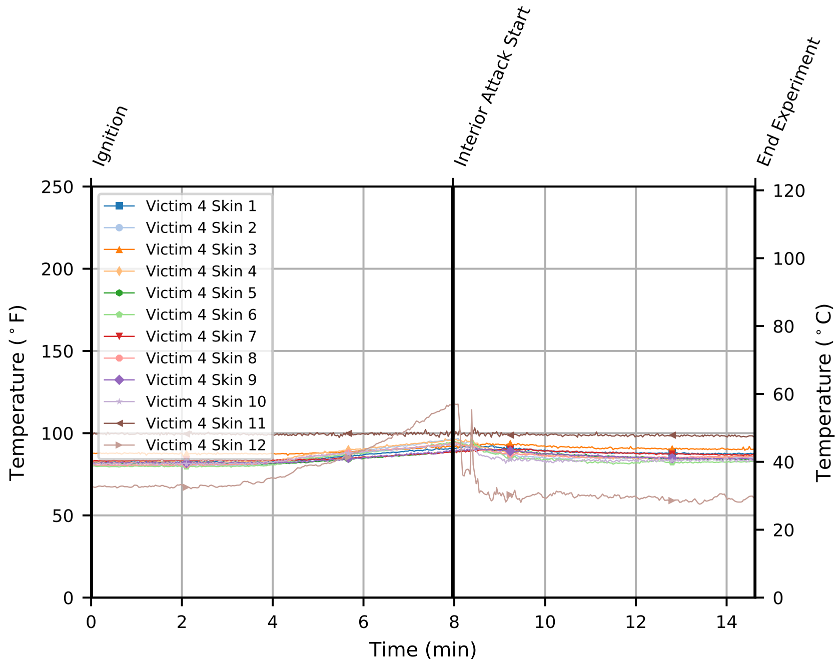


Figure E.211: Experiment 6 - Victim 4 Skin Temps

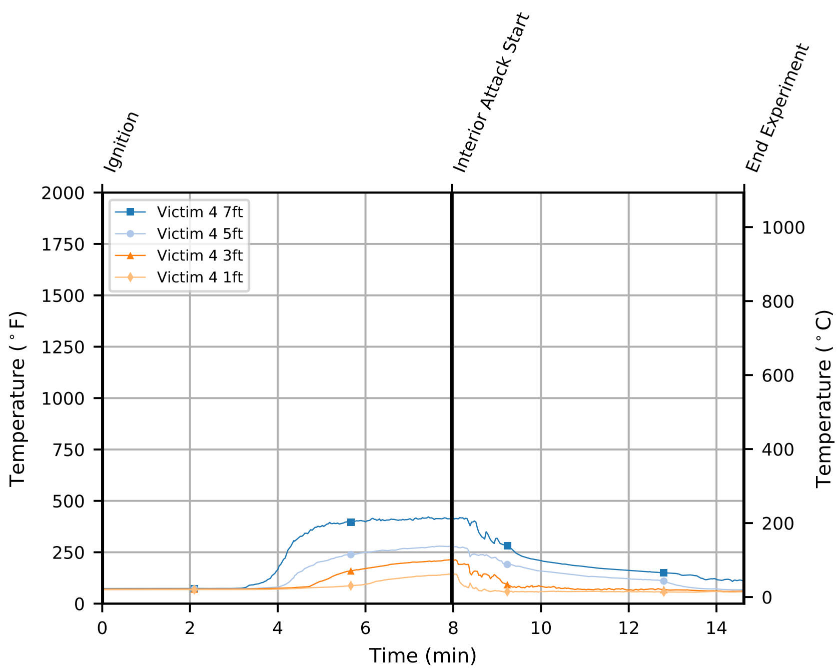


Figure E.212: Experiment 6 - Victim 4 Temps

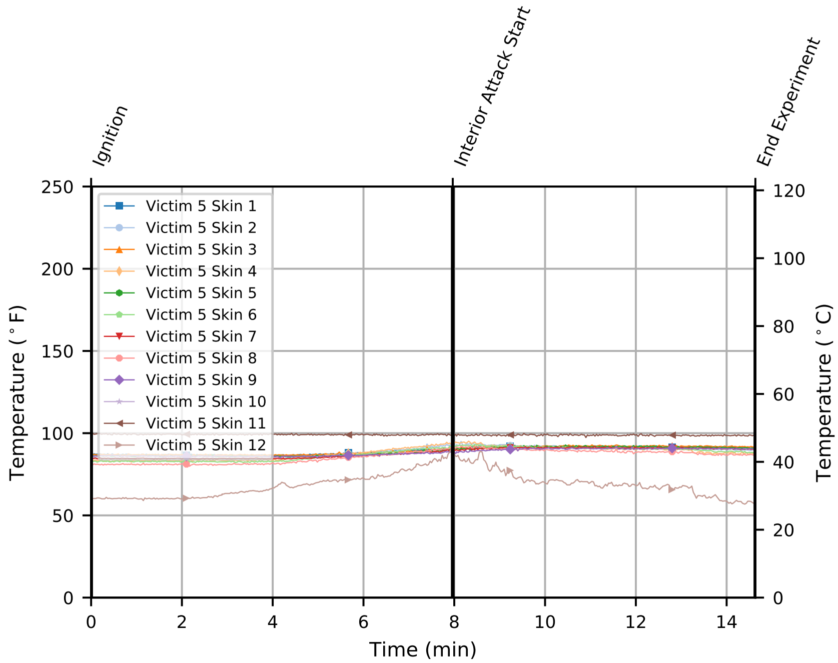


Figure E.213: Experiment 6 - Victim 5 Skin Temps

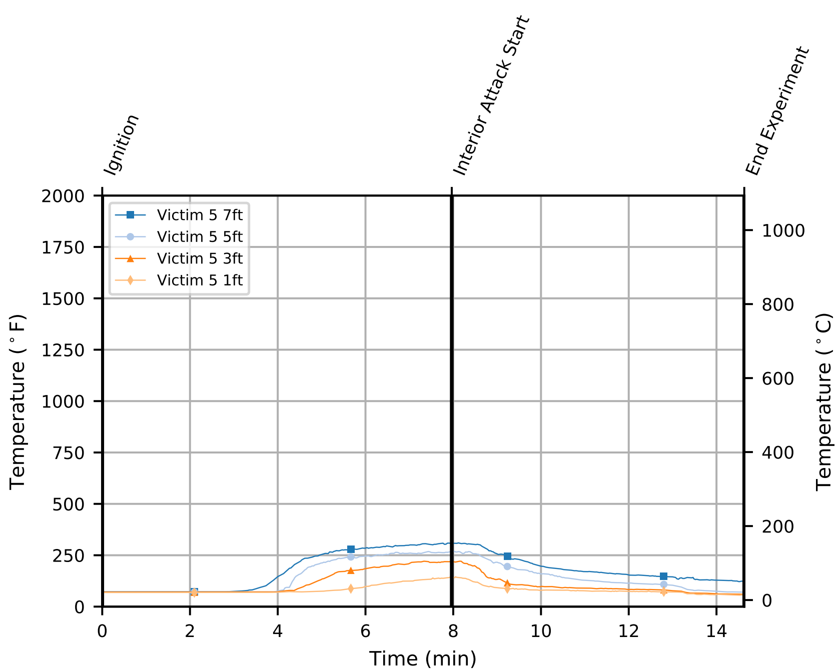


Figure E.214: Experiment 6 - Victim 5 Temps

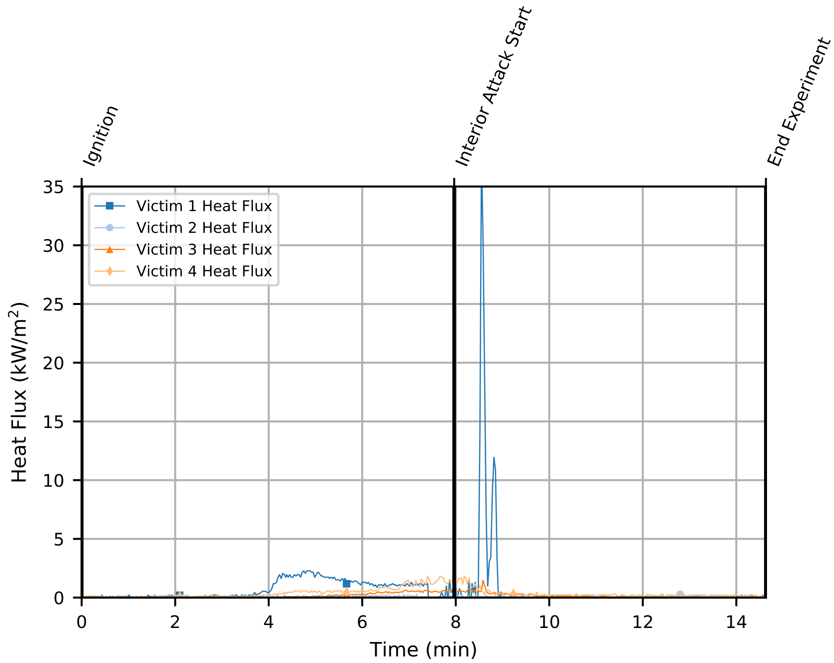


Figure E.215: Experiment 6 - Victim Heat Flux

E.7 Experiment 7 Data

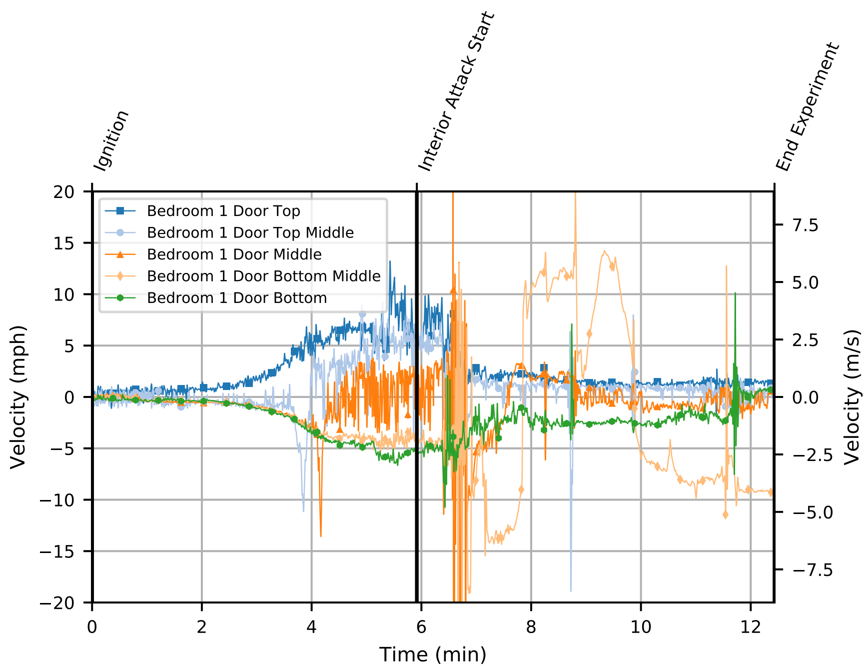


Figure E.216: Experiment 7 - Bedroom 1 Door

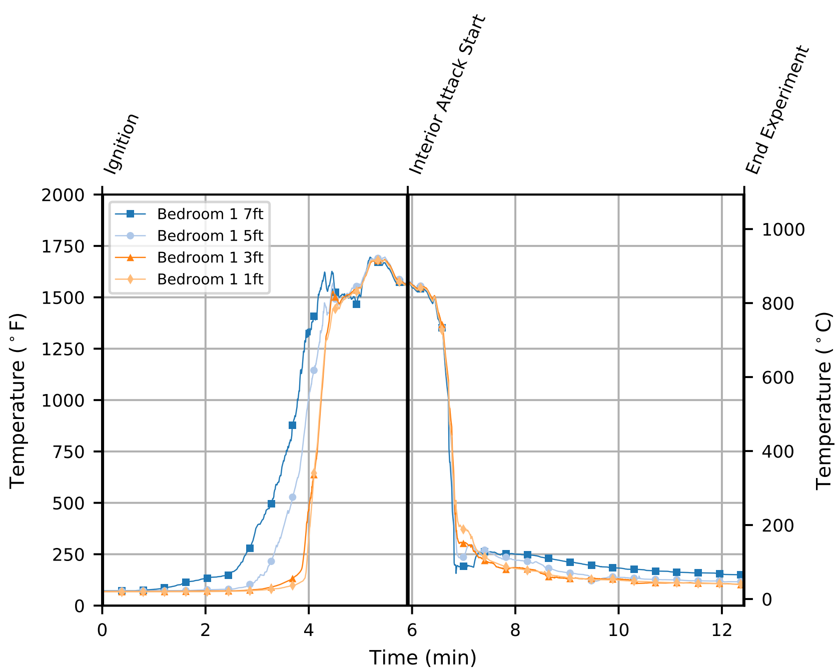


Figure E.217: Experiment 7 - Bedroom 1 Temps

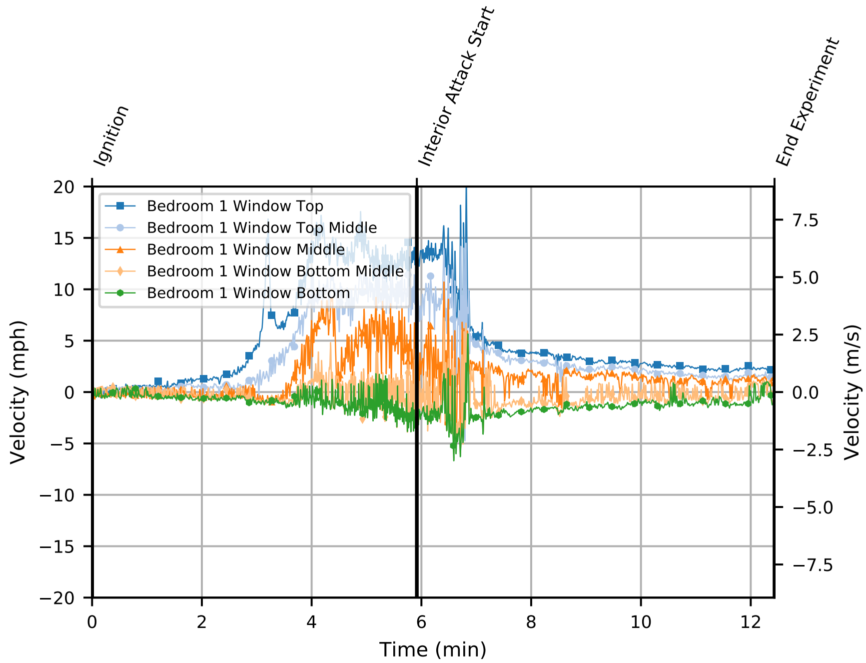


Figure E.218: Experiment 7 - Bedroom 1 Window

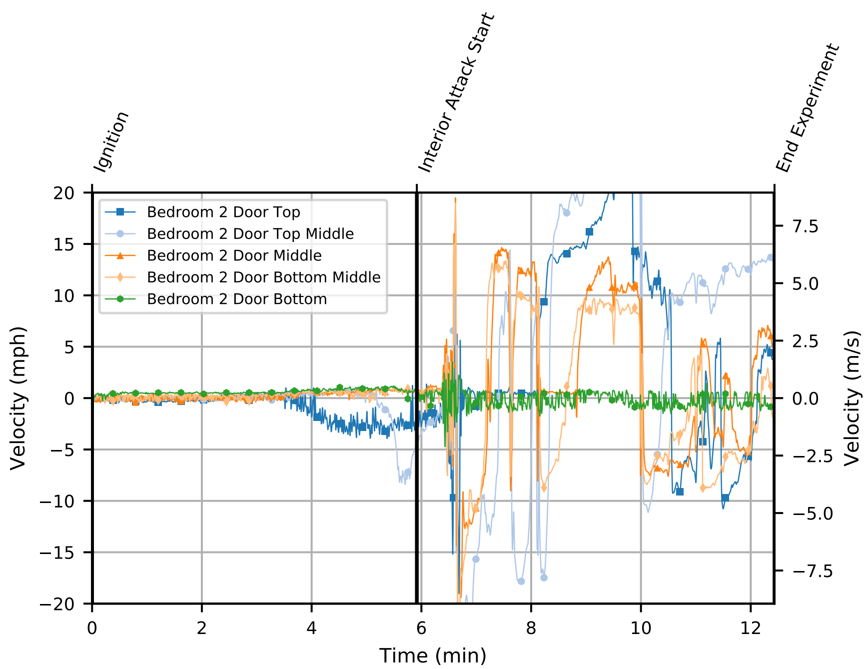


Figure E.219: Experiment 7 - Bedroom 2 Door

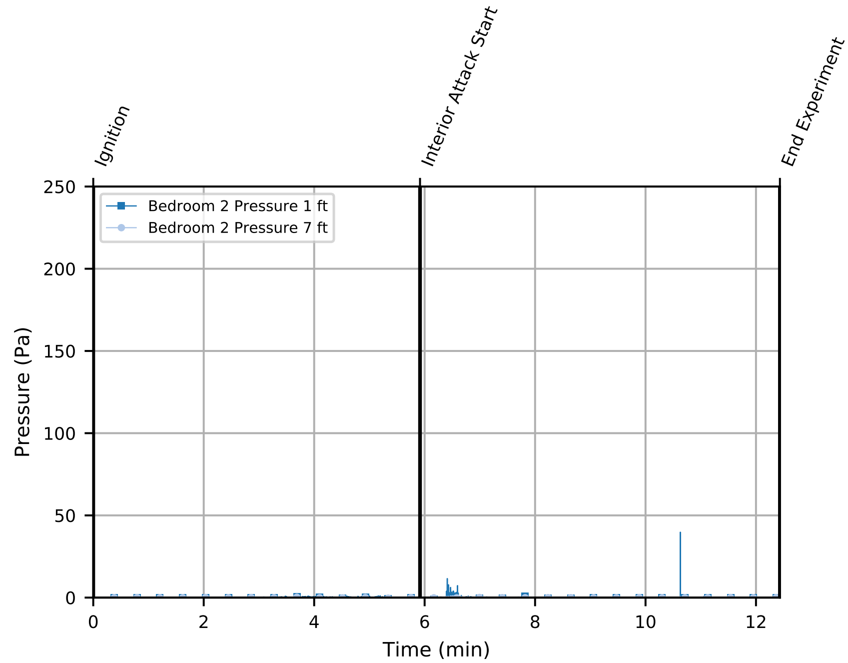


Figure E.220: Experiment 7 - Bedroom 2 Pressure

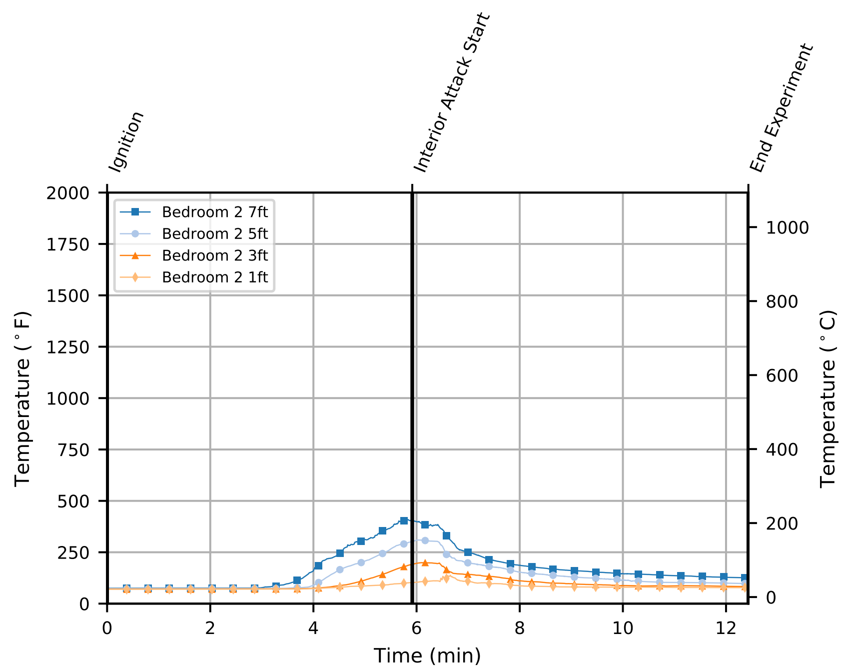


Figure E.221: Experiment 7 - Bedroom 2 Temps

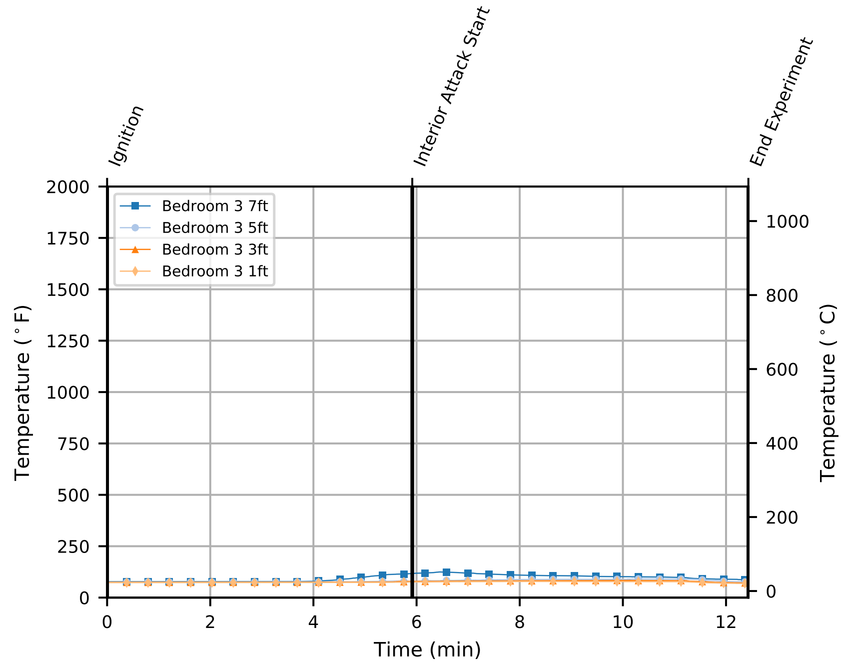


Figure E.222: Experiment 7 - Bedroom 3 Temps

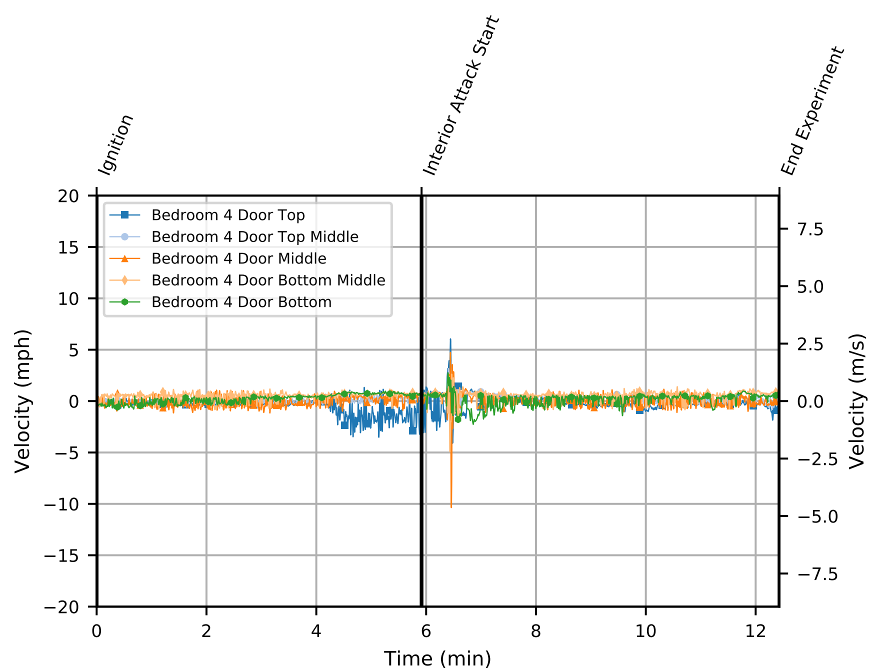


Figure E.223: Experiment 7 - Bedroom 4 Door

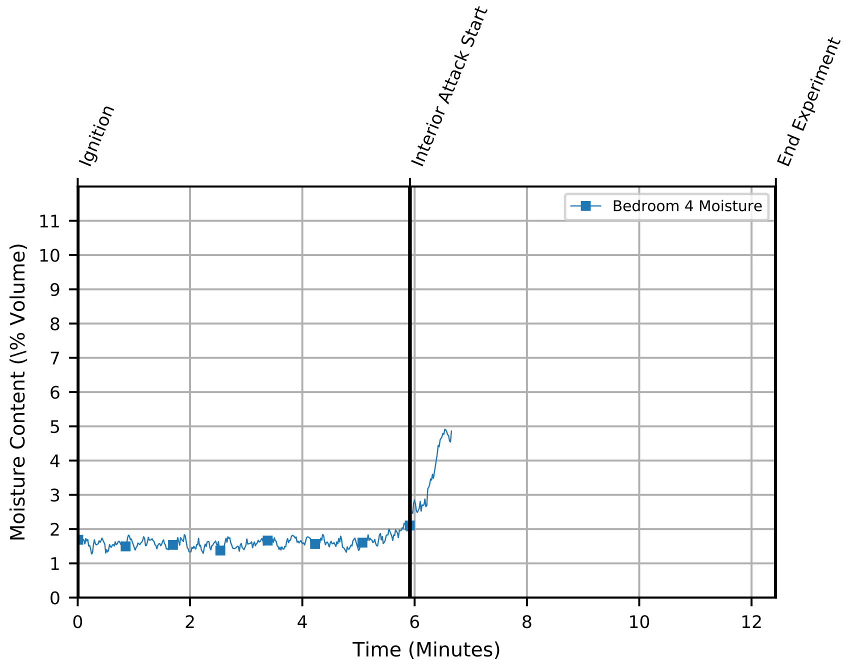


Figure E.224: Experiment 7 - Bedroom 4 Moisture

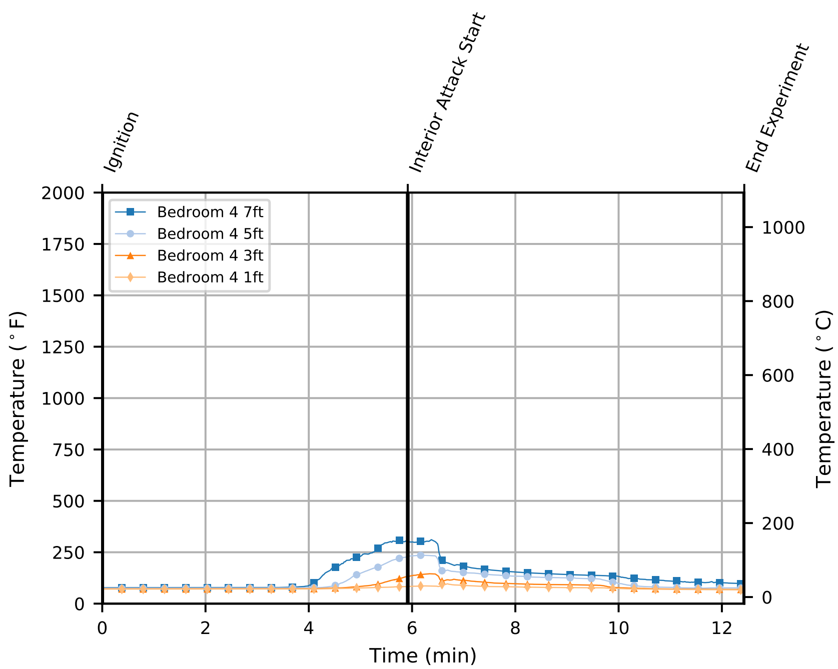


Figure E.225: Experiment 7 - Bedroom 4 Temps

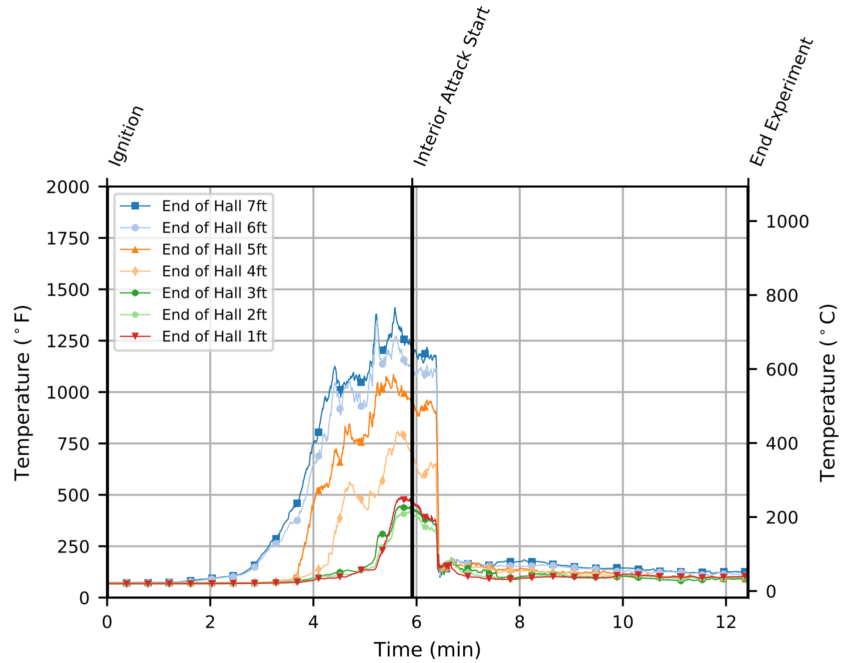


Figure E.226: Experiment 7 - End Hall Temps

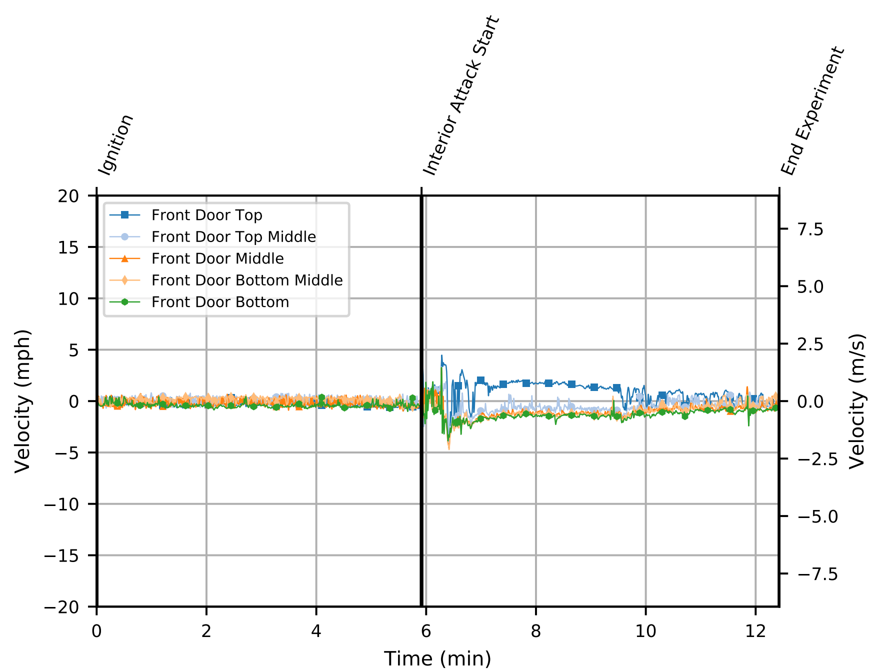


Figure E.227: Experiment 7 - Front Door Flow

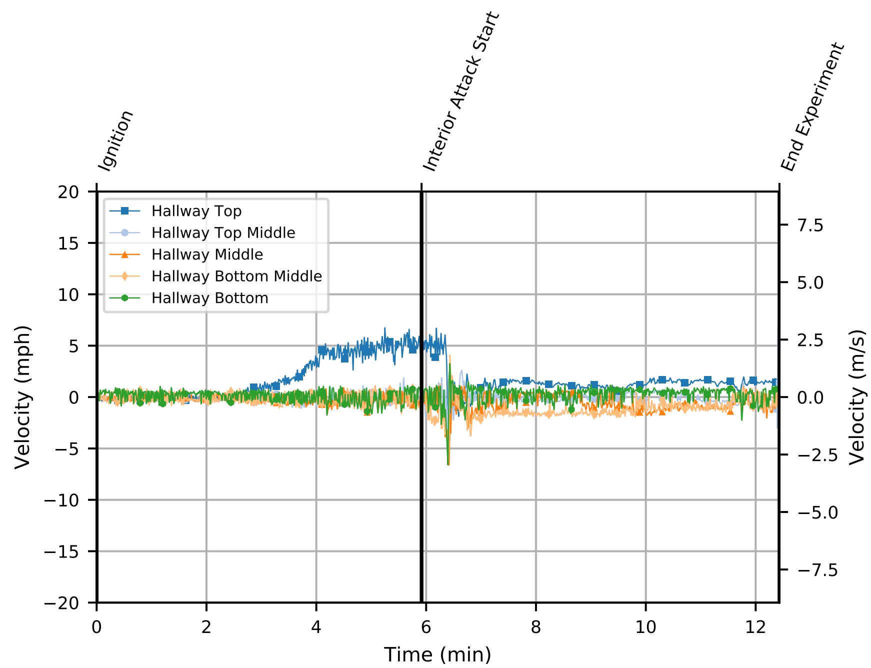


Figure E.228: Experiment 7 - Hallway Flow

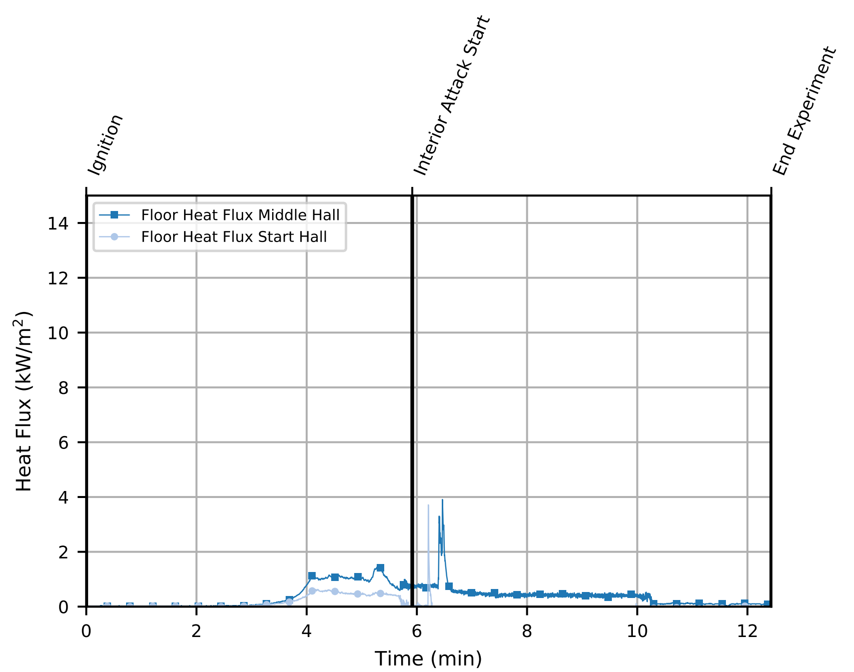


Figure E.229: Experiment 7 - Heat Flux Floor

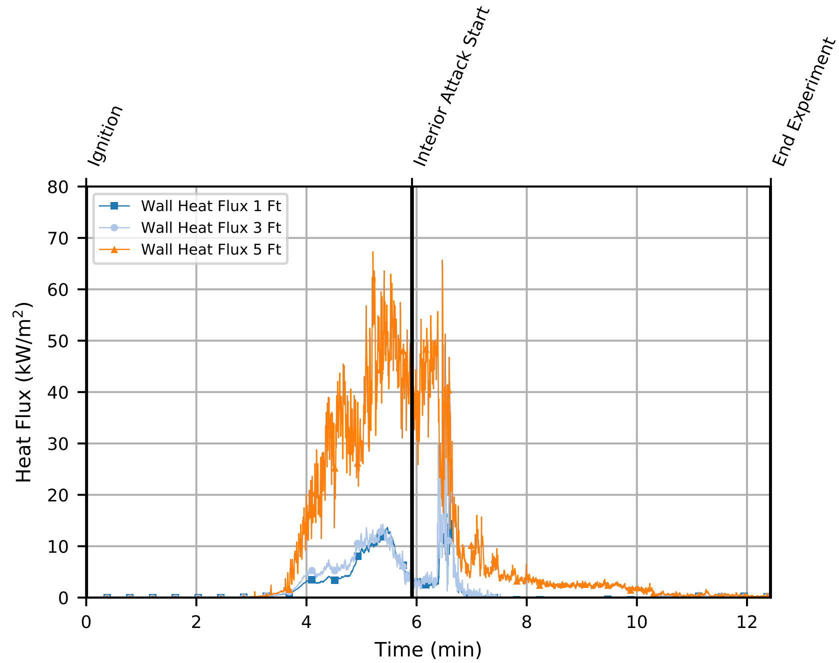


Figure E.230: Experiment 7 - Heat Flux Wall

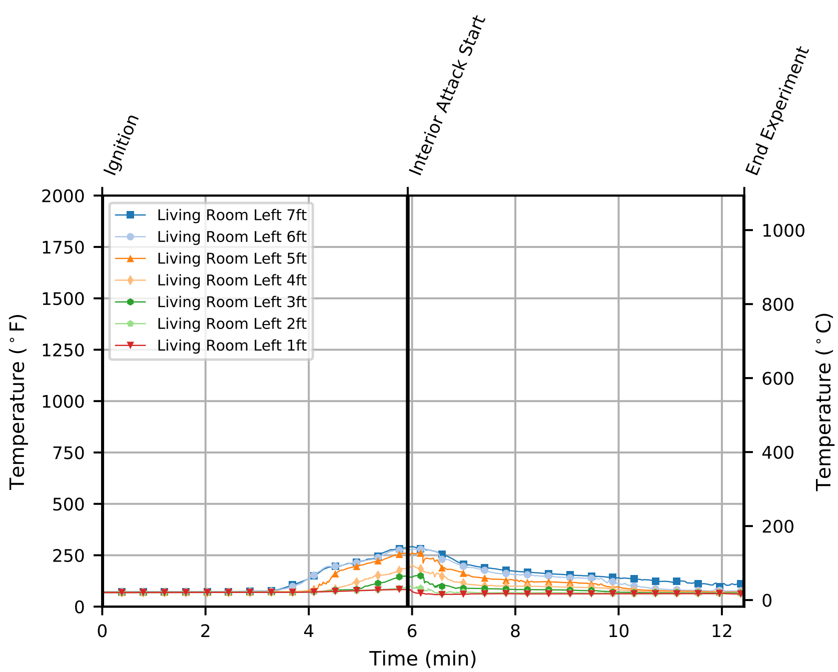


Figure E.231: Experiment 7 - Living Room Left Temps

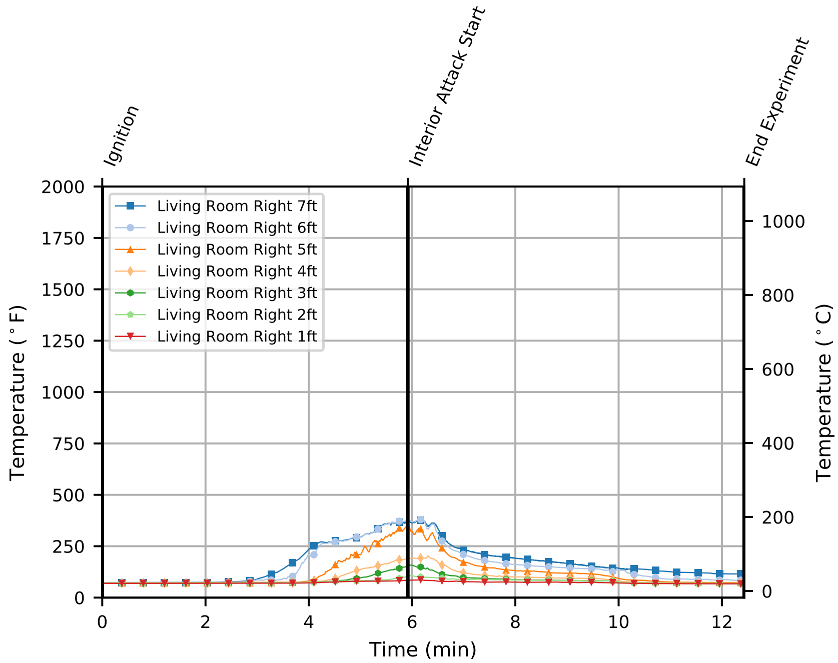


Figure E.232: Experiment 7 - Living Room Right Temps

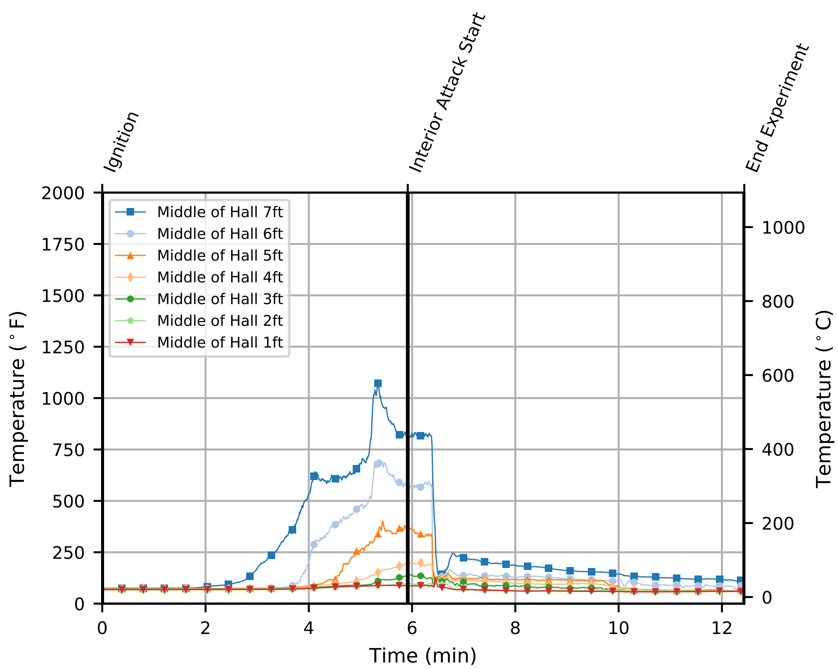


Figure E.233: Experiment 7 - Middle Hall Temps

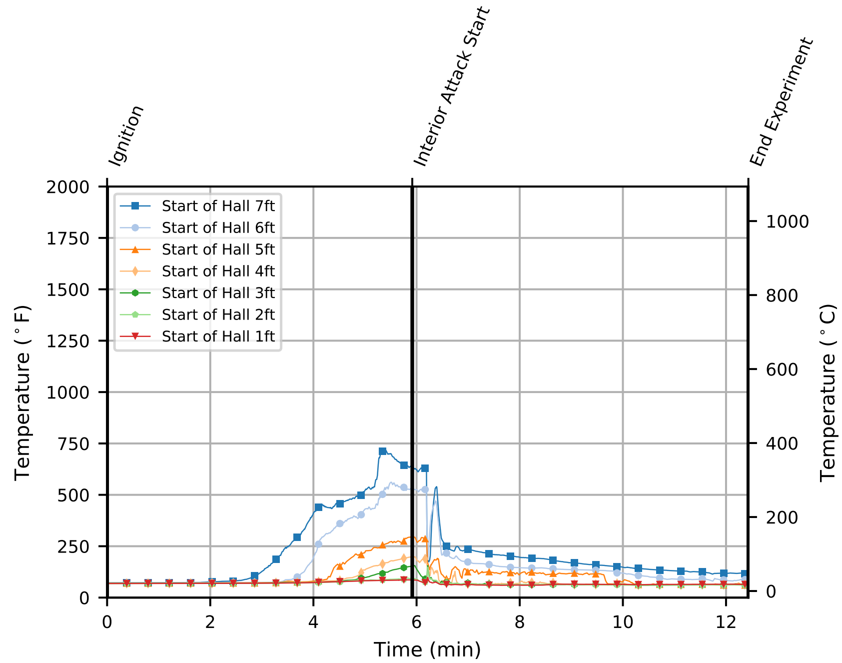


Figure E.234: Experiment 7 - Start Hall Temps

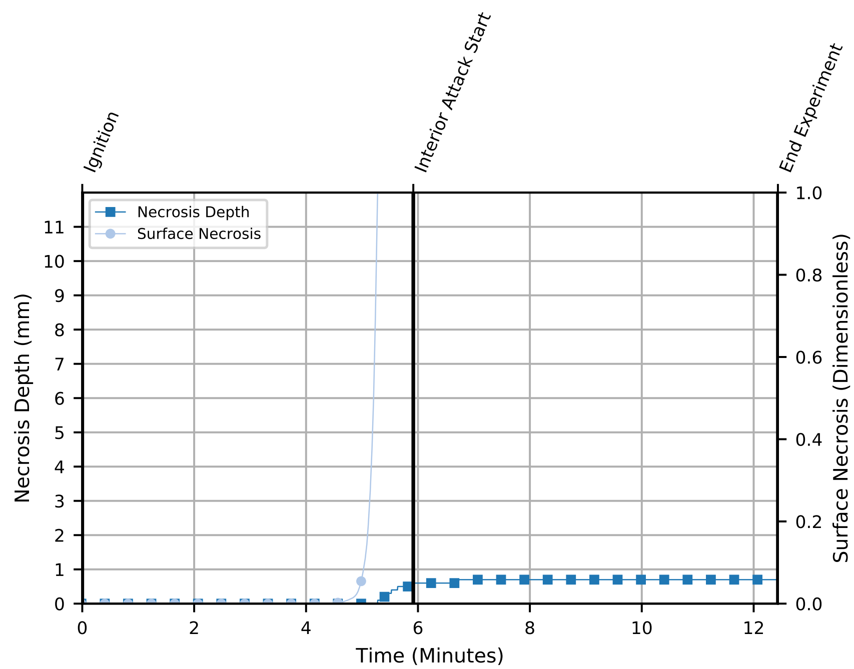


Figure E.235: Experiment 7 - Vic 1 Necrosis Depth

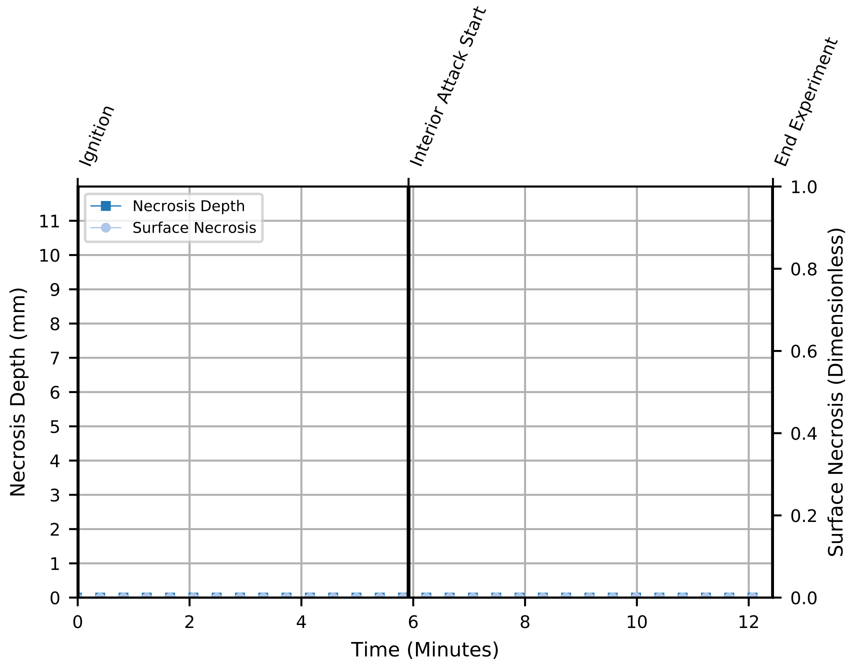


Figure E.236: Experiment 7 - Vic 3 Necrosis Depth

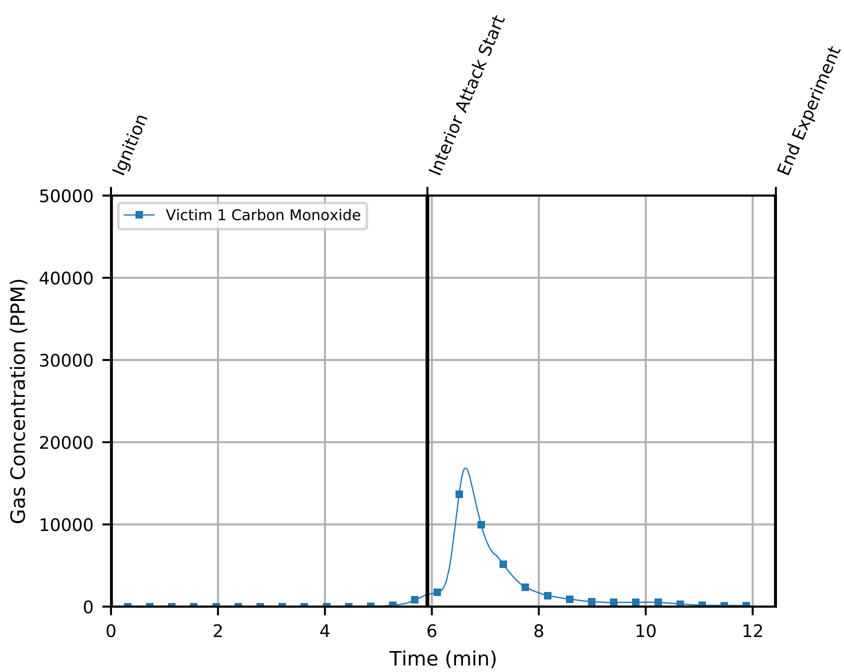


Figure E.237: Experiment 7 - Victim 1 Carbon Monoxide

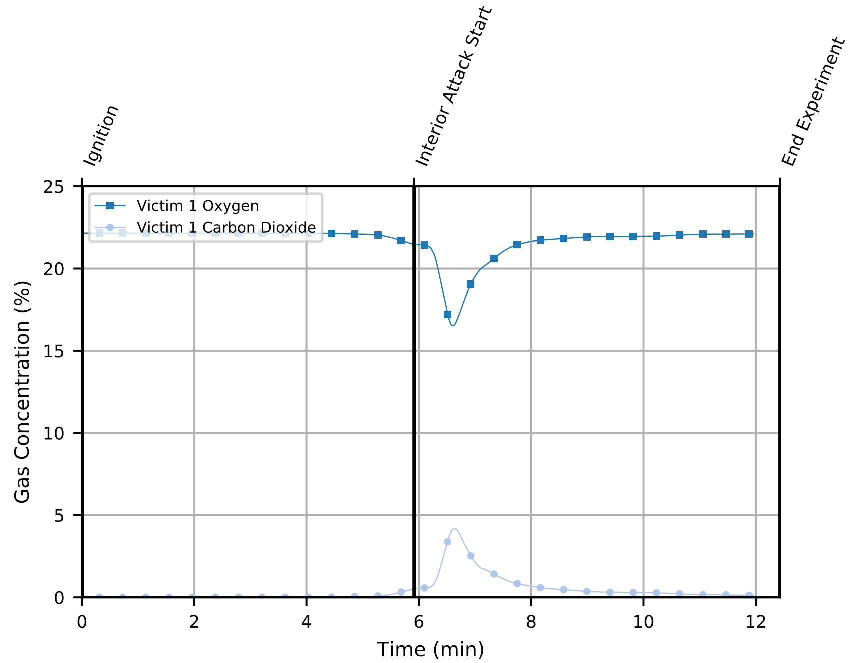


Figure E.238: Experiment 7 - Victim 1 Gas

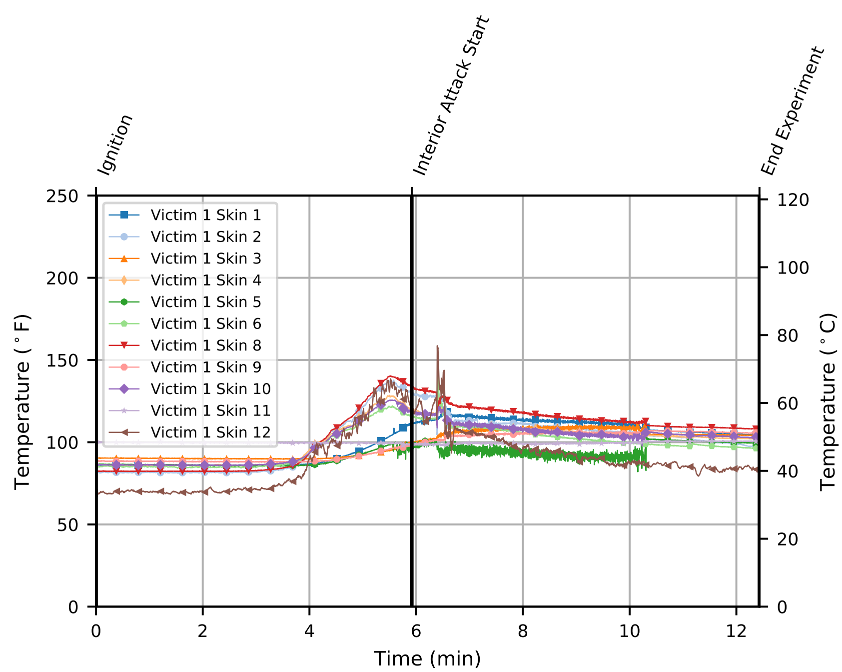


Figure E.239: Experiment 7 - Victim 1 Skin Temps

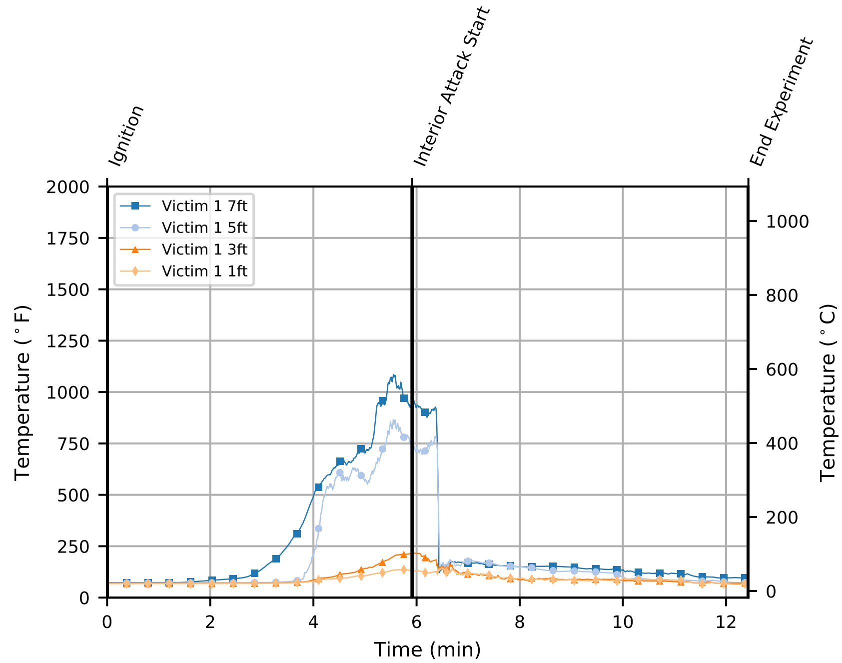


Figure E.240: Experiment 7 - Victim 1 Temps

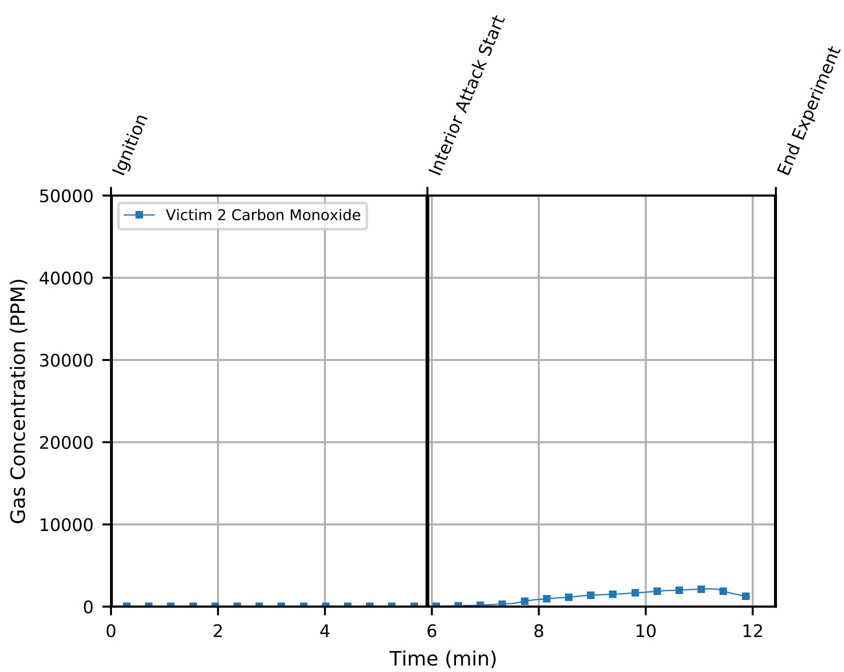


Figure E.241: Experiment 7 - Victim 2 Carbon Monoxide

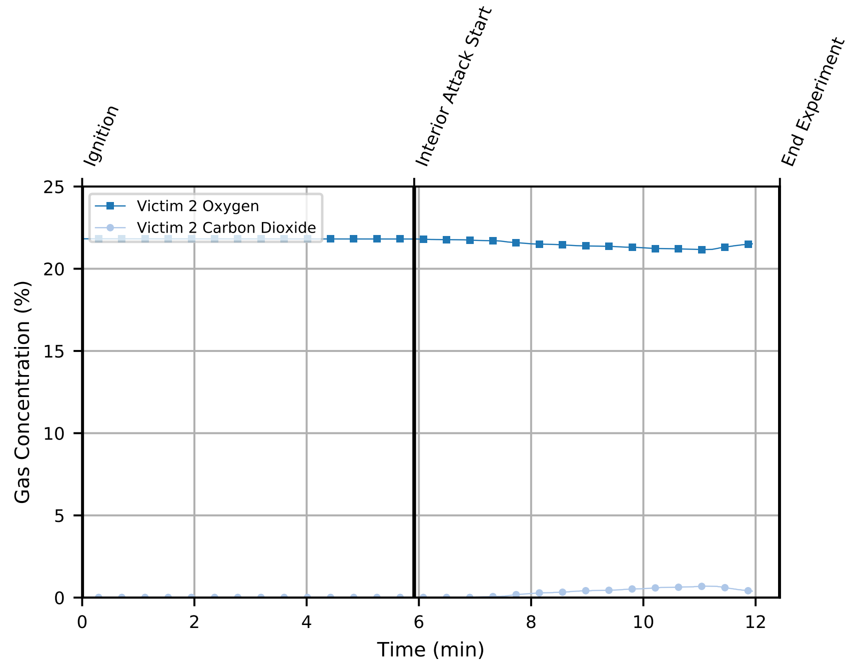


Figure E.242: Experiment 7 - Victim 2 Gas

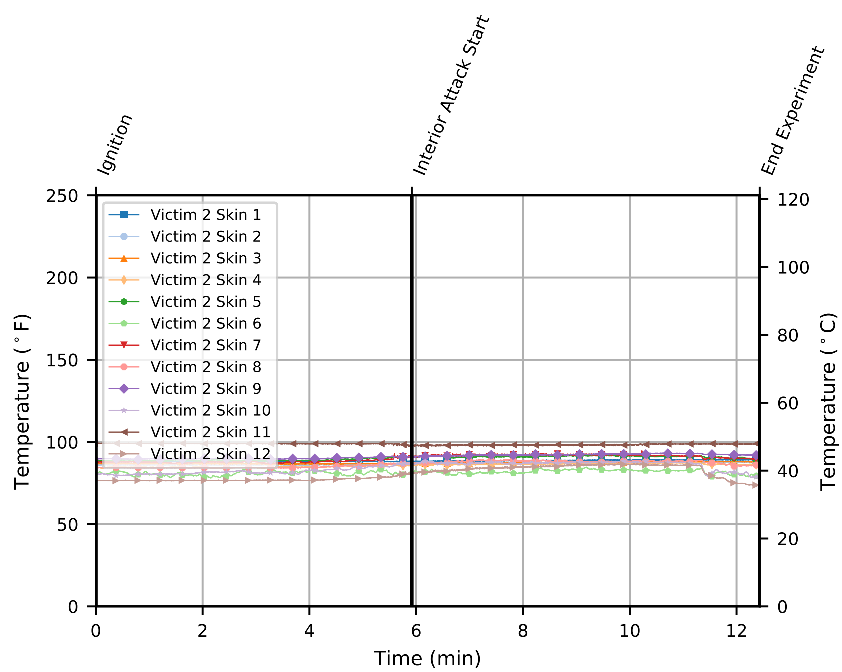


Figure E.243: Experiment 7 - Victim 2 Skin Temps

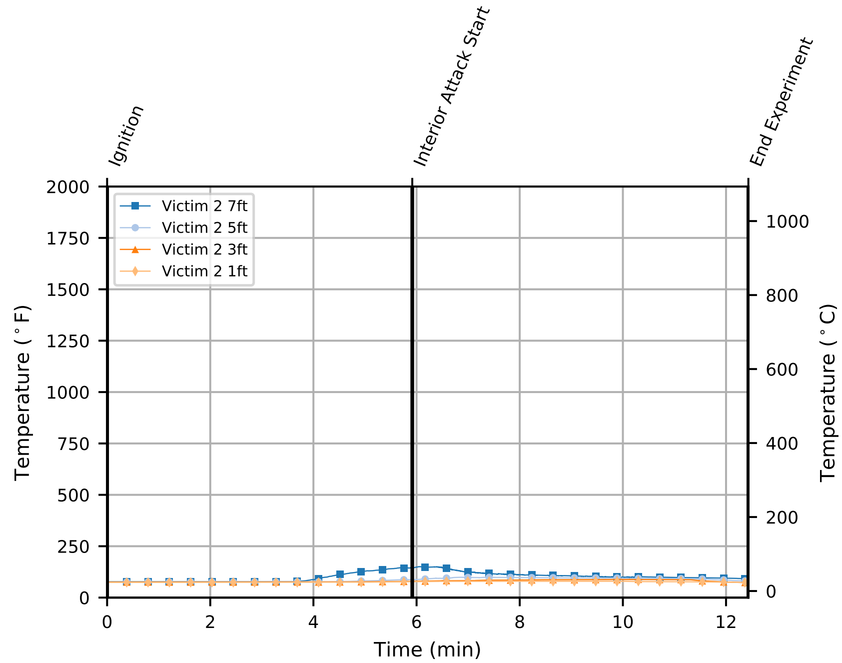


Figure E.244: Experiment 7 - Victim 2 Temps

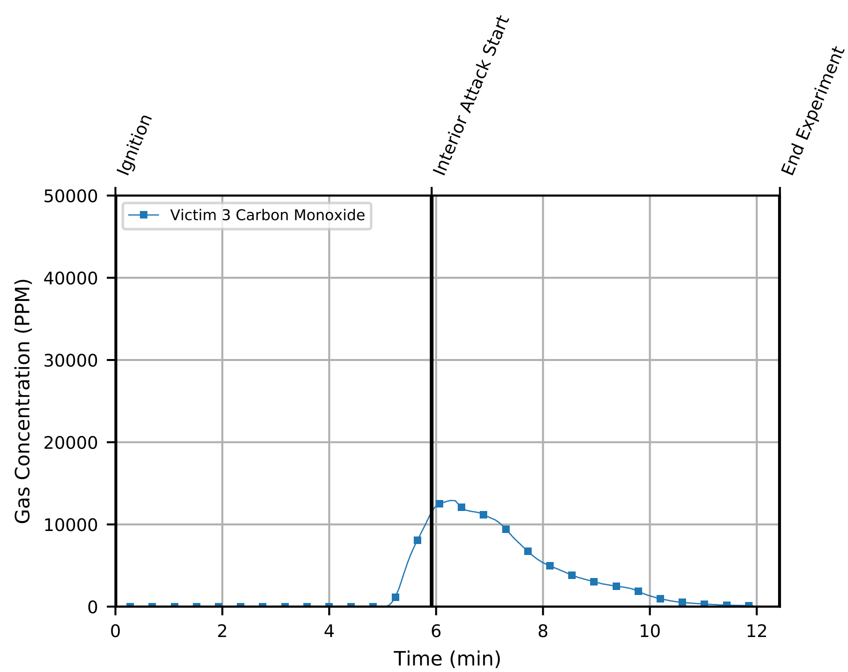


Figure E.245: Experiment 7 - Victim 3 Carbon Monoxide

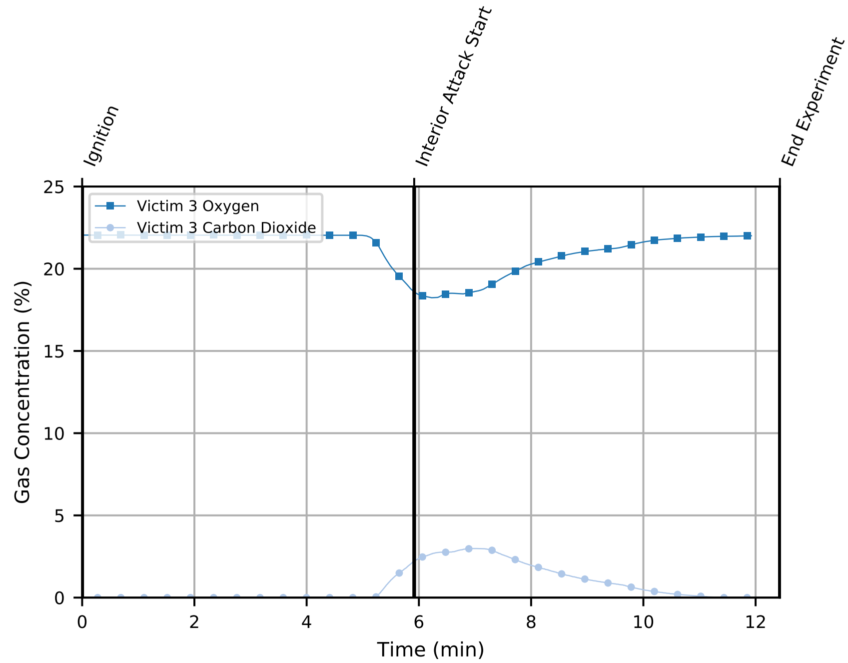


Figure E.246: Experiment 7 - Victim 3 Gas

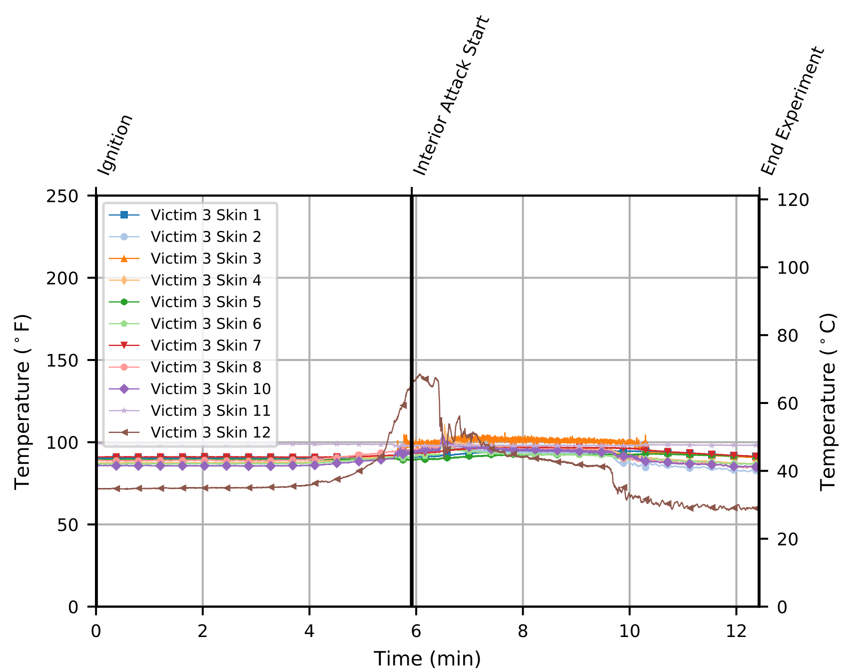


Figure E.247: Experiment 7 - Victim 3 Skin Temps

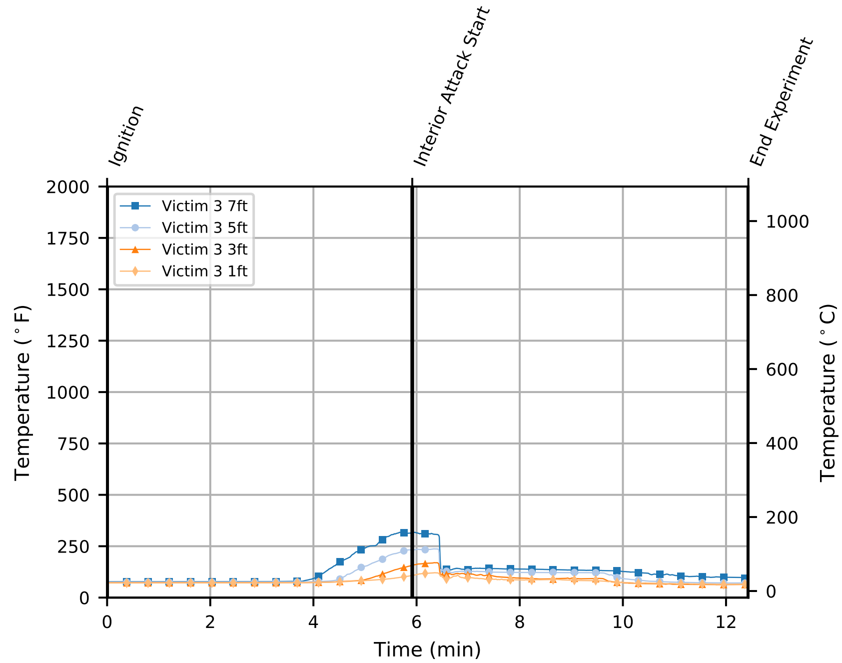


Figure E.248: Experiment 7 - Victim 3 Temps

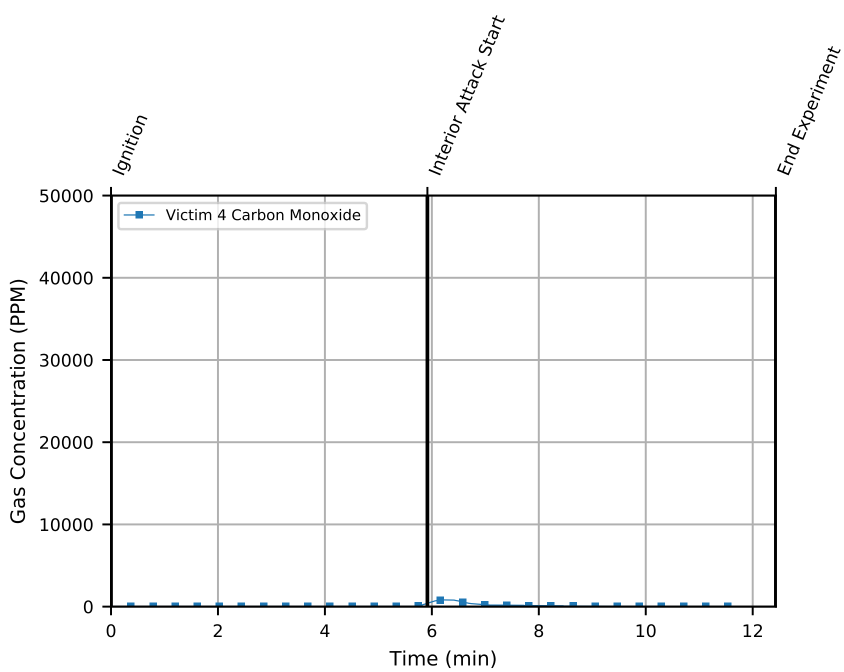


Figure E.249: Experiment 7 - Victim 4 Carbon Monoxide

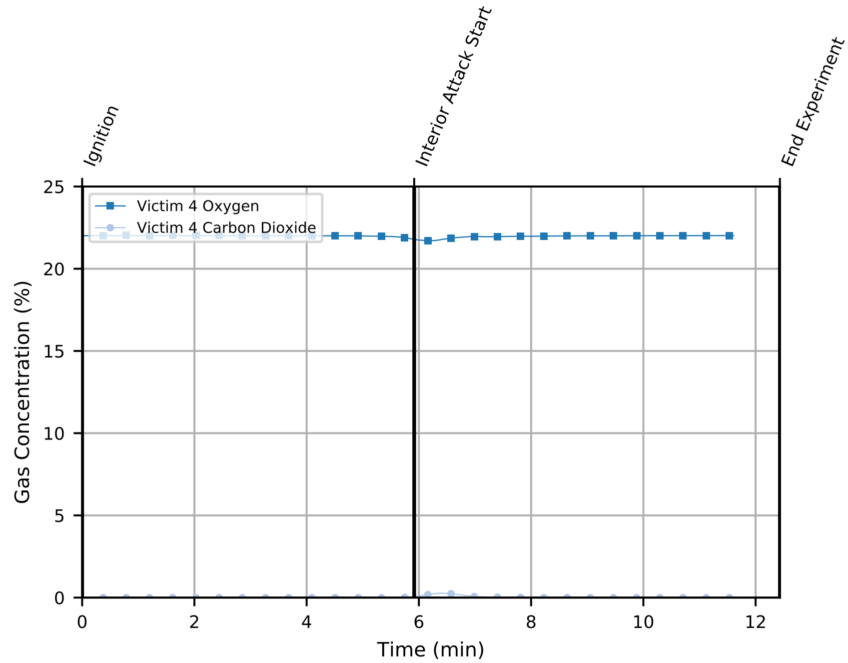


Figure E.250: Experiment 7 - Victim 4 Gas

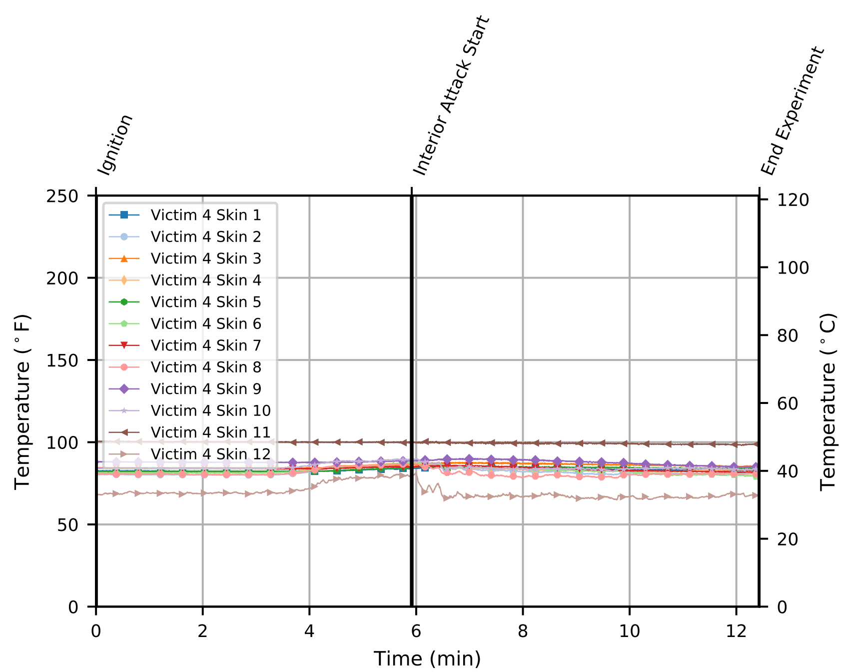


Figure E.251: Experiment 7 - Victim 4 Skin Temps

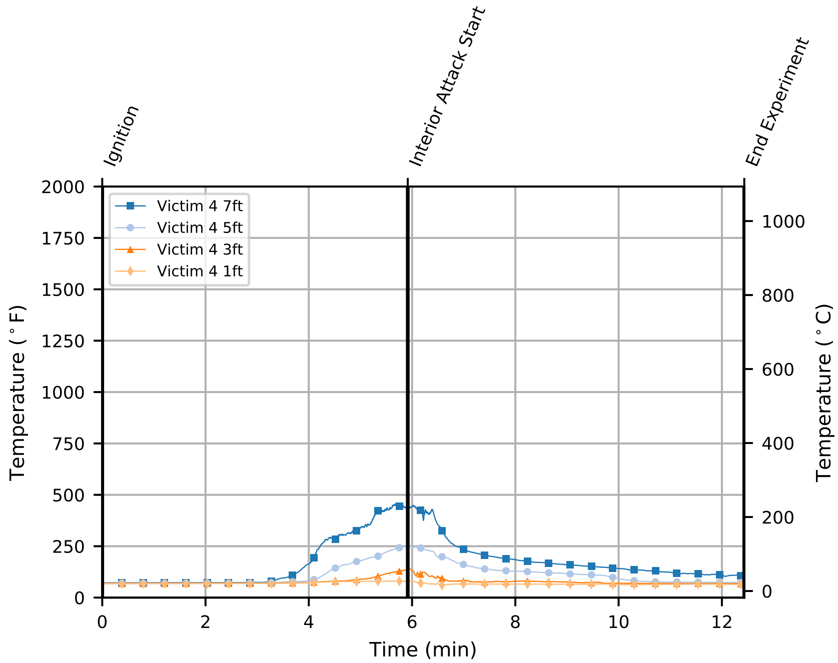


Figure E.252: Experiment 7 - Victim 4 Temps

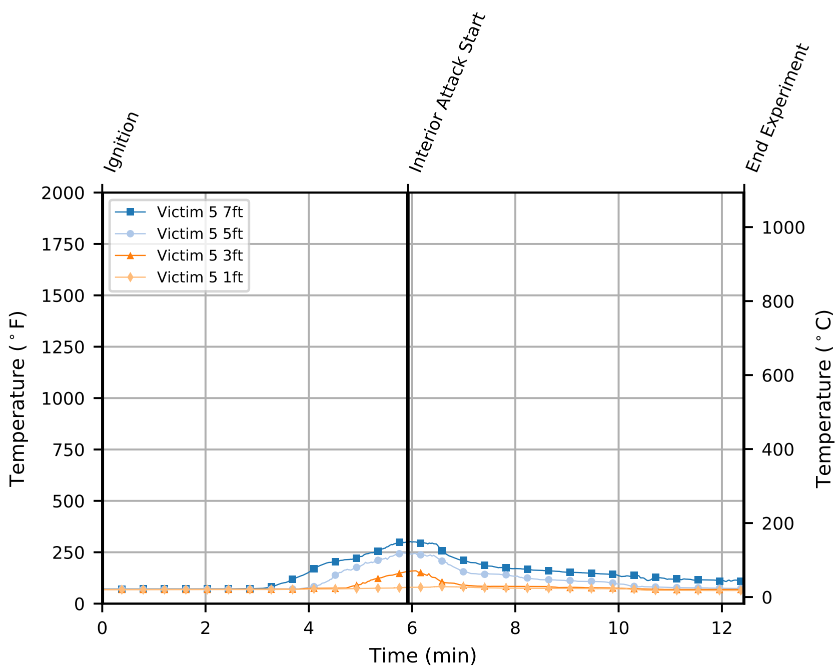


Figure E.253: Experiment 7 - Victim 5 Temps

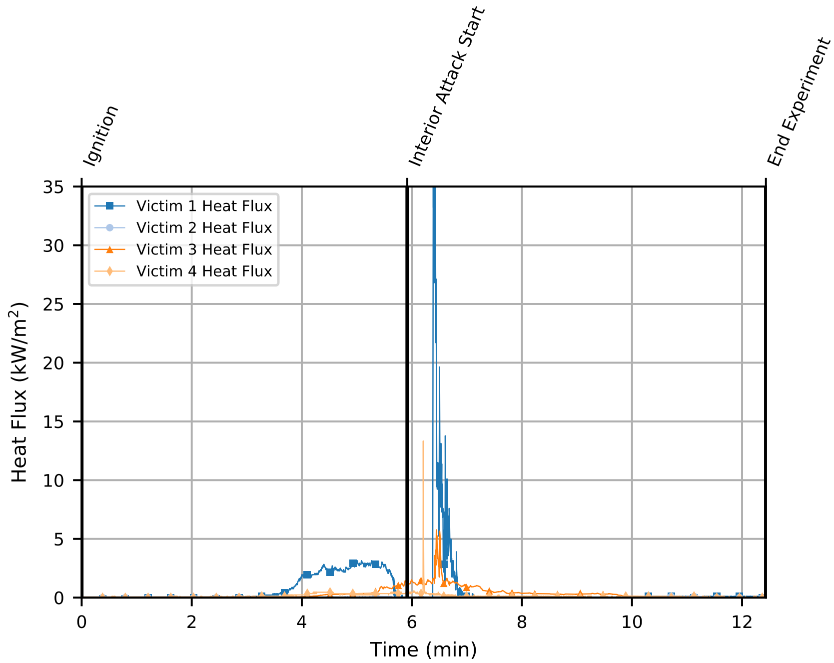


Figure E.254: Experiment 7 - Victim Heat Flux

E.8 Experiment 8 Data

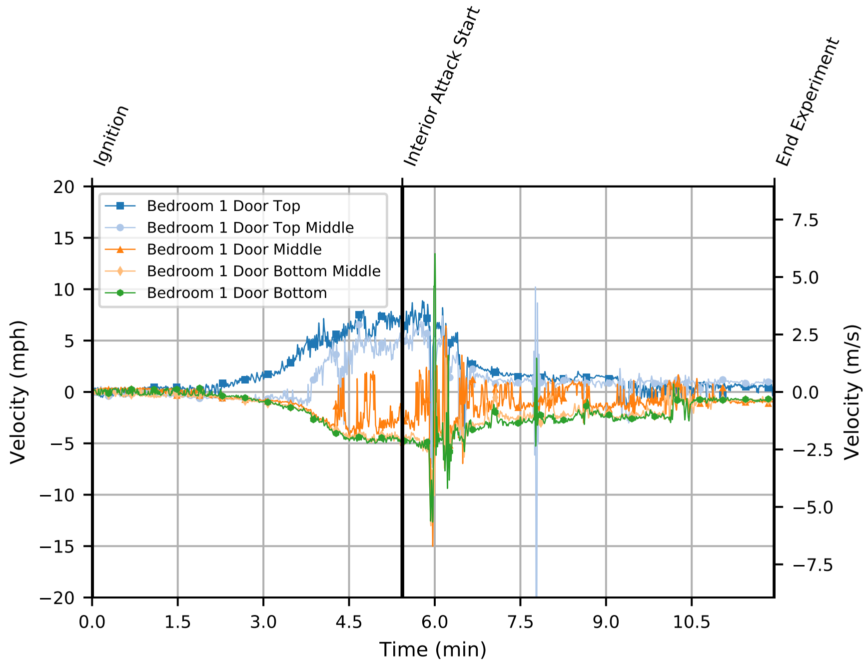


Figure E.255: Experiment 8 - Bedroom 1 Door

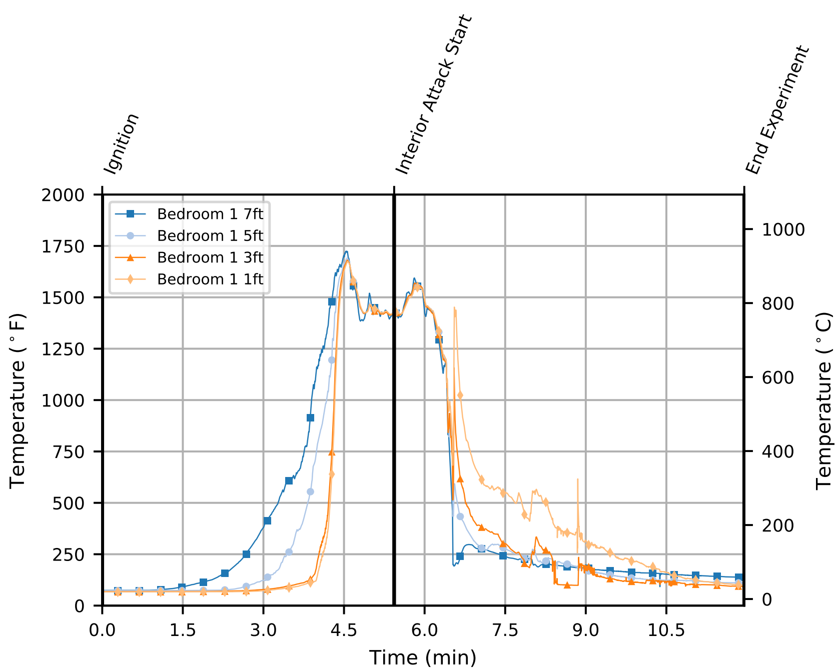


Figure E.256: Experiment 8 - Bedroom 1 Temps

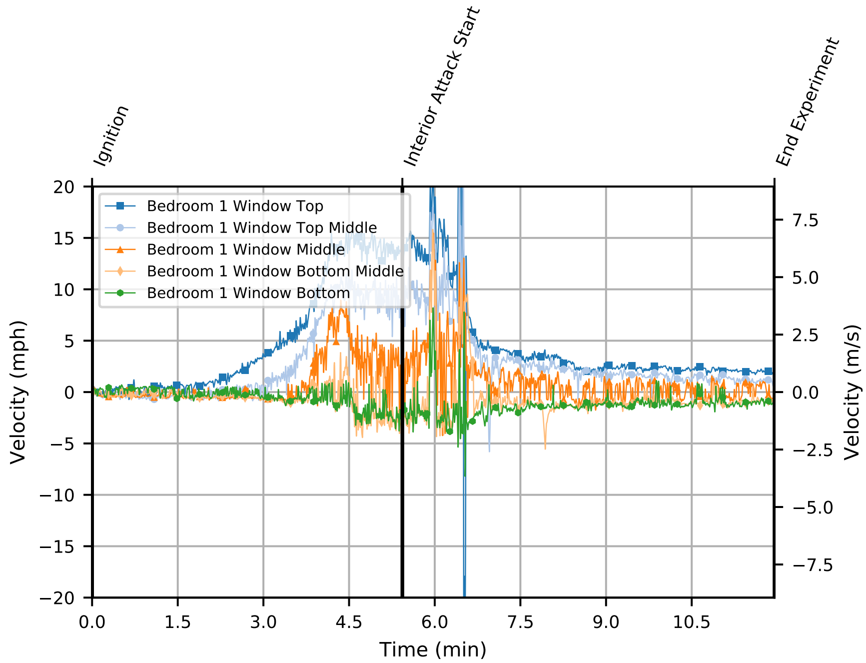


Figure E.257: Experiment 8 - Bedroom 1 Window

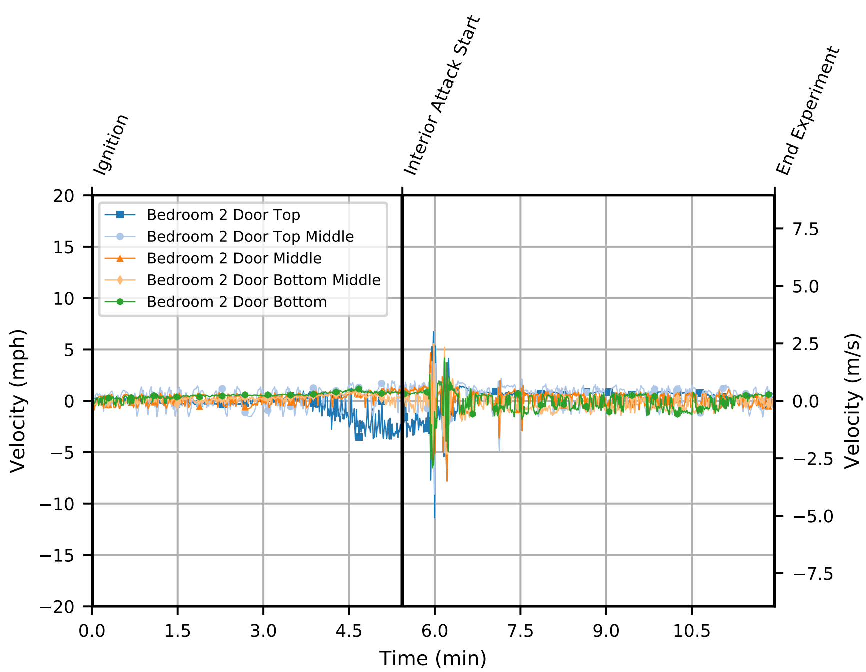


Figure E.258: Experiment 8 - Bedroom 2 Door

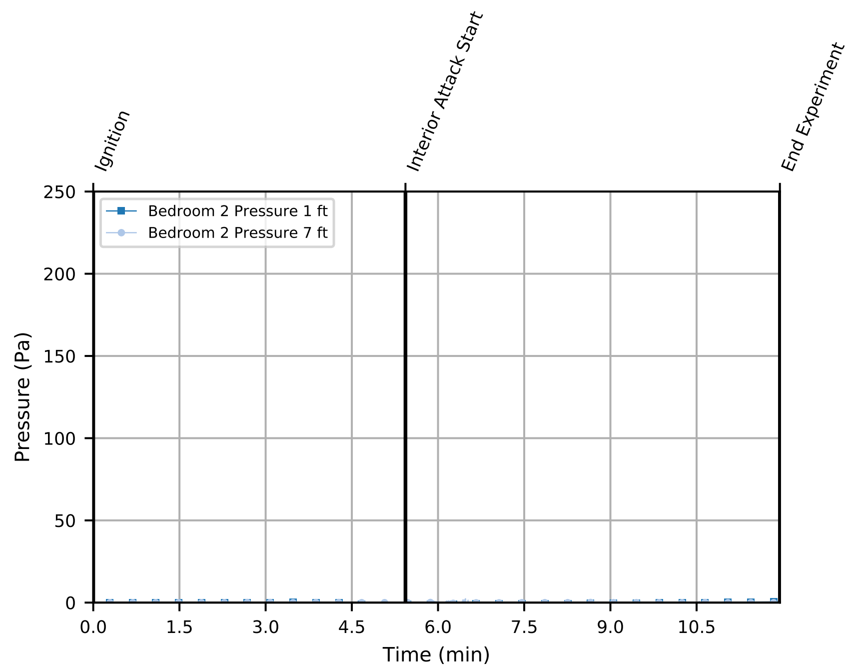


Figure E.259: Experiment 8 - Bedroom 2 Pressure

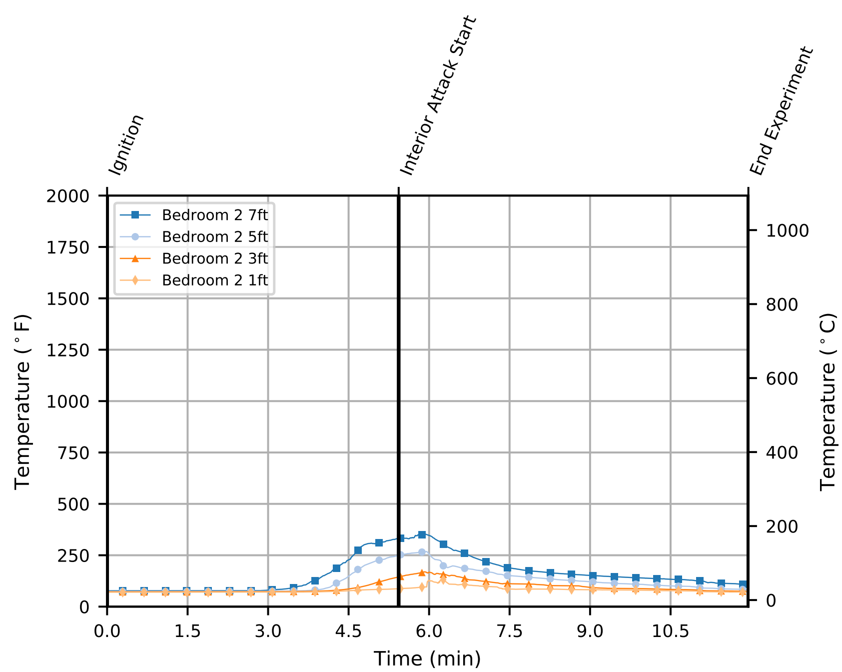


Figure E.260: Experiment 8 - Bedroom 2 Temps

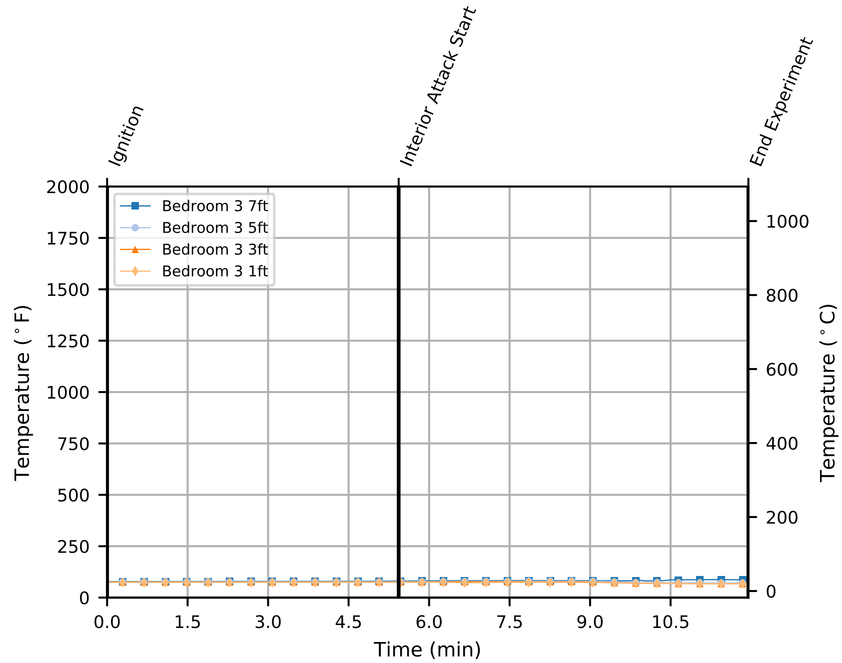


Figure E.261: Experiment 8 - Bedroom 3 Temps

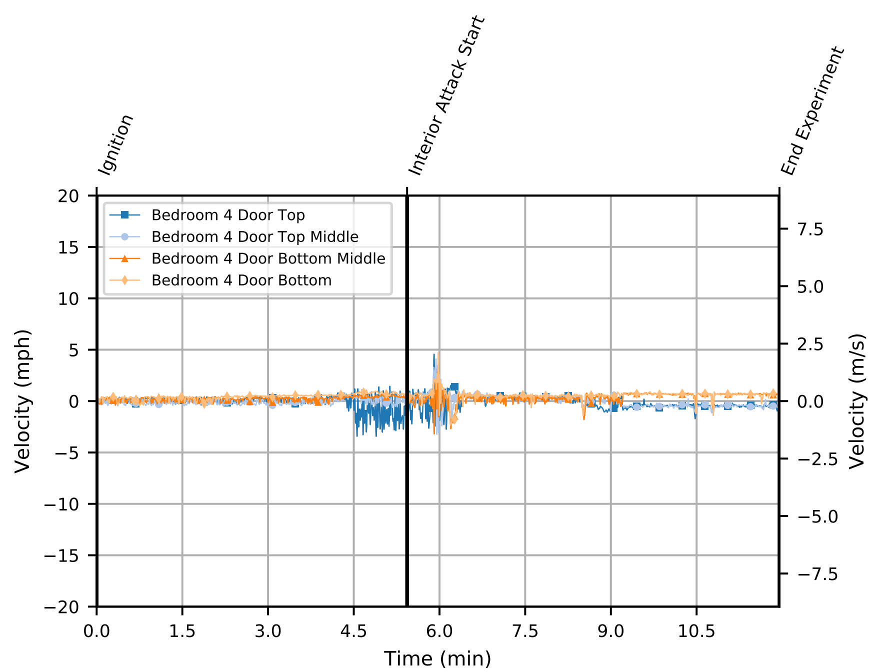


Figure E.262: Experiment 8 - Bedroom 4 Door

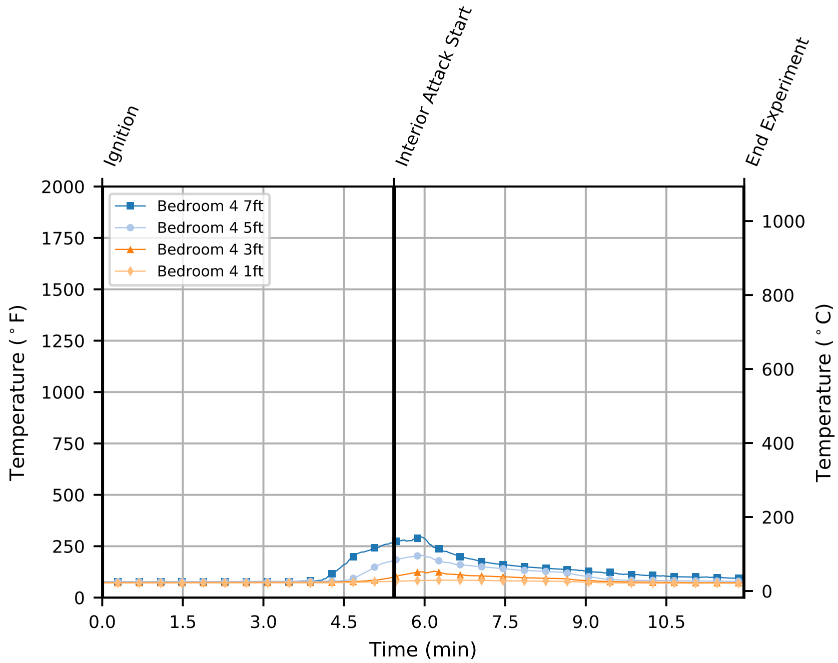


Figure E.263: Experiment 8 - Bedroom 4 Temps

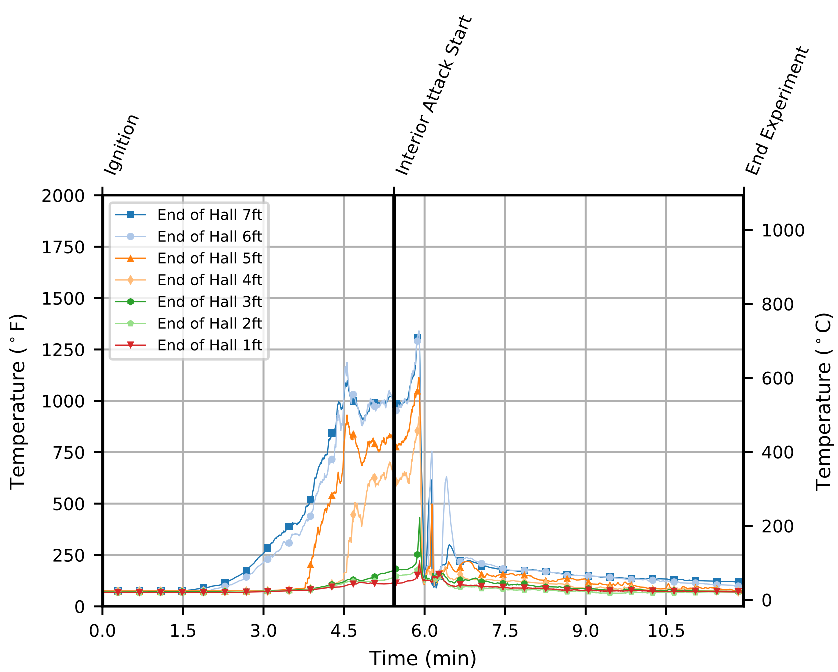


Figure E.264: Experiment 8 - End Hall Temps

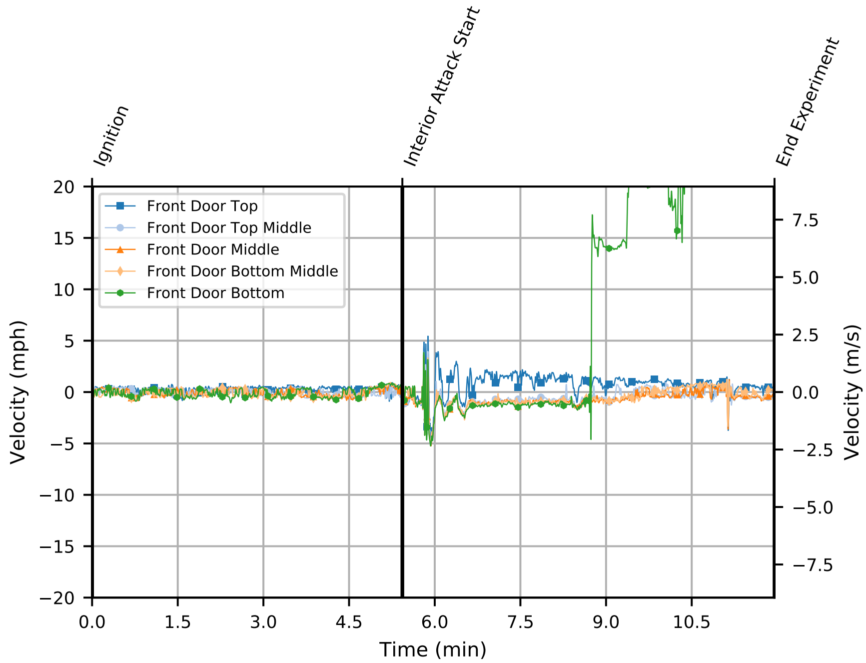


Figure E.265: Experiment 8 - Front Door Flow

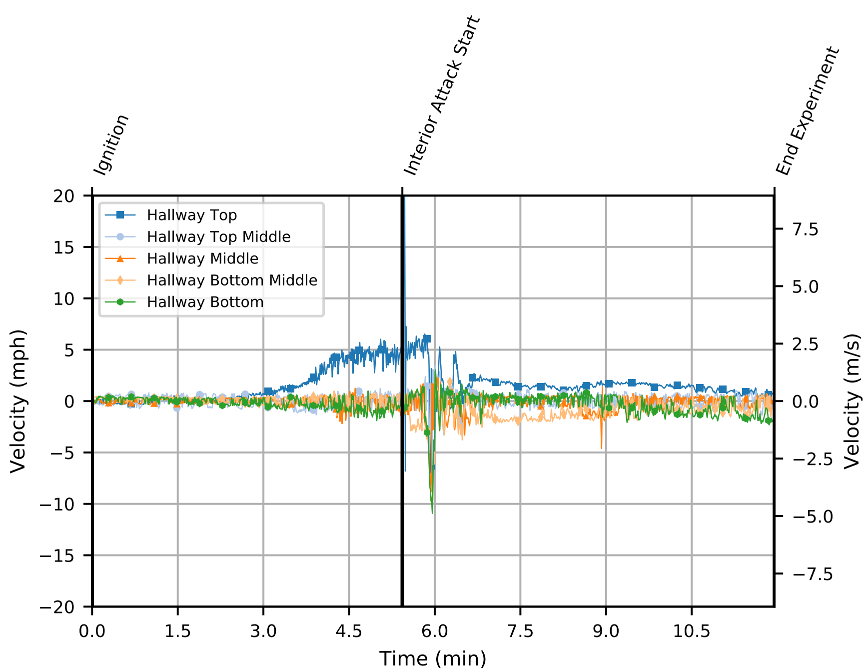


Figure E.266: Experiment 8 - Hallway Flow

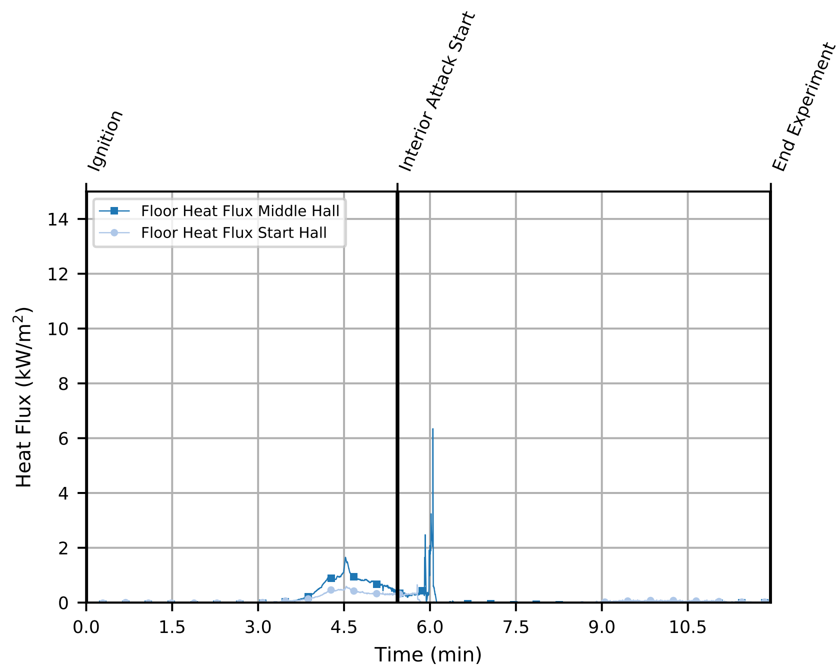


Figure E.267: Experiment 8 - Heat Flux Floor

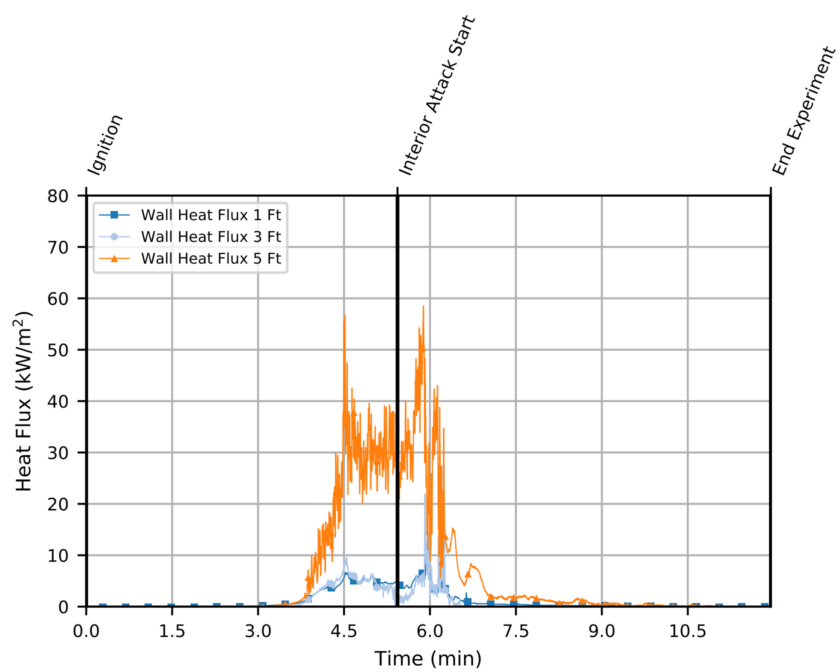


Figure E.268: Experiment 8 - Heat Flux Wall

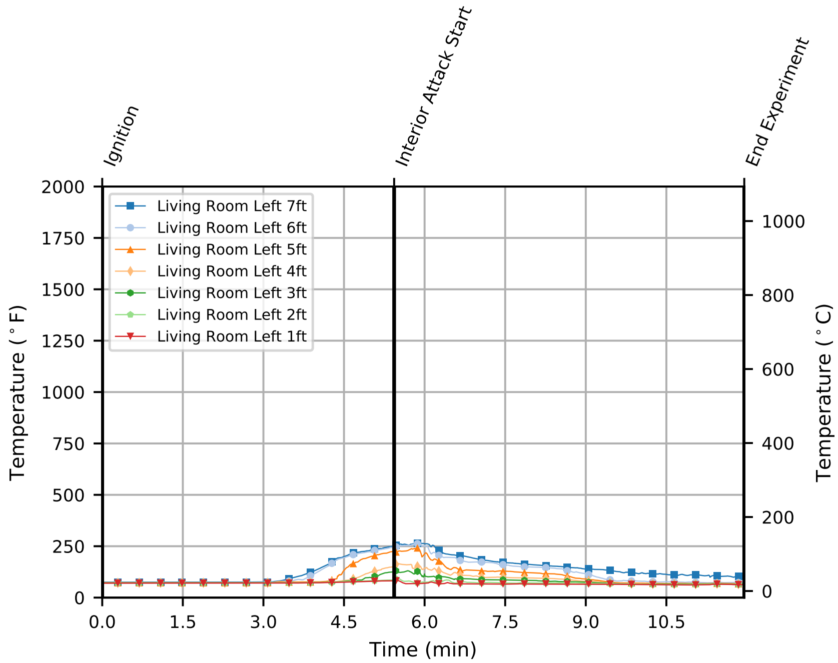


Figure E.269: Experiment 8 - Living Room Left Temps

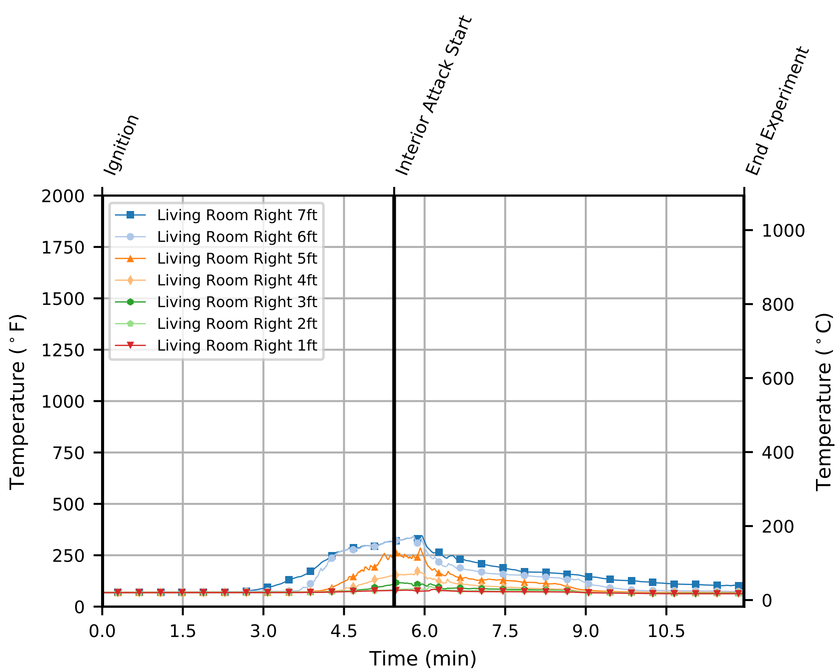


Figure E.270: Experiment 8 - Living Room Right Temps

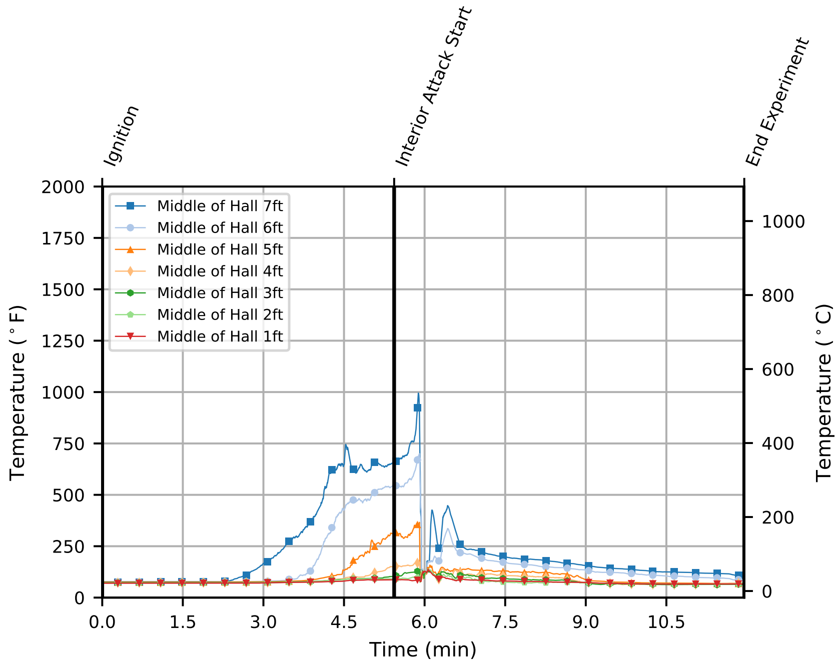


Figure E.271: Experiment 8 - Middle Hall Temps

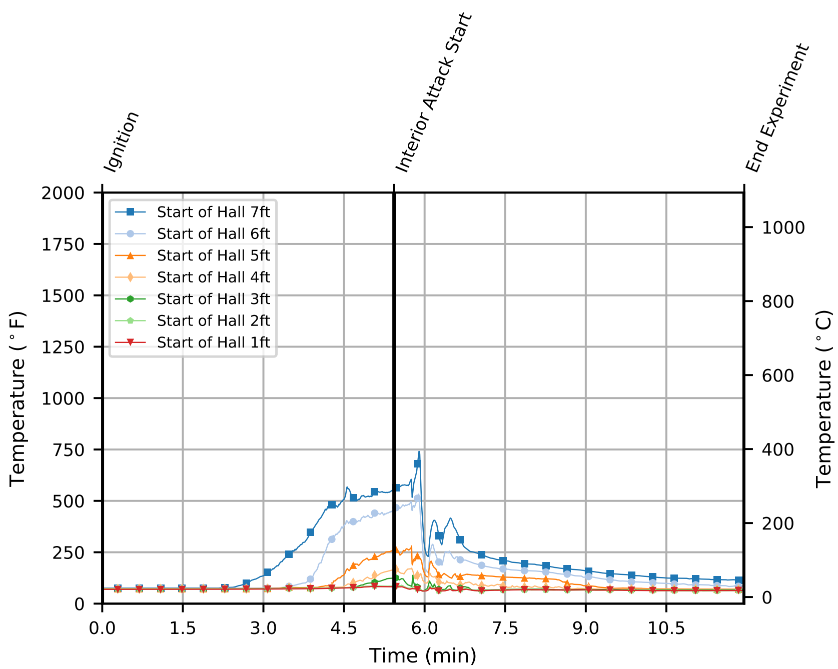


Figure E.272: Experiment 8 - Start Hall Temps

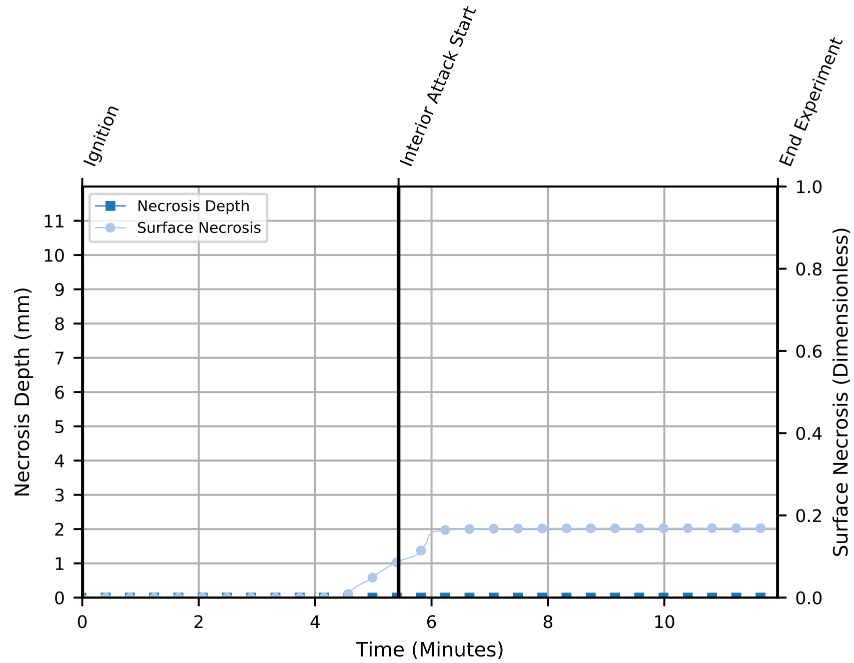


Figure E.273: Experiment 8 - Vic 1 Necrosis Depth

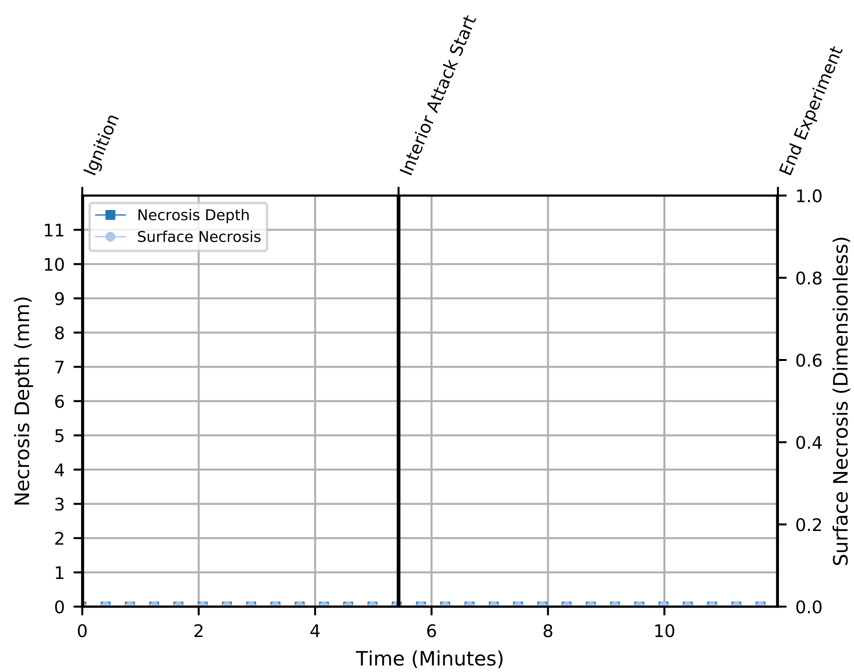


Figure E.274: Experiment 8 - Vic 3 Necrosis Depth

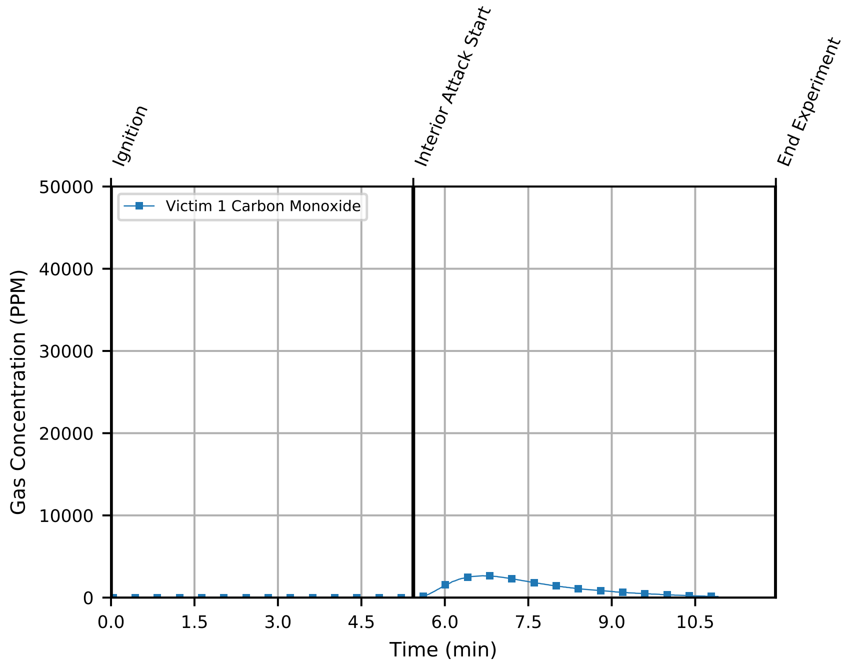


Figure E.275: Experiment 8 - Victim 1 Carbon Monoxide

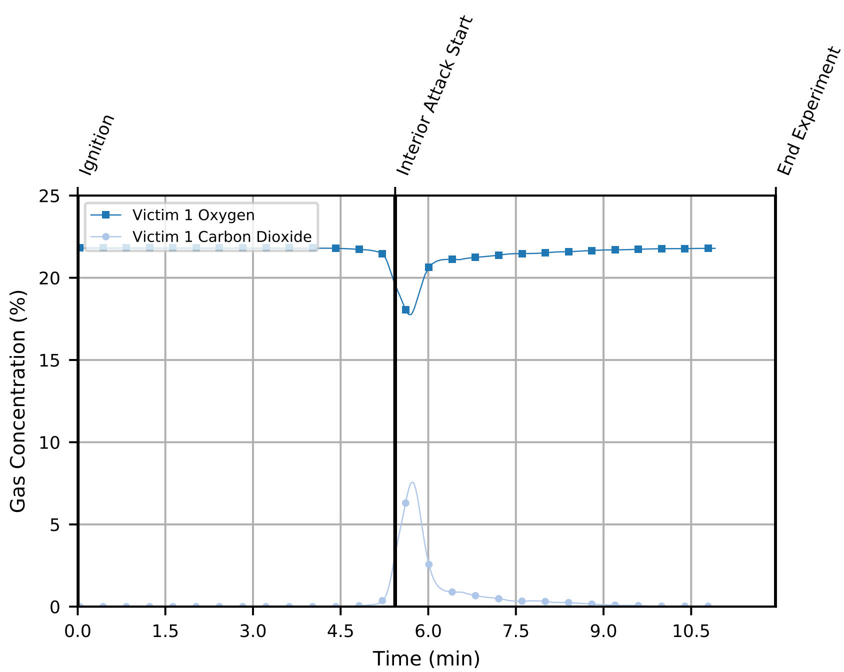


Figure E.276: Experiment 8 - Victim 1 Gas

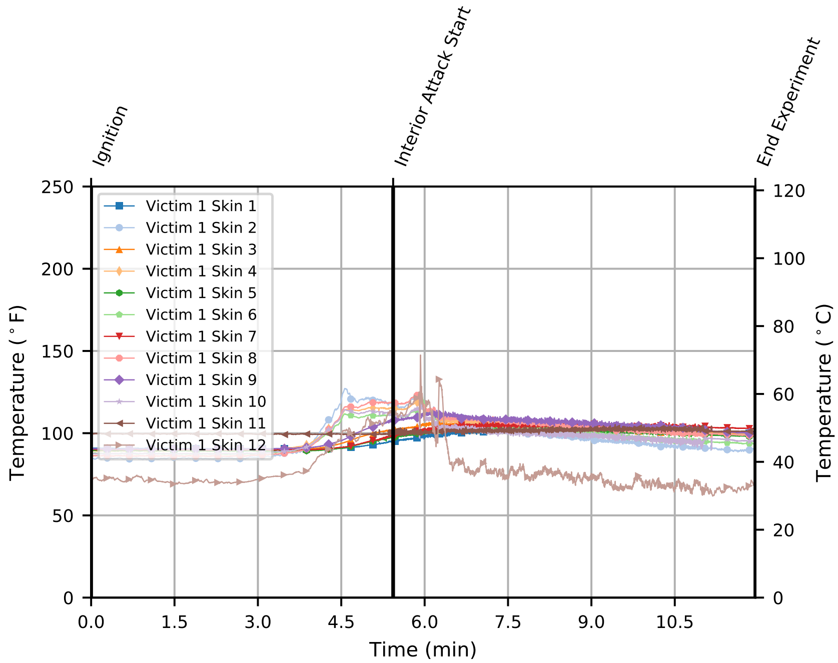


Figure E.277: Experiment 8 - Victim 1 Skin Temps

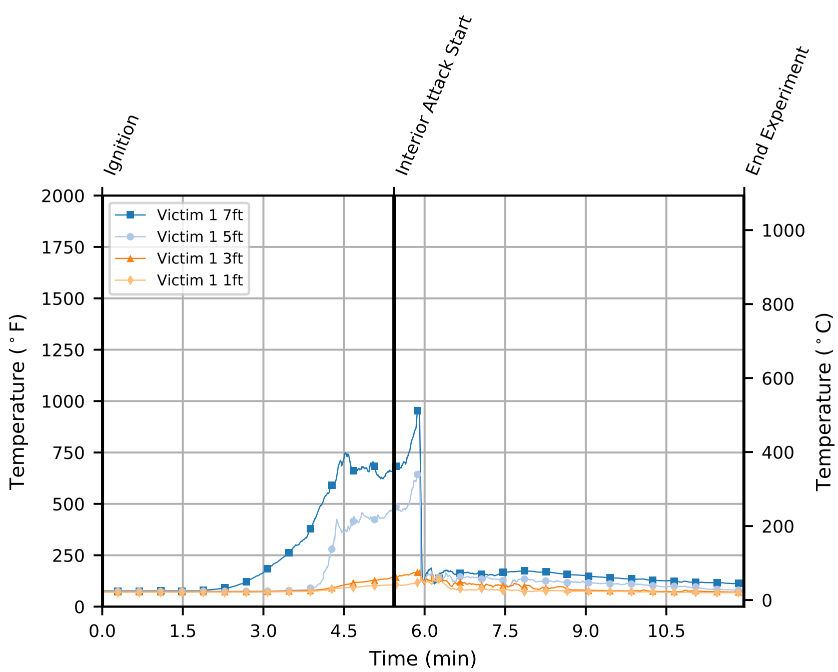


Figure E.278: Experiment 8 - Victim 1 Temps

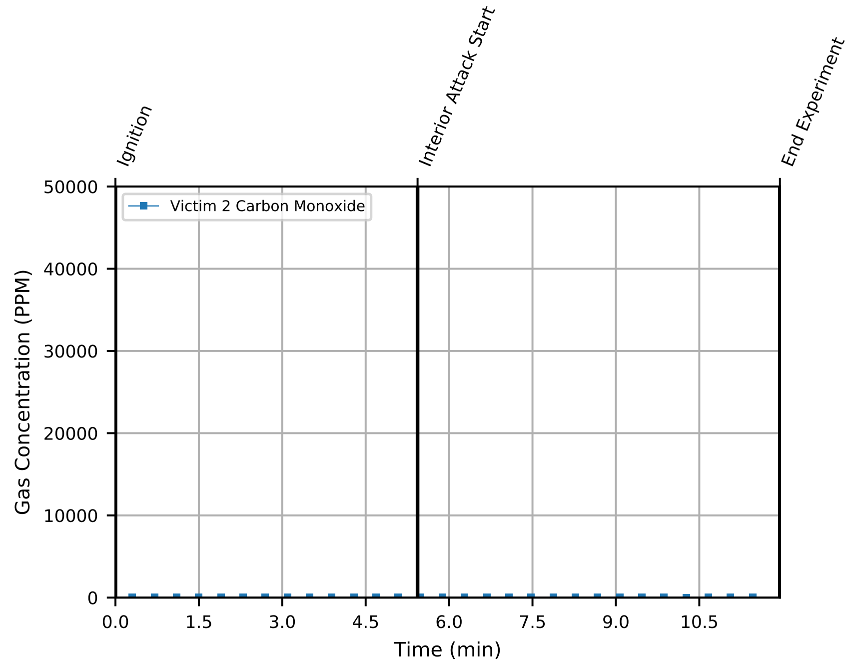


Figure E.279: Experiment 8 - Victim 2 Carbon Monoxide

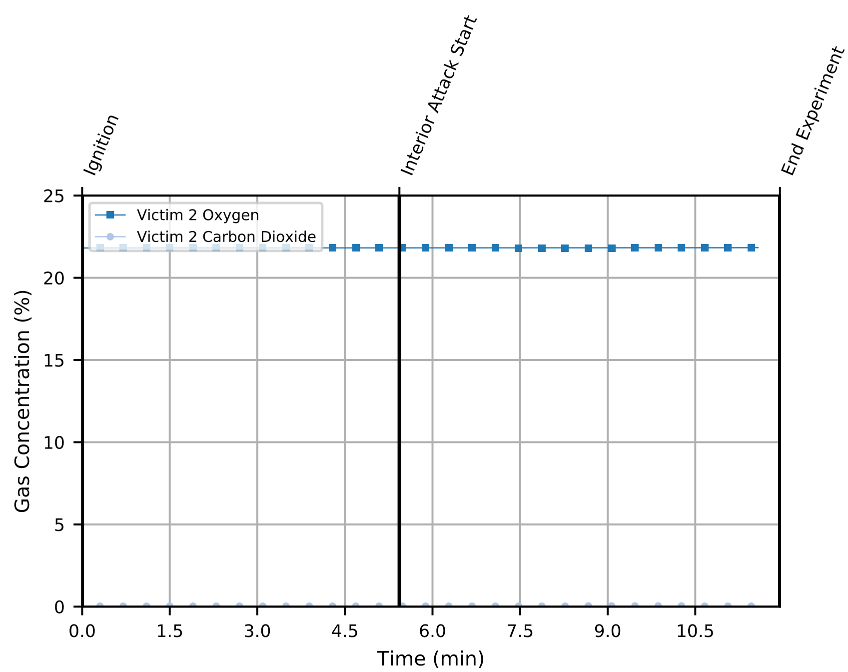


Figure E.280: Experiment 8 - Victim 2 Gas

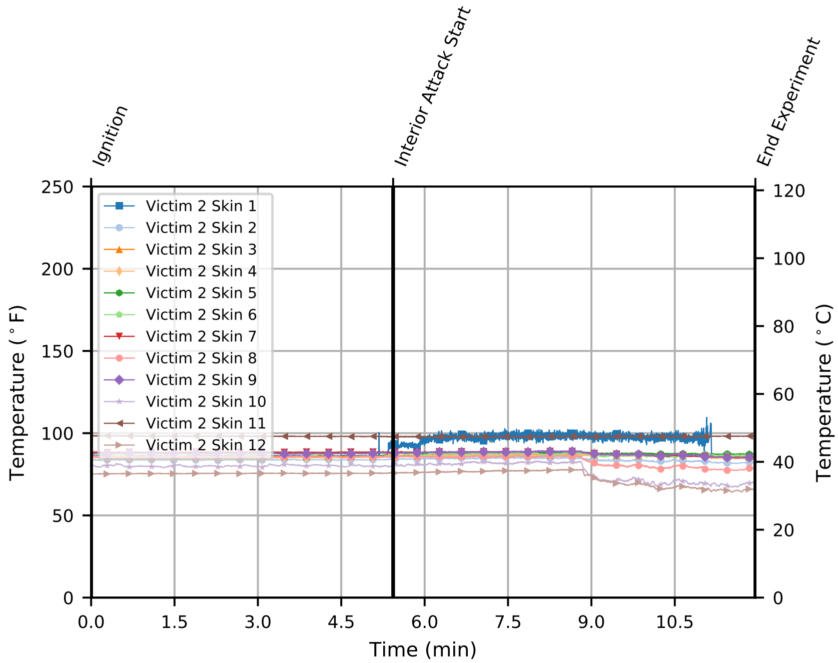


Figure E.281: Experiment 8 - Victim 2 Skin Temps

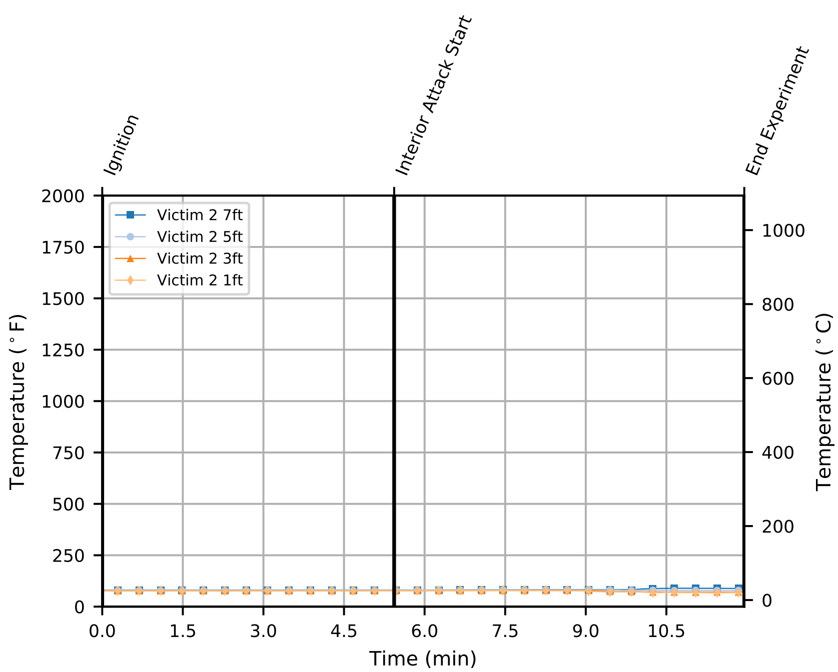


Figure E.282: Experiment 8 - Victim 2 Temps

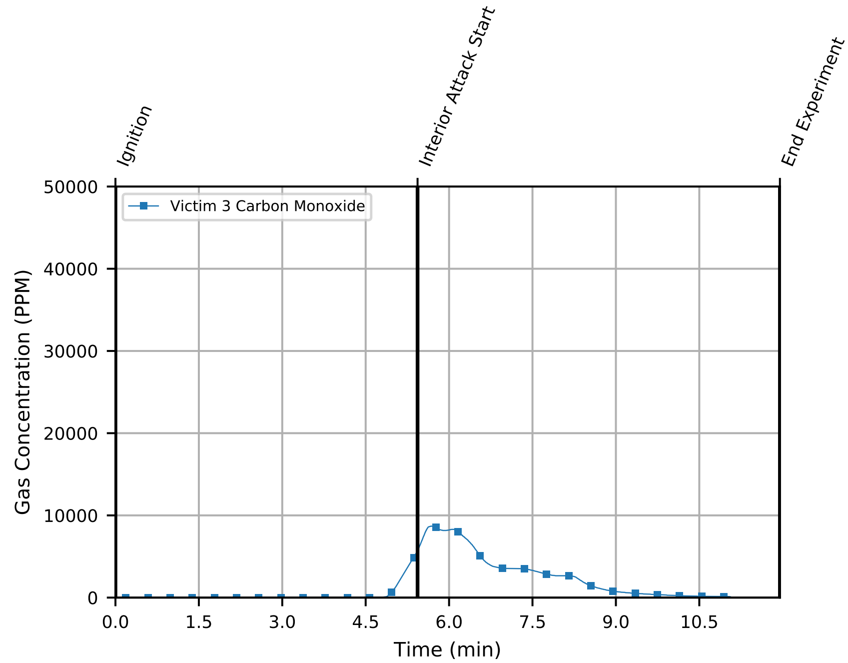


Figure E.283: Experiment 8 - Victim 3 Carbon Monoxide

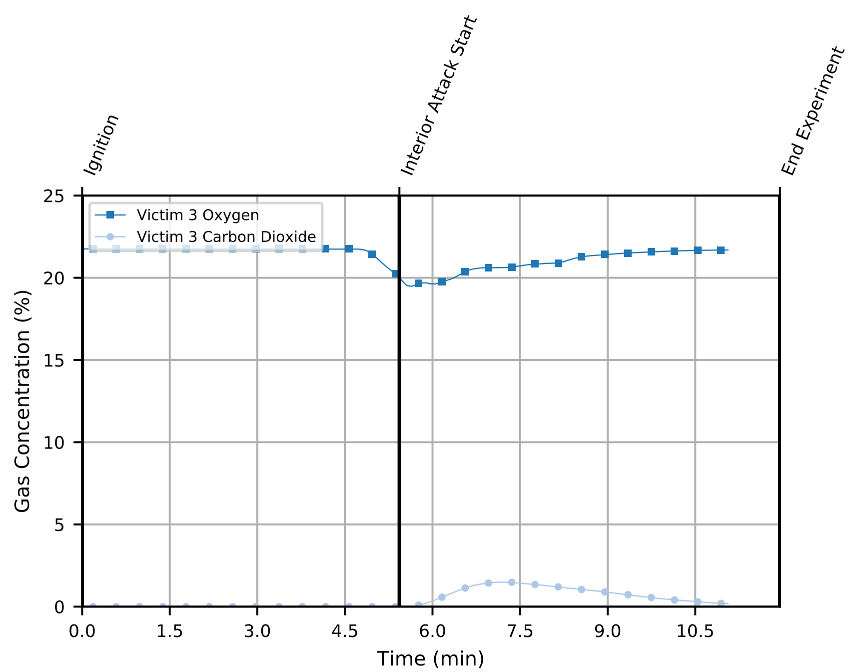


Figure E.284: Experiment 8 - Victim 3 Gas

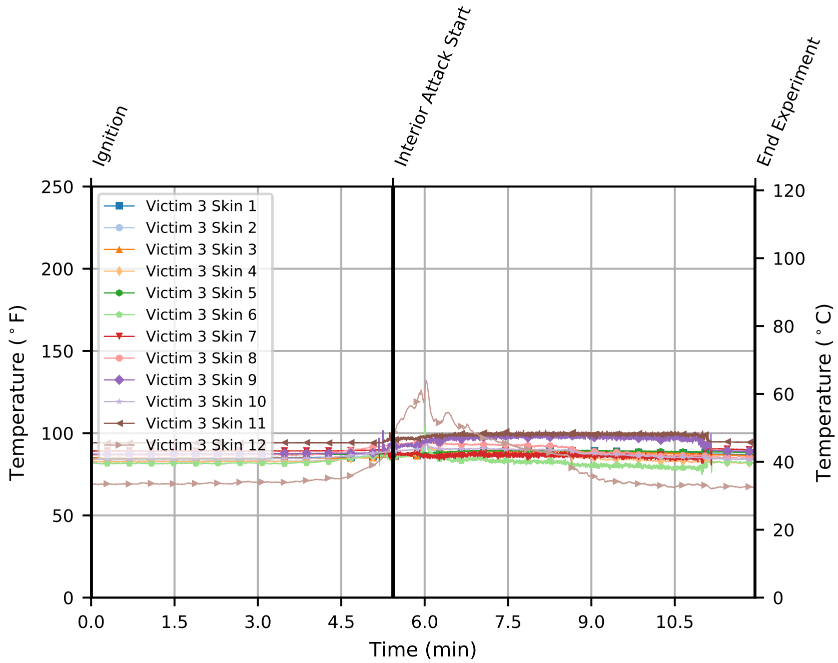


Figure E.285: Experiment 8 - Victim 3 Skin Temps

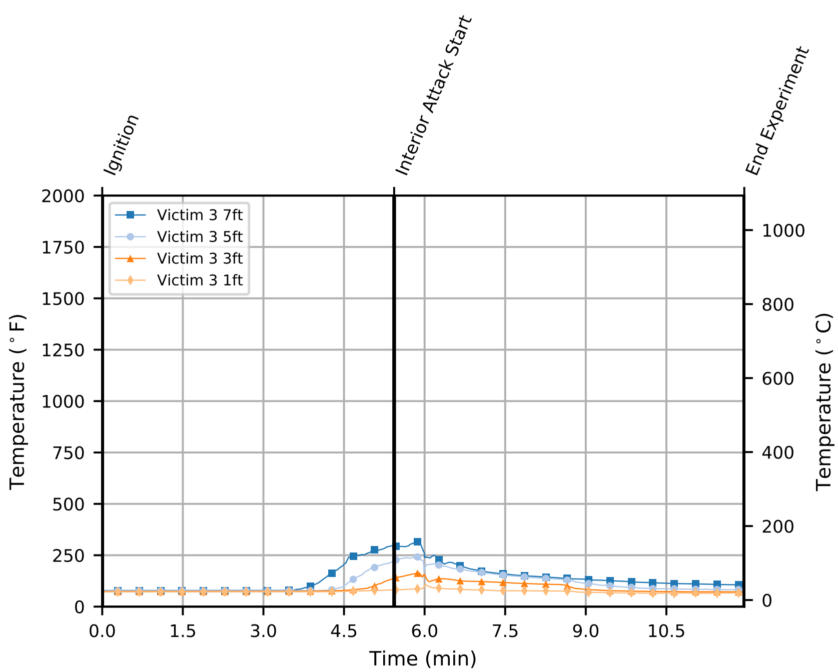


Figure E.286: Experiment 8 - Victim 3 Temps

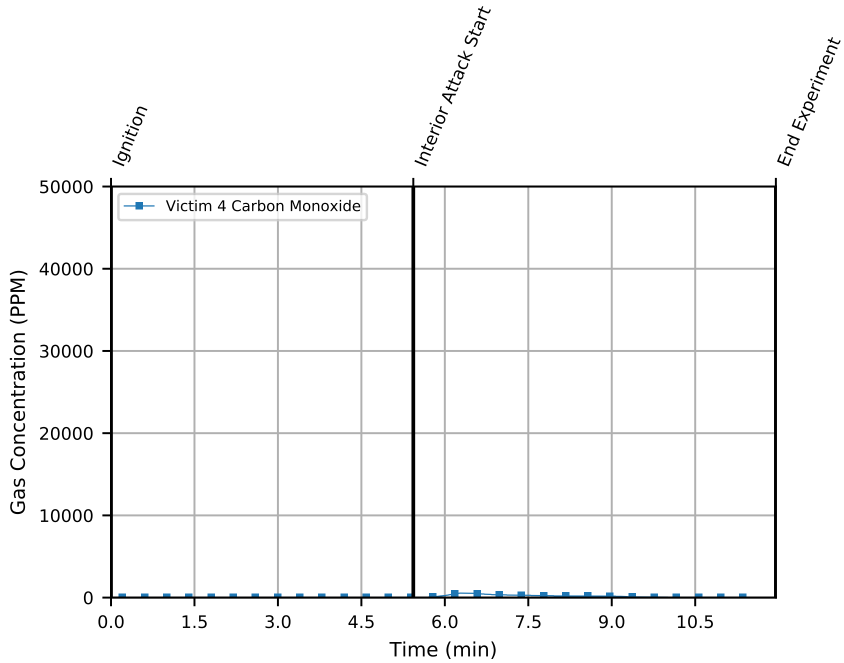


Figure E.287: Experiment 8 - Victim 4 Carbon Monoxide

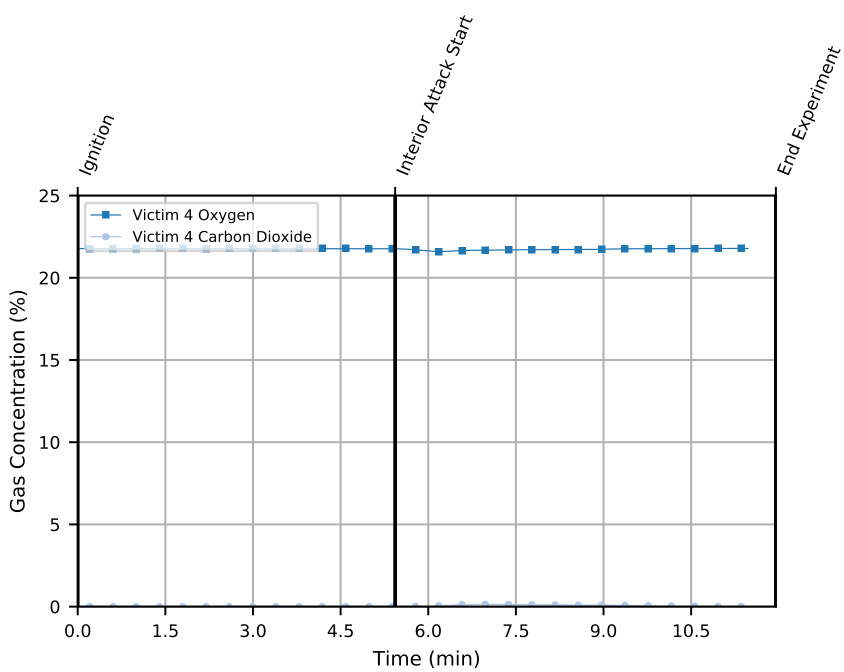


Figure E.288: Experiment 8 - Victim 4 Gas

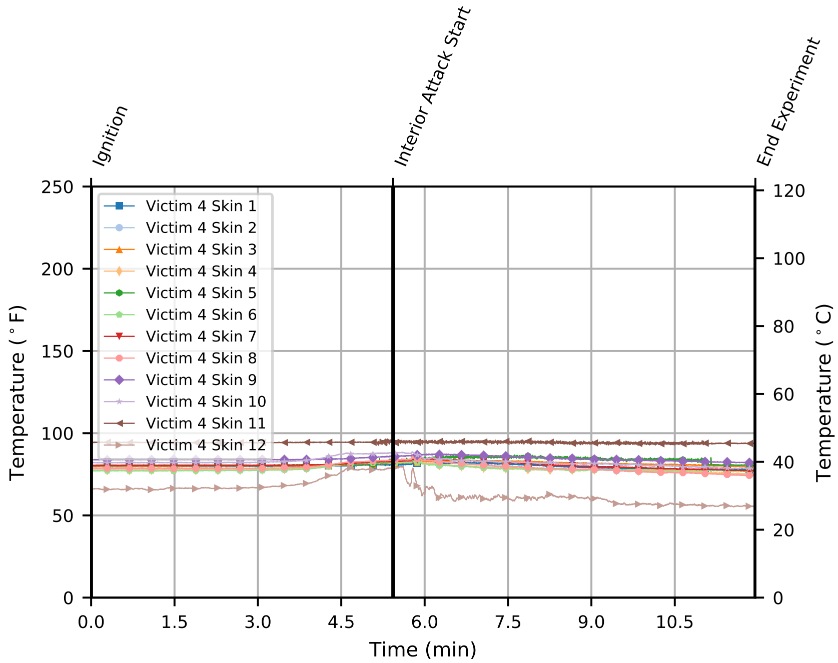


Figure E.289: Experiment 8 - Victim 4 Skin Temps

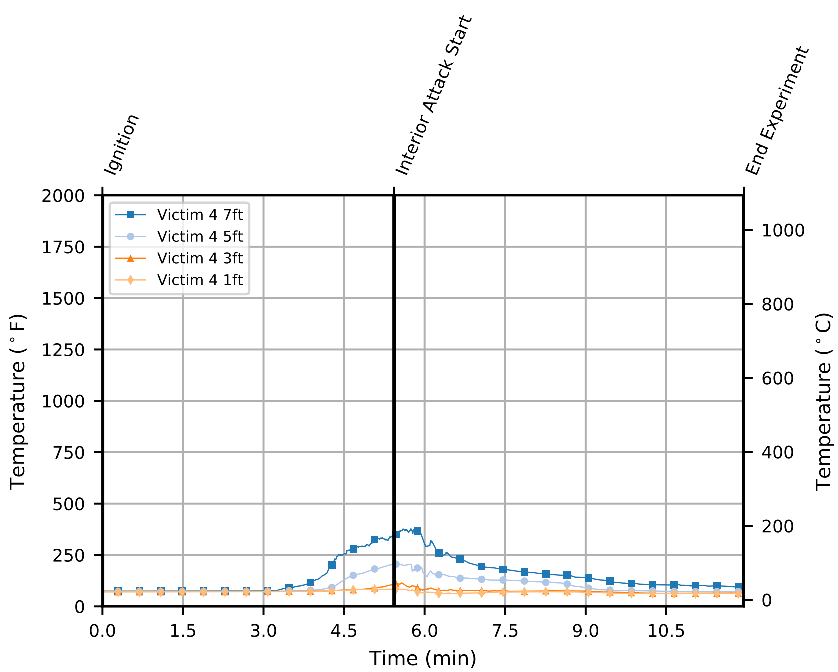


Figure E.290: Experiment 8 - Victim 4 Temps

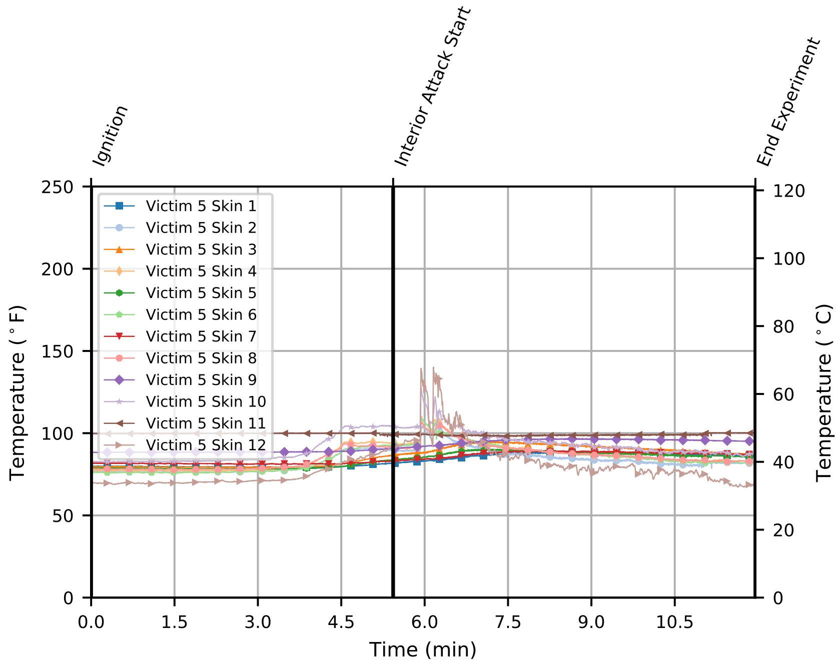


Figure E.291: Experiment 8 - Victim 5 Skin Temps

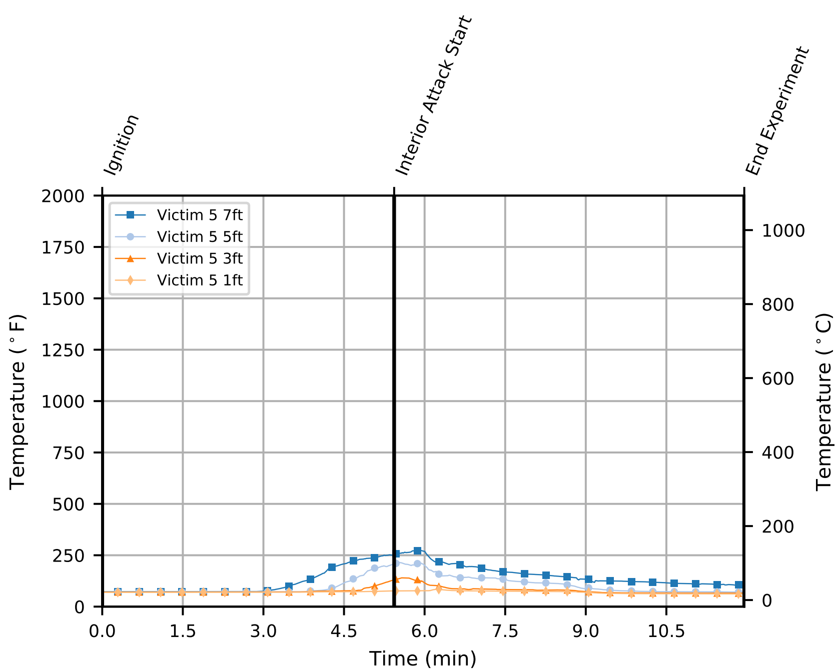


Figure E.292: Experiment 8 - Victim 5 Temps

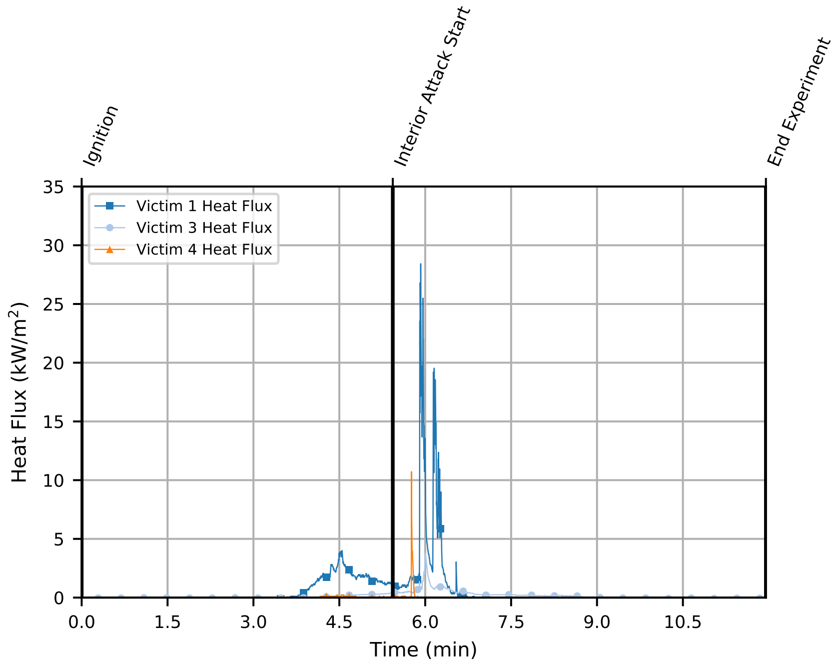


Figure E.293: Experiment 8 - Victim Heat Flux

E.9 Experiment 9 Data

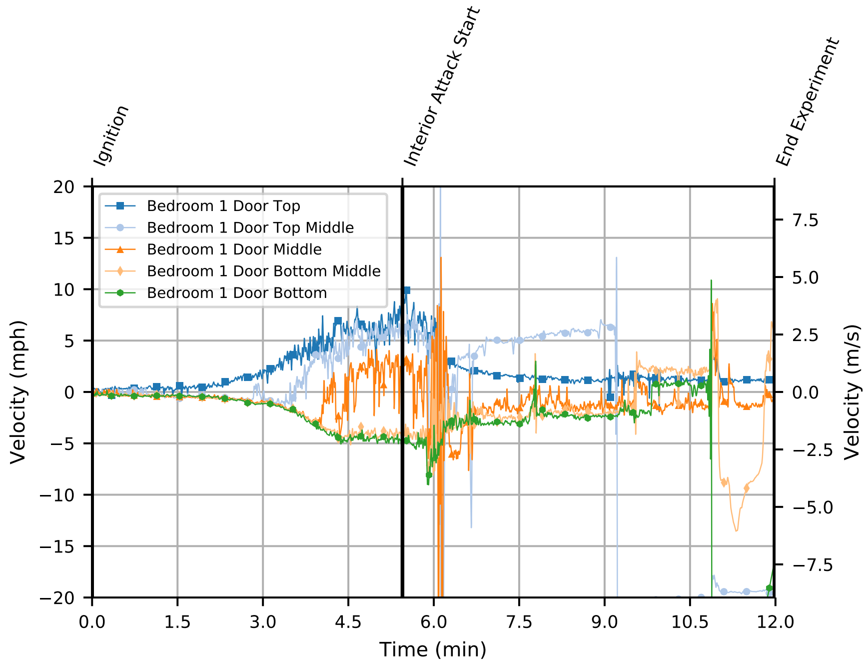


Figure E.294: Experiment 9 - Bedroom 1 Door

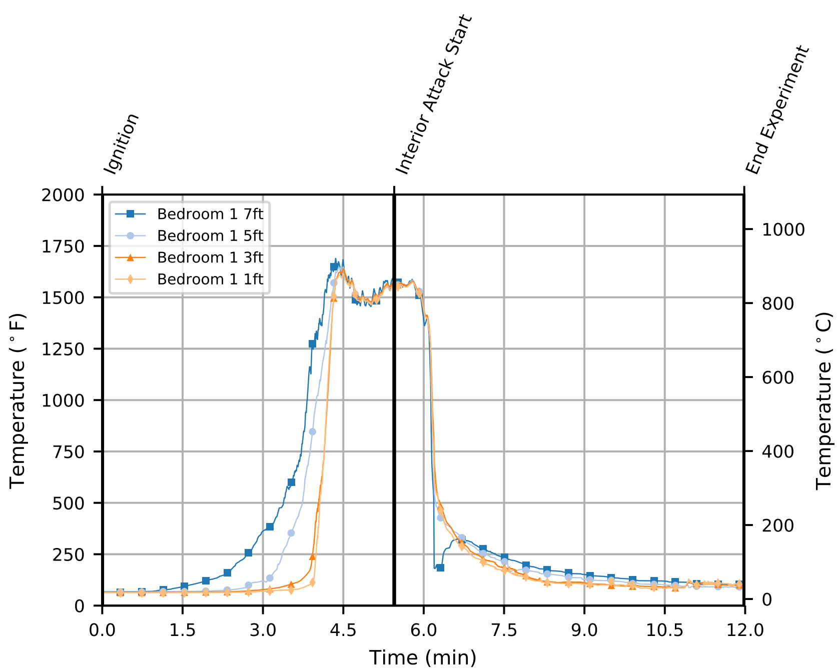


Figure E.295: Experiment 9 - Bedroom 1 Temps

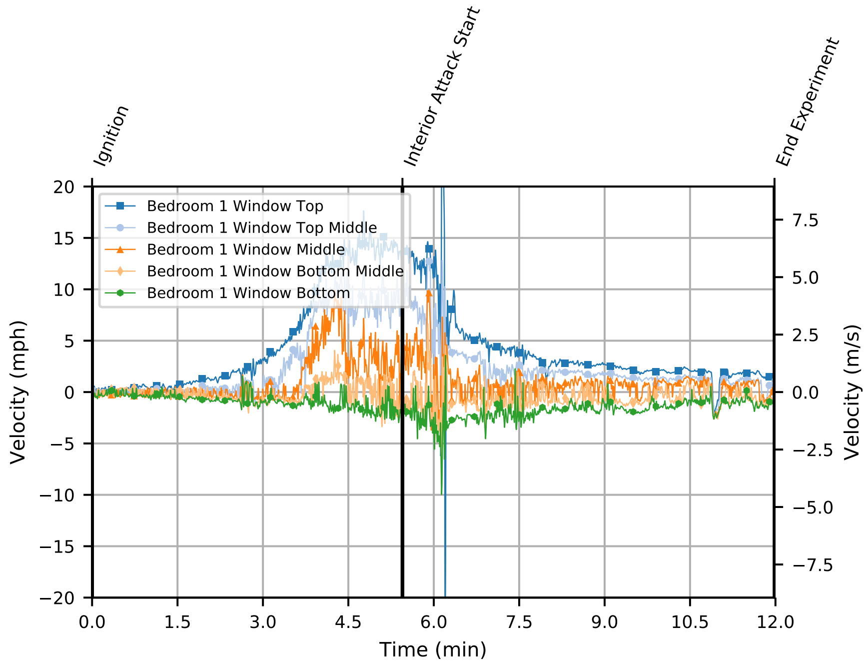


Figure E.296: Experiment 9 - Bedroom 1 Window

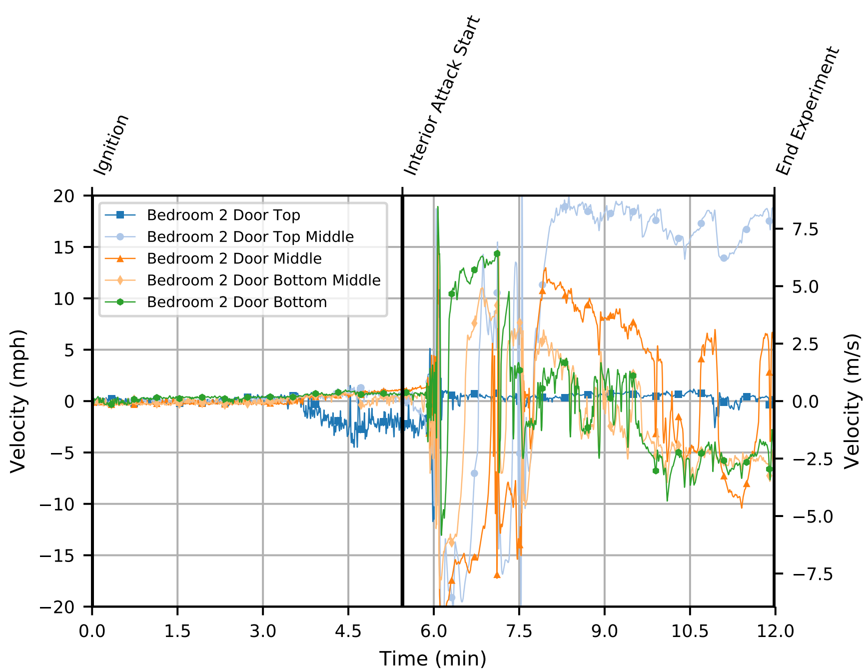


Figure E.297: Experiment 9 - Bedroom 2 Door

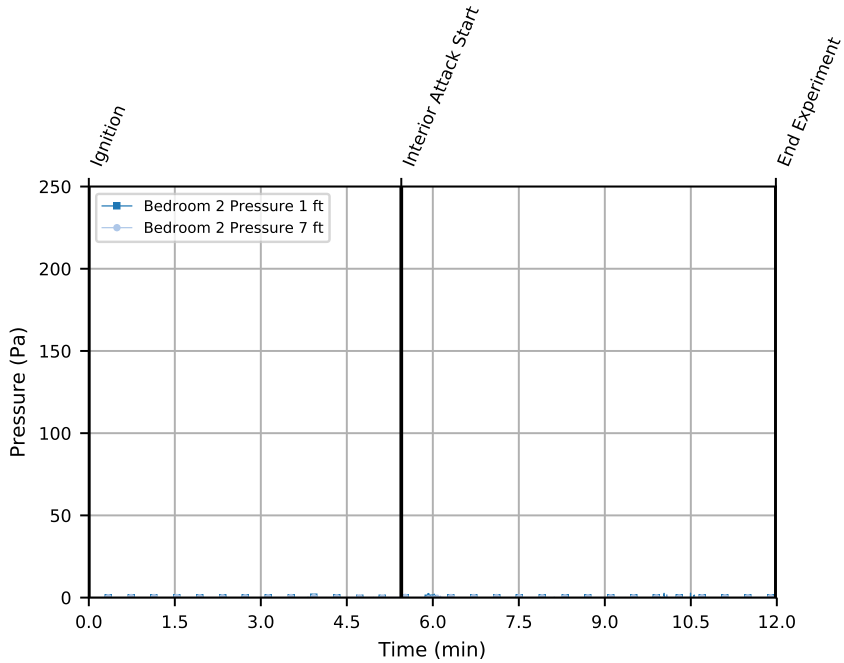


Figure E.298: Experiment 9 - Bedroom 2 Pressure

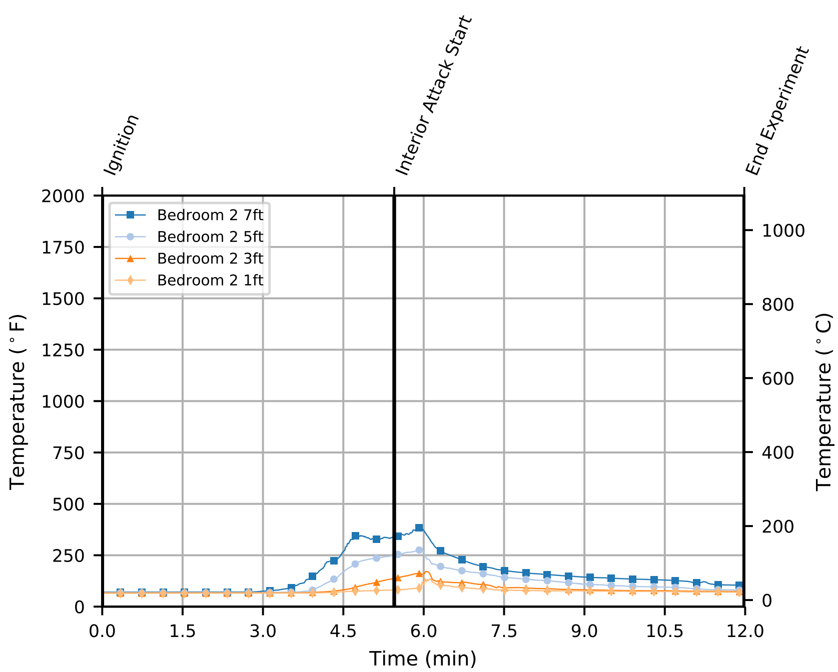


Figure E.299: Experiment 9 - Bedroom 2 Temps

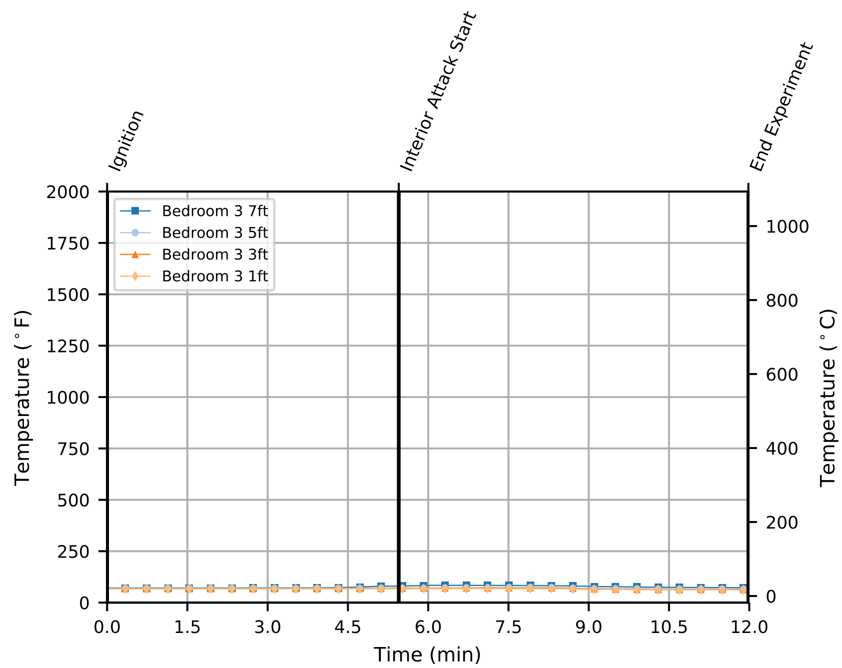


Figure E.300: Experiment 9 - Bedroom 3 Temps

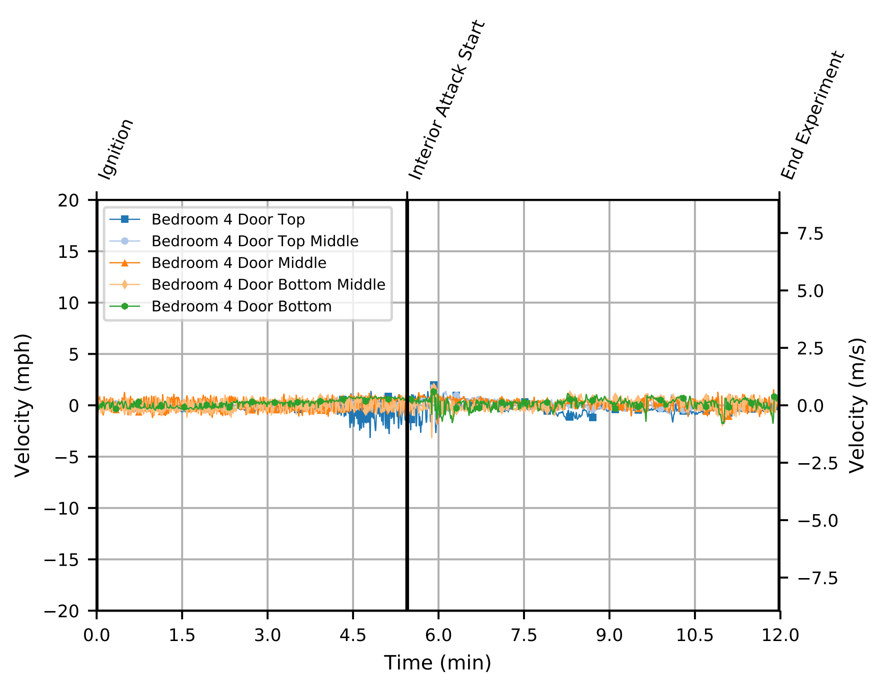


Figure E.301: Experiment 9 - Bedroom 4 Door

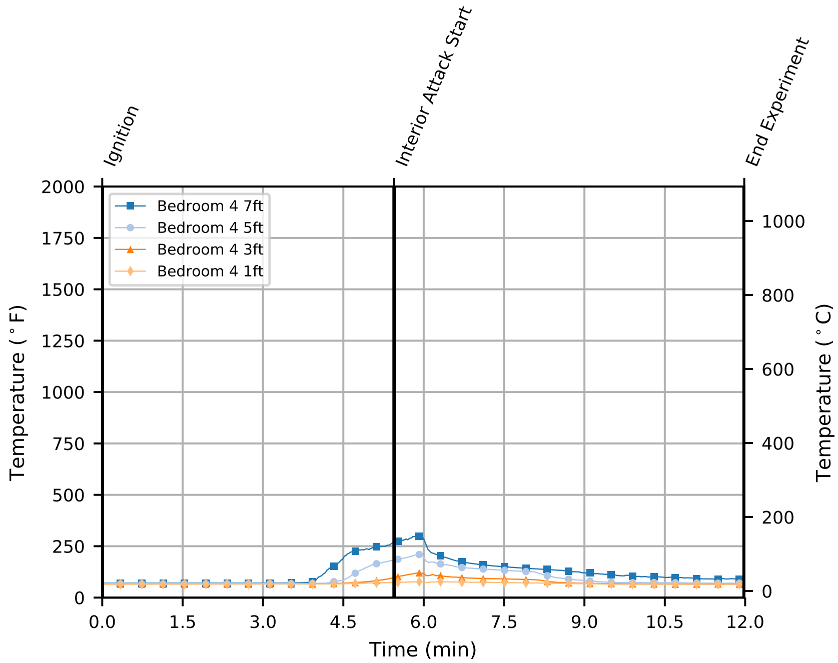


Figure E.302: Experiment 9 - Bedroom 4 Temps

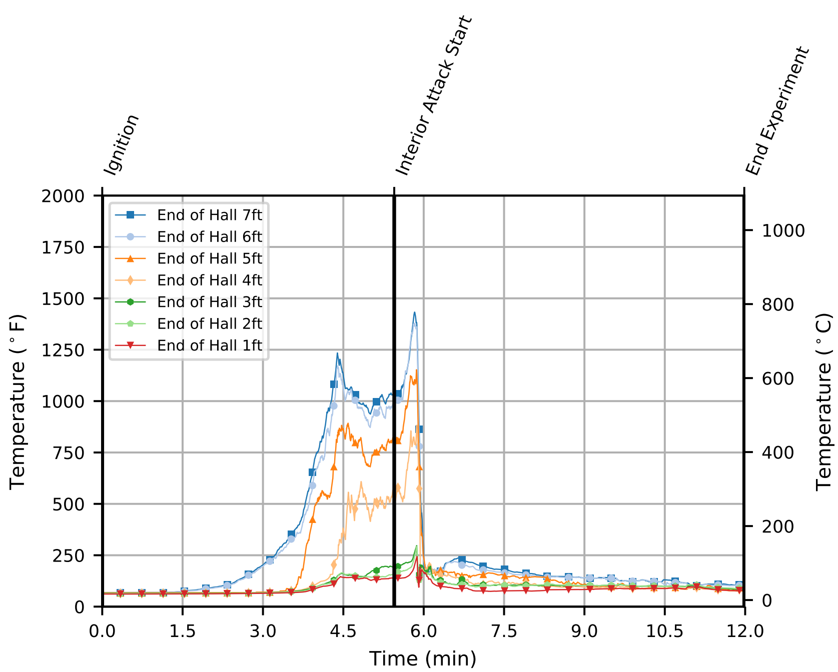


Figure E.303: Experiment 9 - End Hall Temps

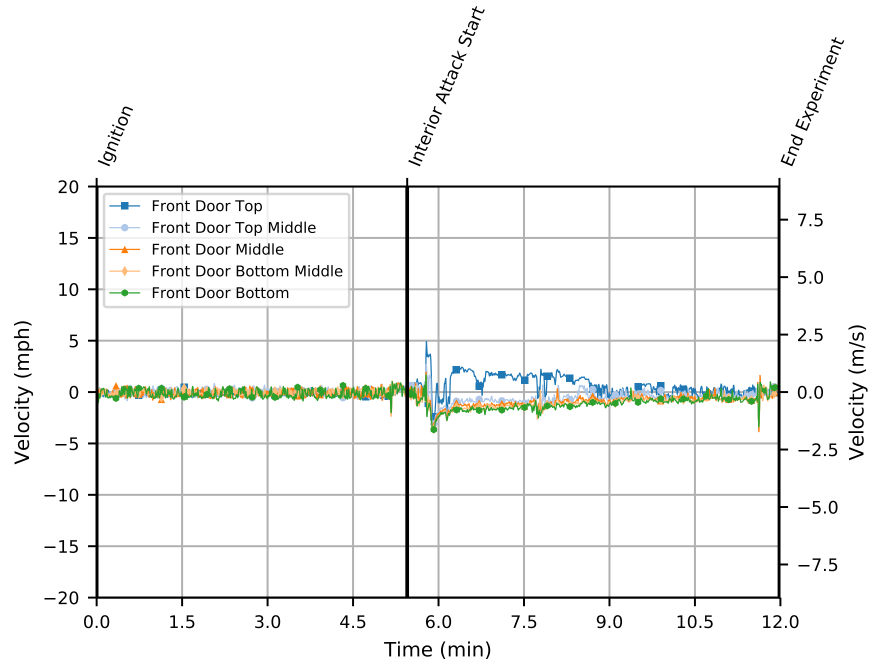


Figure E.304: Experiment 9 - Front Door Flow

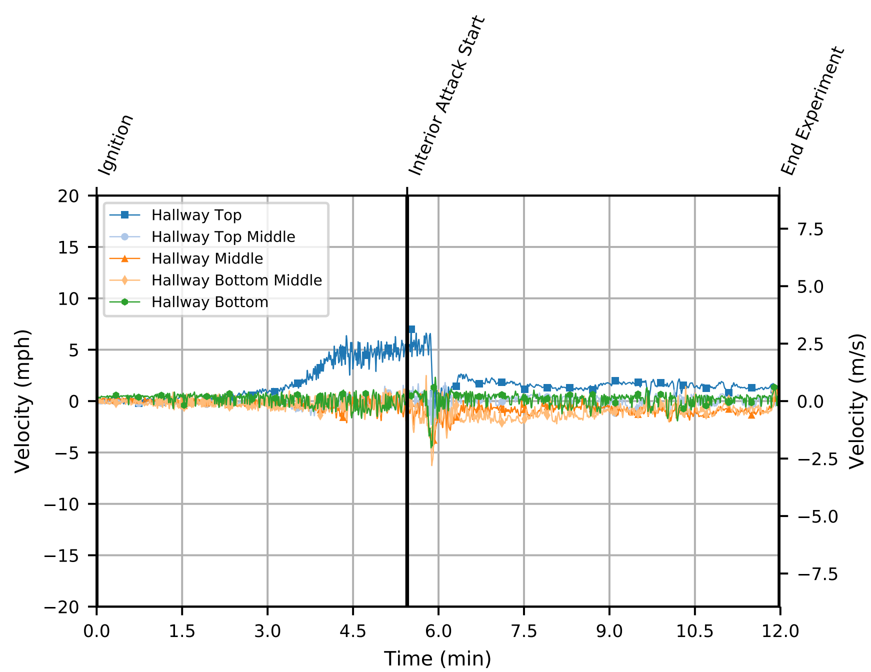


Figure E.305: Experiment 9 - Hallway Flow

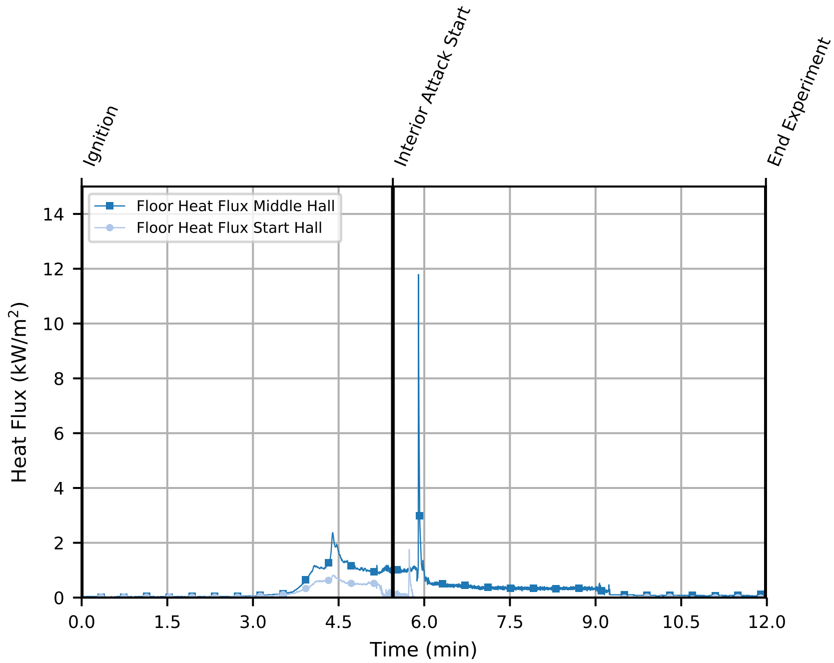


Figure E.306: Experiment 9 - Heat Flux Floor

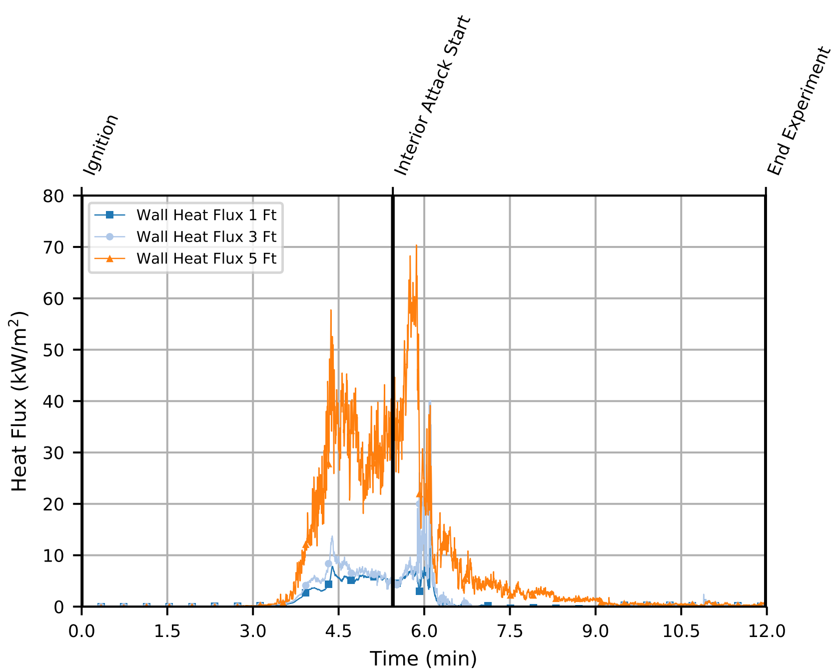


Figure E.307: Experiment 9 - Heat Flux Wall

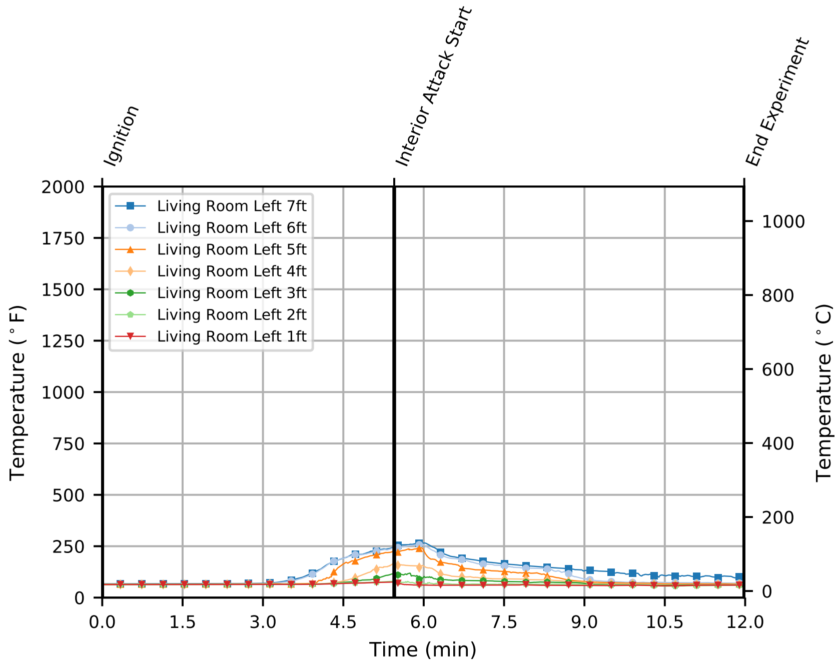


Figure E.308: Experiment 9 - Living Room Left Temps

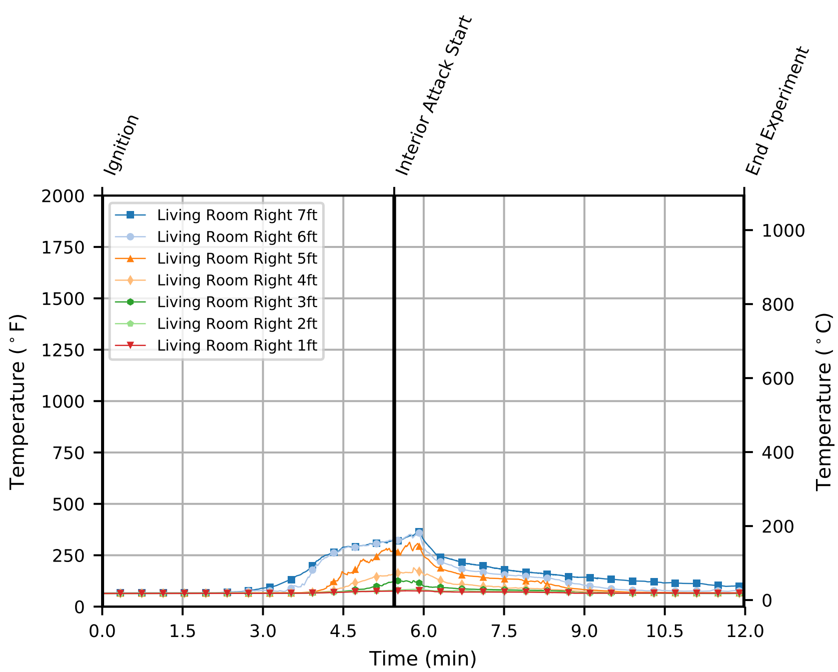


Figure E.309: Experiment 9 - Living Room Right Temps

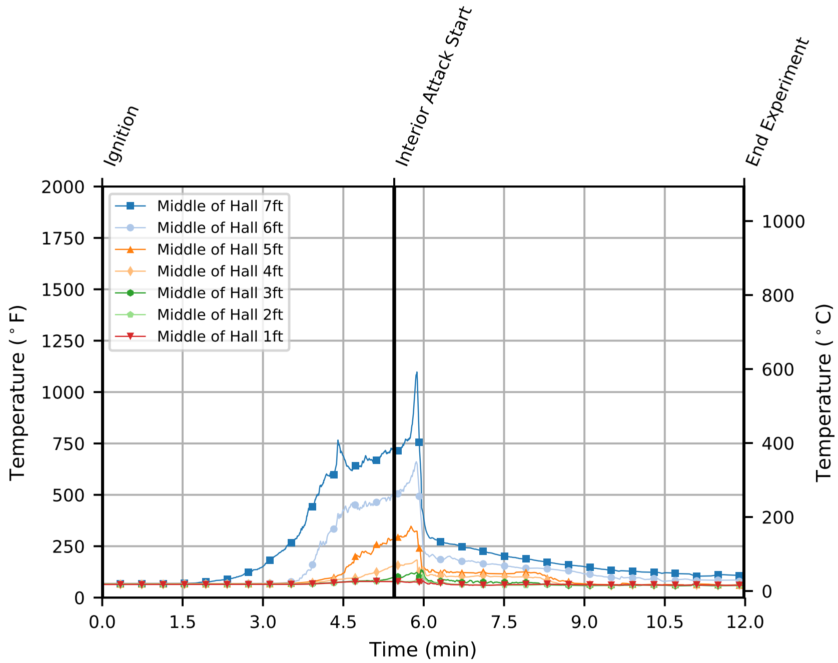


Figure E.310: Experiment 9 - Middle Hall Temps

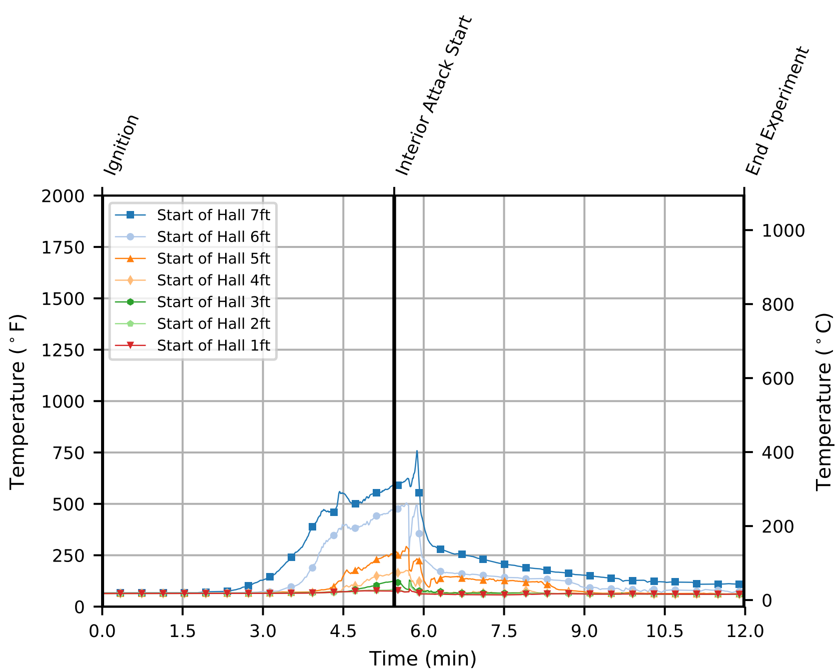


Figure E.311: Experiment 9 - Start Hall Temps

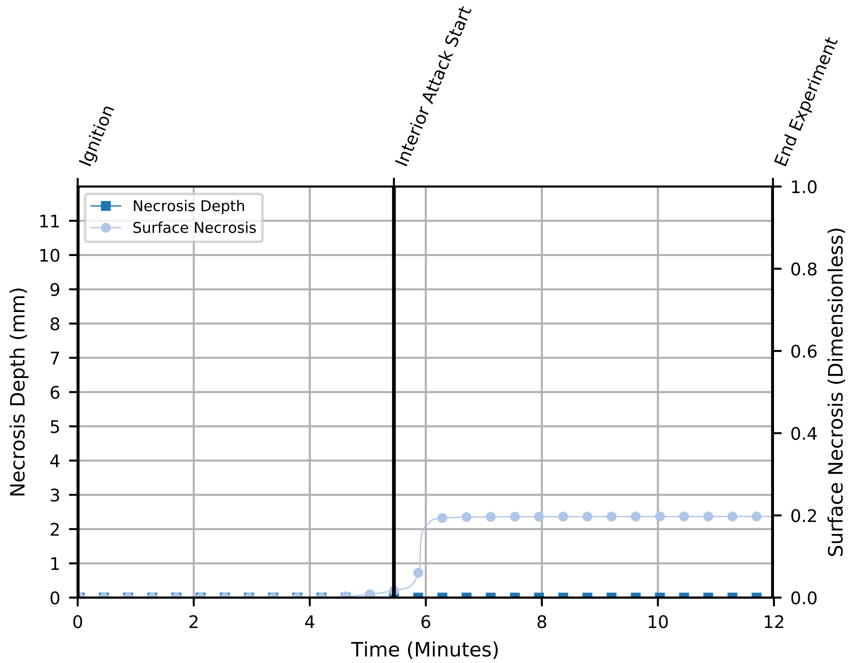


Figure E.312: Experiment 9 - Vic 1 Necrosis Depth

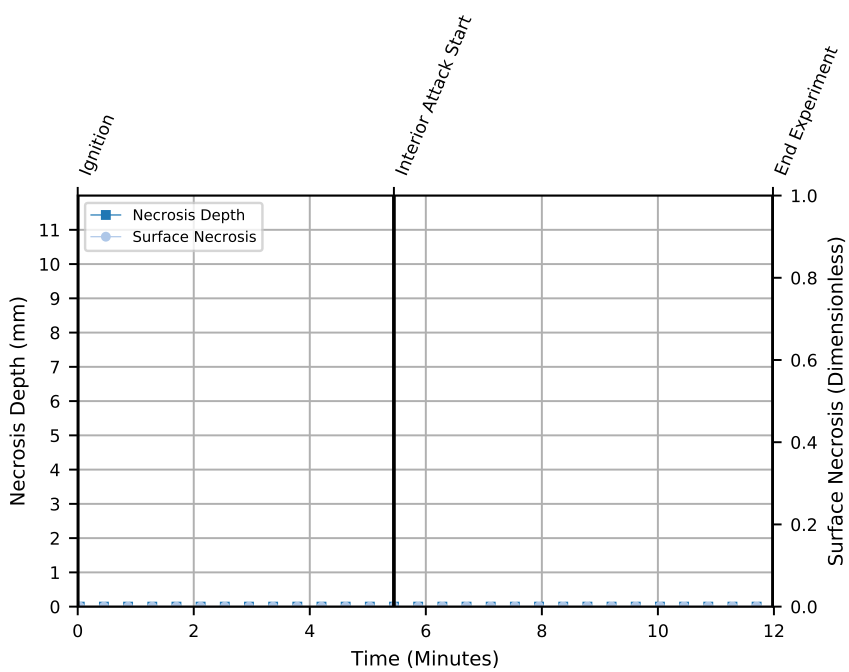


Figure E.313: Experiment 9 - Vic 3 Necrosis Depth

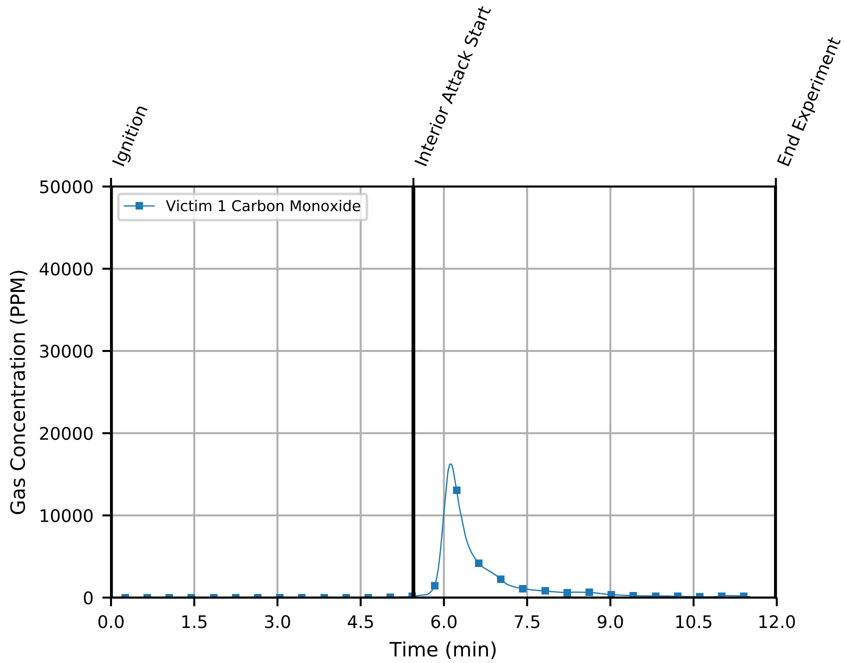


Figure E.314: Experiment 9 - Victim 1 Carbon Monoxide

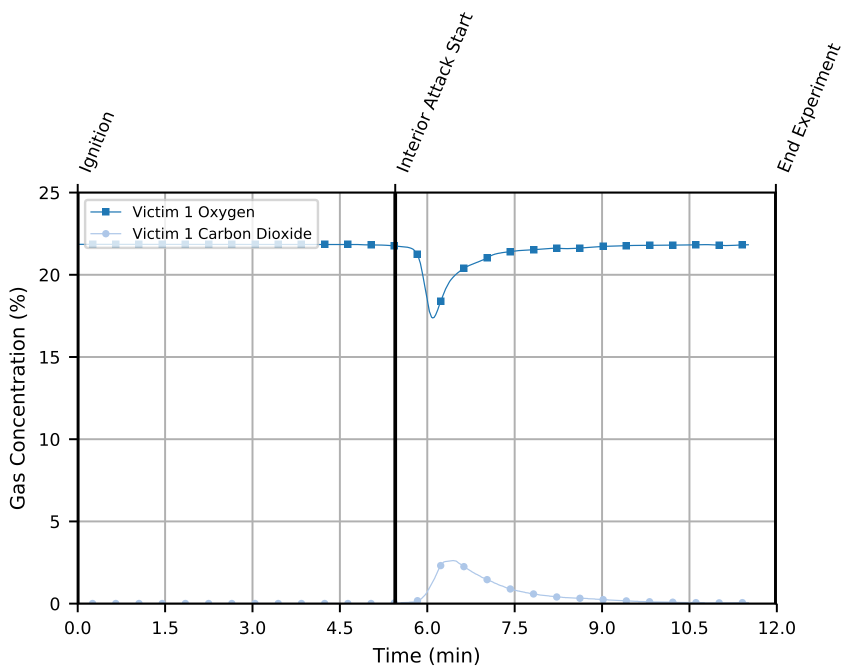


Figure E.315: Experiment 9 - Victim 1 Gas

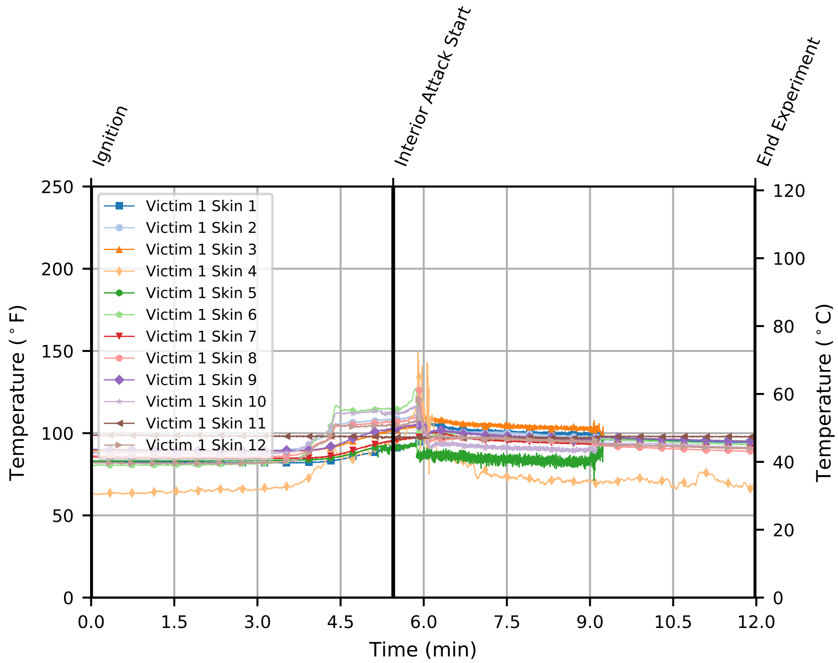


Figure E.316: Experiment 9 - Victim 1 Skin Temps

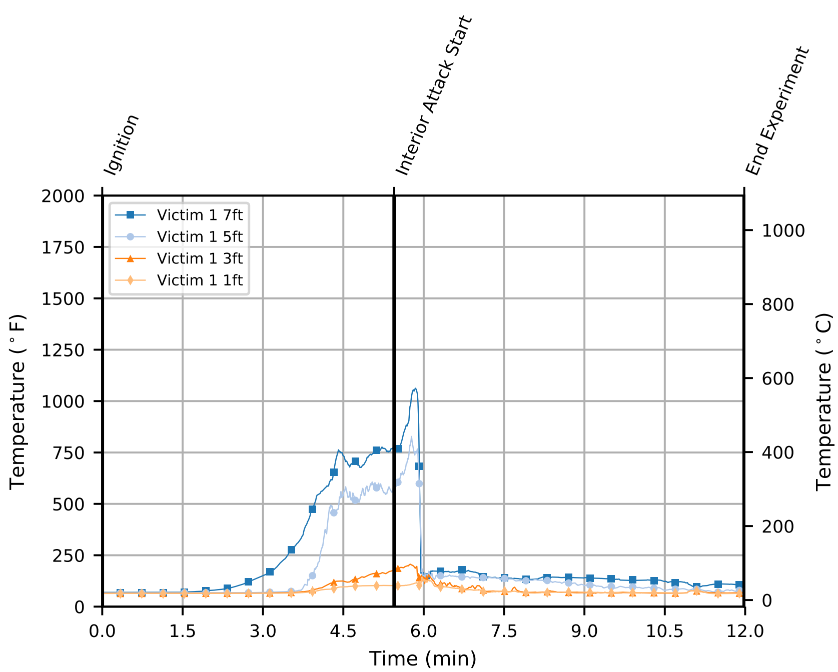


Figure E.317: Experiment 9 - Victim 1 Temps

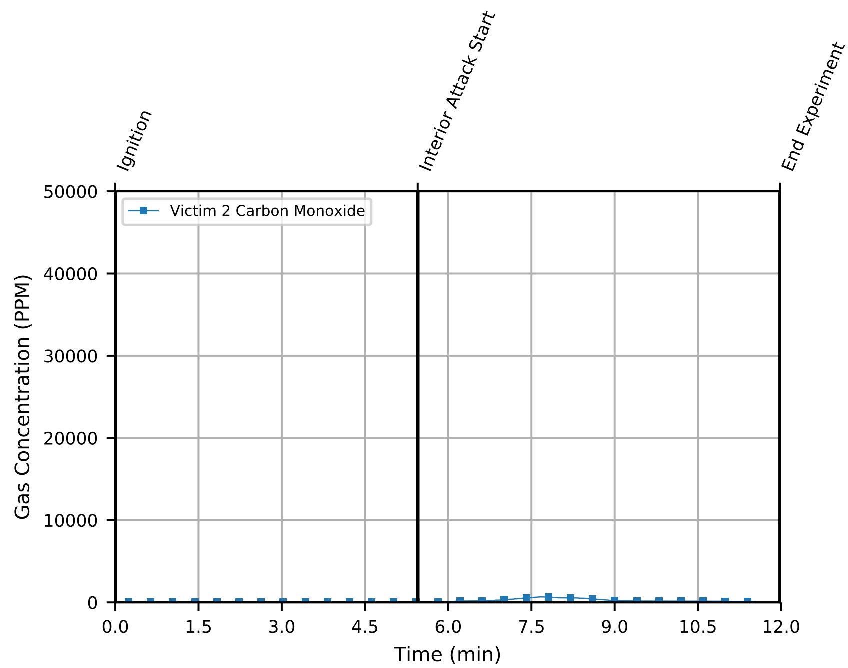


Figure E.318: Experiment 9 - Victim 2 Carbon Monoxide

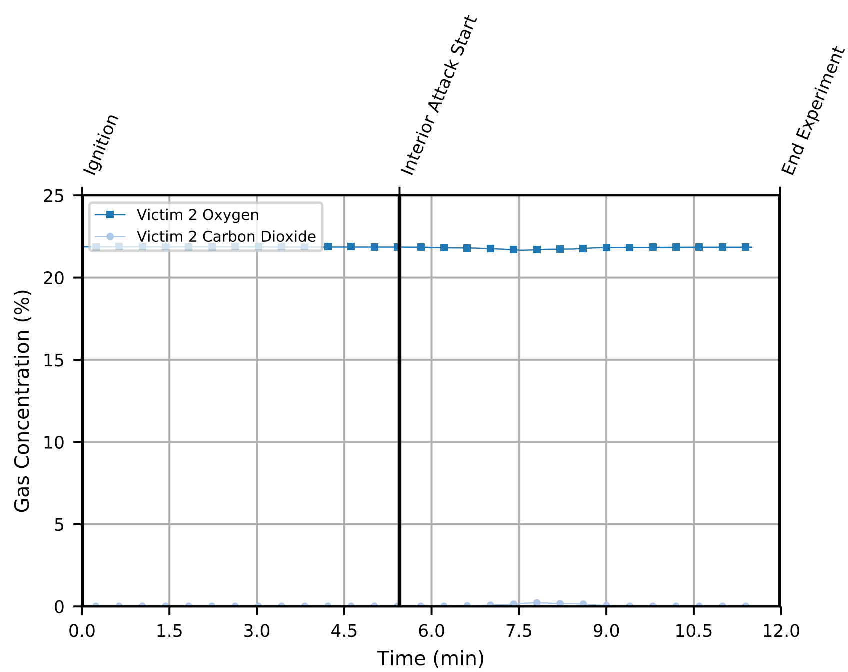


Figure E.319: Experiment 9 - Victim 2 Gas

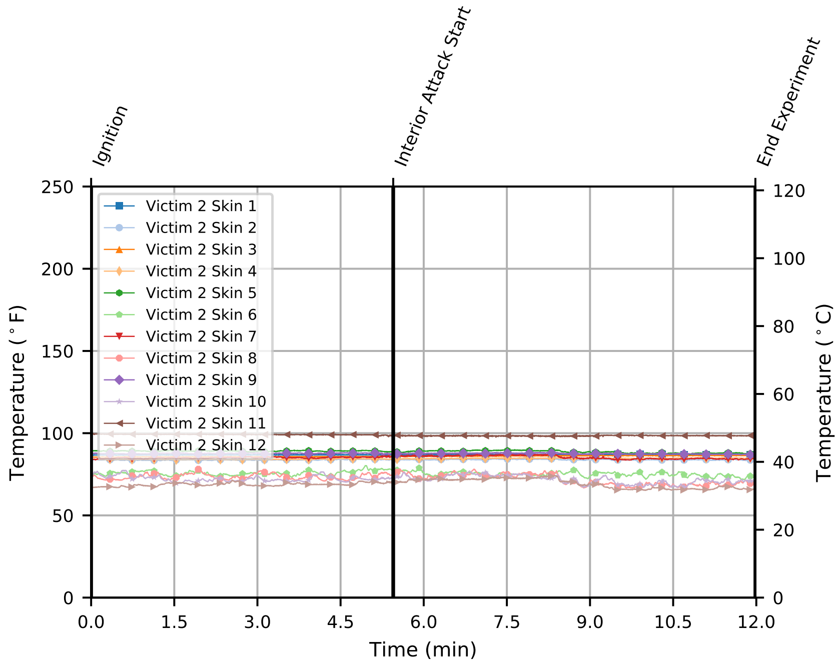


Figure E.320: Experiment 9 - Victim 2 Skin Temps

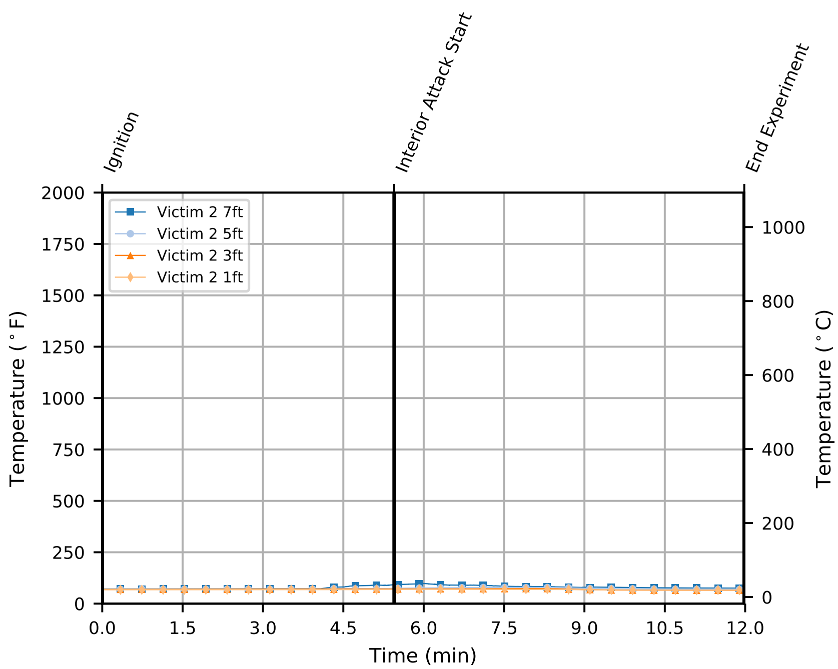


Figure E.321: Experiment 9 - Victim 2 Temps

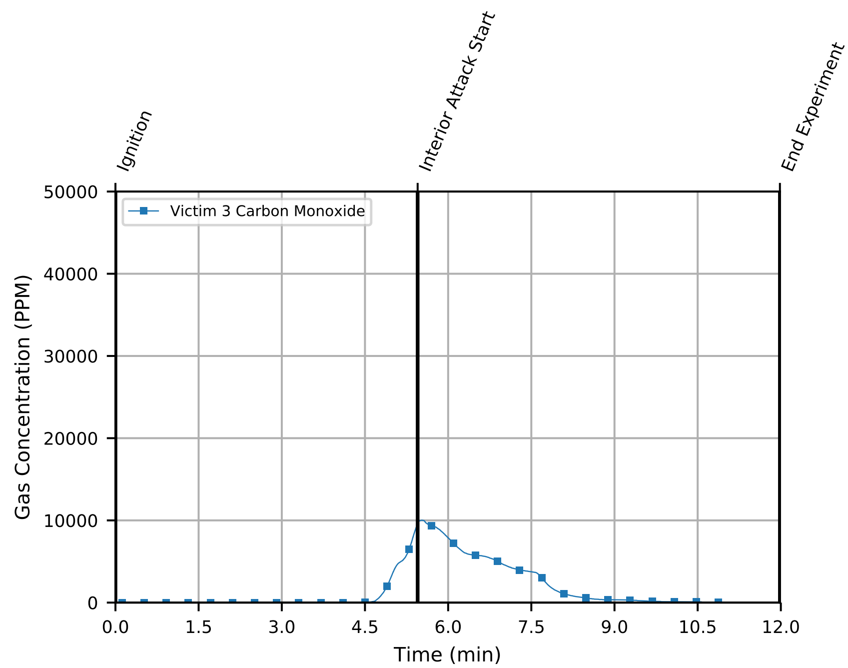


Figure E.322: Experiment 9 - Victim 3 Carbon Monoxide

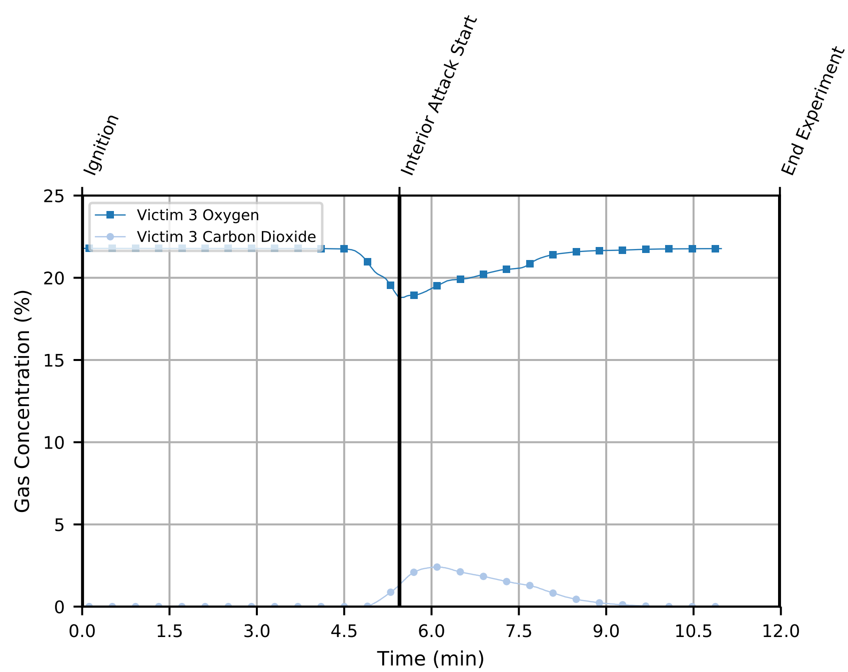


Figure E.323: Experiment 9 - Victim 3 Gas

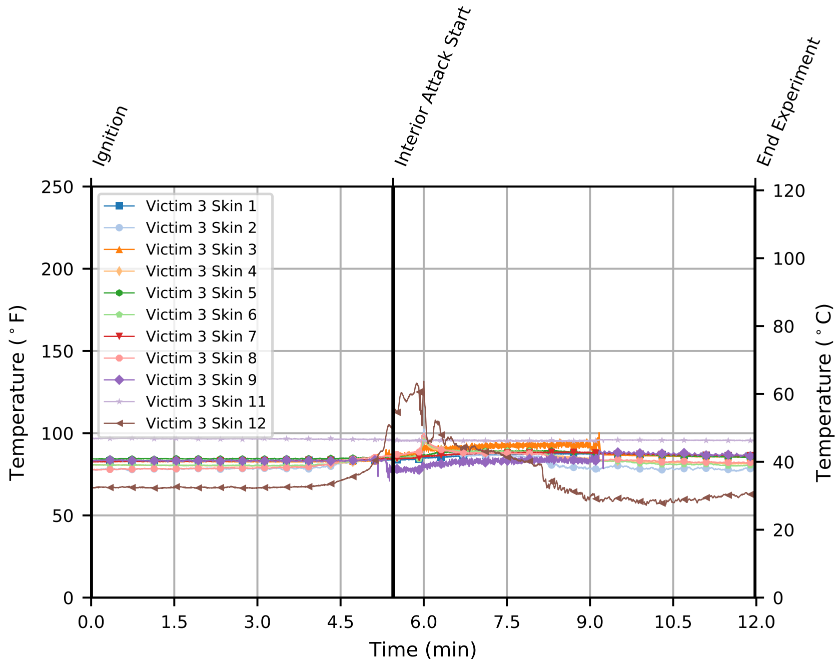


Figure E.324: Experiment 9 - Victim 3 Skin Temps

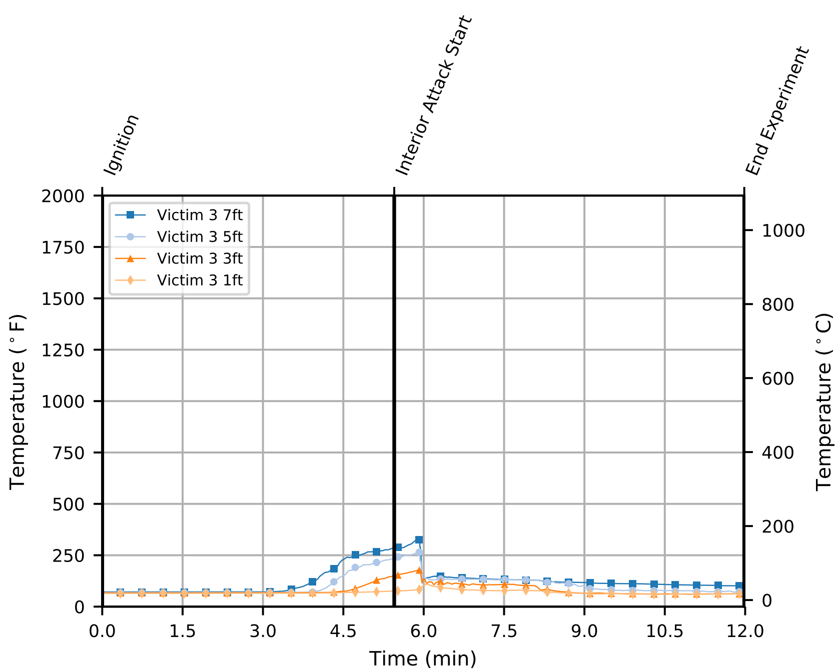


Figure E.325: Experiment 9 - Victim 3 Temps

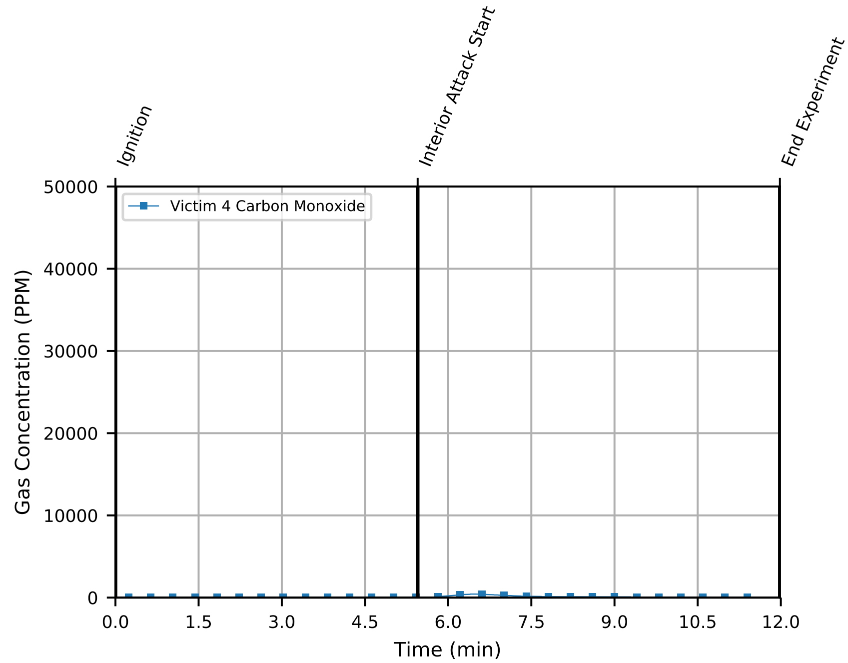


Figure E.326: Experiment 9 - Victim 4 Carbon Monoxide

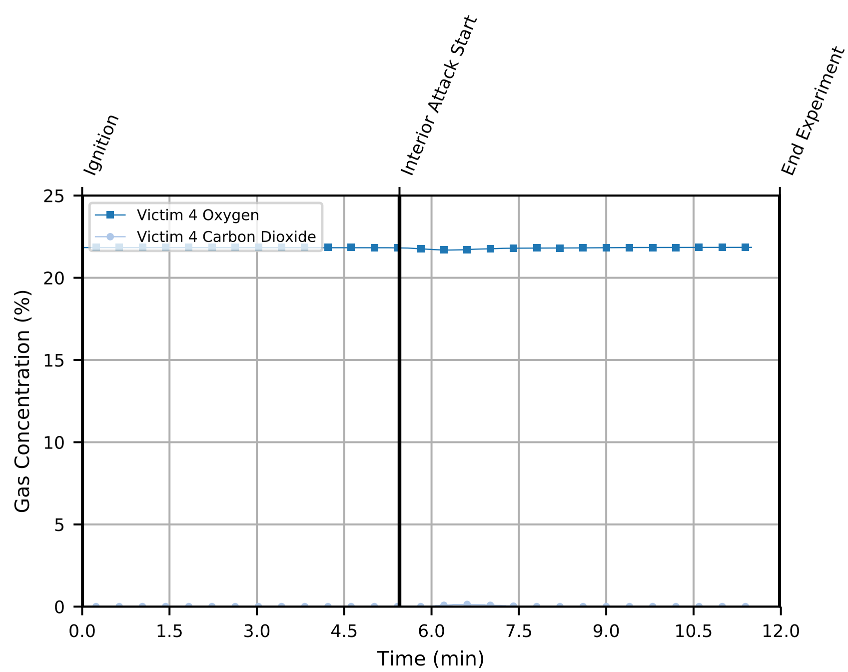


Figure E.327: Experiment 9 - Victim 4 Gas

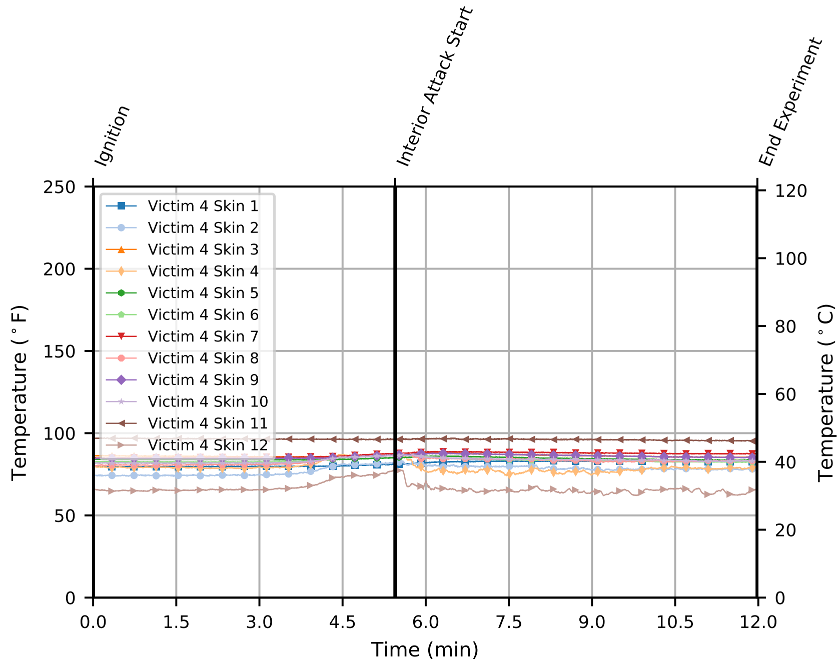


Figure E.328: Experiment 9 - Victim 4 Skin Temps

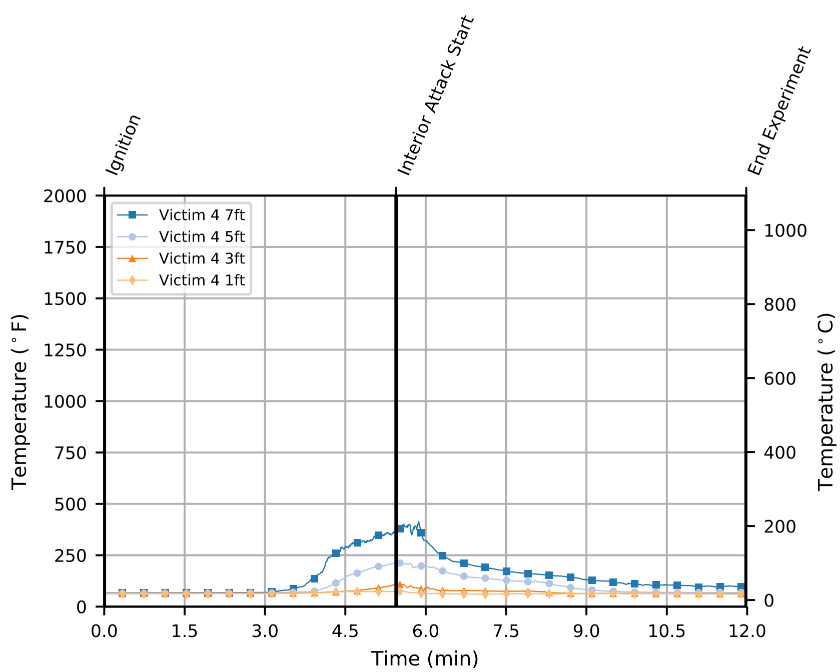


Figure E.329: Experiment 9 - Victim 4 Temps

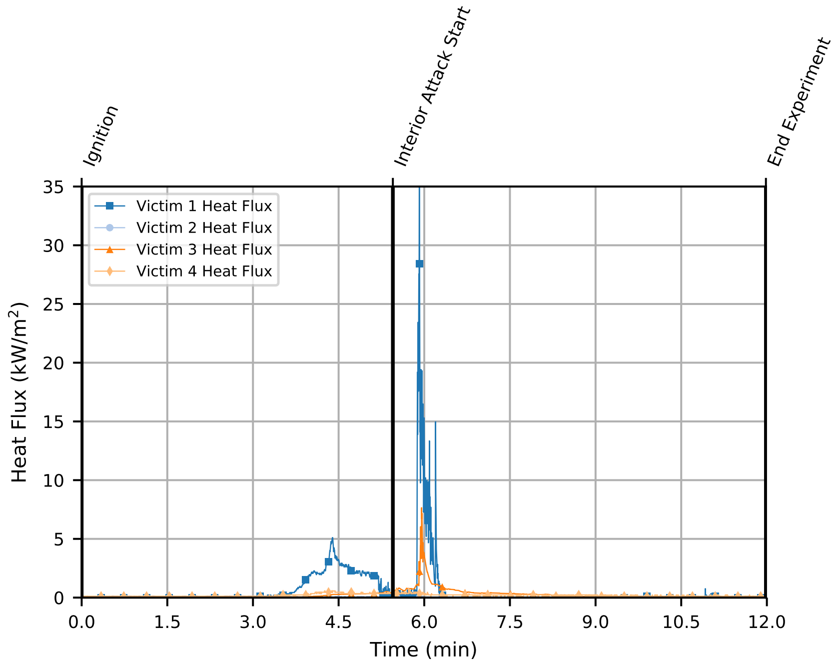


Figure E.330: Experiment 9 - Victim Heat Flux

E.10 Experiment 10 Data

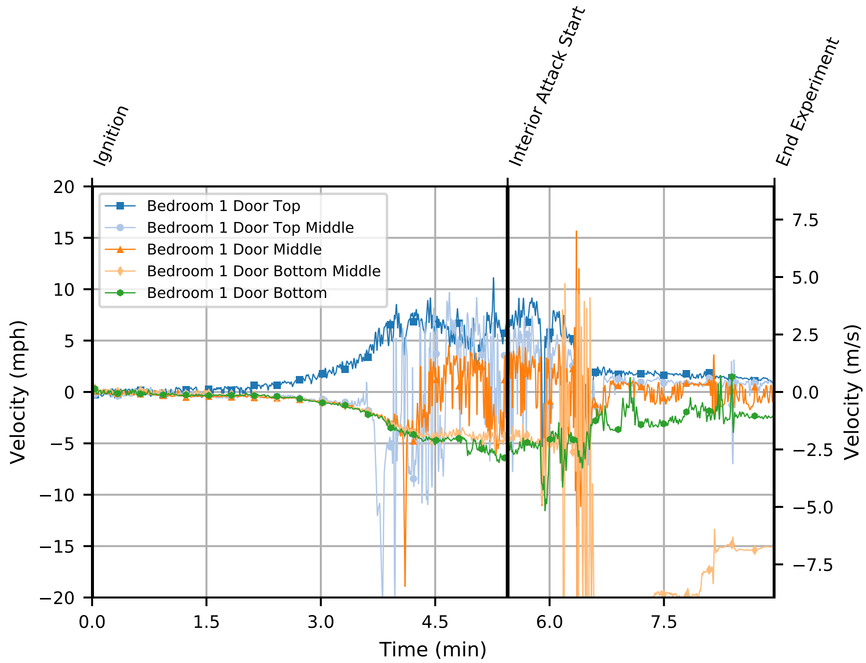


Figure E.331: Experiment 10 - Bedroom 1 Door

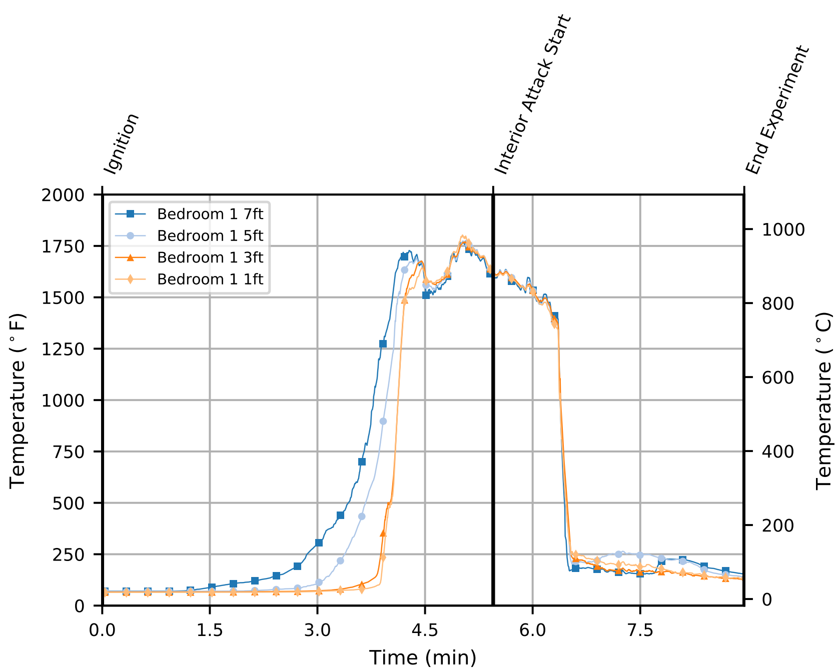


Figure E.332: Experiment 10 - Bedroom 1 Temps

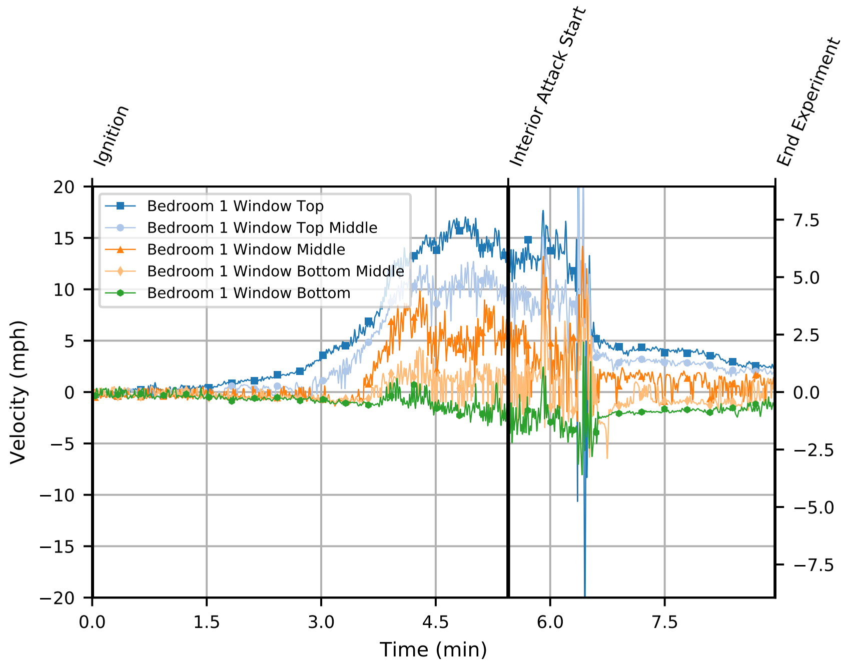


Figure E.333: Experiment 10 - Bedroom 1 Window

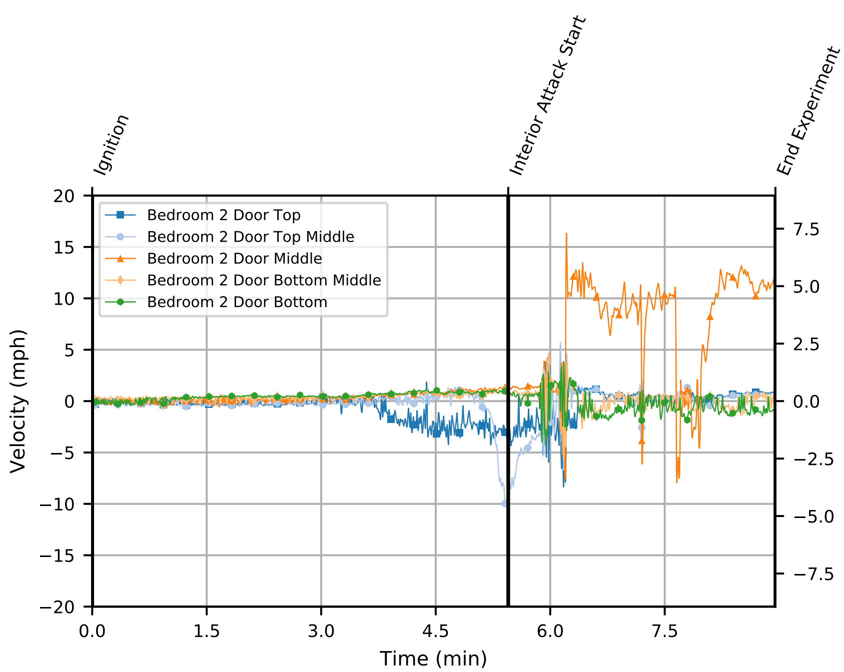


Figure E.334: Experiment 10 - Bedroom 2 Door

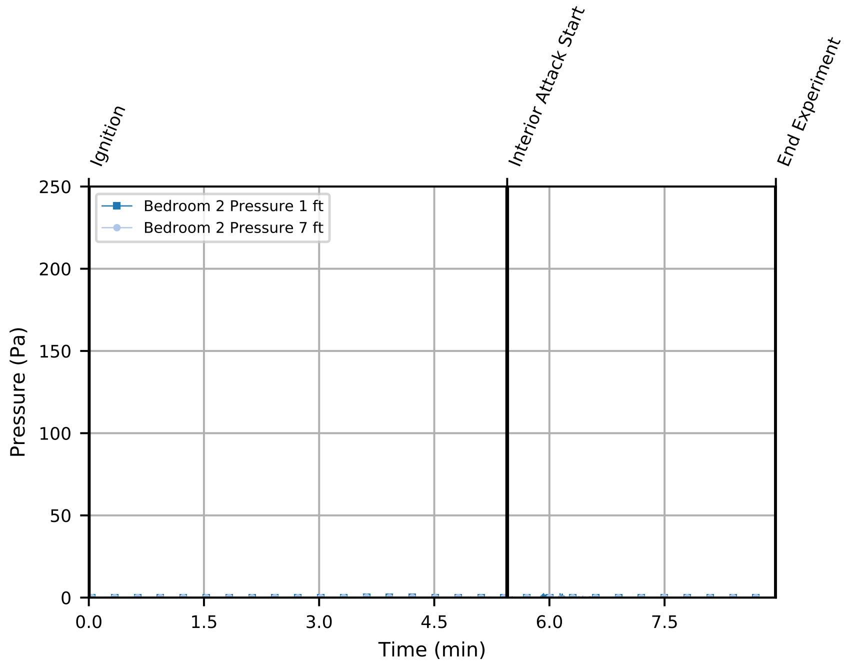


Figure E.335: Experiment 10 - Bedroom 2 Pressure

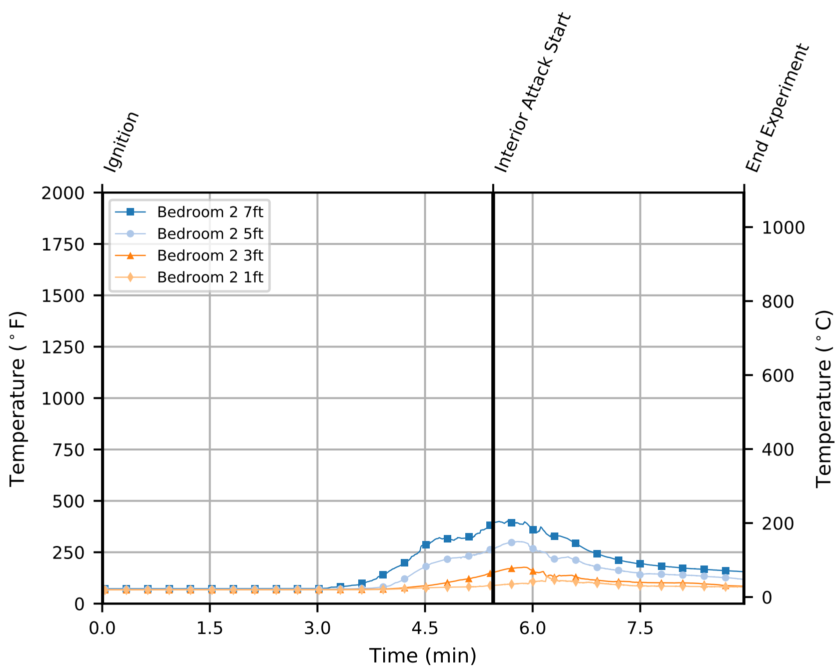


Figure E.336: Experiment 10 - Bedroom 2 Temps

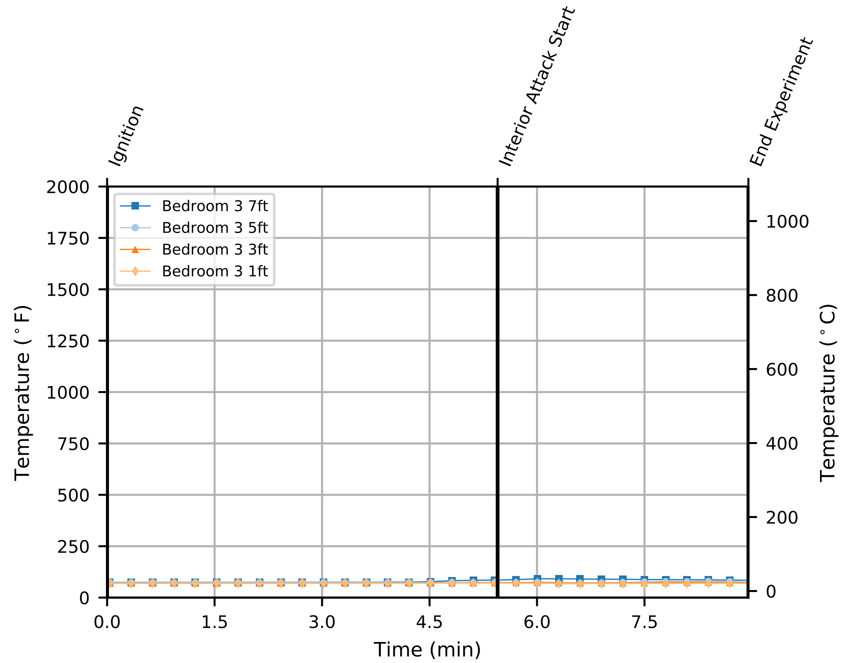


Figure E.337: Experiment 10 - Bedroom 3 Temps

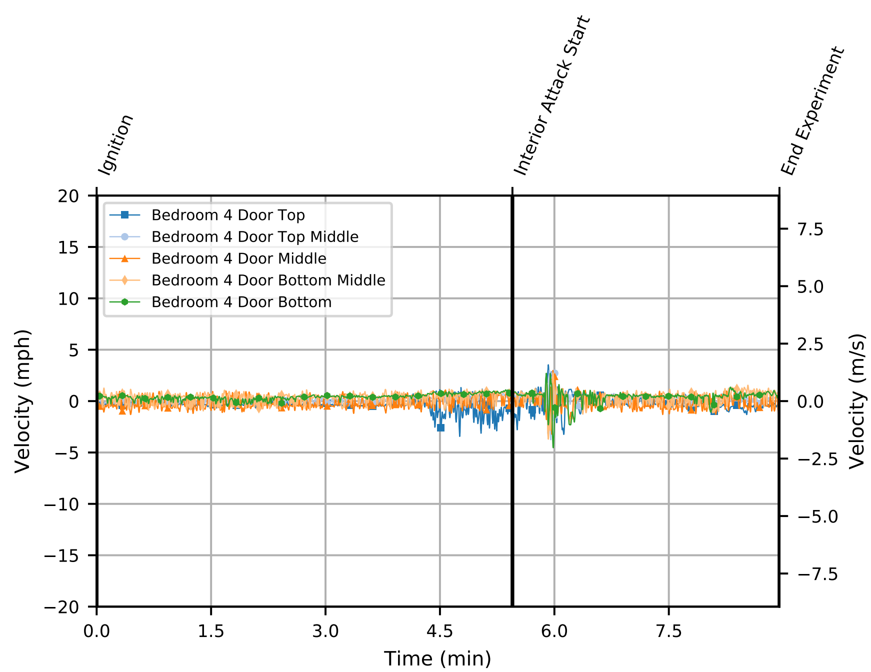


Figure E.338: Experiment 10 - Bedroom 4 Door

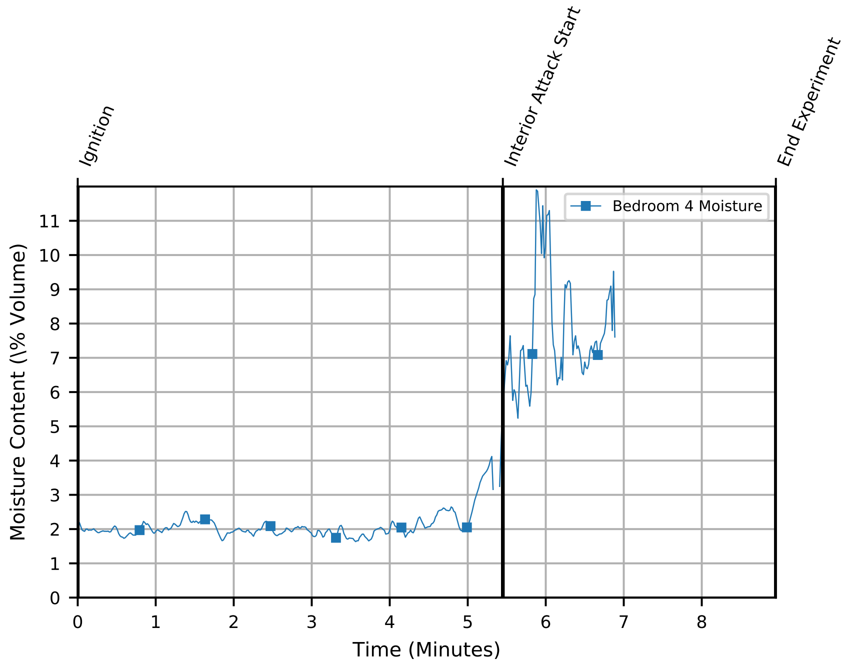


Figure E.339: Experiment 10 - Bedroom 4 Moisture

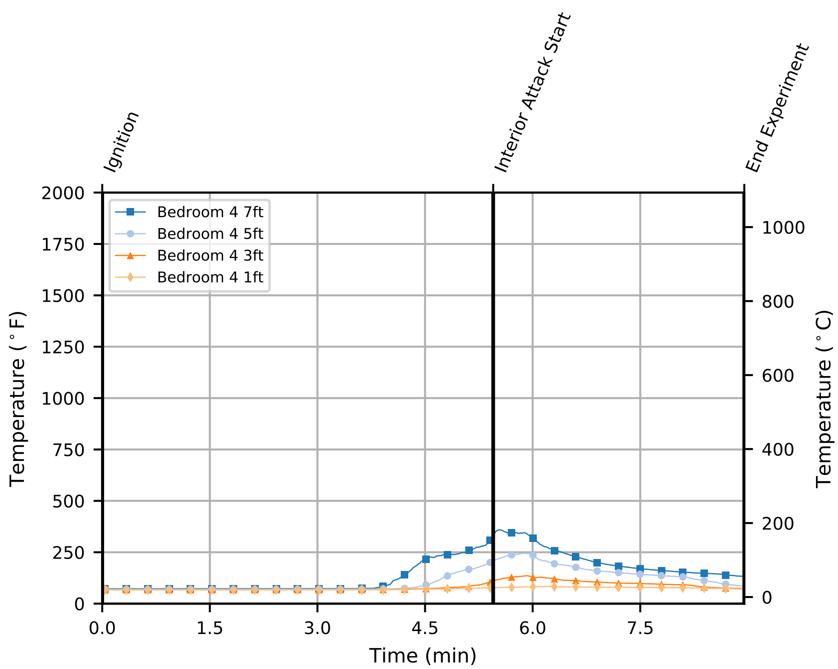


Figure E.340: Experiment 10 - Bedroom 4 Temps

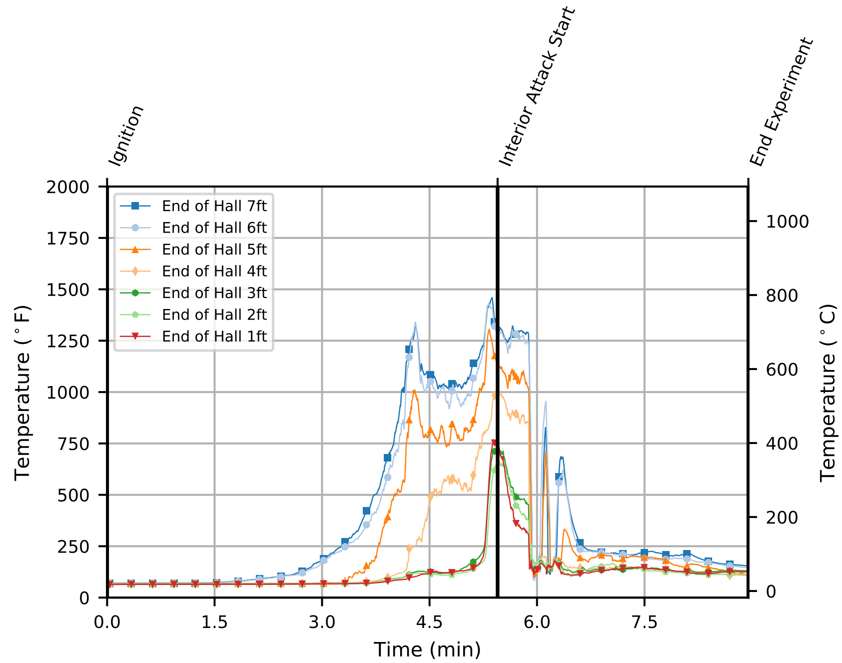


Figure E.341: Experiment 10 - End Hall Temps

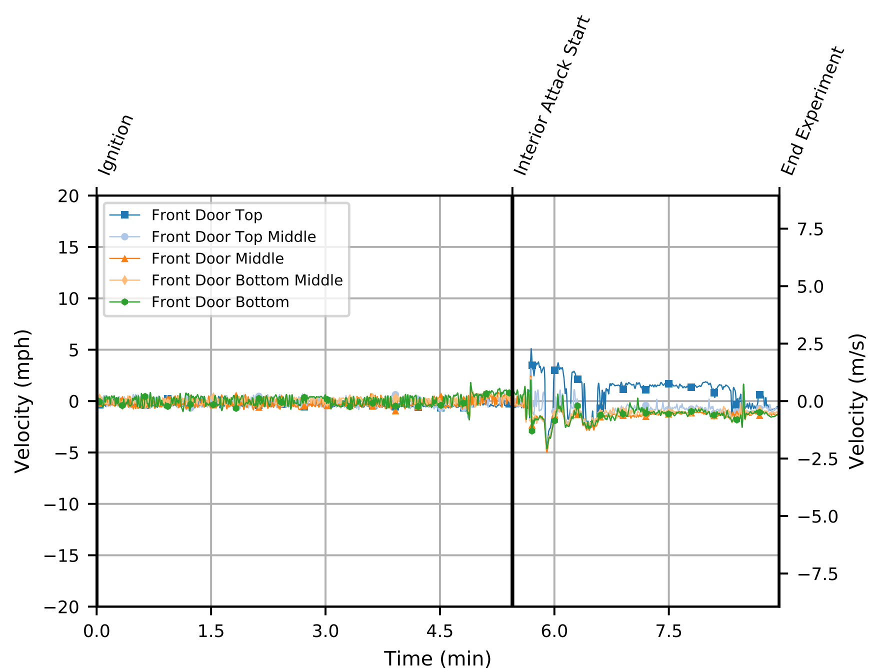


Figure E.342: Experiment 10 - Front Door Flow

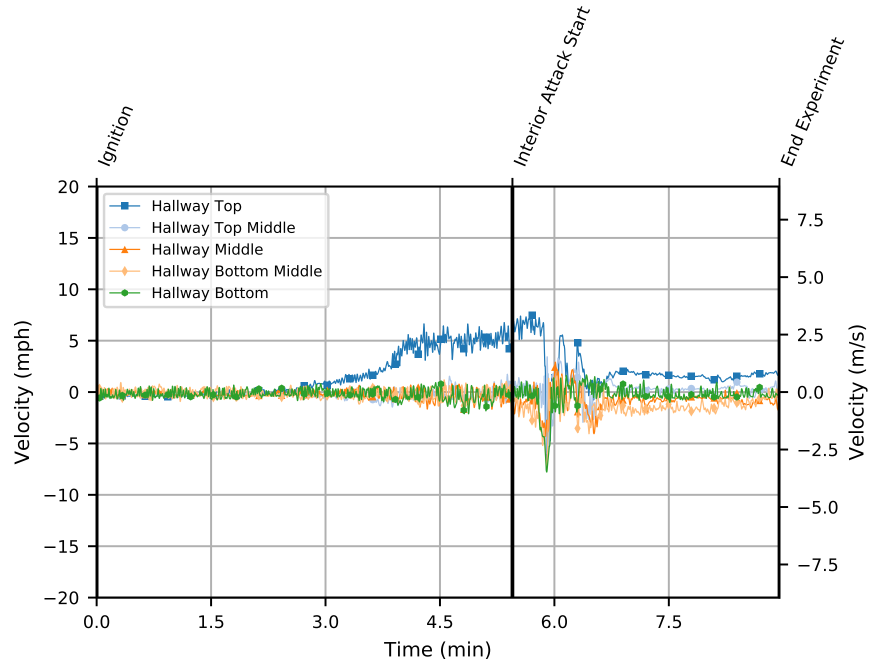


Figure E.343: Experiment 10 - Hallway Flow

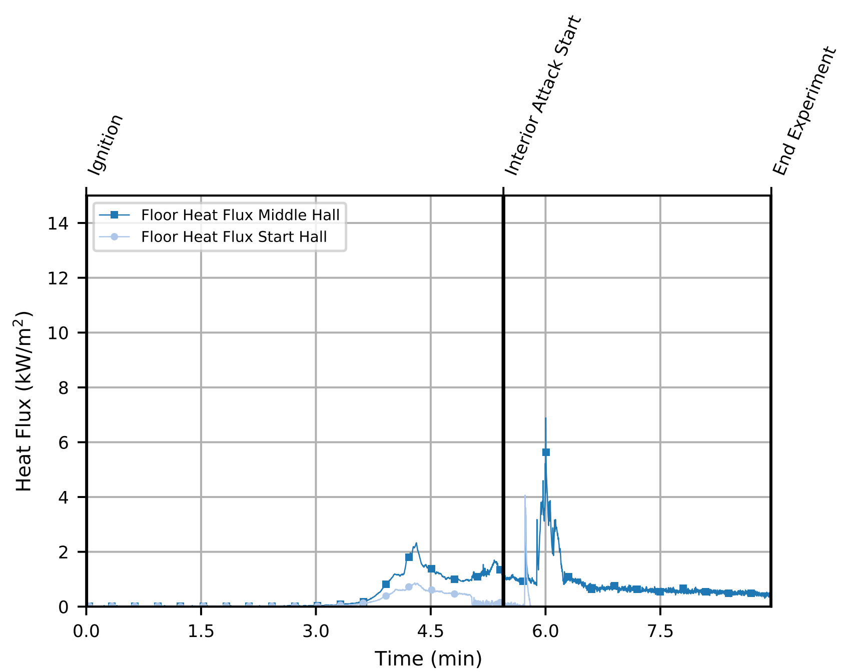


Figure E.344: Experiment 10 - Heat Flux Floor

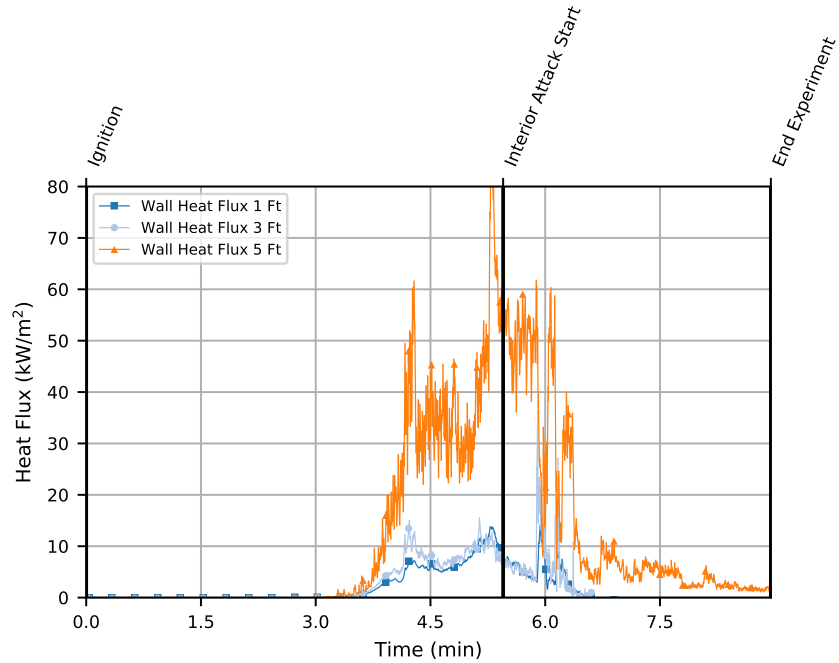


Figure E.345: Experiment 10 - Heat Flux Wall

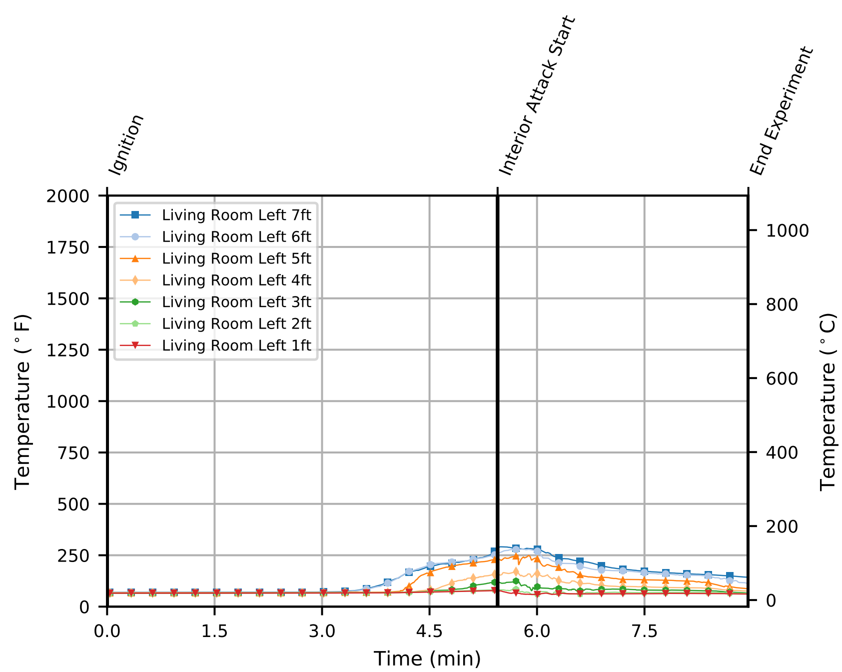


Figure E.346: Experiment 10 - Living Room Left Temps

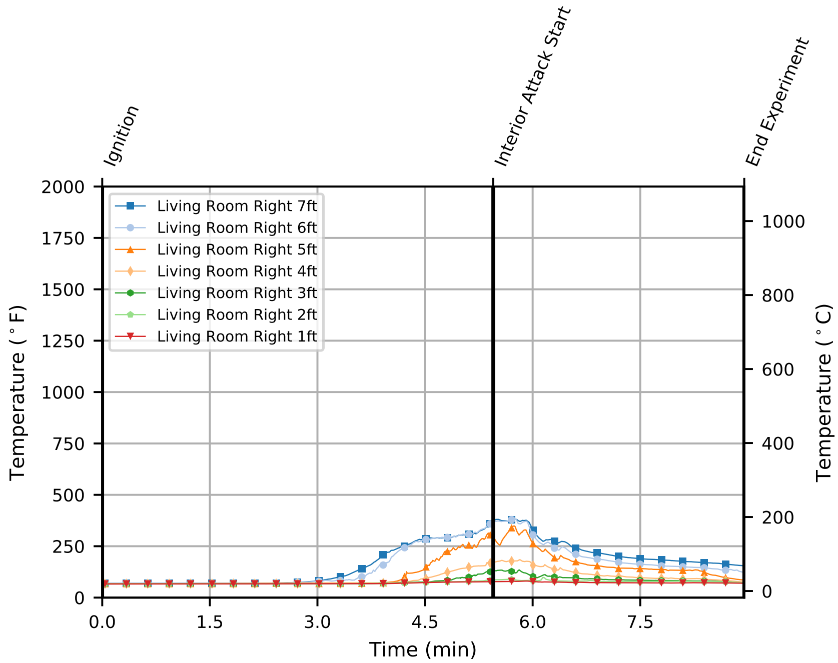


Figure E.347: Experiment 10 - Living Room Right Temps

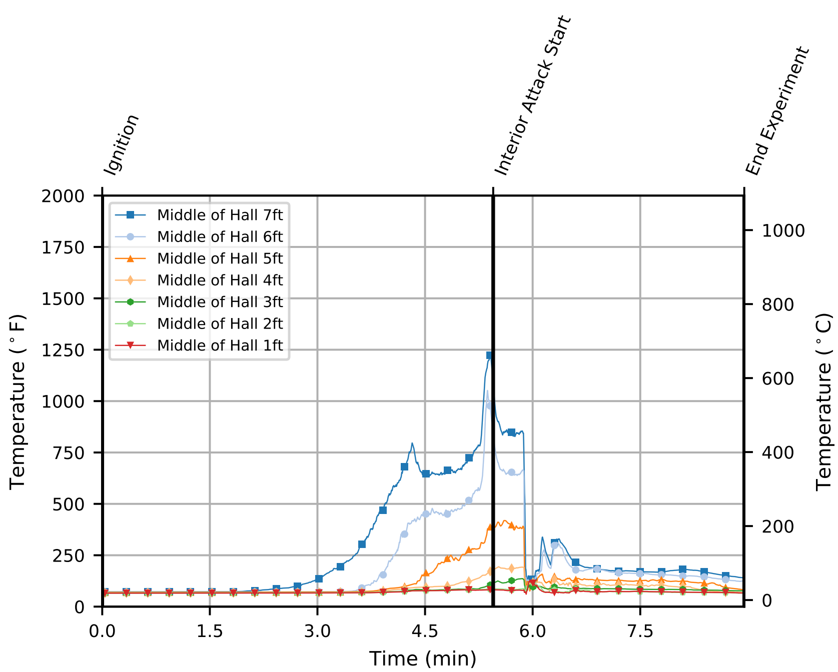


Figure E.348: Experiment 10 - Middle Hall Temps

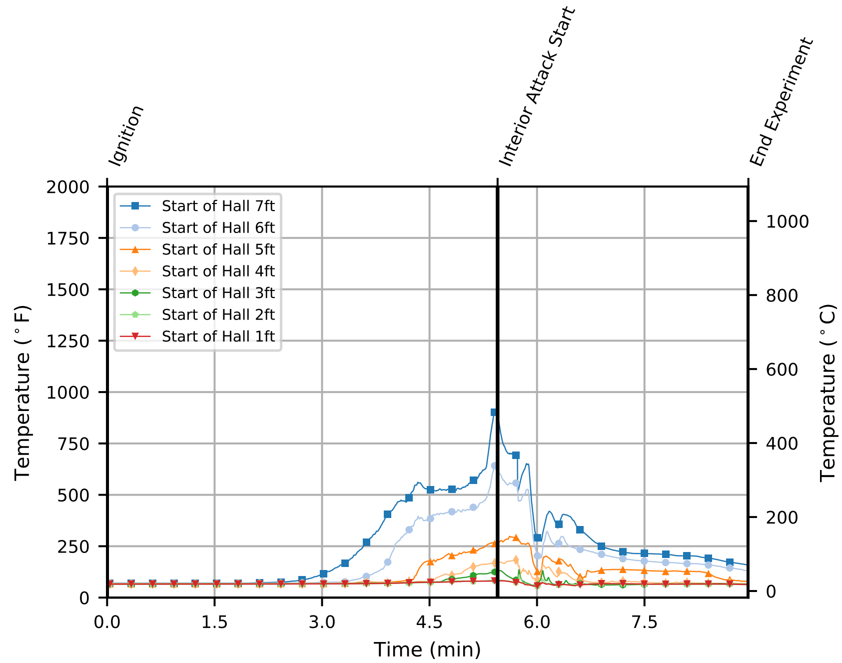


Figure E.349: Experiment 10 - Start Hall Temps

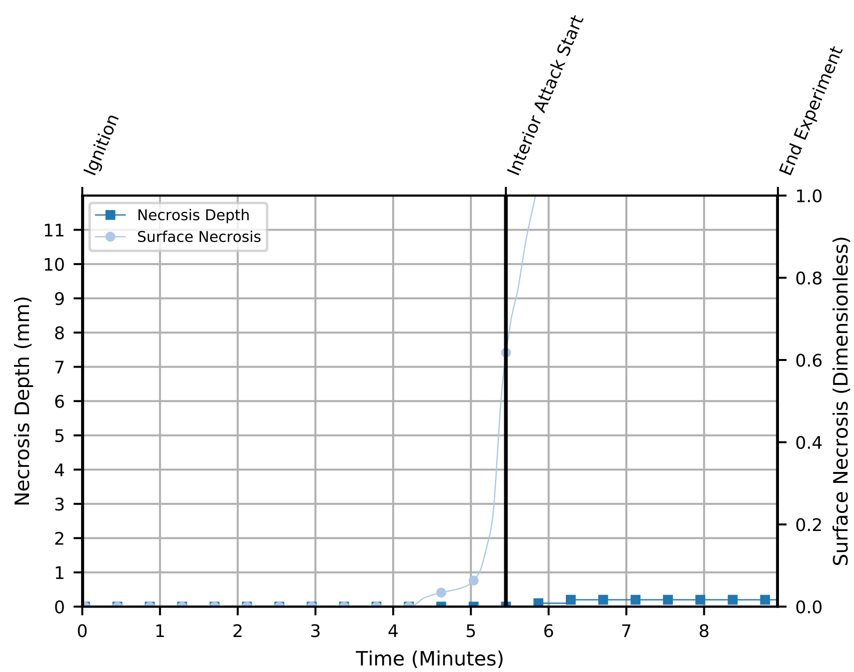


Figure E.350: Experiment 10 - Vic 1 Necrosis Depth

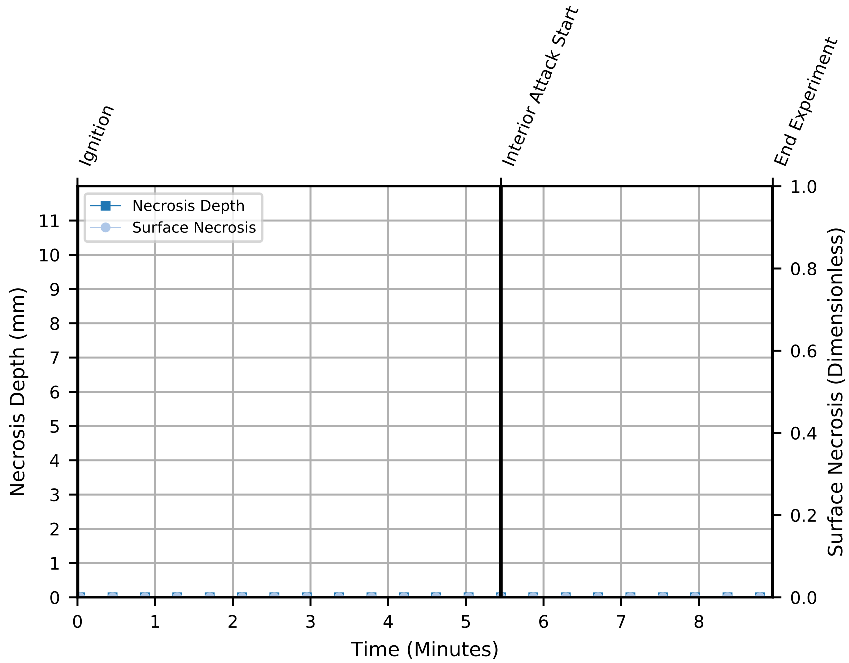


Figure E.351: Experiment 10 - Vic 3 Necrosis Depth

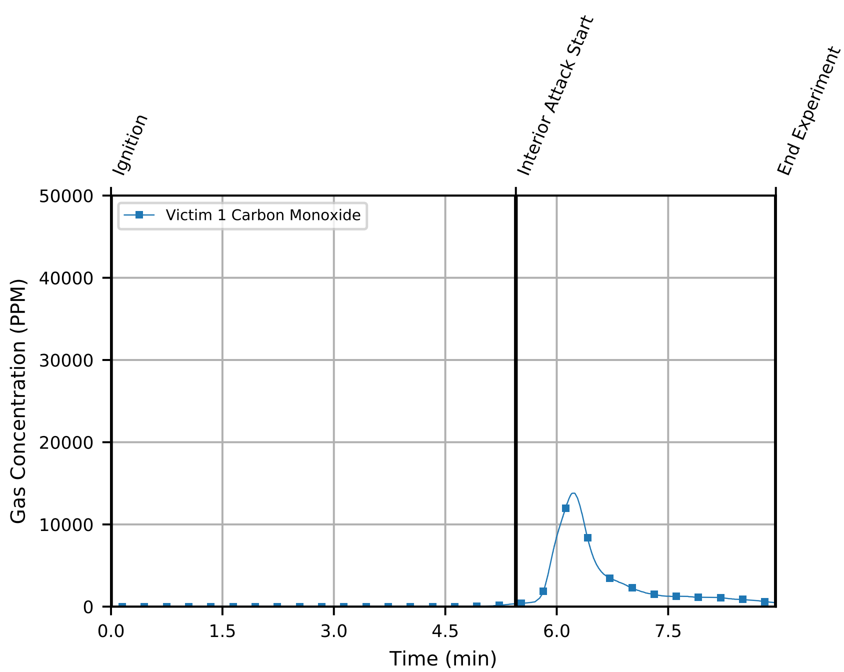


Figure E.352: Experiment 10 - Victim 1 Carbon Monoxide

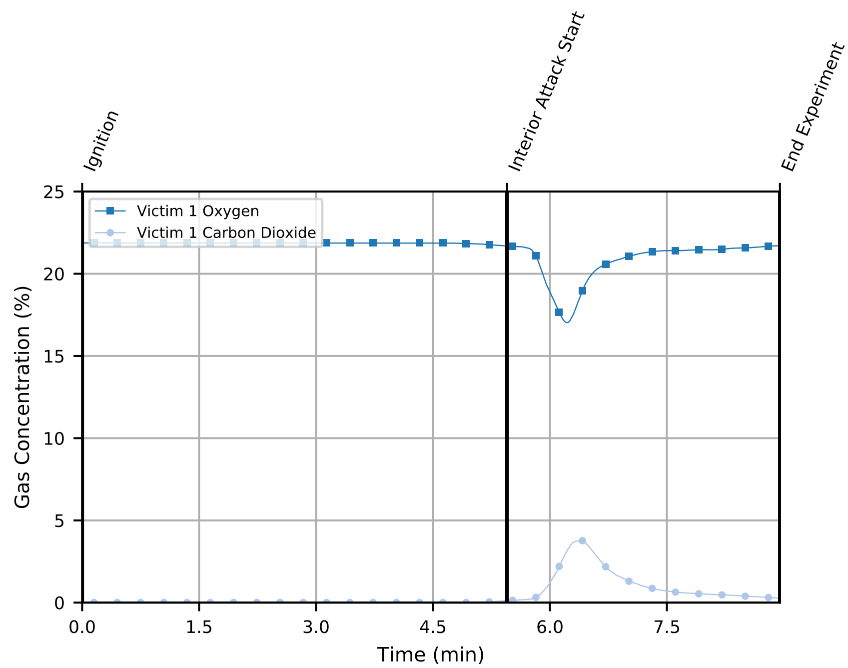


Figure E.353: Experiment 10 - Victim 1 Gas

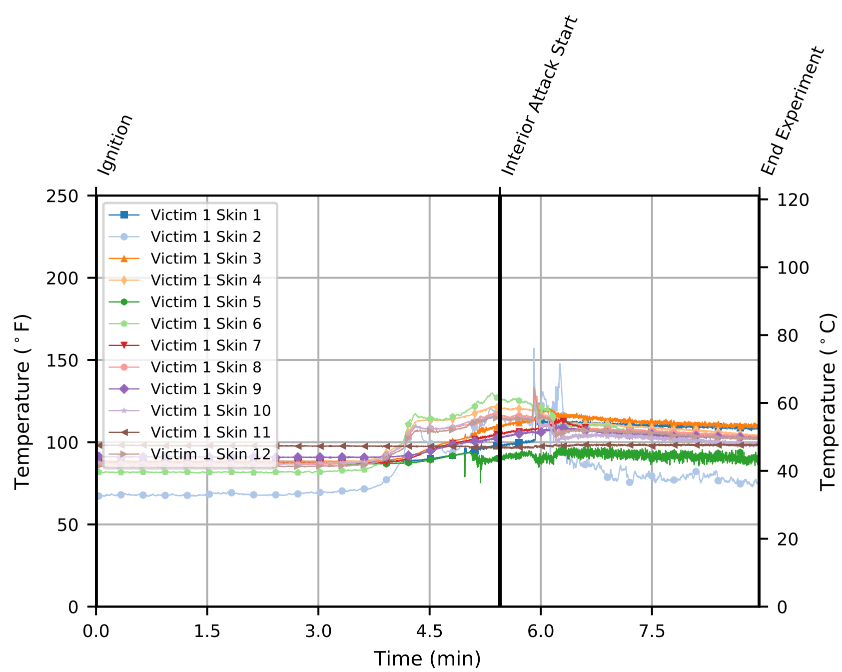


Figure E.354: Experiment 10 - Victim 1 Skin Temps

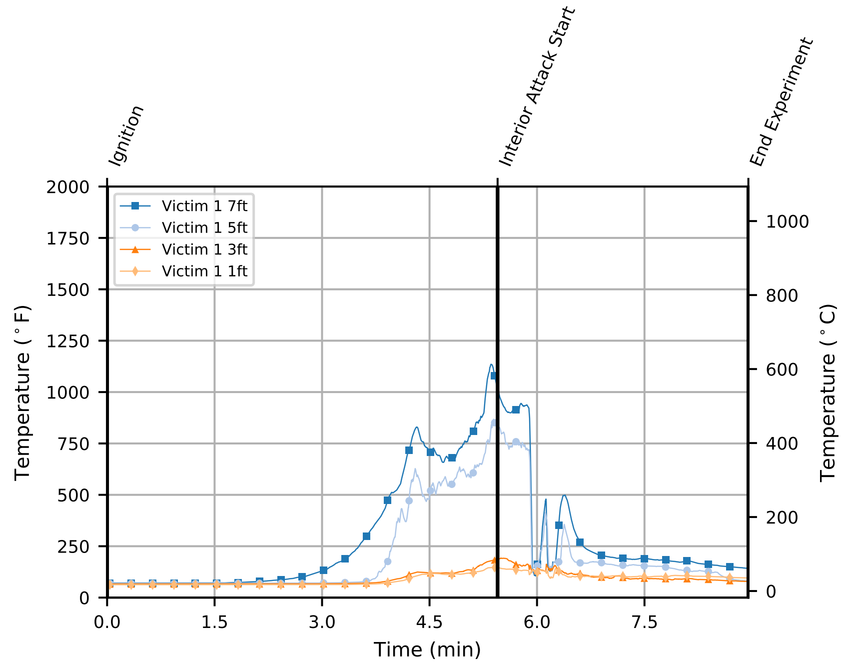


Figure E.355: Experiment 10 - Victim 1 Temps

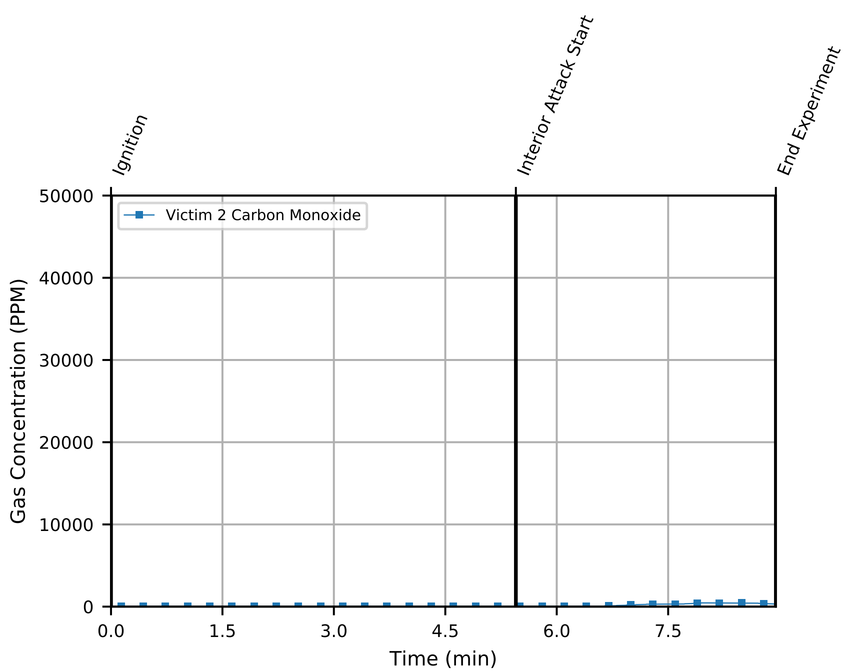


Figure E.356: Experiment 10 - Victim 2 Carbon Monoxide

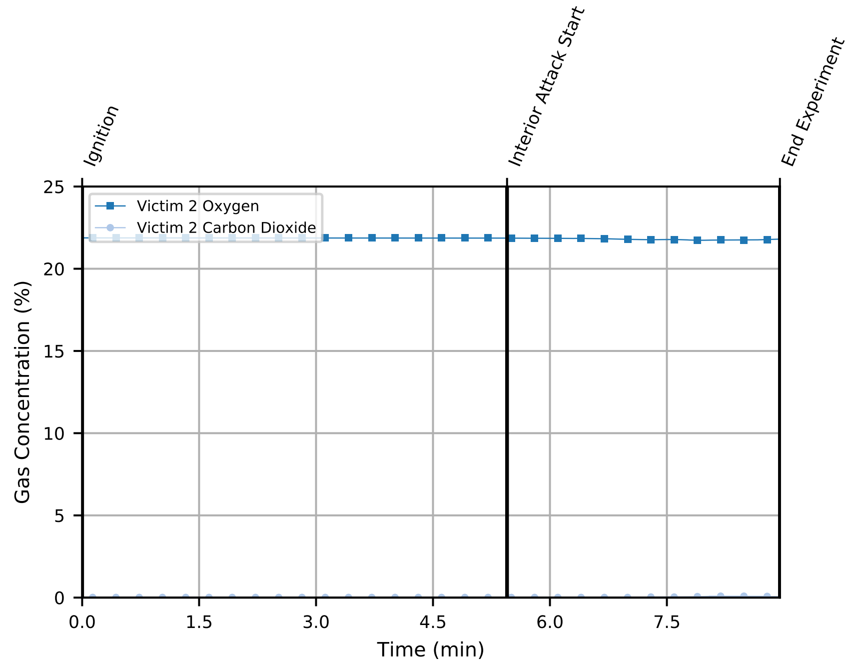


Figure E.357: Experiment 10 - Victim 2 Gas

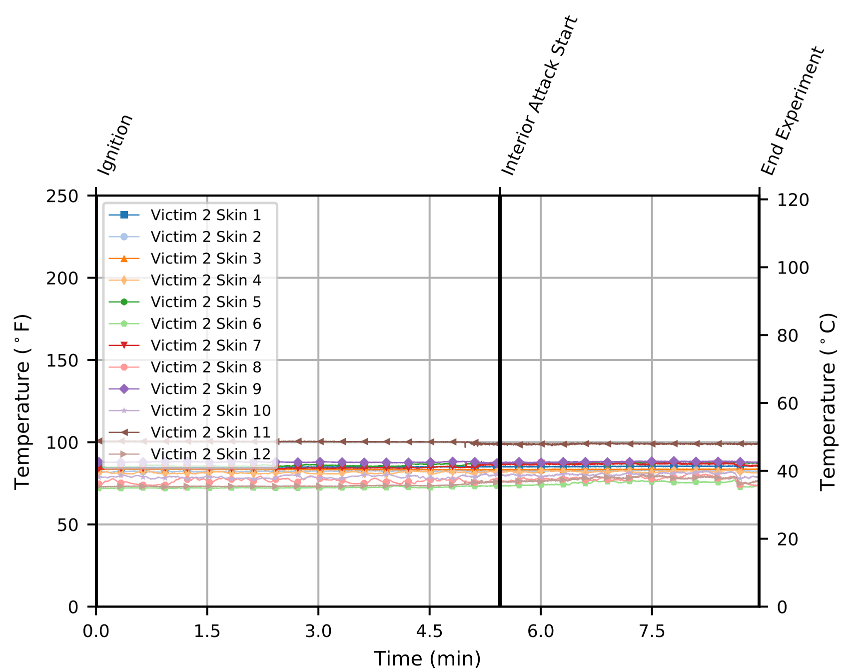


Figure E.358: Experiment 10 - Victim 2 Skin Temps

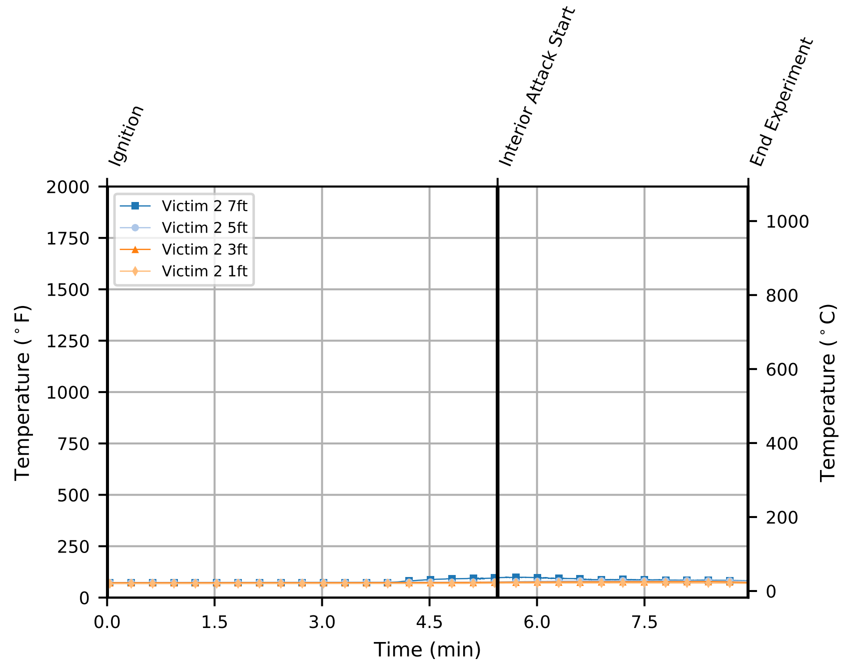


Figure E.359: Experiment 10 - Victim 2 Temps

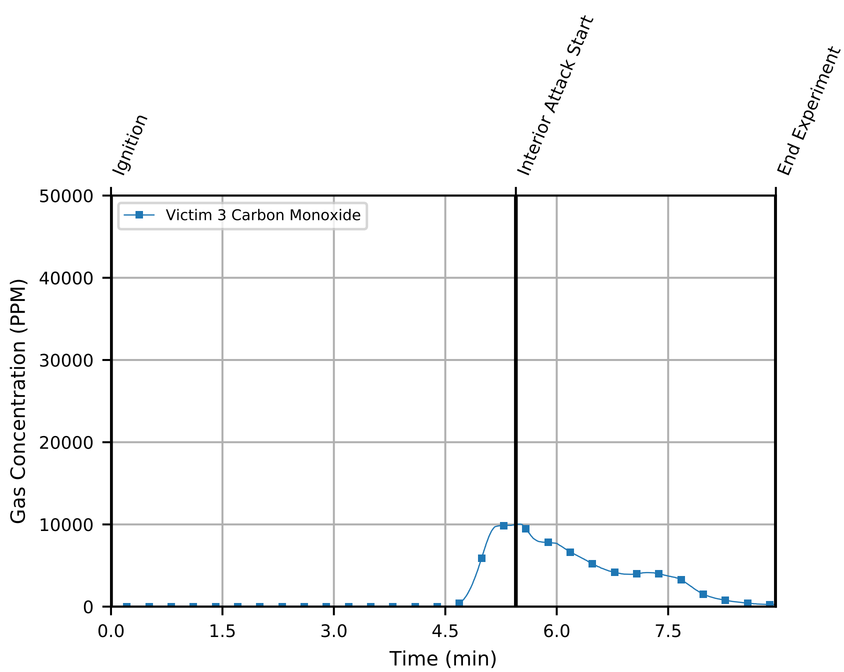


Figure E.360: Experiment 10 - Victim 3 Carbon Monoxide

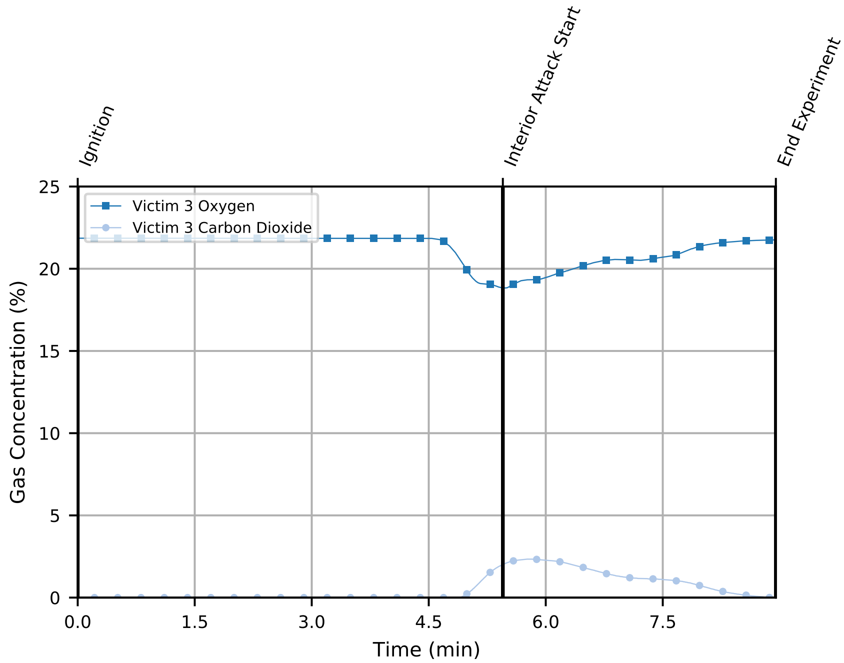


Figure E.361: Experiment 10 - Victim 3 Gas

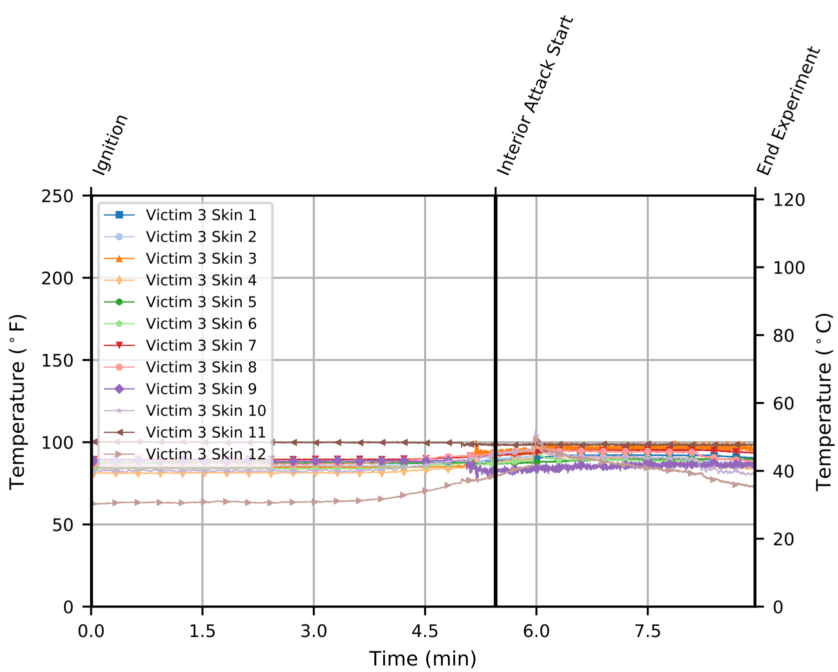


Figure E.362: Experiment 10 - Victim 3 Skin Temps

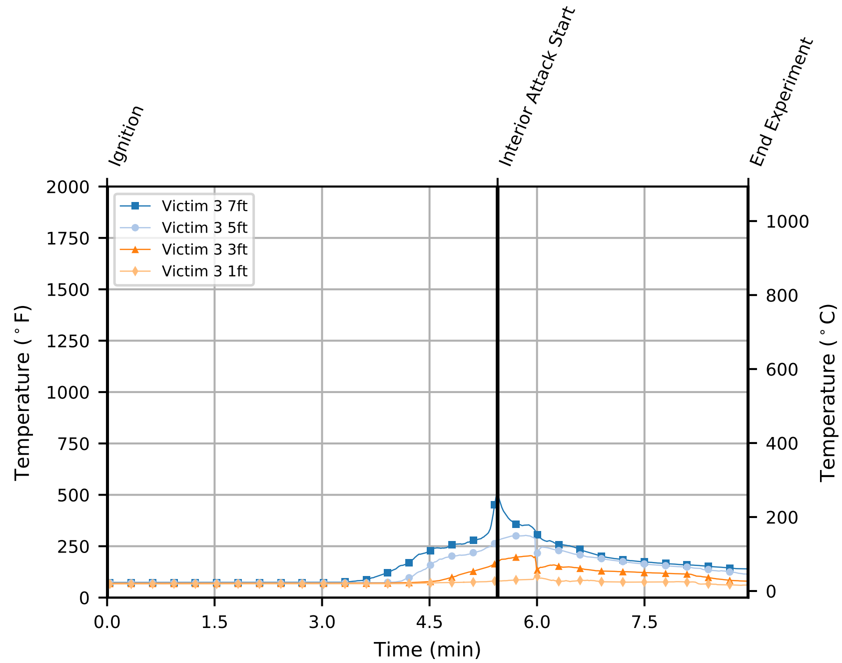


Figure E.363: Experiment 10 - Victim 3 Temps

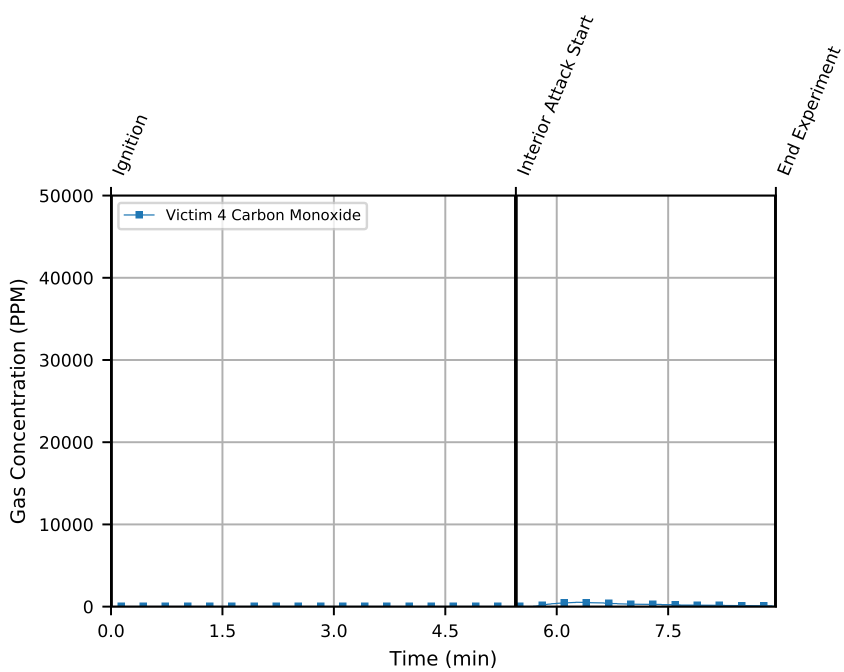


Figure E.364: Experiment 10 - Victim 4 Carbon Monoxide

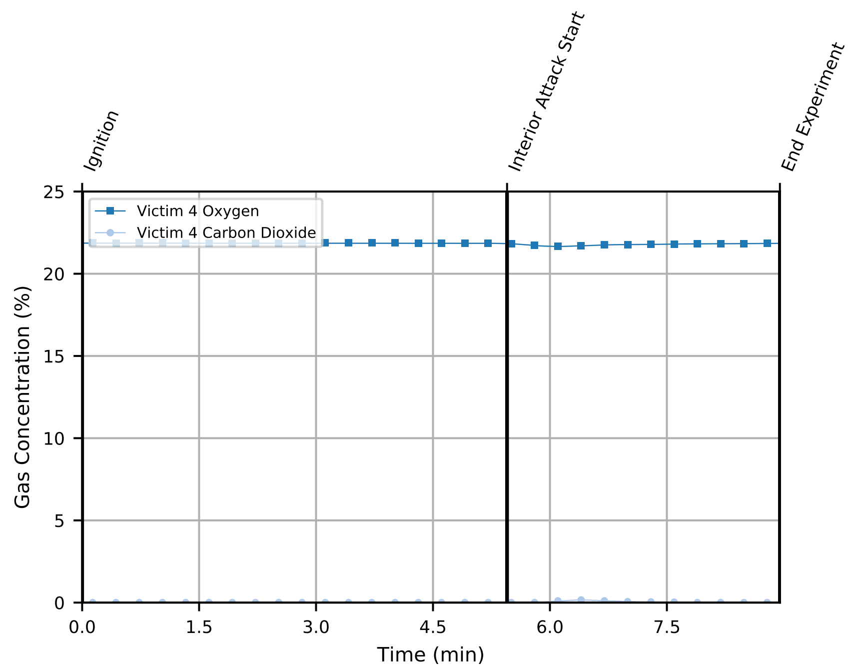


Figure E.365: Experiment 10 - Victim 4 Gas

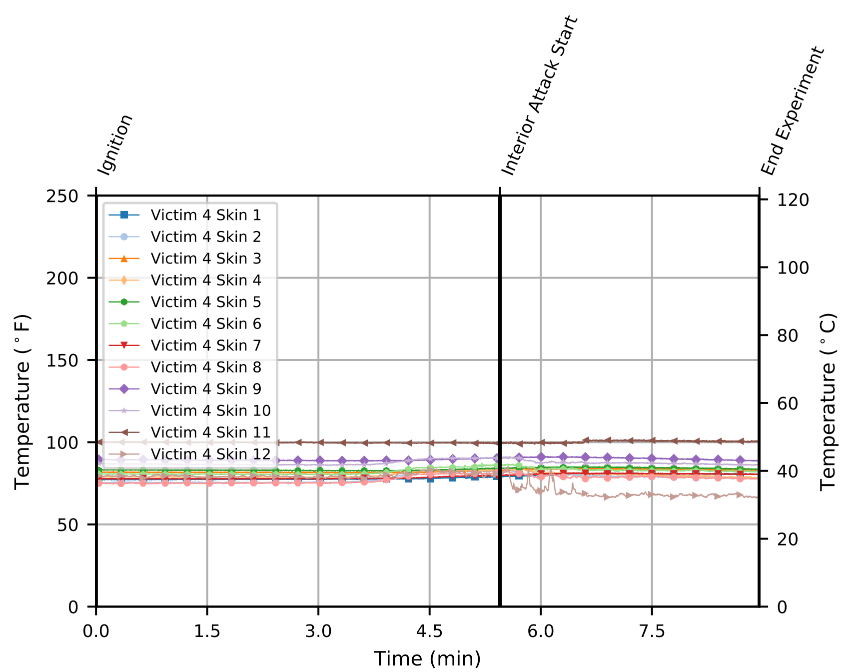


Figure E.366: Experiment 10 - Victim 4 Skin Temps

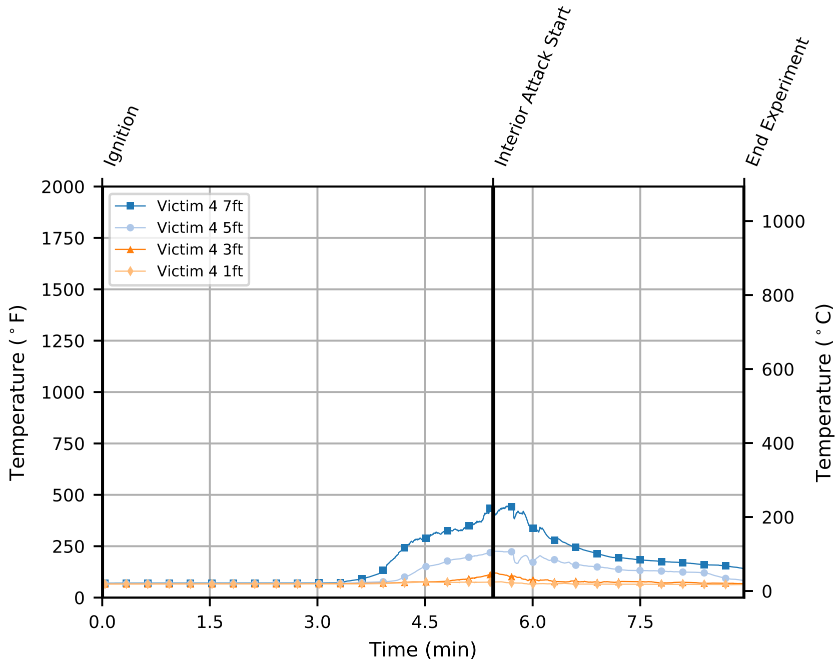


Figure E.367: Experiment 10 - Victim 4 Temps

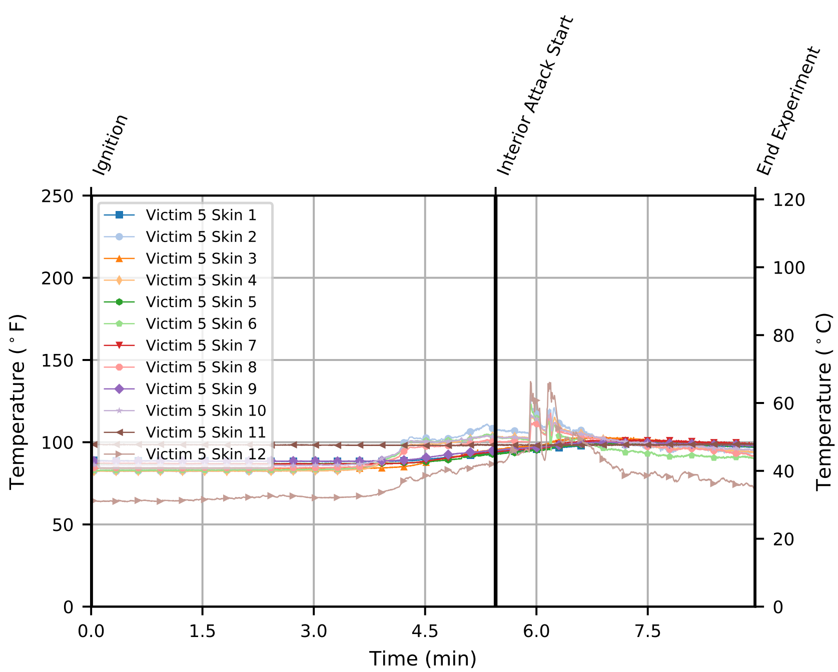


Figure E.368: Experiment 10 - Victim 5 Skin Temps

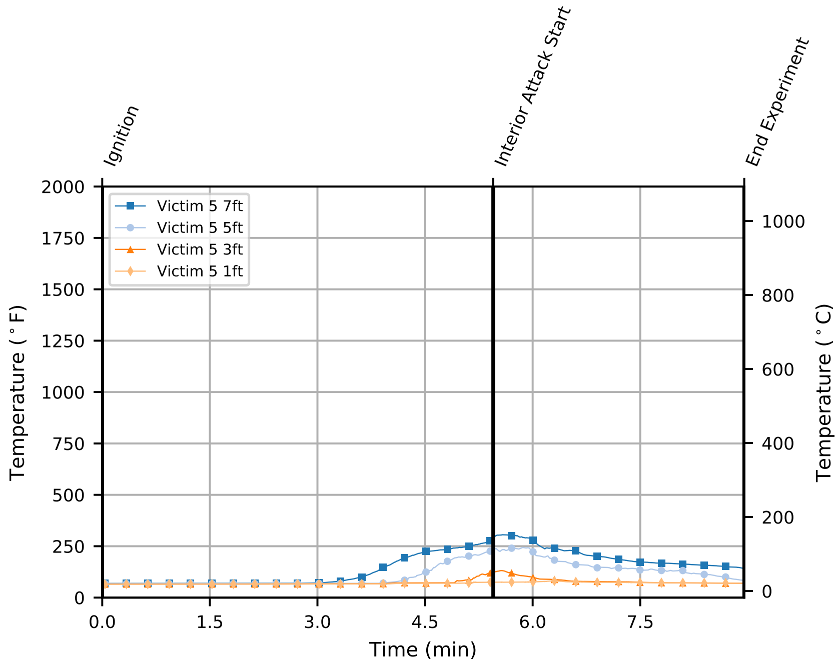


Figure E.369: Experiment 10 - Victim 5 Temps

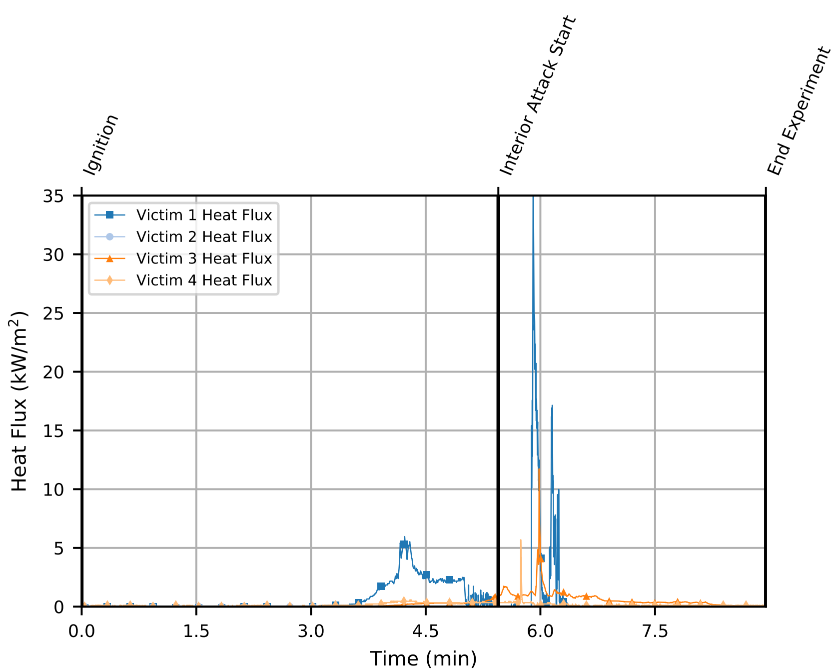


Figure E.370: Experiment 10 - Victim Heat Flux

E.11 Experiment 11 Data

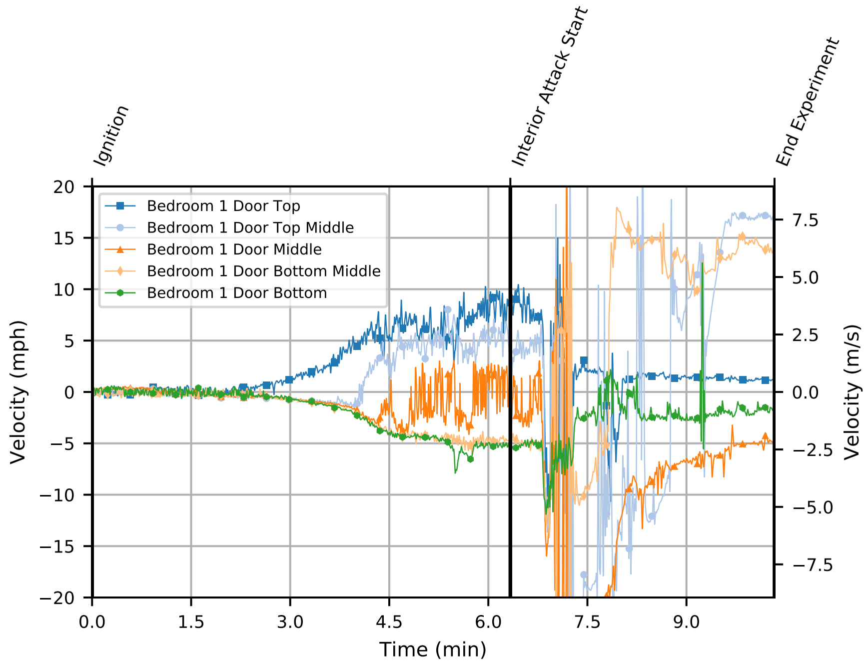


Figure E.371: Experiment 11 - Bedroom 1 Door

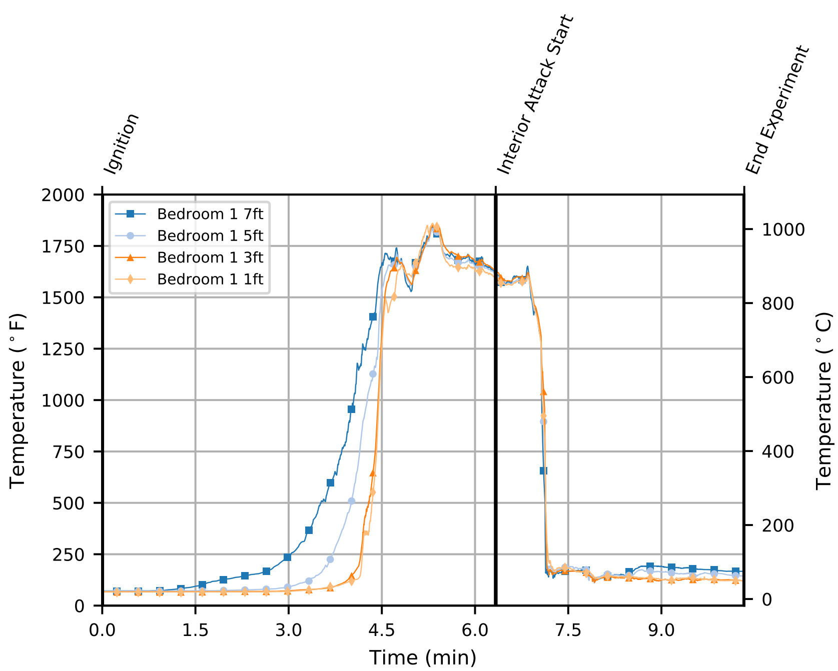


Figure E.372: Experiment 11 - Bedroom 1 Temps

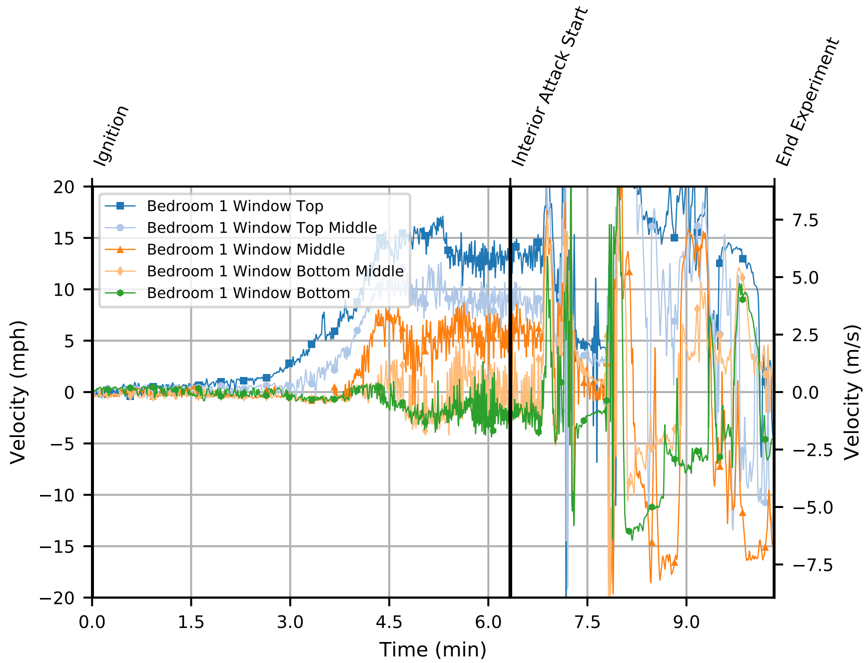


Figure E.373: Experiment 11 - Bedroom 1 Window

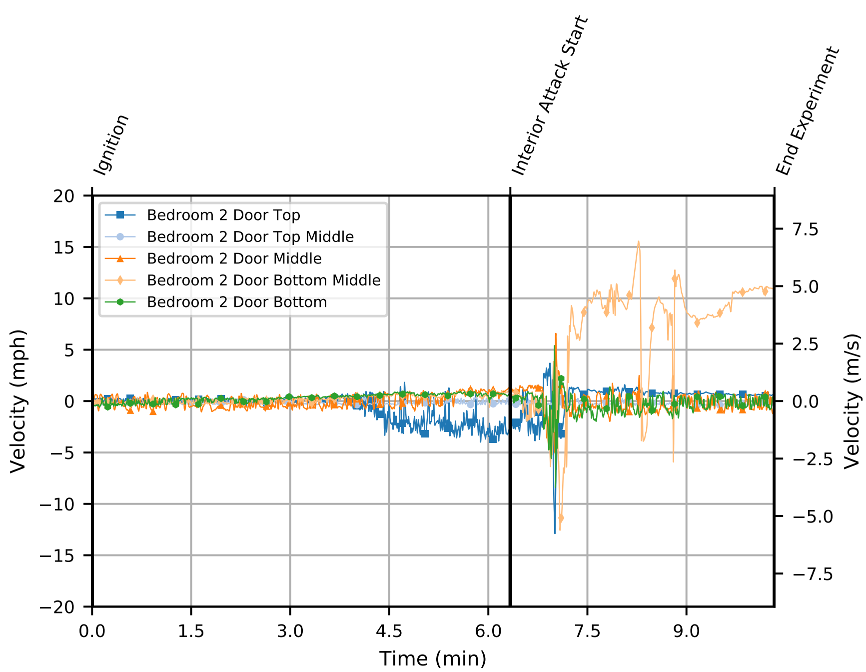


Figure E.374: Experiment 11 - Bedroom 2 Door

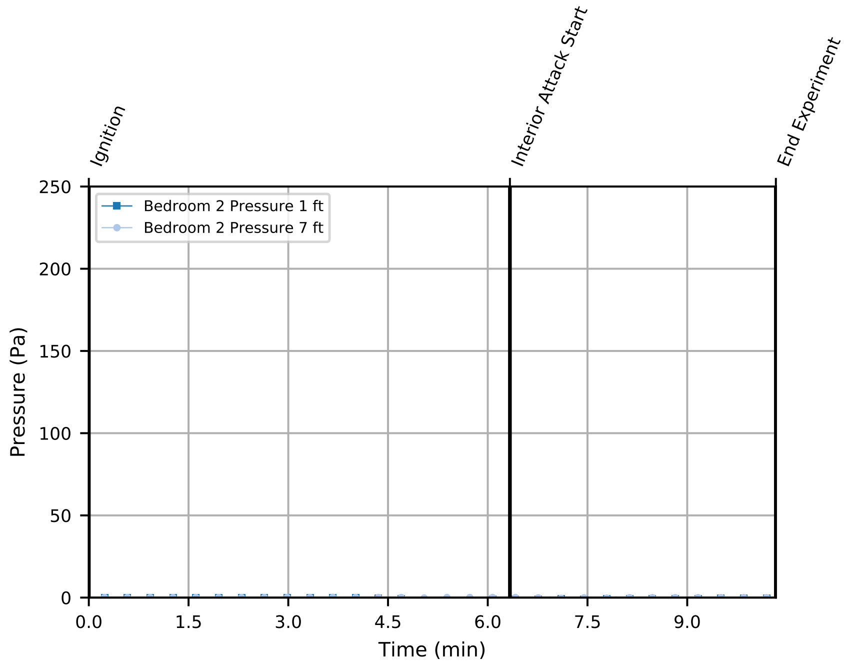


Figure E.375: Experiment 11 - Bedroom 2 Pressure

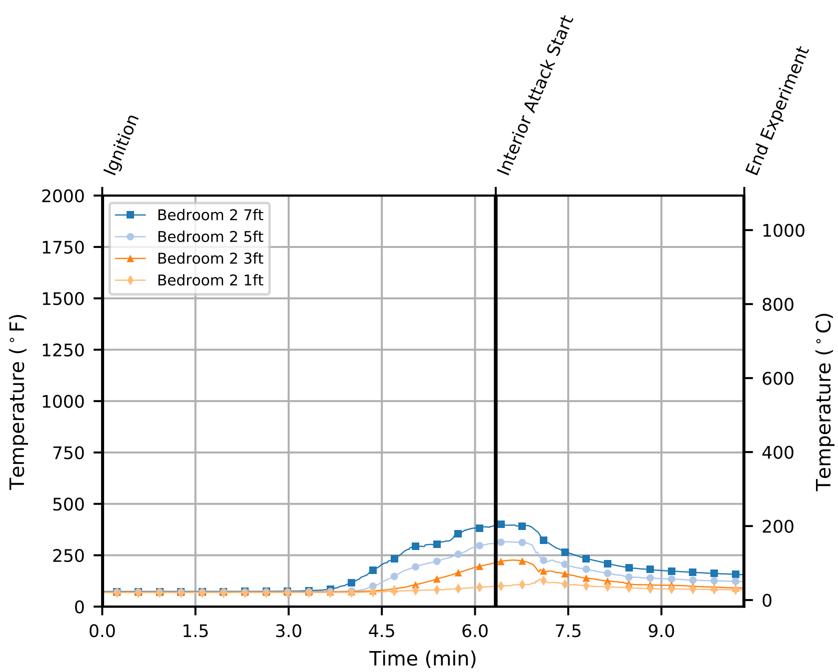


Figure E.376: Experiment 11 - Bedroom 2 Temps

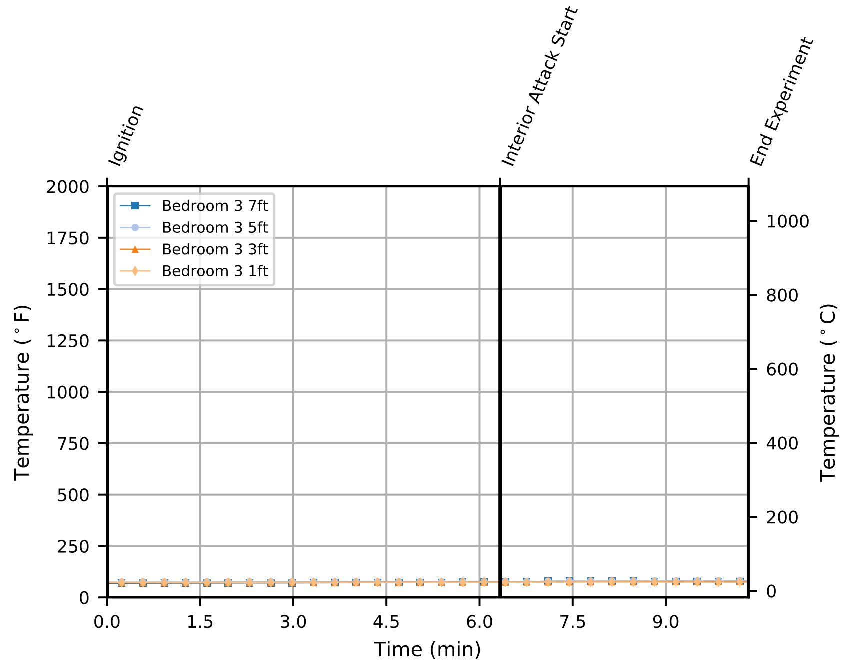


Figure E.377: Experiment 11 - Bedroom 3 Temps

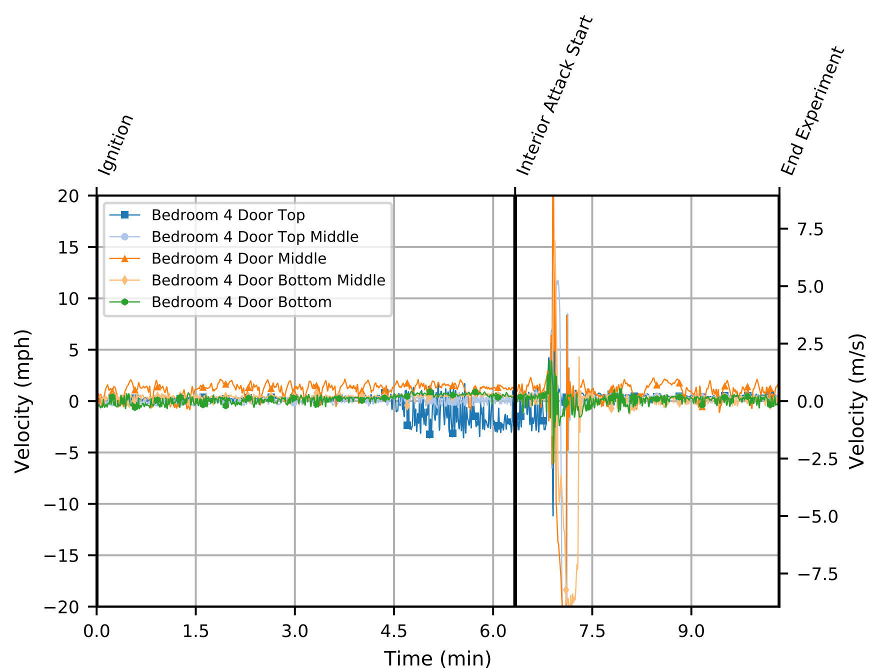


Figure E.378: Experiment 11 - Bedroom 4 Door

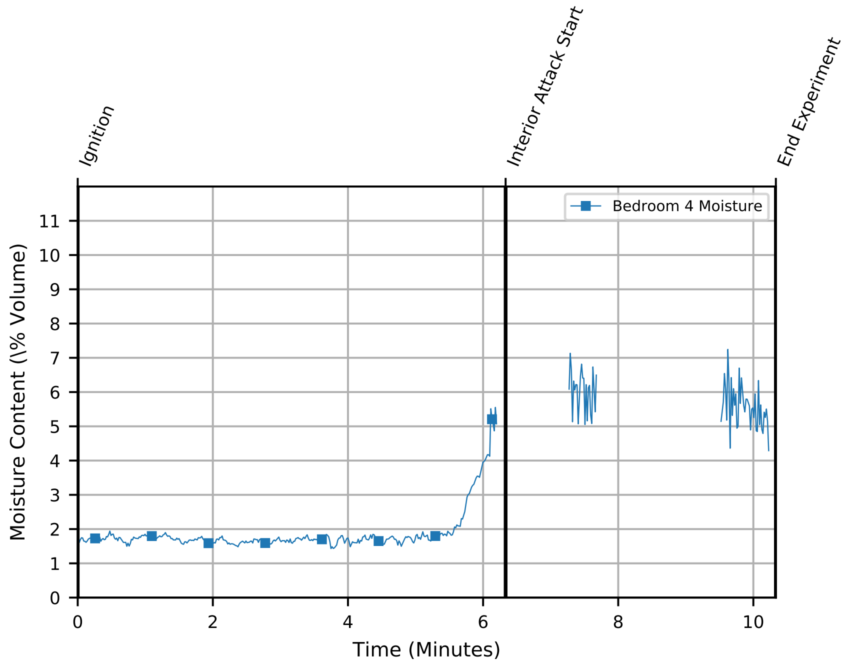


Figure E.379: Experiment 11 - Bedroom 4 Moisture

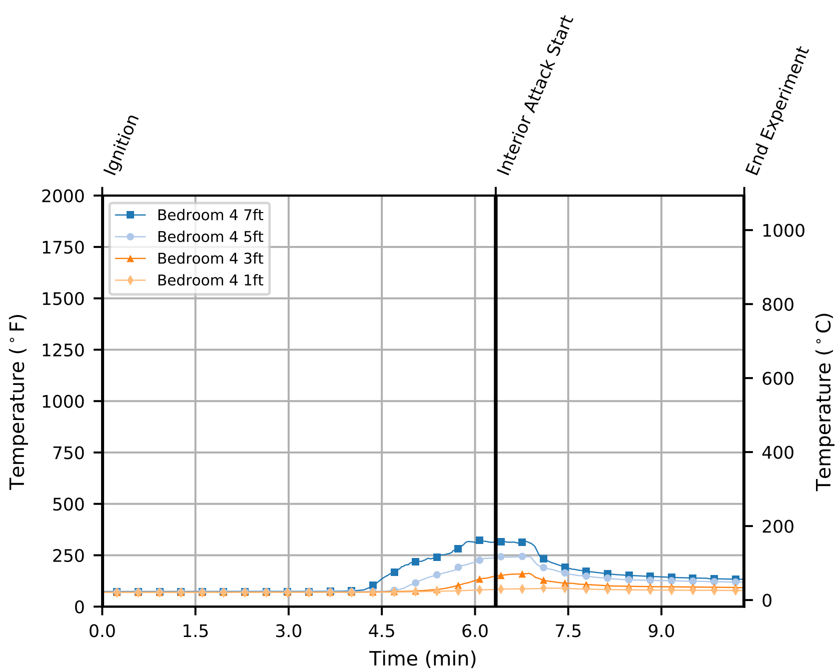


Figure E.380: Experiment 11 - Bedroom 4 Temps

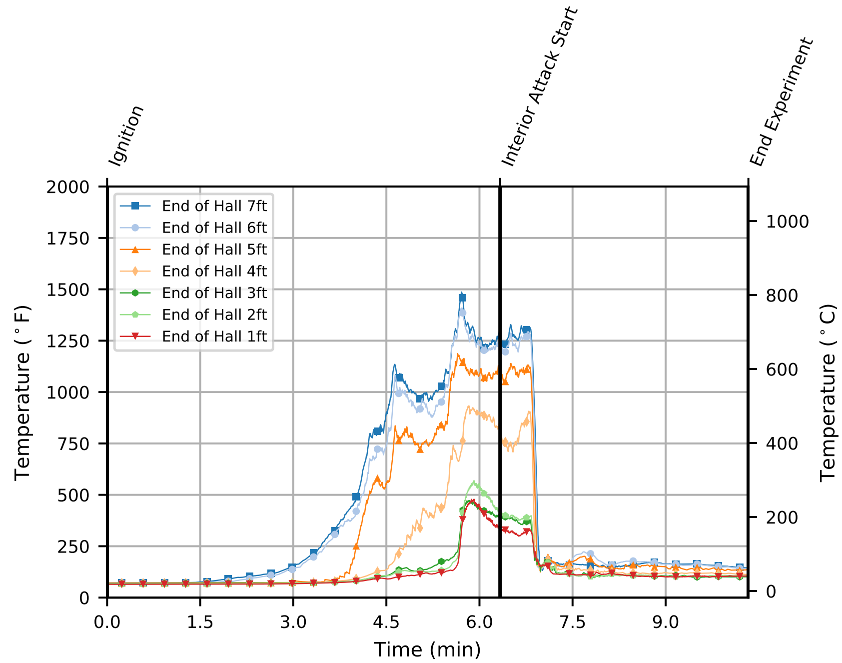


Figure E.381: Experiment 11 - End Hall Temps

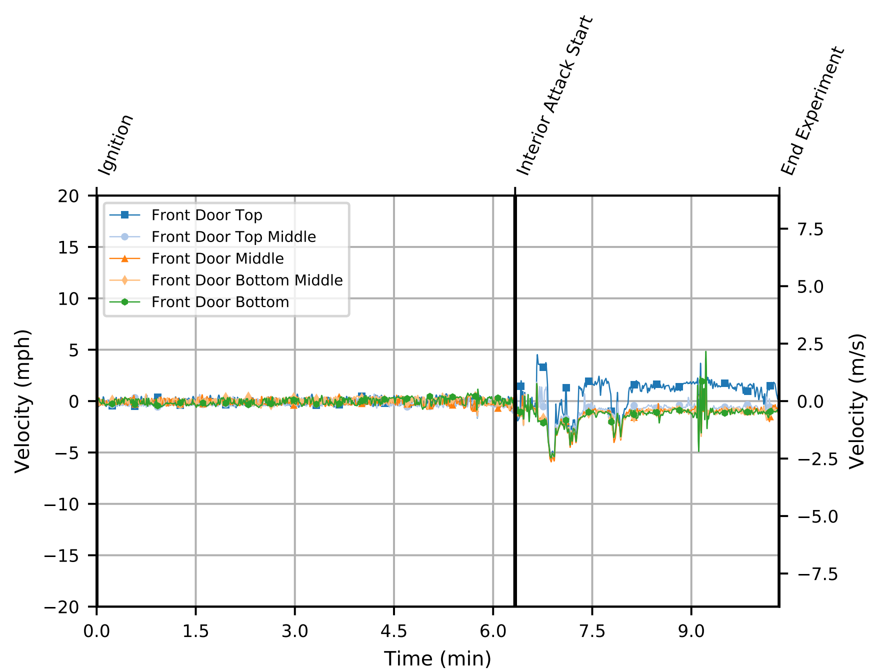


Figure E.382: Experiment 11 - Front Door Flow

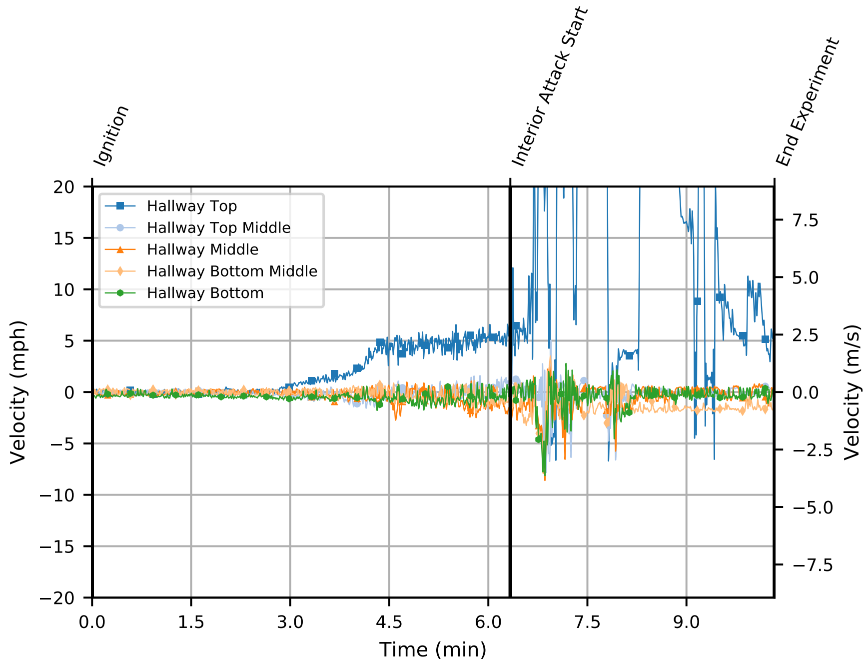


Figure E.383: Experiment 11 - Hallway Flow

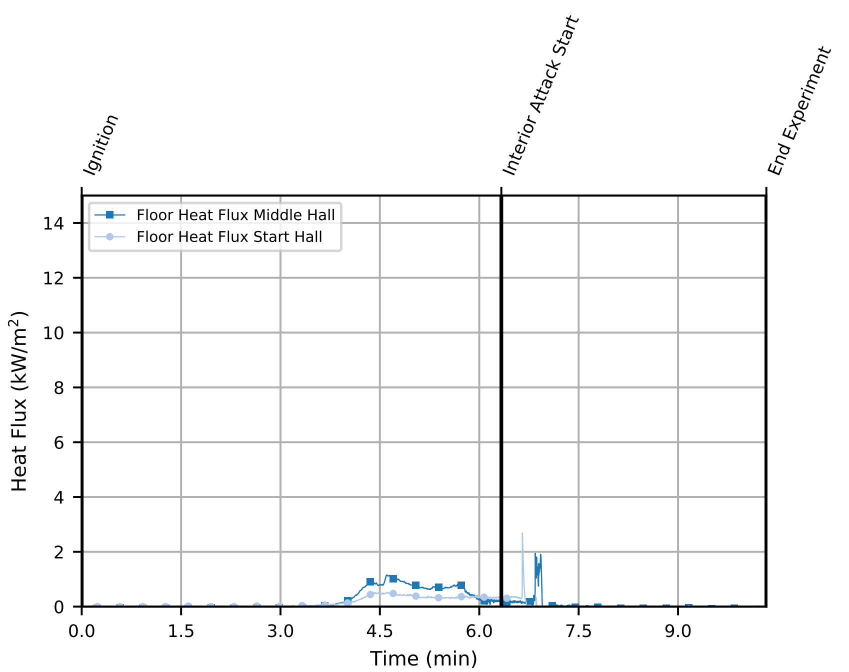


Figure E.384: Experiment 11 - Heat Flux Floor

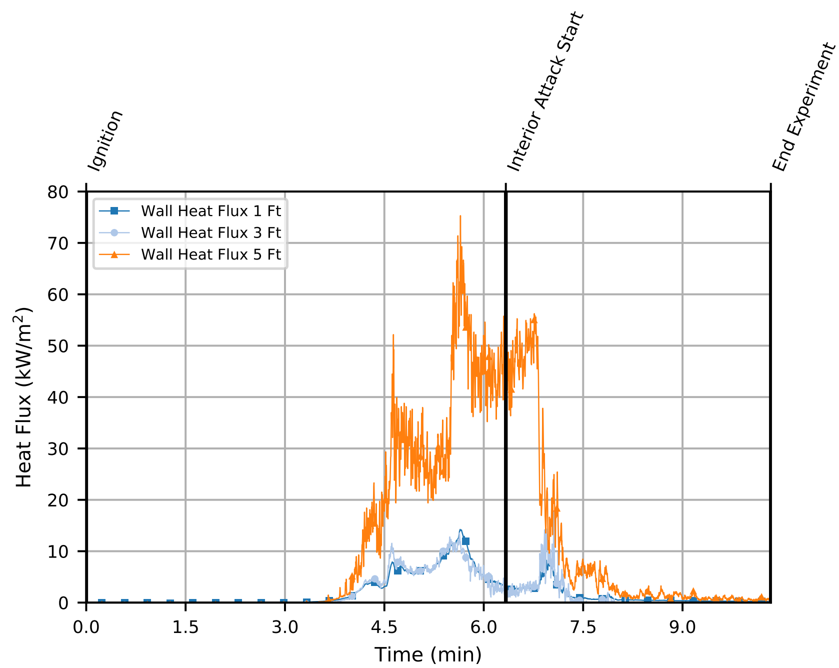


Figure E.385: Experiment 11 - Heat Flux Wall

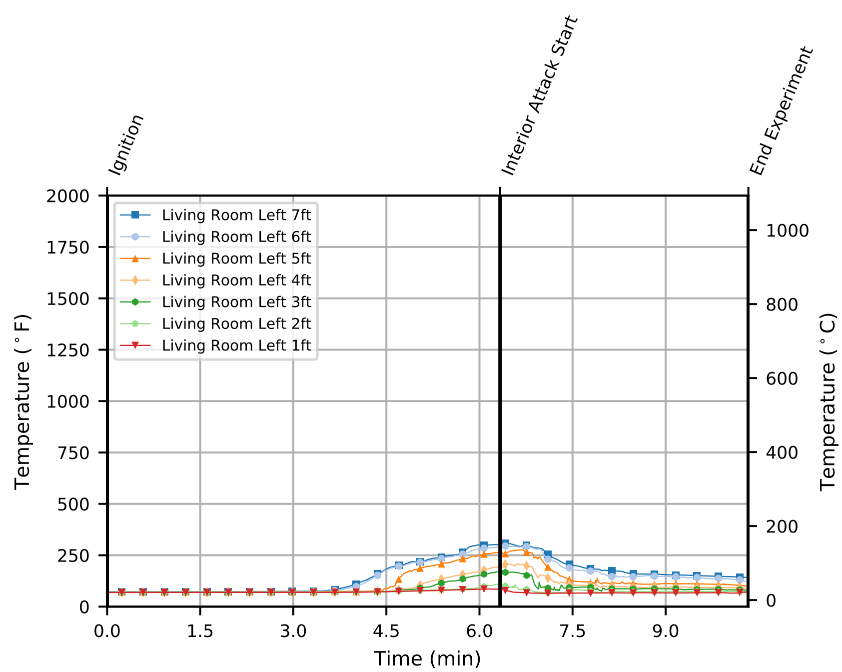


Figure E.386: Experiment 11 - Living Room Left Temps

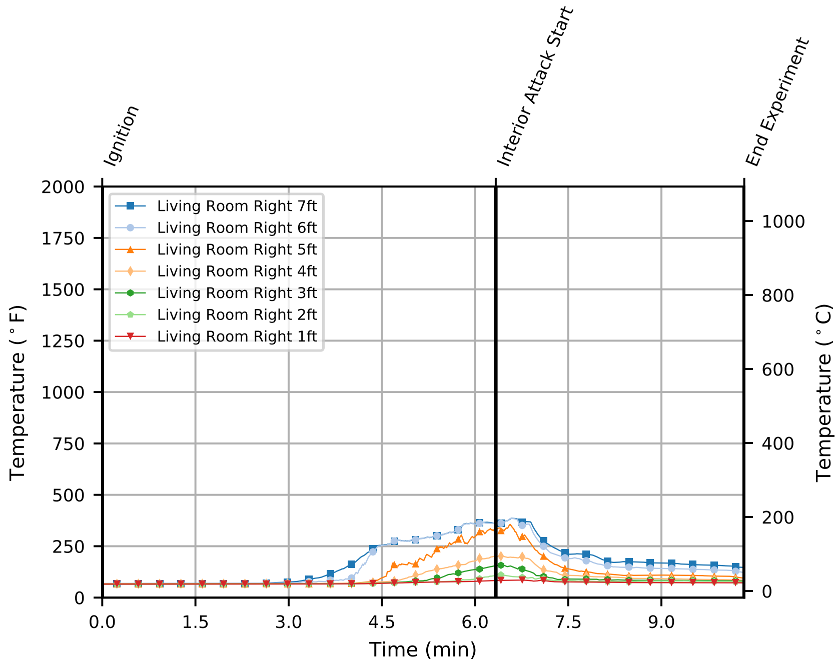


Figure E.387: Experiment 11 - Living Room Right Temps

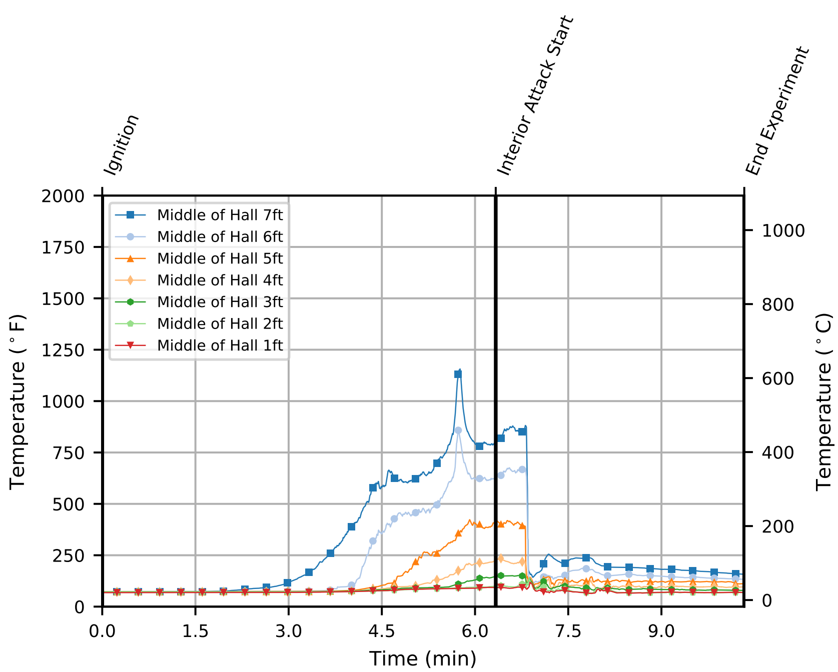


Figure E.388: Experiment 11 - Middle Hall Temps

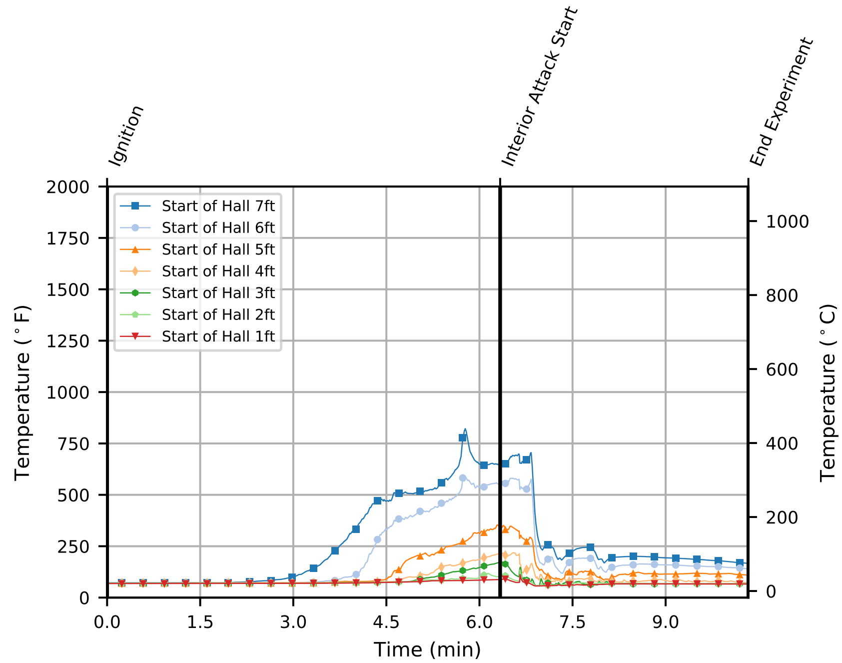


Figure E.389: Experiment 11 - Start Hall Temps

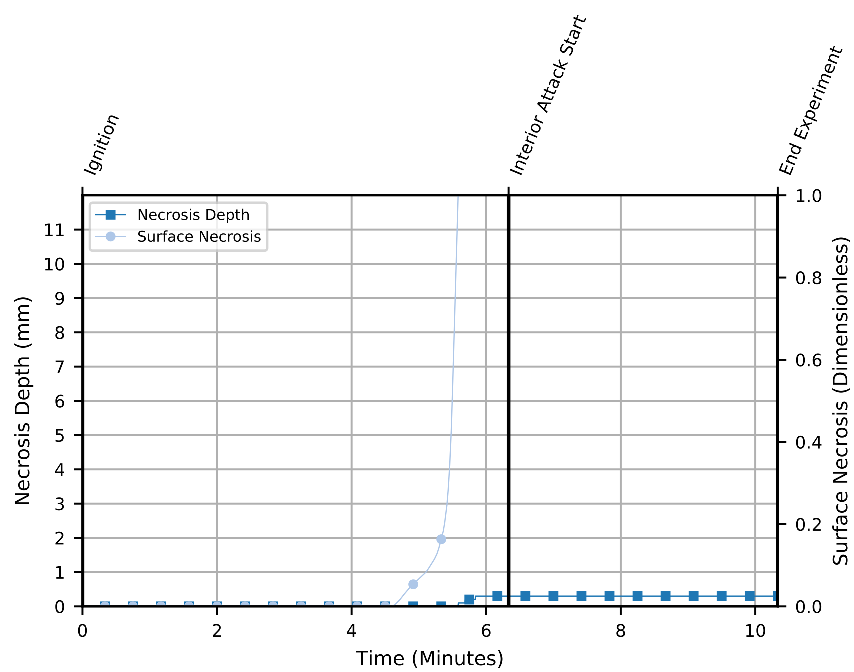


Figure E.390: Experiment 11 - Vic 1 Necrosis Depth

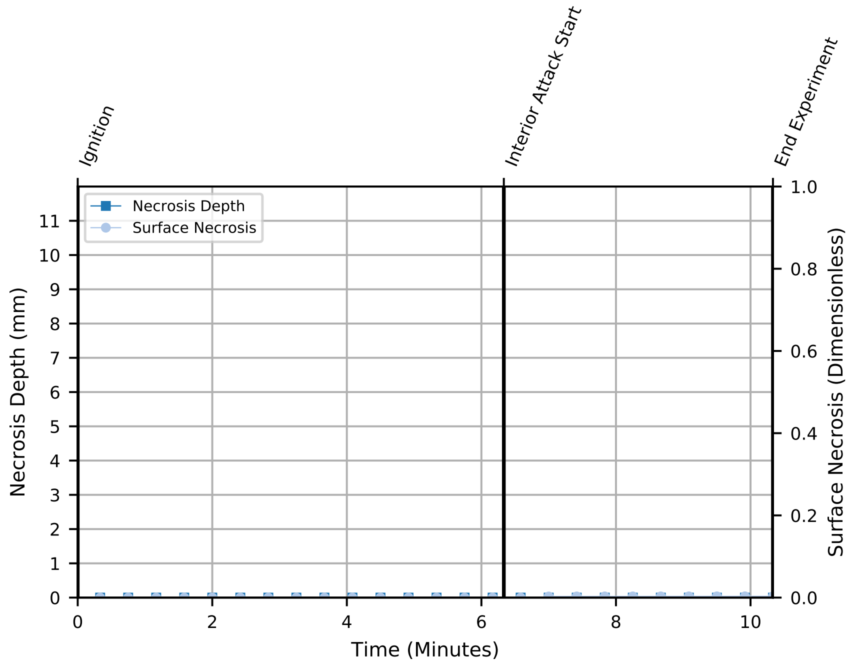


Figure E.391: Experiment 11 - Vic 3 Necrosis Depth

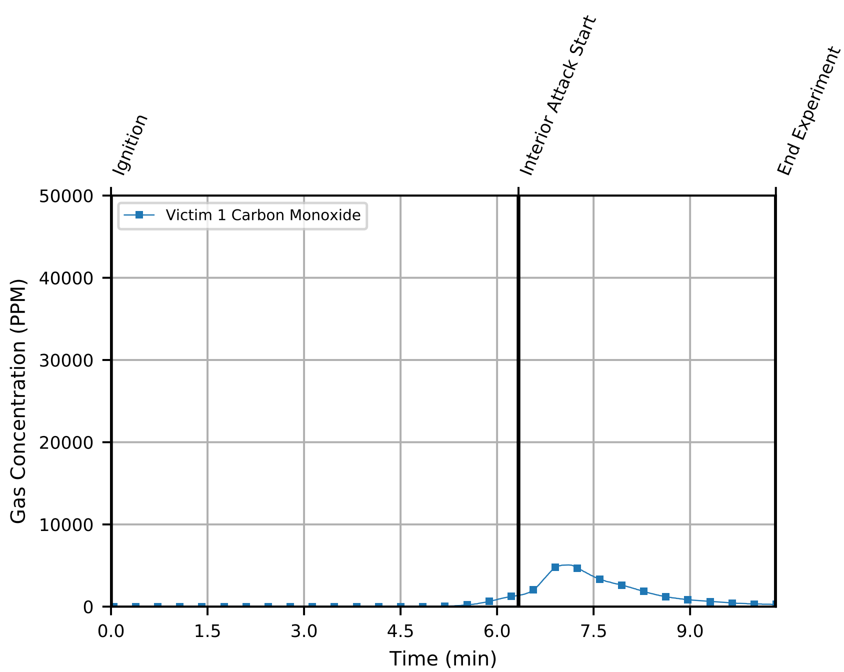


Figure E.392: Experiment 11 - Victim 1 Carbon Monoxide

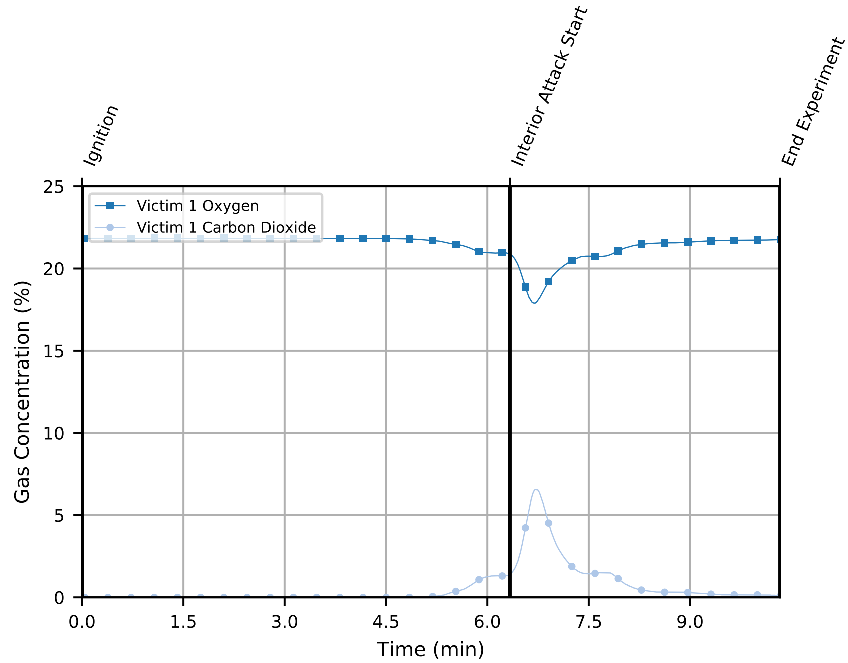


Figure E.393: Experiment 11 - Victim 1 Gas

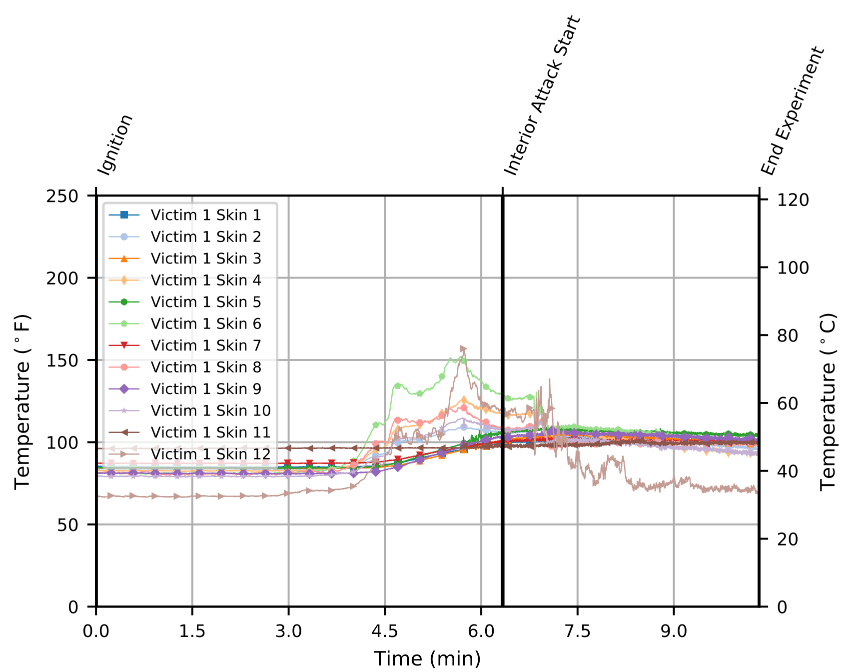


Figure E.394: Experiment 11 - Victim 1 Skin Temps

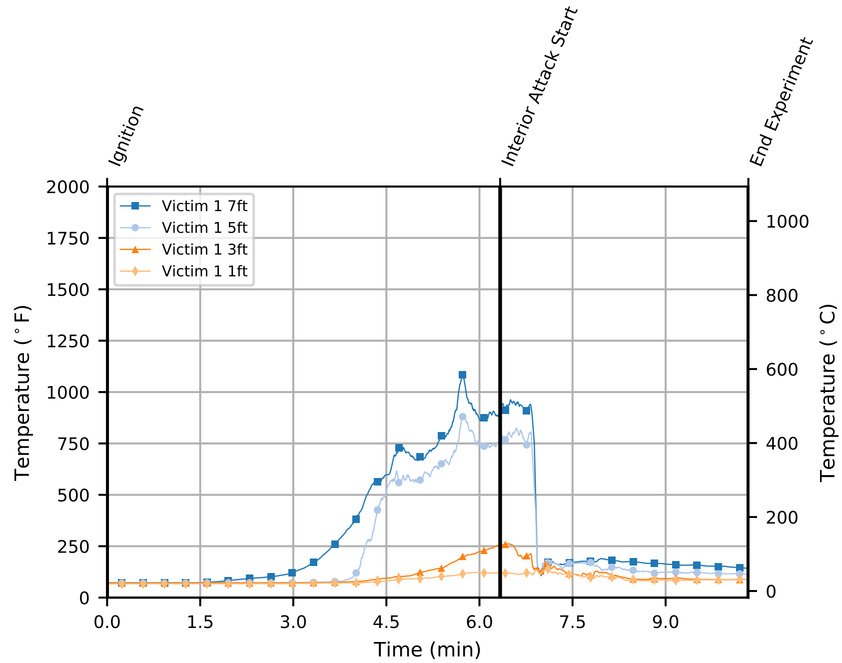


Figure E.395: Experiment 11 - Victim 1 Temps

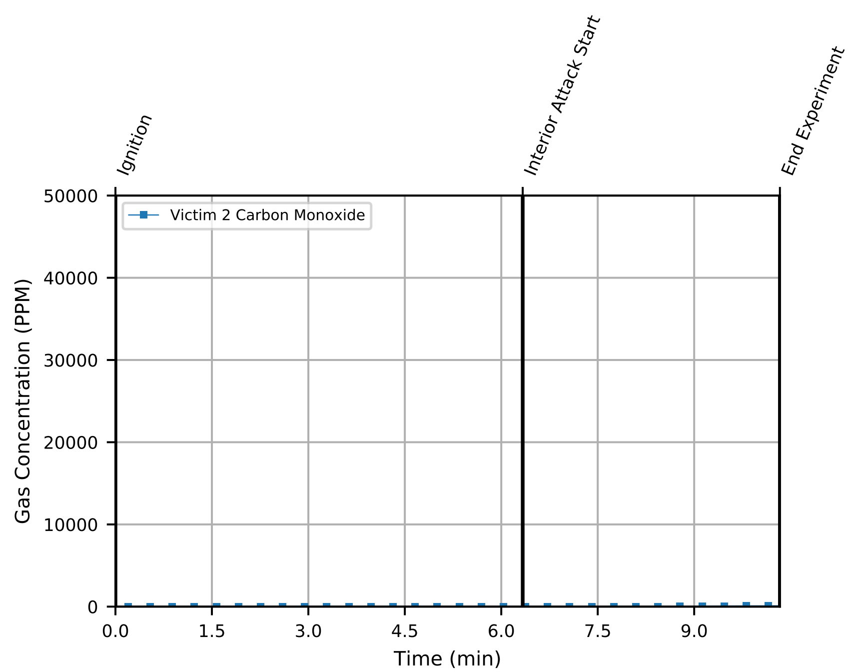


Figure E.396: Experiment 11 - Victim 2 Carbon Monoxide

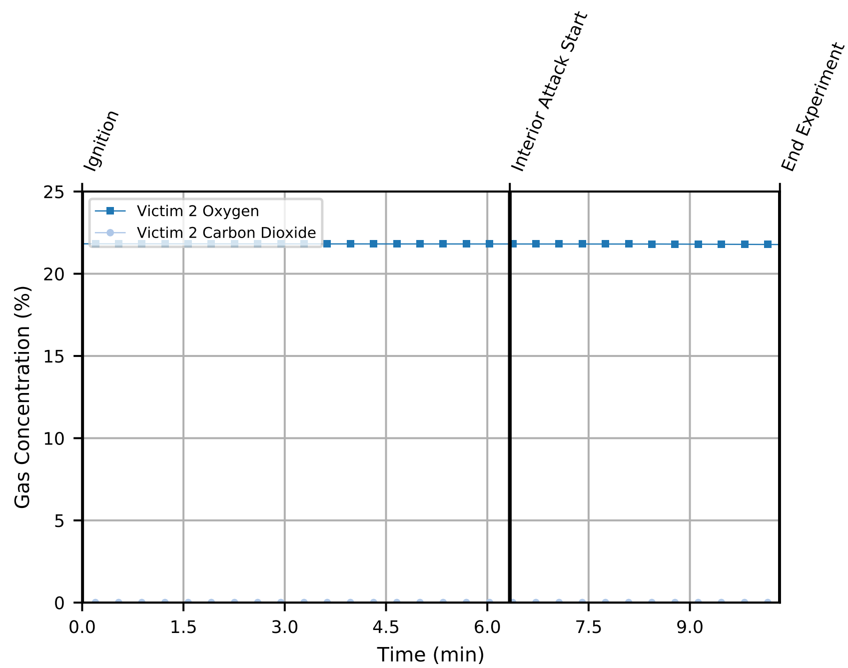


Figure E.397: Experiment 11 - Victim 2 Gas

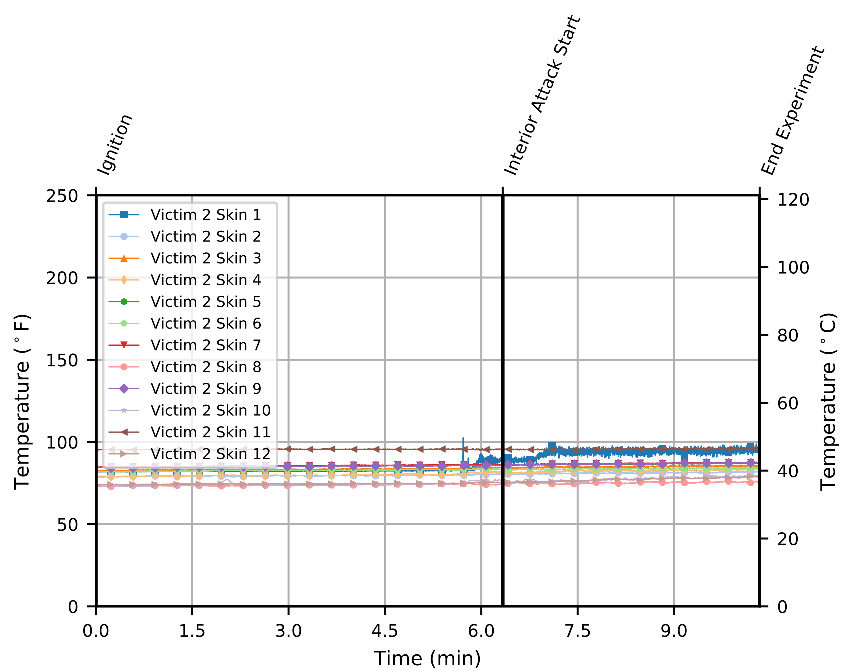


Figure E.398: Experiment 11 - Victim 2 Skin Temps

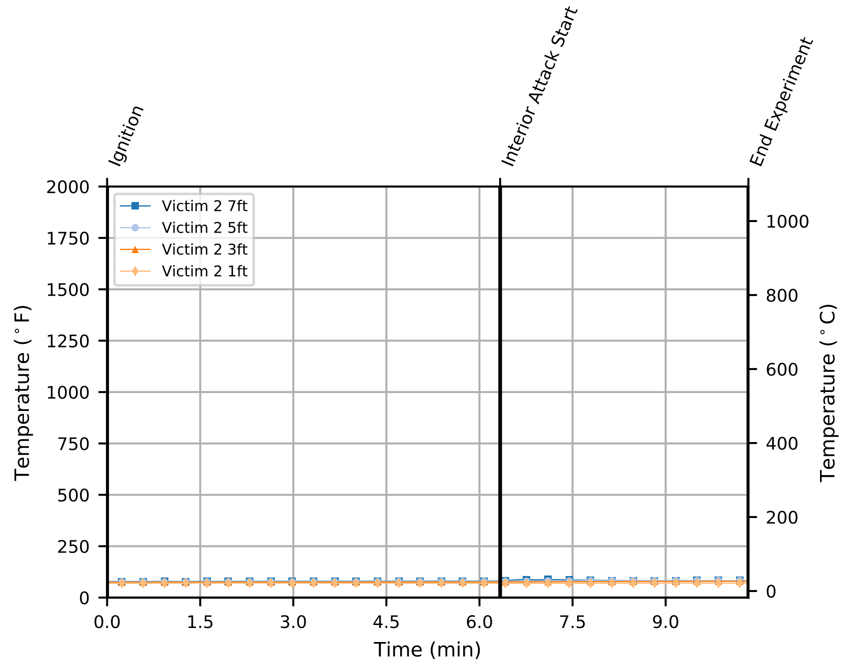


Figure E.399: Experiment 11 - Victim 2 Temps

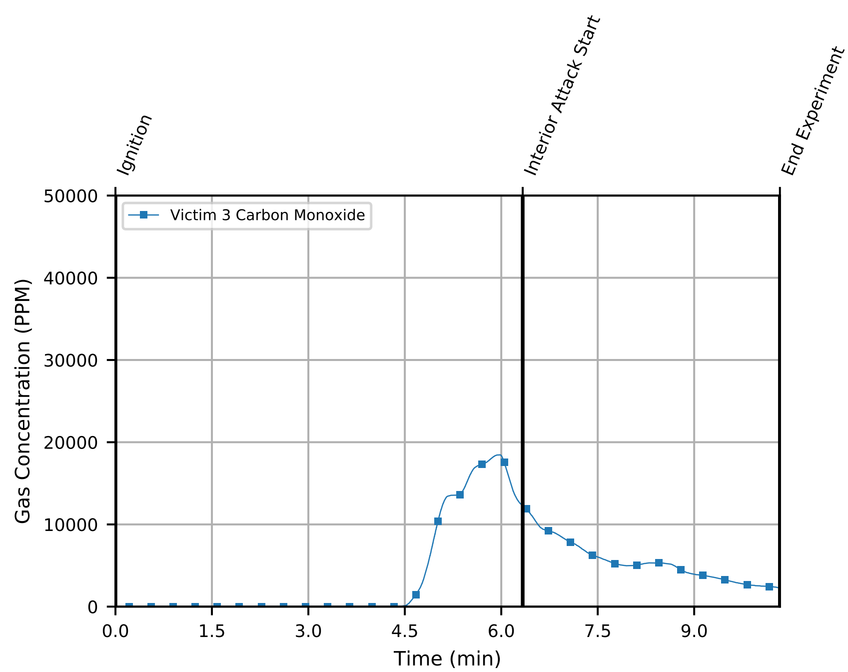


Figure E.400: Experiment 11 - Victim 3 Carbon Monoxide

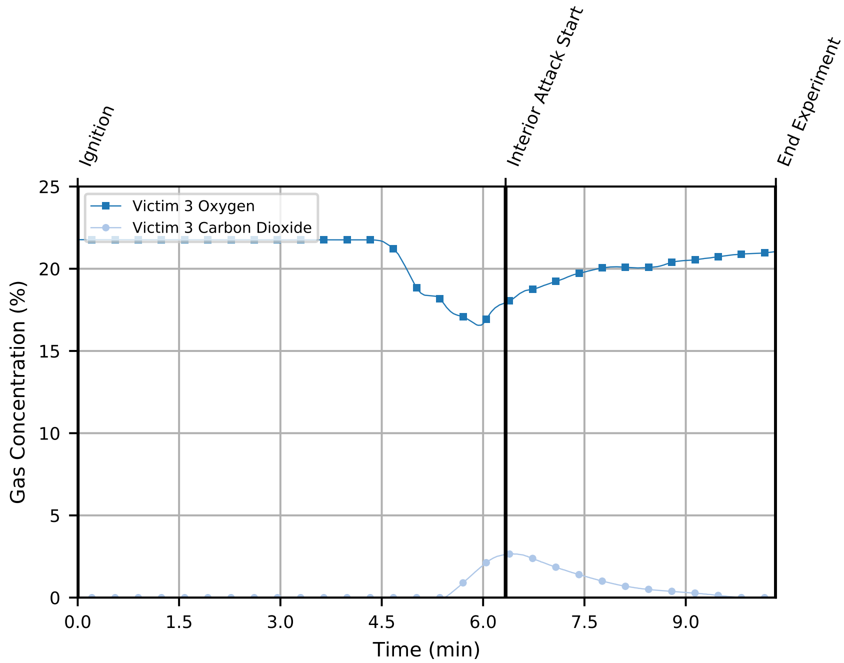


Figure E.401: Experiment 11 - Victim 3 Gas

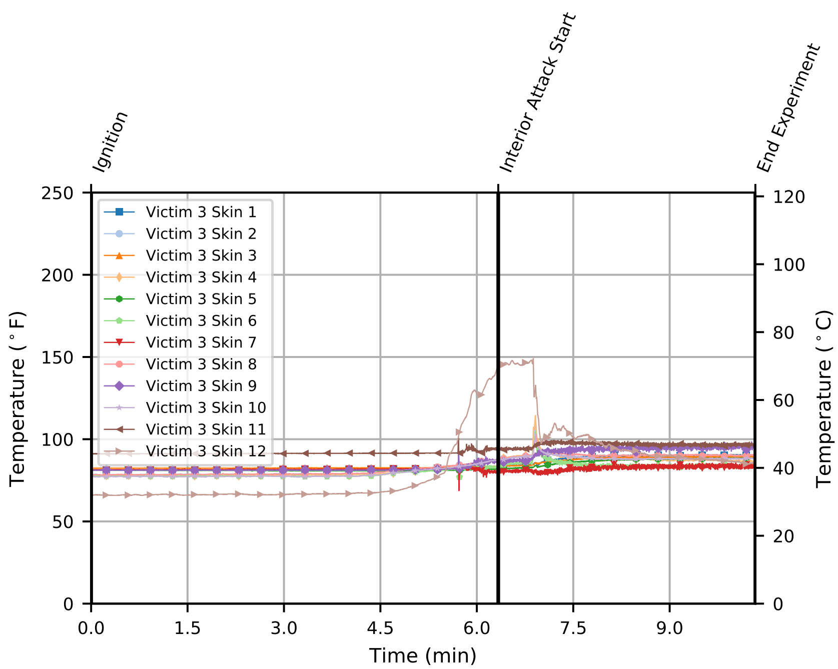


Figure E.402: Experiment 11 - Victim 3 Skin Temps

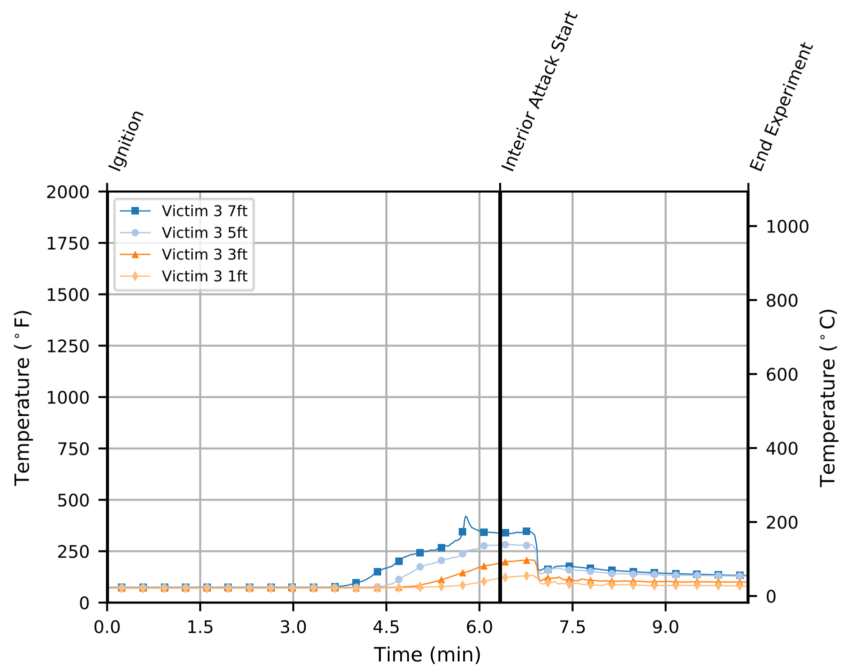


Figure E.403: Experiment 11 - Victim 3 Temps

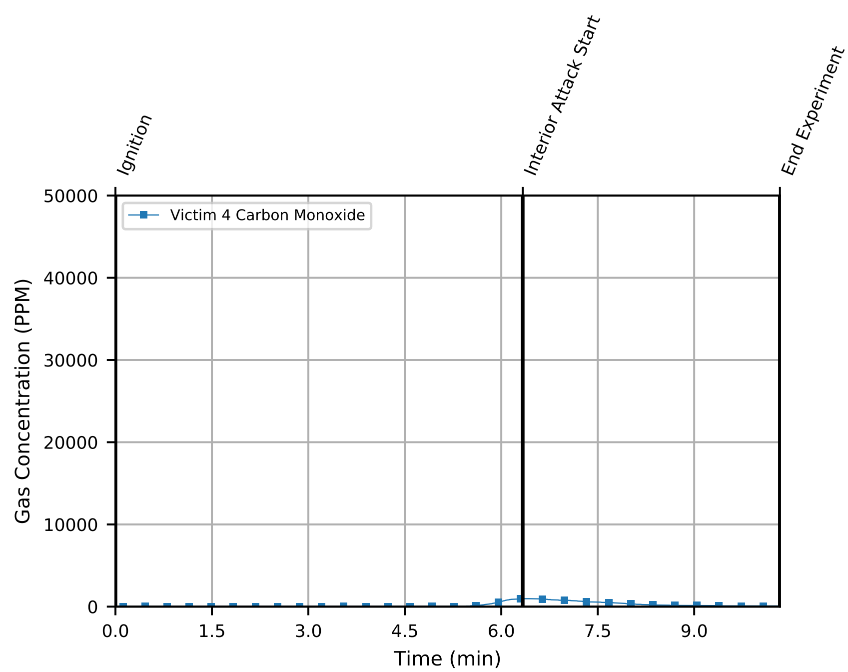


Figure E.404: Experiment 11 - Victim 4 Carbon Monoxide

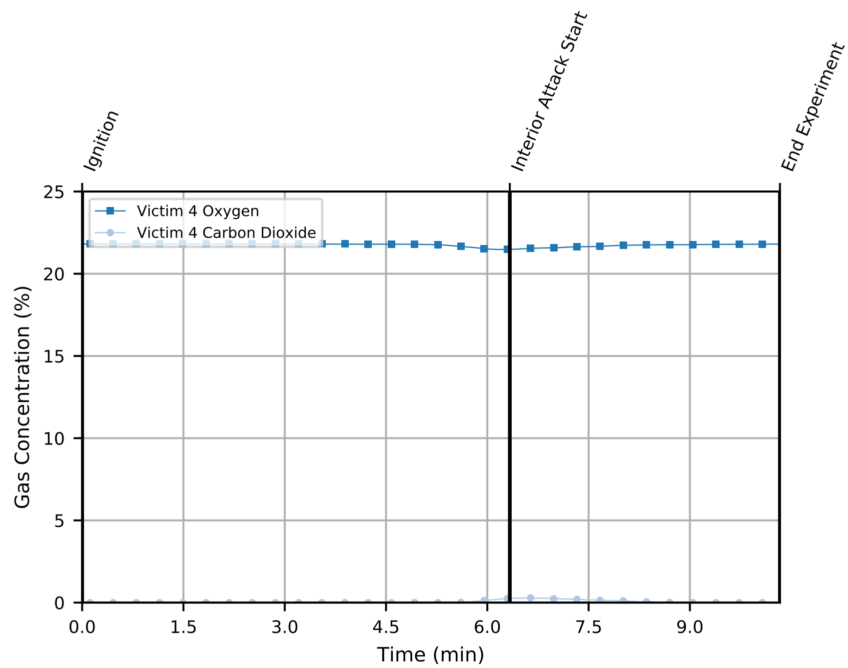


Figure E.405: Experiment 11 - Victim 4 Gas

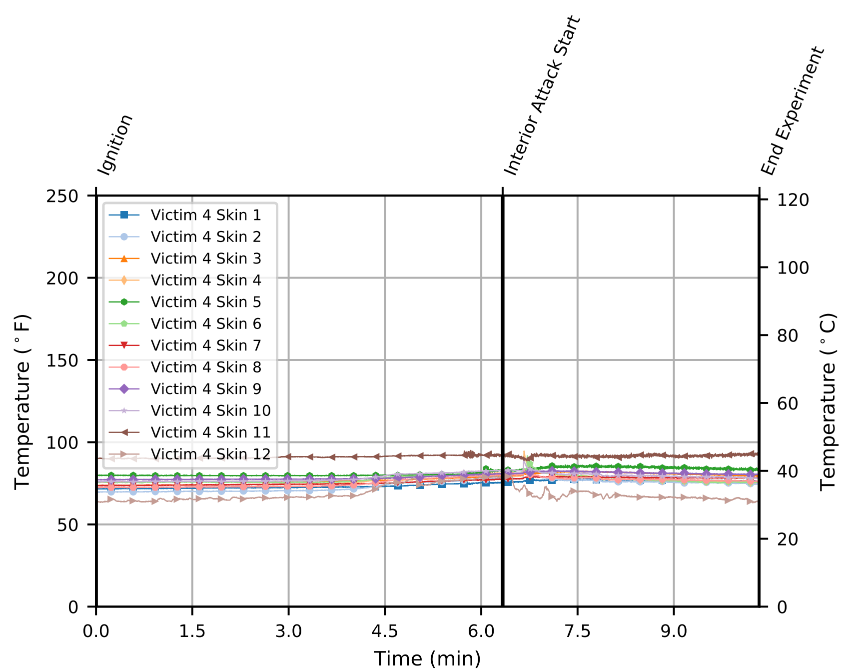


Figure E.406: Experiment 11 - Victim 4 Skin Temps

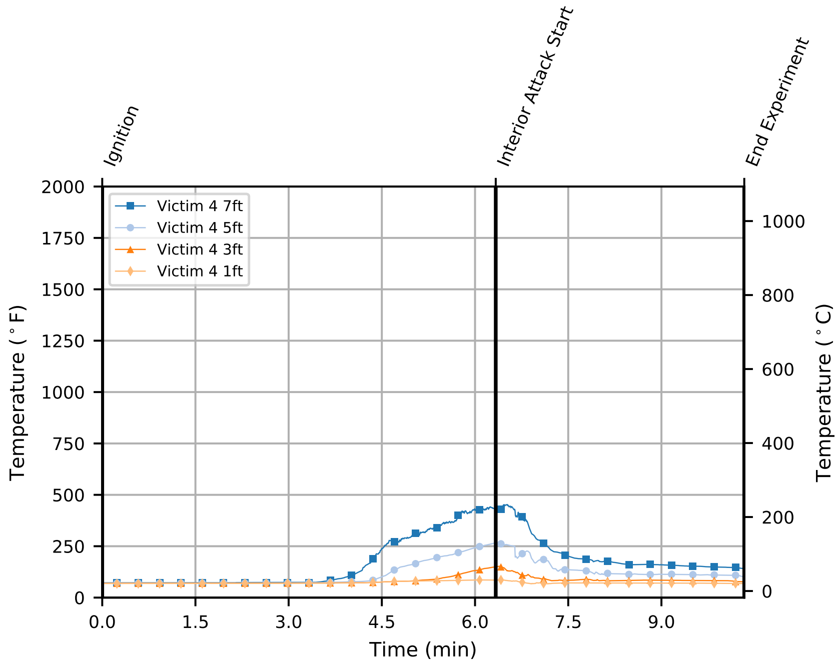


Figure E.407: Experiment 11 - Victim 4 Temps

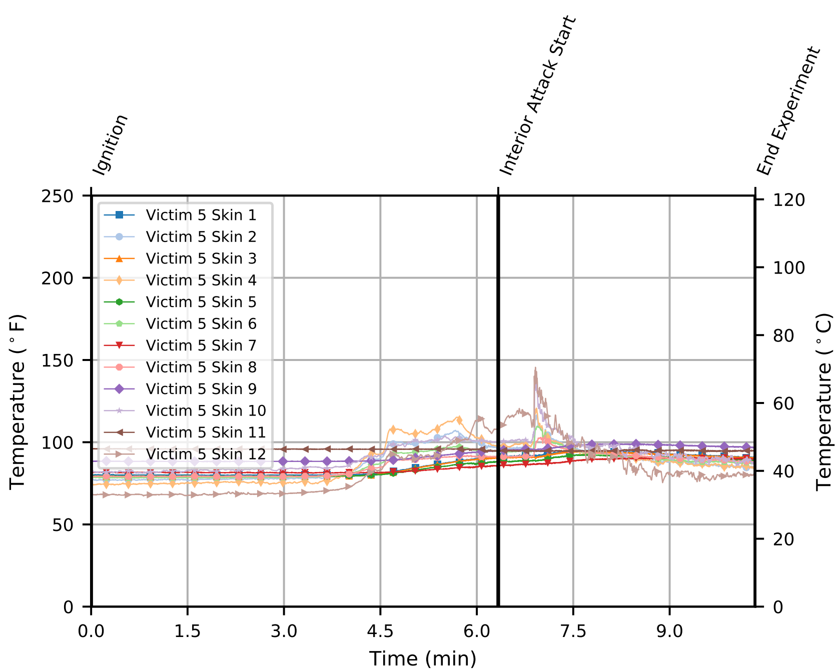


Figure E.408: Experiment 11 - Victim 5 Skin Temps

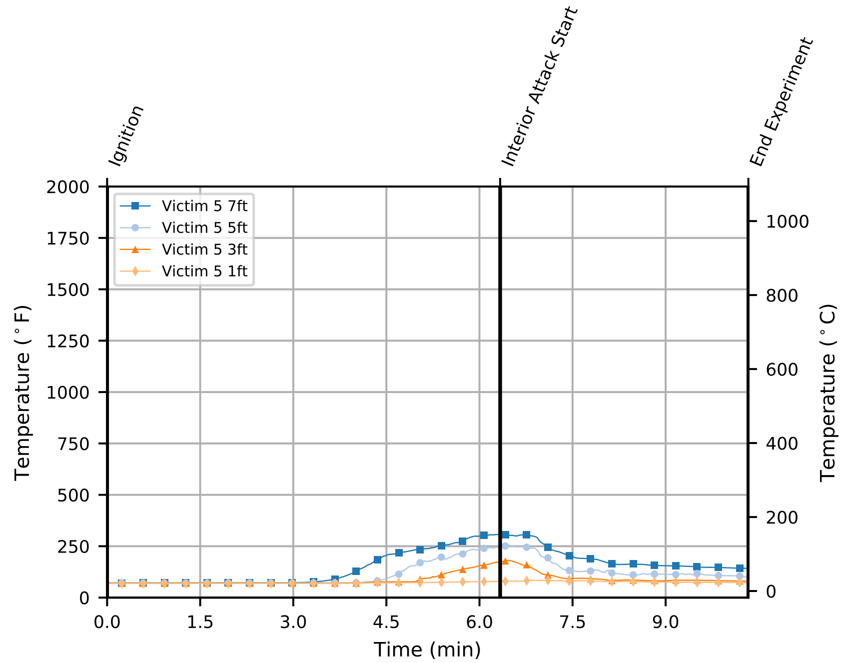


Figure E.409: Experiment 11 - Victim 5 Temps

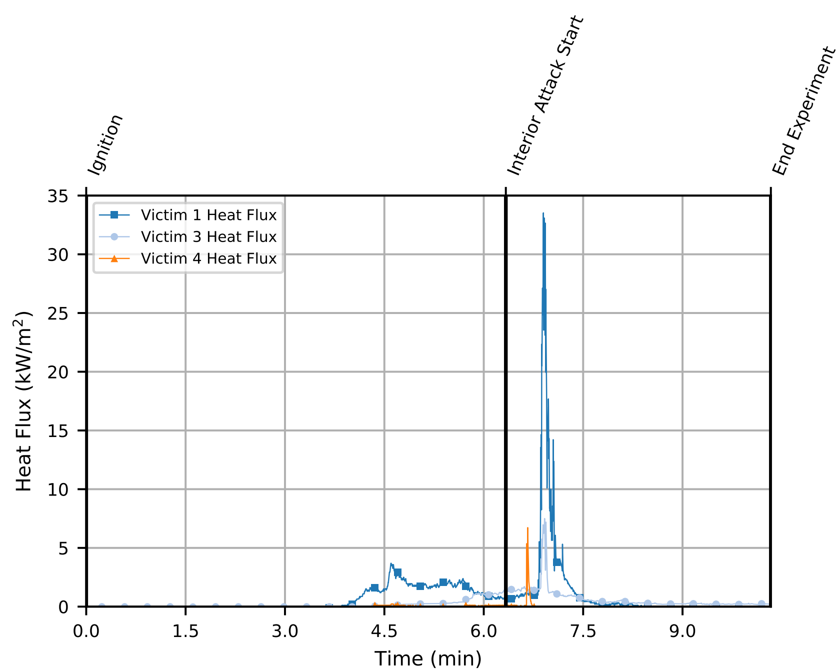


Figure E.410: Experiment 11 - Victim Heat Flux

E.12 Experiment 12 Data

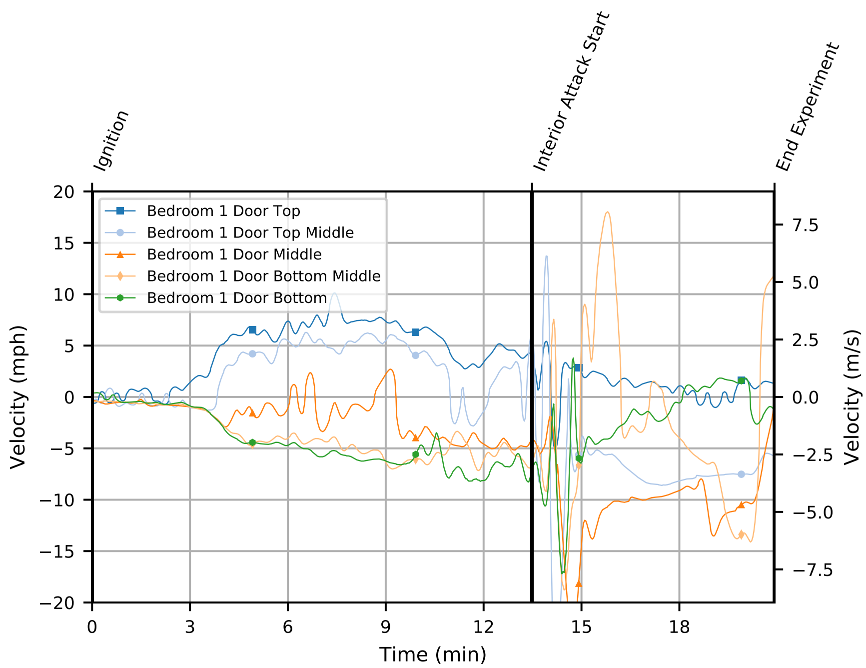


Figure E.411: Experiment 12 - Bedroom 1 Door

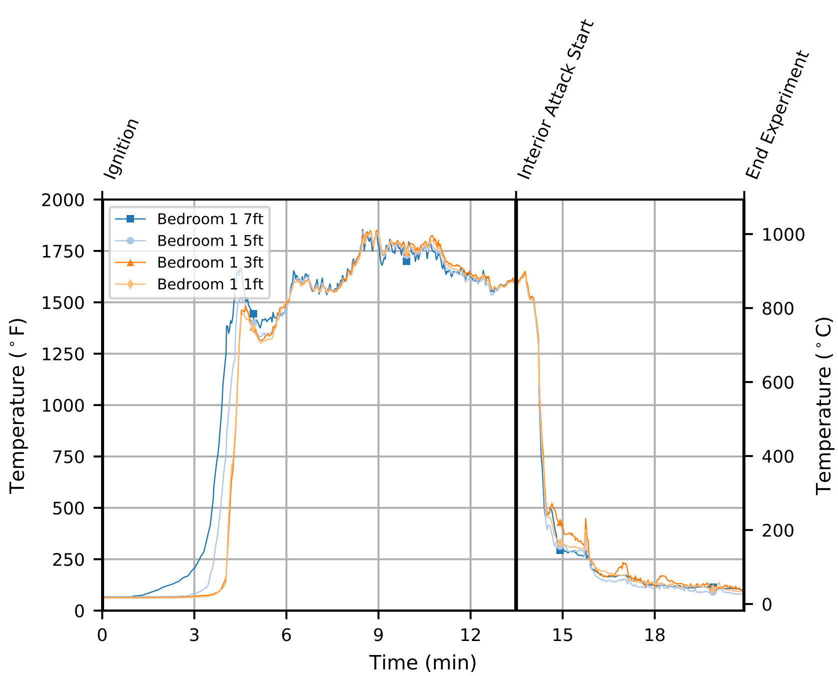


Figure E.412: Experiment 12 - Bedroom 1 Temps

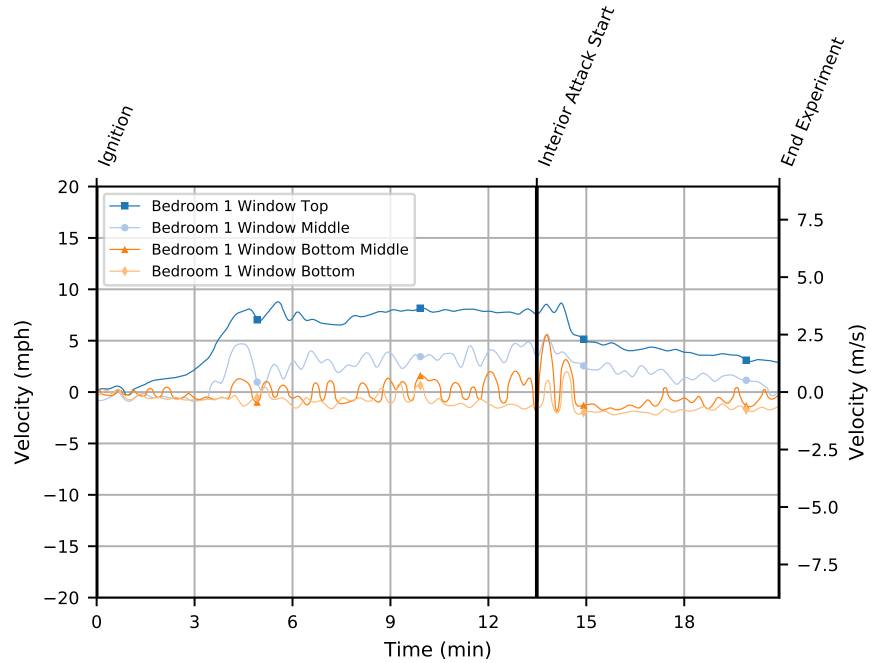


Figure E.413: Experiment 12 - Bedroom 1 Window

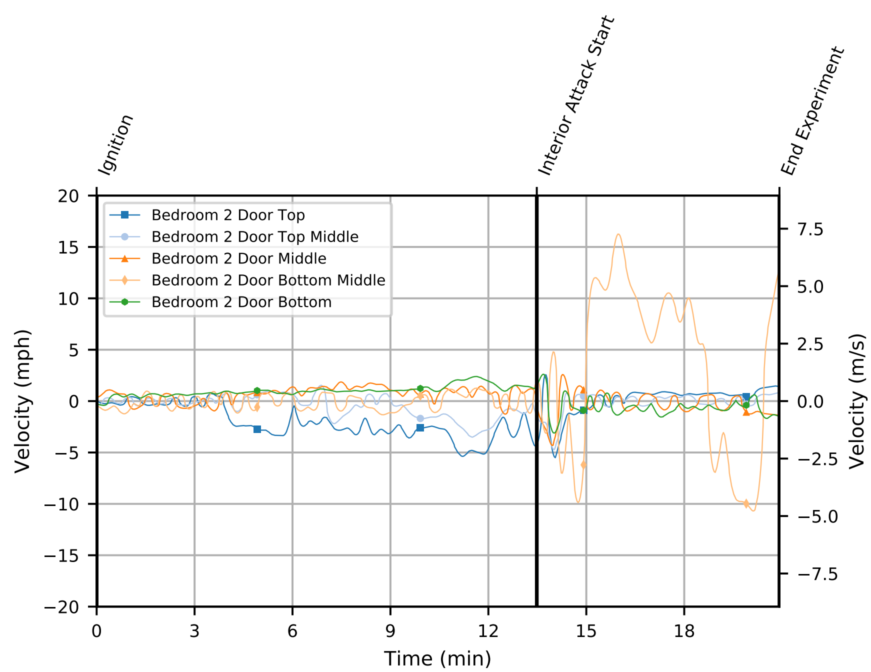


Figure E.414: Experiment 12 - Bedroom 2 Door

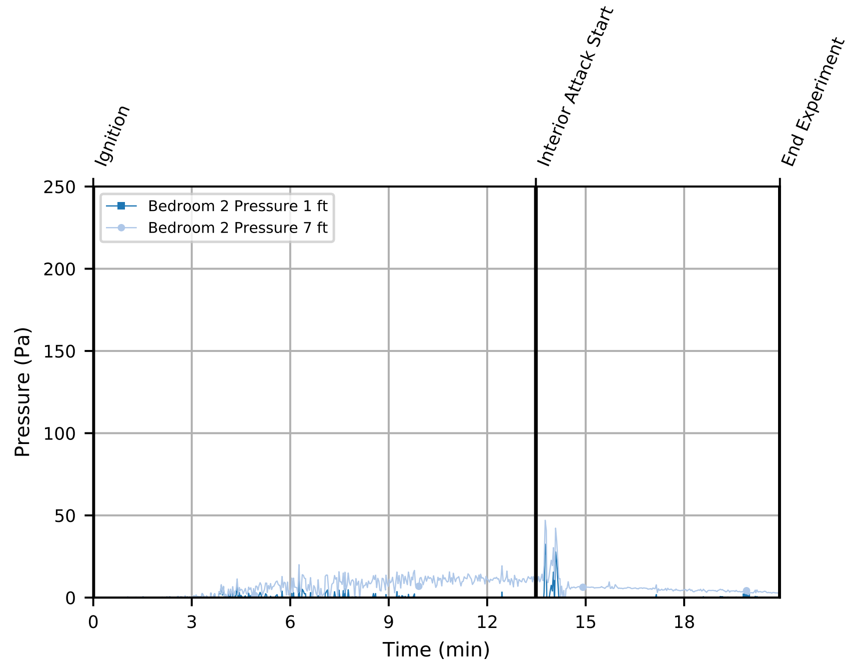


Figure E.415: Experiment 12 - Bedroom 2 Pressure

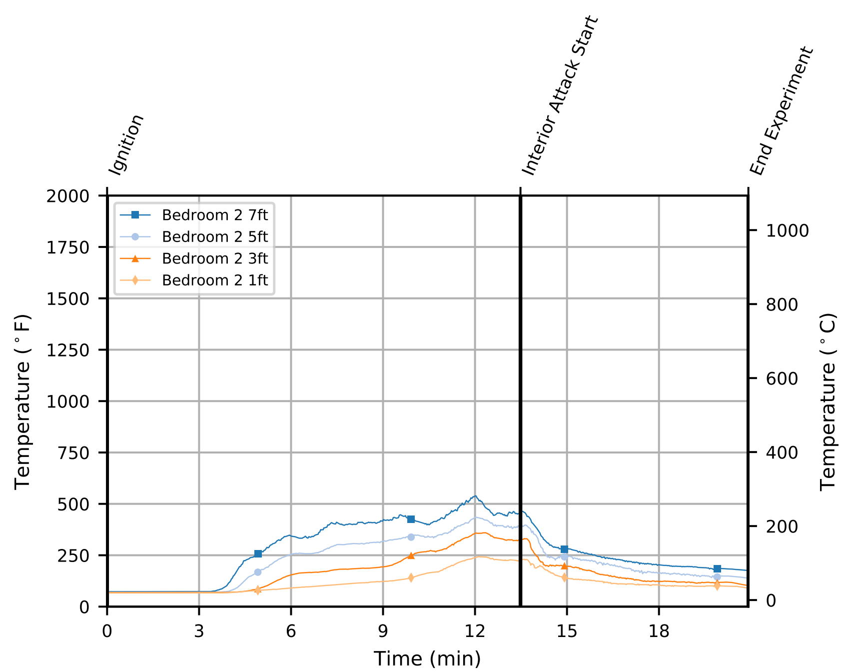


Figure E.416: Experiment 12 - Bedroom 2 Temps

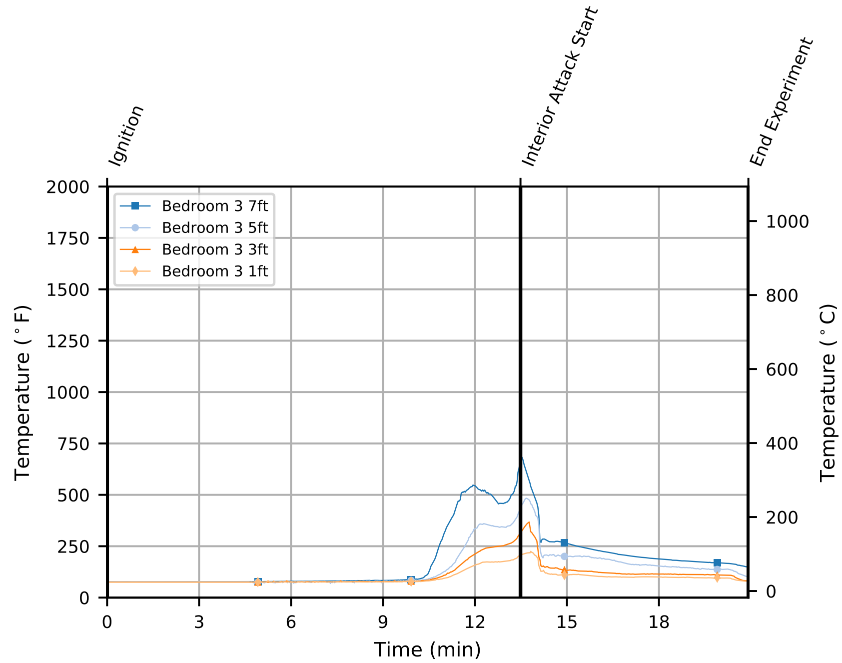


Figure E.417: Experiment 12 - Bedroom 3 Temps

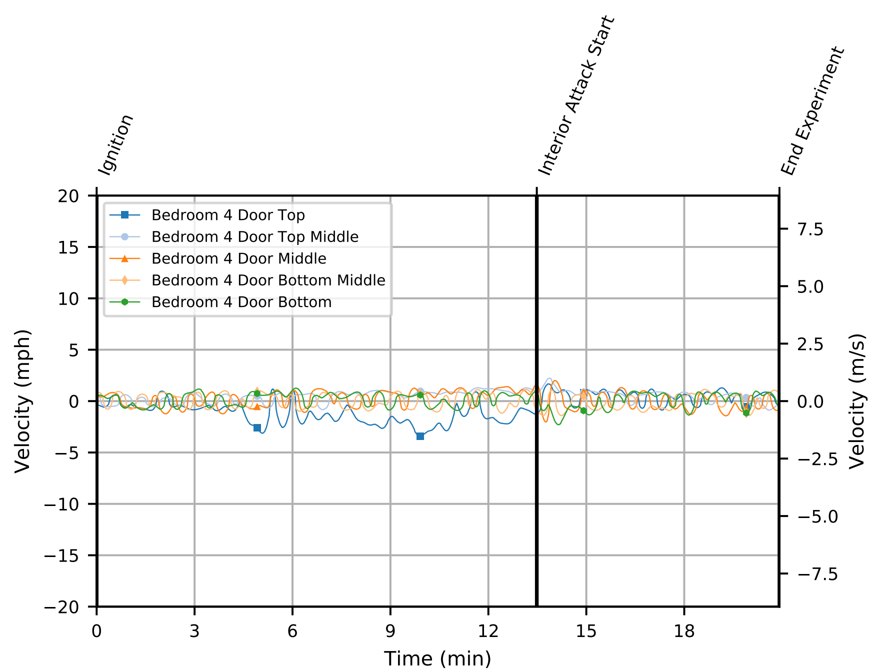


Figure E.418: Experiment 12 - Bedroom 4 Door

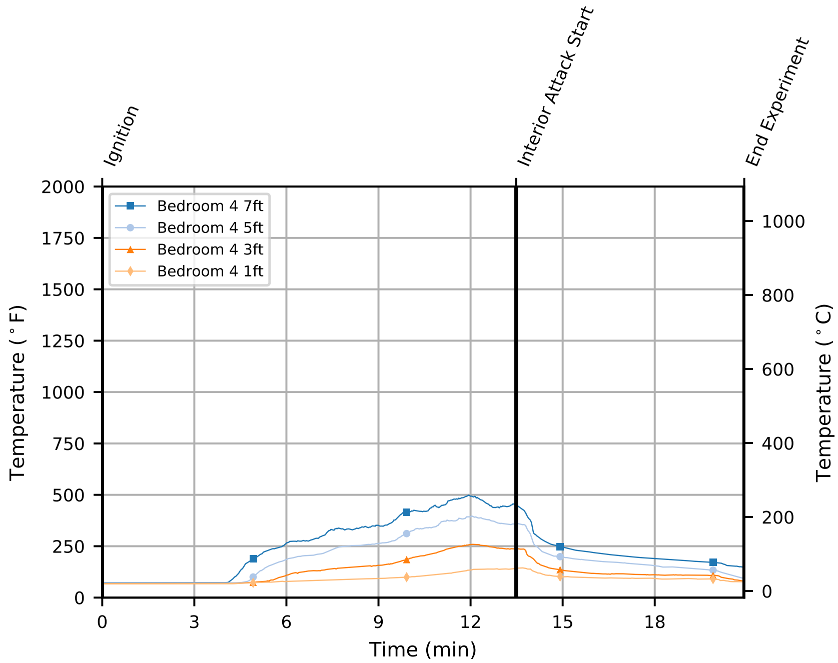


Figure E.419: Experiment 12 - Bedroom 4 Temps

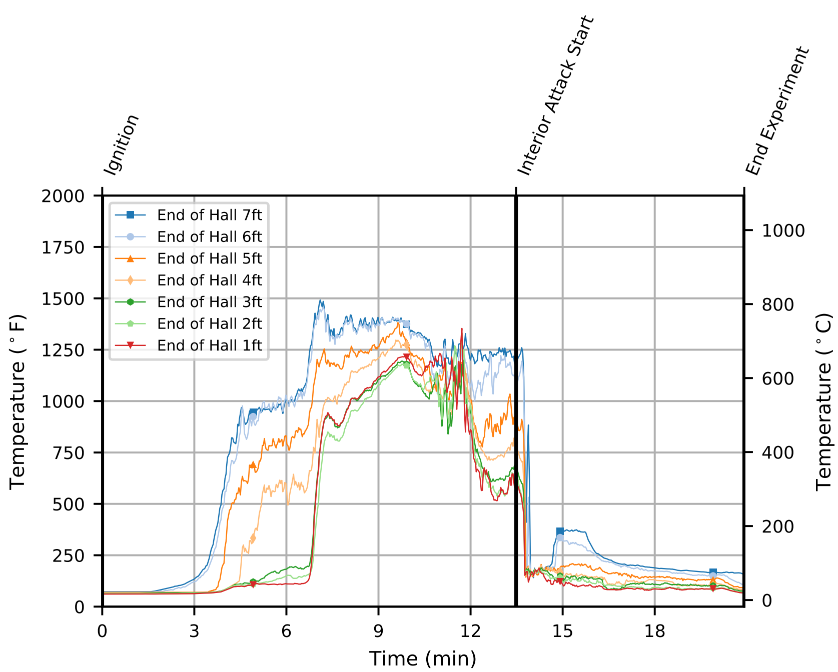


Figure E.420: Experiment 12 - End Hall Temps

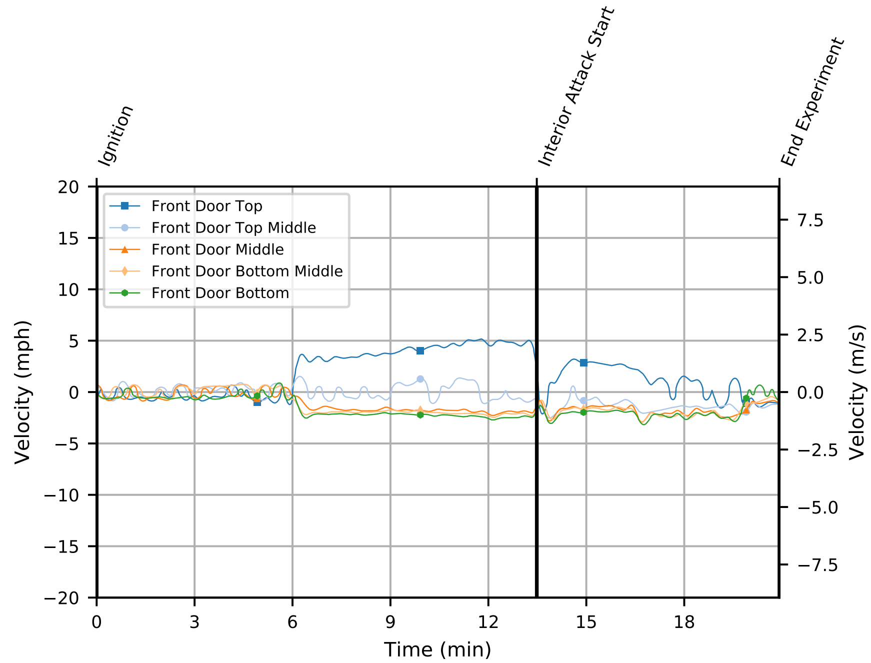


Figure E.421: Experiment 12 - Front Door Flow

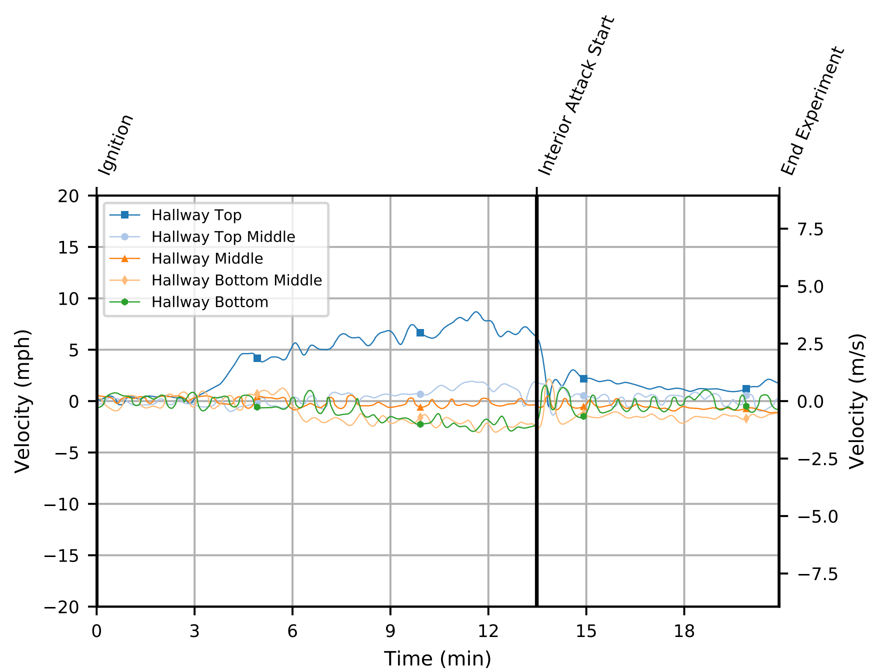


Figure E.422: Experiment 12 - Hallway Flow

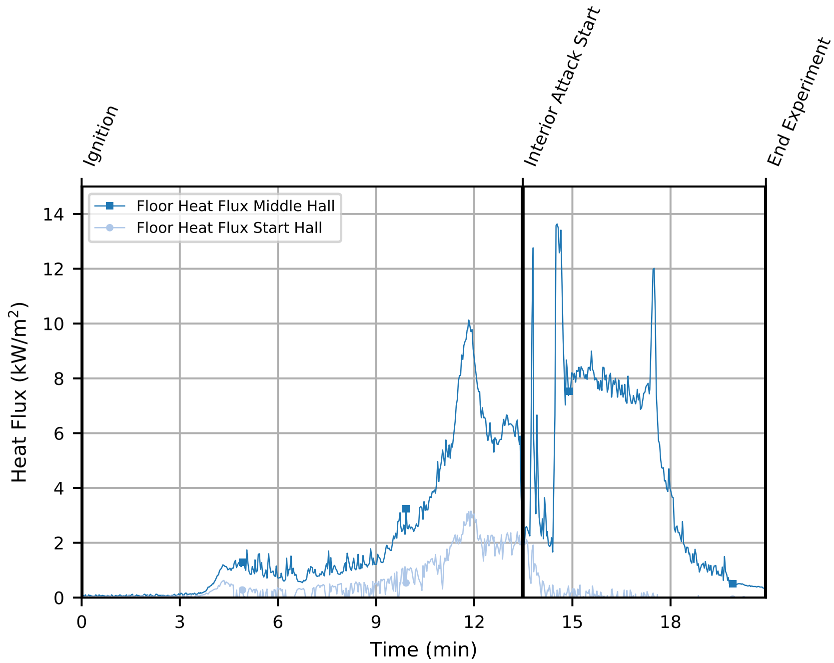


Figure E.423: Experiment 12 - Heat Flux Floor

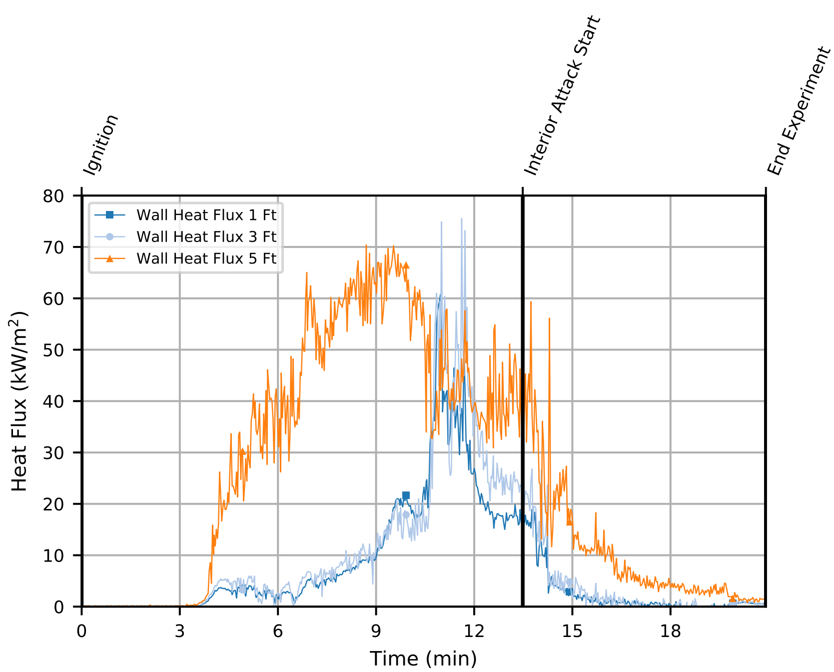


Figure E.424: Experiment 12 - Heat Flux Wall

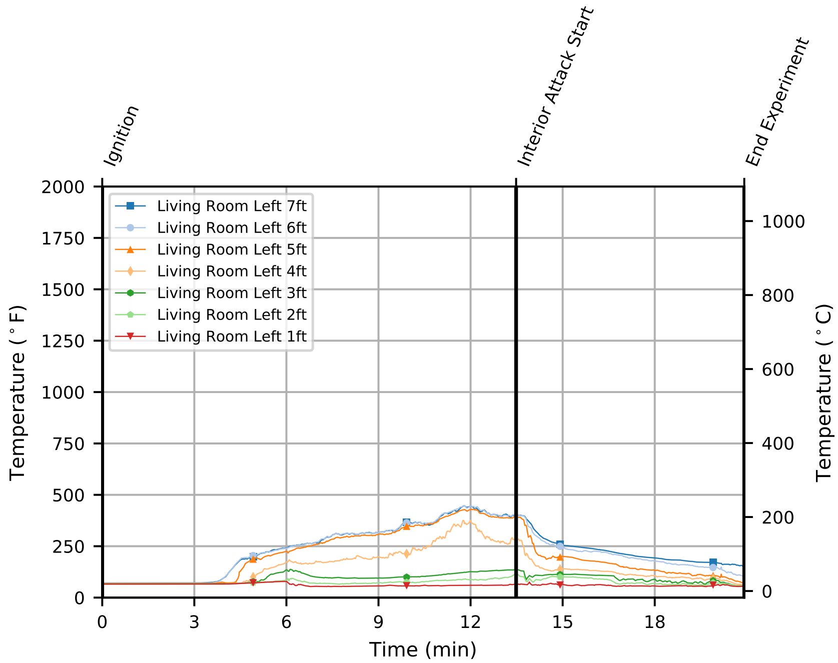


Figure E.425: Experiment 12 - Living Room Left Temps

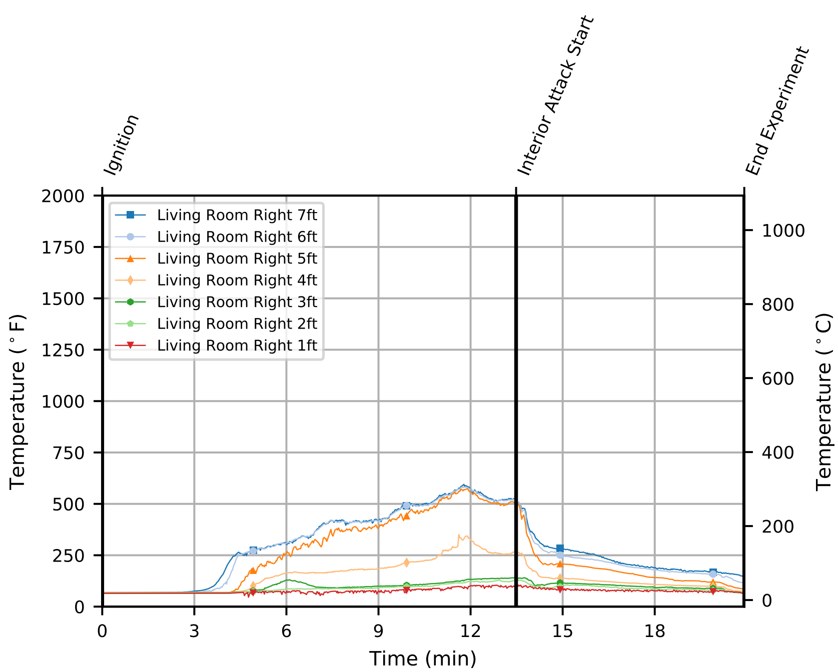


Figure E.426: Experiment 12 - Living Room Right Temps

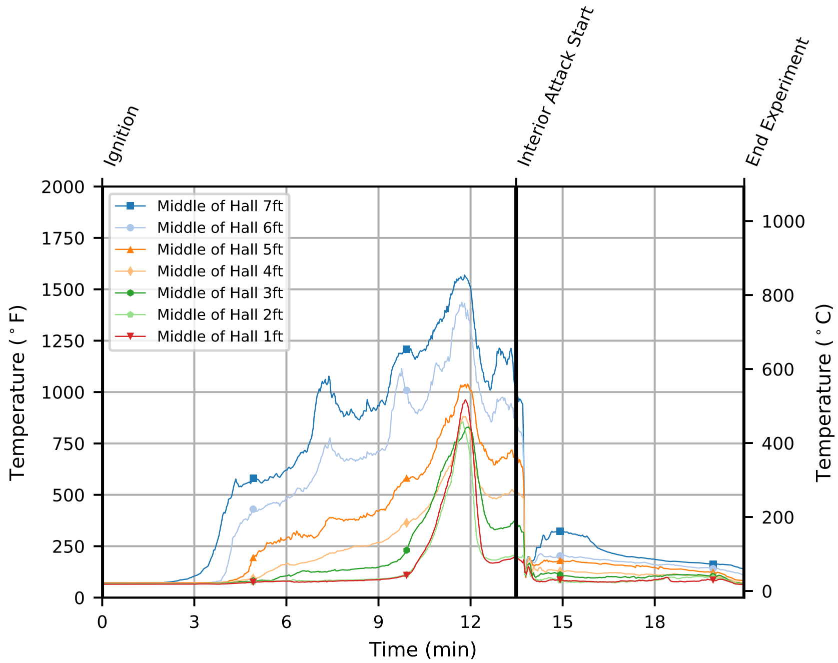


Figure E.427: Experiment 12 - Middle Hall Temps

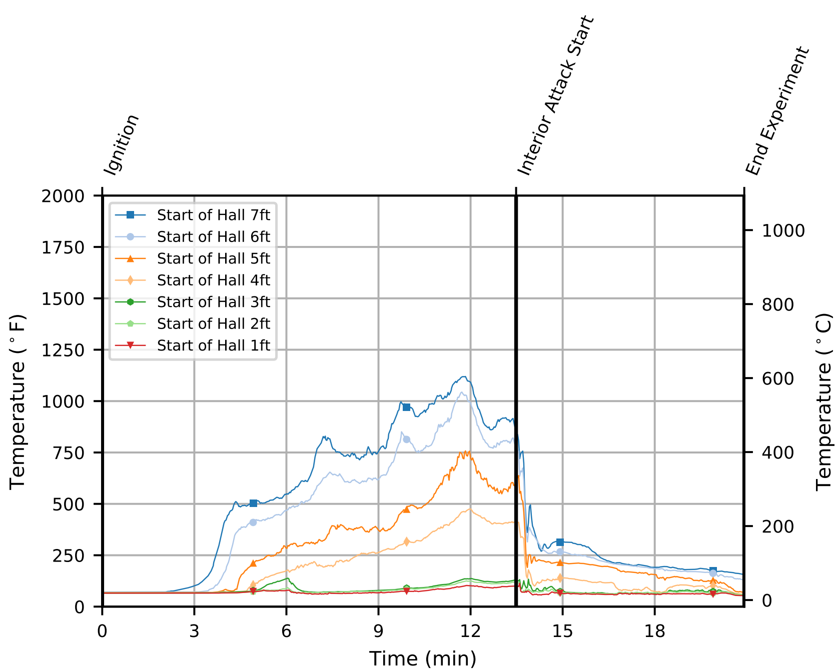


Figure E.428: Experiment 12 - Start Hall Temps

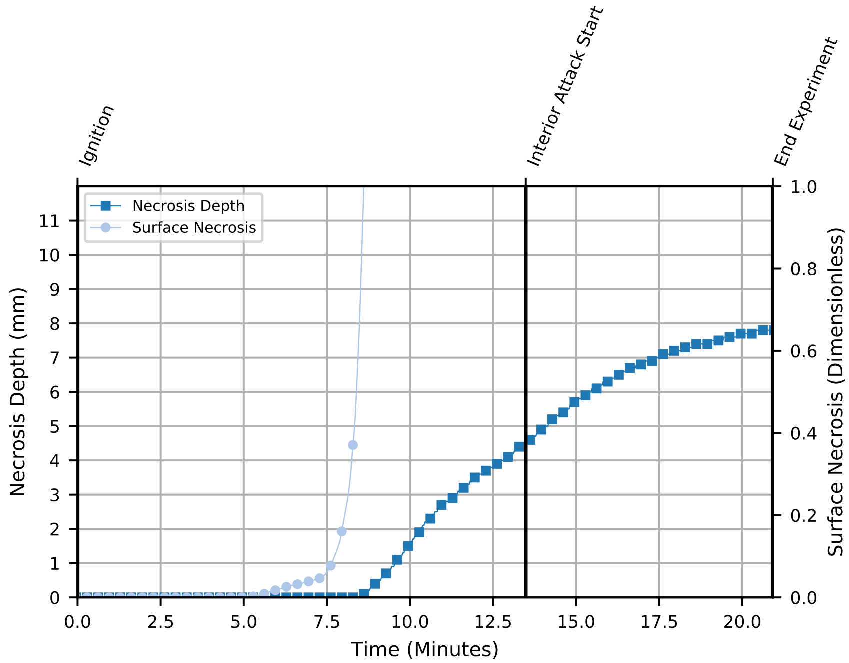


Figure E.429: Experiment 12 - Vic 1 Necrosis Depth

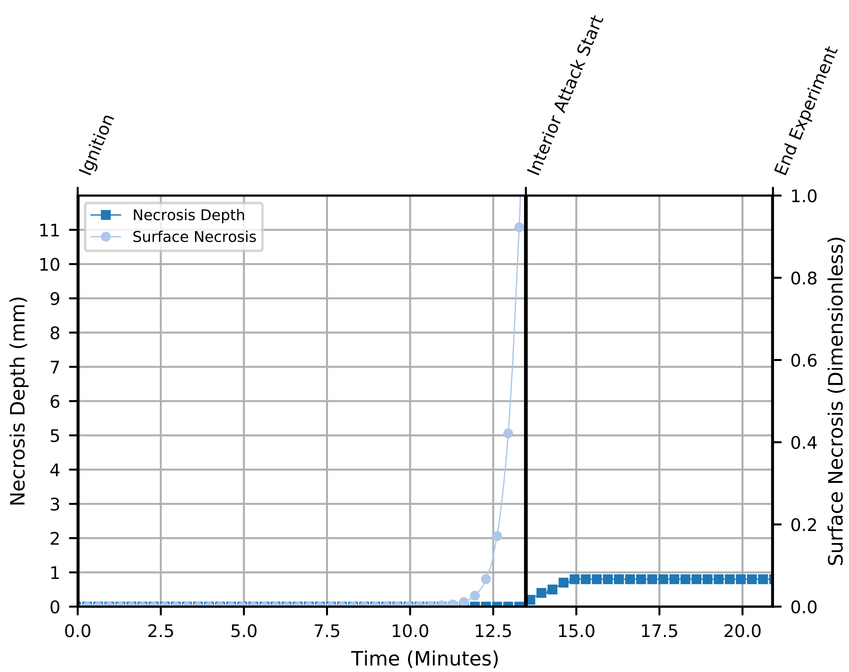


Figure E.430: Experiment 12 - Vic 3 Necrosis Depth

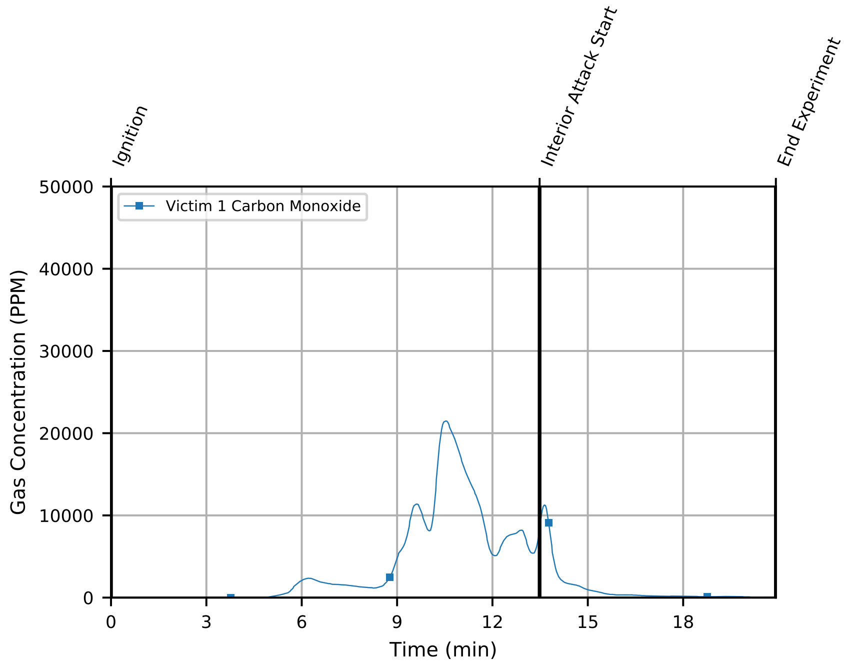


Figure E.431: Experiment 12 - Victim 1 Carbon Monoxide

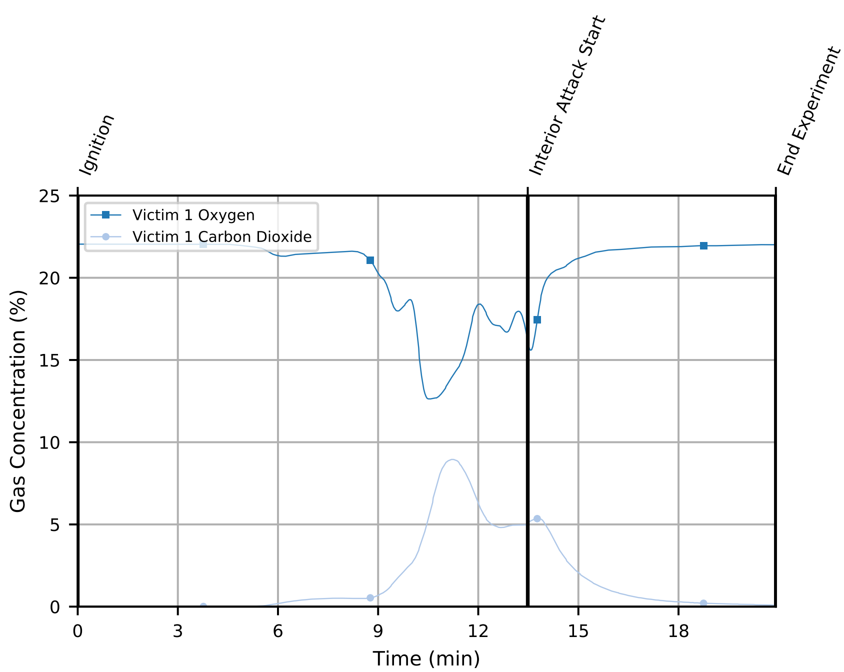


Figure E.432: Experiment 12 - Victim 1 Gas

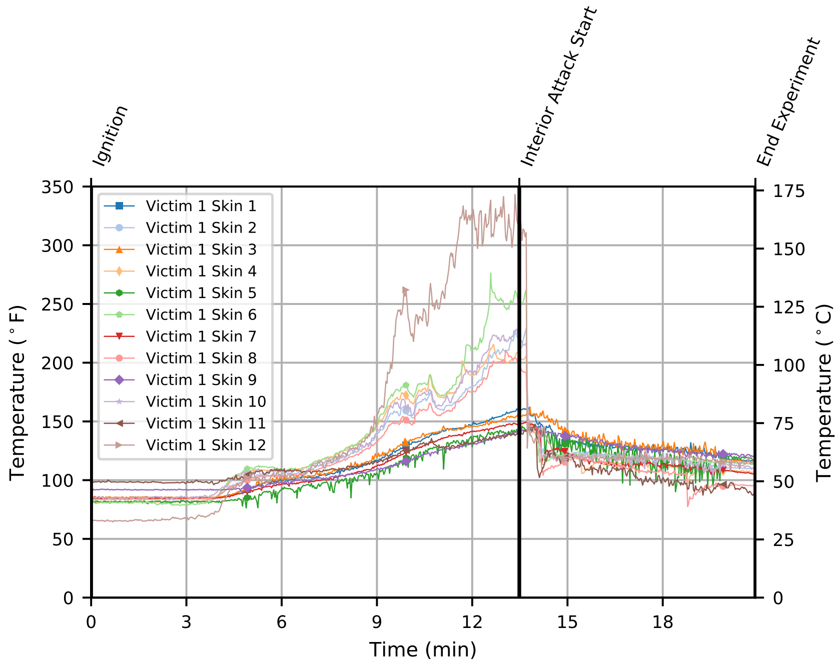


Figure E.433: Experiment 12 - Victim 1 Skin Temps

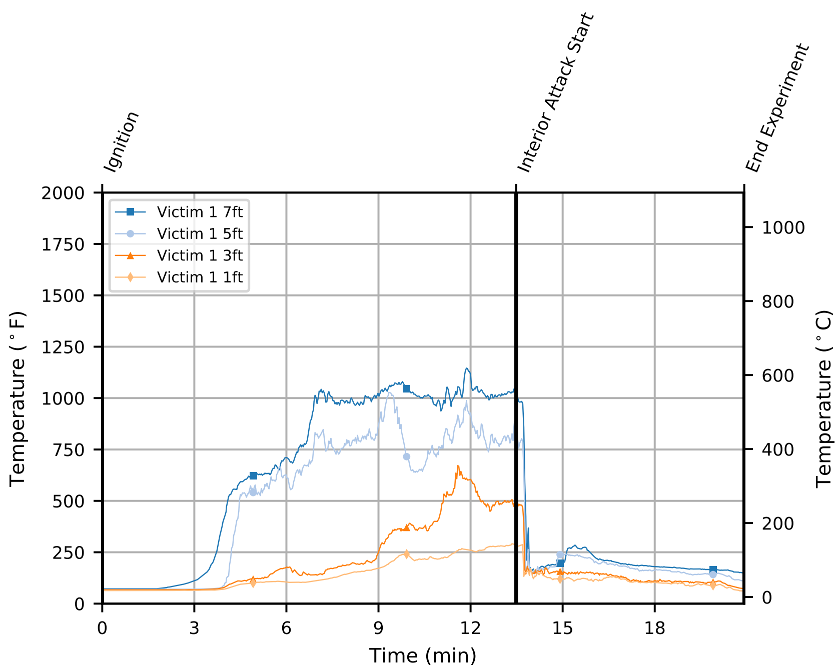


Figure E.434: Experiment 12 - Victim 1 Temps

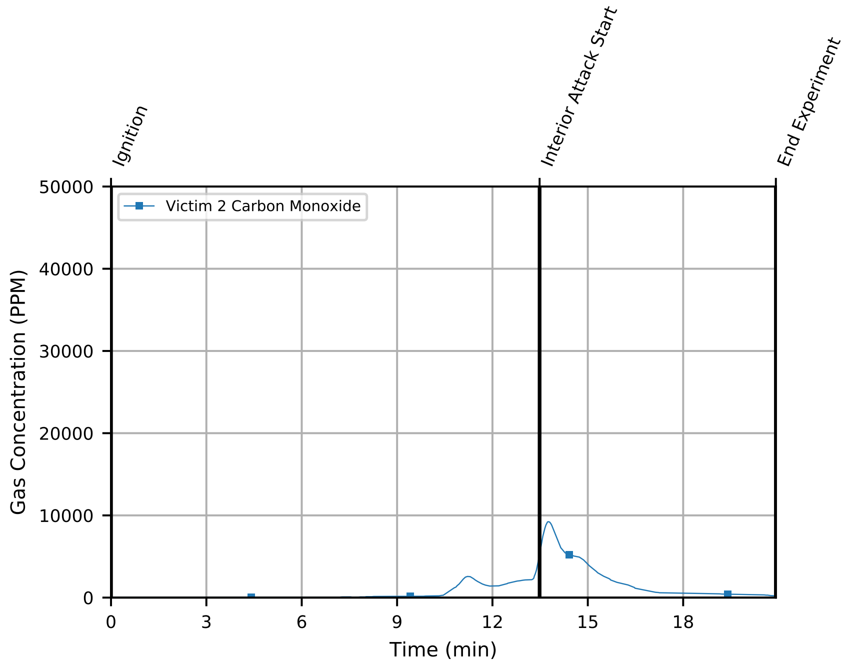


Figure E.435: Experiment 12 - Victim 2 Carbon Monoxide

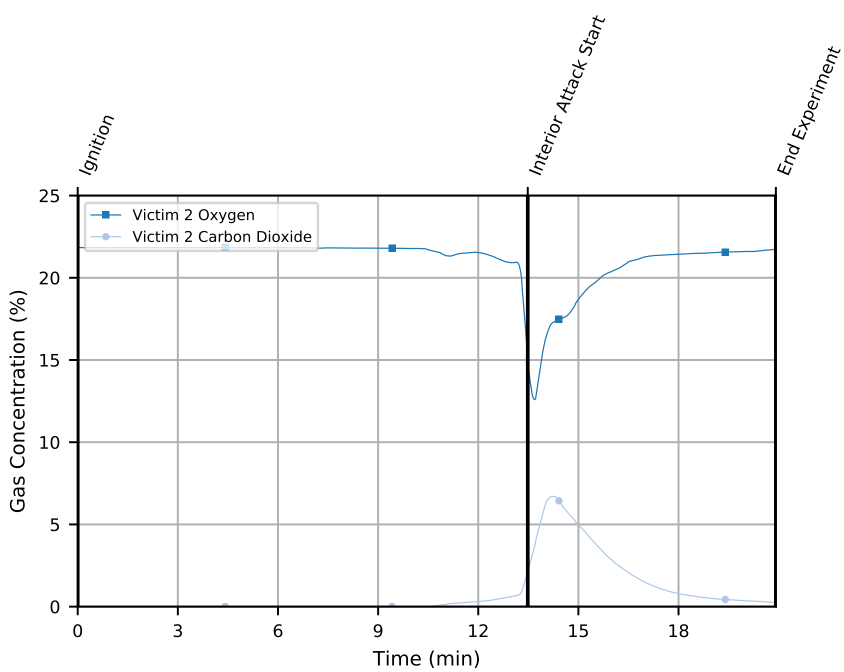


Figure E.436: Experiment 12 - Victim 2 Gas

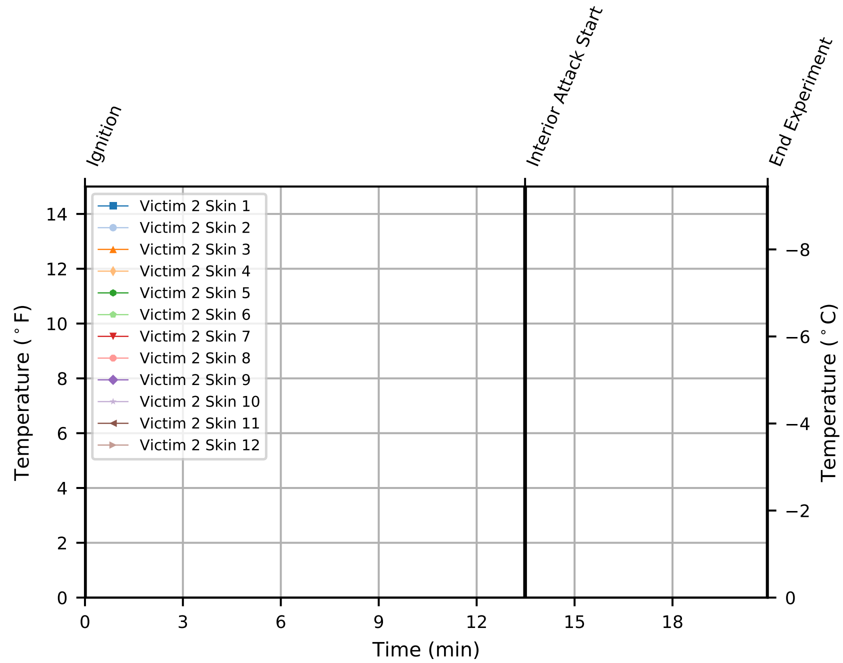


Figure E.437: Experiment 12 - Victim 2 Skin Temps

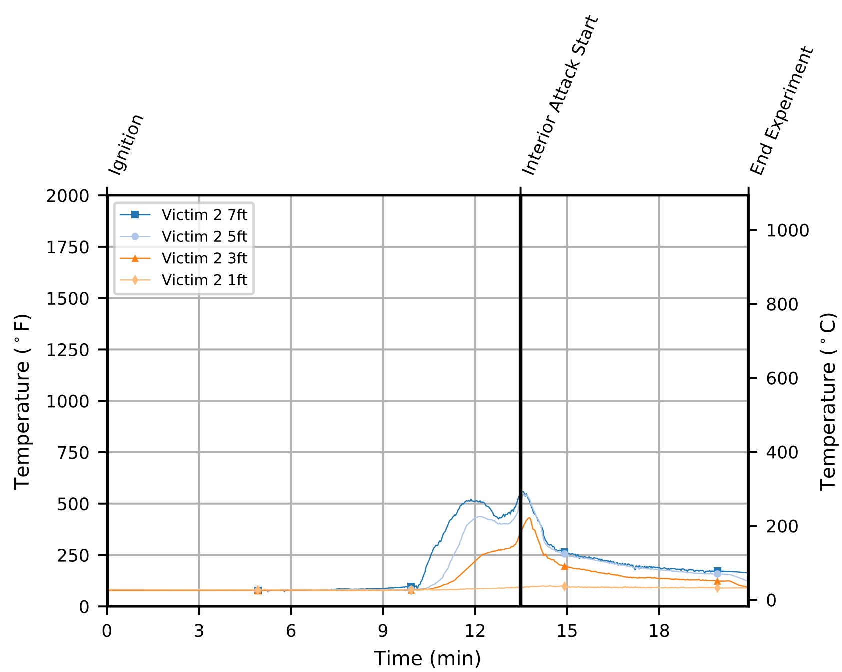


Figure E.438: Experiment 12 - Victim 2 Temps

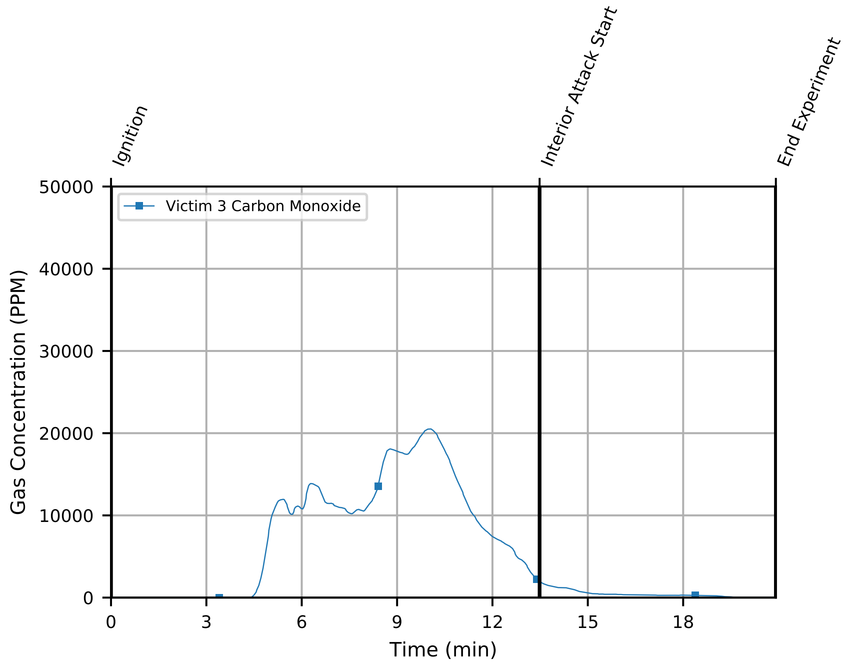


Figure E.439: Experiment 12 - Victim 3 Carbon Monoxide

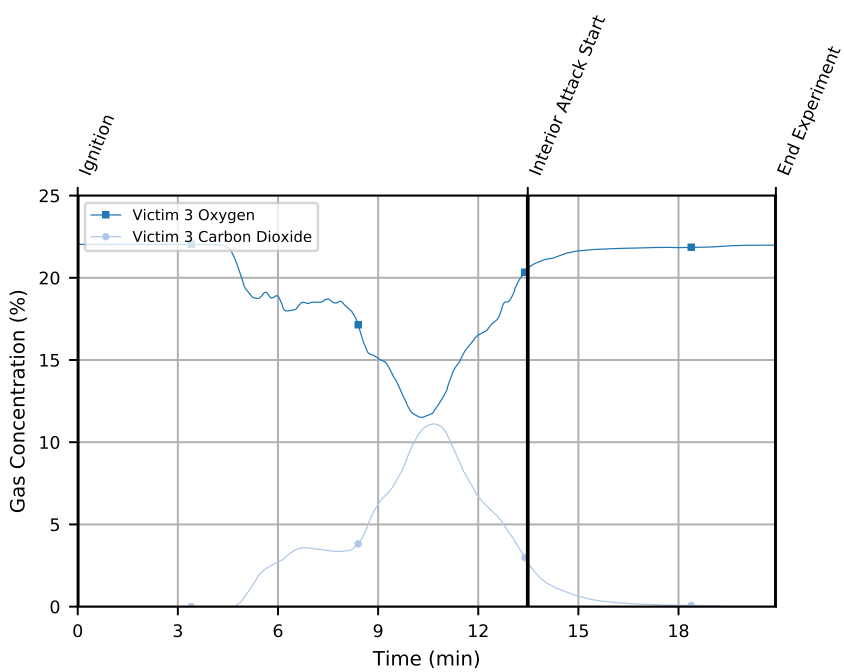


Figure E.440: Experiment 12 - Victim 3 Gas

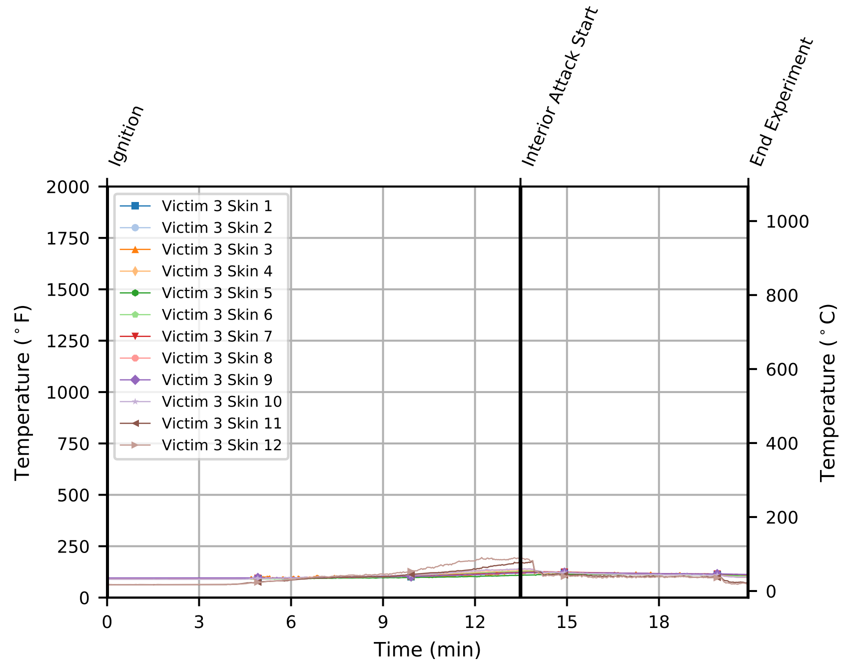


Figure E.441: Experiment 12 - Victim 3 Skin Temps

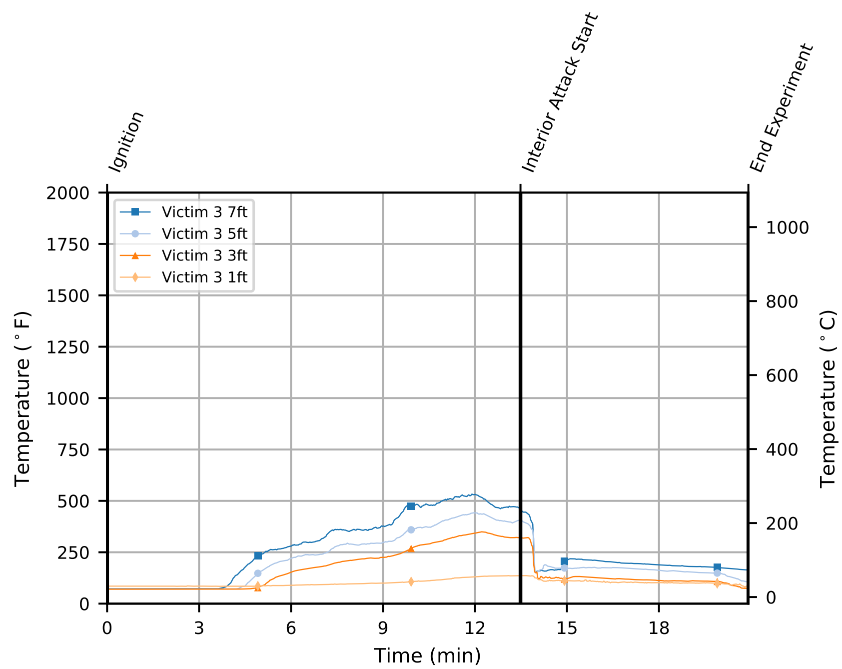


Figure E.442: Experiment 12 - Victim 3 Temps

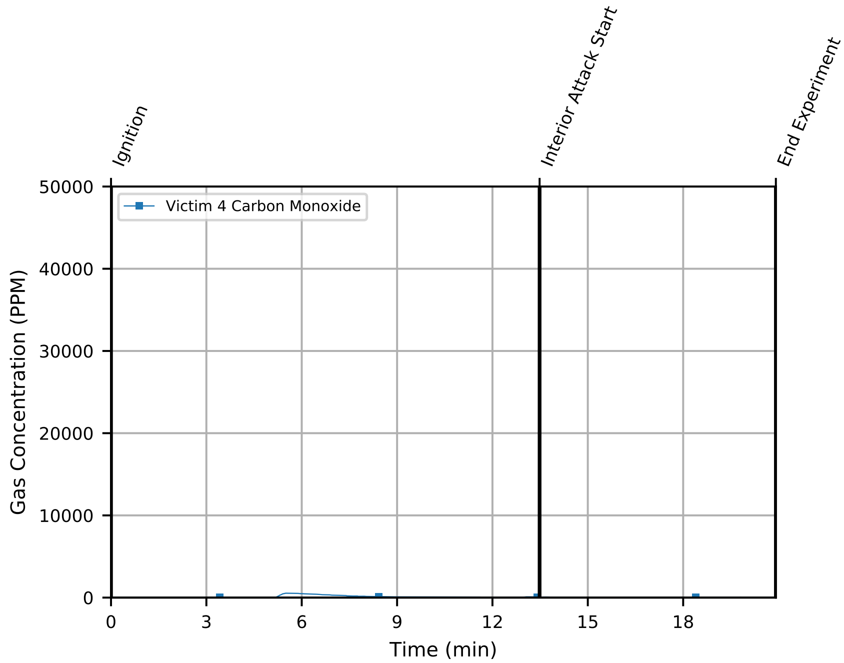


Figure E.443: Experiment 12 - Victim 4 Carbon Monoxide

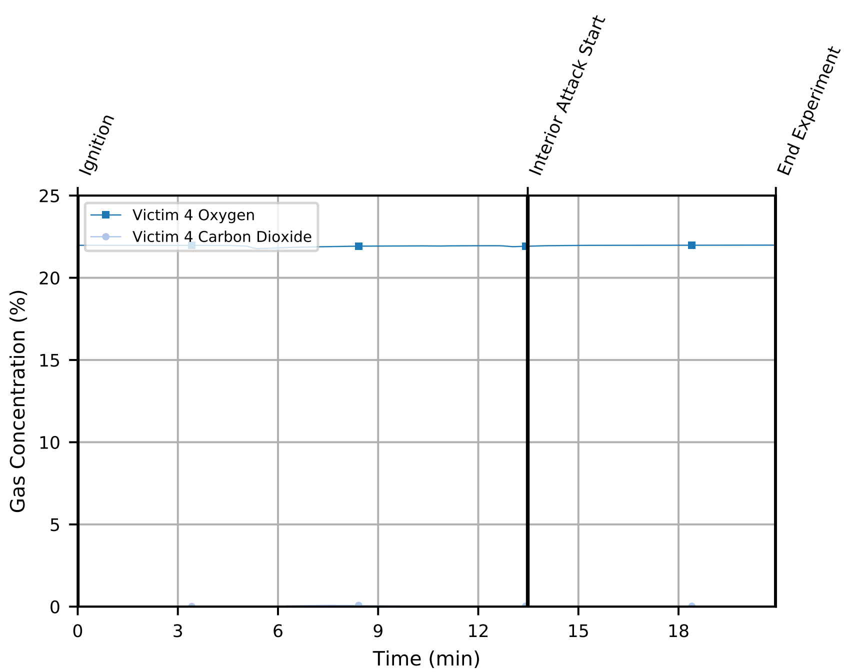


Figure E.444: Experiment 12 - Victim 4 Gas

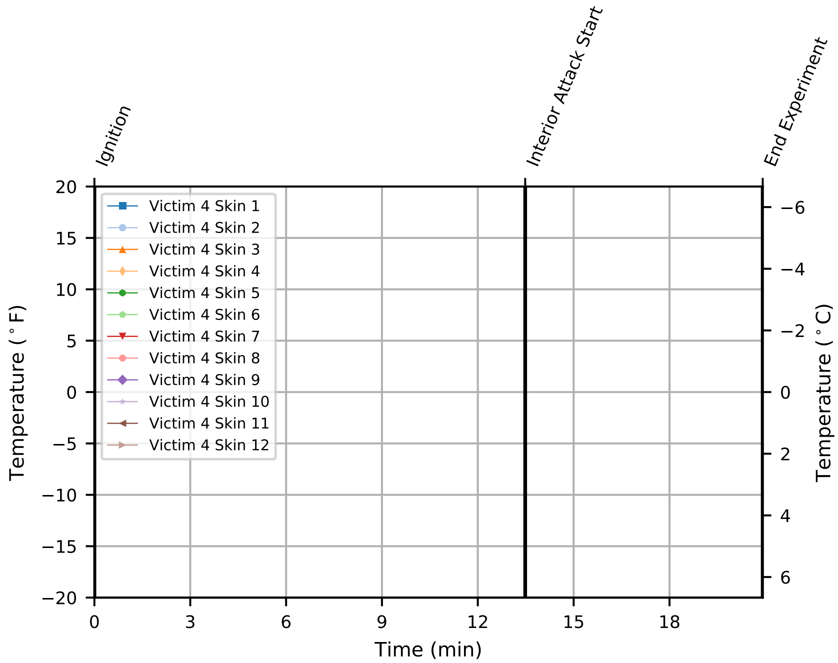


Figure E.445: Experiment 12 - Victim 4 Skin Temps

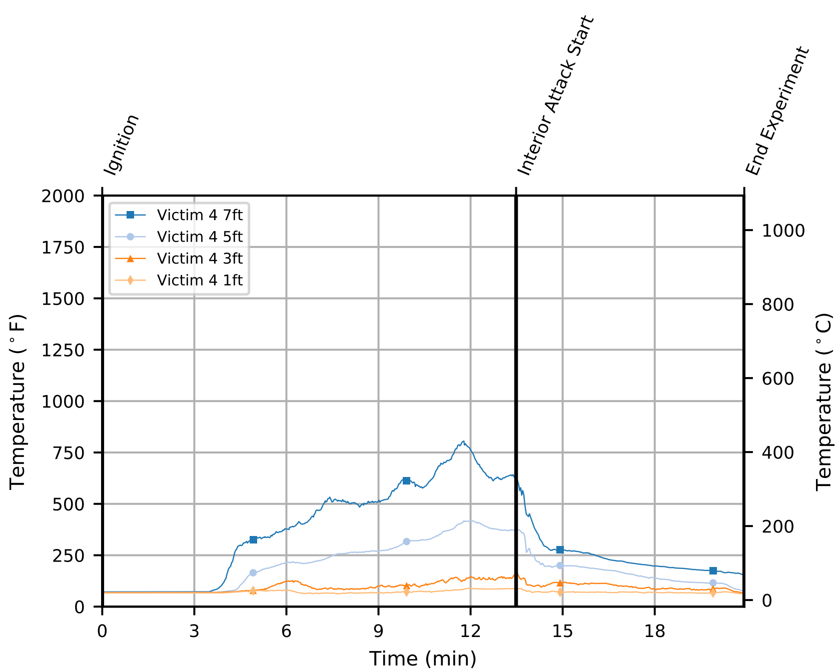


Figure E.446: Experiment 12 - Victim 4 Temps

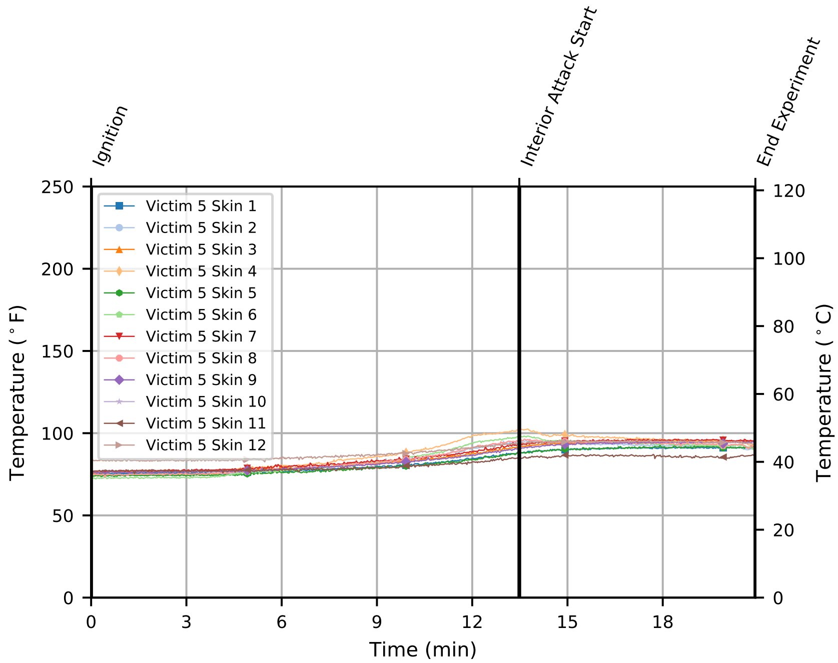


Figure E.447: Experiment 12 - Victim 5 Skin Temps

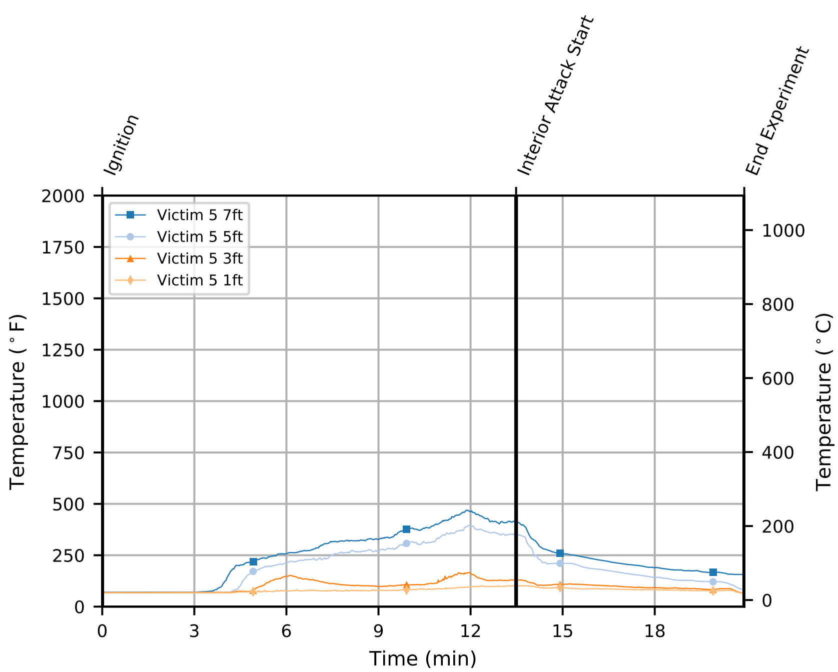


Figure E.448: Experiment 12 - Victim 5 Temps

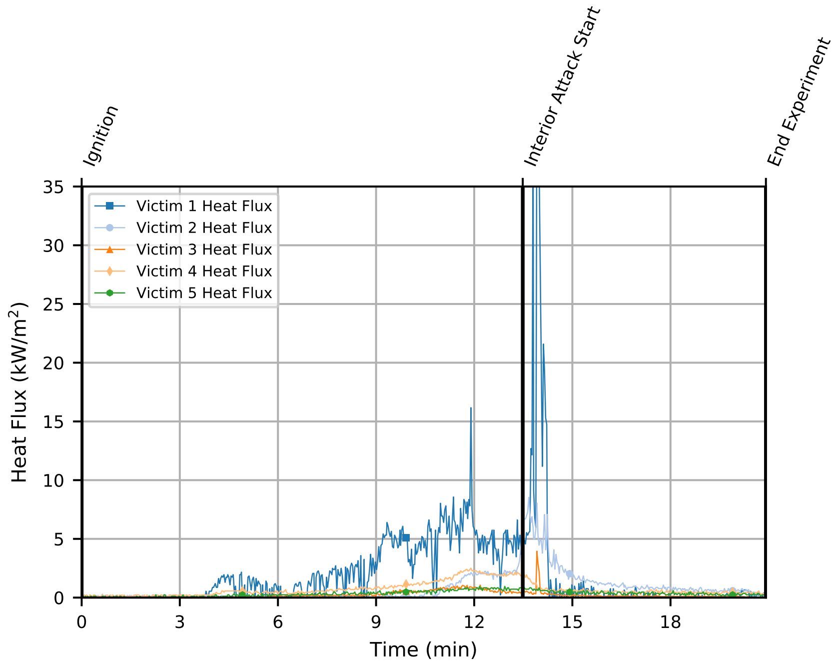


Figure E.449: Experiment 12 - Victim Heat Flux

E.13 Experiment 13 Data

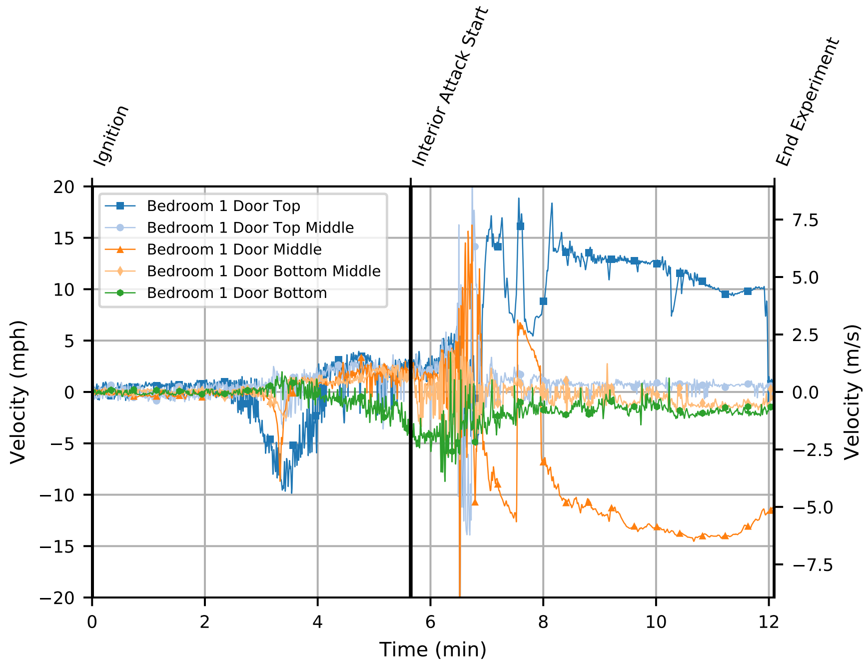


Figure E.450: Experiment 13 - Bedroom 1 Door

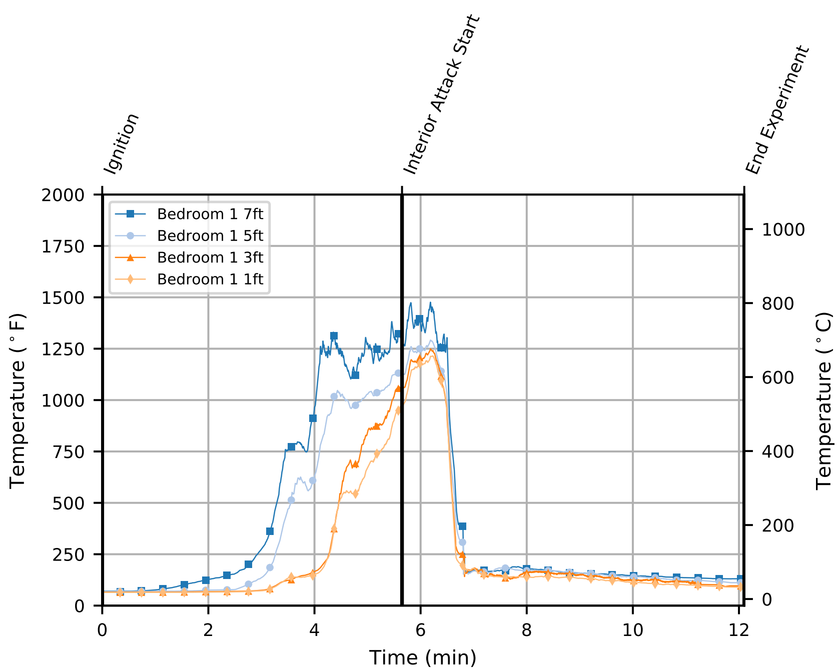


Figure E.451: Experiment 13 - Bedroom 1 Temps

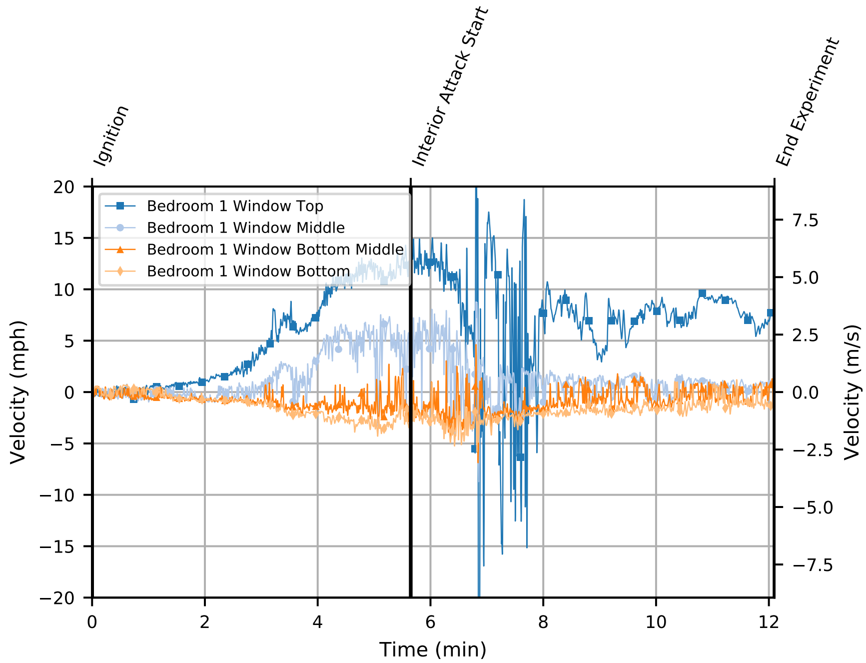


Figure E.452: Experiment 13 - Bedroom 1 Window

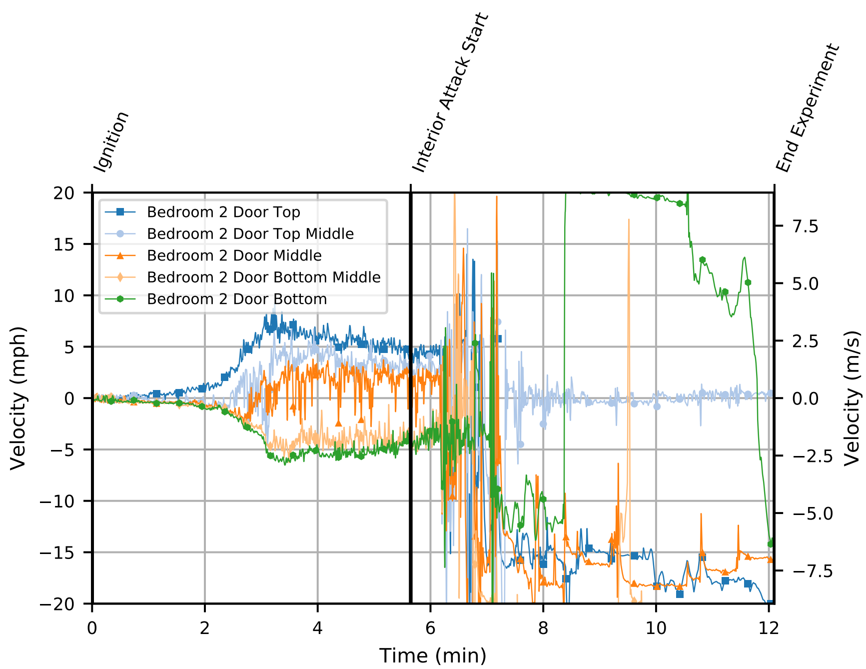


Figure E.453: Experiment 13 - Bedroom 2 Door

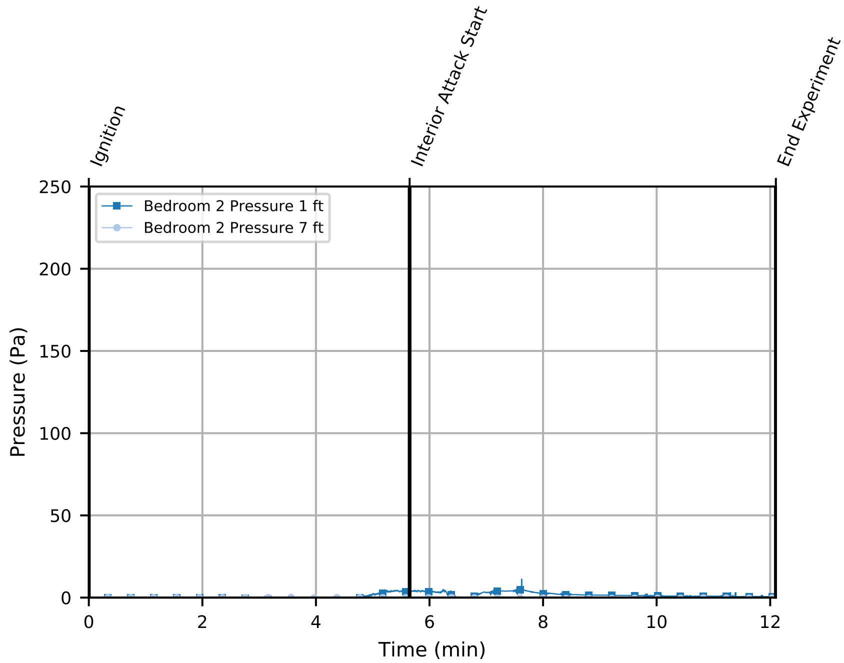


Figure E.454: Experiment 13 - Bedroom 2 Pressure

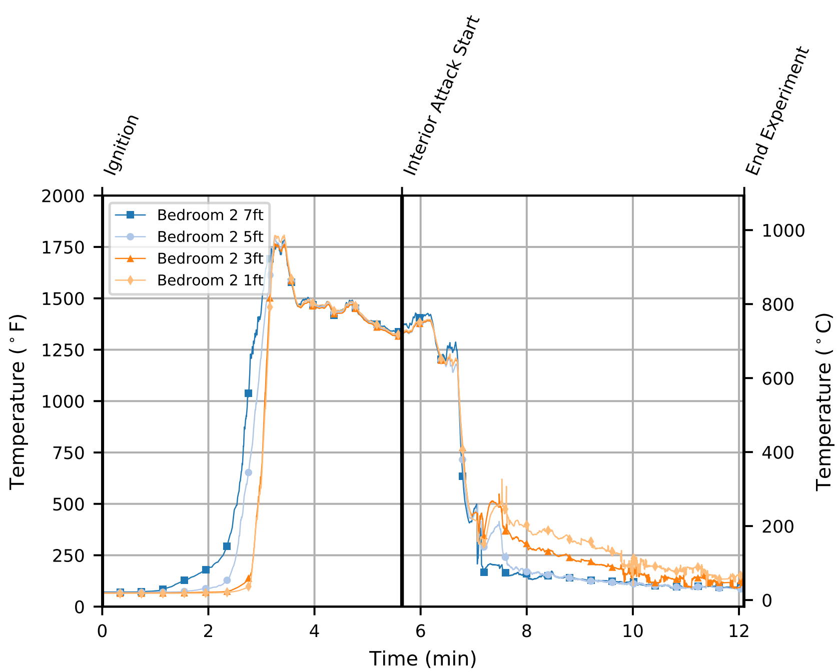


Figure E.455: Experiment 13 - Bedroom 2 Temps

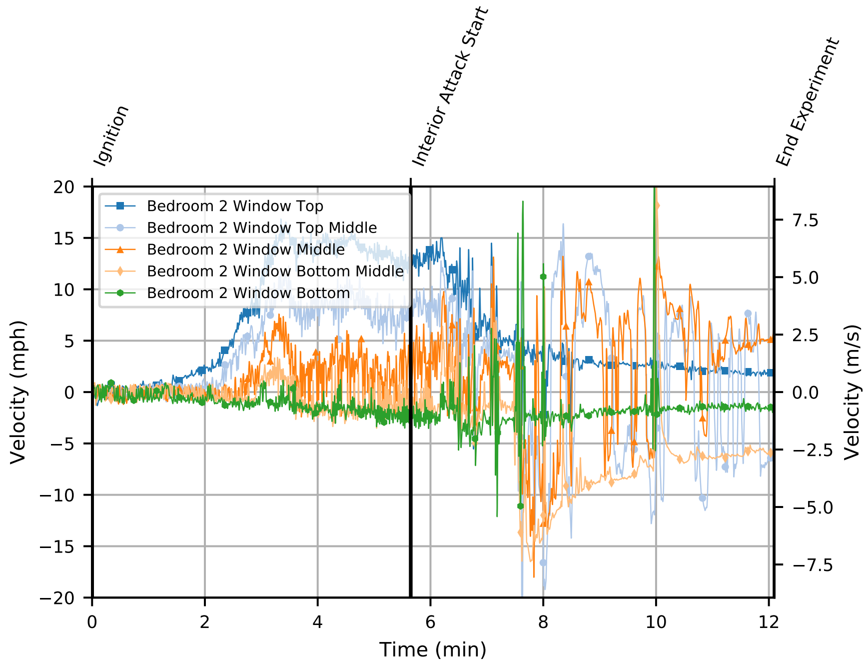


Figure E.456: Experiment 13 - Bedroom 2 Window

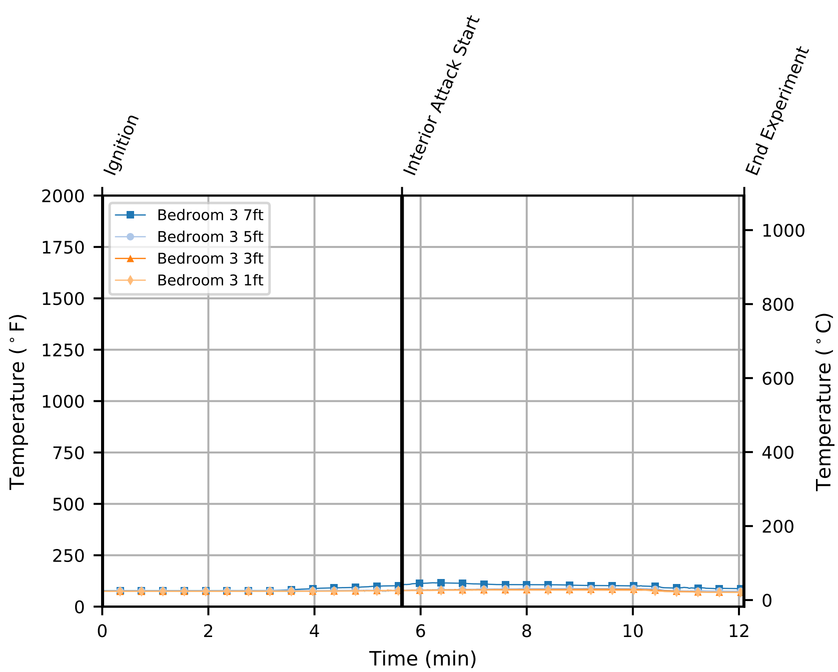


Figure E.457: Experiment 13 - Bedroom 3 Temps

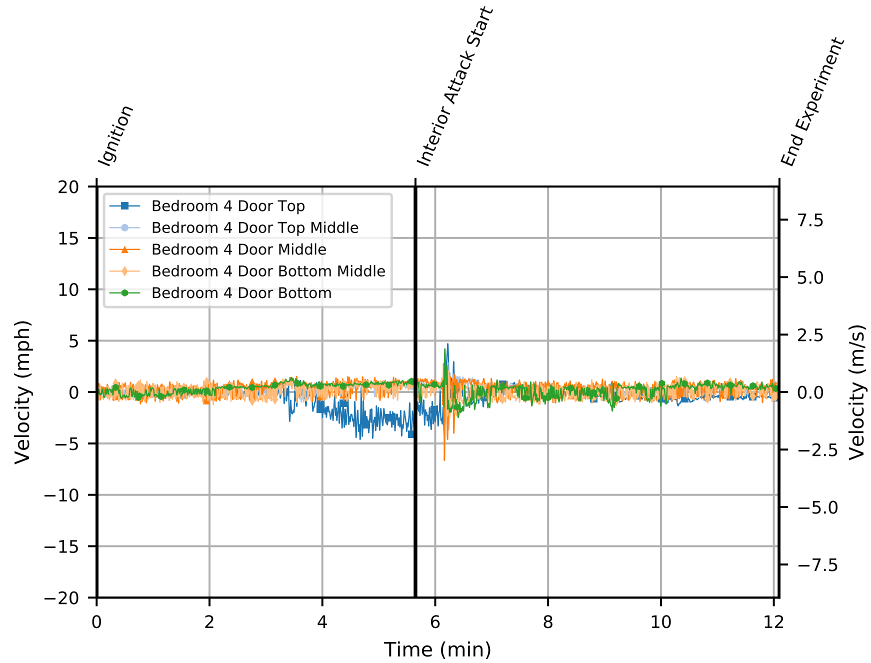


Figure E.458: Experiment 13 - Bedroom 4 Door

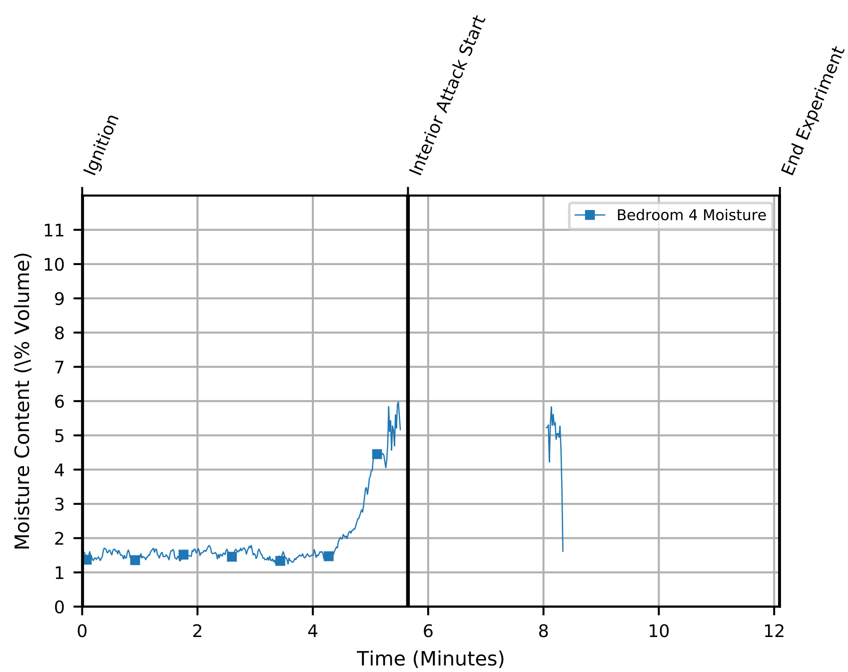


Figure E.459: Experiment 13 - Bedroom 4 Moisture

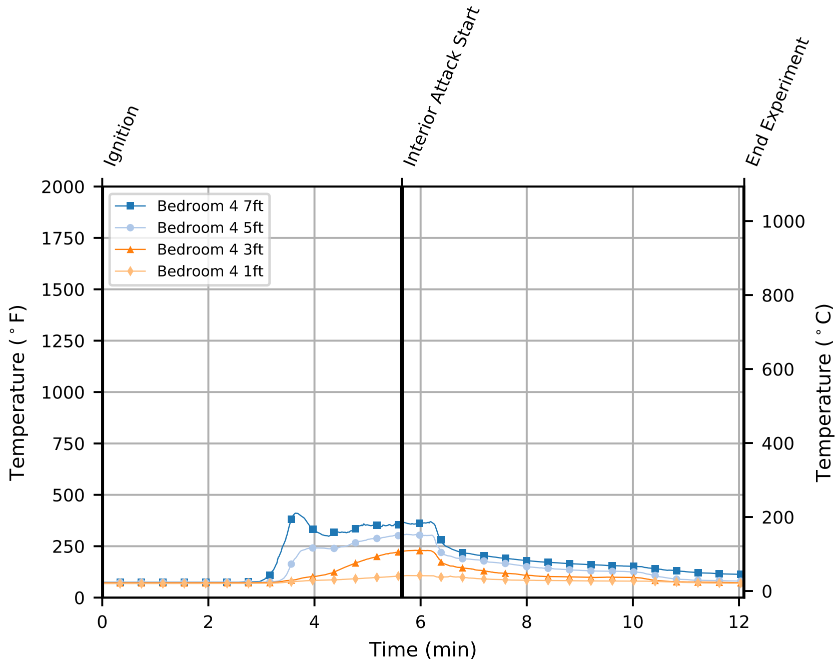


Figure E.460: Experiment 13 - Bedroom 4 Temps

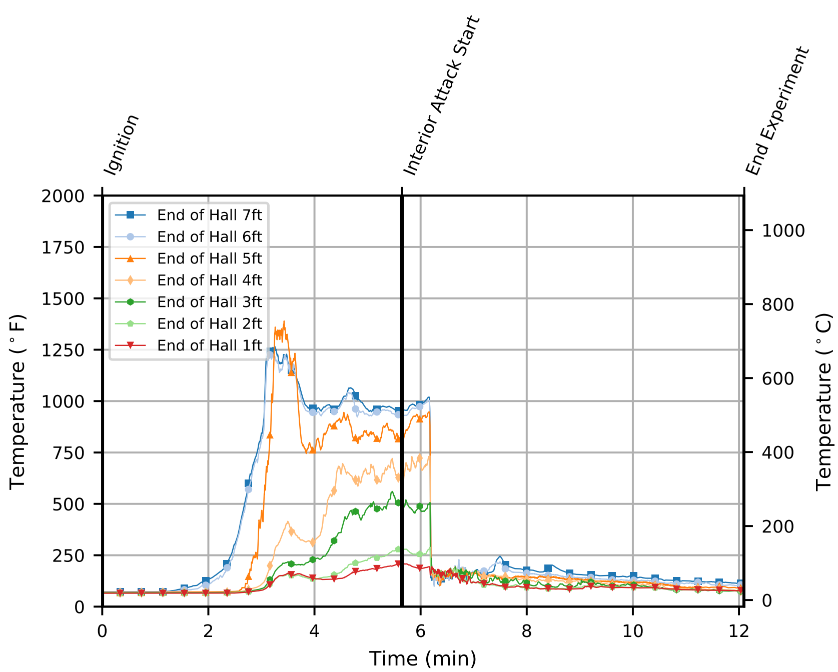


Figure E.461: Experiment 13 - End Hall Temps

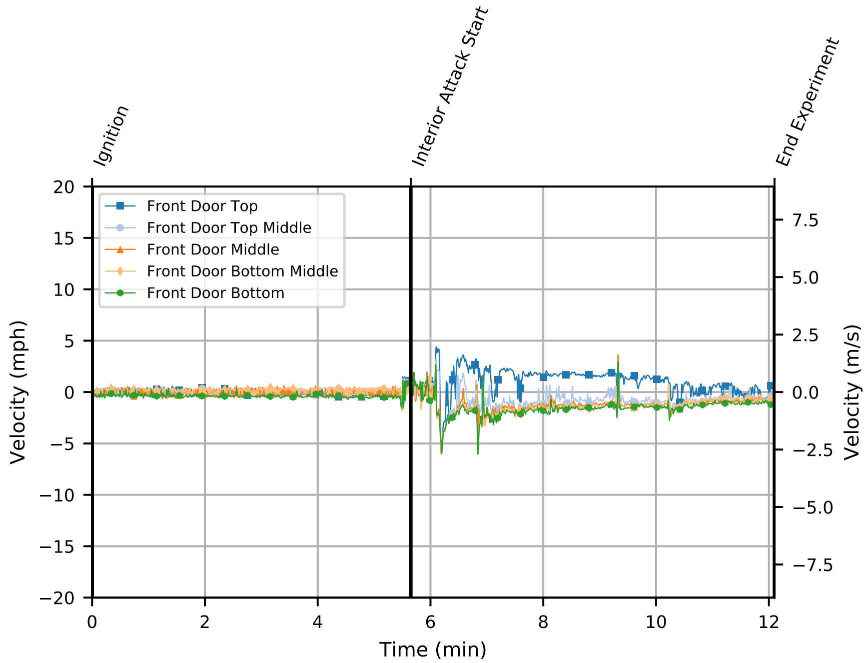


Figure E.462: Experiment 13 - Front Door Flow

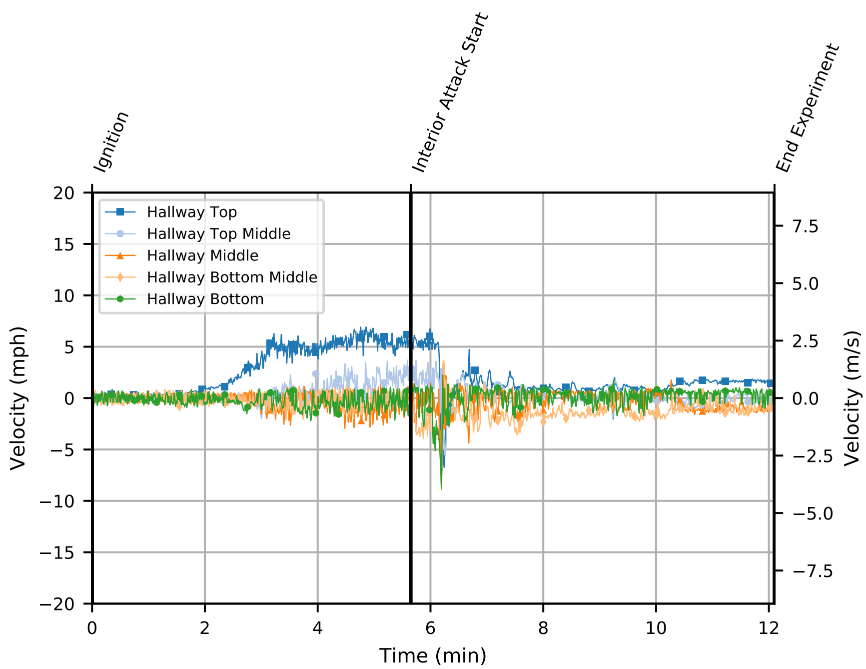


Figure E.463: Experiment 13 - Hallway Flow

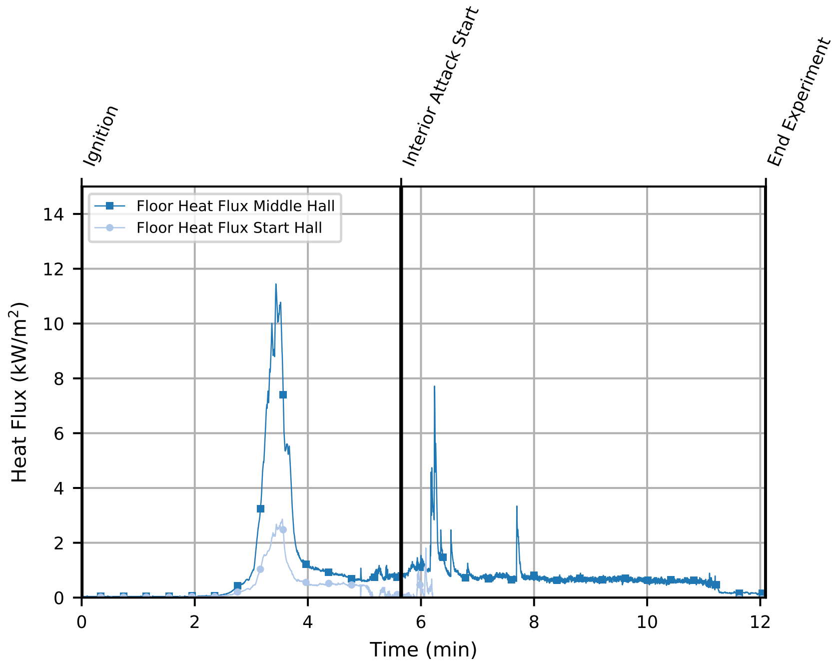


Figure E.464: Experiment 13 - Heat Flux Floor

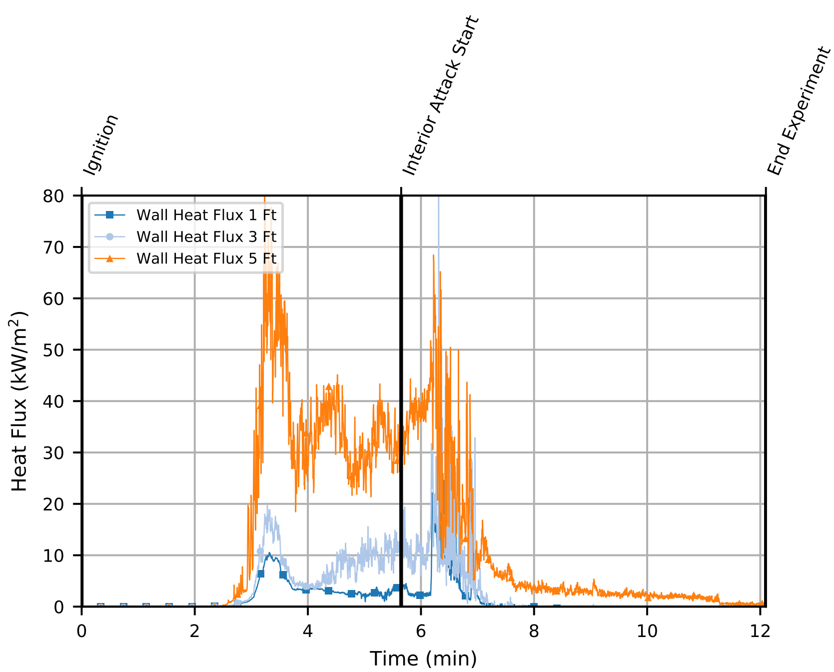


Figure E.465: Experiment 13 - Heat Flux Wall

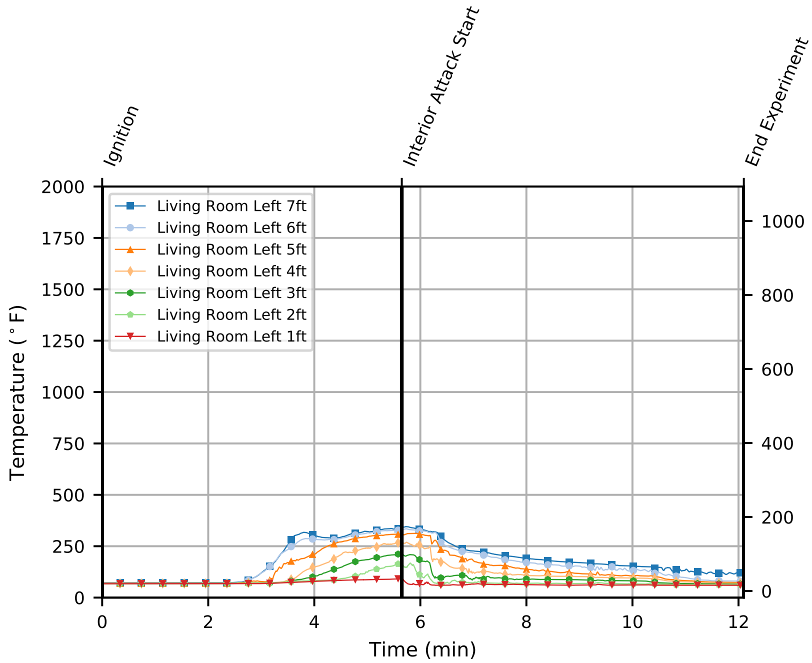


Figure E.466: Experiment 13 - Living Room Left Temps

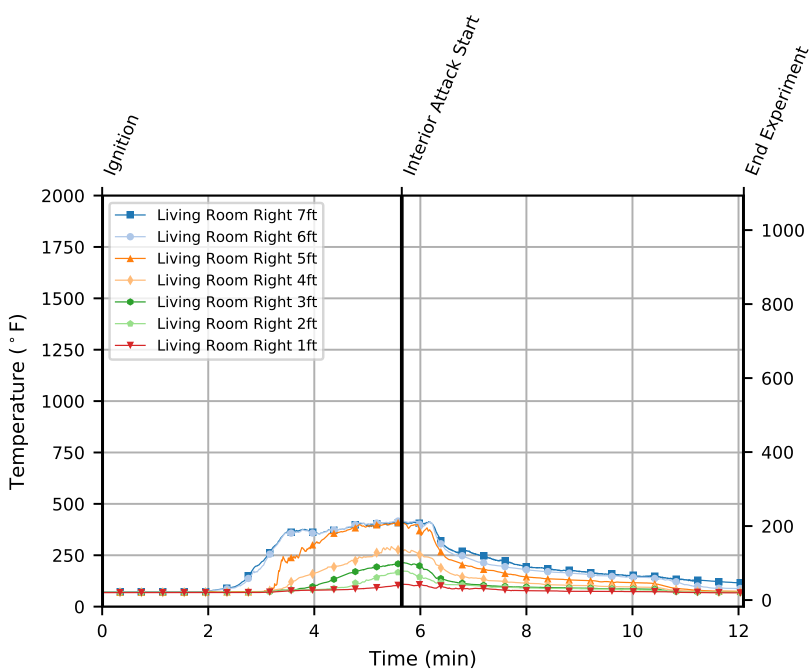


Figure E.467: Experiment 13 - Living Room Right Temps

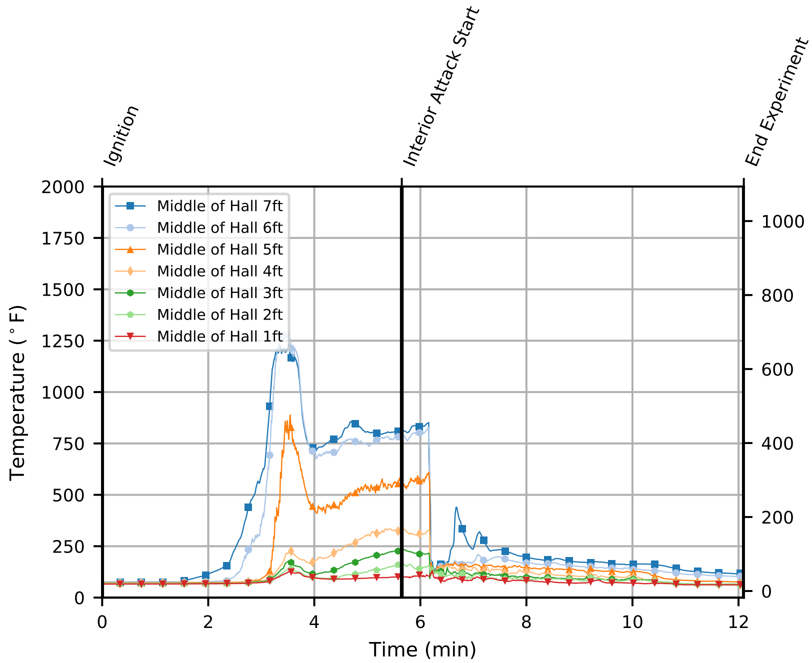


Figure E.468: Experiment 13 - Middle Hall Temps

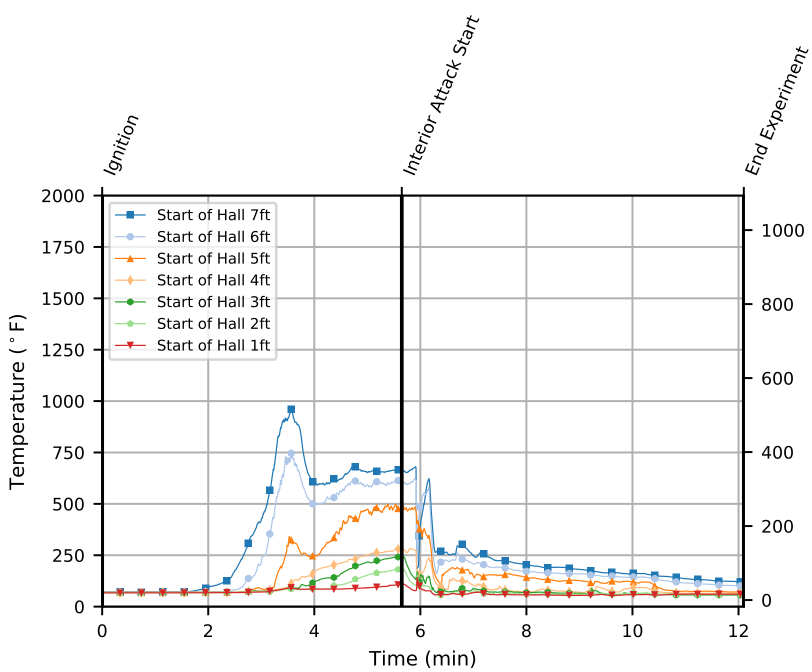


Figure E.469: Experiment 13 - Start Hall Temps

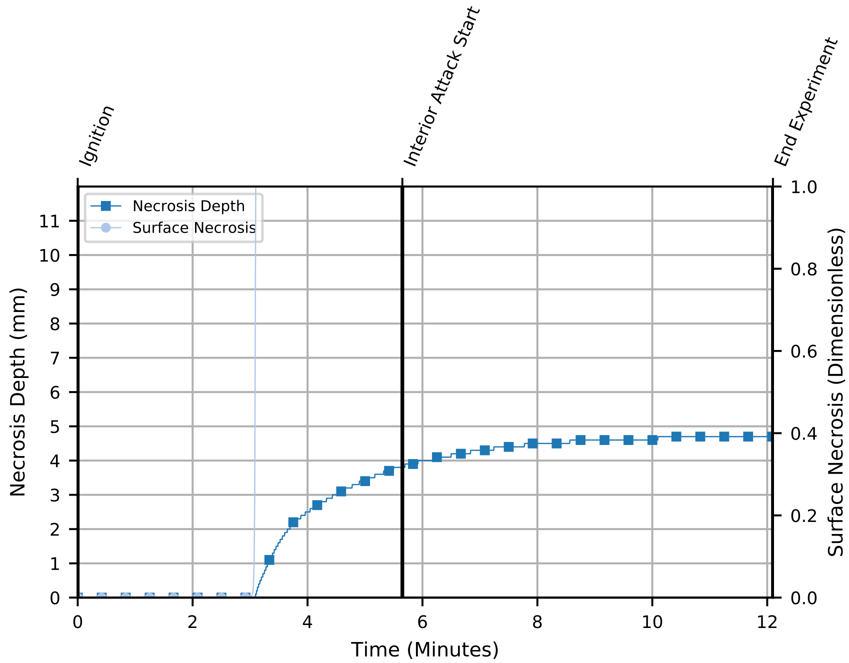


Figure E.470: Experiment 13 - Vic 1 Necrosis Depth

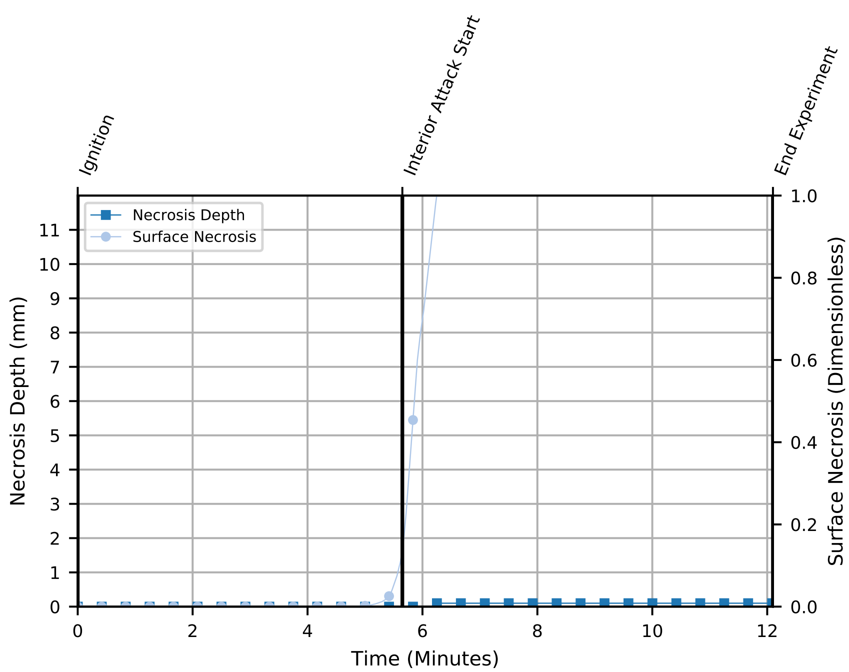


Figure E.471: Experiment 13 - Vic 3 Necrosis Depth

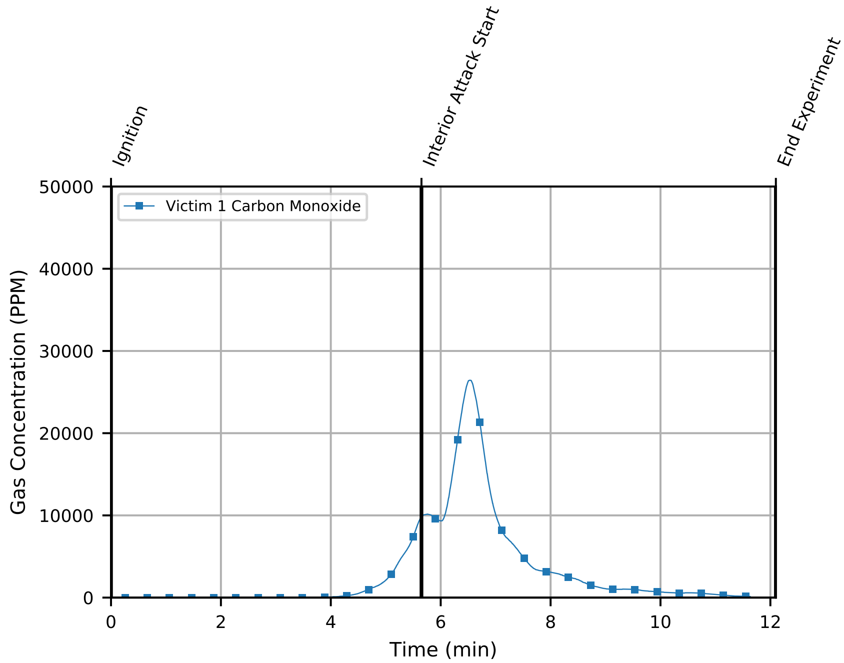


Figure E.472: Experiment 13 - Victim 1 Carbon Monoxide

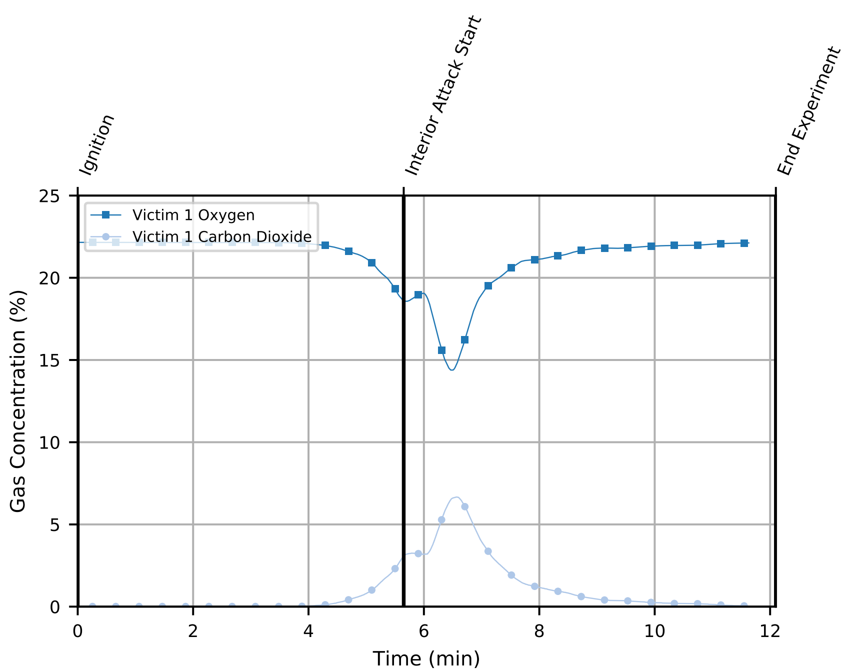


Figure E.473: Experiment 13 - Victim 1 Gas

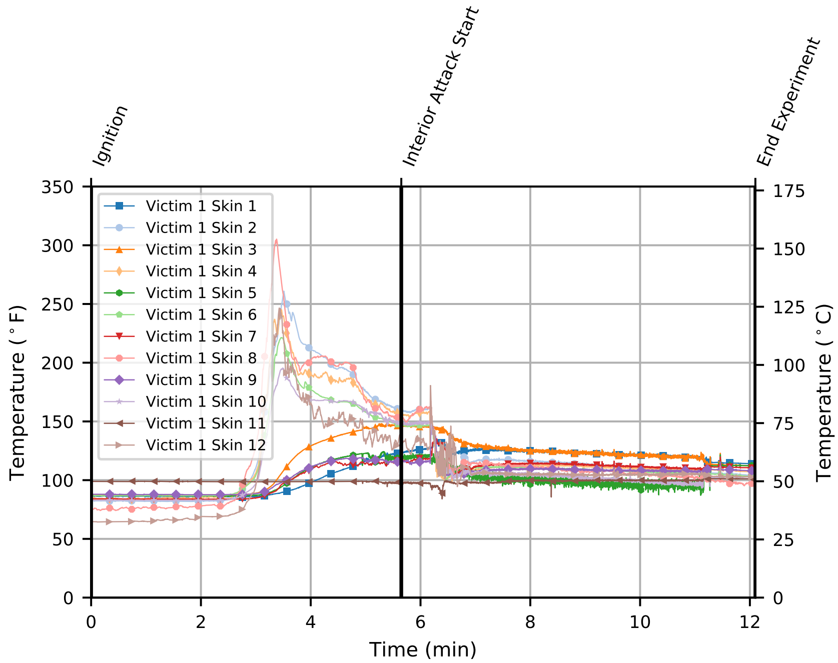


Figure E.474: Experiment 13 - Victim 1 Skin Temps

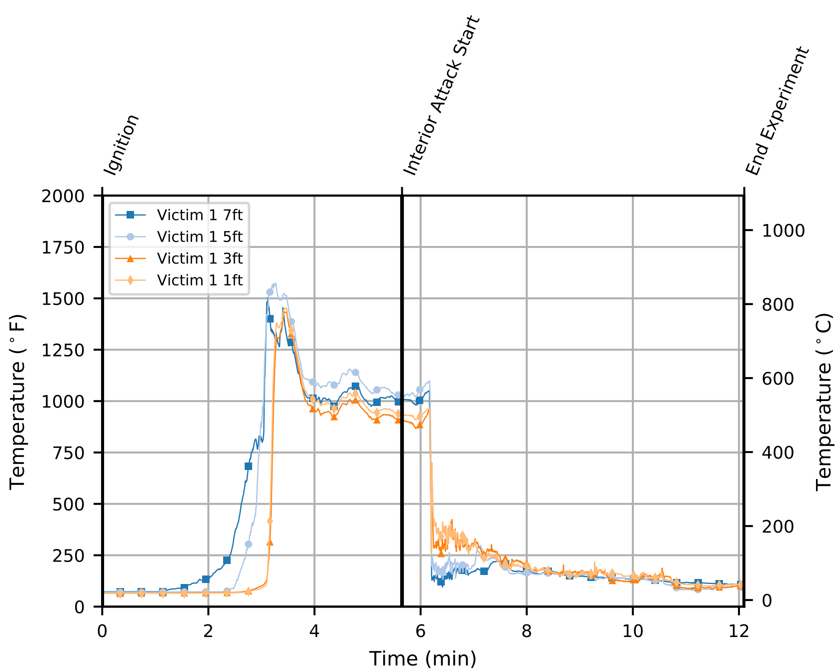


Figure E.475: Experiment 13 - Victim 1 Temps

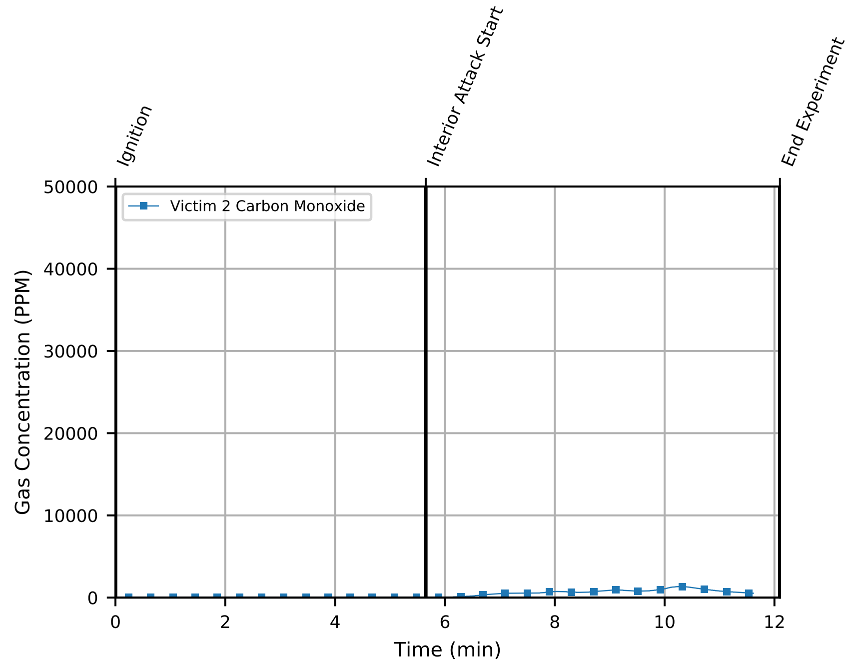


Figure E.476: Experiment 13 - Victim 2 Carbon Monoxide

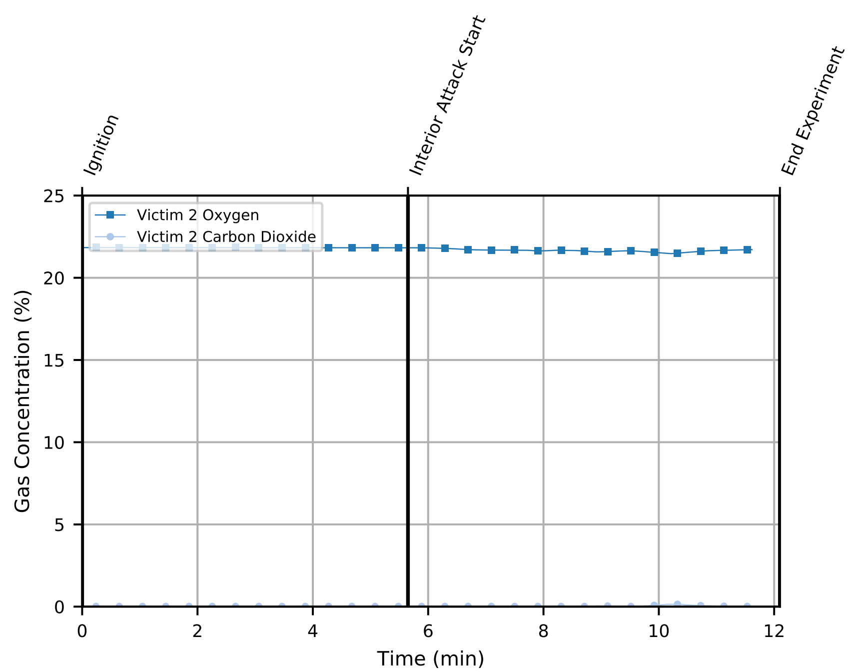


Figure E.477: Experiment 13 - Victim 2 Gas

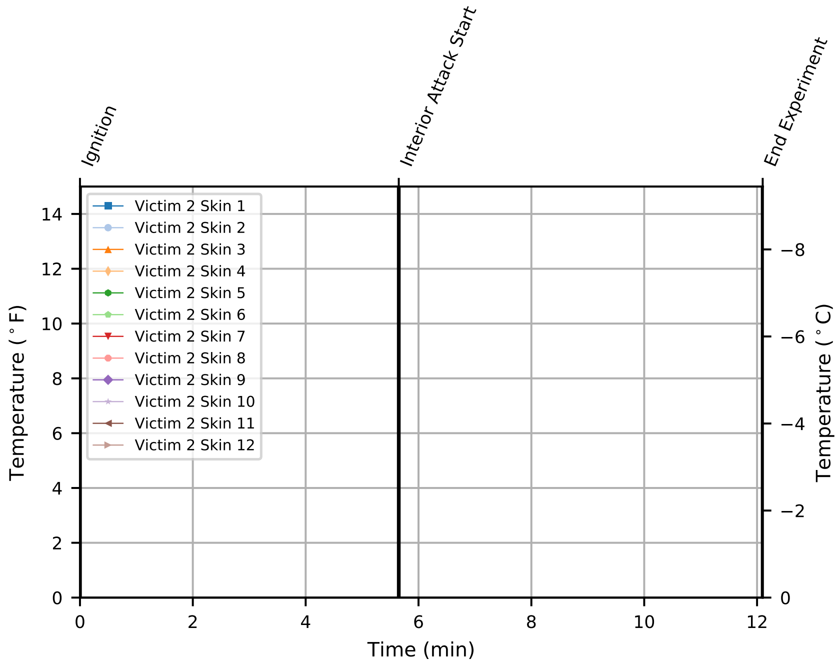


Figure E.478: Experiment 13 - Victim 2 Skin Temps

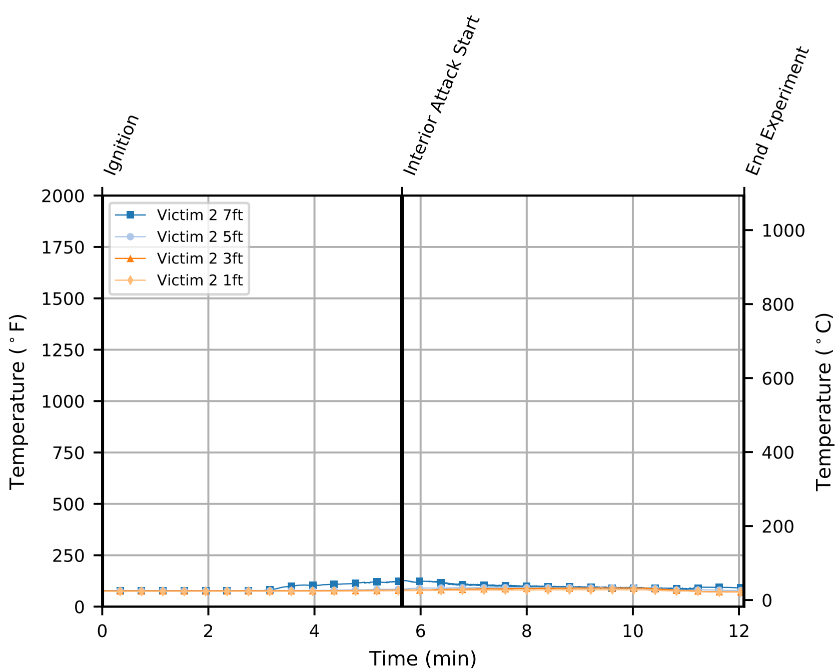


Figure E.479: Experiment 13 - Victim 2 Temps

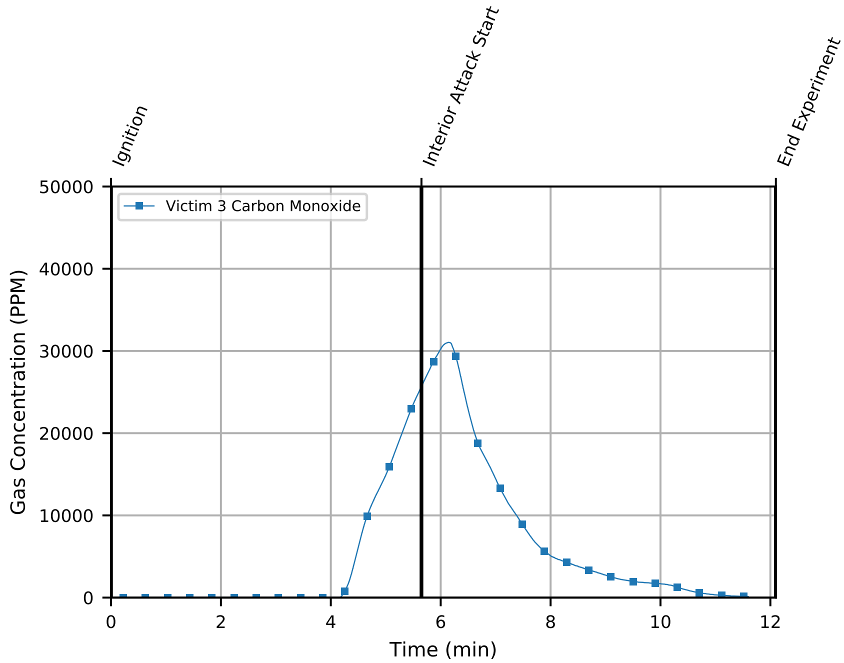


Figure E.480: Experiment 13 - Victim 3 Carbon Monoxide

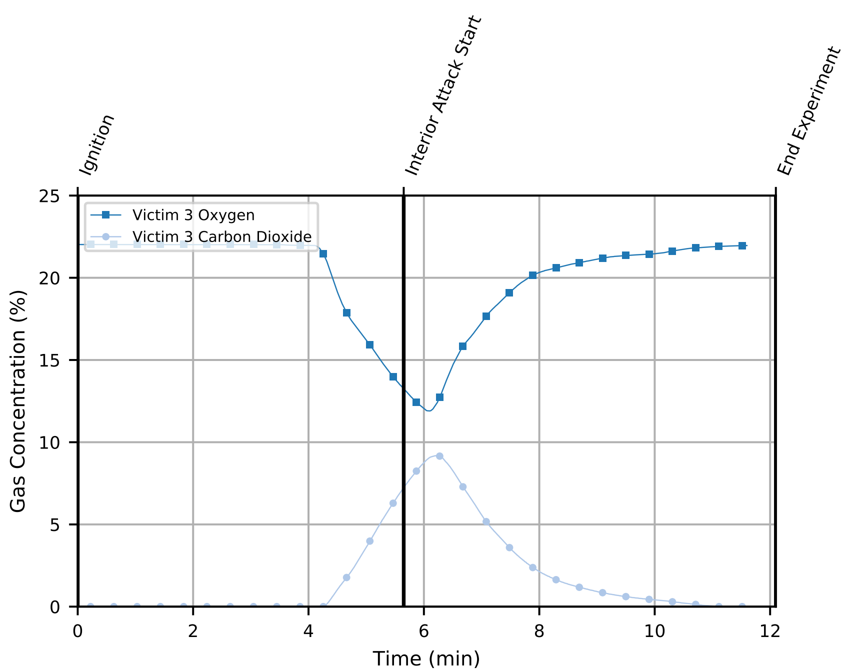


Figure E.481: Experiment 13 - Victim 3 Gas

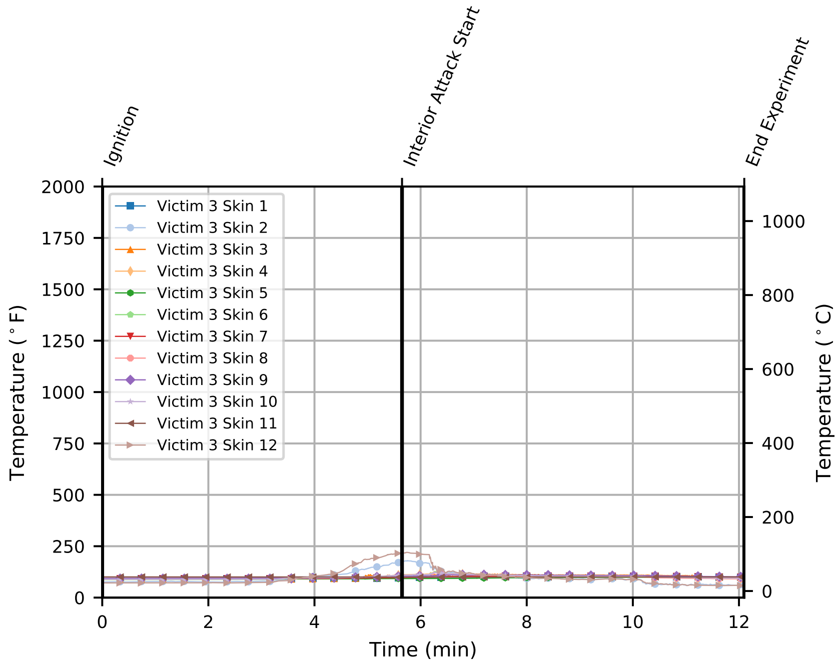


Figure E.482: Experiment 13 - Victim 3 Skin Temps

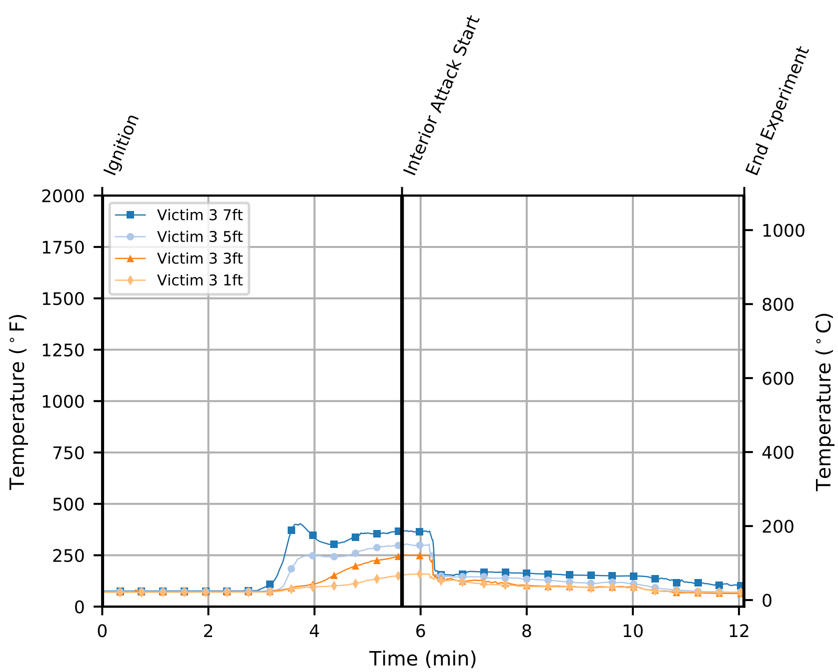


Figure E.483: Experiment 13 - Victim 3 Temps

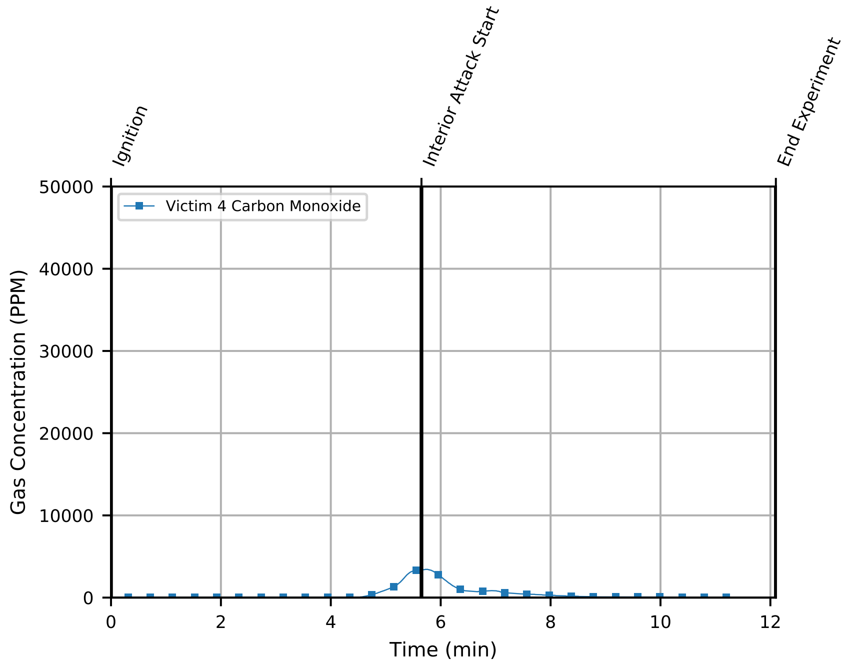


Figure E.484: Experiment 13 - Victim 4 Carbon Monoxide

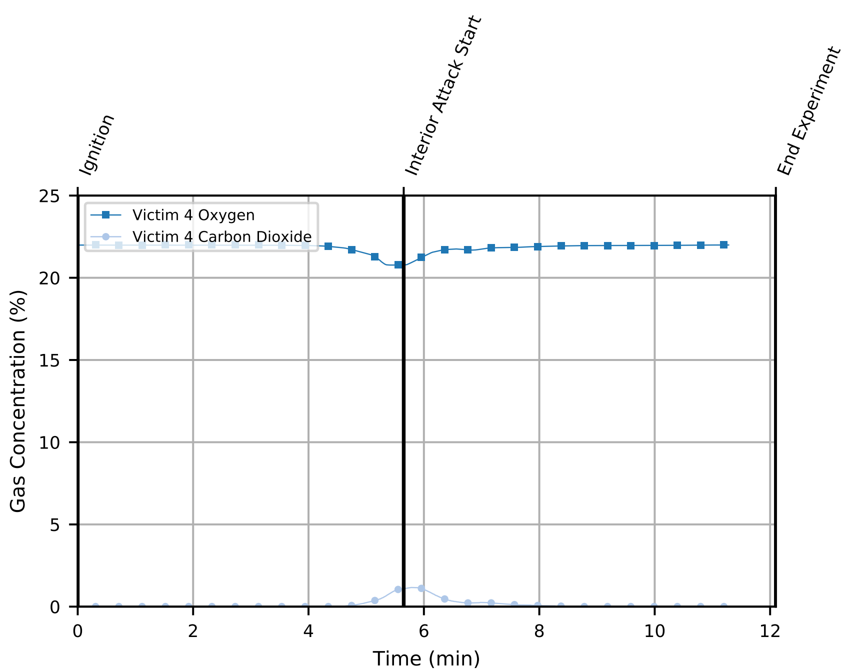


Figure E.485: Experiment 13 - Victim 4 Gas

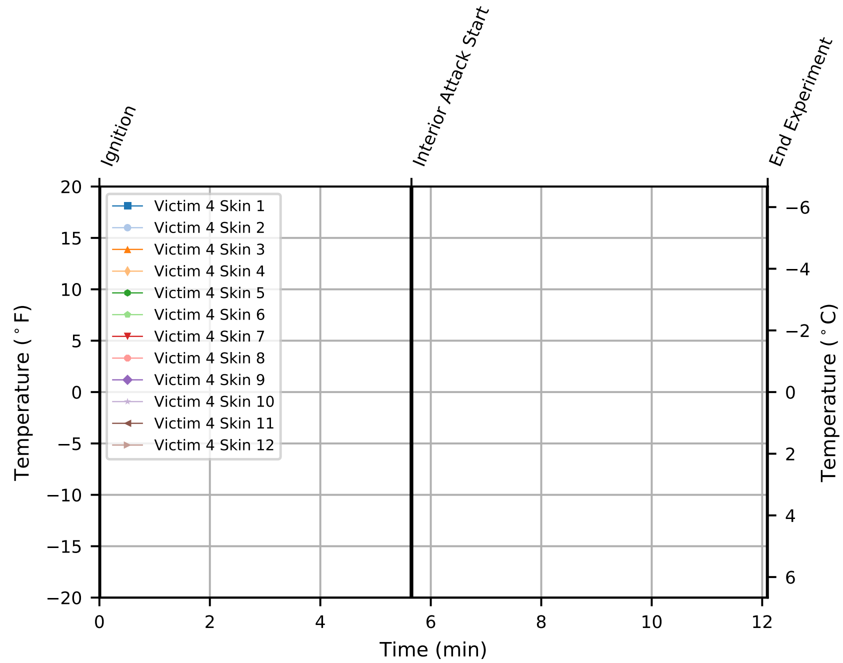


Figure E.486: Experiment 13 - Victim 4 Skin Temps

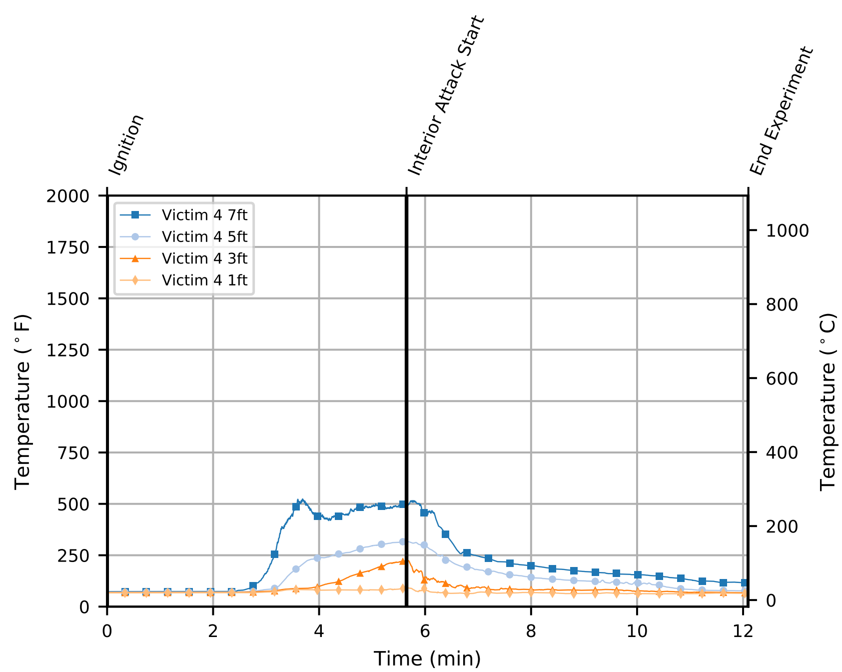


Figure E.487: Experiment 13 - Victim 4 Temps

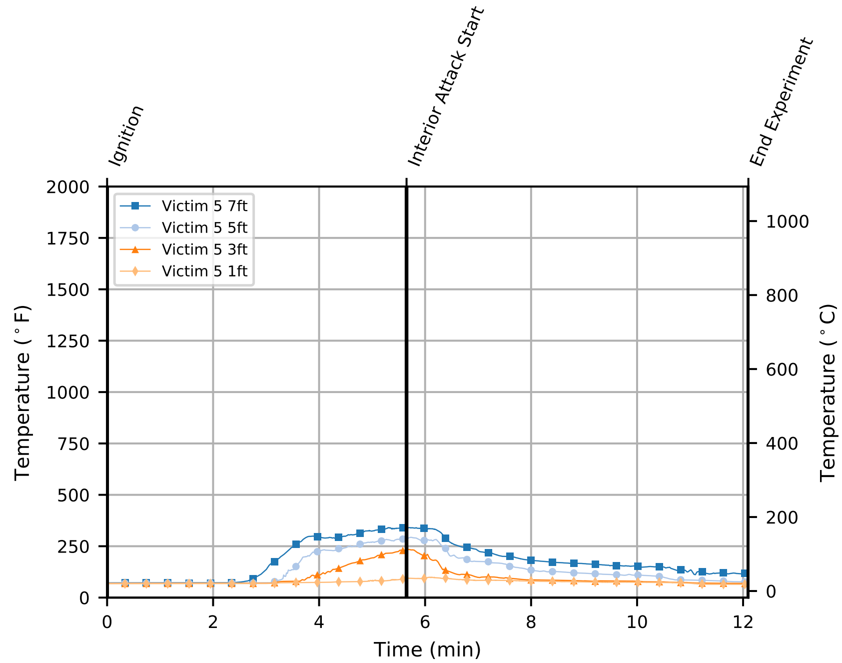


Figure E.488: Experiment 13 - Victim 5 Temps

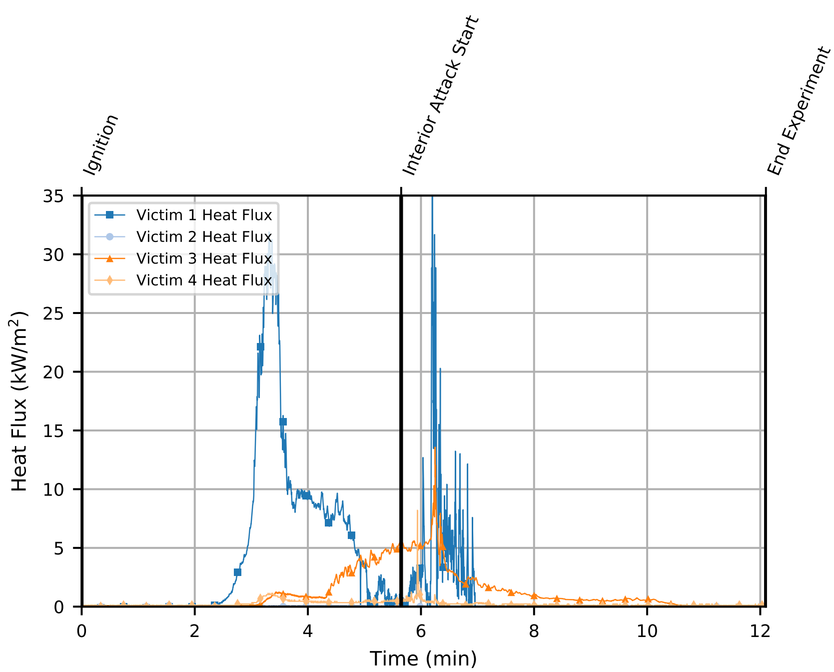


Figure E.489: Experiment 13 - Victim Heat Flux

E.14 Experiment 14 Data

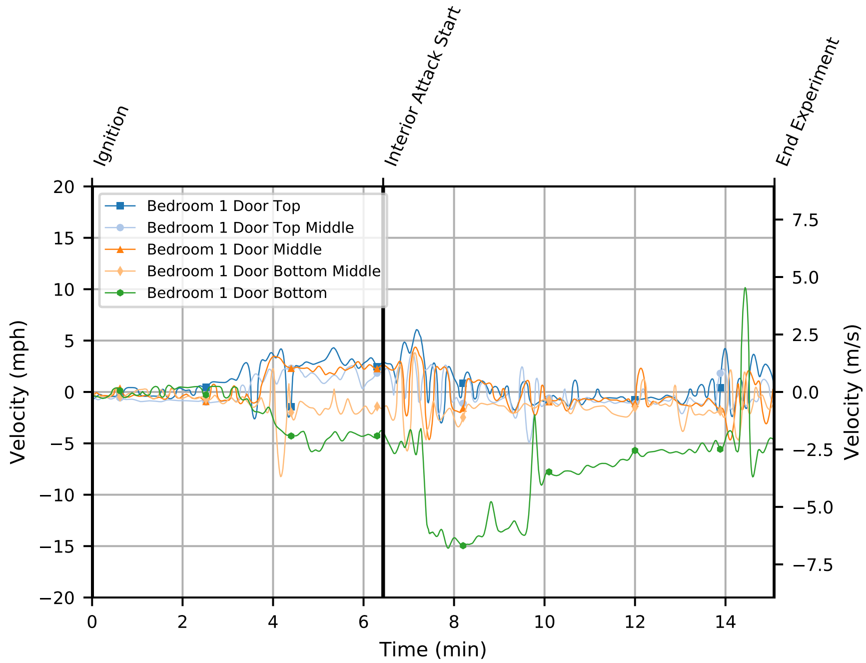


Figure E.490: Experiment 14 - Bedroom 1 Door

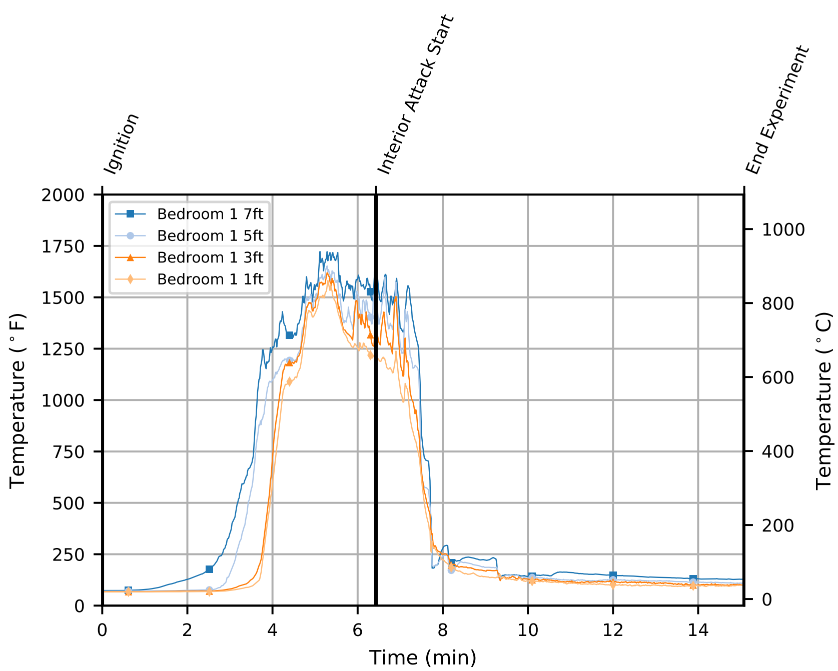


Figure E.491: Experiment 14 - Bedroom 1 Temps

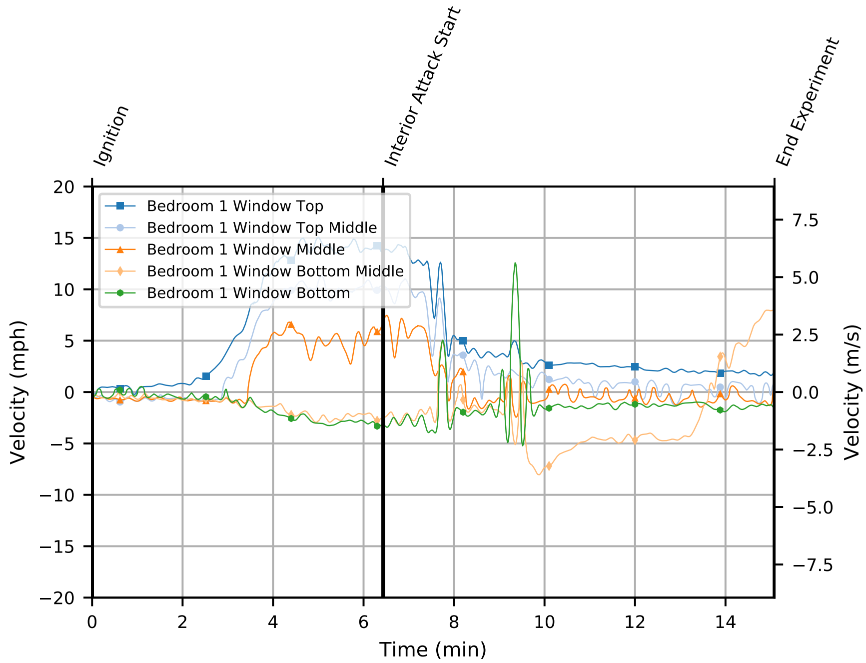


Figure E.492: Experiment 14 - Bedroom 1 Window

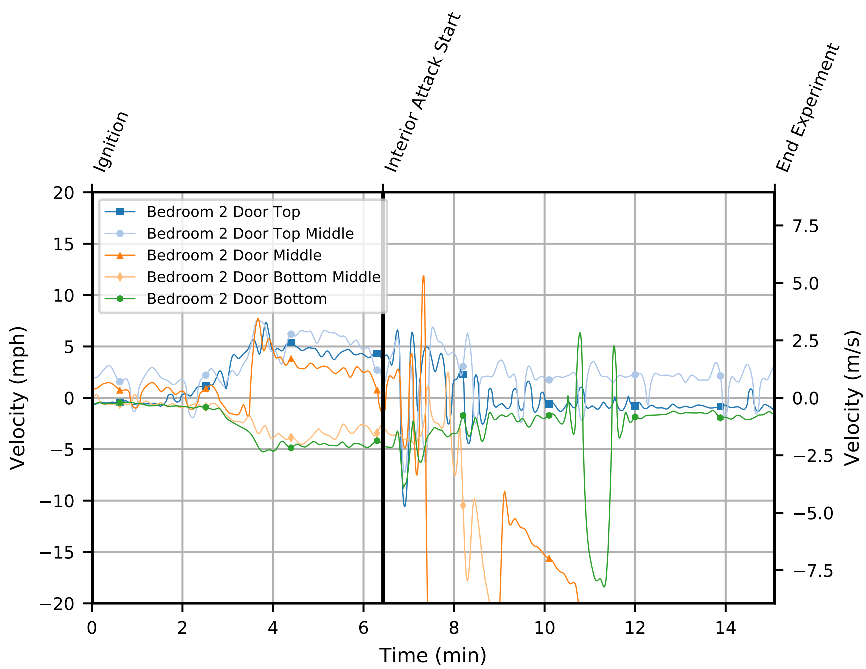


Figure E.493: Experiment 14 - Bedroom 2 Door

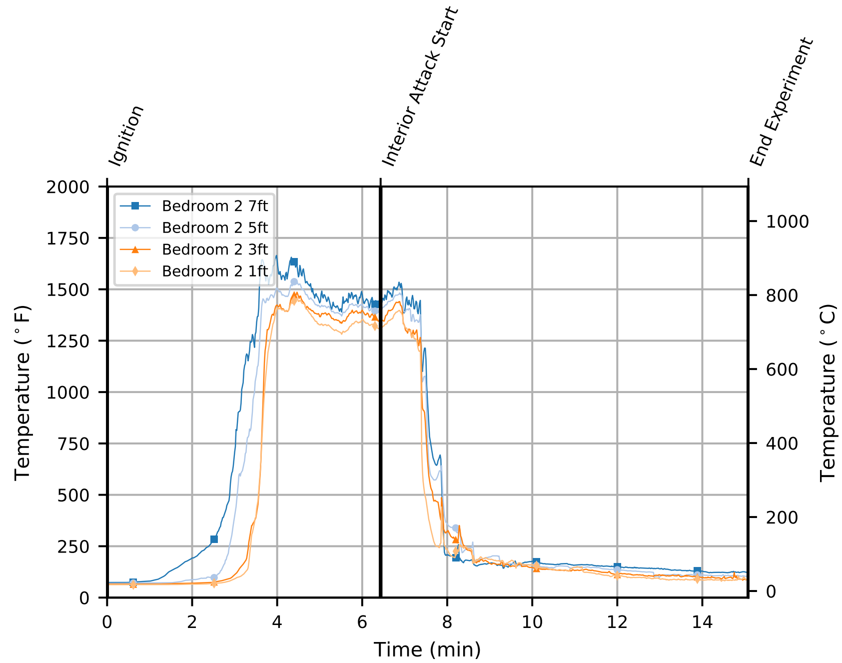


Figure E.494: Experiment 14 - Bedroom 2 Temps

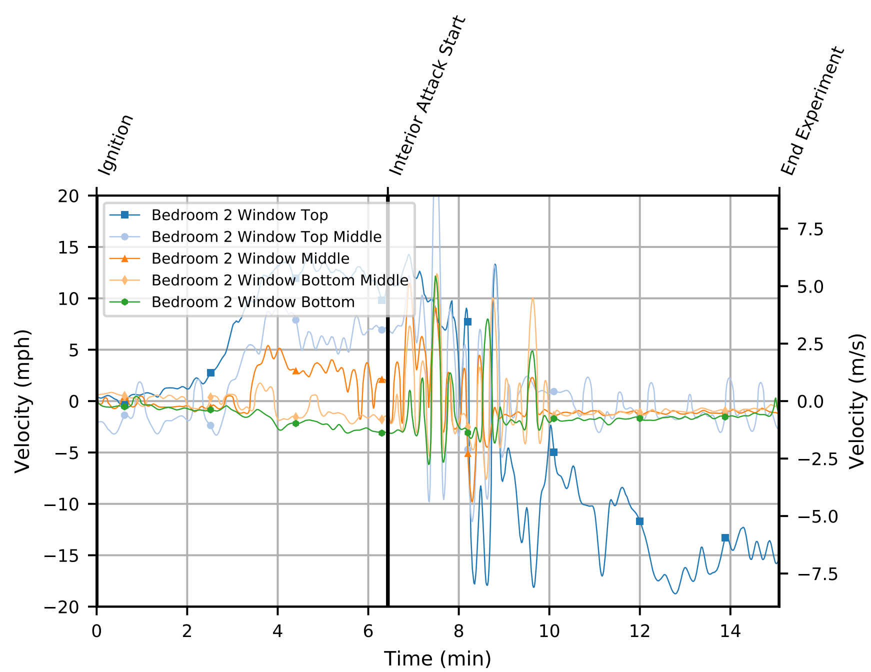


Figure E.495: Experiment 14 - Bedroom 2 Window

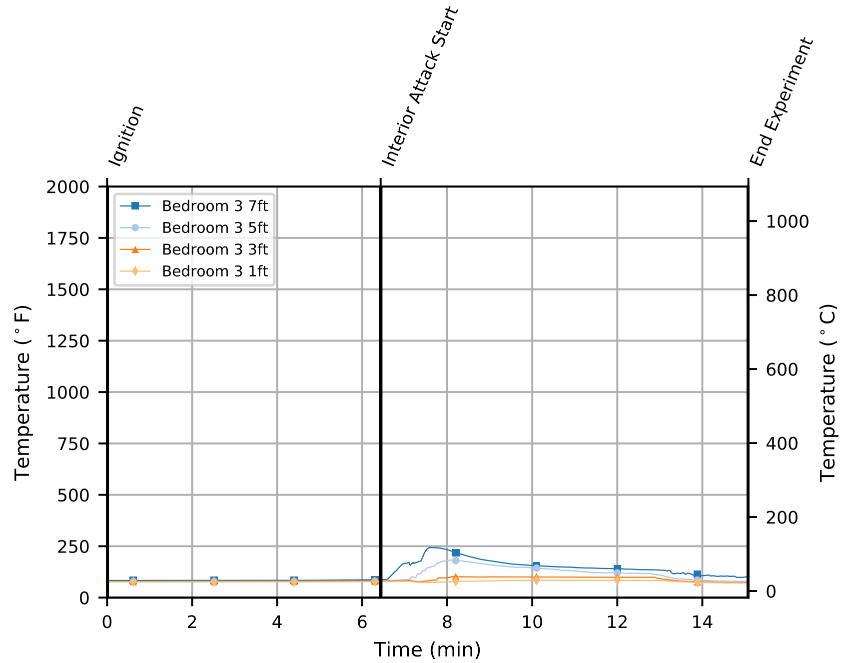


Figure E.496: Experiment 14 - Bedroom 3 Temps

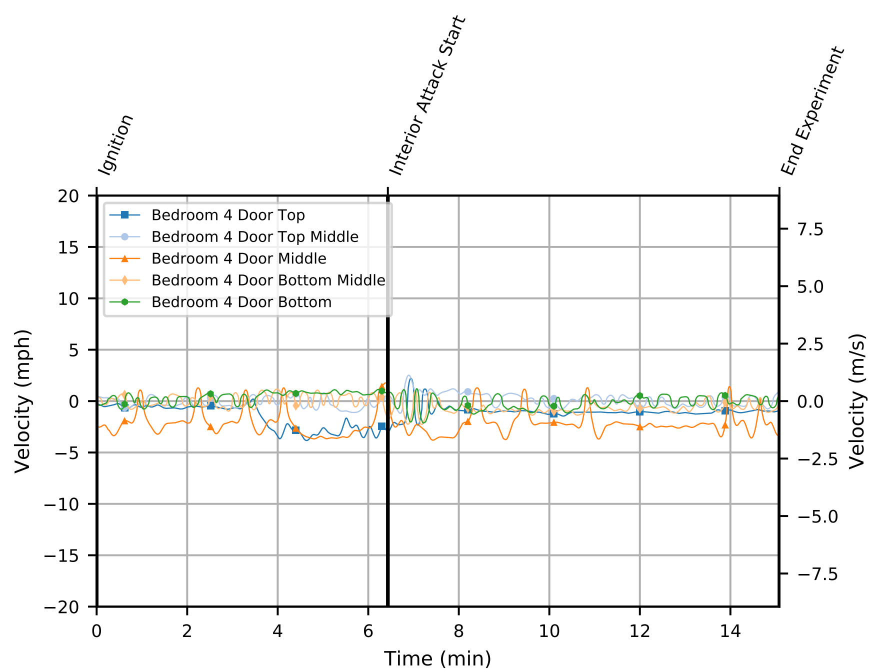


Figure E.497: Experiment 14 - Bedroom 4 Door

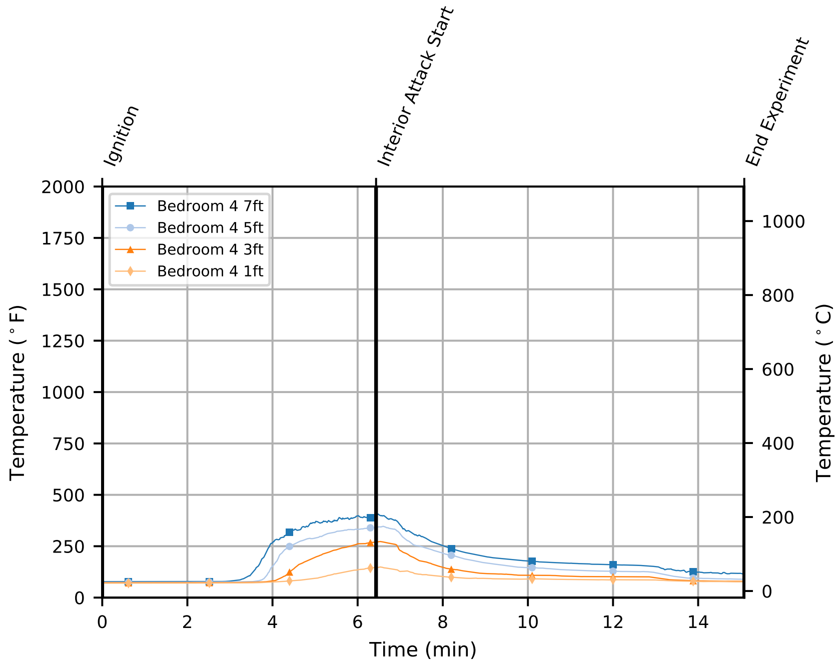


Figure E.498: Experiment 14 - Bedroom 4 Temps

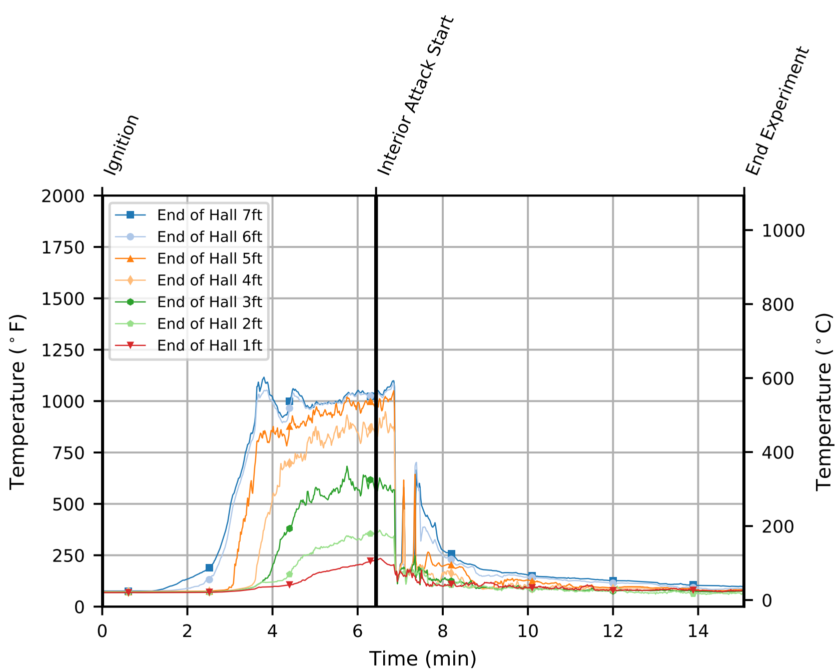


Figure E.499: Experiment 14 - End Hall Temps

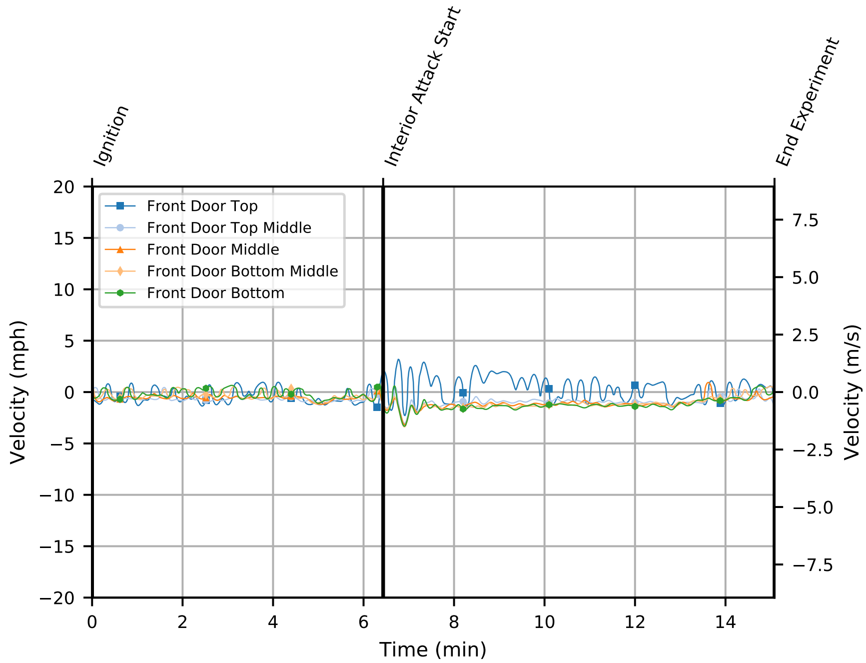


Figure E.500: Experiment 14 - Front Door Flow

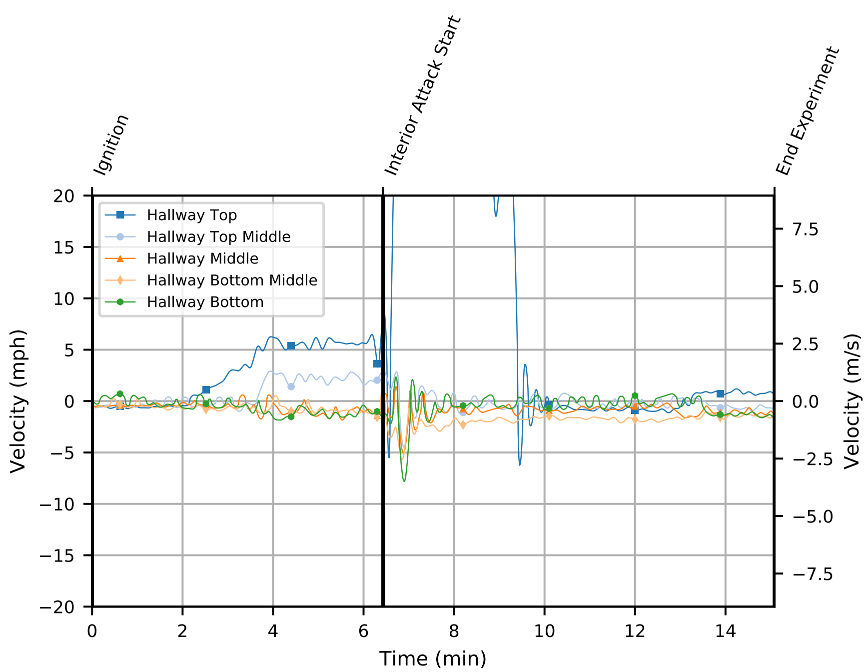


Figure E.501: Experiment 14 - Hallway Flow

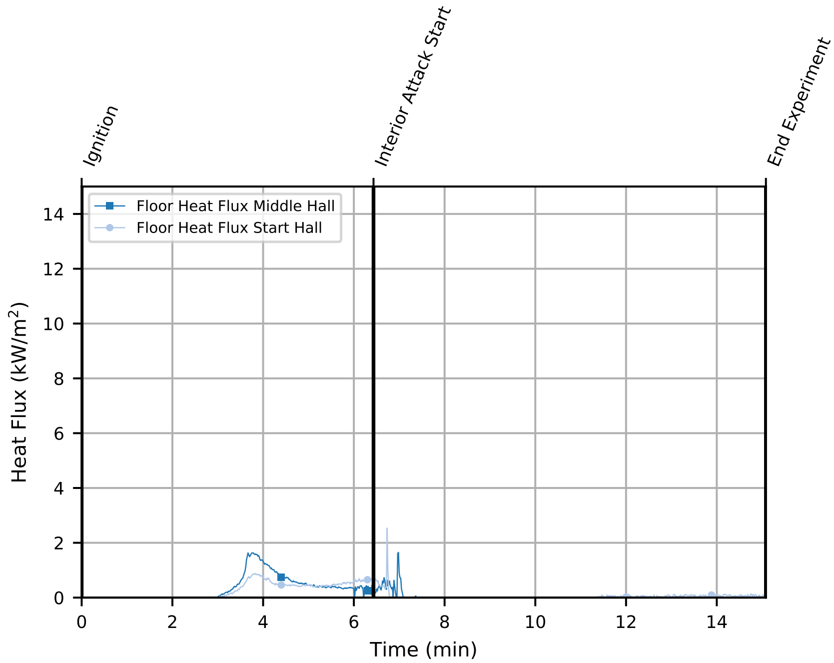


Figure E.502: Experiment 14 - Heat Flux Floor

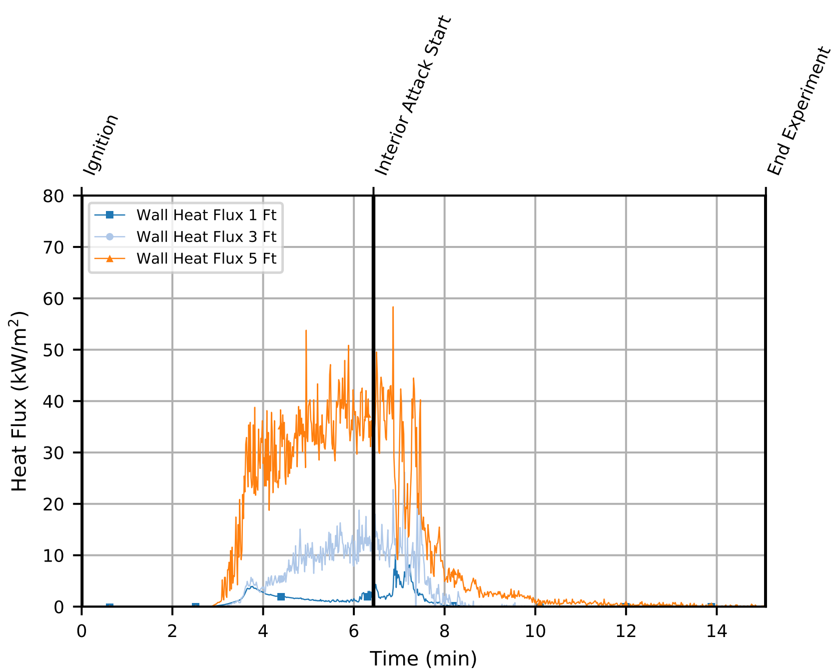


Figure E.503: Experiment 14 - Heat Flux Wall

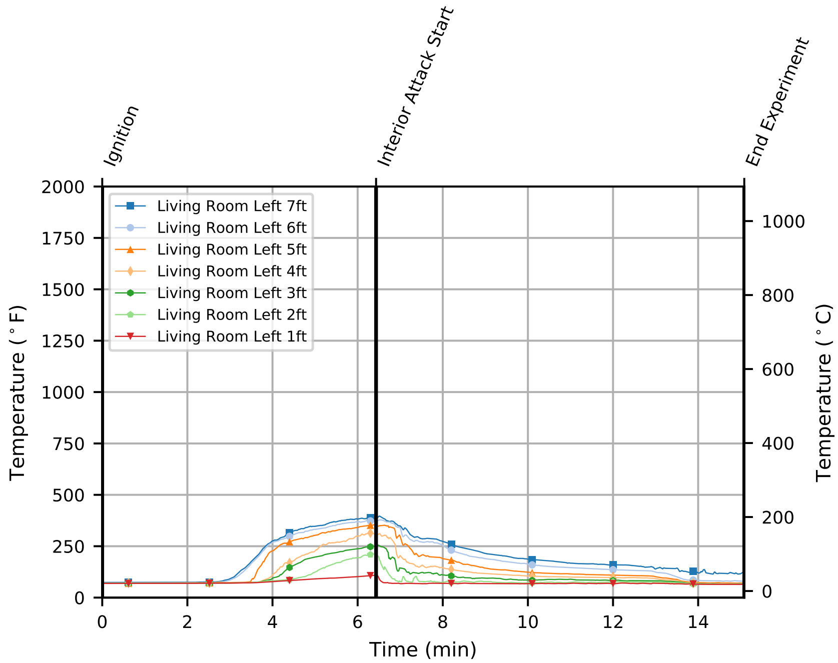


Figure E.504: Experiment 14 - Living Room Left Temps

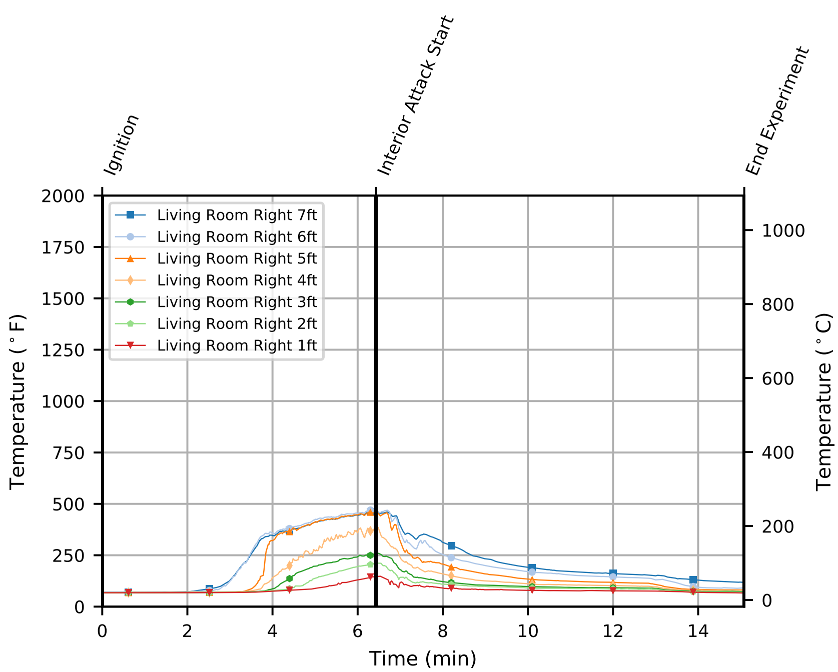


Figure E.505: Experiment 14 - Living Room Right Temps

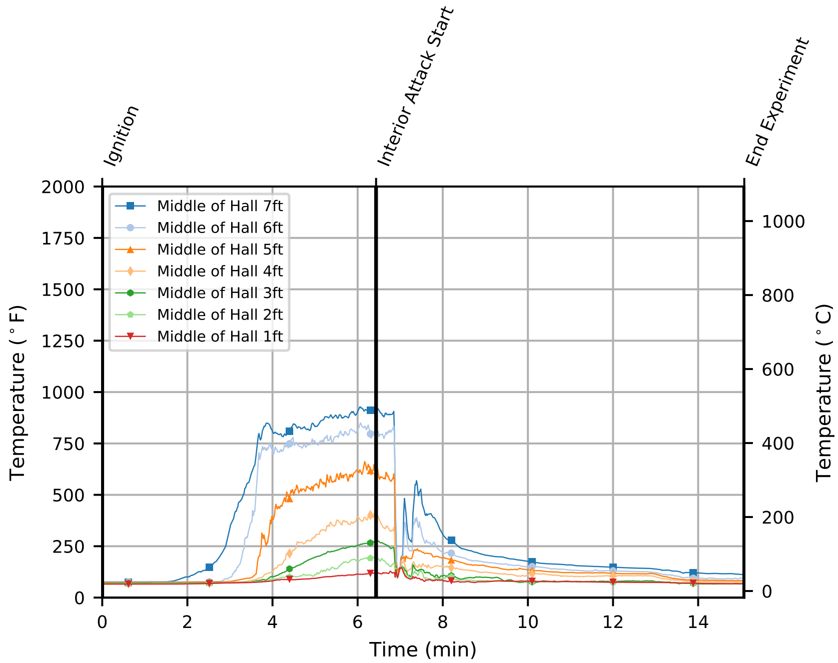


Figure E.506: Experiment 14 - Middle Hall Temps

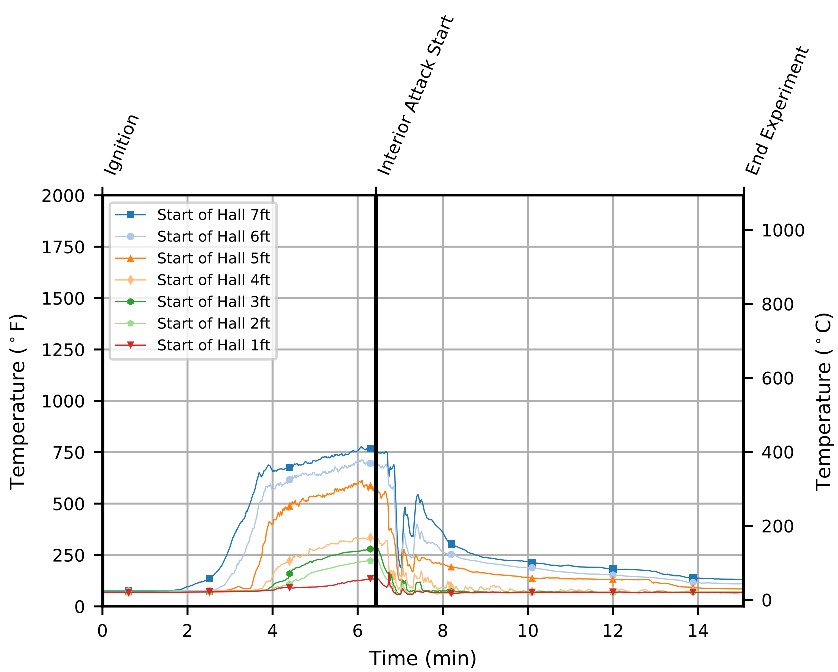


Figure E.507: Experiment 14 - Start Hall Temps

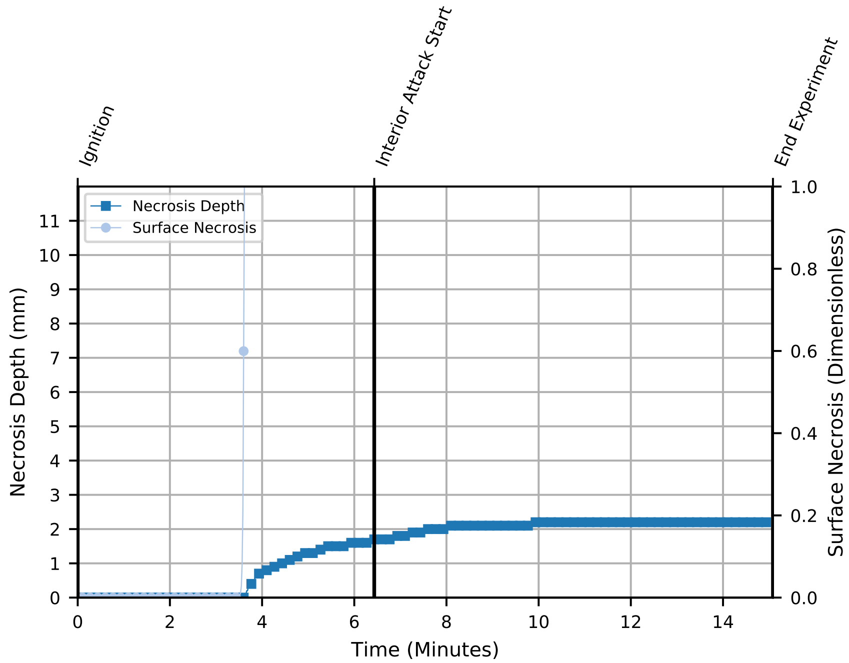


Figure E.508: Experiment 14 - Vic 1 Necrosis Depth

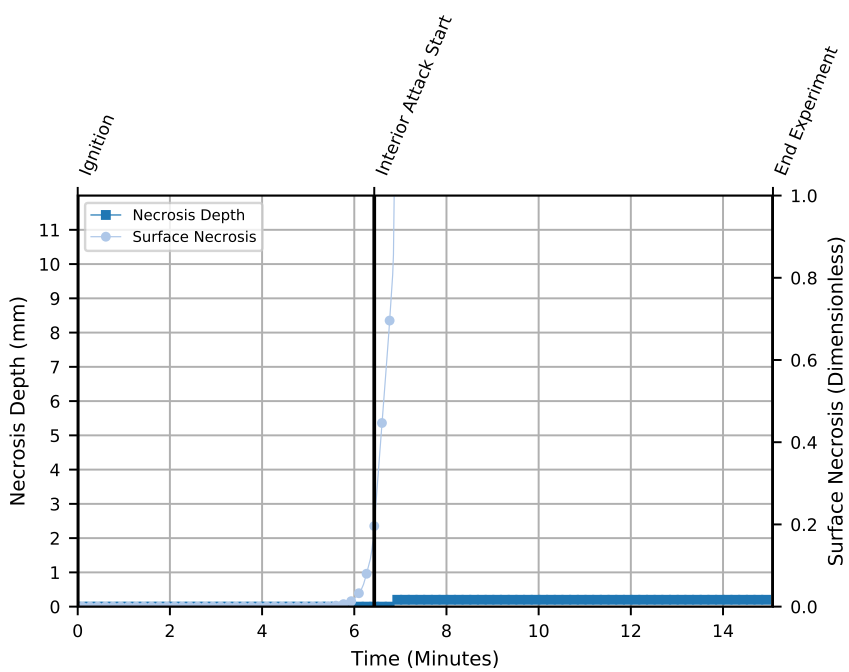


Figure E.509: Experiment 14 - Vic 3 Necrosis Depth

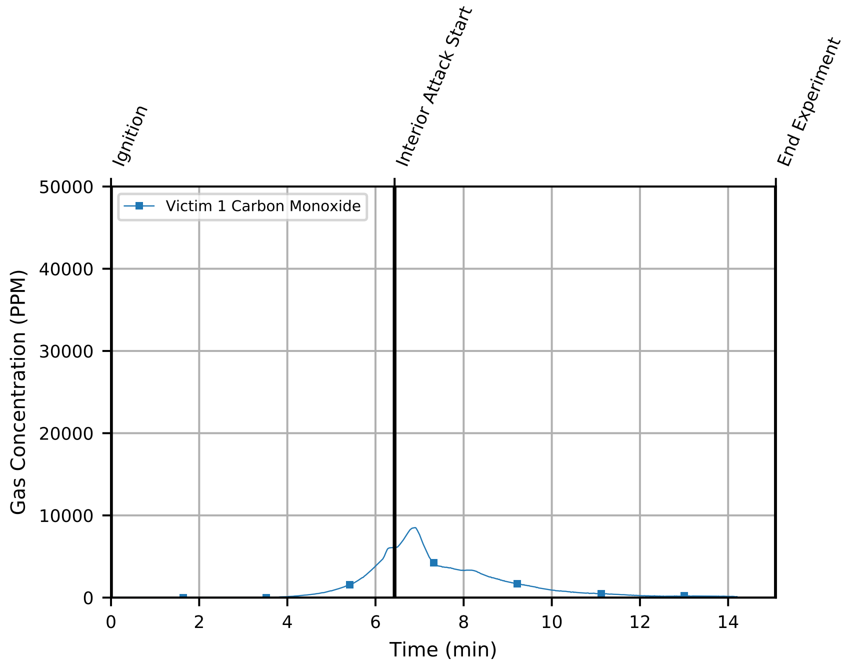


Figure E.510: Experiment 14 - Victim 1 Carbon Monoxide

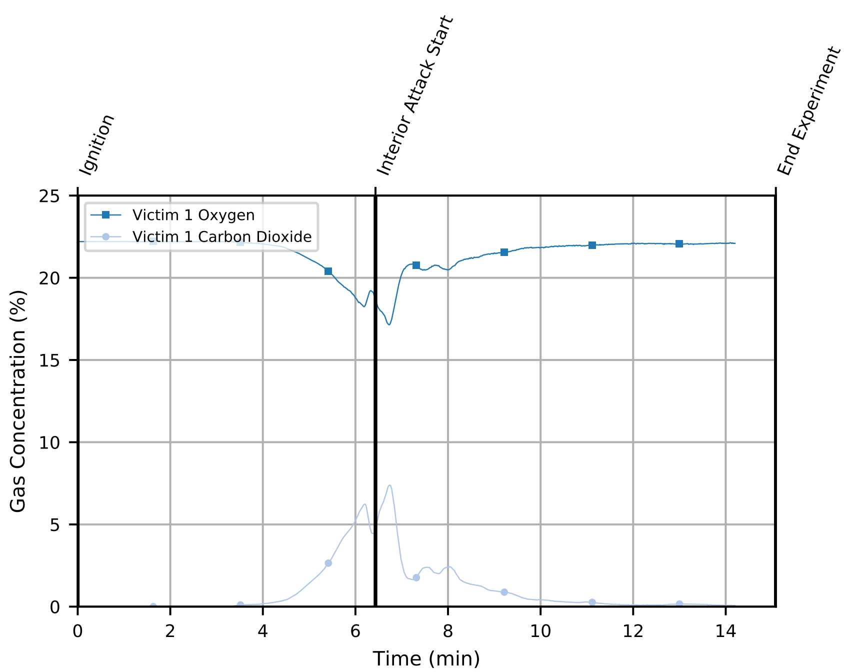


Figure E.511: Experiment 14 - Victim 1 Gas

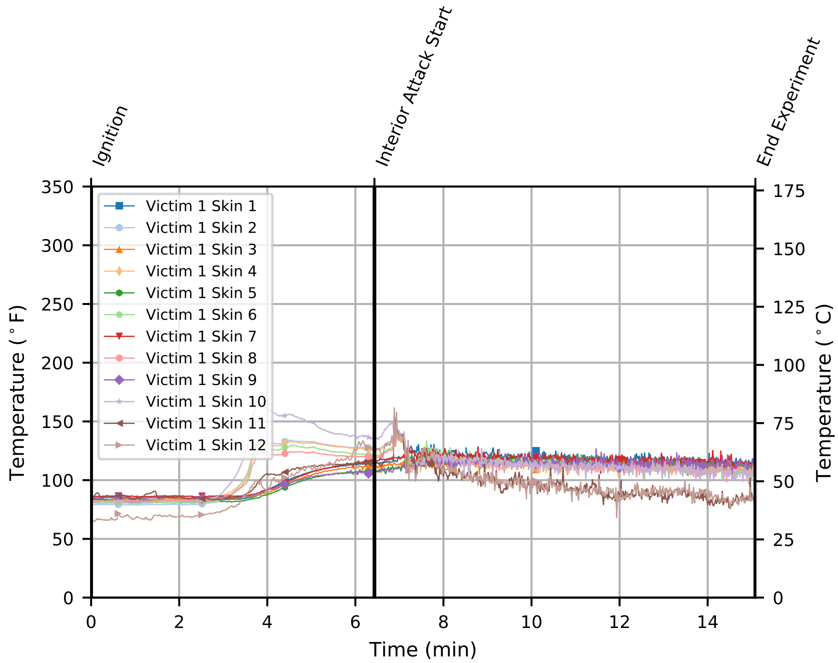


Figure E.512: Experiment 14 - Victim 1 Skin Temps

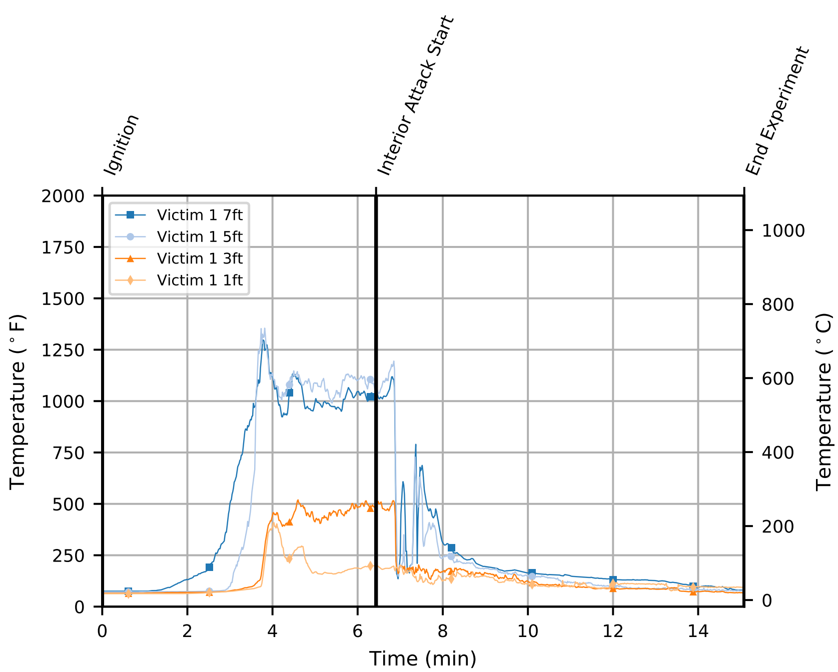


Figure E.513: Experiment 14 - Victim 1 Temps

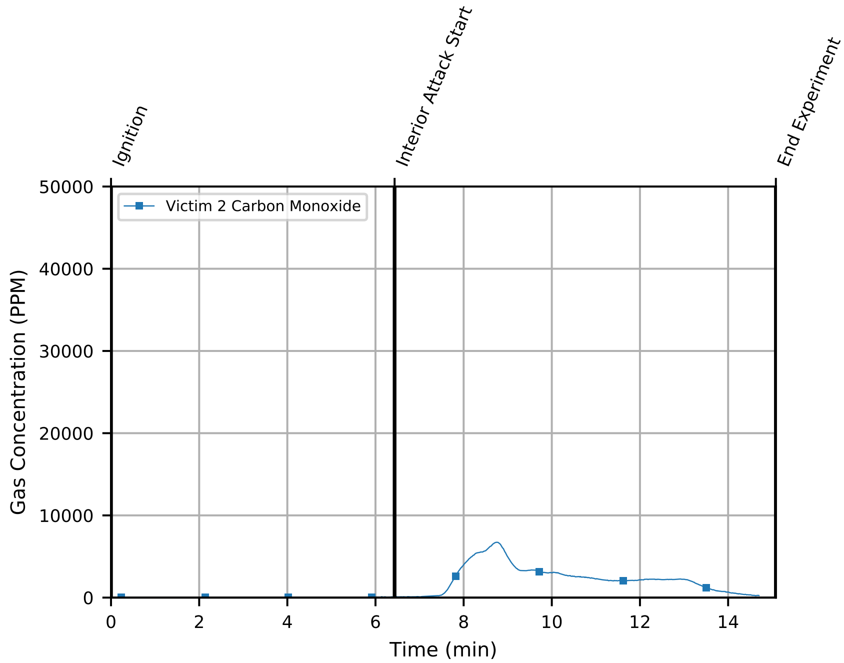


Figure E.514: Experiment 14 - Victim 2 Carbon Monoxide

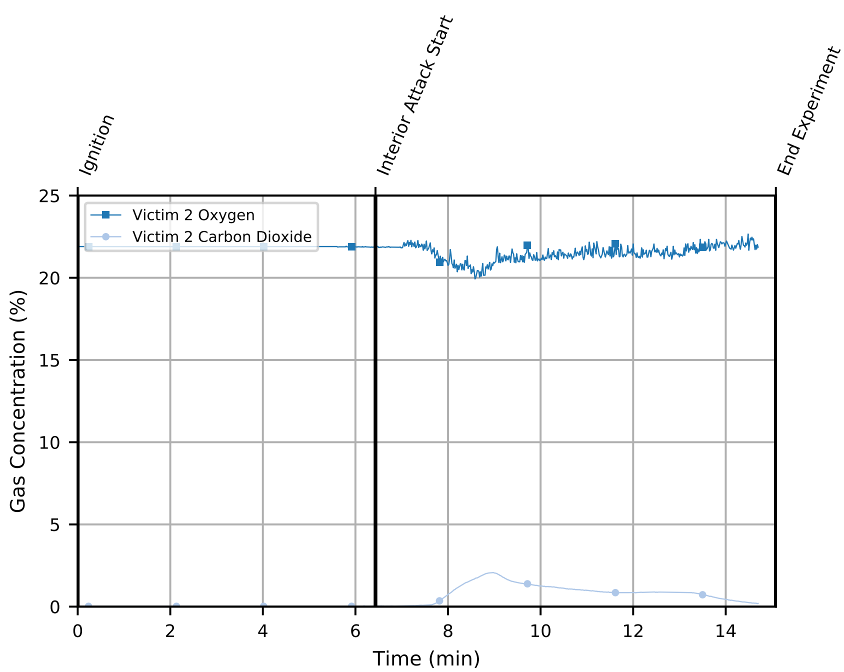


Figure E.515: Experiment 14 - Victim 2 Gas

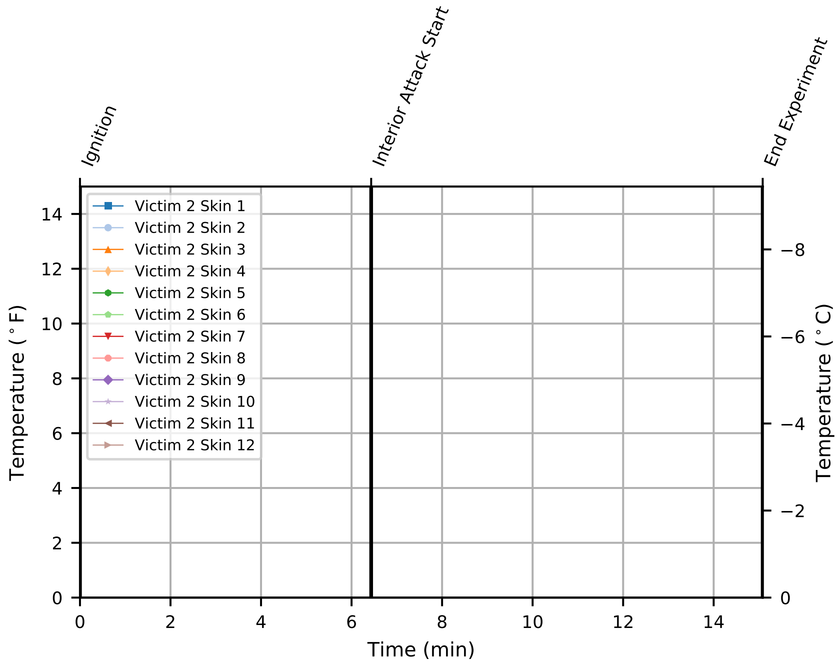


Figure E.516: Experiment 14 - Victim 2 Skin Temps

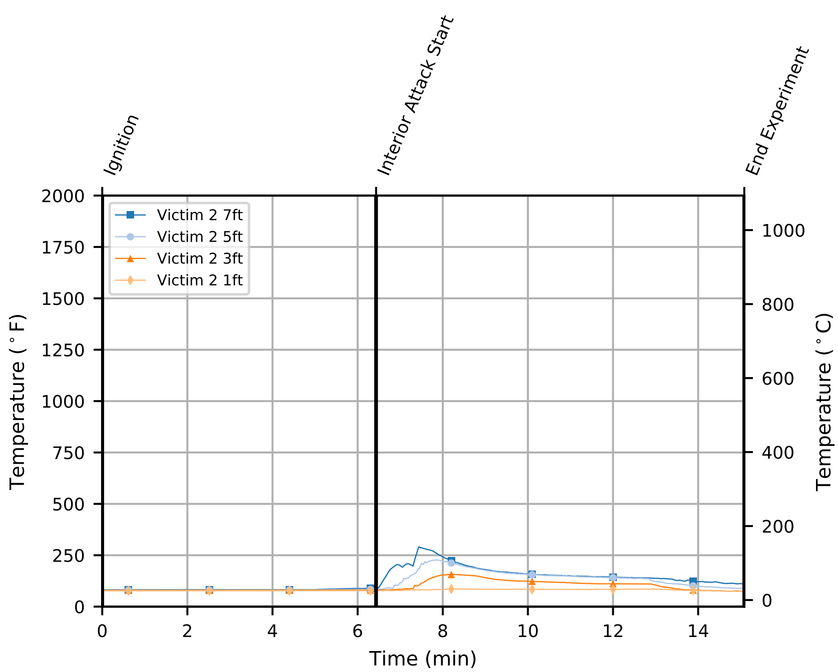


Figure E.517: Experiment 14 - Victim 2 Temps

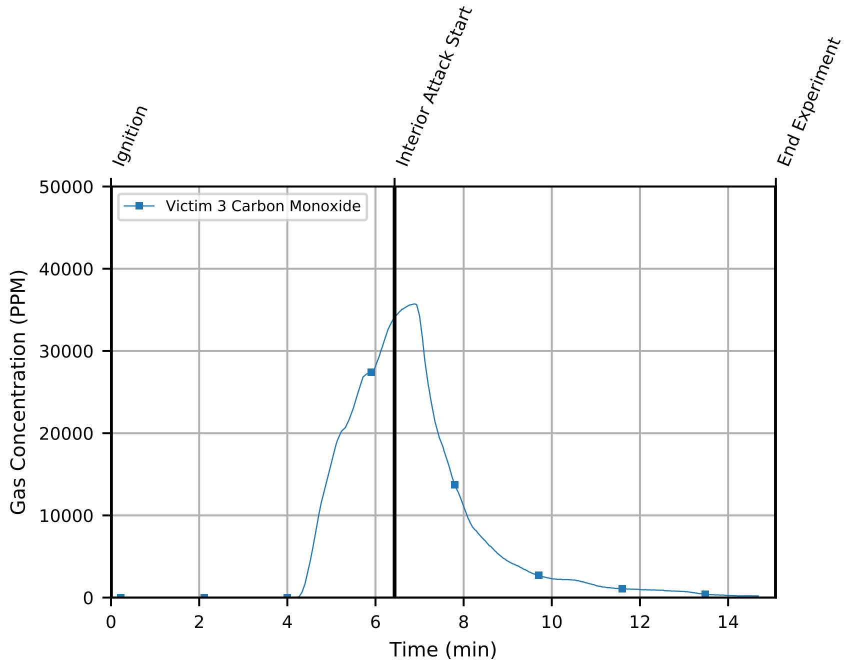


Figure E.518: Experiment 14 - Victim 3 Carbon Monoxide

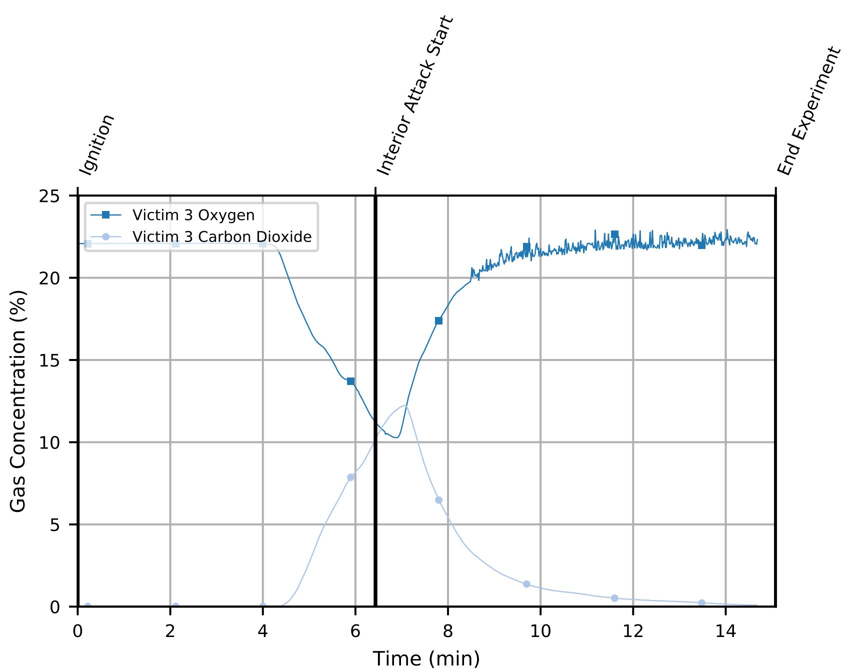


Figure E.519: Experiment 14 - Victim 3 Gas

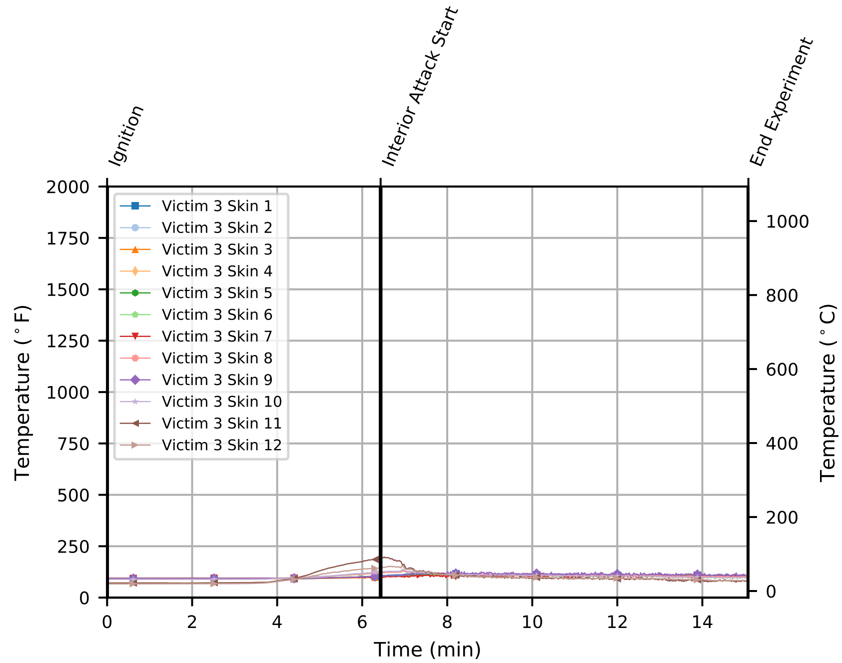


Figure E.520: Experiment 14 - Victim 3 Skin Temps

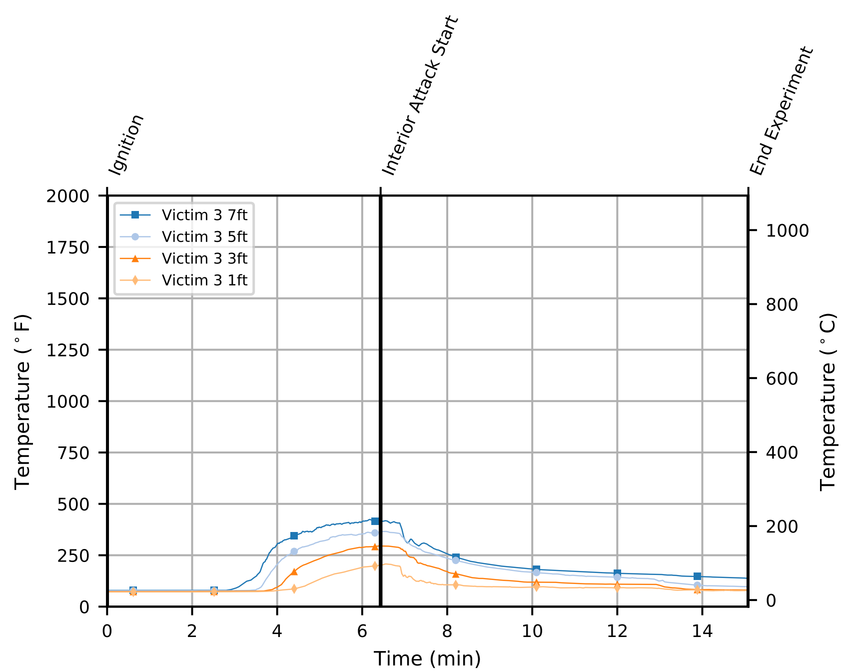


Figure E.521: Experiment 14 - Victim 3 Temps

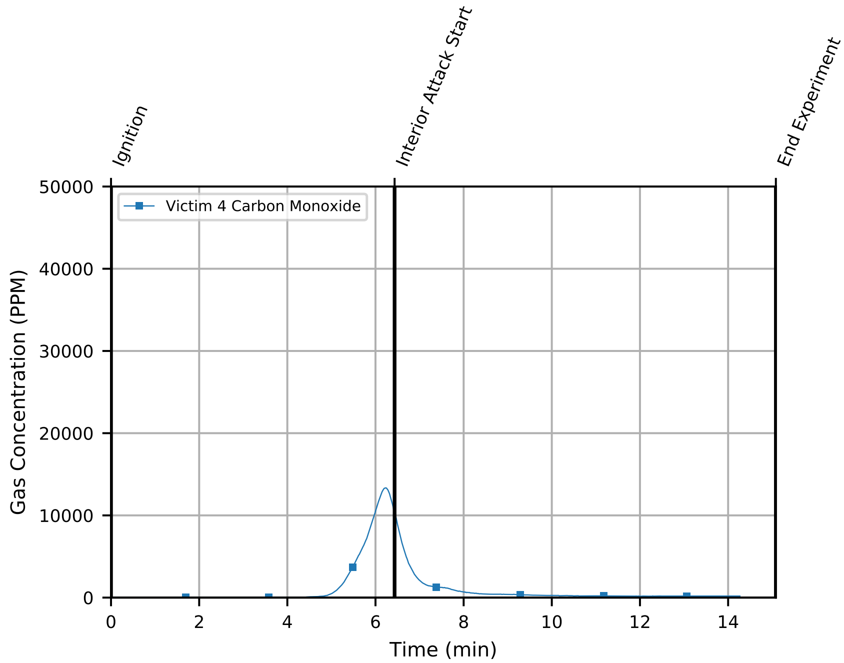


Figure E.522: Experiment 14 - Victim 4 Carbon Monoxide

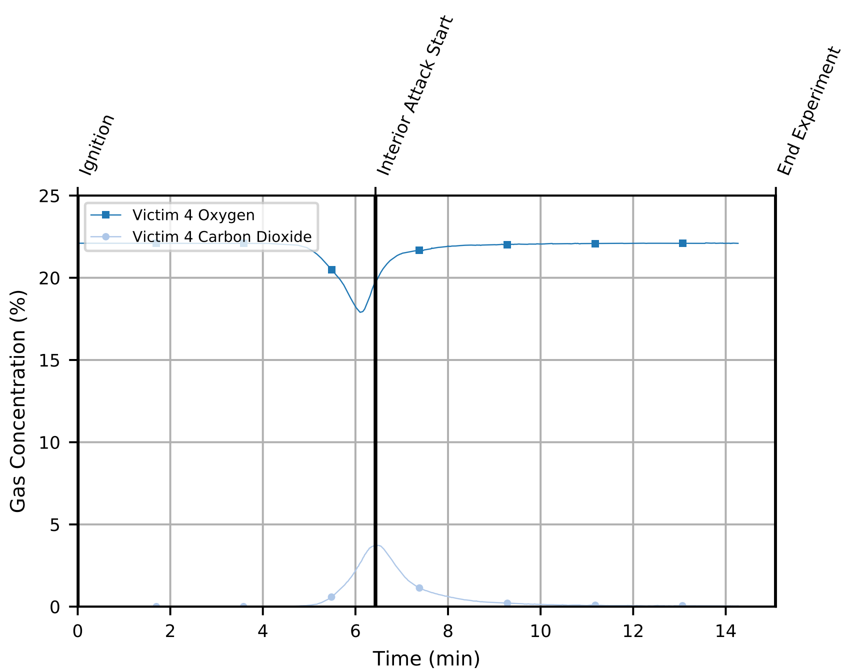


Figure E.523: Experiment 14 - Victim 4 Gas

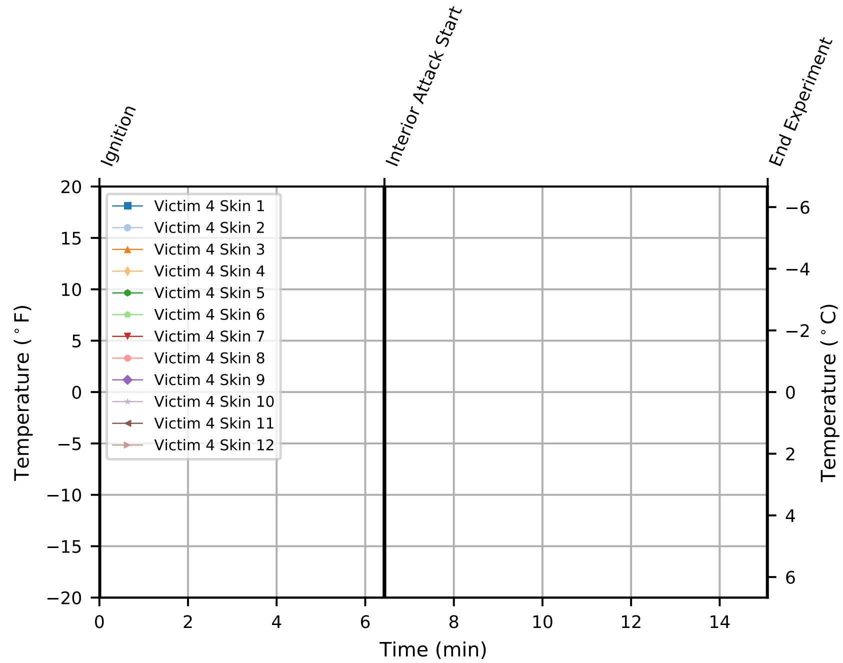


Figure E.524: Experiment 14 - Victim 4 Skin Temps

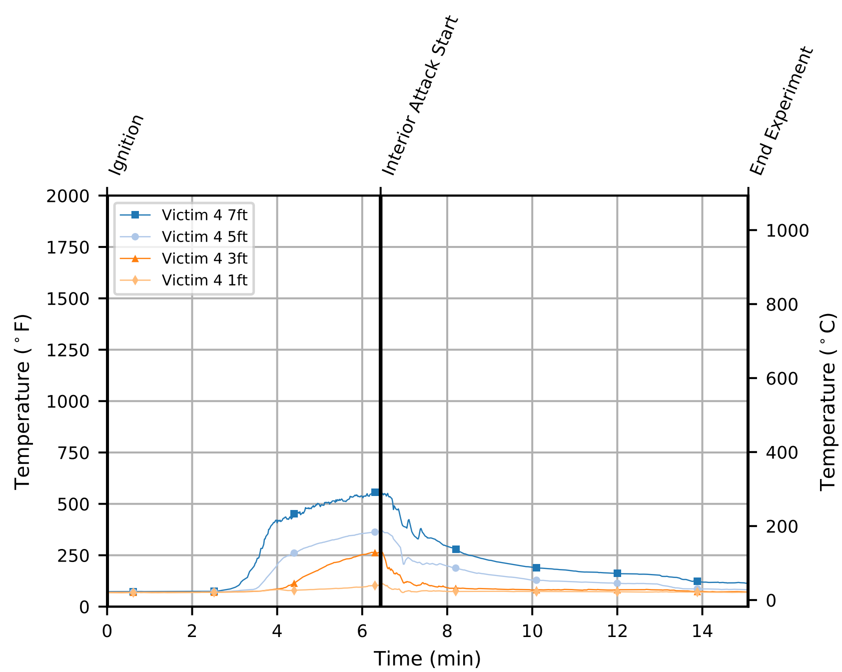


Figure E.525: Experiment 14 - Victim 4 Temps

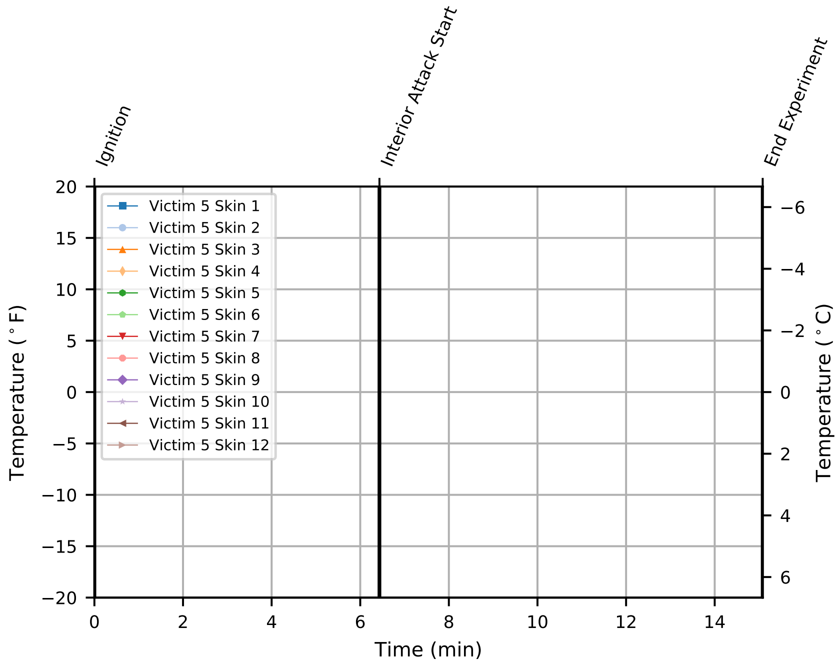


Figure E.526: Experiment 14 - Victim 5 Skin Temps

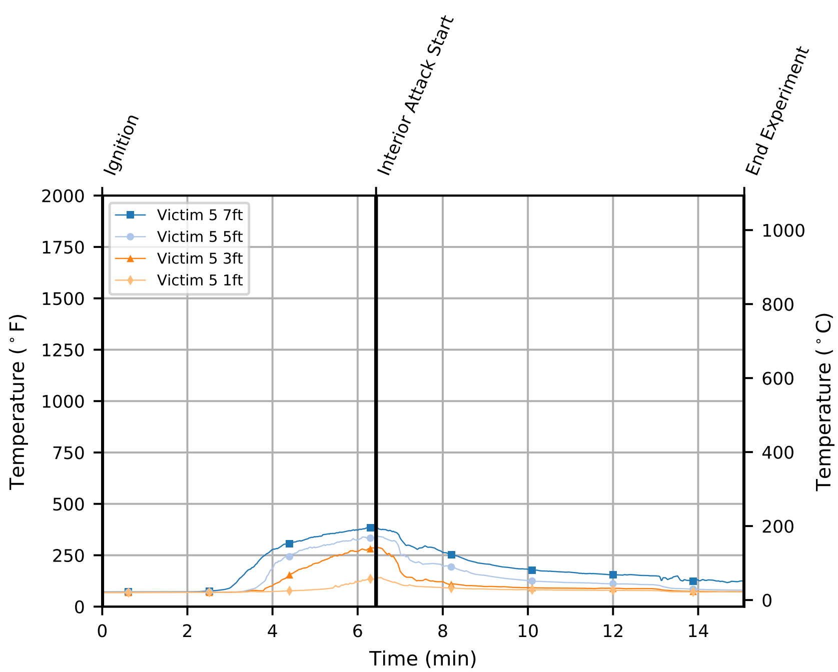


Figure E.527: Experiment 14 - Victim 5 Temps

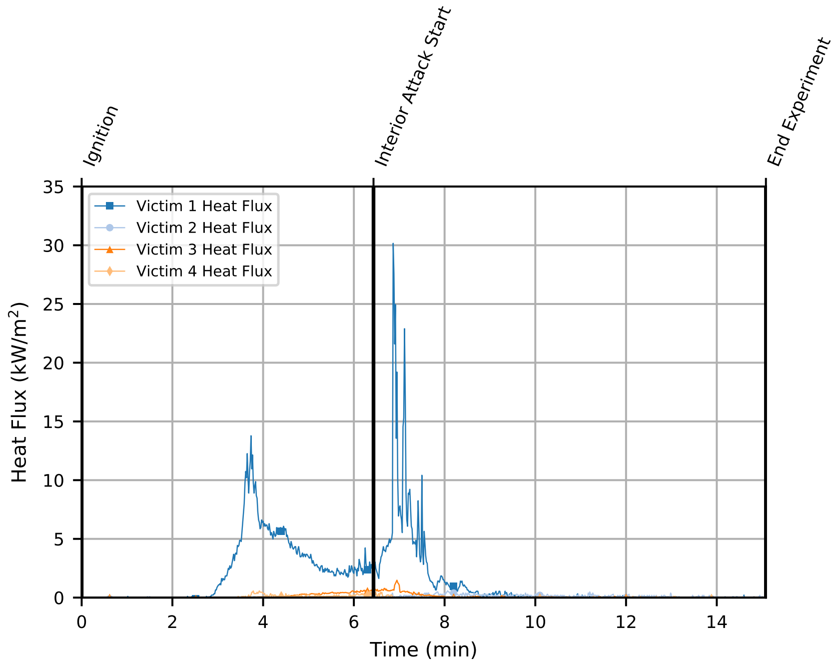


Figure E.528: Experiment 14 - Victim Heat Flux

E.15 Experiment 15 Data

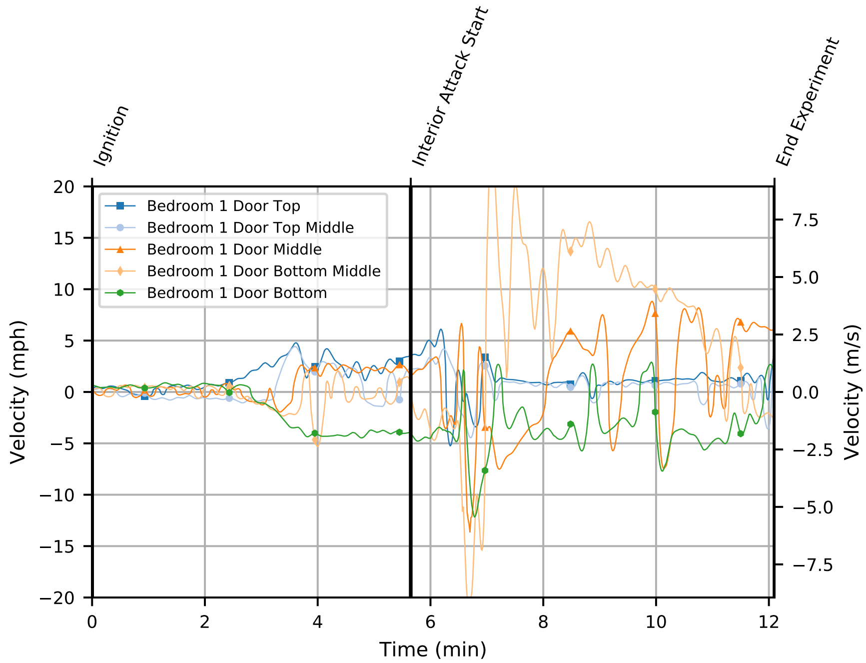


Figure E.529: Experiment 15 - Bedroom 1 Door

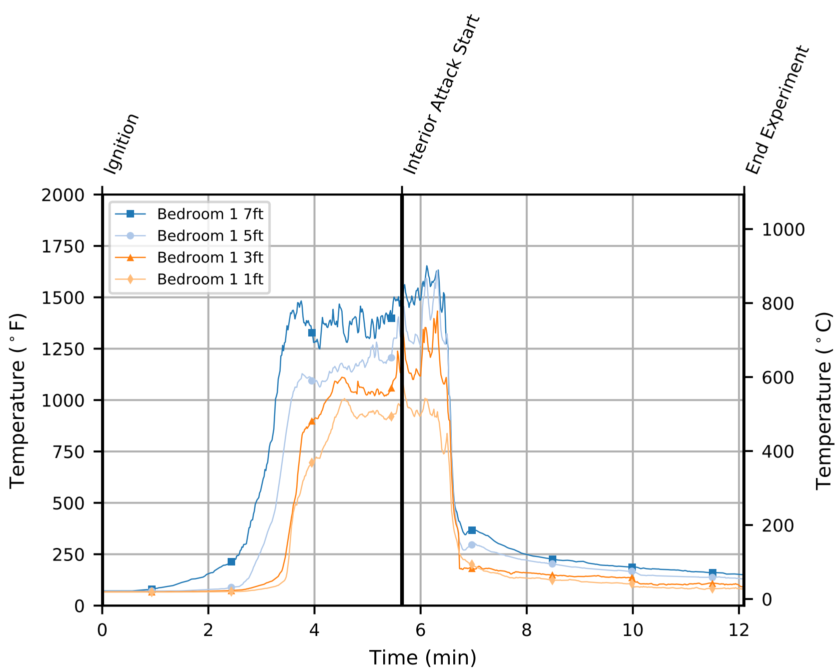


Figure E.530: Experiment 15 - Bedroom 1 Temps

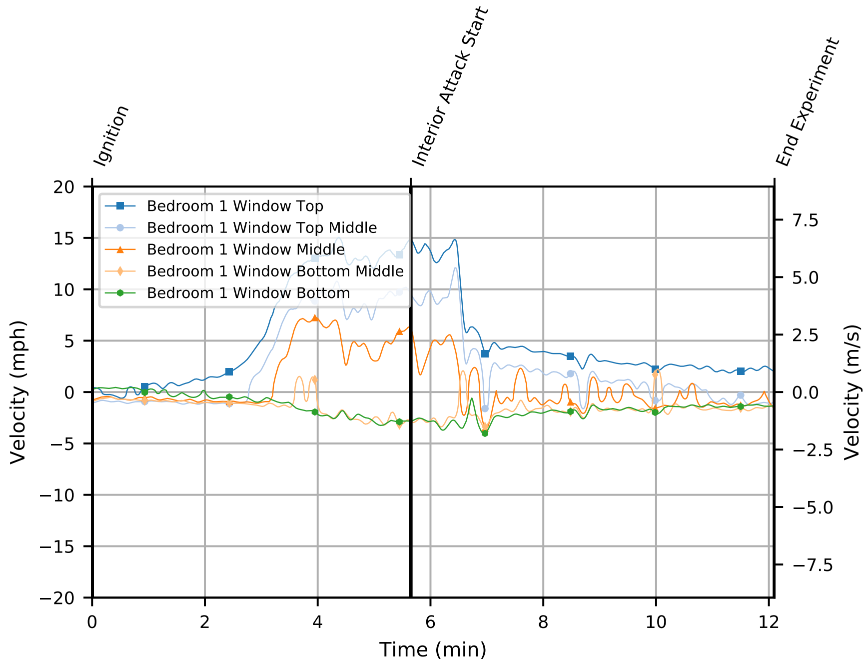


Figure E.531: Experiment 15 - Bedroom 1 Window

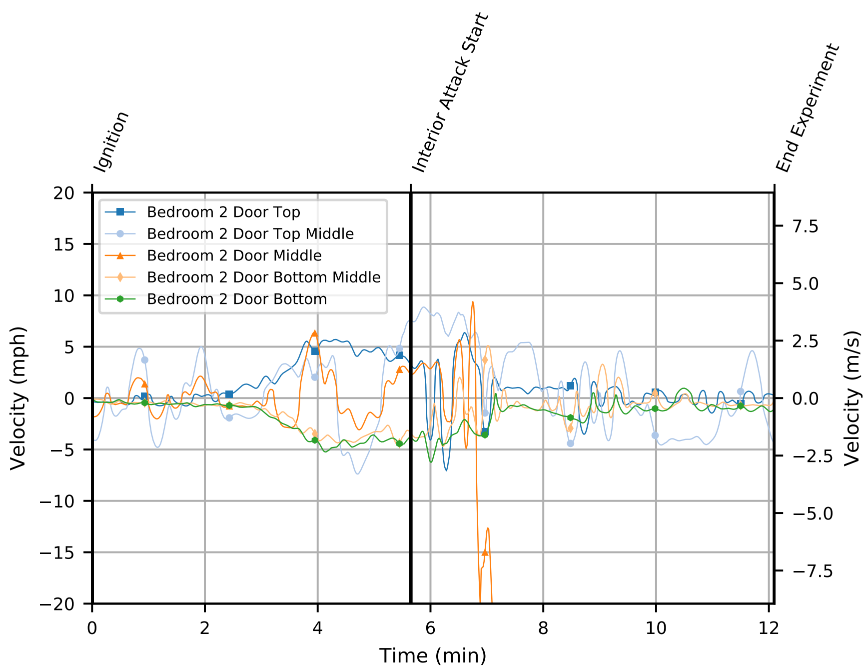


Figure E.532: Experiment 15 - Bedroom 2 Door

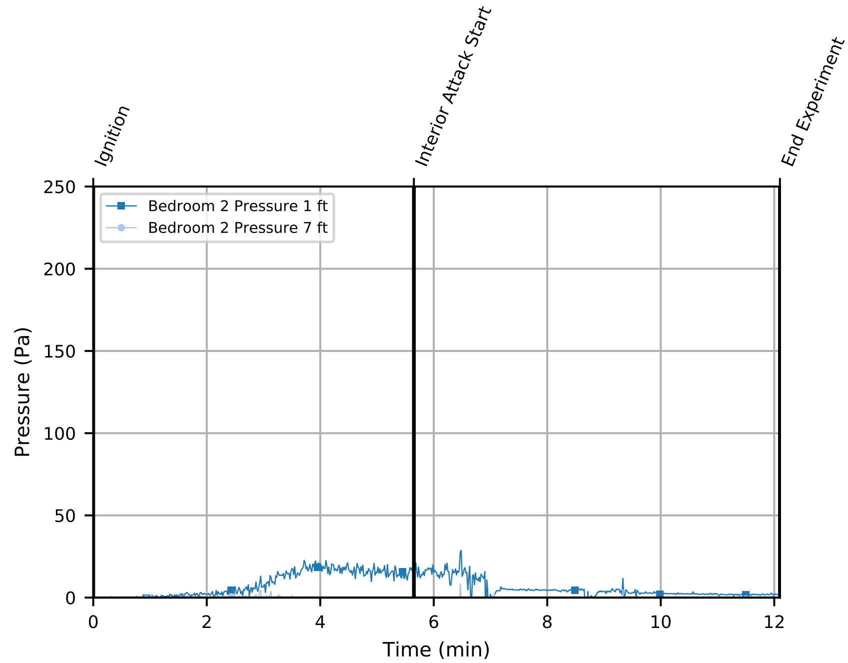


Figure E.533: Experiment 15 - Bedroom 2 Pressure

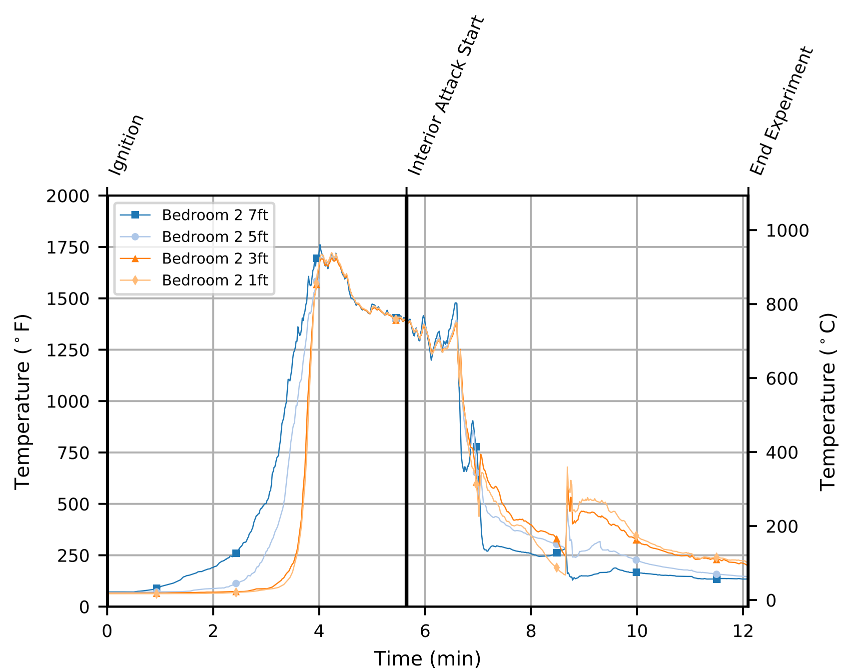


Figure E.534: Experiment 15 - Bedroom 2 Temps

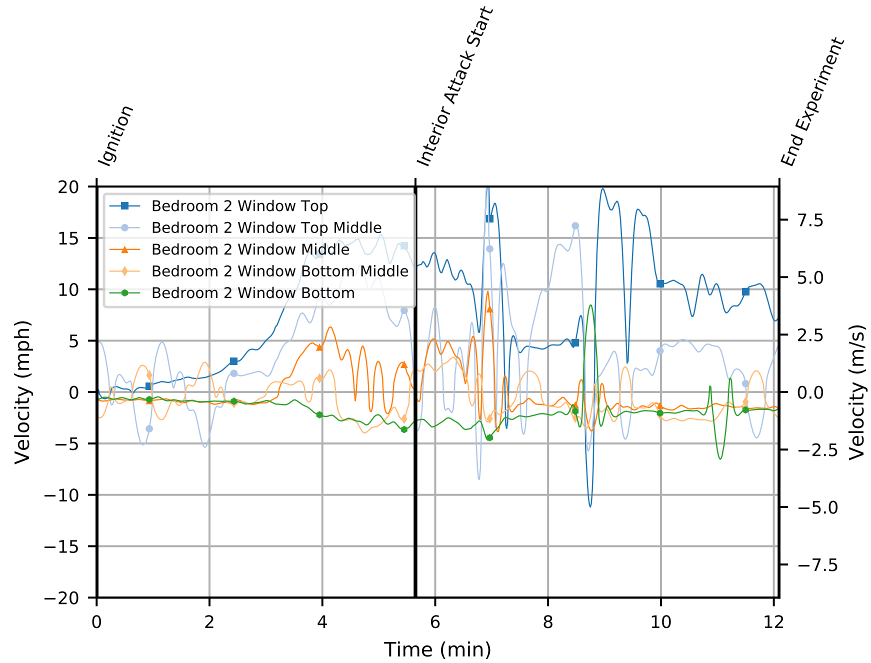


Figure E.535: Experiment 15 - Bedroom 2 Window

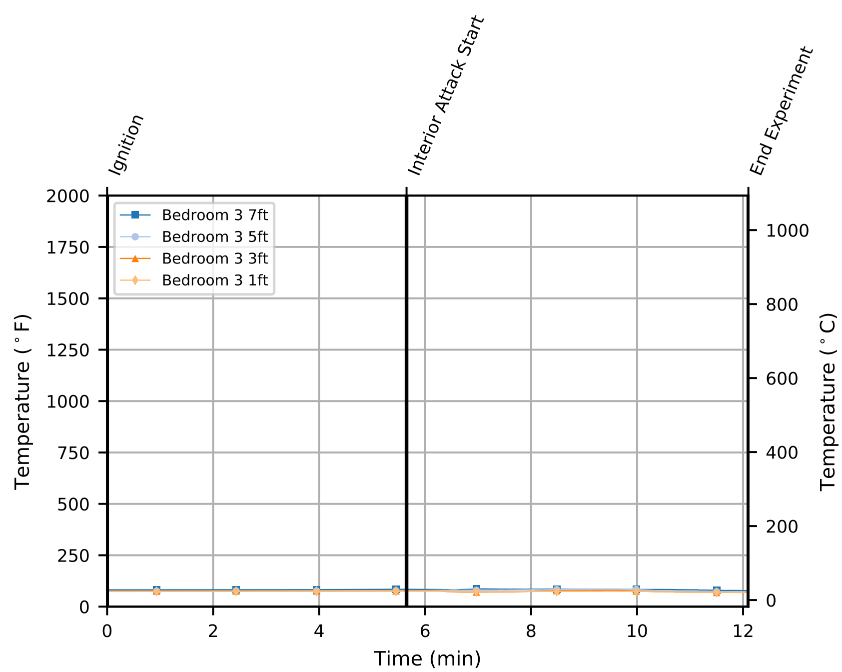


Figure E.536: Experiment 15 - Bedroom 3 Temps

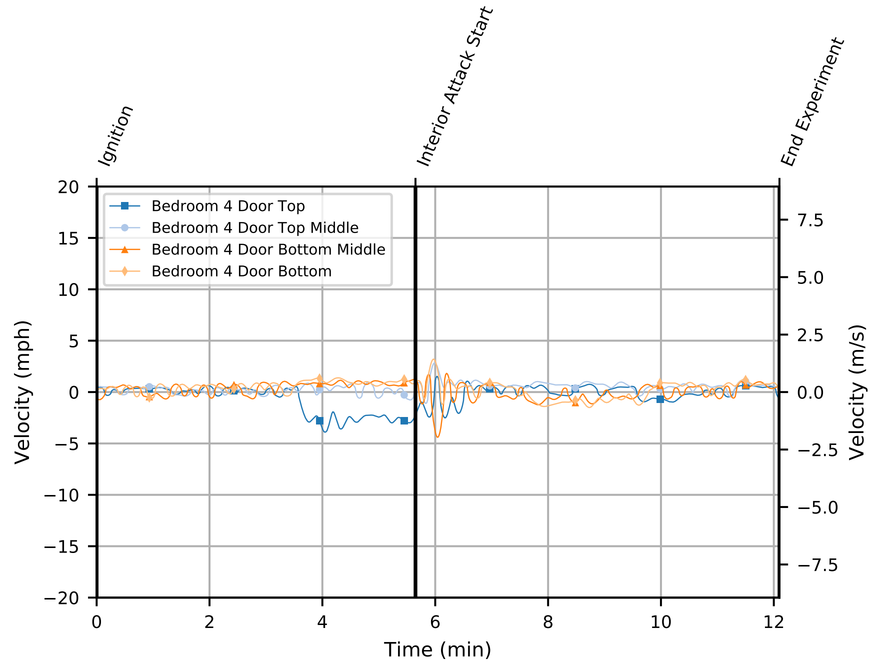


Figure E.537: Experiment 15 - Bedroom 4 Door

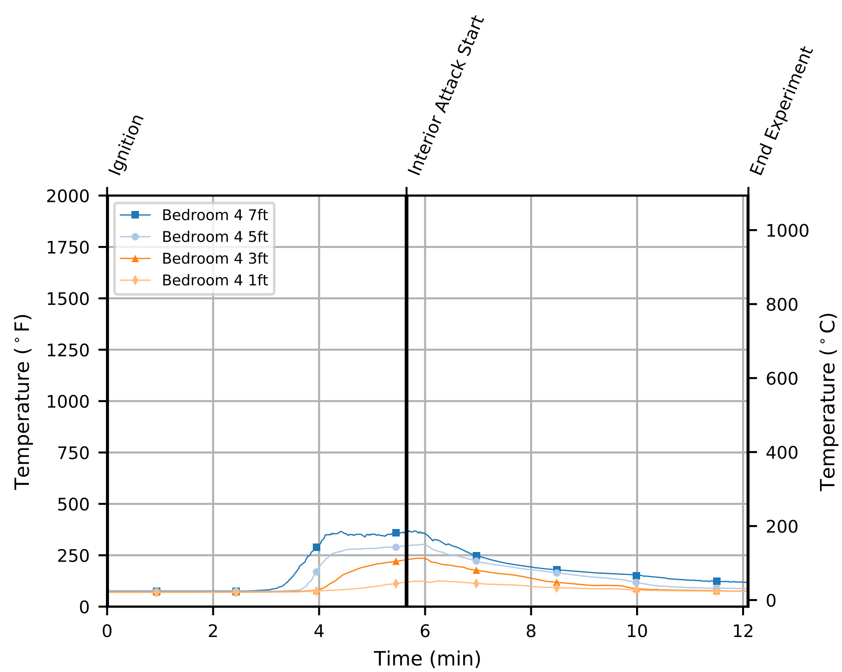


Figure E.538: Experiment 15 - Bedroom 4 Temps

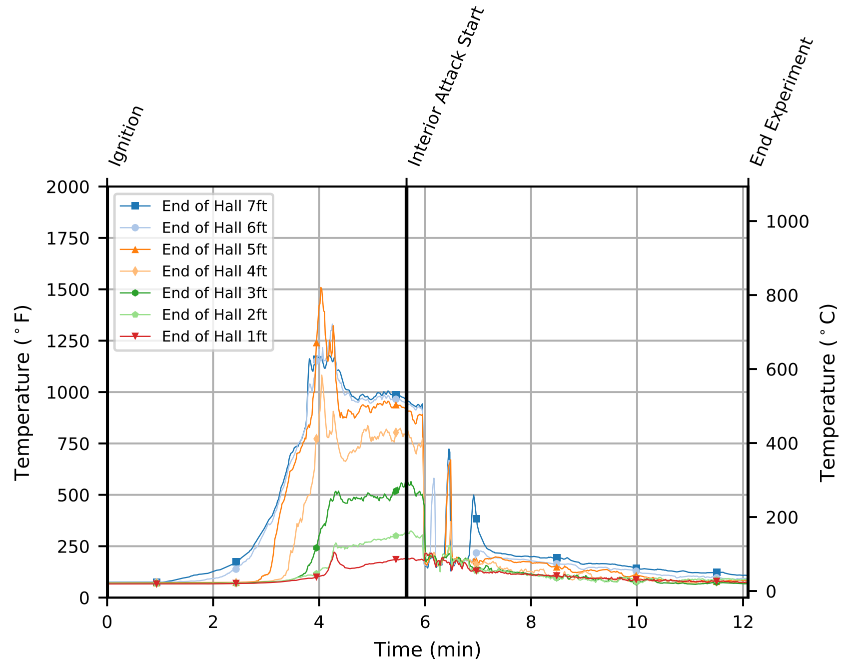


Figure E.539: Experiment 15 - End Hall Temps

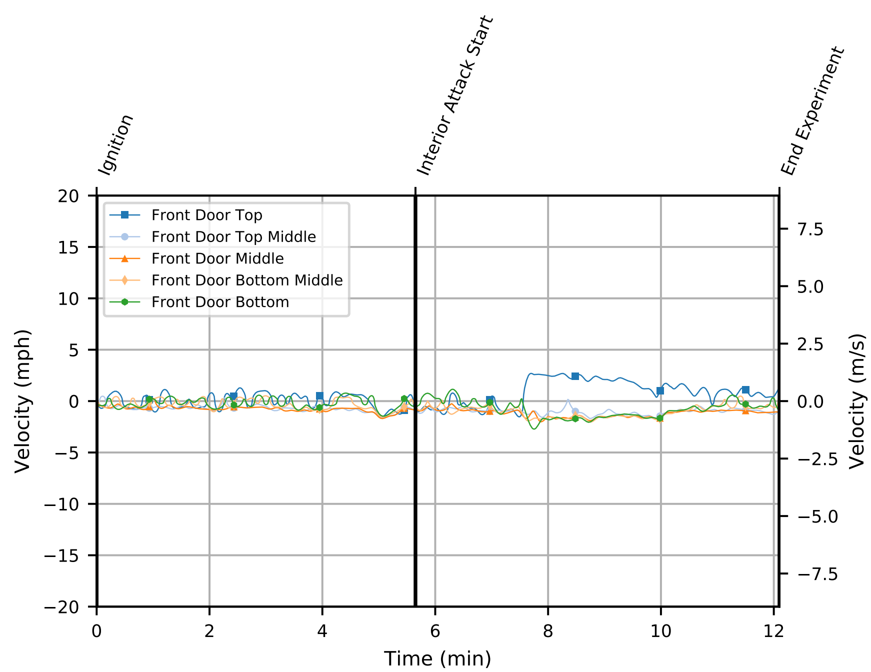


Figure E.540: Experiment 15 - Front Door Flow

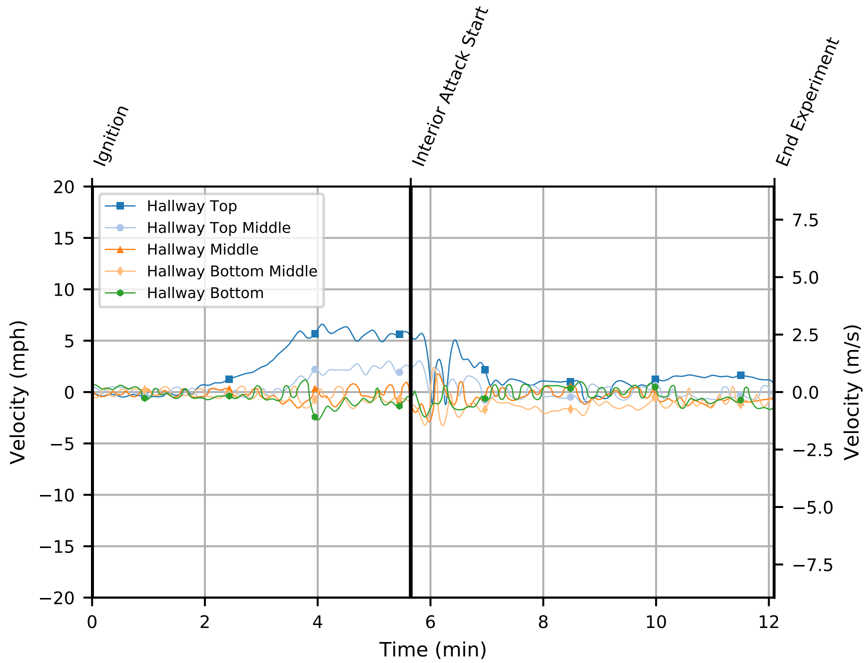


Figure E.541: Experiment 15 - Hallway Flow

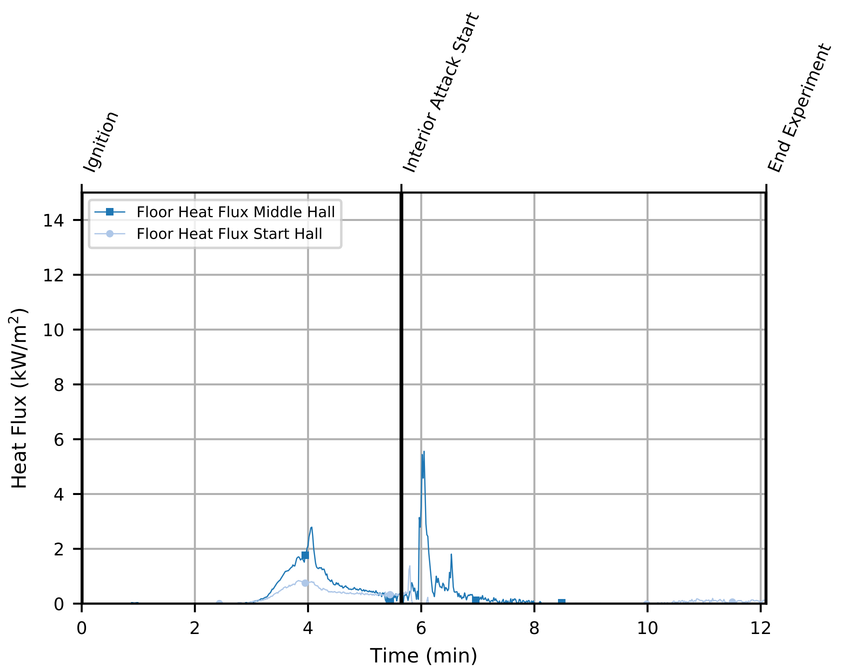


Figure E.542: Experiment 15 - Heat Flux Floor

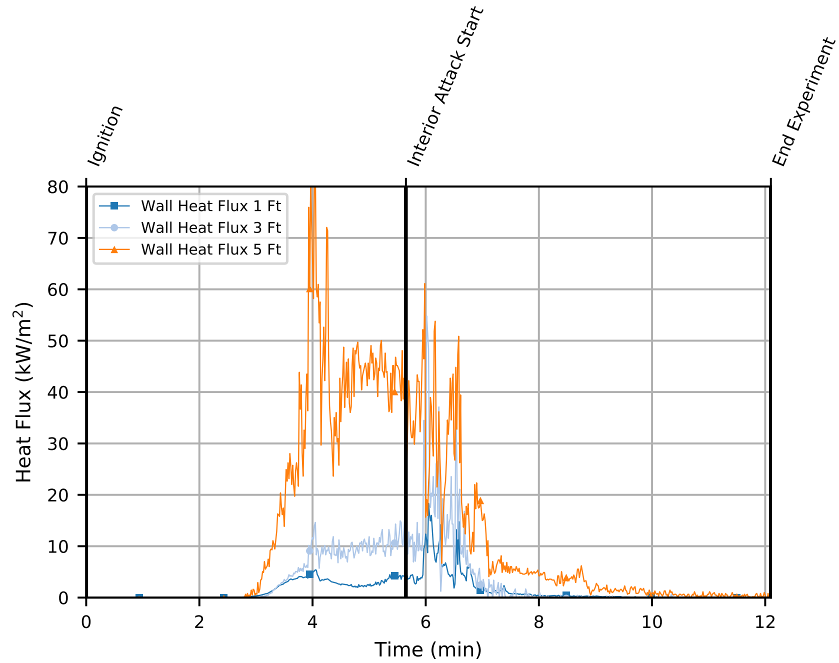


Figure E.543: Experiment 15 - Heat Flux Wall

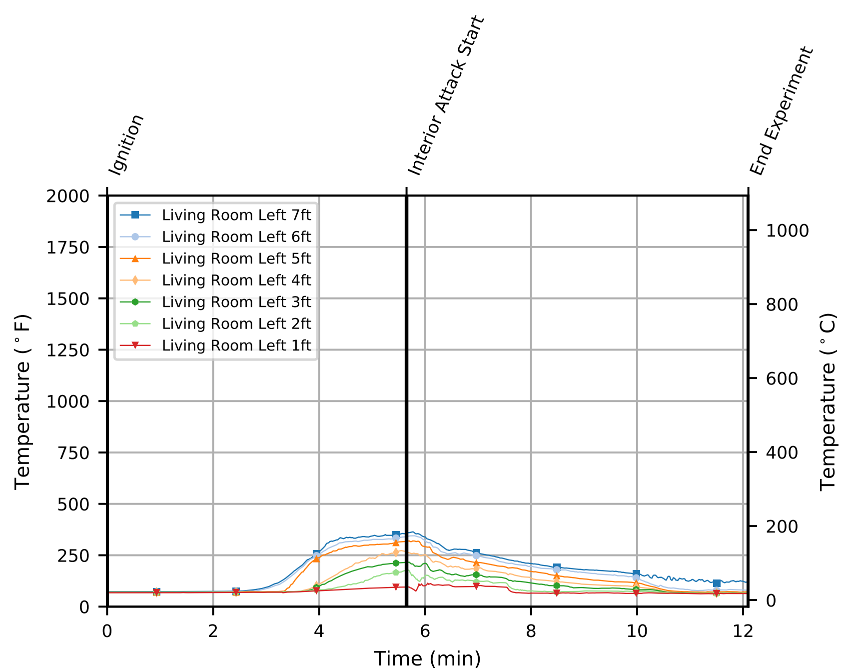


Figure E.544: Experiment 15 - Living Room Left Temps

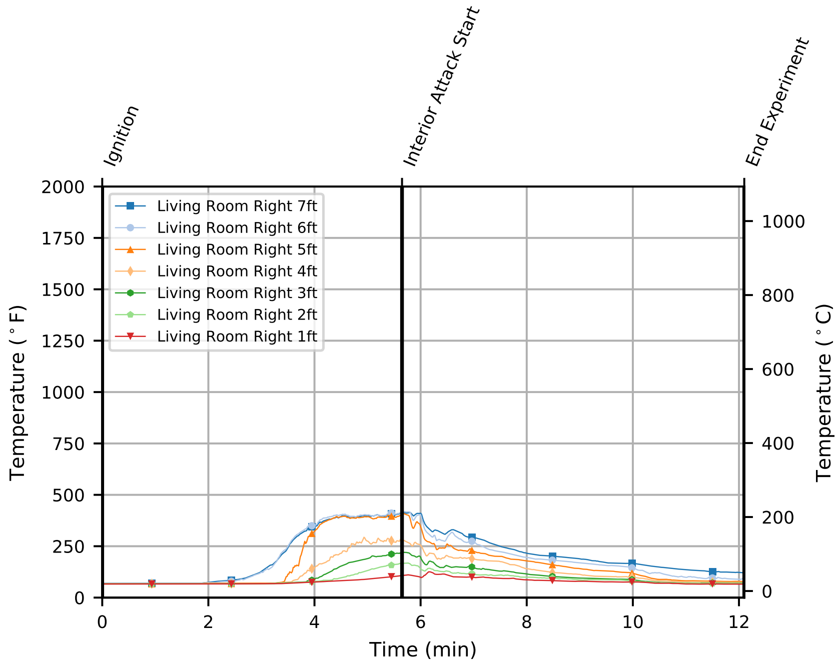


Figure E.545: Experiment 15 - Living Room Right Temps

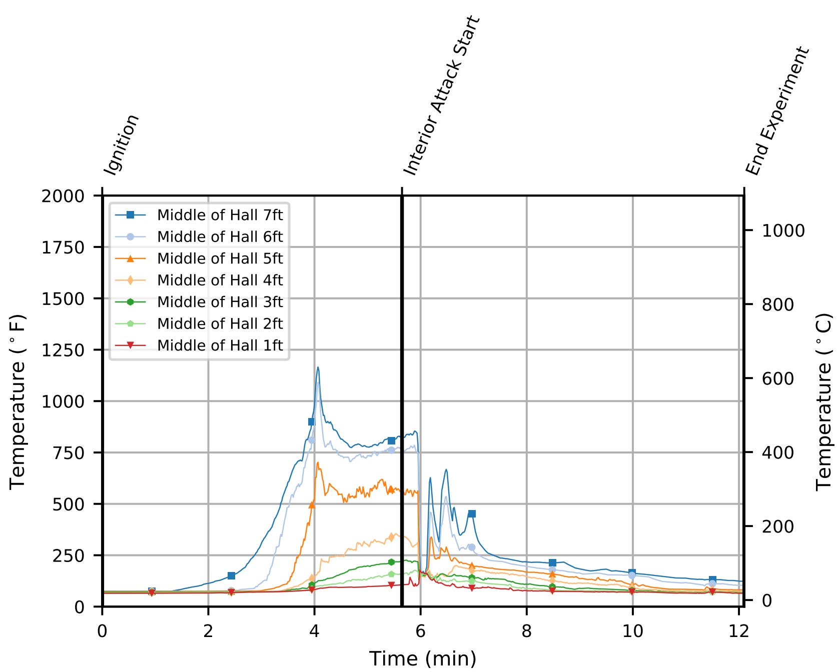


Figure E.546: Experiment 15 - Middle Hall Temps

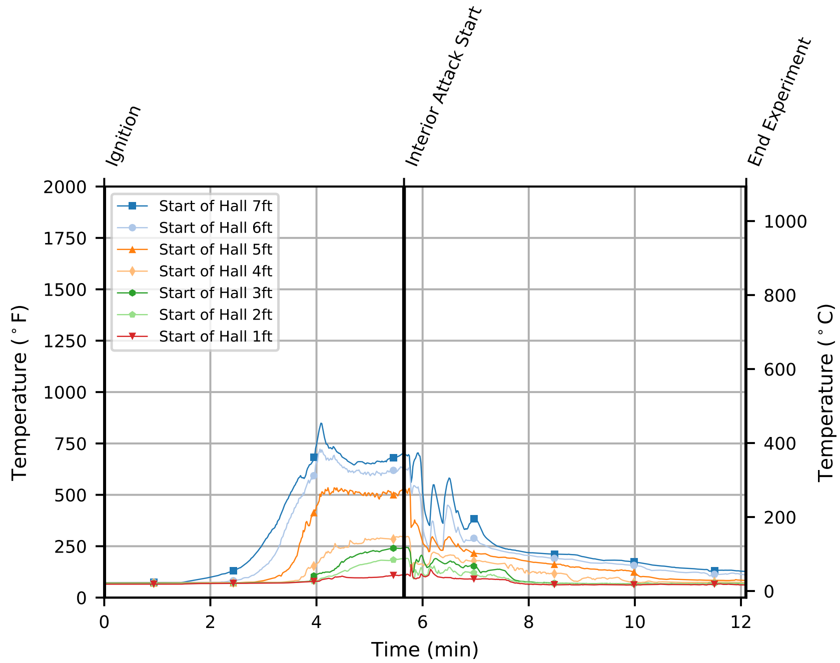


Figure E.547: Experiment 15 - Start Hall Temps

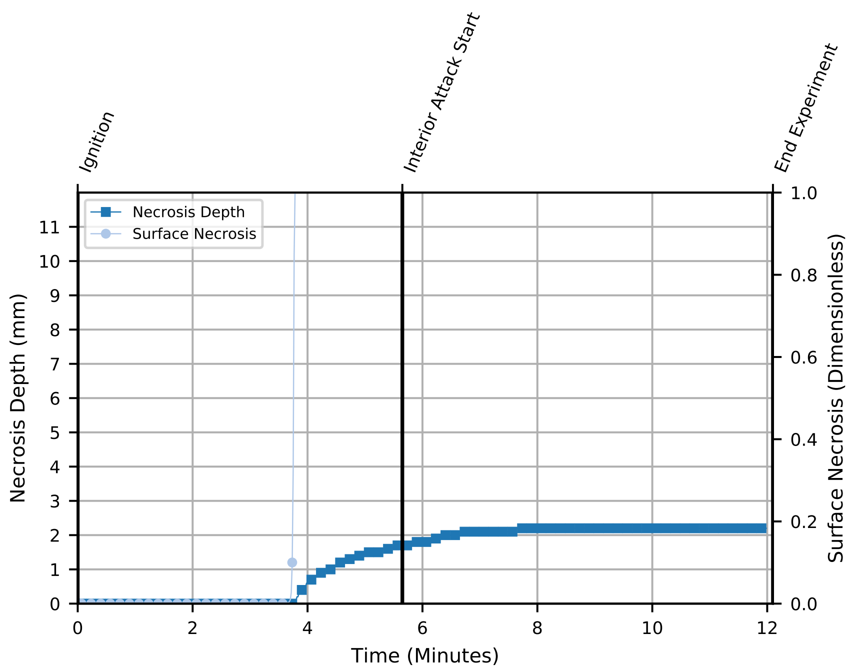


Figure E.548: Experiment 15 - Vic 1 Necrosis Depth

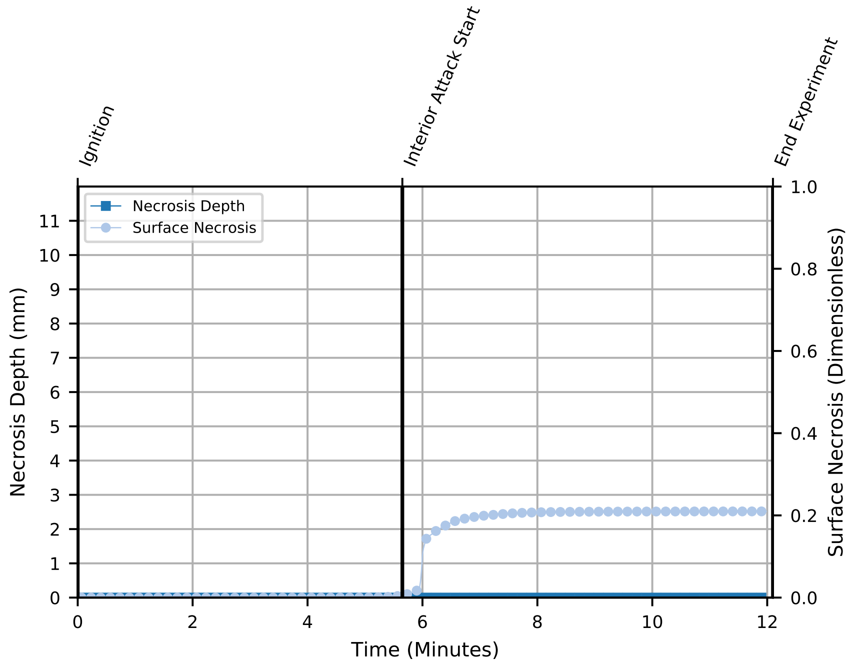


Figure E.549: Experiment 15 - Vic 3 Necrosis Depth

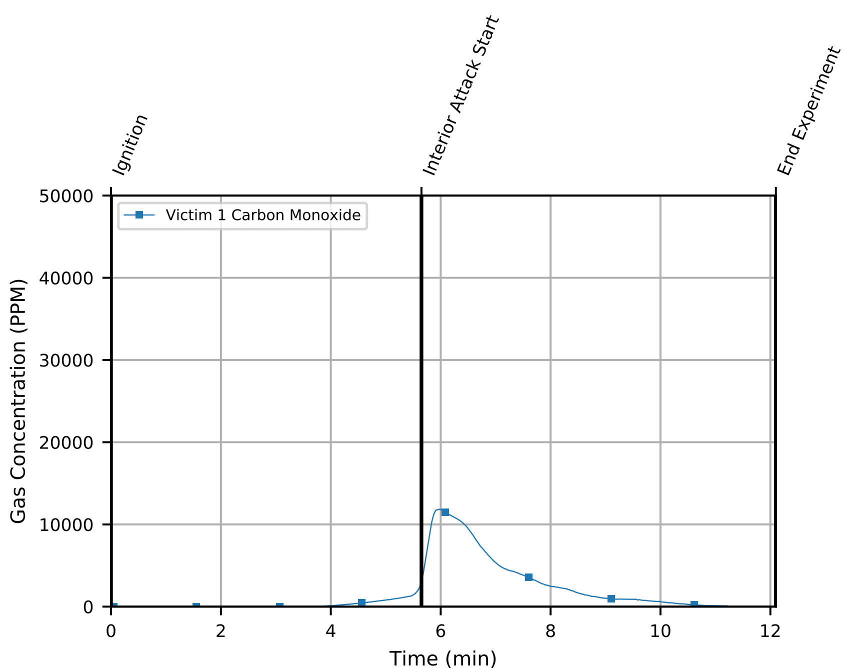


Figure E.550: Experiment 15 - Victim 1 Carbon Monoxide

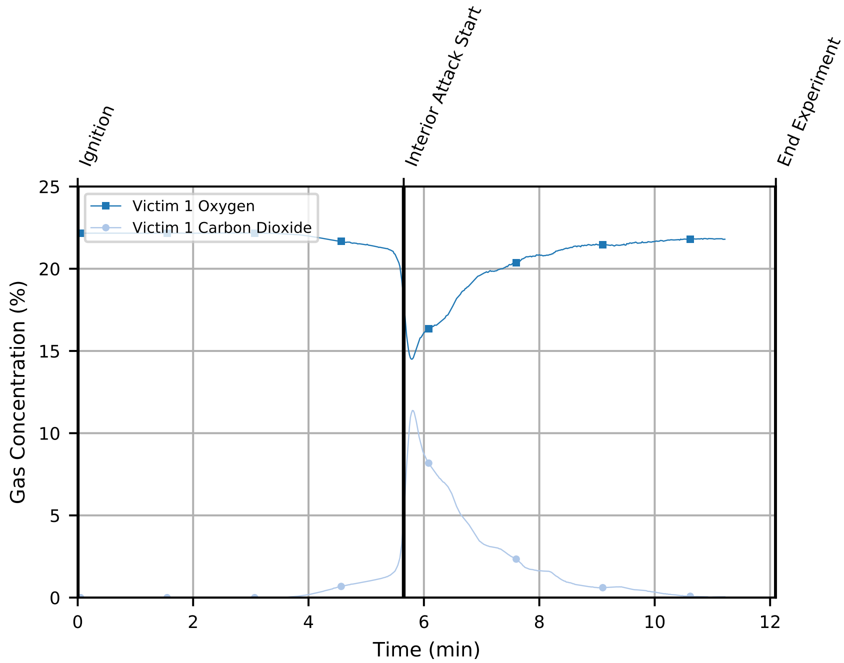


Figure E.551: Experiment 15 - Victim 1 Gas

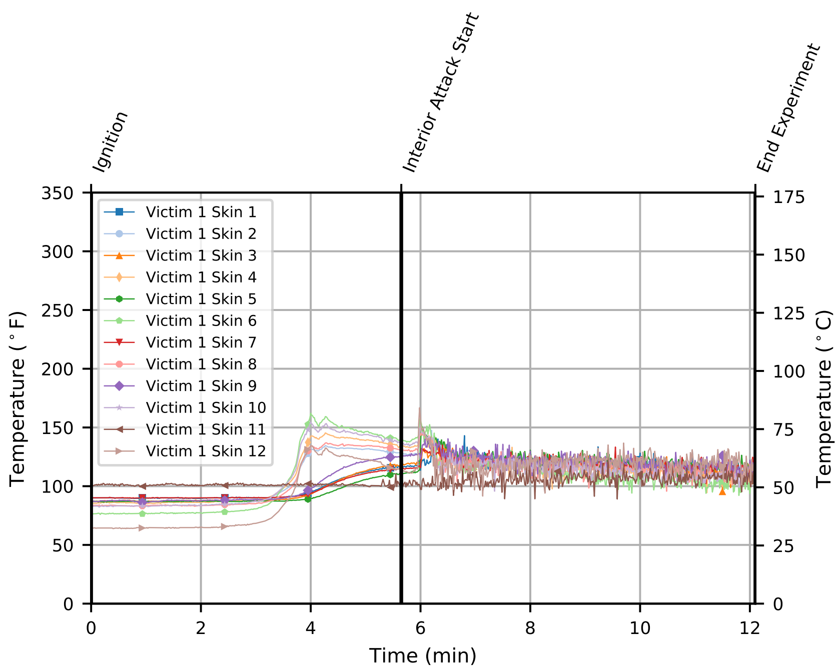


Figure E.552: Experiment 15 - Victim 1 Skin Temps

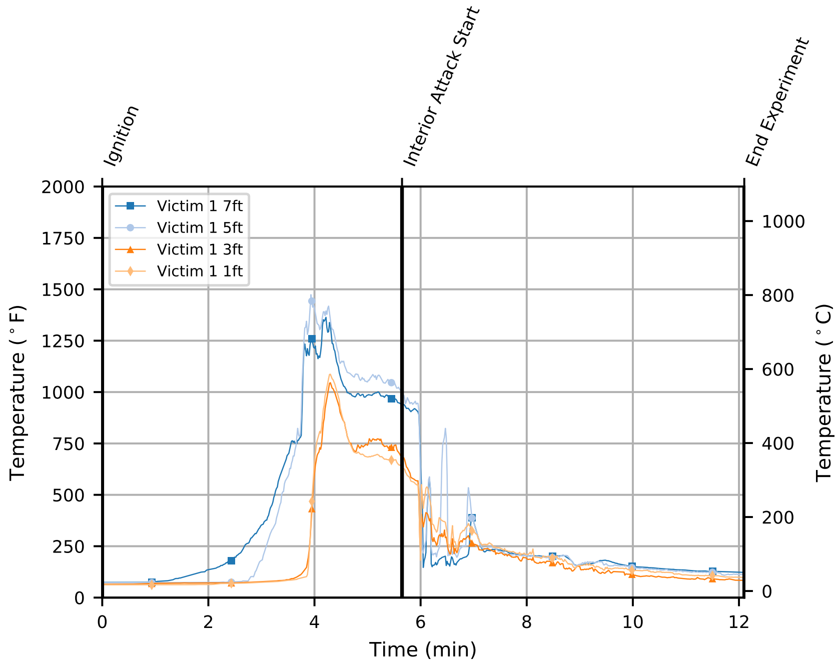


Figure E.553: Experiment 15 - Victim 1 Temps

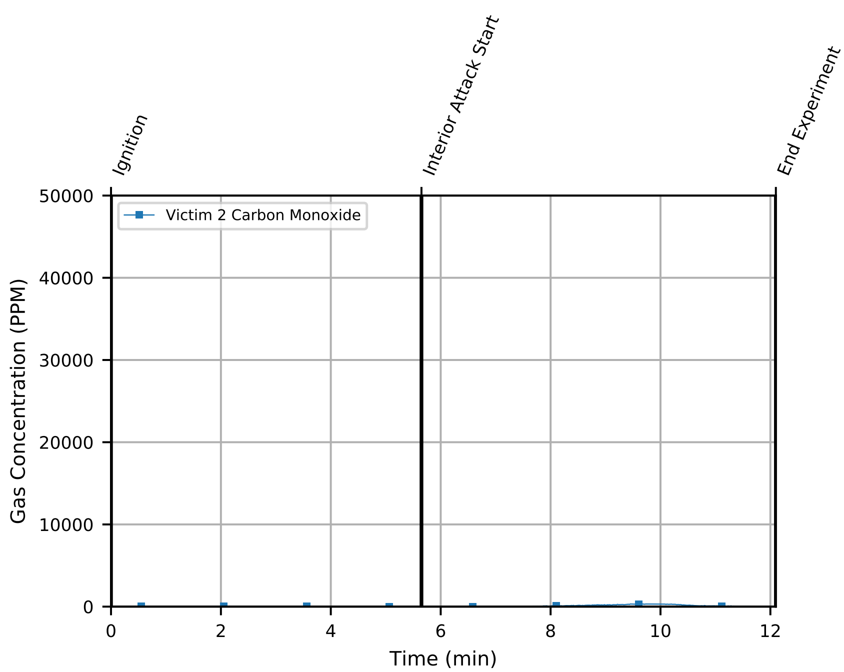


Figure E.554: Experiment 15 - Victim 2 Carbon Monoxide

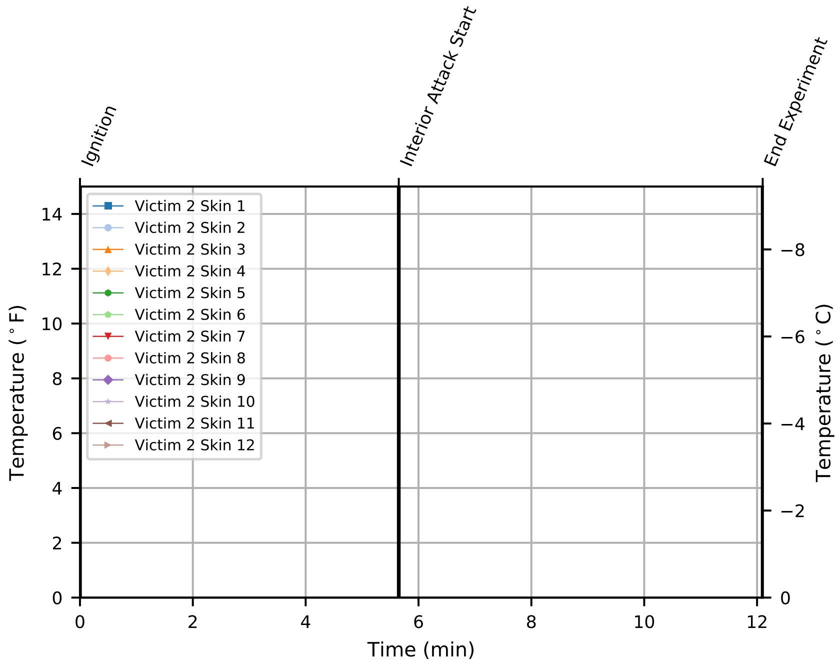


Figure E.555: Experiment 15 - Victim 2 Skin Temps

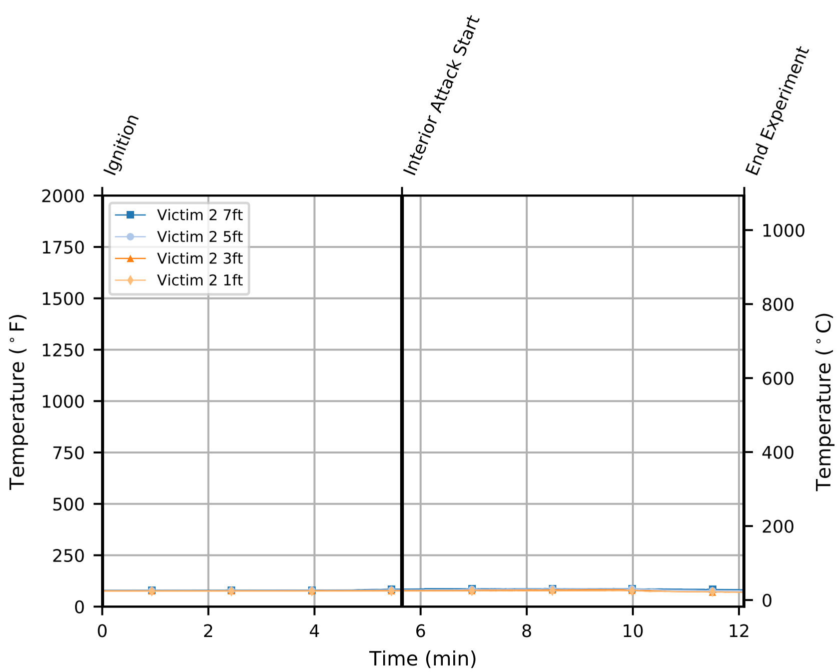


Figure E.556: Experiment 15 - Victim 2 Temps

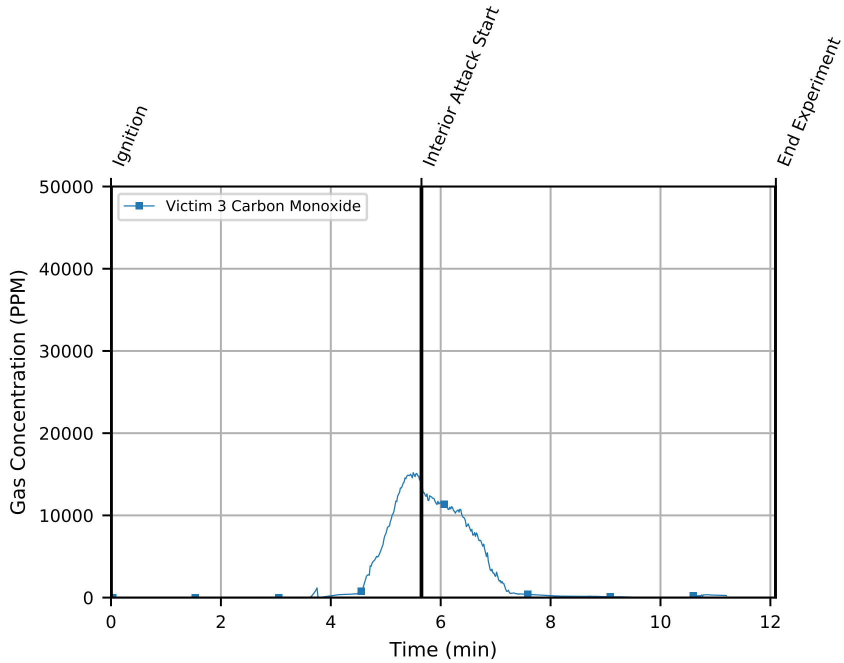


Figure E.557: Experiment 15 - Victim 3 Carbon Monoxide

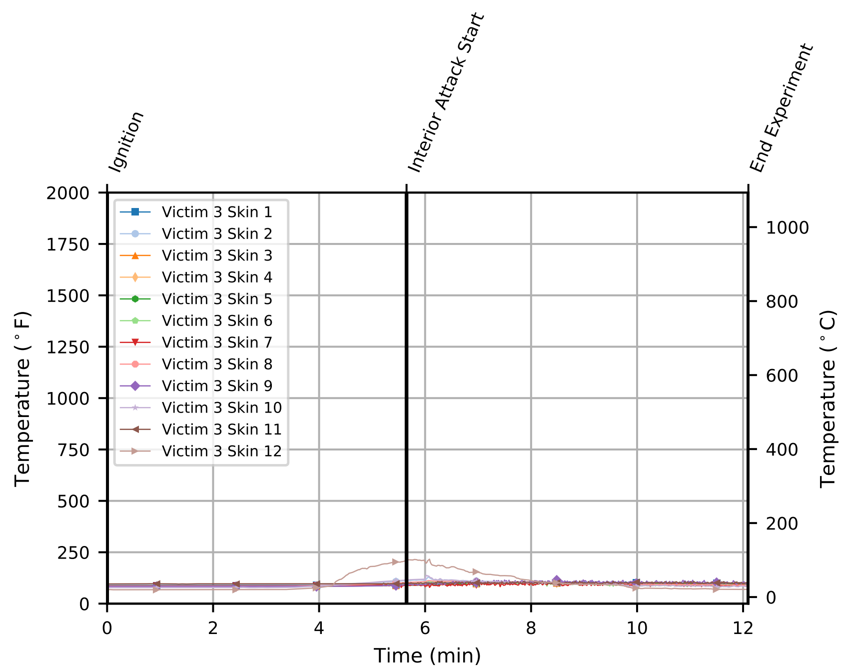


Figure E.558: Experiment 15 - Victim 3 Skin Temps

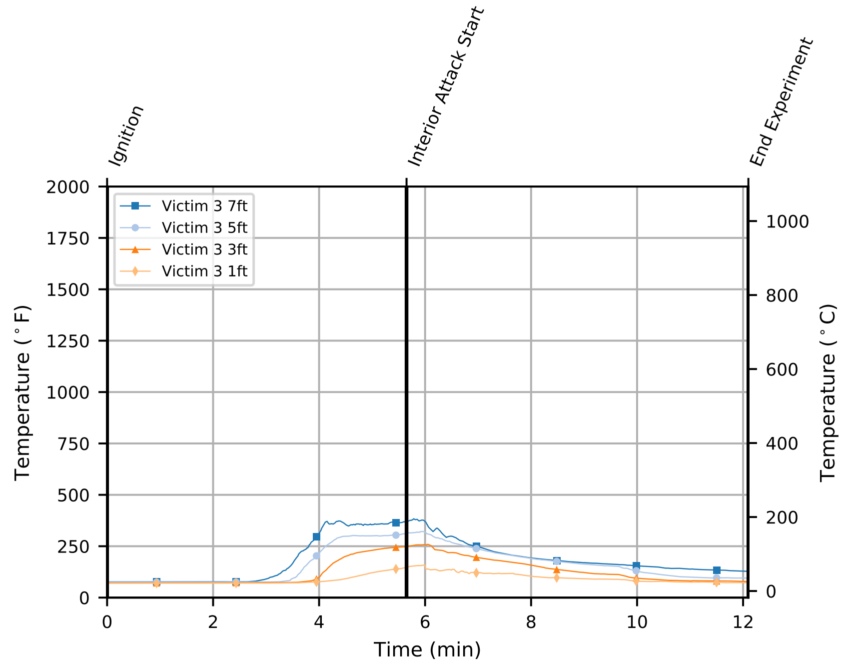


Figure E.559: Experiment 15 - Victim 3 Temps

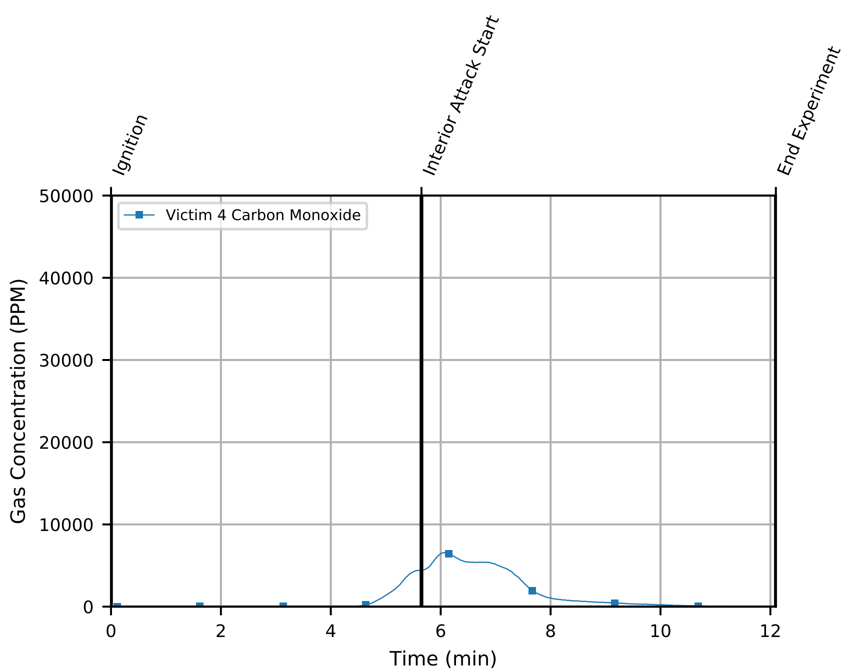


Figure E.560: Experiment 15 - Victim 4 Carbon Monoxide

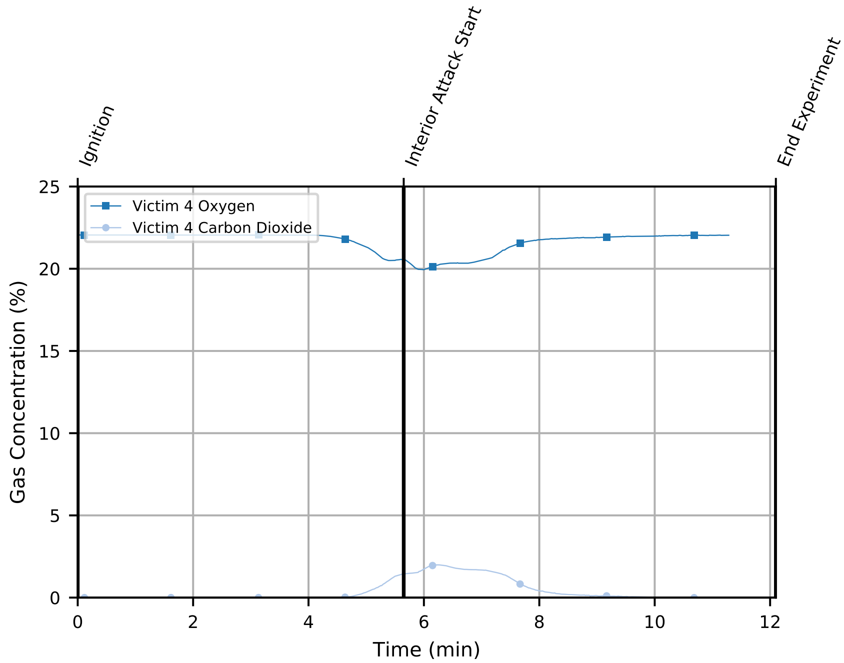


Figure E.561: Experiment 15 - Victim 4 Gas

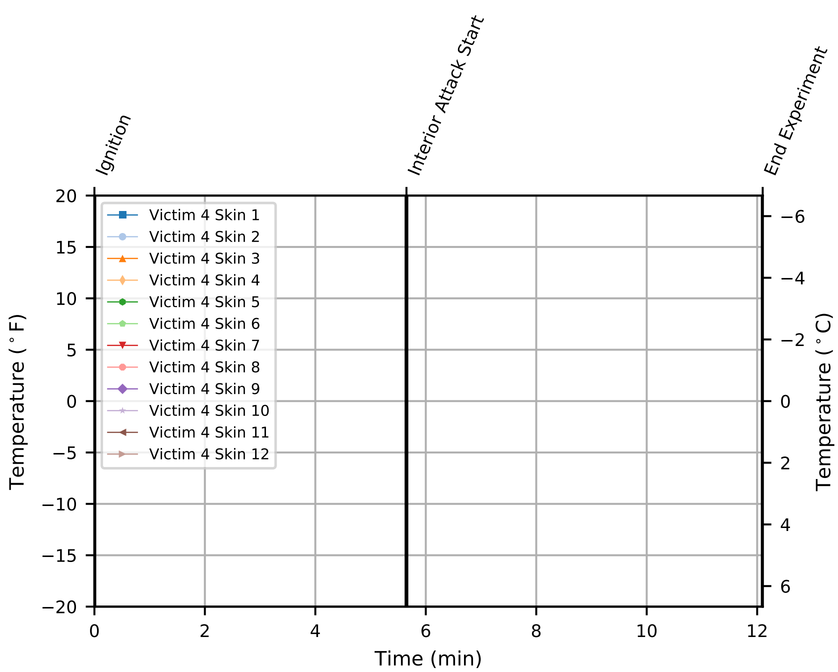


Figure E.562: Experiment 15 - Victim 4 Skin Temps

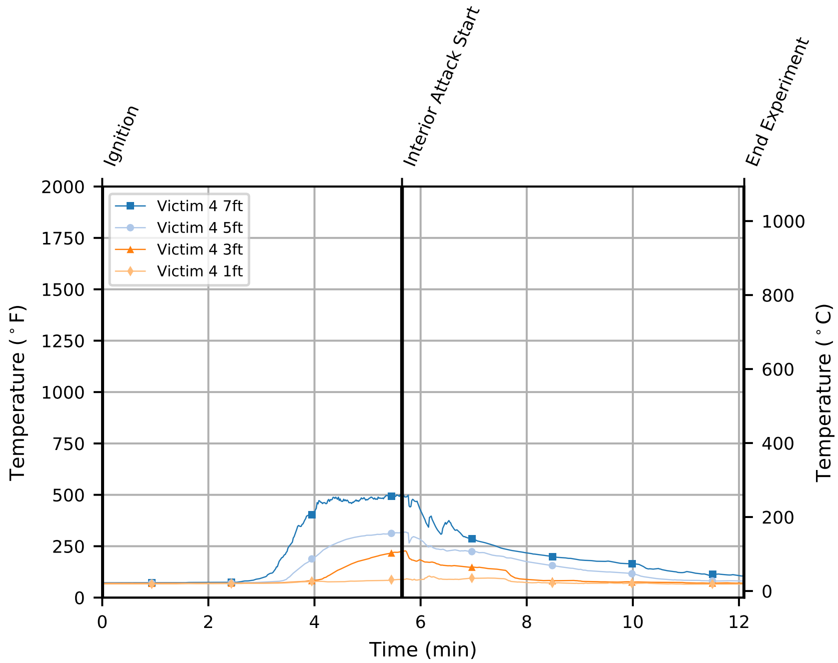


Figure E.563: Experiment 15 - Victim 4 Temps

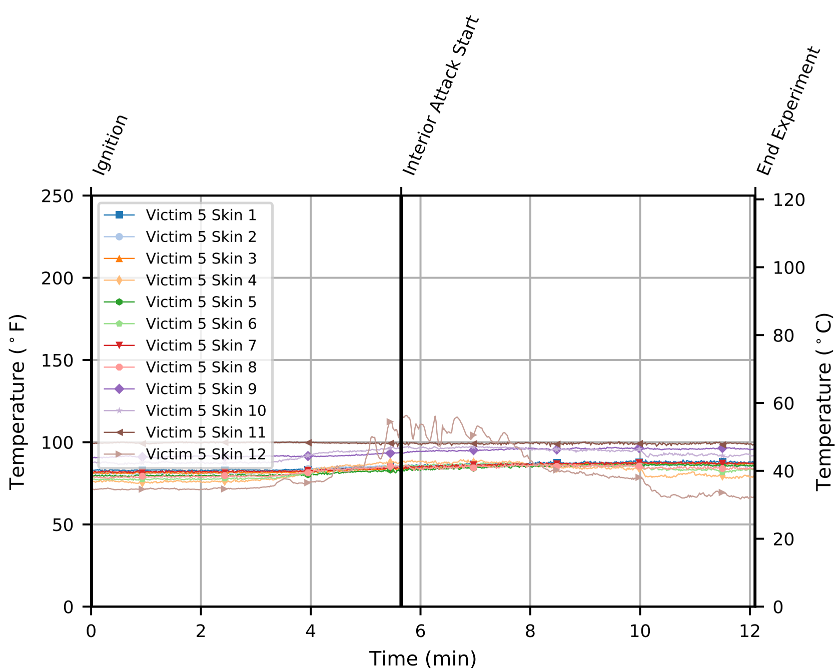


Figure E.564: Experiment 15 - Victim 5 Skin Temps

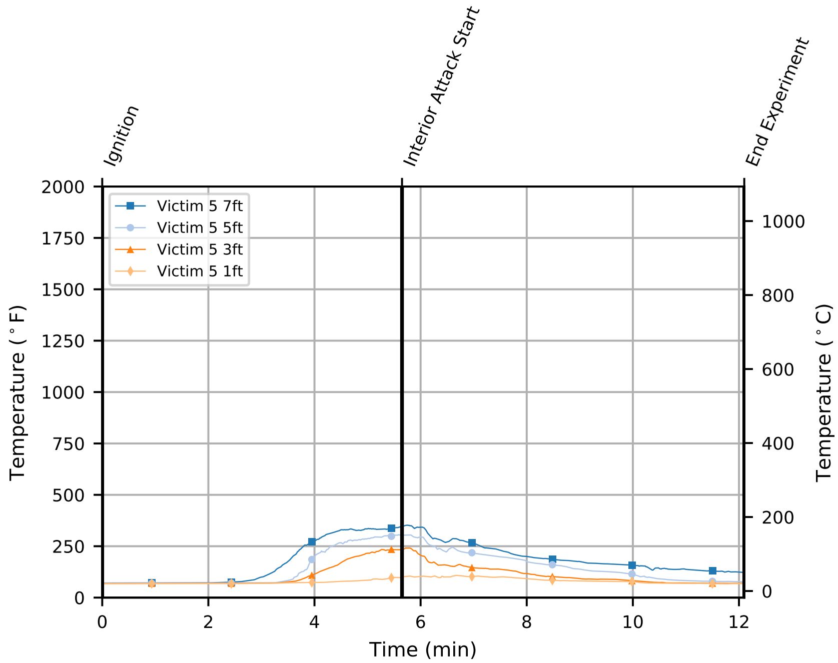


Figure E.565: Experiment 15 - Victim 5 Temps

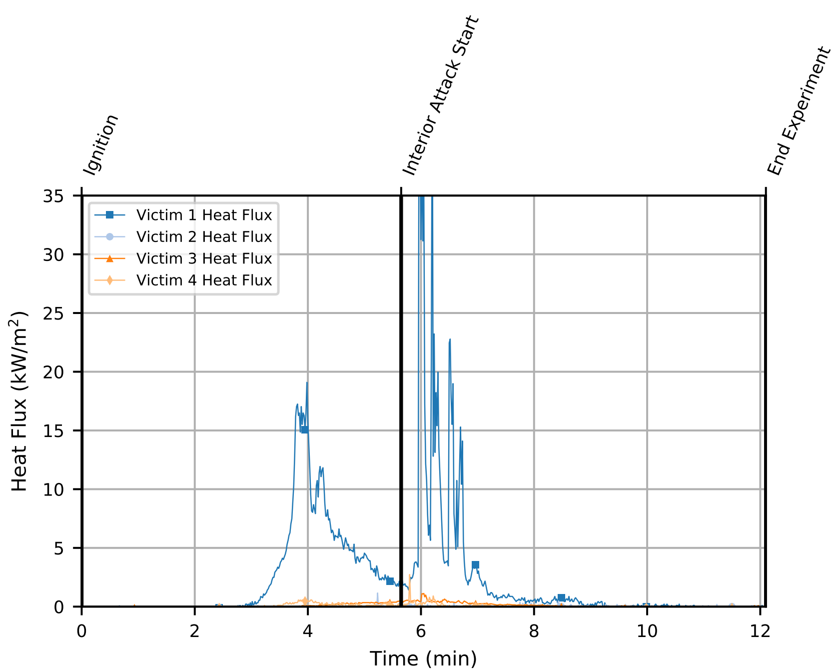


Figure E.566: Experiment 15 - Victim Heat Flux

E.16 Experiment 16 Data

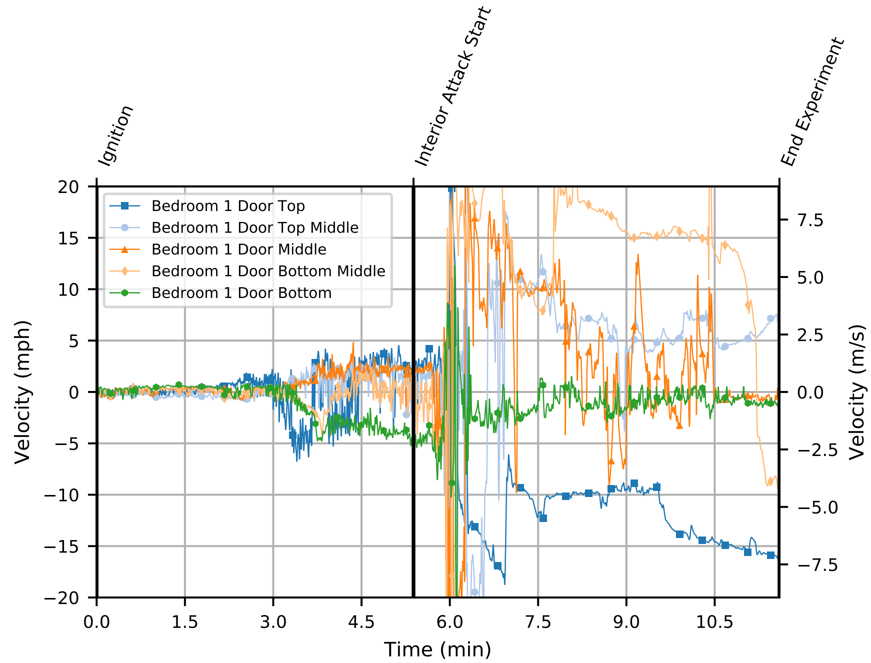


Figure E.567: Experiment 16 - Bedroom 1 Door

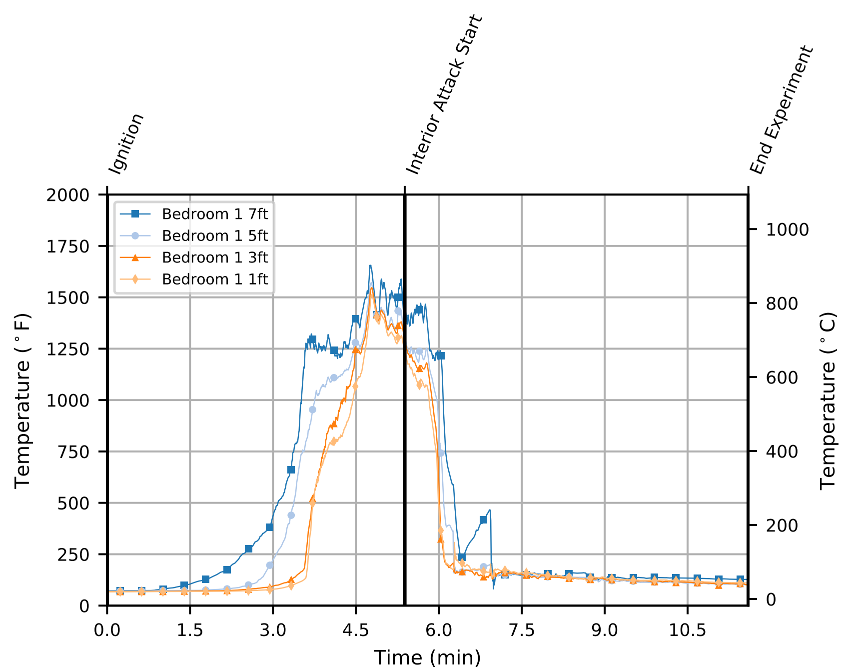


Figure E.568: Experiment 16 - Bedroom 1 Temps

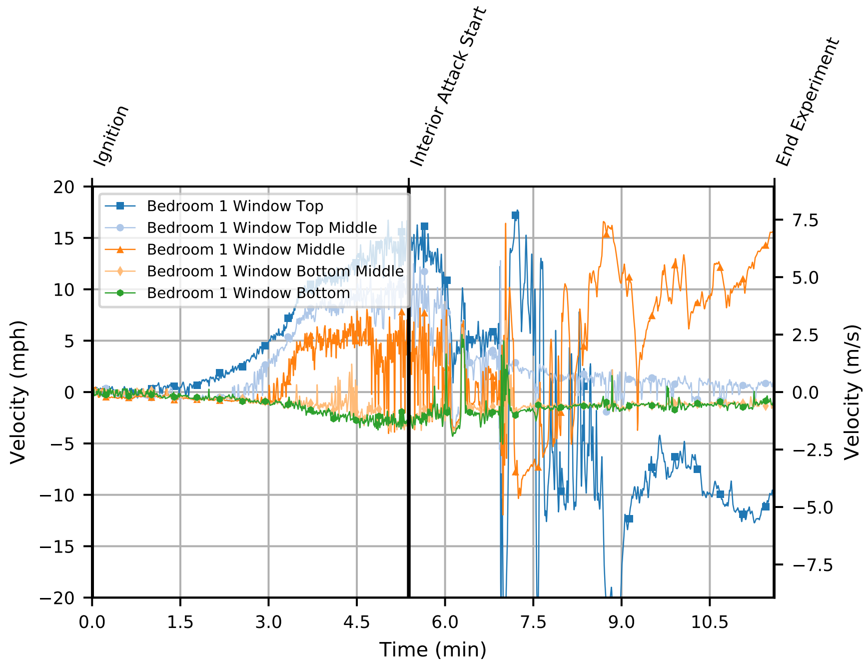


Figure E.569: Experiment 16 - Bedroom 1 Window

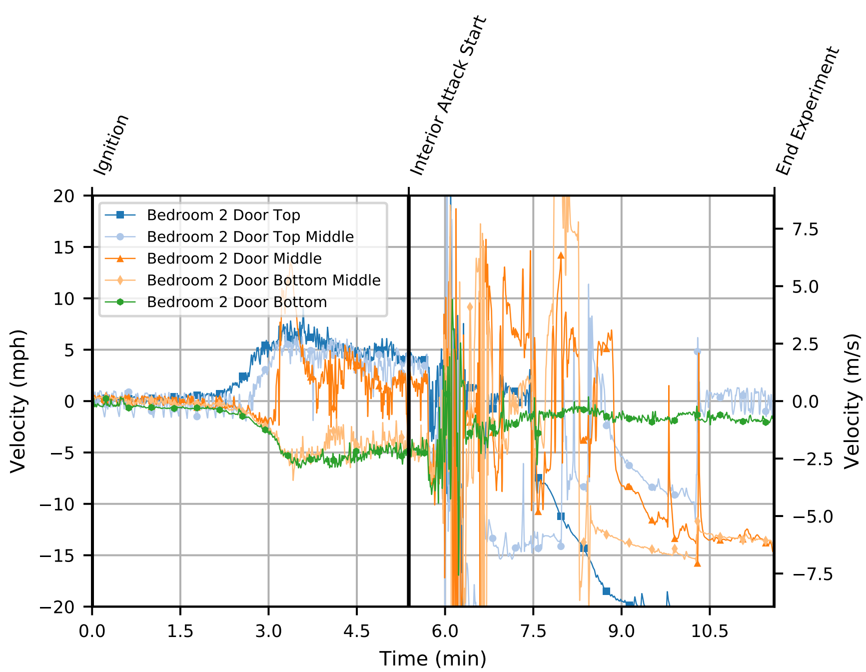


Figure E.570: Experiment 16 - Bedroom 2 Door

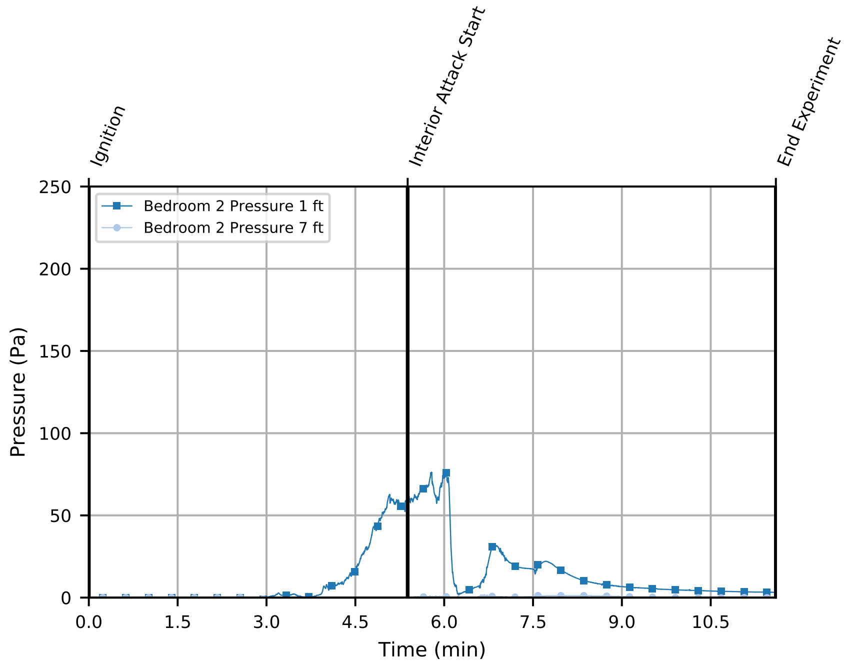


Figure E.571: Experiment 16 - Bedroom 2 Pressure

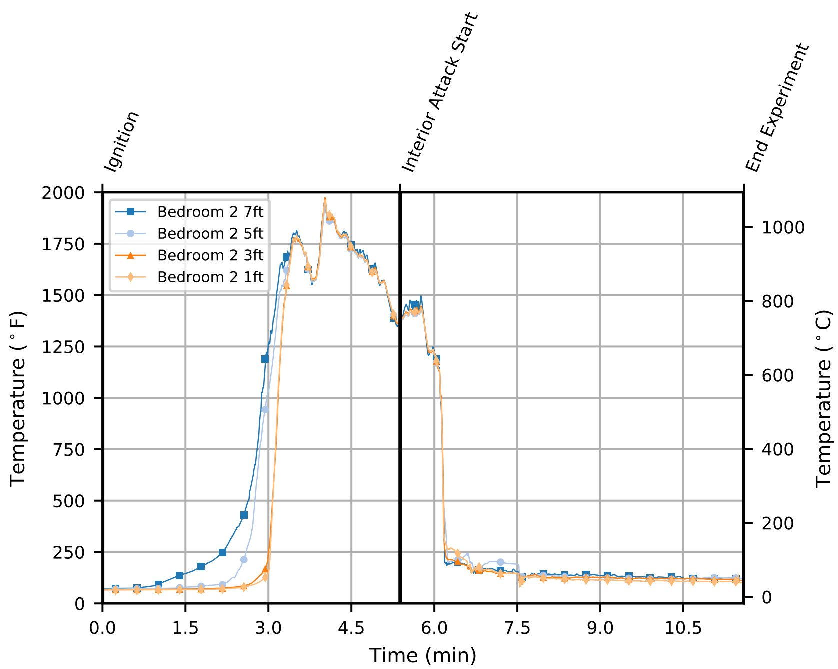


Figure E.572: Experiment 16 - Bedroom 2 Temps

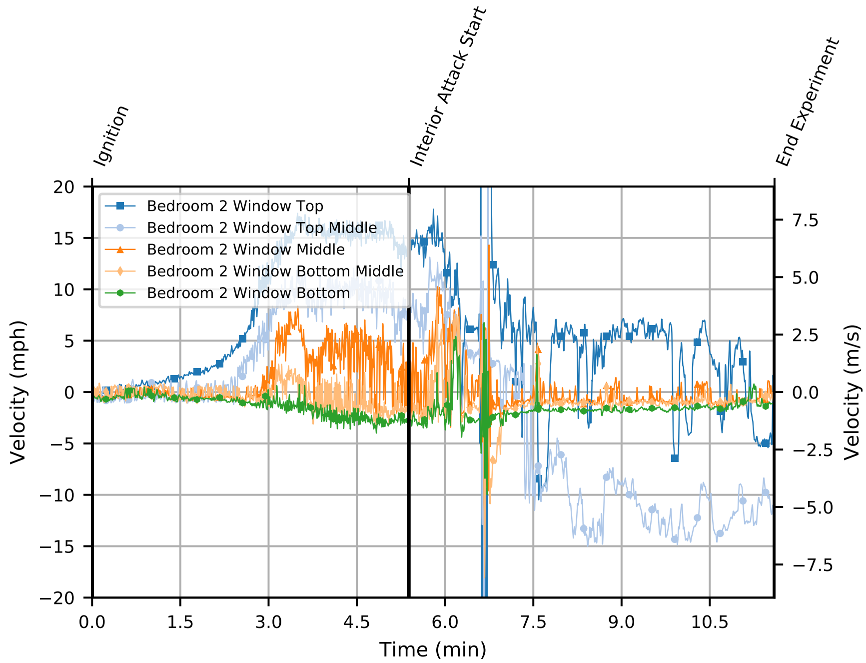


Figure E.573: Experiment 16 - Bedroom 2 Window

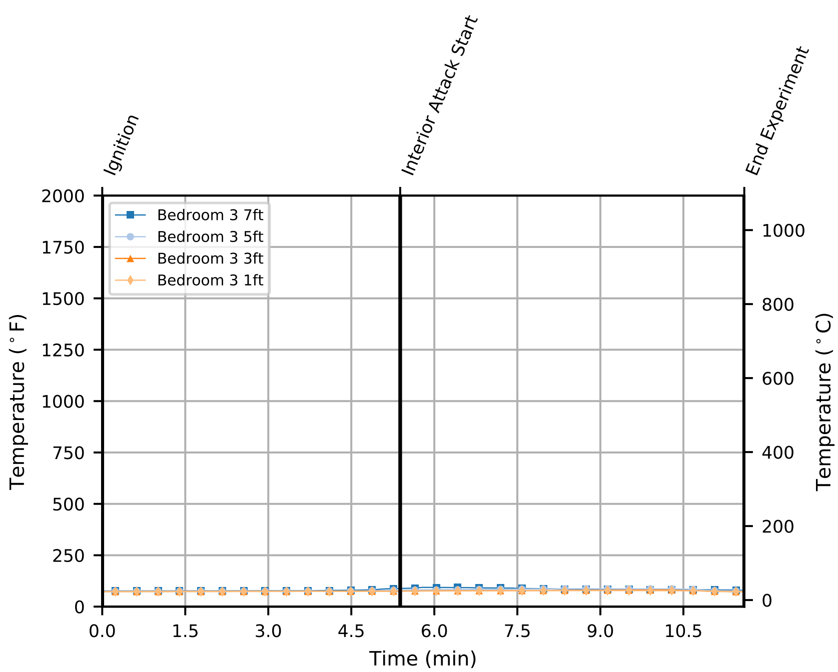


Figure E.574: Experiment 16 - Bedroom 3 Temps

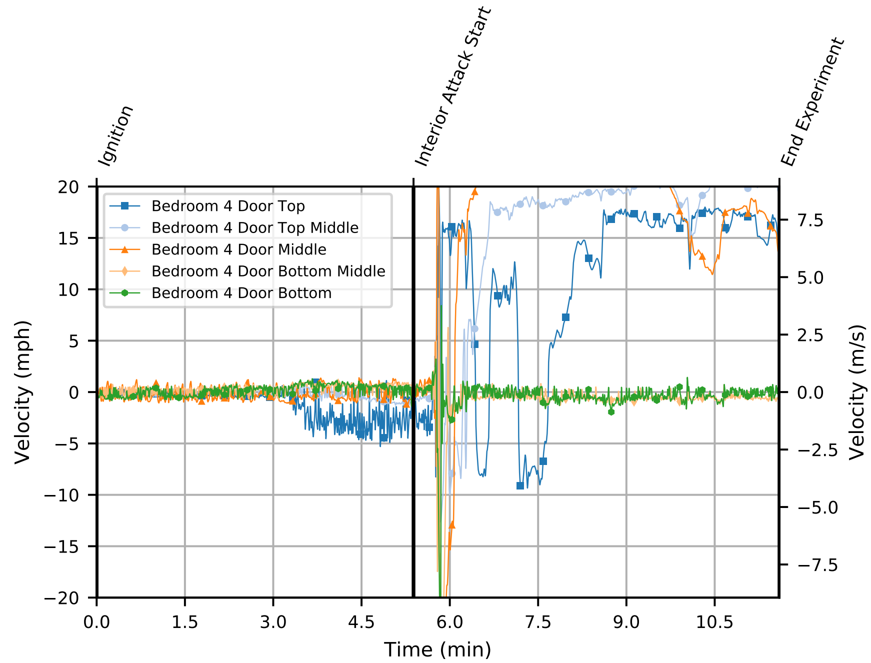


Figure E.575: Experiment 16 - Bedroom 4 Door

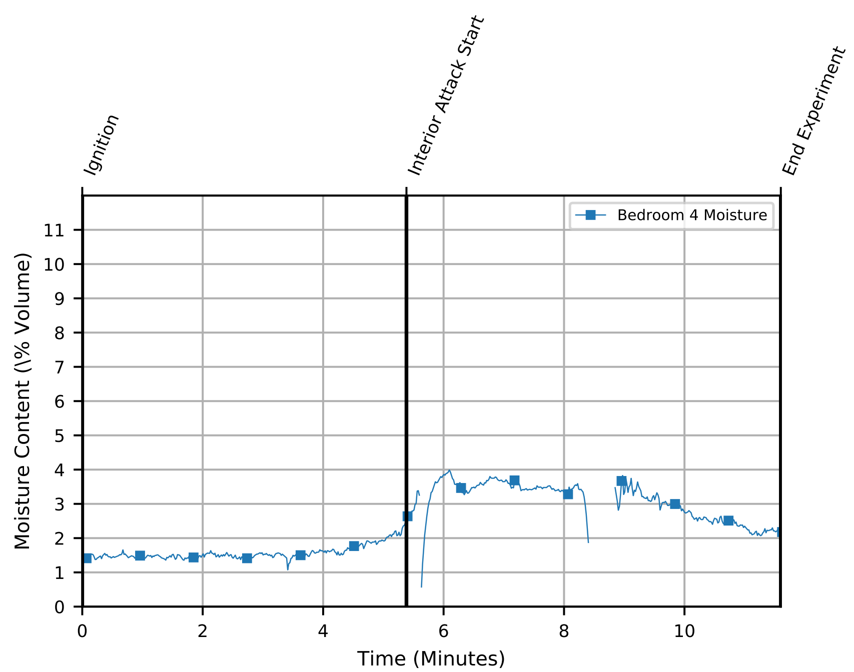


Figure E.576: Experiment 16 - Bedroom 4 Moisture

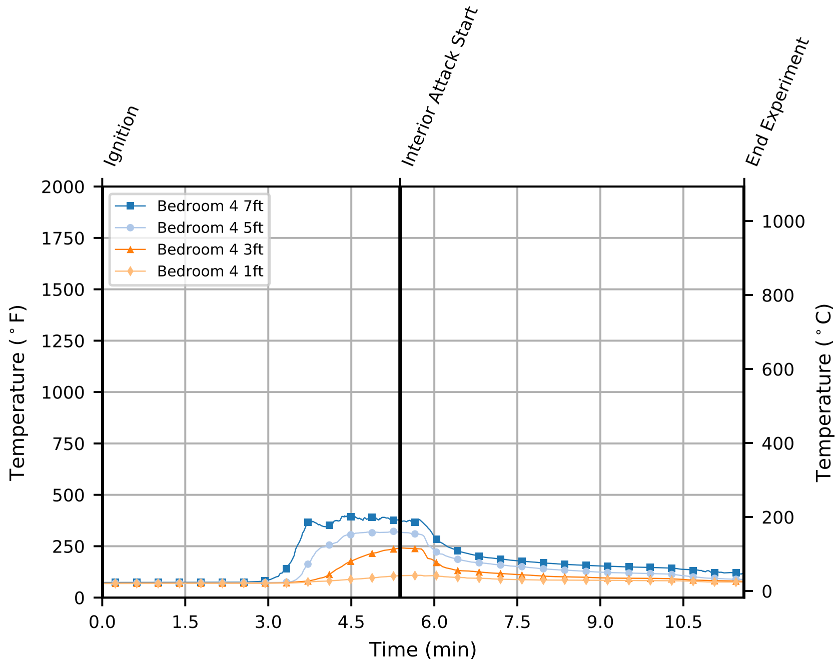


Figure E.577: Experiment 16 - Bedroom 4 Temps

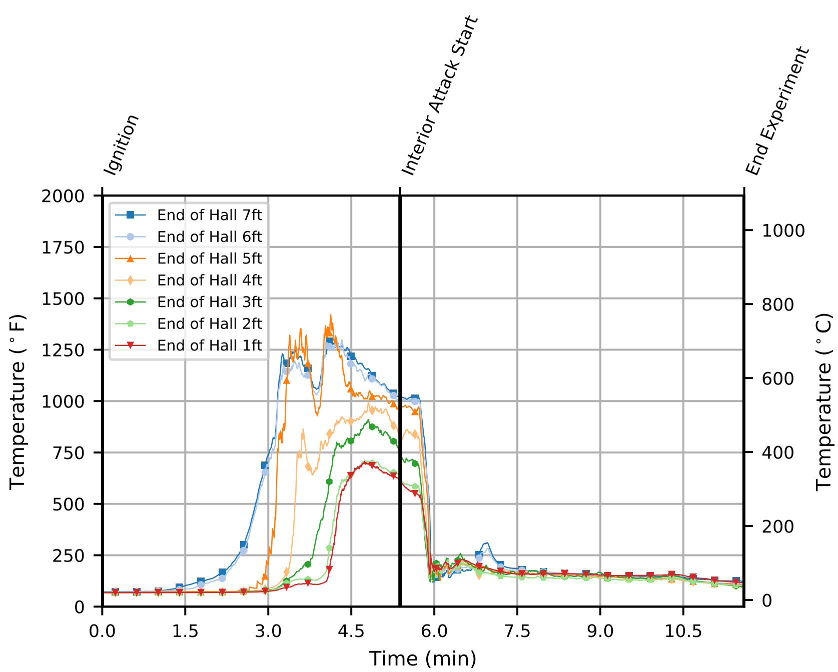


Figure E.578: Experiment 16 - End Hall Temps

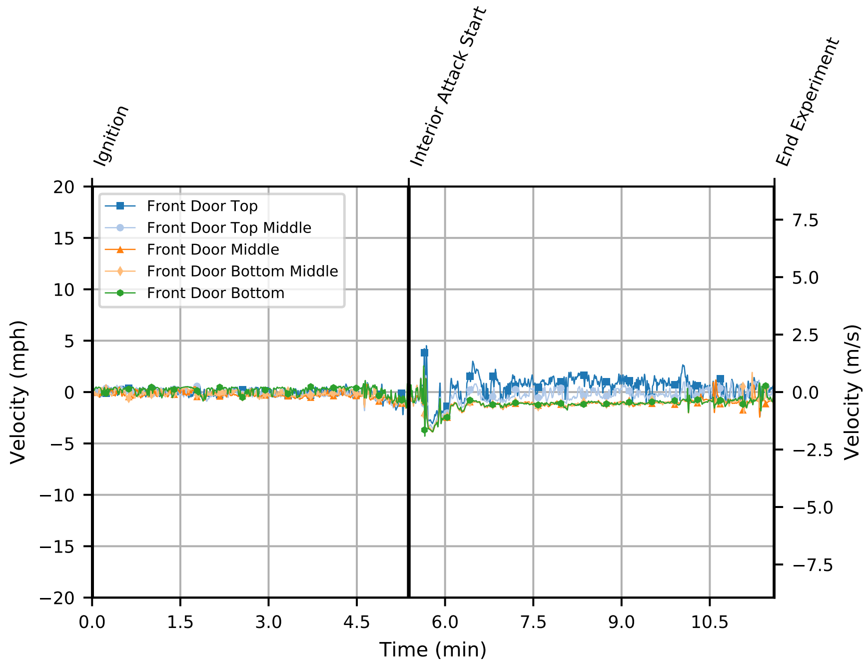


Figure E.579: Experiment 16 - Front Door Flow

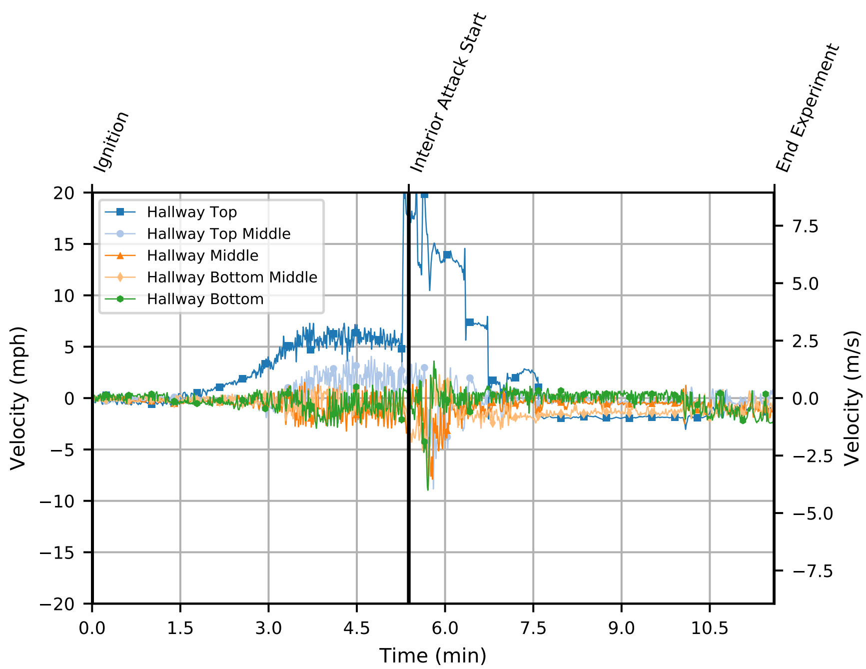


Figure E.580: Experiment 16 - Hallway Flow

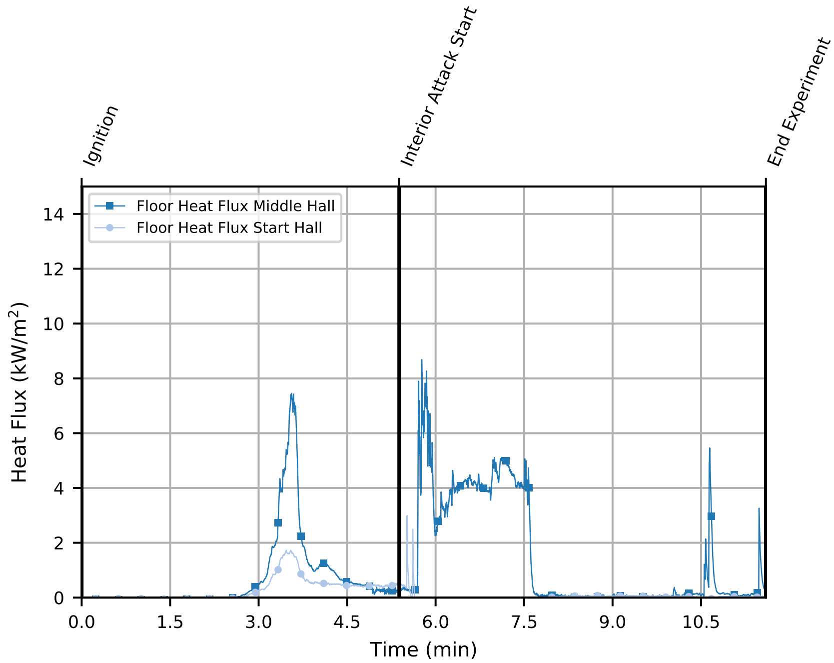


Figure E.581: Experiment 16 - Heat Flux Floor

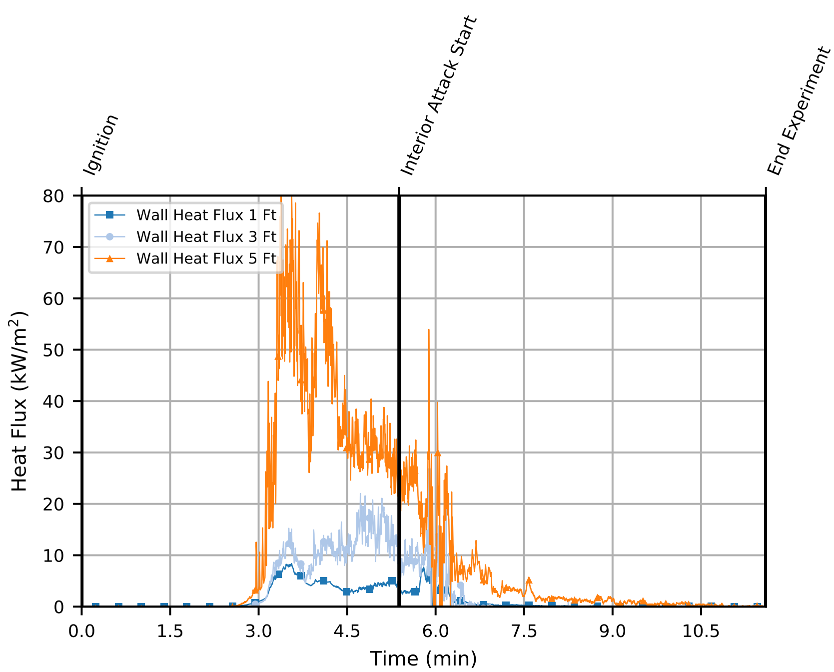


Figure E.582: Experiment 16 - Heat Flux Wall

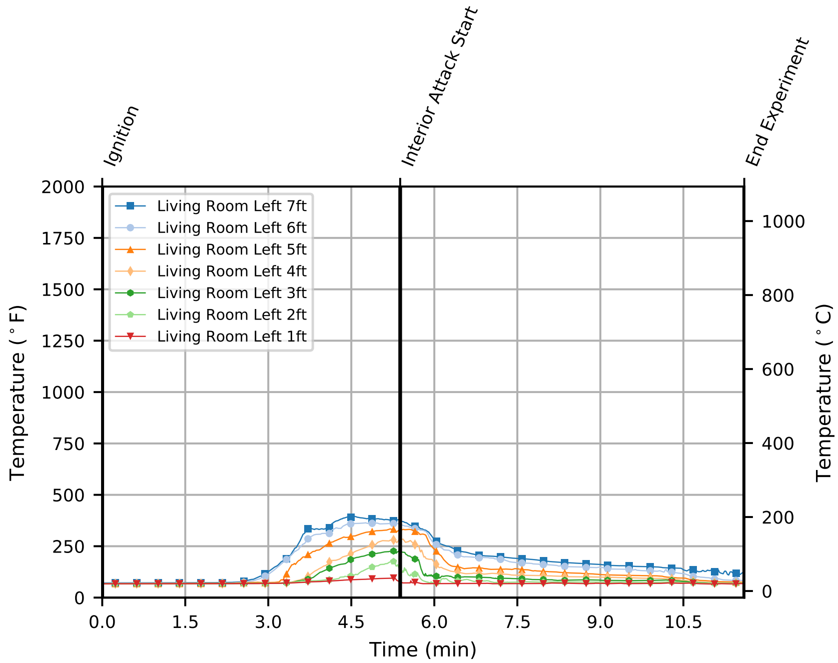


Figure E.583: Experiment 16 - Living Room Left Temps

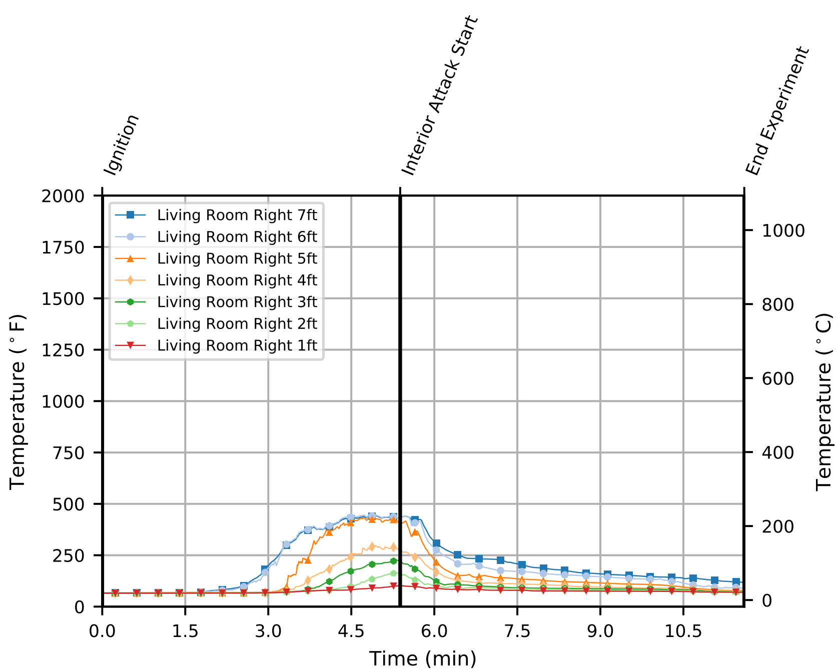


Figure E.584: Experiment 16 - Living Room Right Temps

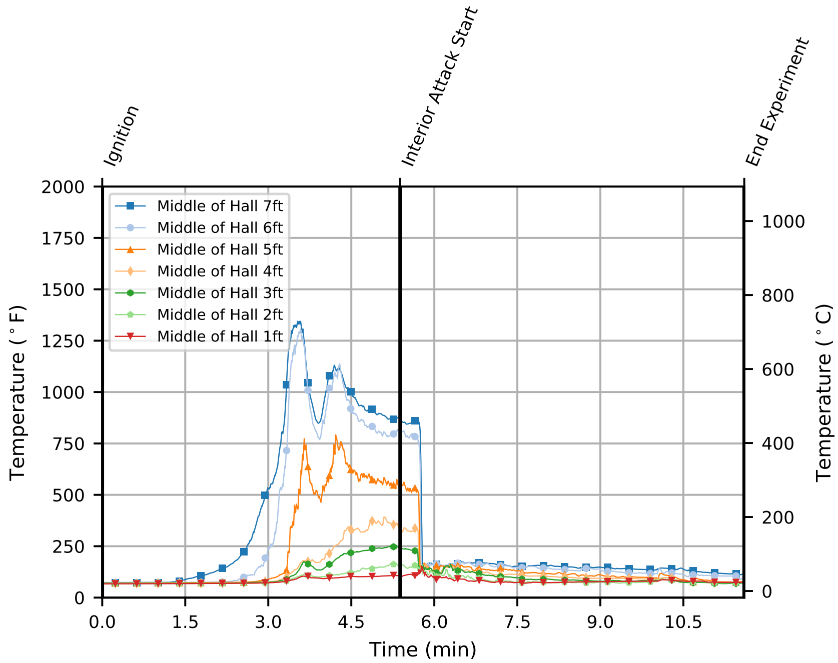


Figure E.585: Experiment 16 - Middle Hall Temps

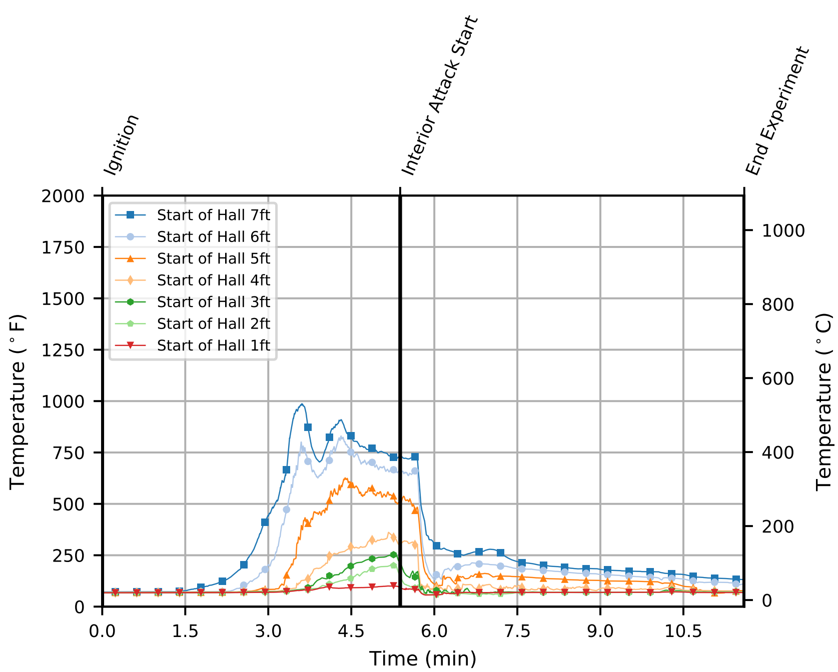


Figure E.586: Experiment 16 - Start Hall Temps

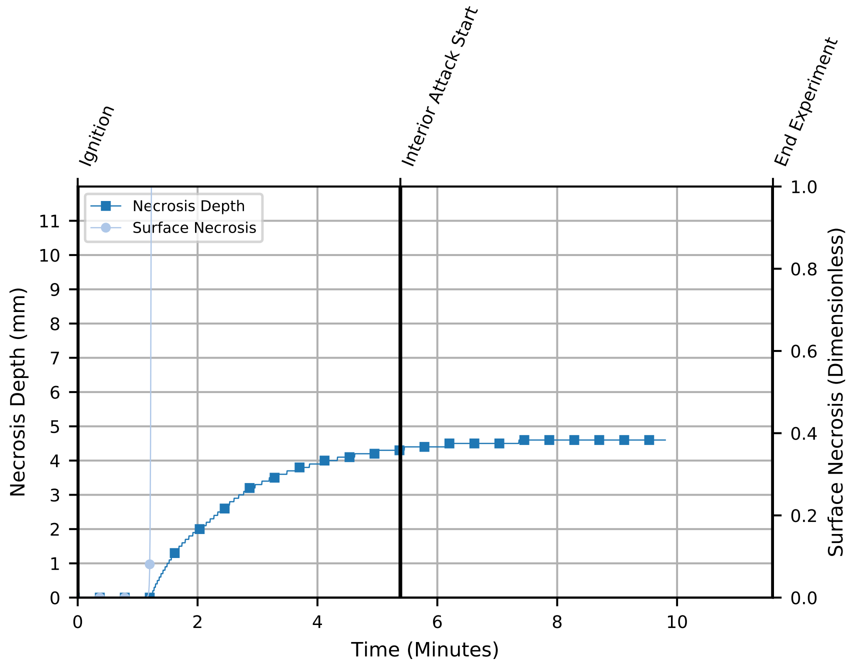


Figure E.587: Experiment 16 - Vic 1 Necrosis Depth

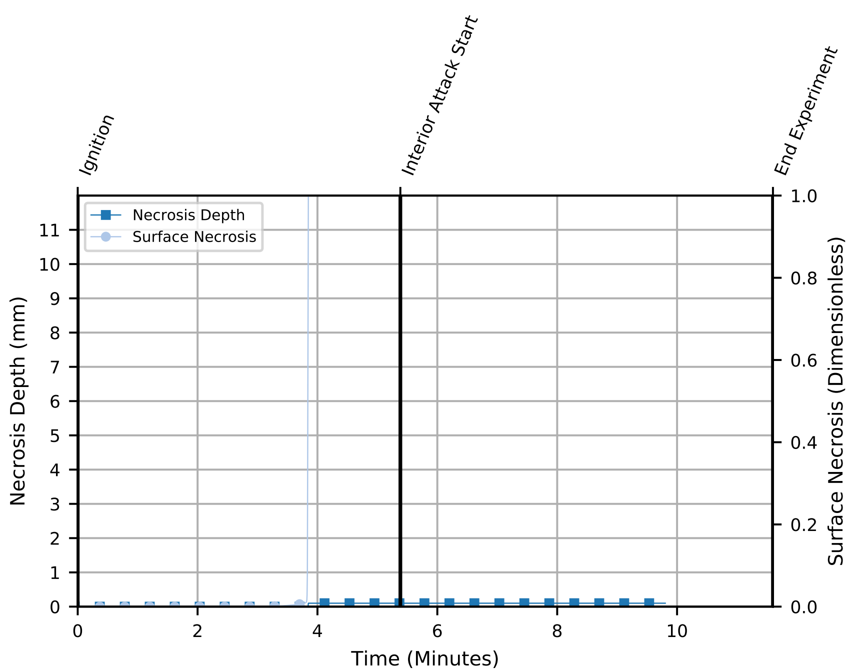


Figure E.588: Experiment 16 - Vic 3 Necrosis Depth

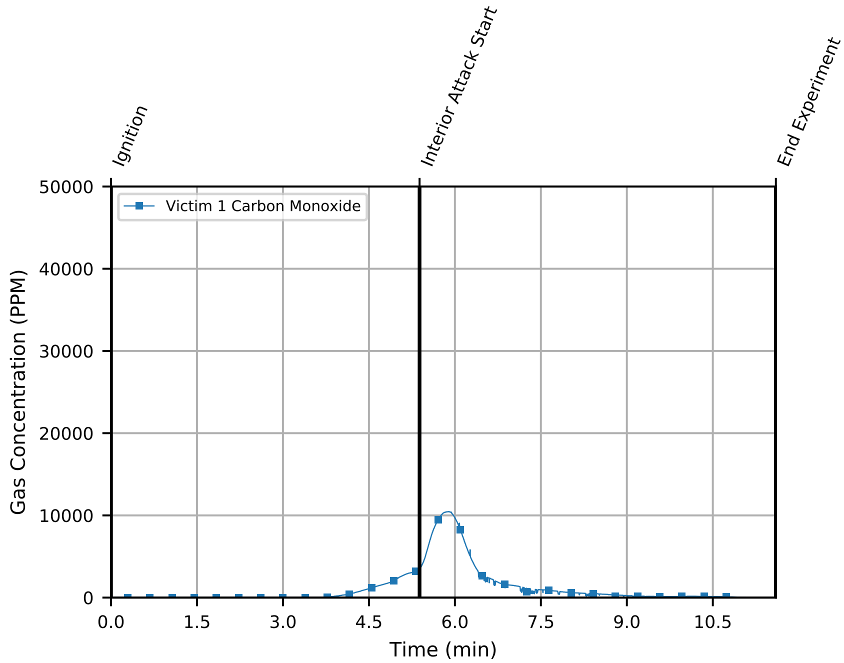


Figure E.589: Experiment 16 - Victim 1 Carbon Monoxide

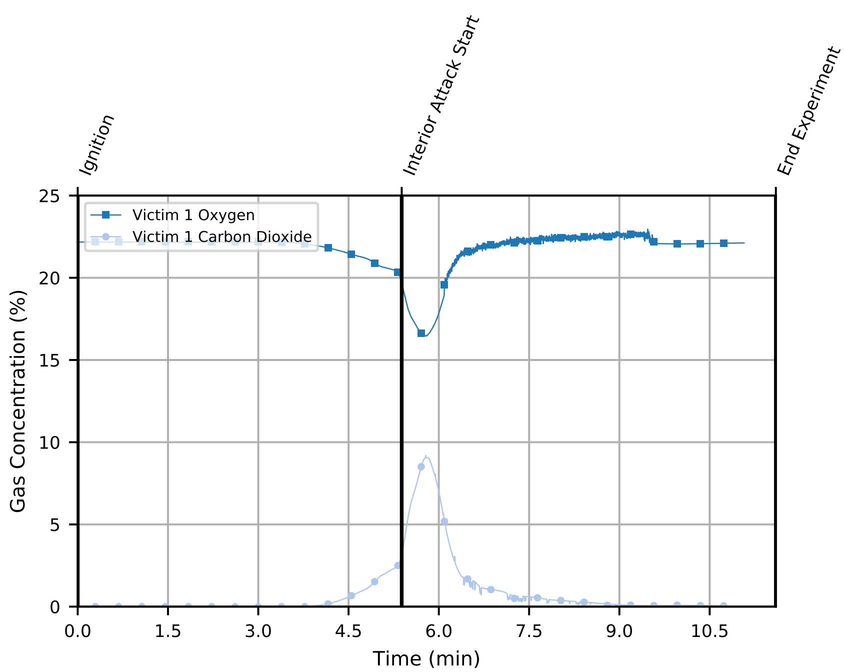


Figure E.590: Experiment 16 - Victim 1 Gas

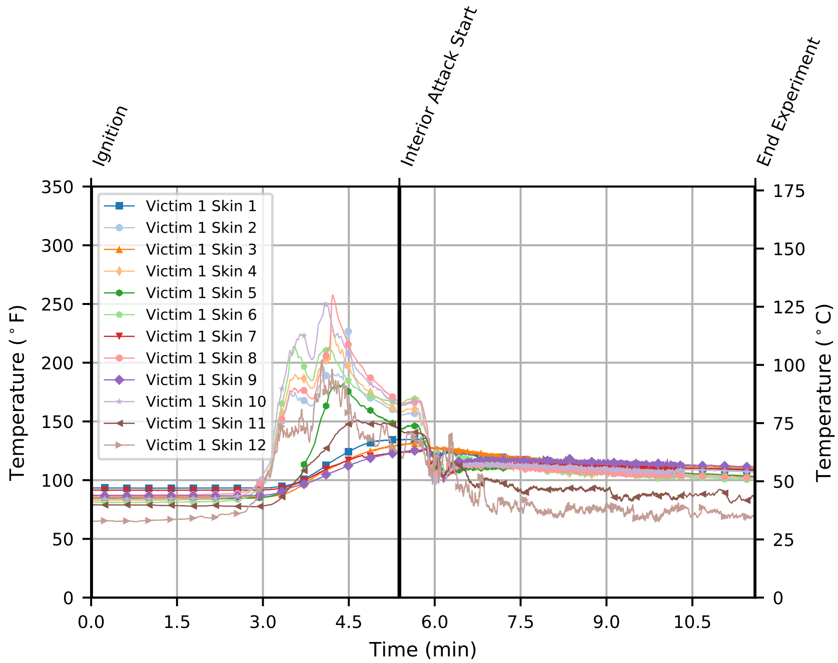


Figure E.591: Experiment 16 - Victim 1 Skin Temps

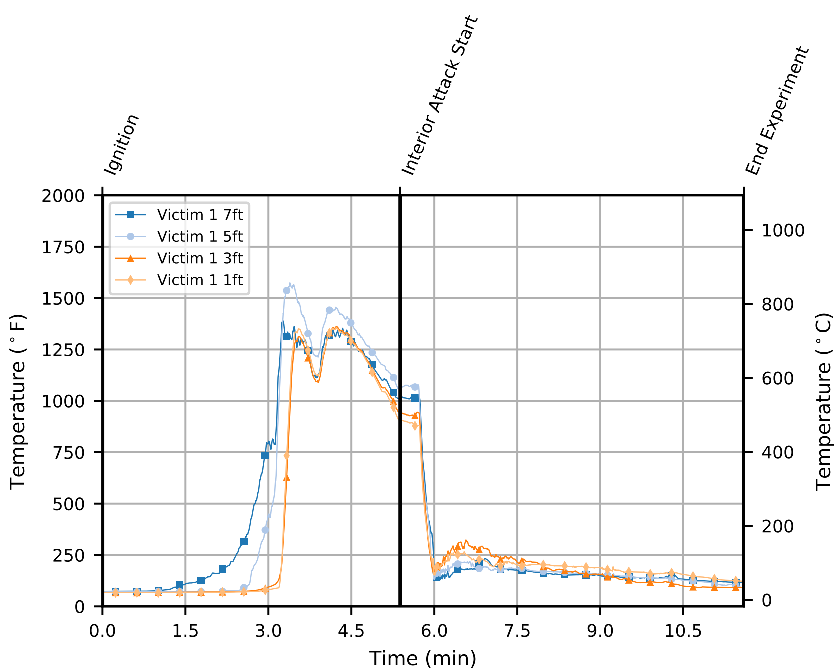


Figure E.592: Experiment 16 - Victim 1 Temps

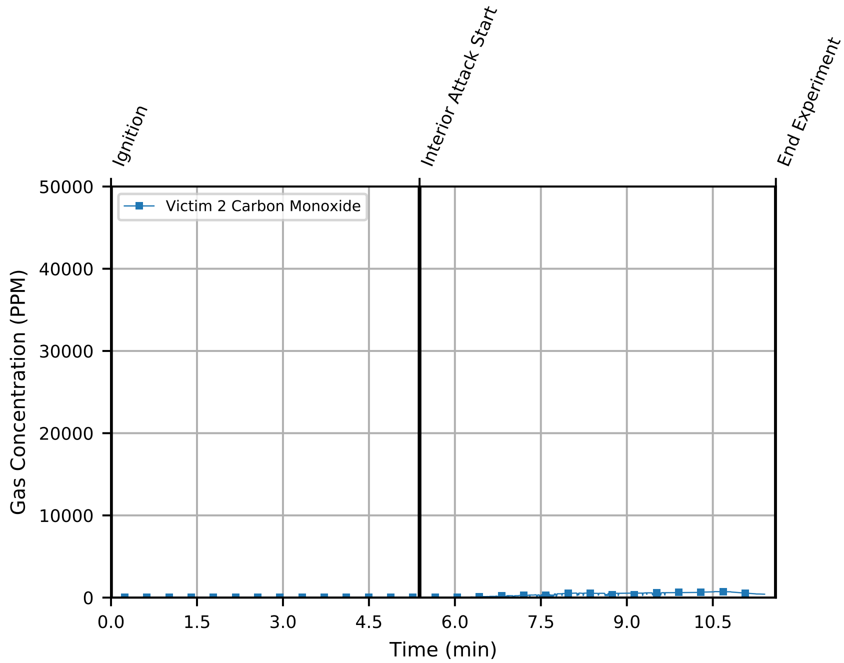


Figure E.593: Experiment 16 - Victim 2 Carbon Monoxide

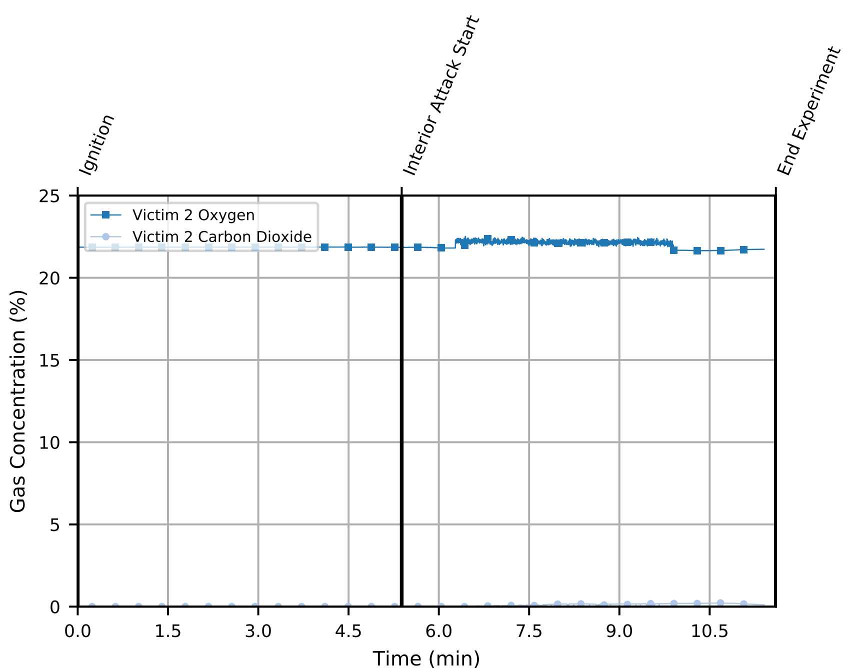


Figure E.594: Experiment 16 - Victim 2 Gas

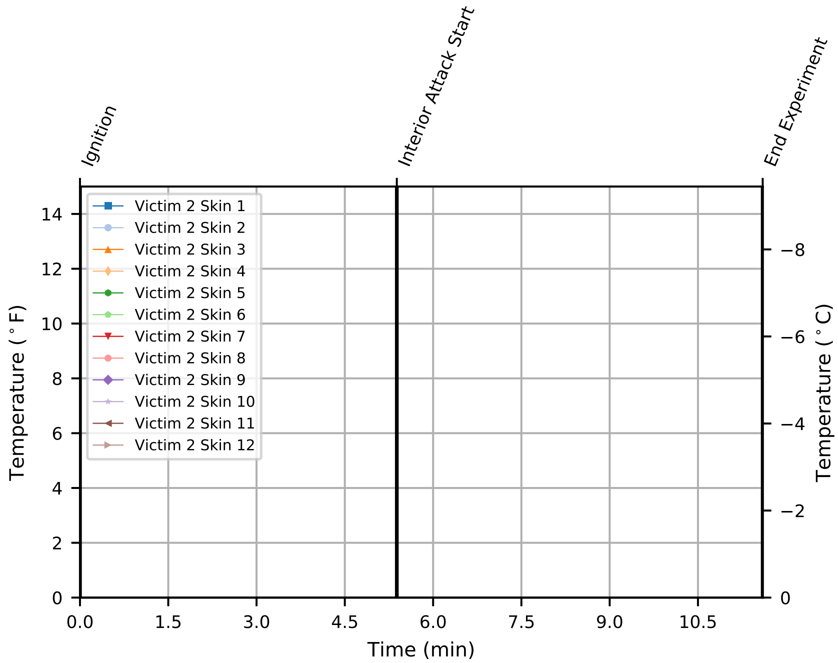


Figure E.595: Experiment 16 - Victim 2 Skin Temps

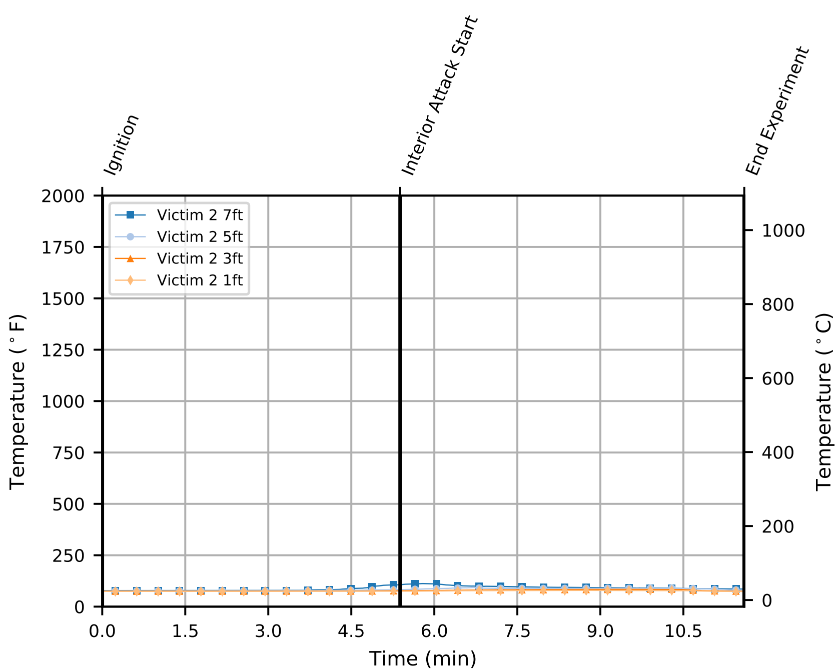


Figure E.596: Experiment 16 - Victim 2 Temps

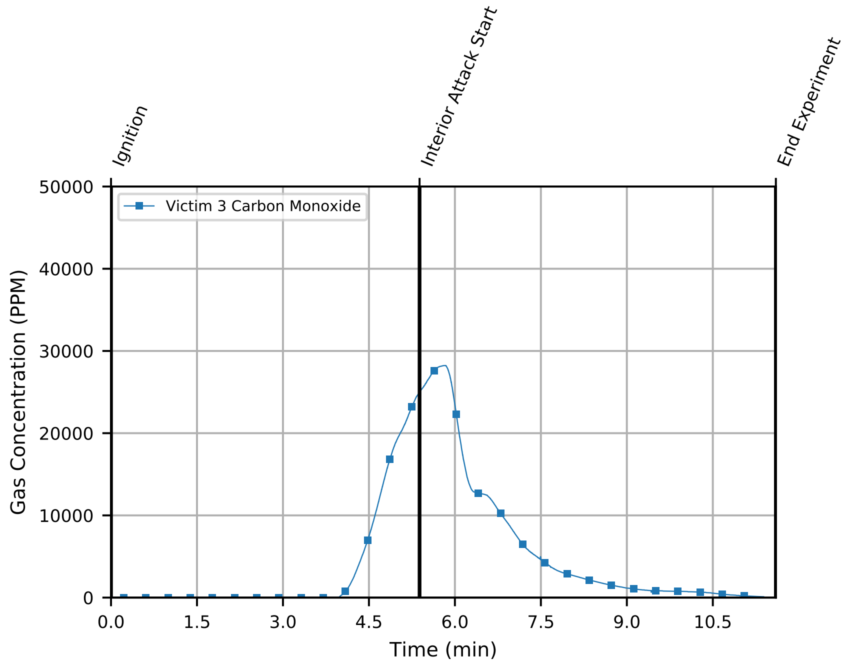


Figure E.597: Experiment 16 - Victim 3 Carbon Monoxide

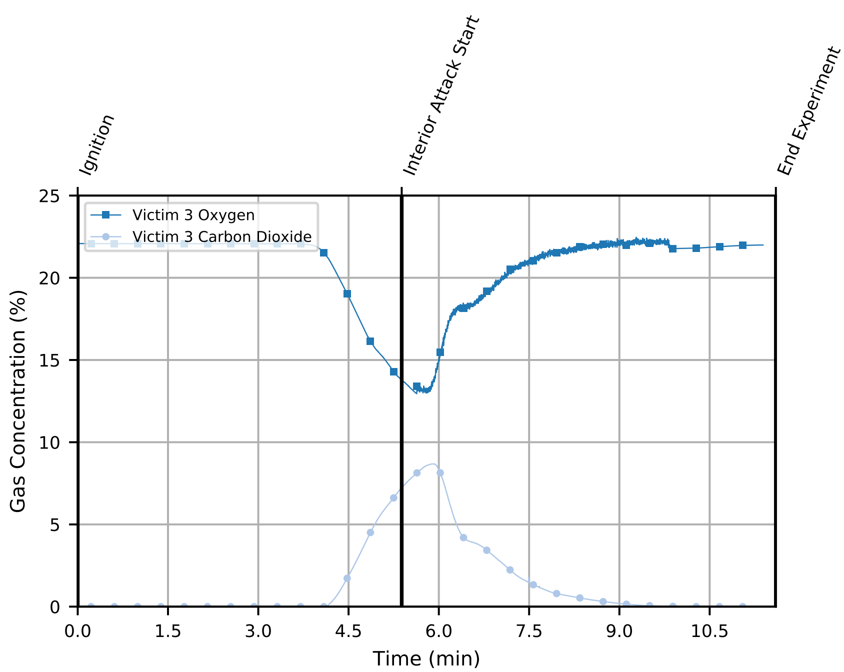


Figure E.598: Experiment 16 - Victim 3 Gas

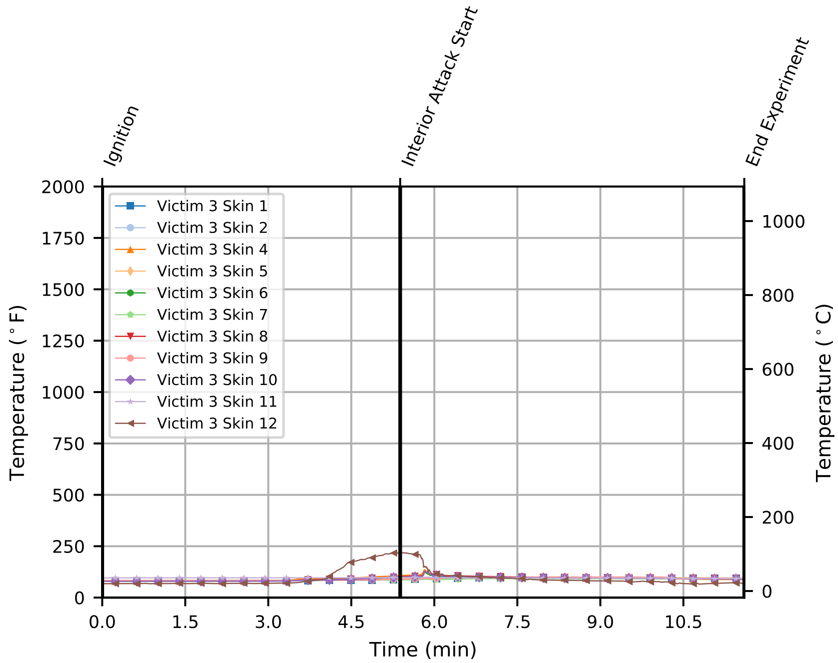


Figure E.599: Experiment 16 - Victim 3 Skin Temps

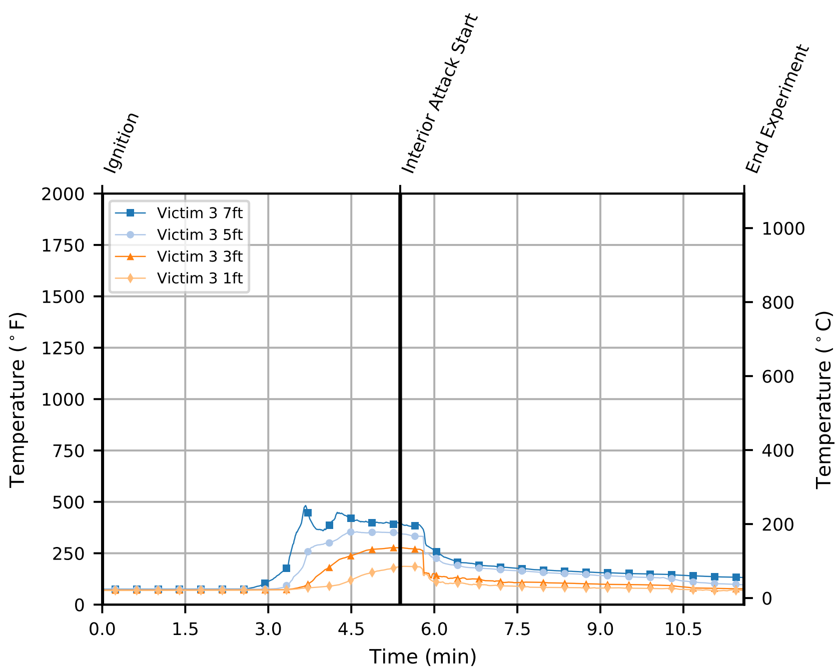


Figure E.600: Experiment 16 - Victim 3 Temps

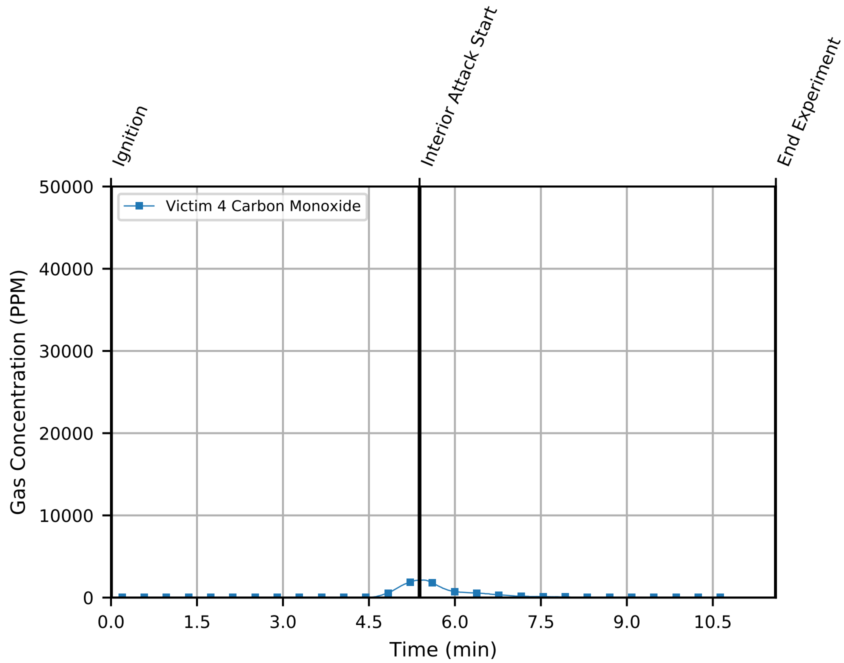


Figure E.601: Experiment 16 - Victim 4 Carbon Monoxide

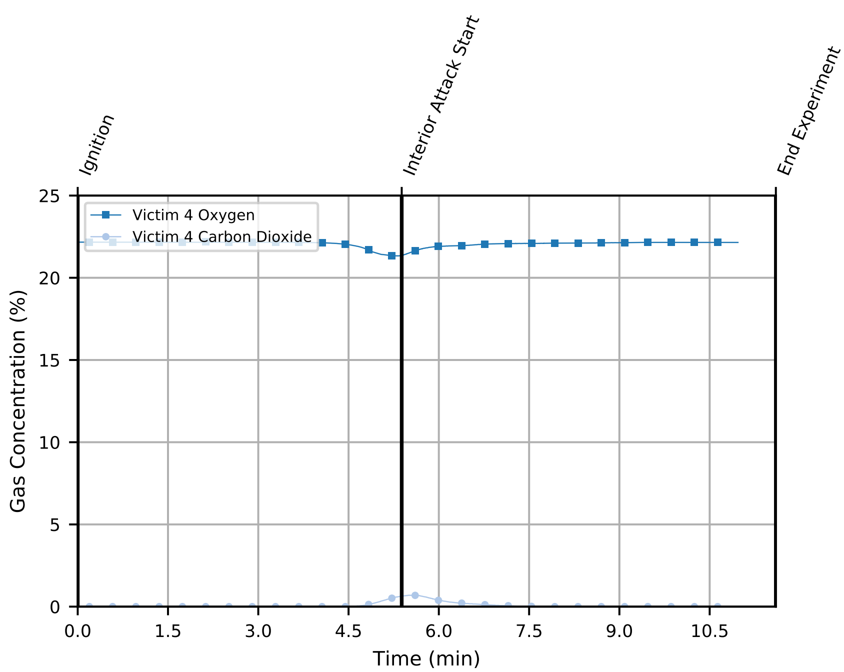


Figure E.602: Experiment 16 - Victim 4 Gas

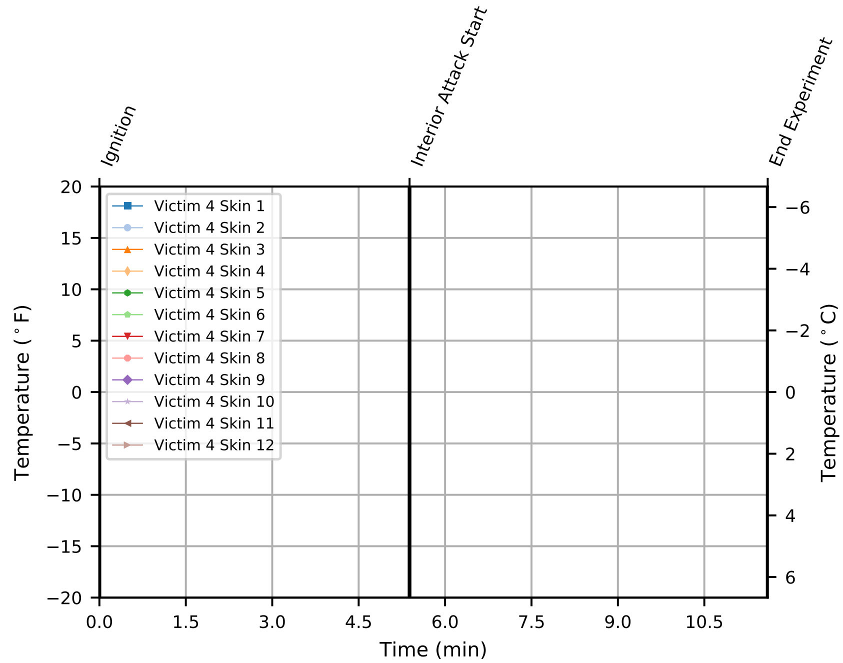


Figure E.603: Experiment 16 - Victim 4 Skin Temps

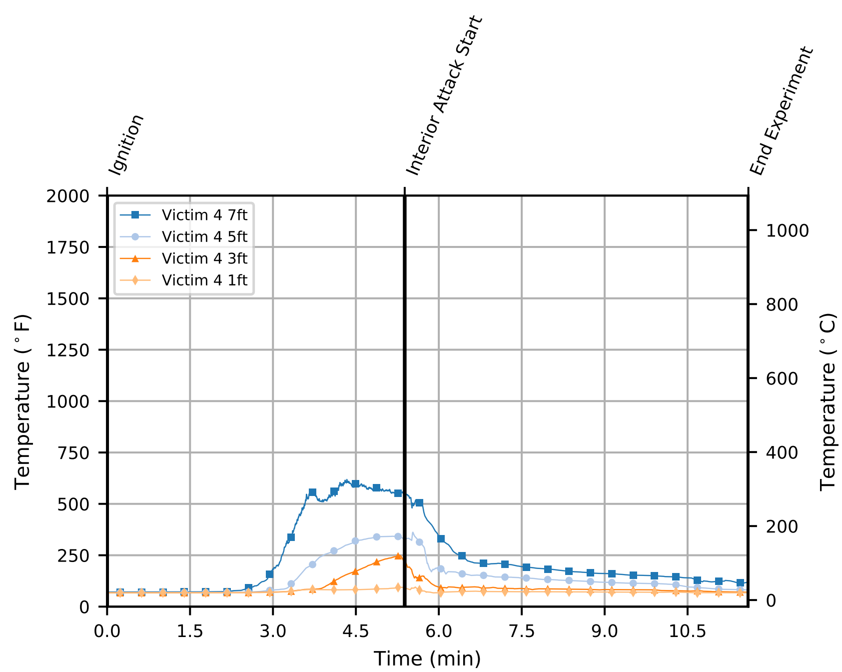


Figure E.604: Experiment 16 - Victim 4 Temps

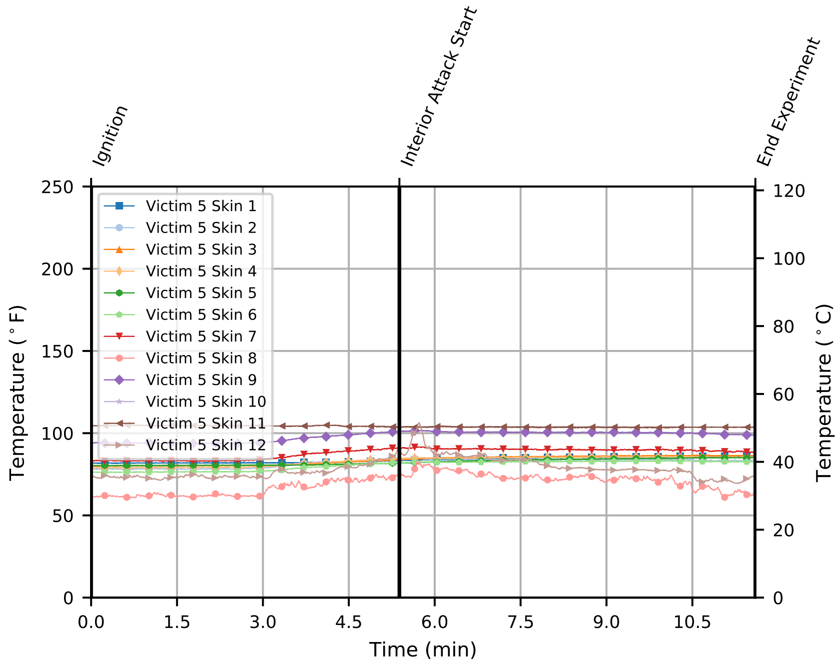


Figure E.605: Experiment 16 - Victim 5 Skin Temps

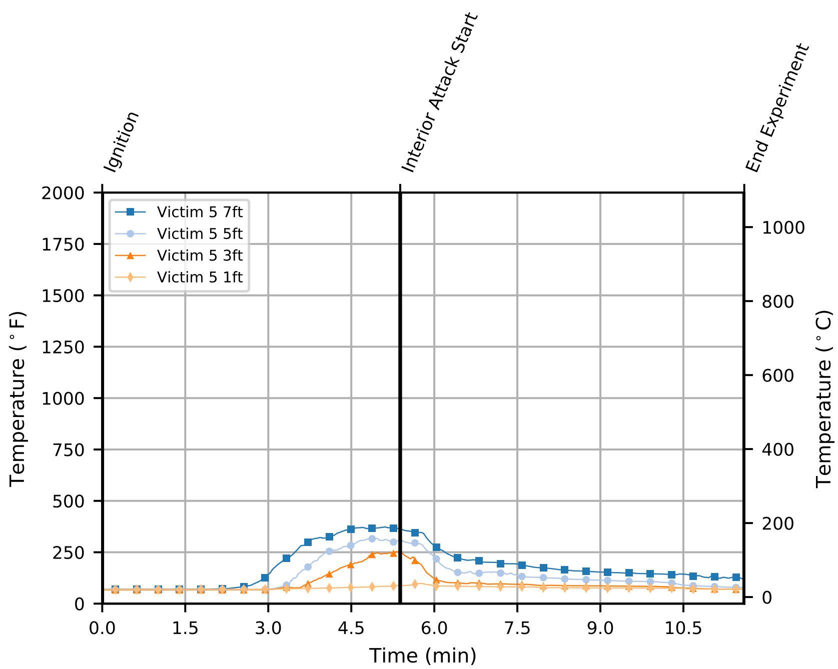


Figure E.606: Experiment 16 - Victim 5 Temps

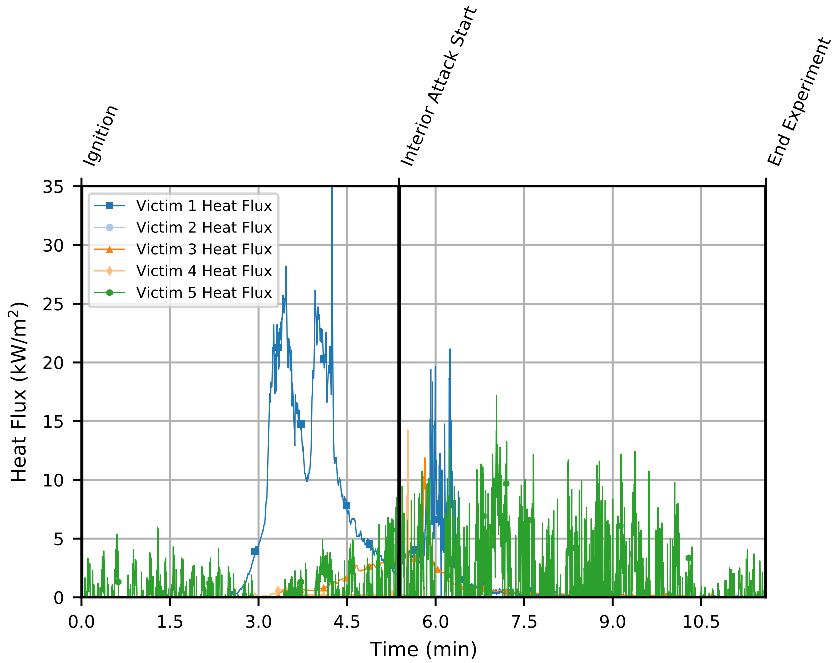


Figure E.607: Experiment 16 - Victim Heat Flux

E.17 Experiment 17 Data

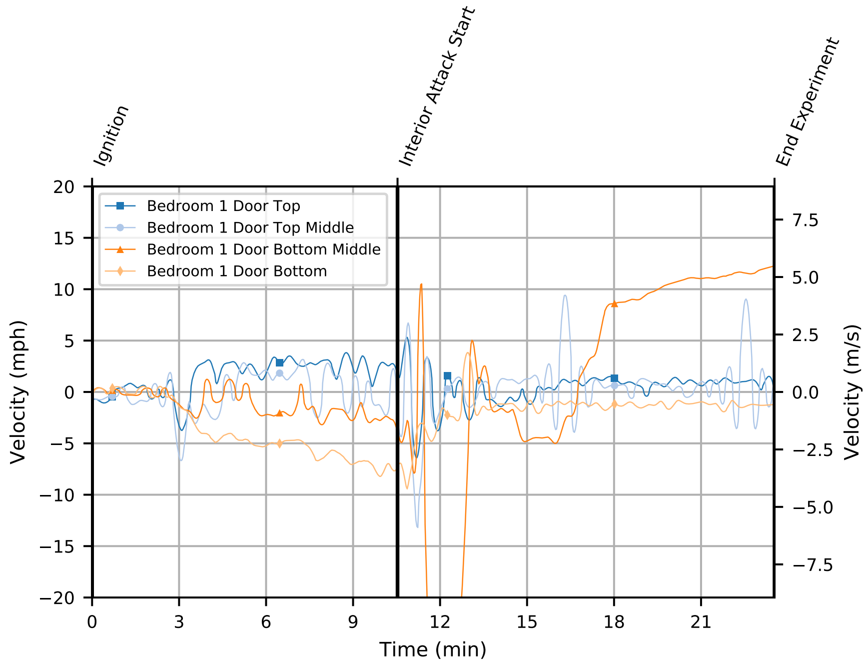


Figure E.608: Experiment 17 - Bedroom 1 Door

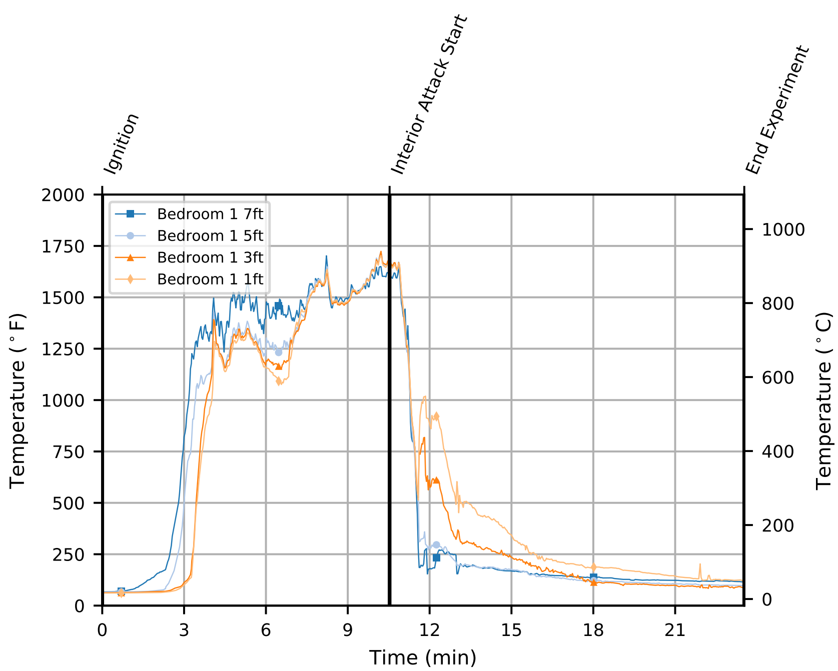


Figure E.609: Experiment 17 - Bedroom 1 Temps

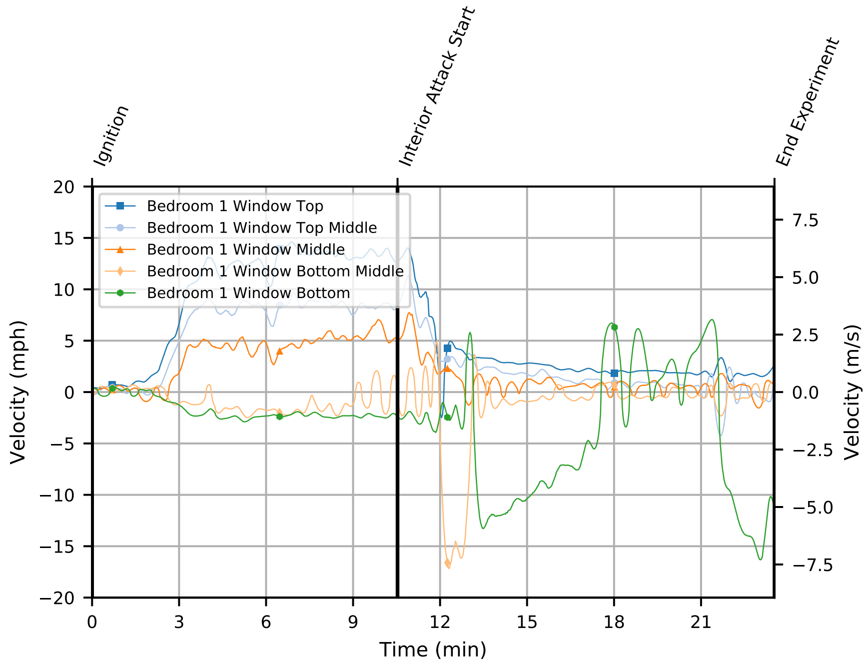


Figure E.610: Experiment 17 - Bedroom 1 Window

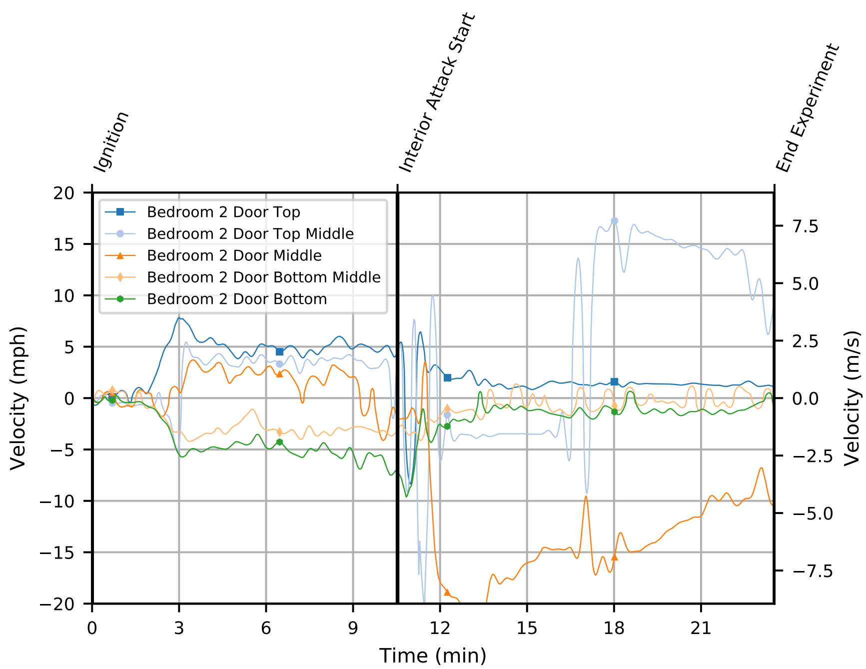


Figure E.611: Experiment 17 - Bedroom 2 Door

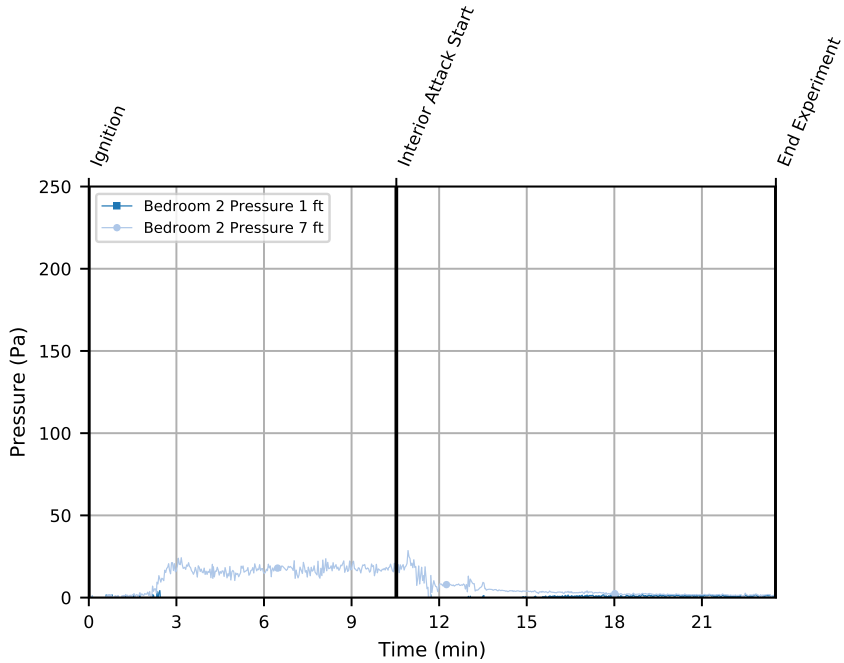


Figure E.612: Experiment 17 - Bedroom 2 Pressure

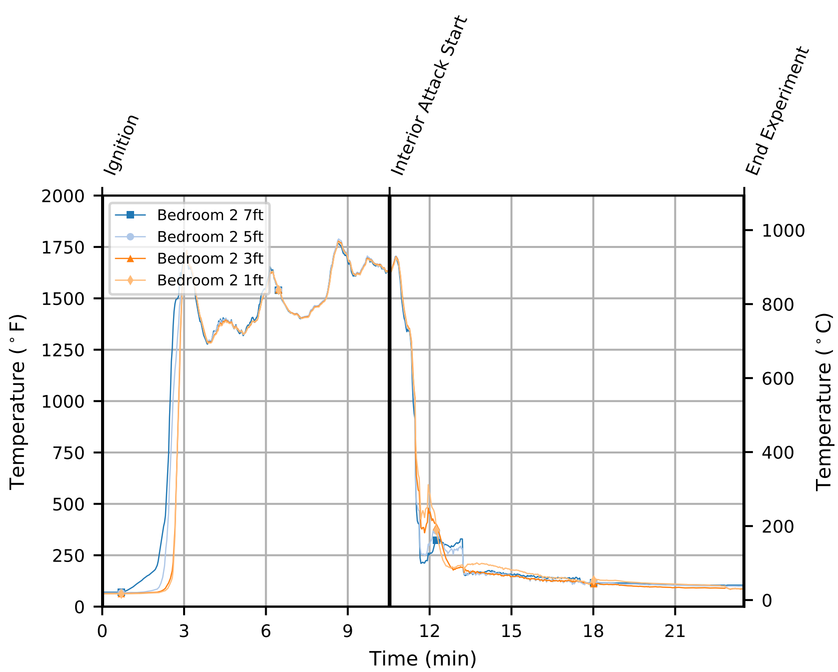


Figure E.613: Experiment 17 - Bedroom 2 Temps

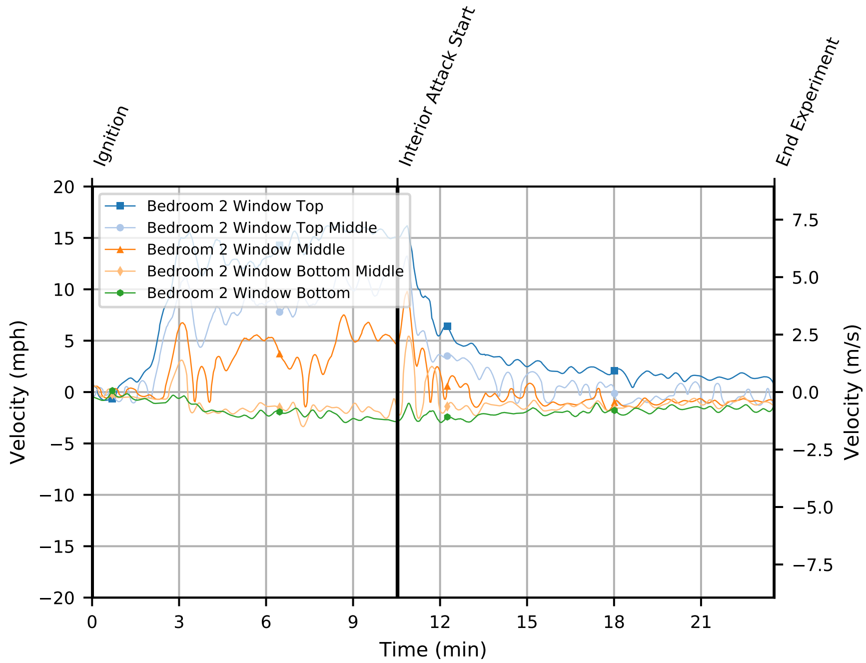


Figure E.614: Experiment 17 - Bedroom 2 Window

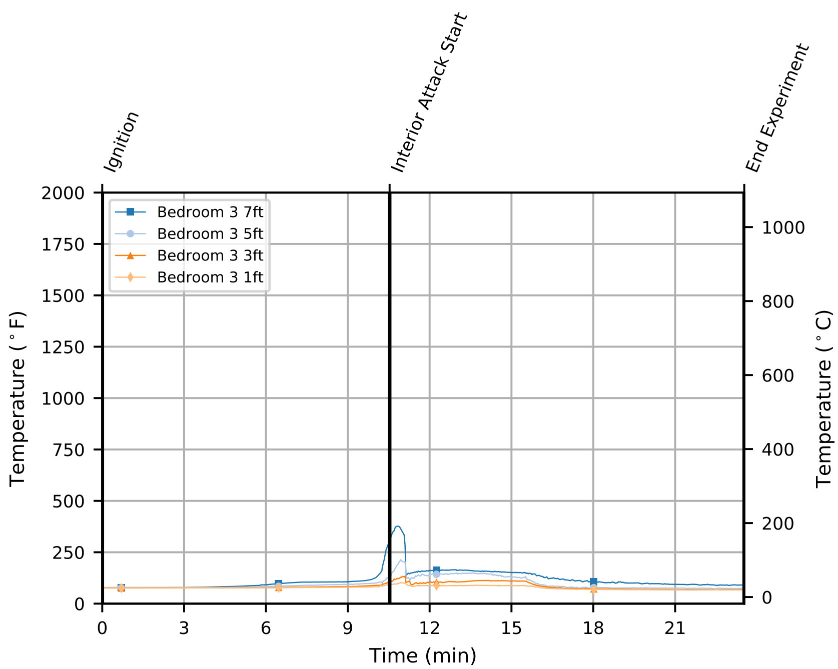


Figure E.615: Experiment 17 - Bedroom 3 Temps

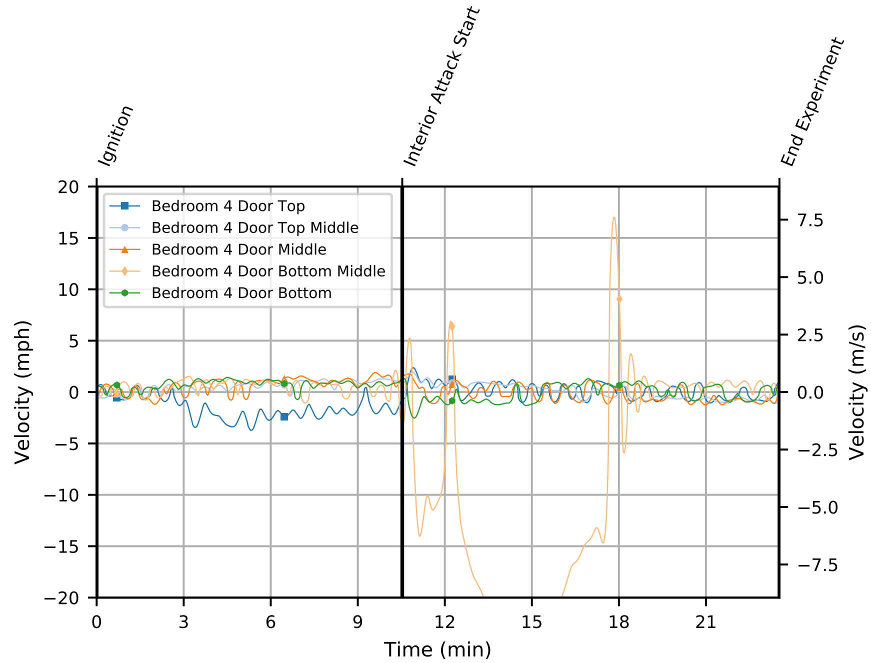


Figure E.616: Experiment 17 - Bedroom 4 Door

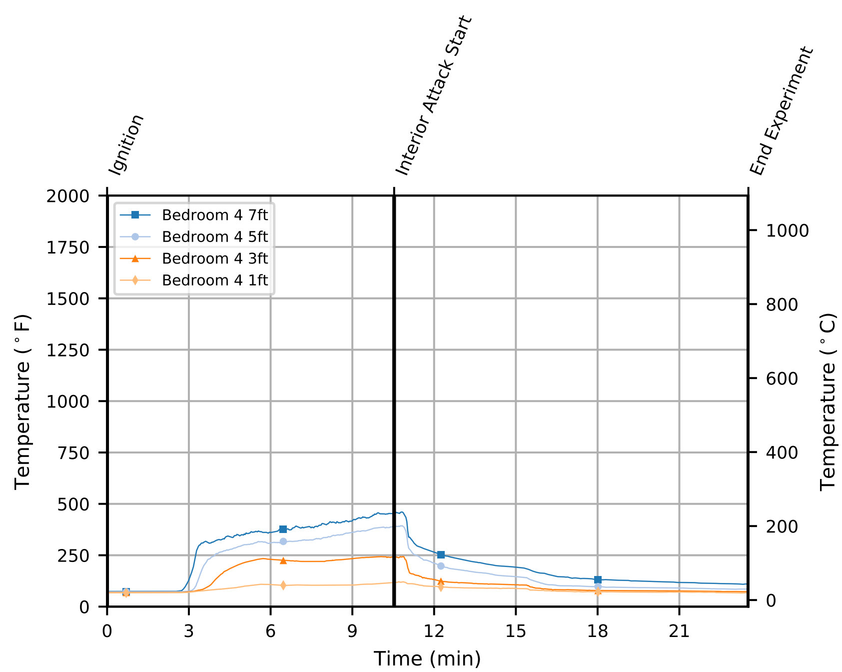


Figure E.617: Experiment 17 - Bedroom 4 Temps

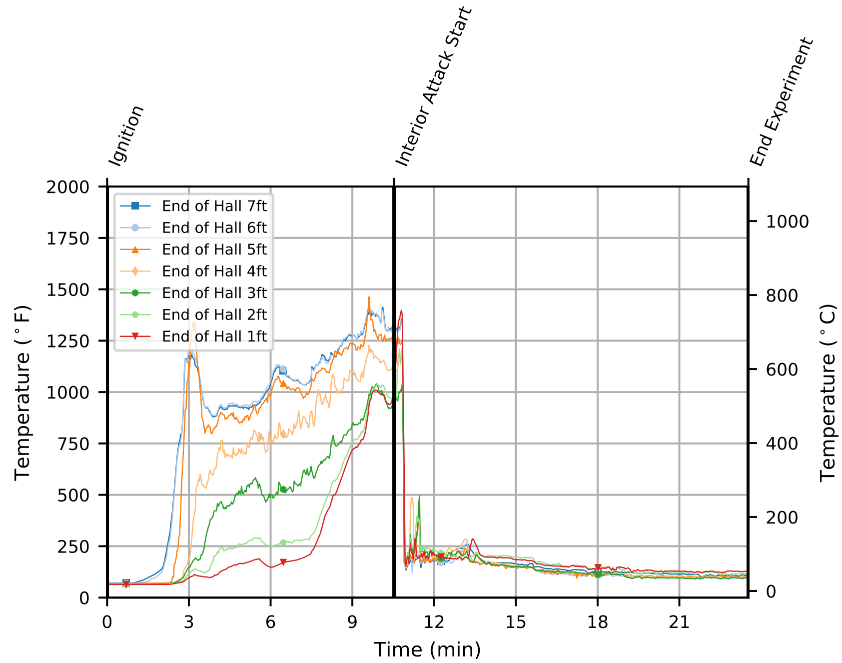


Figure E.618: Experiment 17 - End Hall Temps

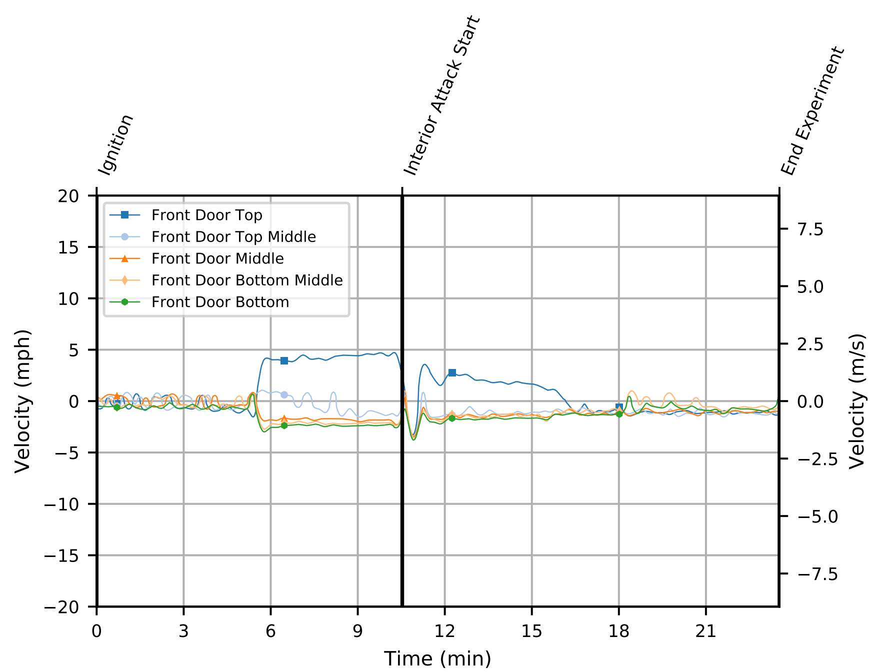


Figure E.619: Experiment 17 - Front Door Flow

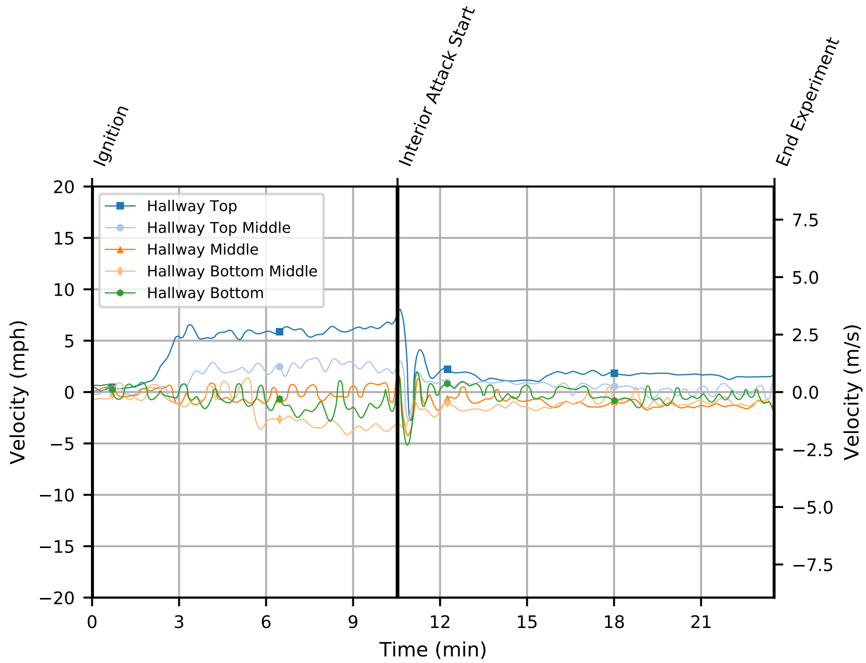


Figure E.620: Experiment 17 - Hallway Flow

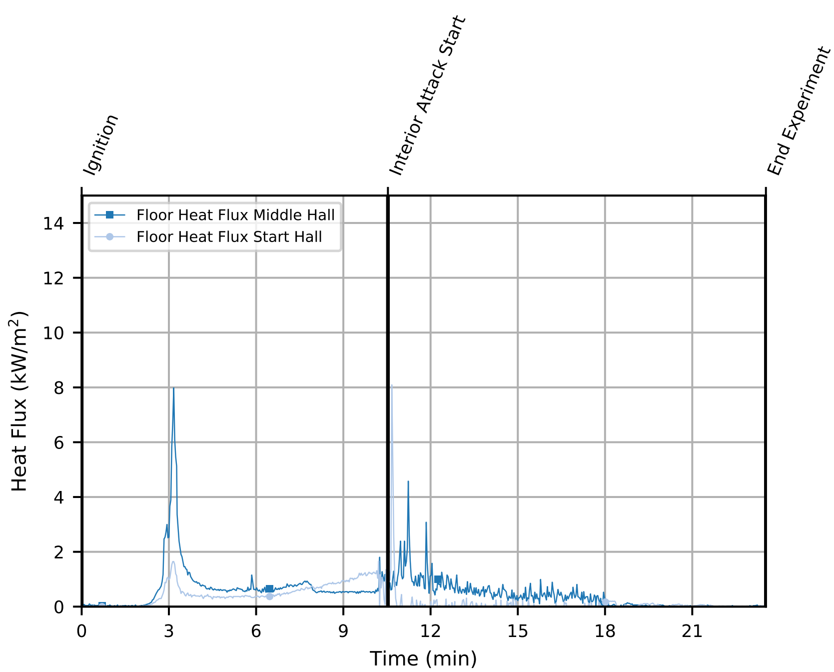


Figure E.621: Experiment 17 - Heat Flux Floor

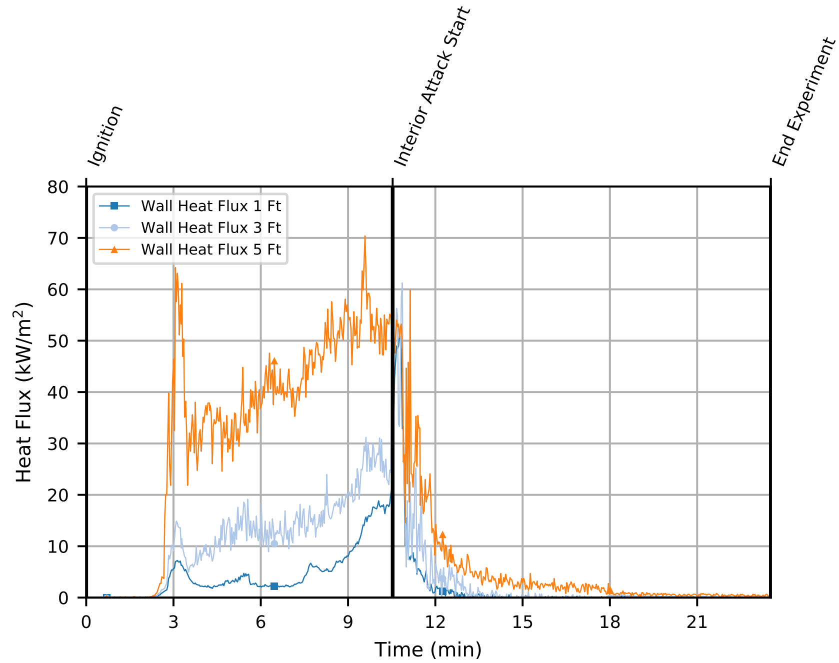


Figure E.622: Experiment 17 - Heat Flux Wall

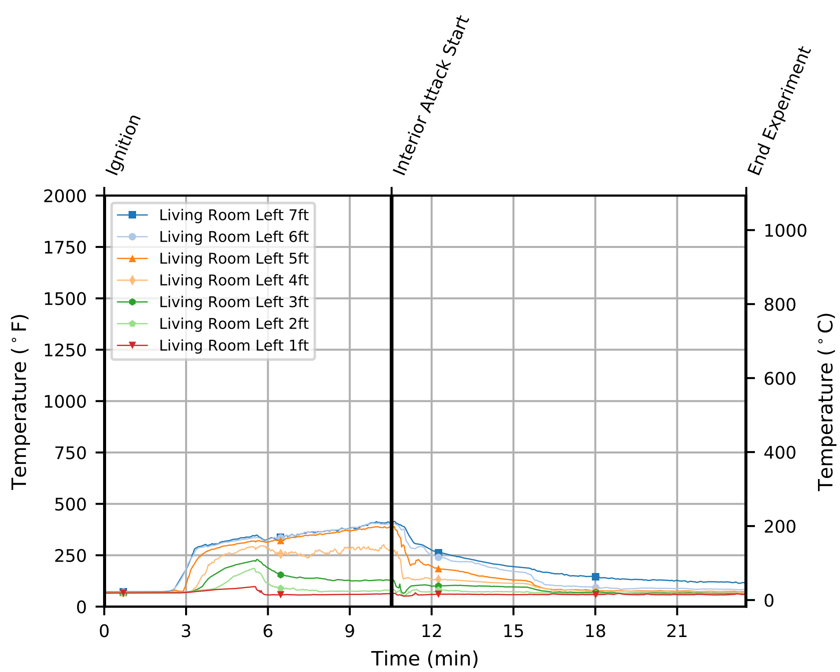


Figure E.623: Experiment 17 - Living Room Left Temps

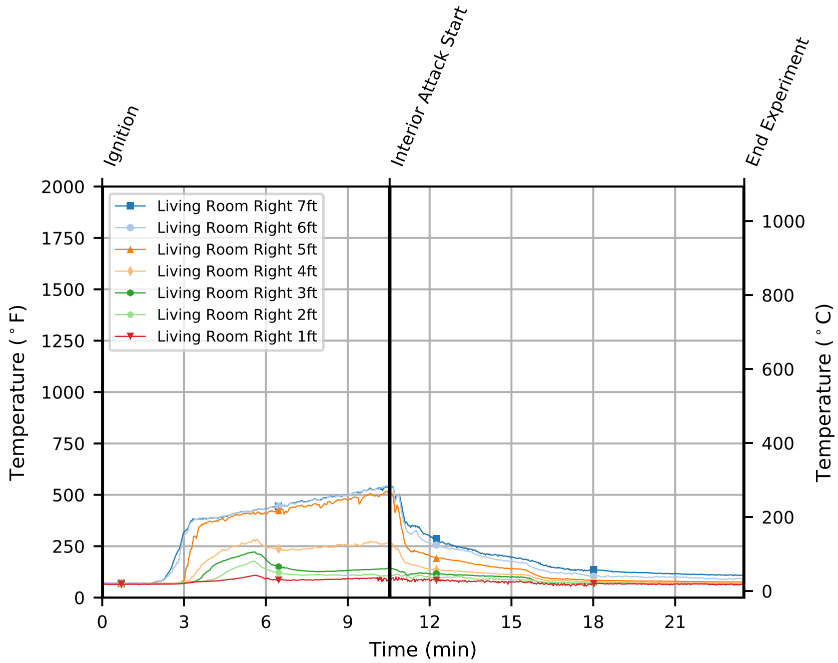


Figure E.624: Experiment 17 - Living Room Right Temps

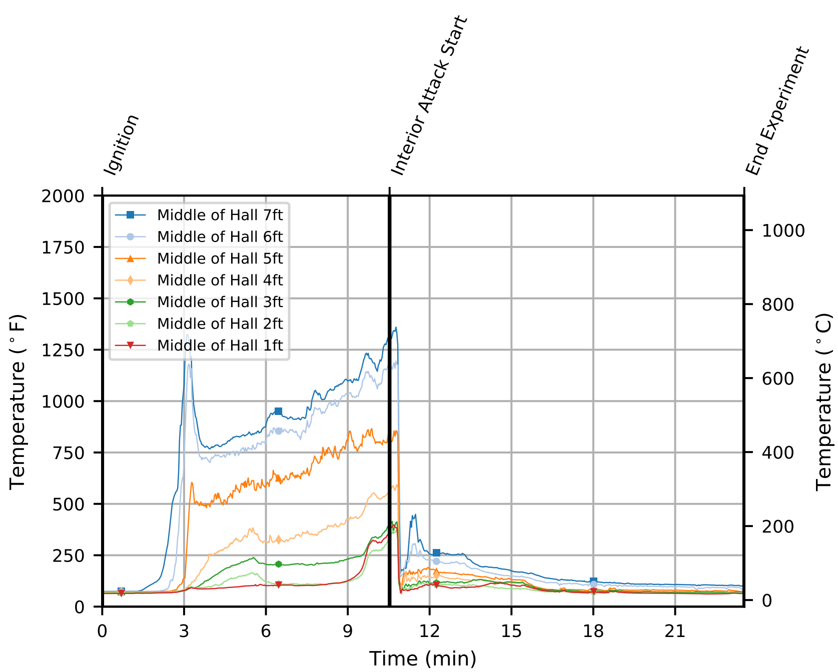


Figure E.625: Experiment 17 - Middle Hall Temps

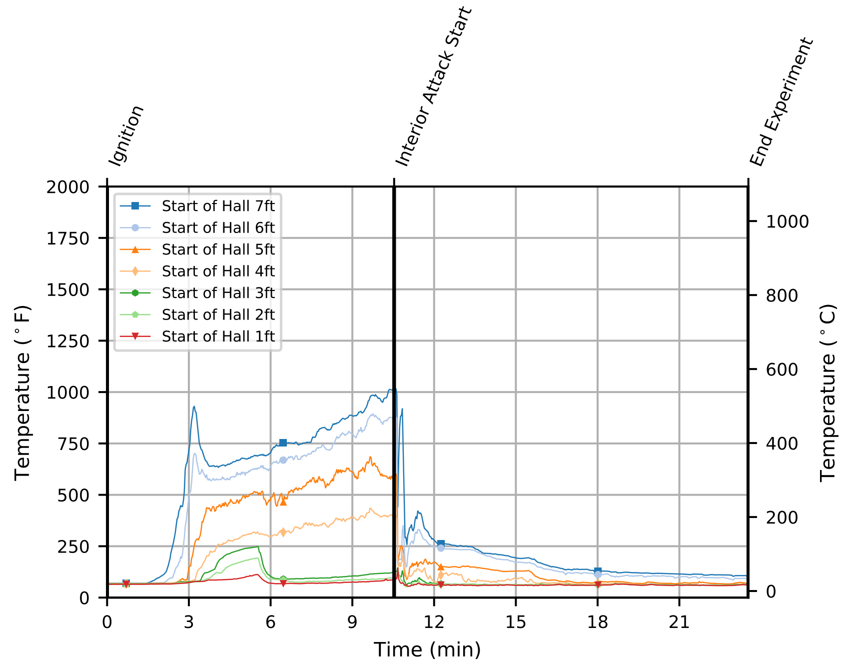


Figure E.626: Experiment 17 - Start Hall Temps

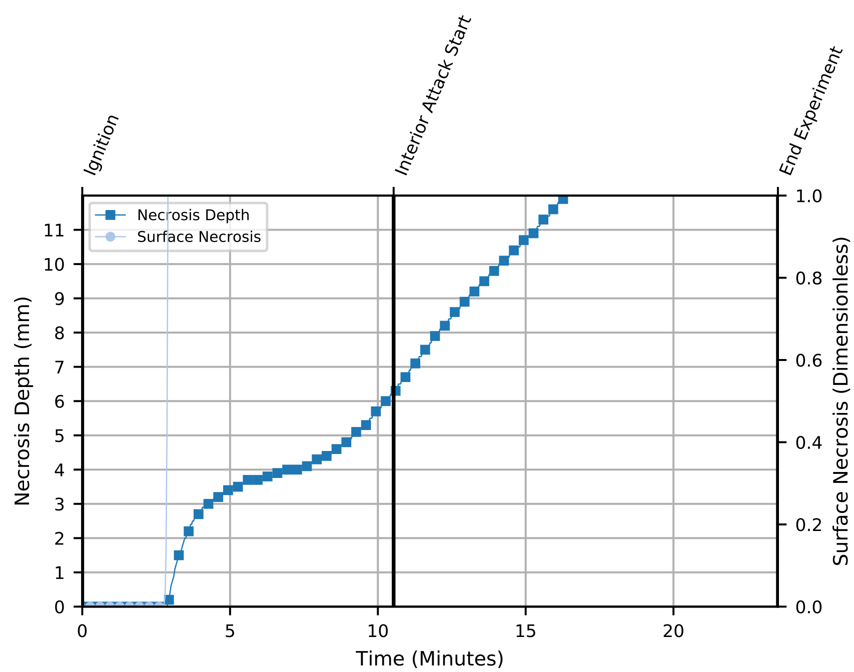


Figure E.627: Experiment 17 - Vic 1 Necrosis Depth

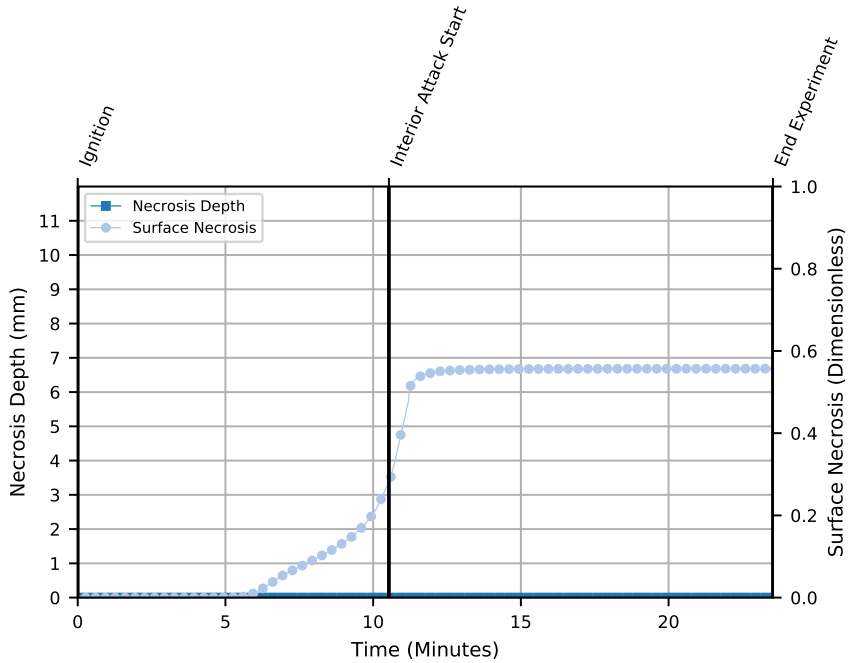


Figure E.628: Experiment 17 - Vic 3 Necrosis Depth

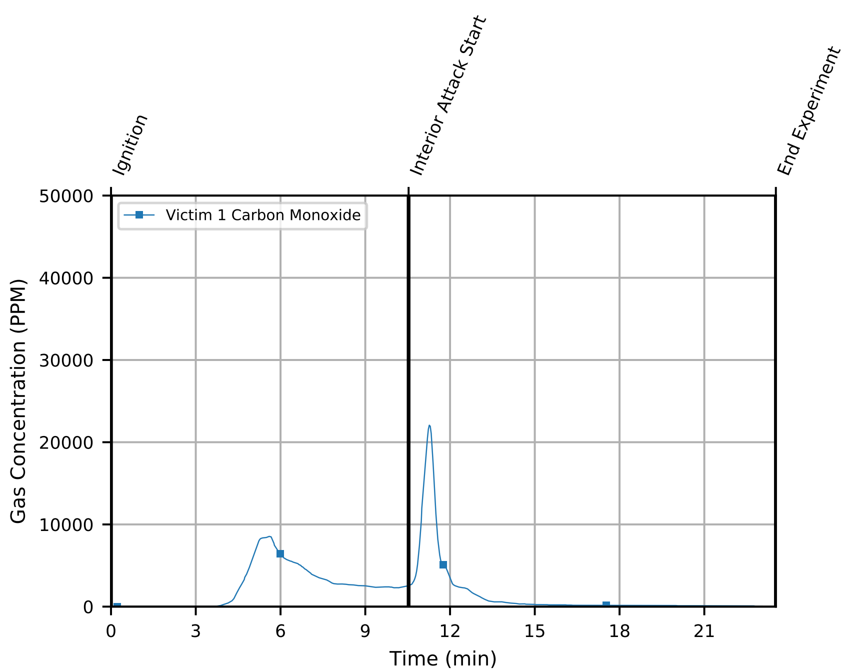


Figure E.629: Experiment 17 - Victim 1 Carbon Monoxide

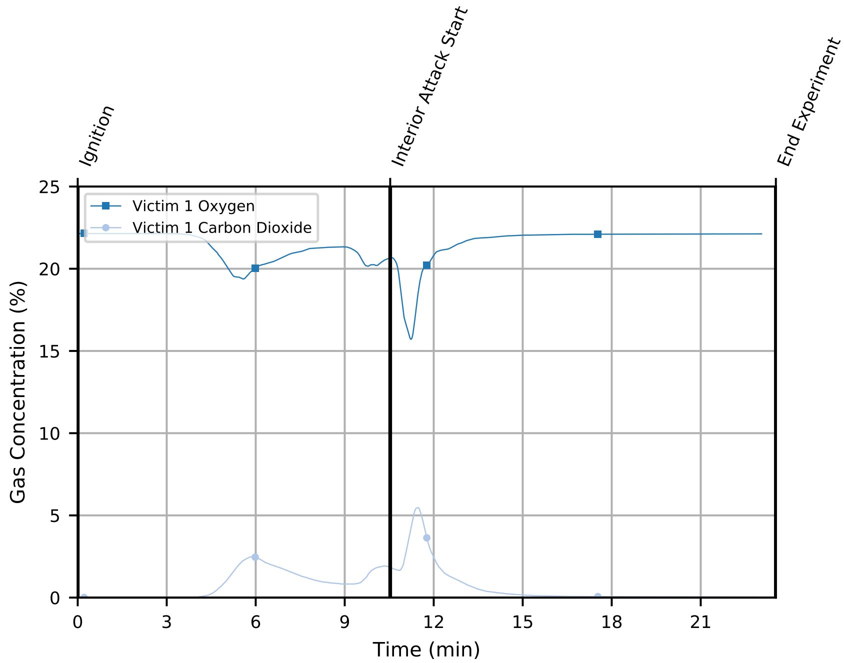


Figure E.630: Experiment 17 - Victim 1 Gas

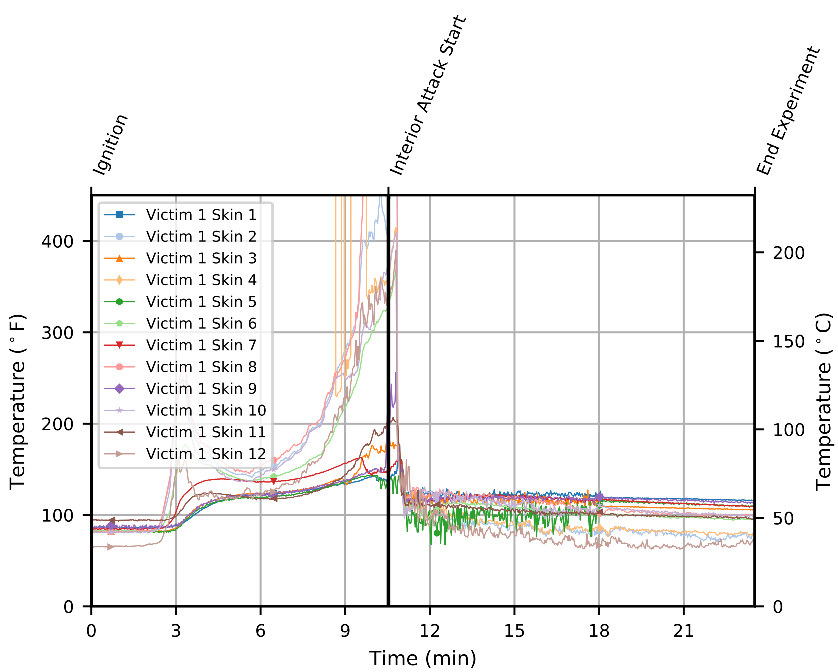


Figure E.631: Experiment 17 - Victim 1 Skin Temps

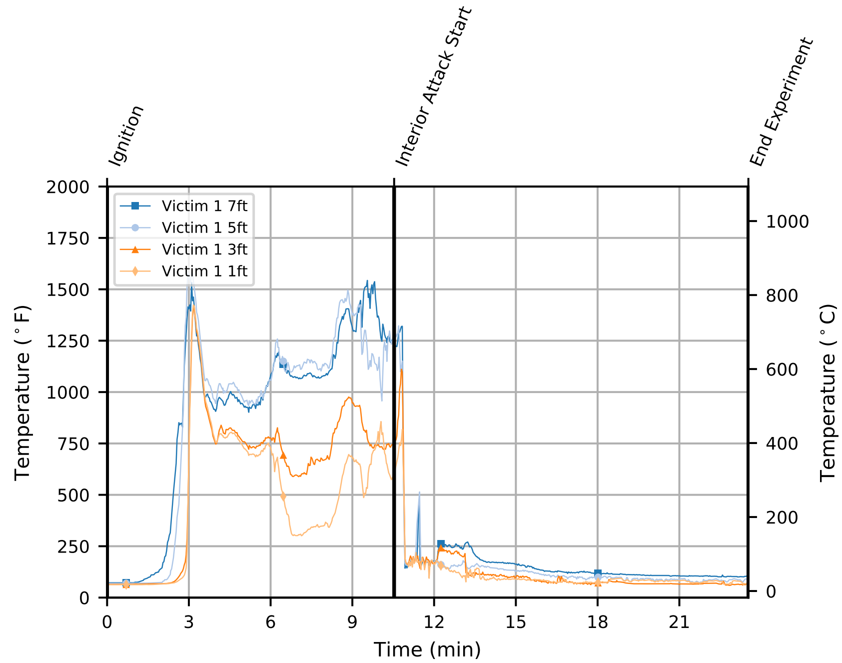


Figure E.632: Experiment 17 - Victim 1 Temps

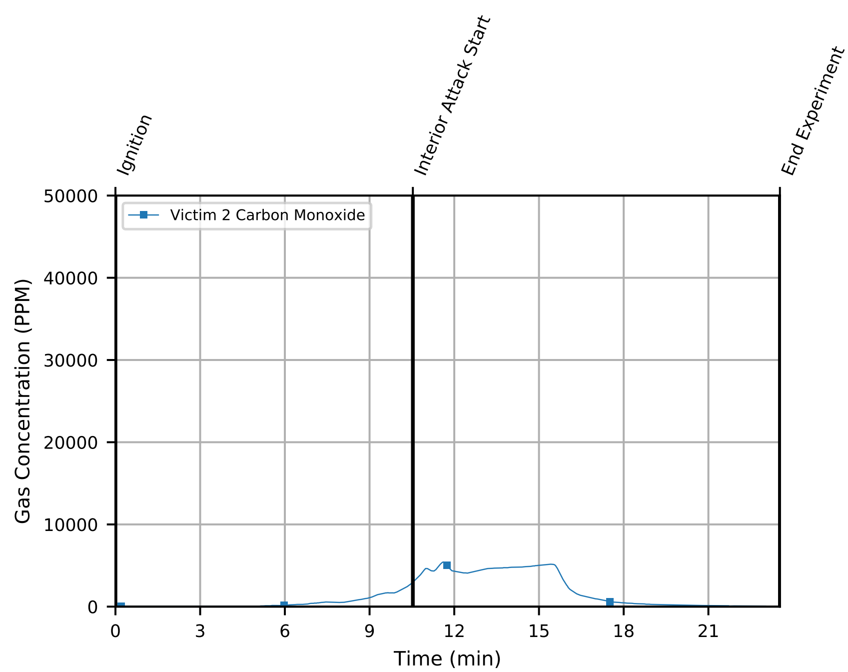


Figure E.633: Experiment 17 - Victim 2 Carbon Monoxide

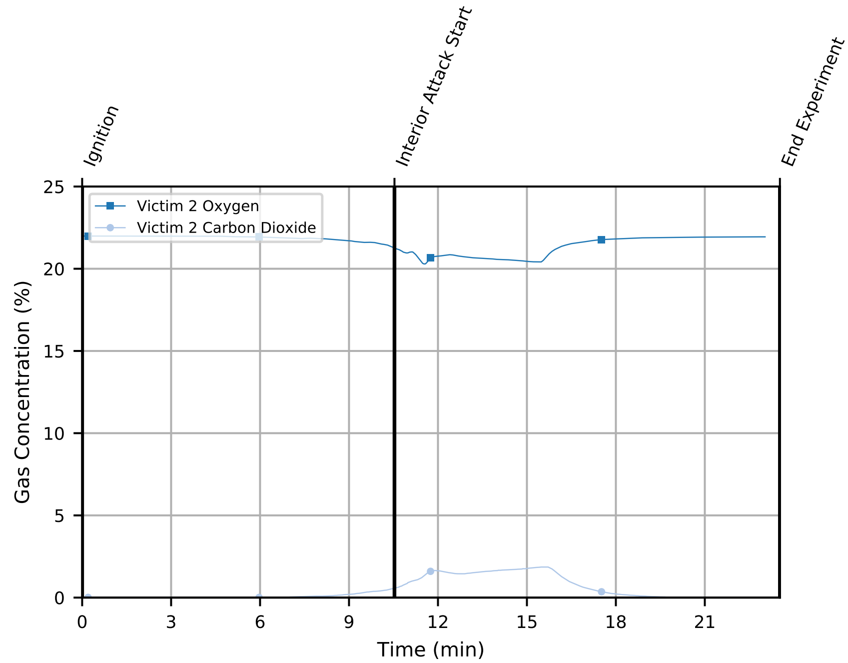


Figure E.634: Experiment 17 - Victim 2 Gas

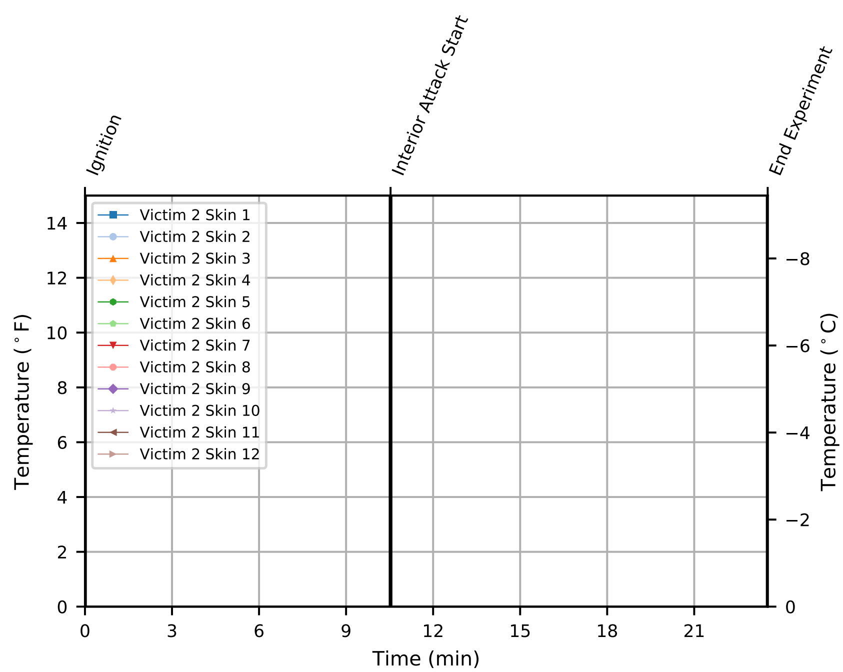


Figure E.635: Experiment 17 - Victim 2 Skin Temps

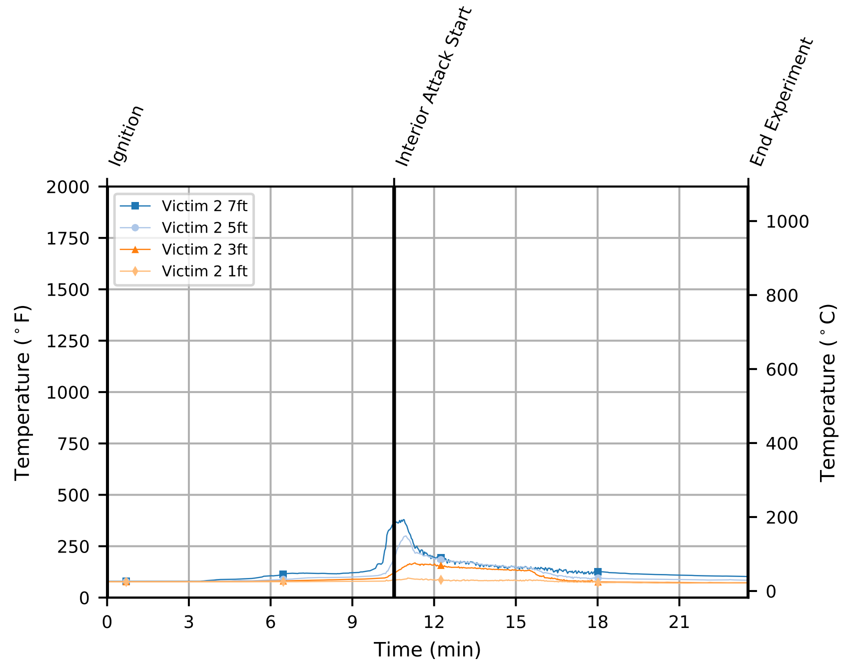


Figure E.636: Experiment 17 - Victim 2 Temps

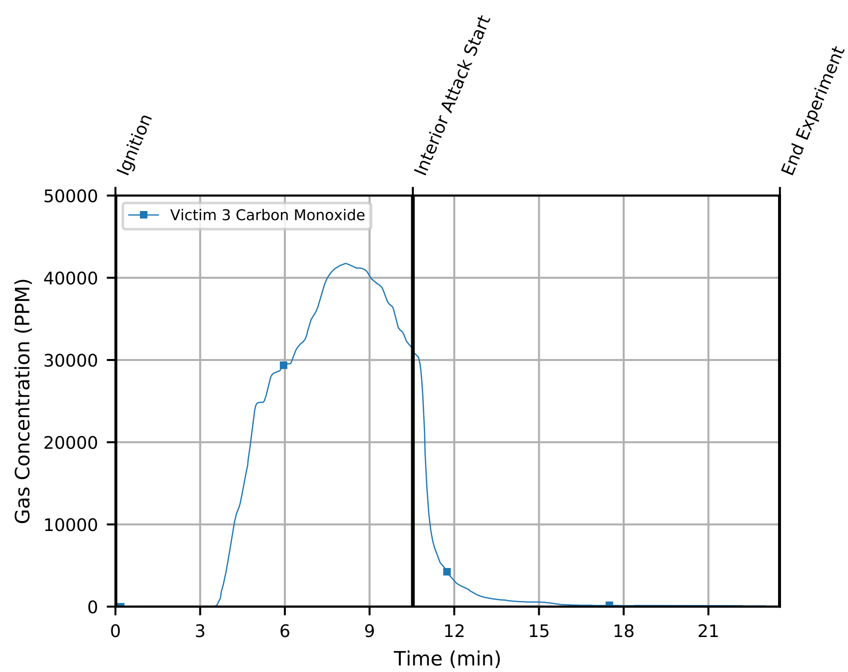


Figure E.637: Experiment 17 - Victim 3 Carbon Monoxide

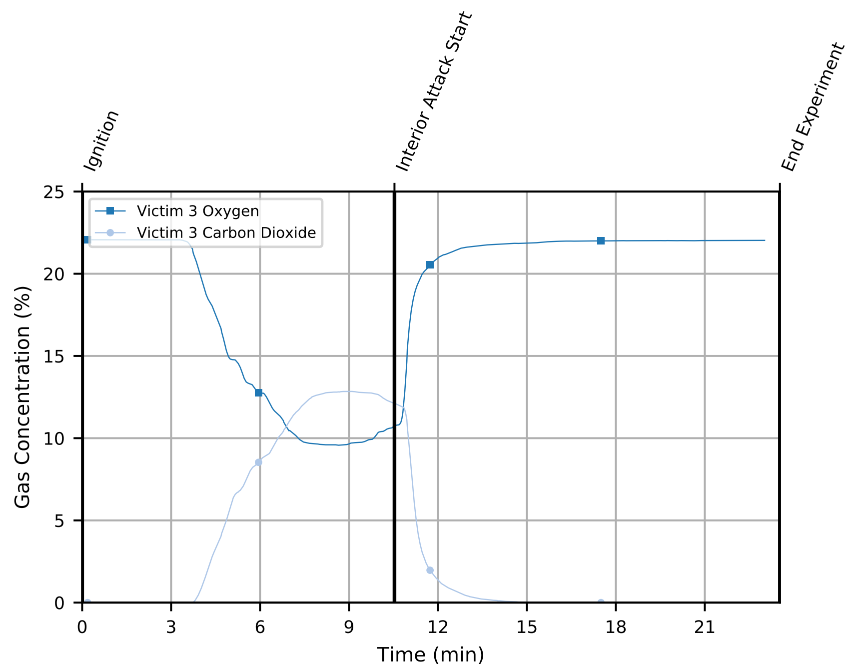


Figure E.638: Experiment 17 - Victim 3 Gas

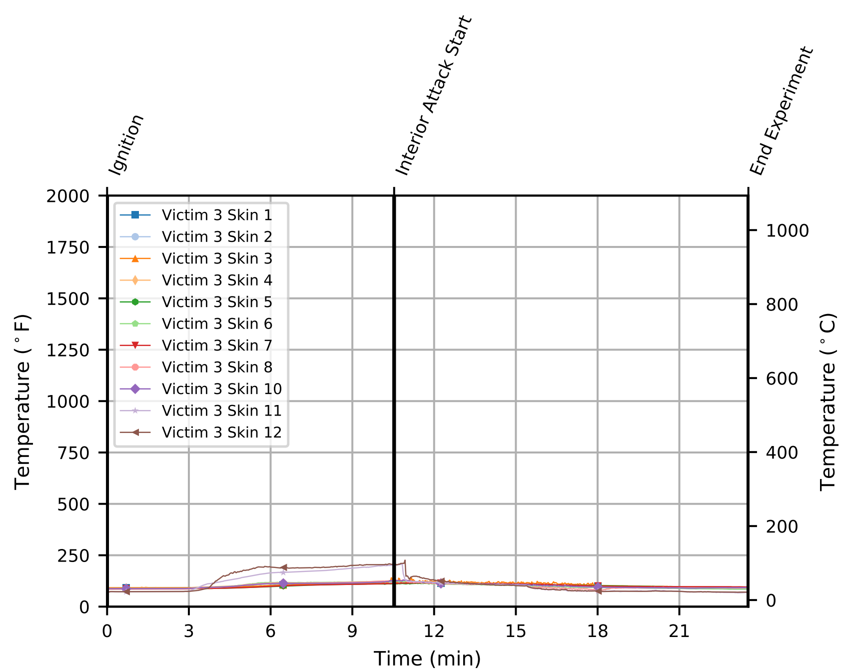


Figure E.639: Experiment 17 - Victim 3 Skin Temps

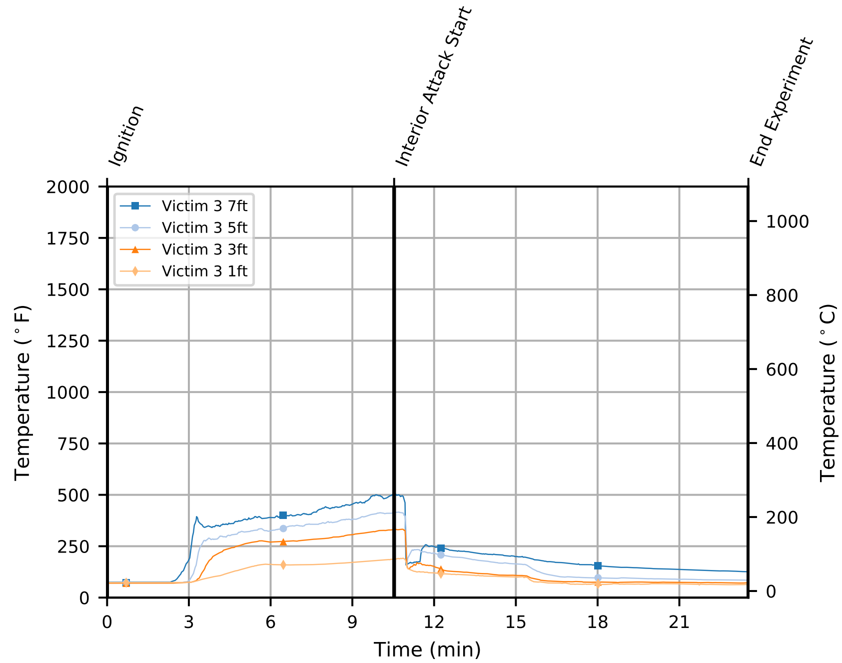


Figure E.640: Experiment 17 - Victim 3 Temps

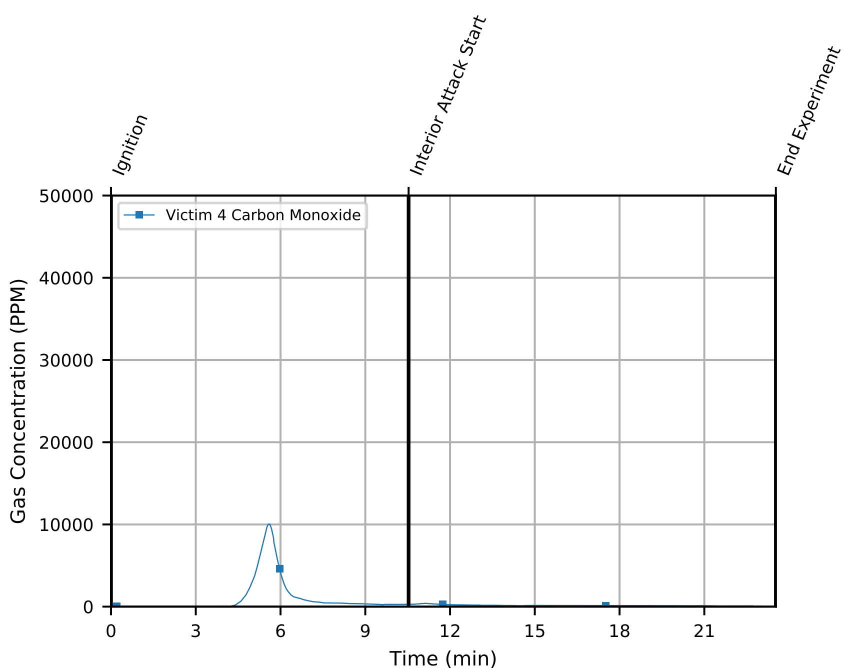


Figure E.641: Experiment 17 - Victim 4 Carbon Monoxide

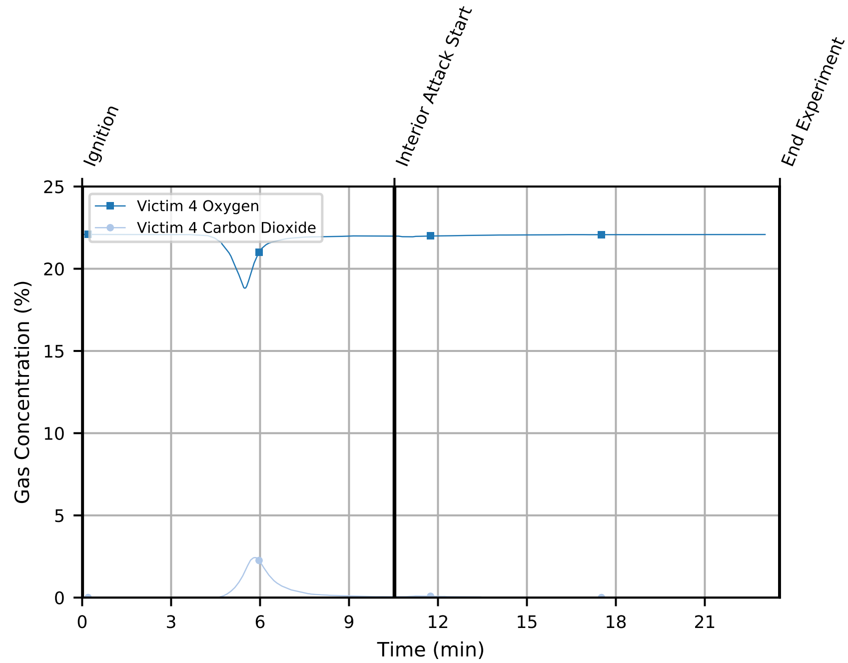


Figure E.642: Experiment 17 - Victim 4 Gas

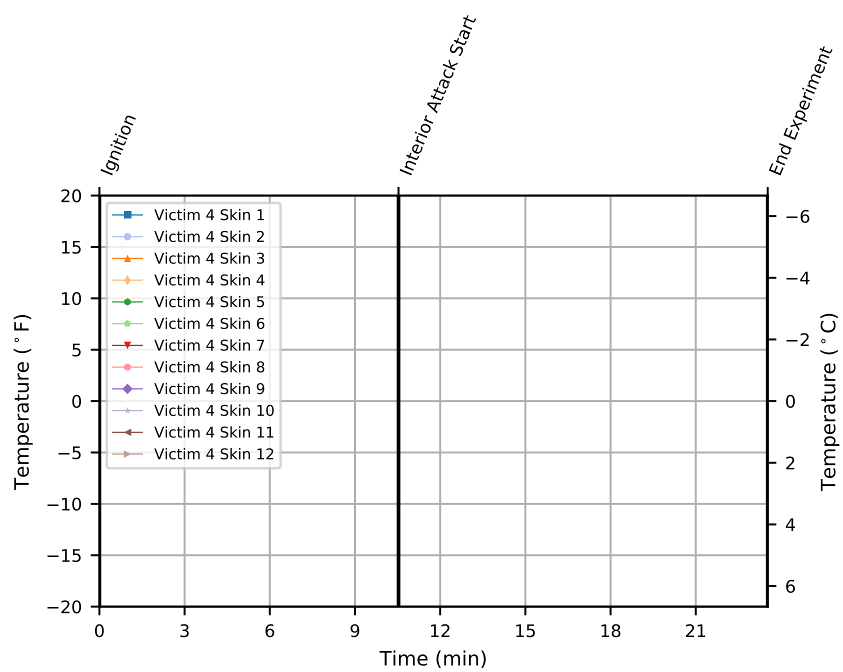


Figure E.643: Experiment 17 - Victim 4 Skin Temps

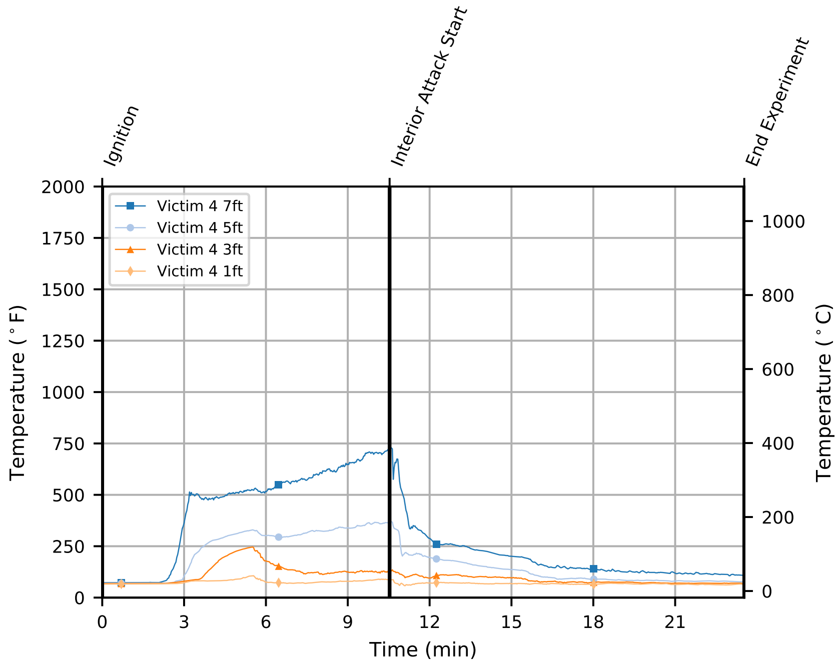


Figure E.644: Experiment 17 - Victim 4 Temps

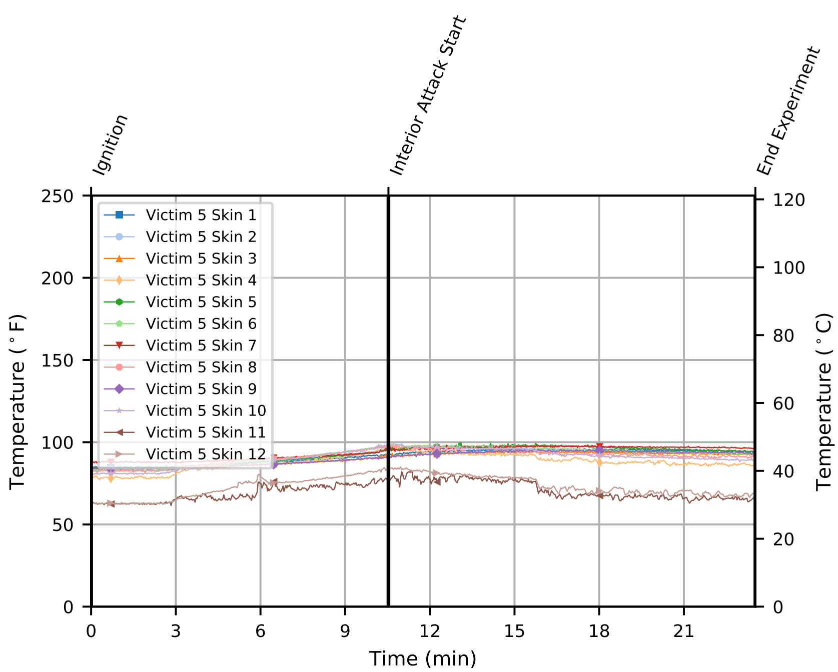


Figure E.645: Experiment 17 - Victim 5 Skin Temps

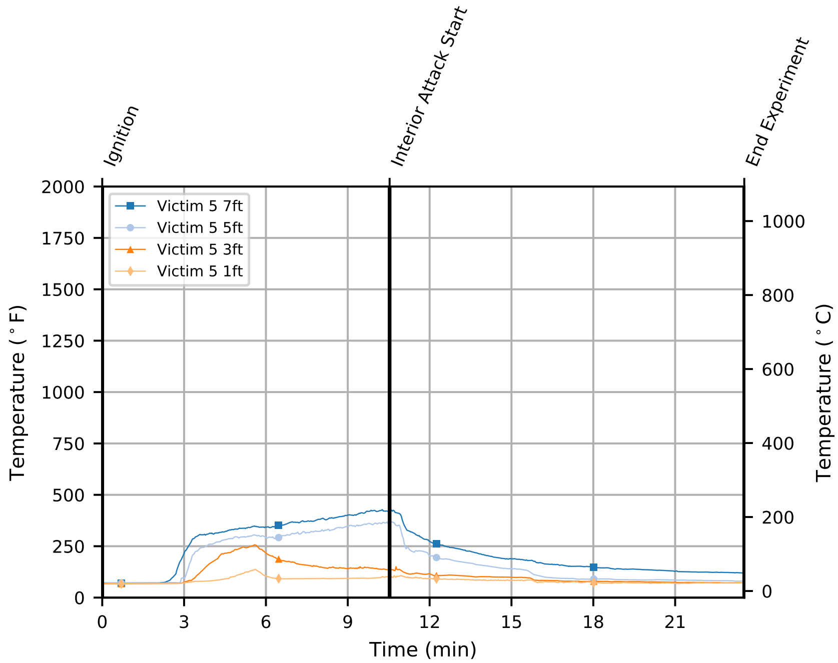


Figure E.646: Experiment 17 - Victim 5 Temps

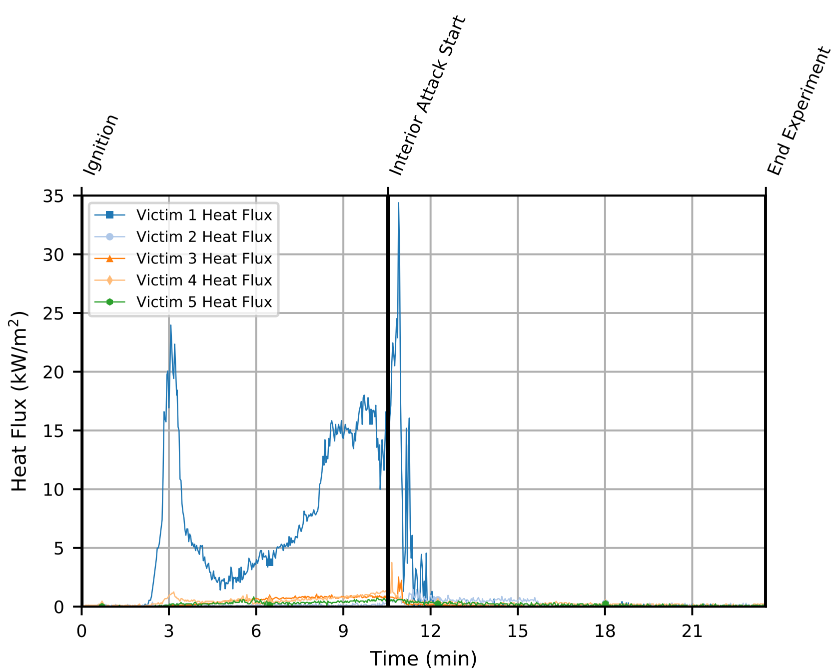


Figure E.647: Experiment 17 - Victim Heat Flux

E.18 Experiment 18 Data

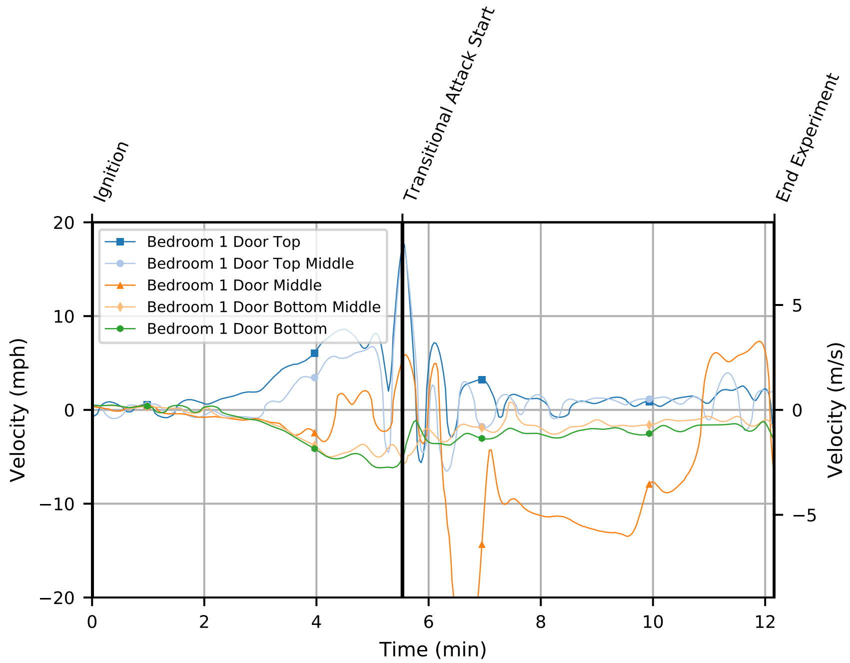


Figure E.648: Experiment 18 - Bedroom 1 Door

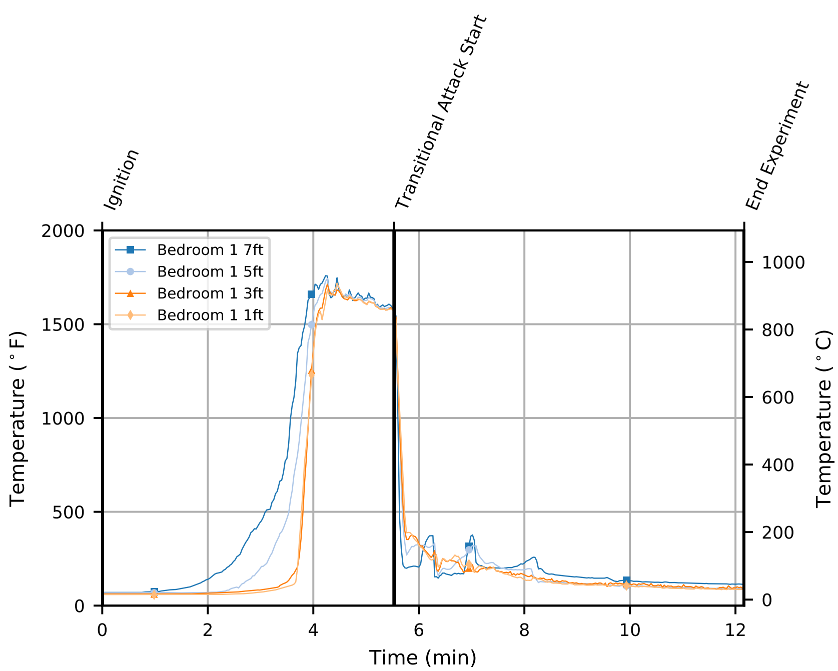


Figure E.649: Experiment 18 - Bedroom 1 Temps

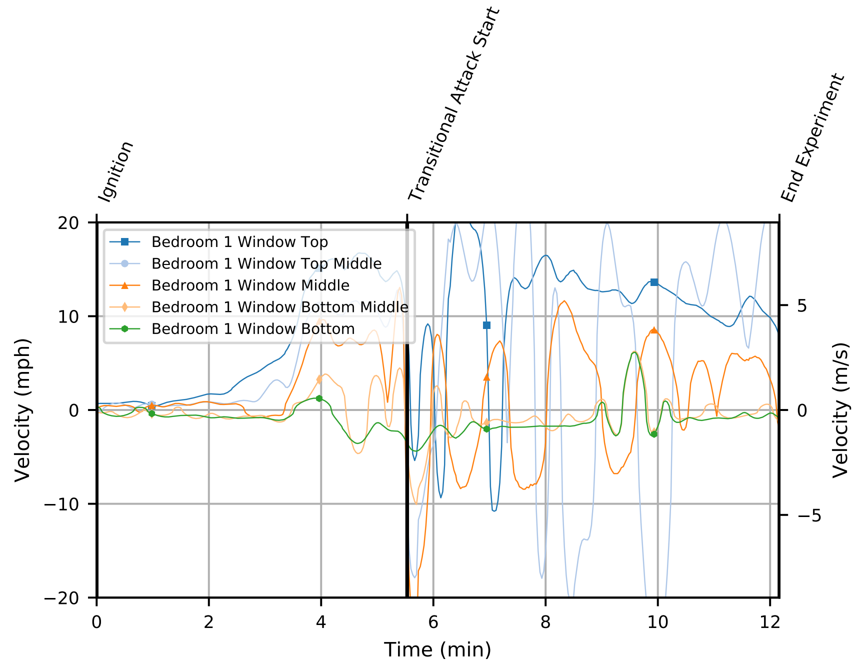


Figure E.650: Experiment 18 - Bedroom 1 Window

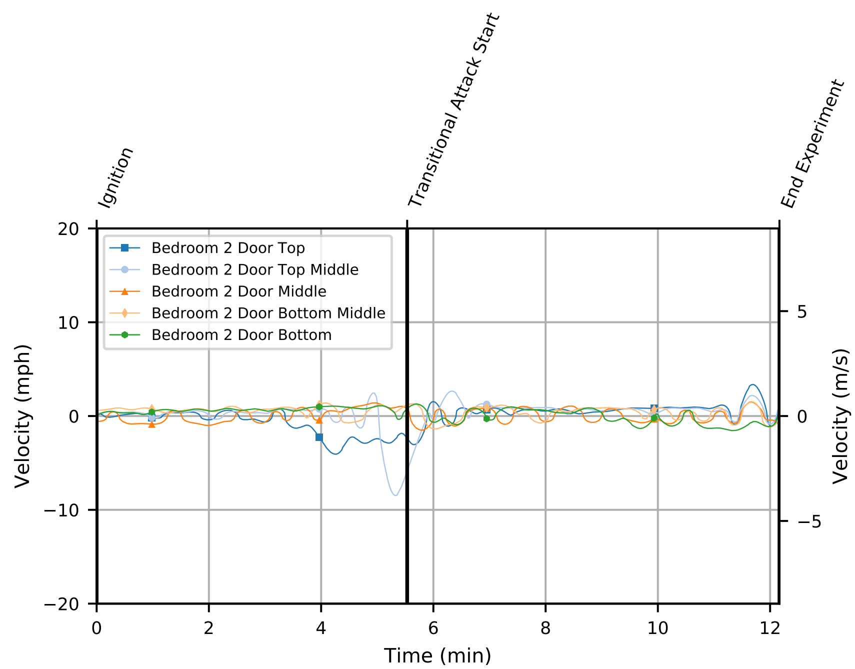


Figure E.651: Experiment 18 - Bedroom 2 Door

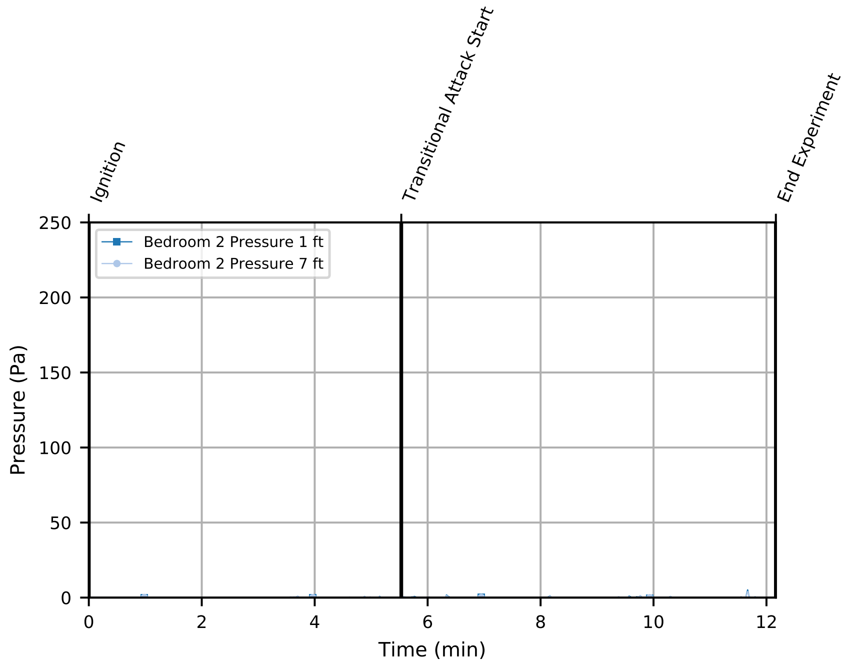


Figure E.652: Experiment 18 - Bedroom 2 Pressure

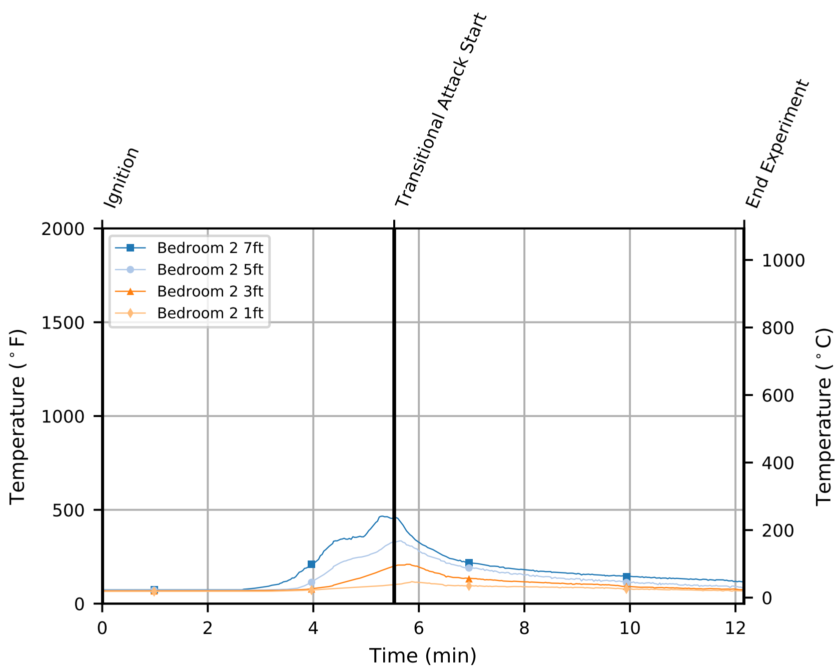


Figure E.653: Experiment 18 - Bedroom 2 Temps

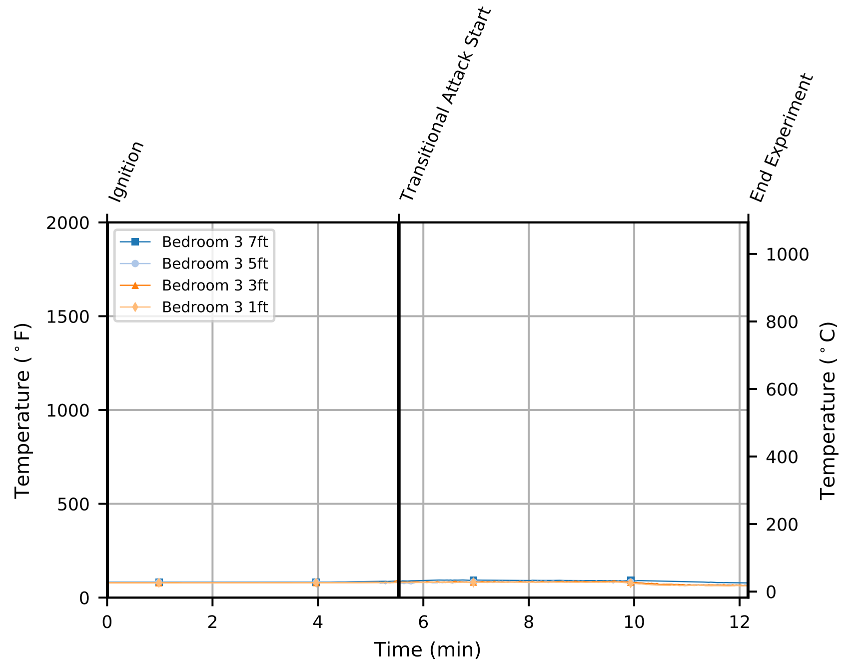


Figure E.654: Experiment 18 - Bedroom 3 Temps

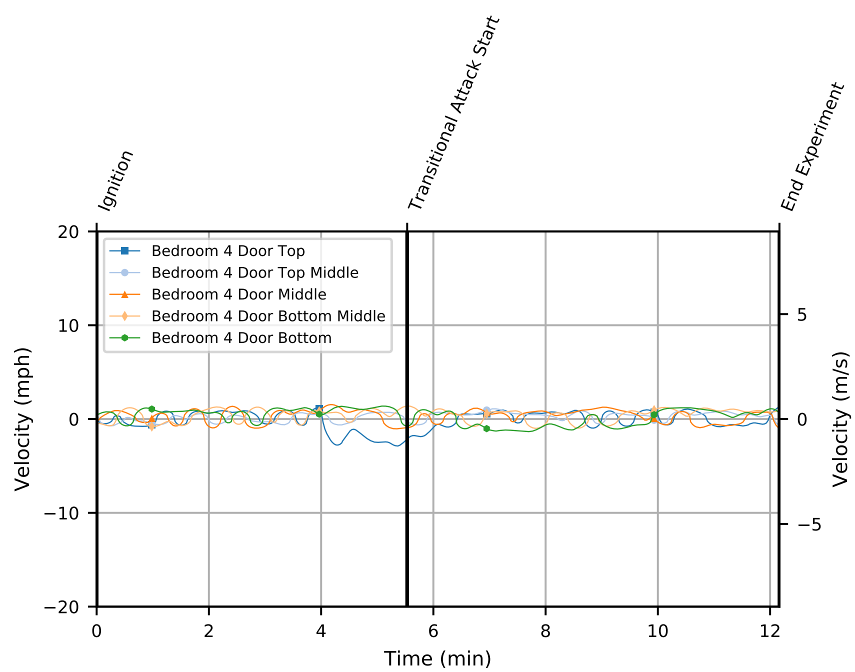


Figure E.655: Experiment 18 - Bedroom 4 Door

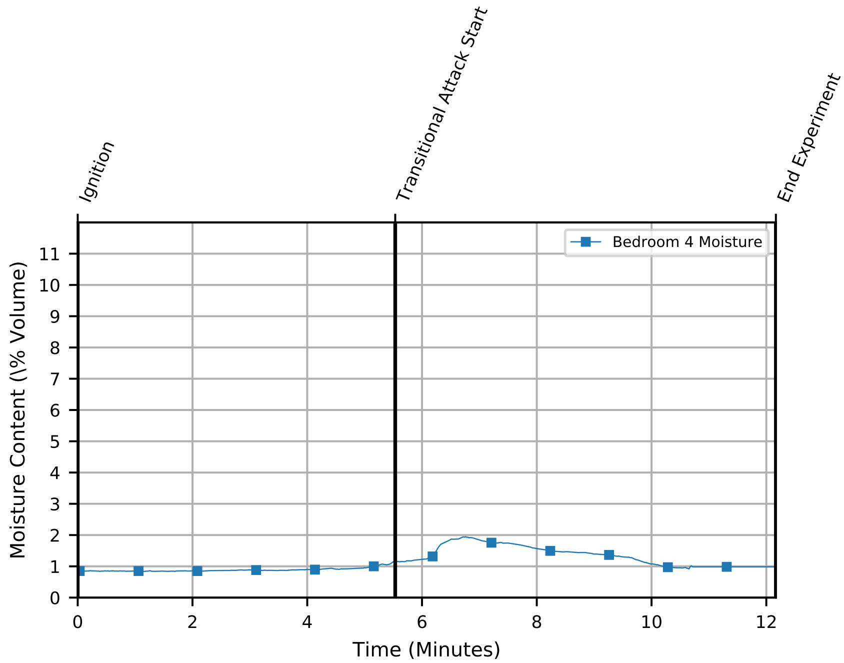


Figure E.656: Experiment 18 - Bedroom 4 Moisture

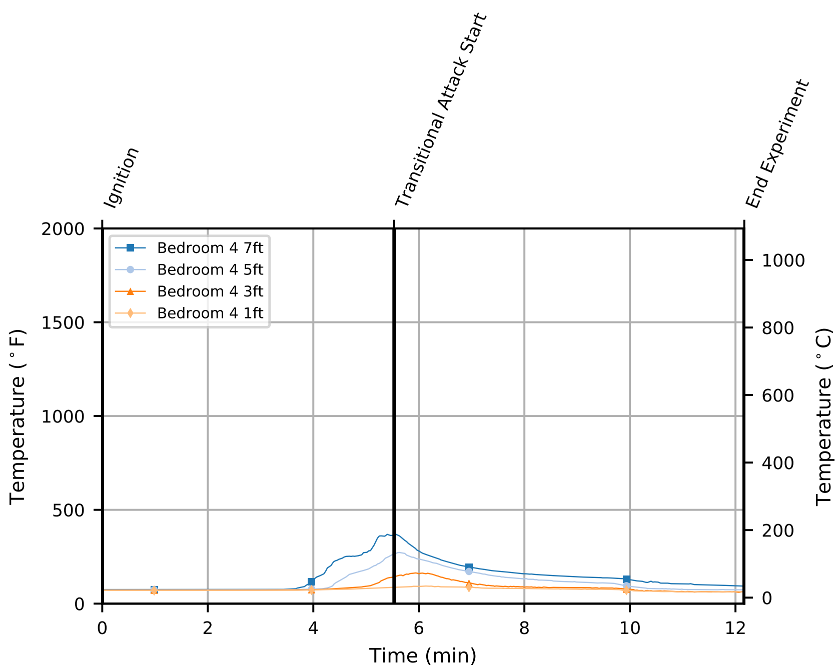


Figure E.657: Experiment 18 - Bedroom 4 Temps

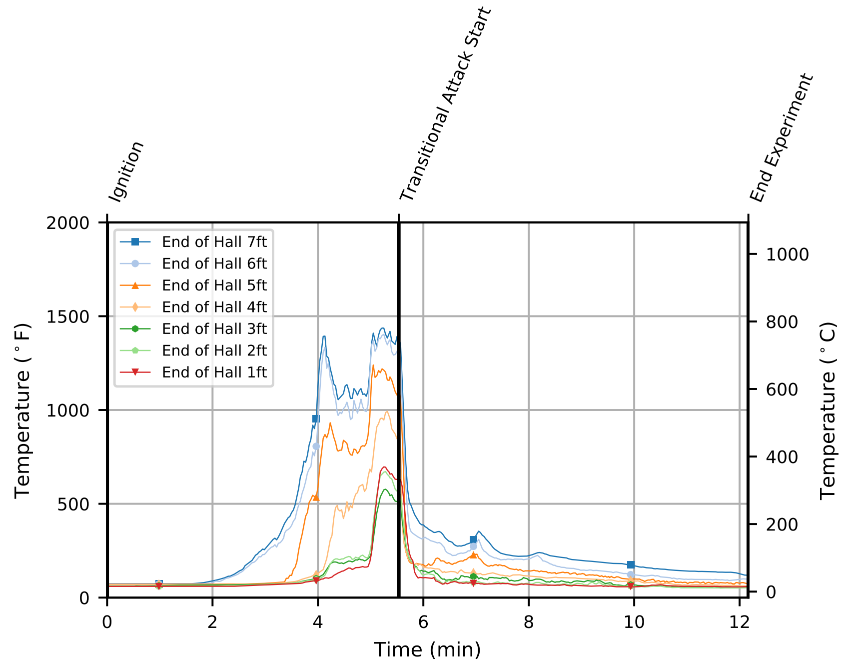


Figure E.658: Experiment 18 - End Hall Temps

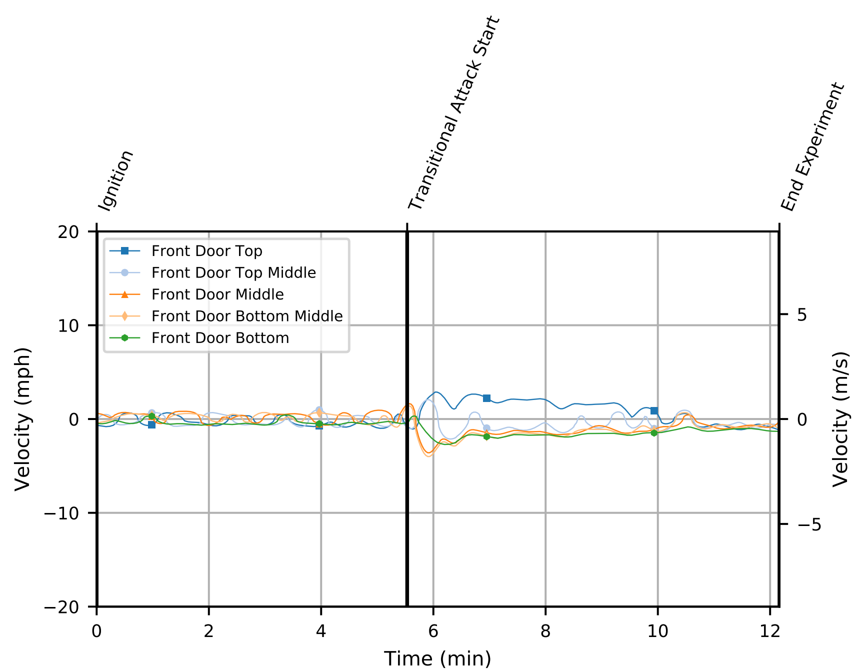


Figure E.659: Experiment 18 - Front Door Flow

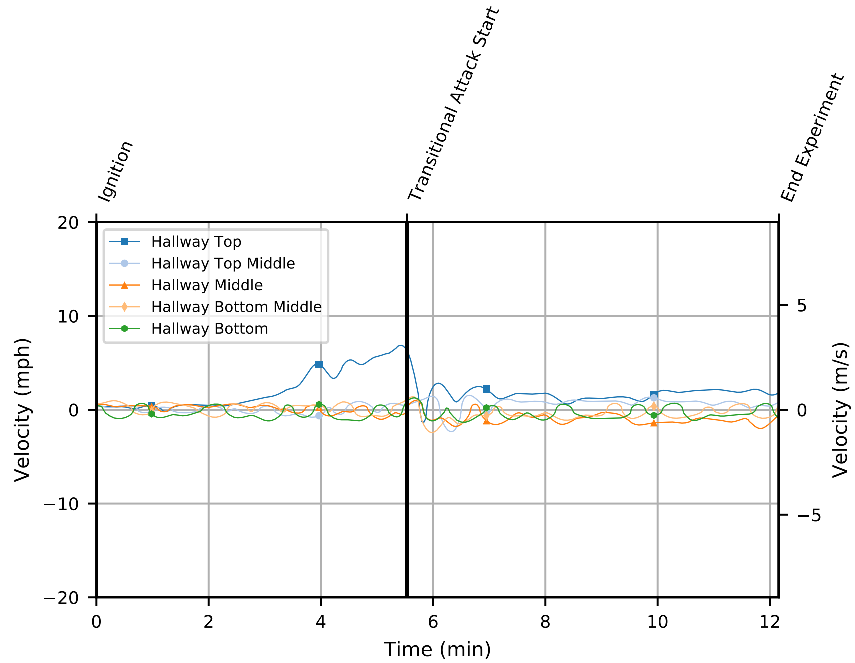


Figure E.660: Experiment 18 - Hallway Flow

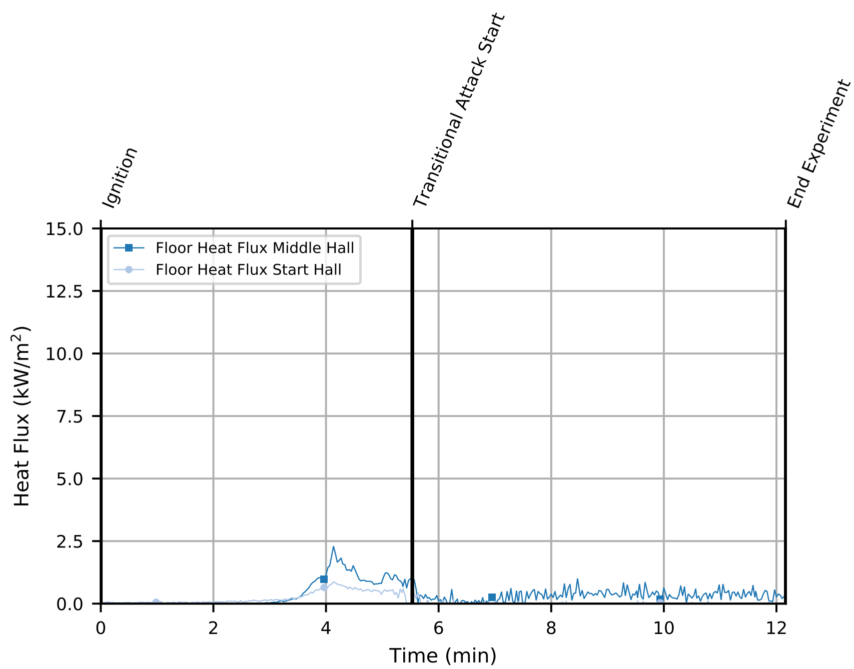


Figure E.661: Experiment 18 - Heat Flux Floor

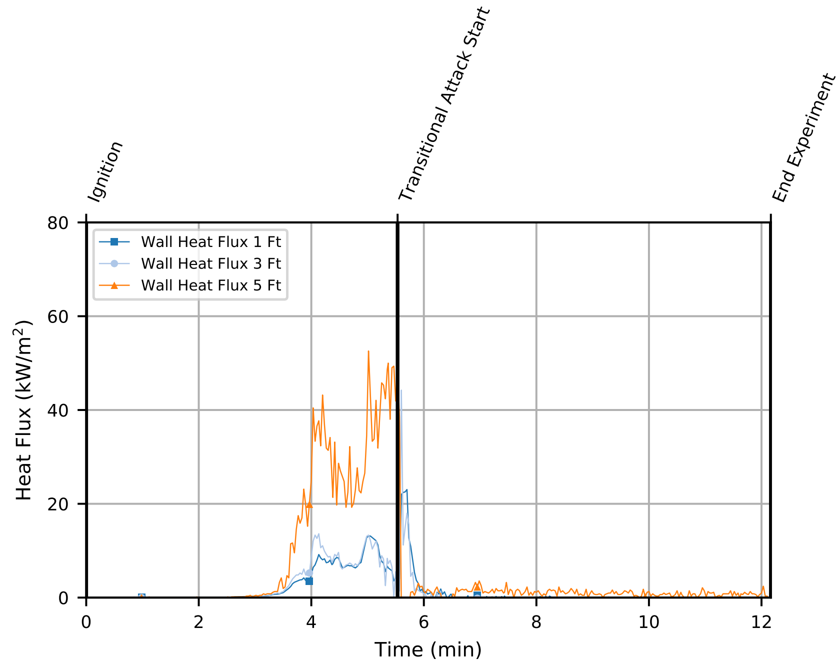


Figure E.662: Experiment 18 - Heat Flux Wall

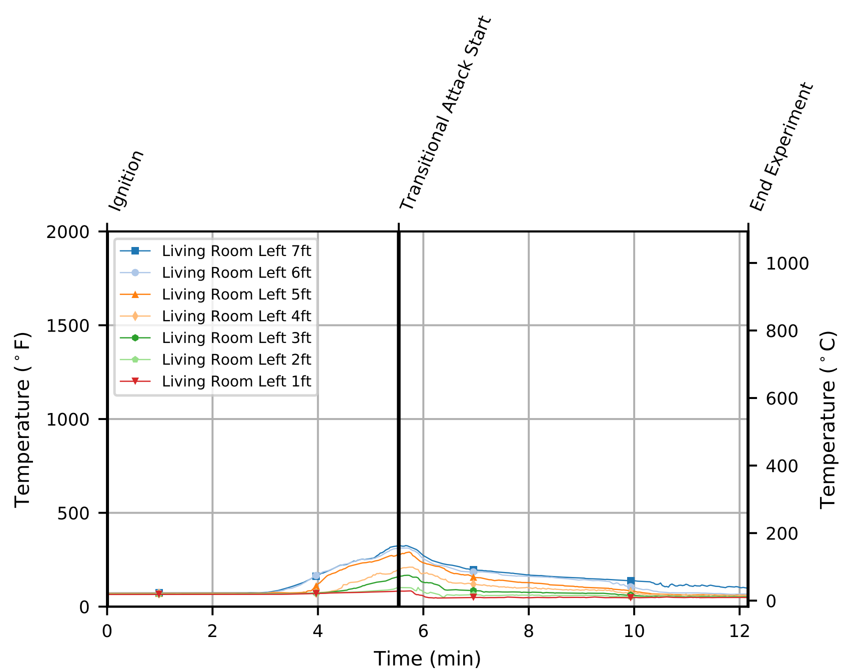


Figure E.663: Experiment 18 - Living Room Left Temps

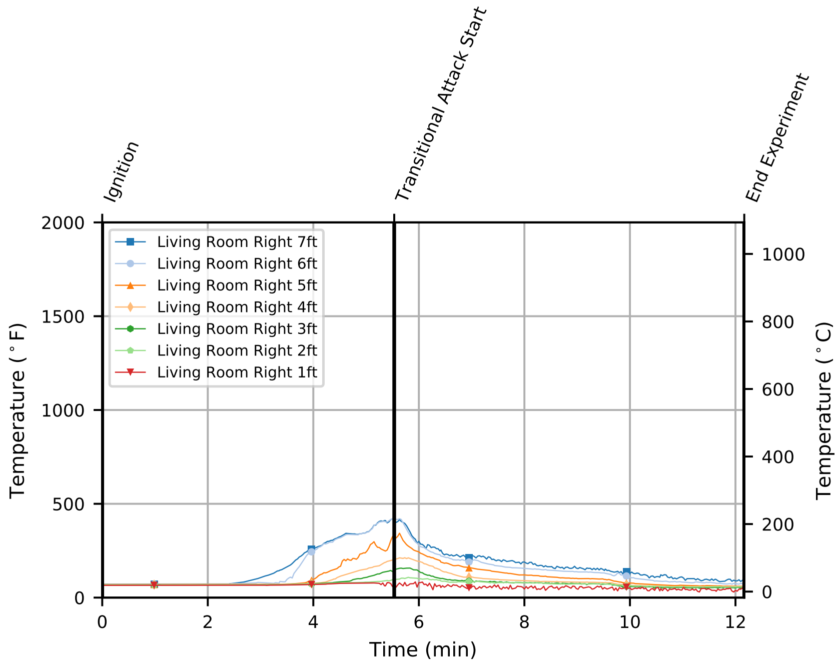


Figure E.664: Experiment 18 - Living Room Right Temps

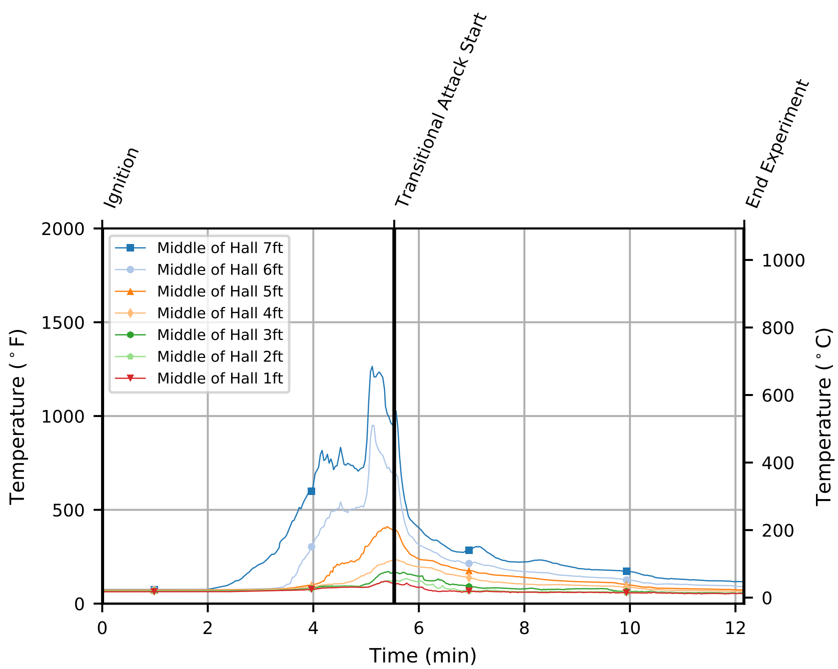


Figure E.665: Experiment 18 - Middle Hall Temps

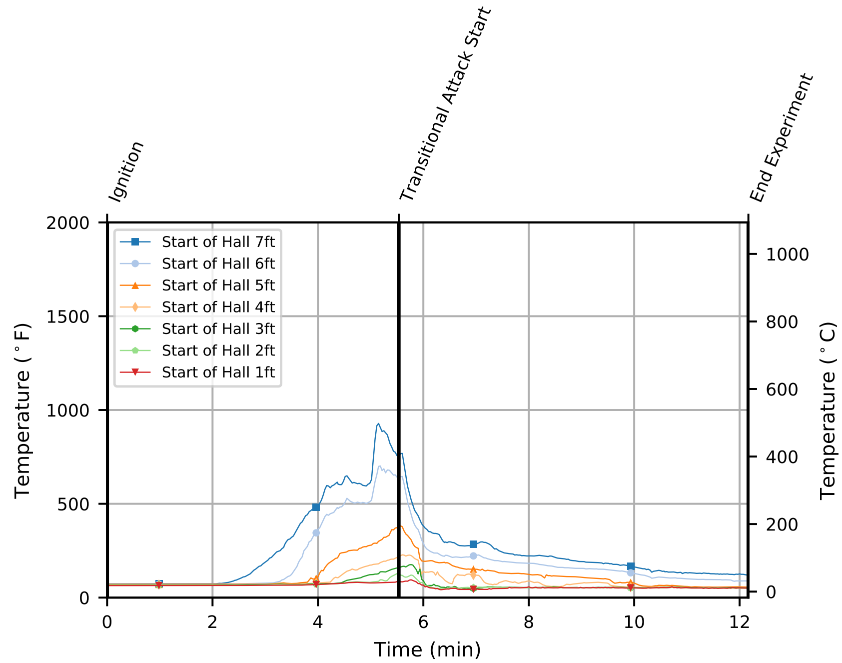


Figure E.666: Experiment 18 - Start Hall Temps

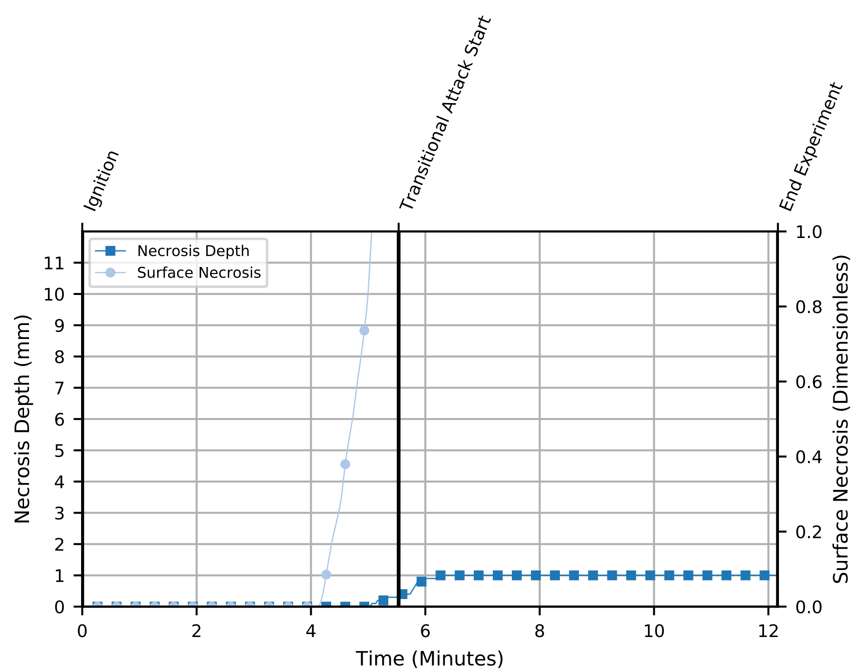


Figure E.667: Experiment 18 - Vic 1 Necrosis Depth

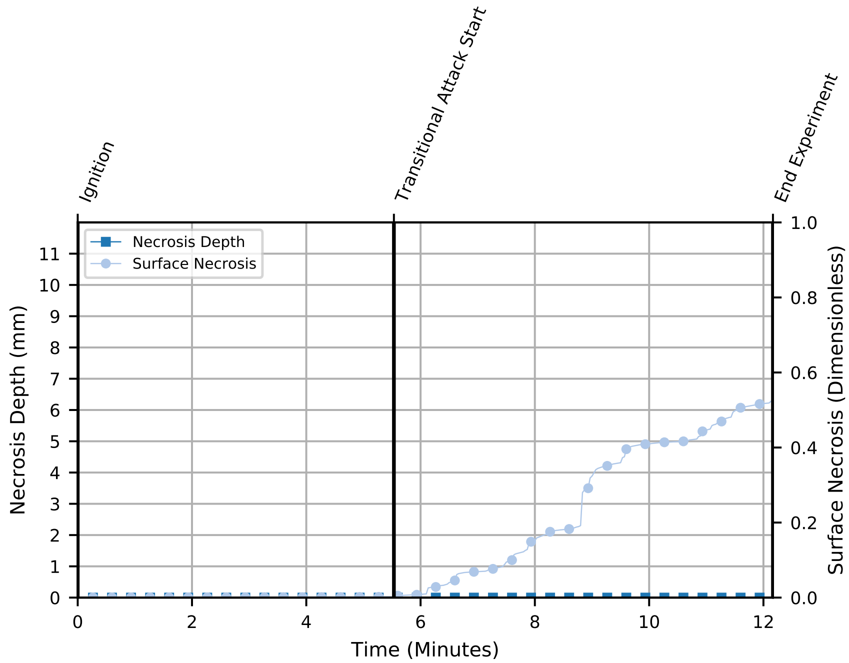


Figure E.668: Experiment 18 - Vic 3 Necrosis Depth

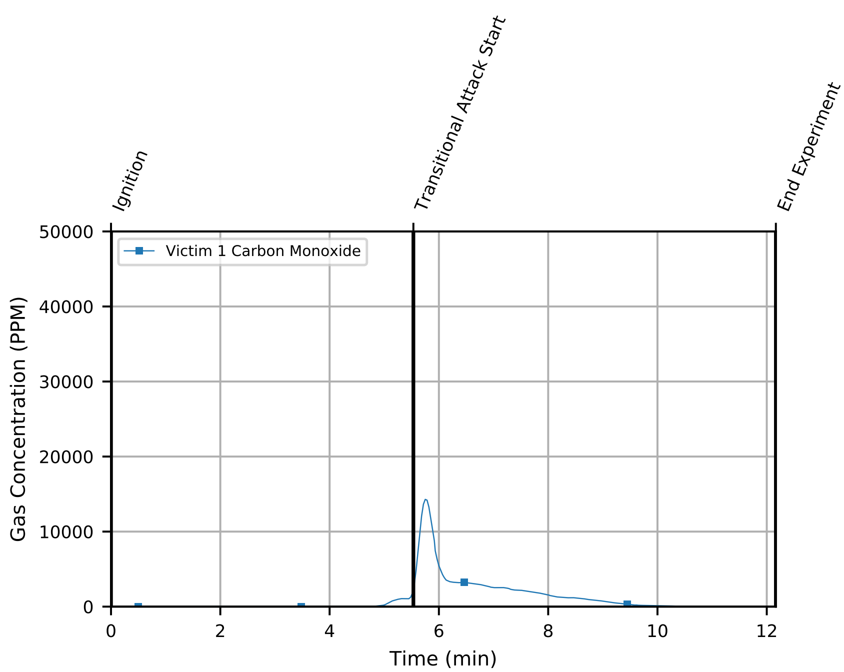


Figure E.669: Experiment 18 - Victim 1 Carbon Monoxide

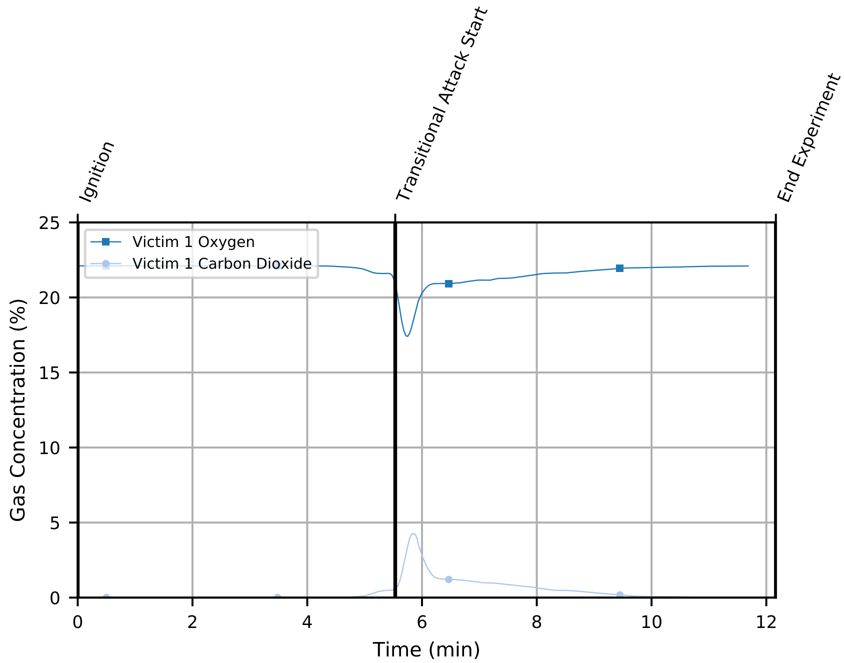


Figure E.670: Experiment 18 - Victim 1 Gas

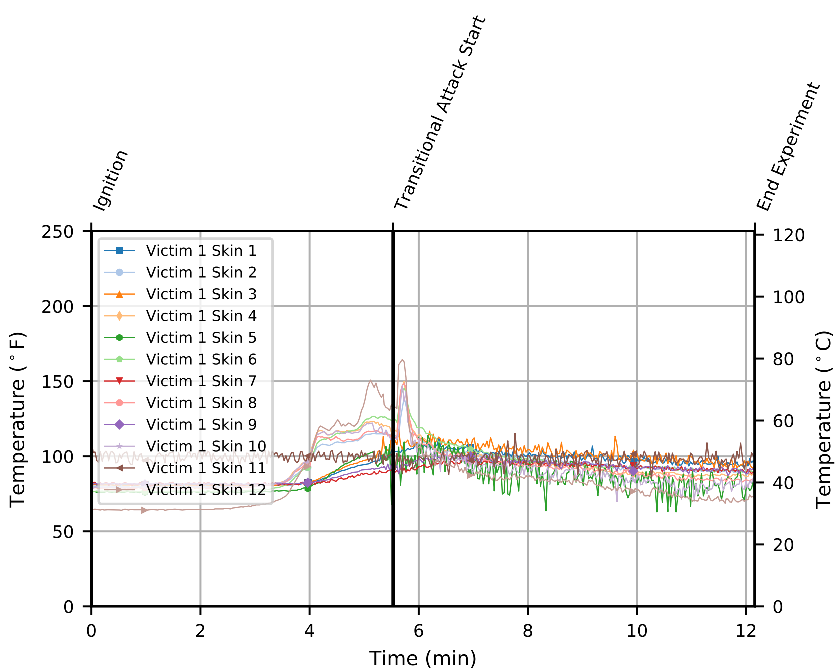


Figure E.671: Experiment 18 - Victim 1 Skin Temps

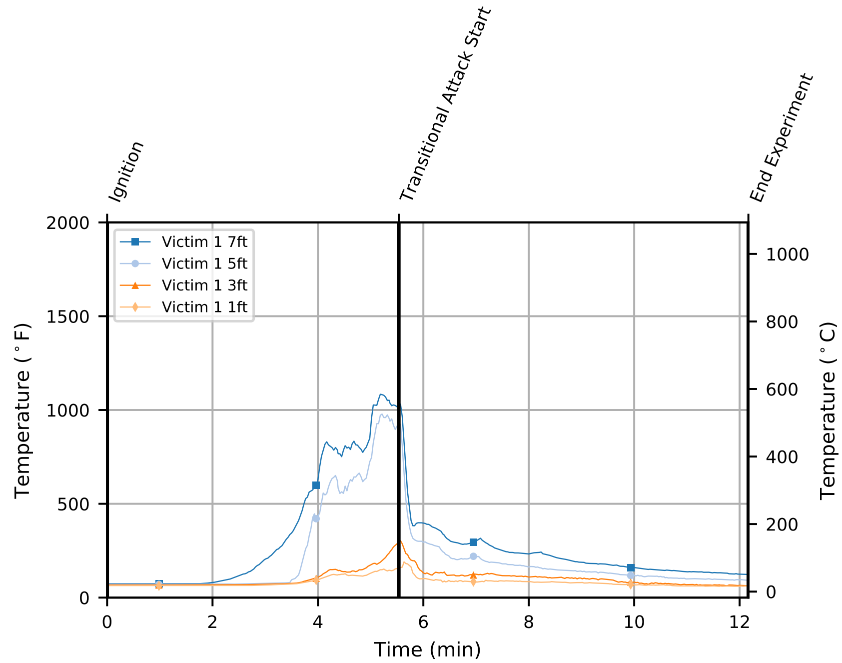


Figure E.672: Experiment 18 - Victim 1 Temps

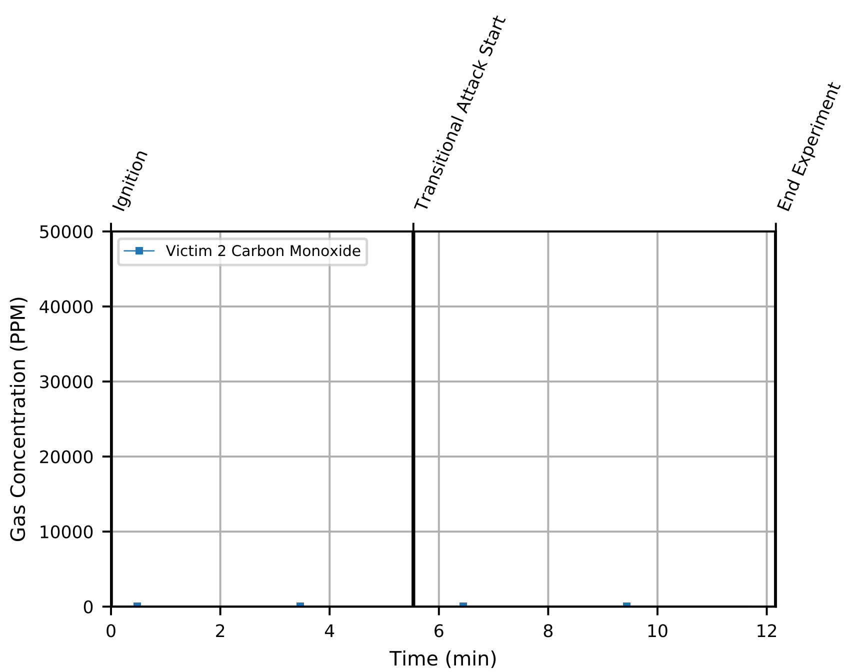


Figure E.673: Experiment 18 - Victim 2 Carbon Monoxide

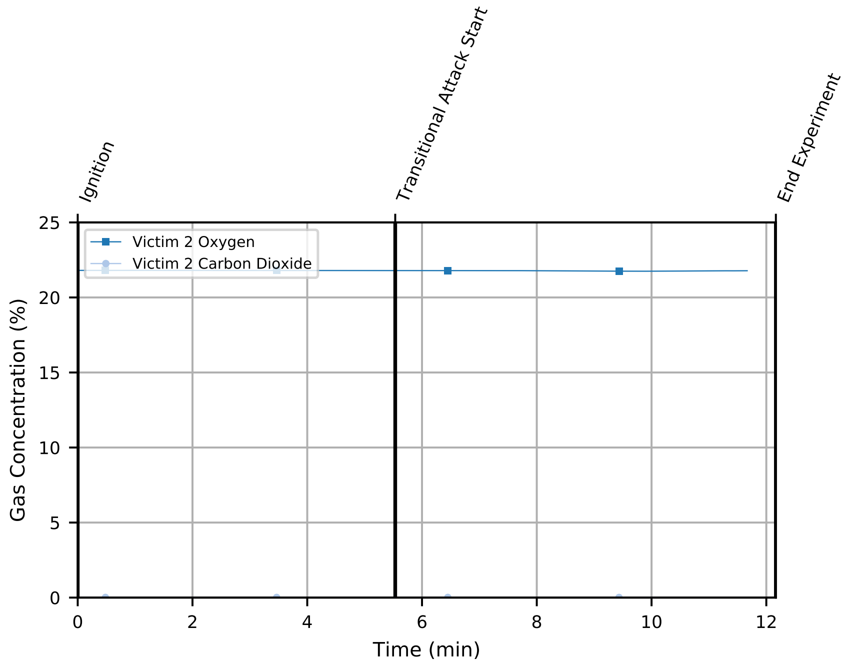


Figure E.674: Experiment 18 - Victim 2 Gas

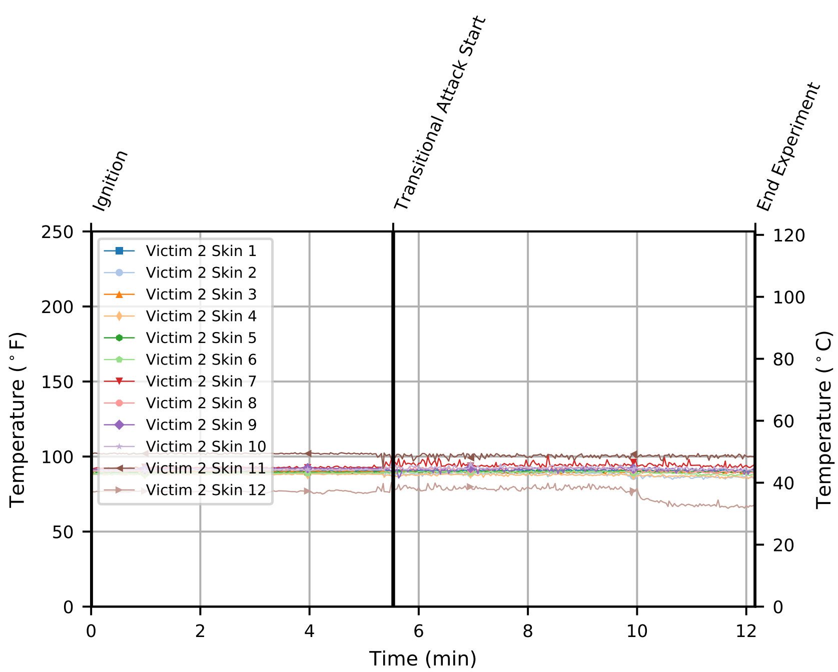


Figure E.675: Experiment 18 - Victim 2 Skin Temps

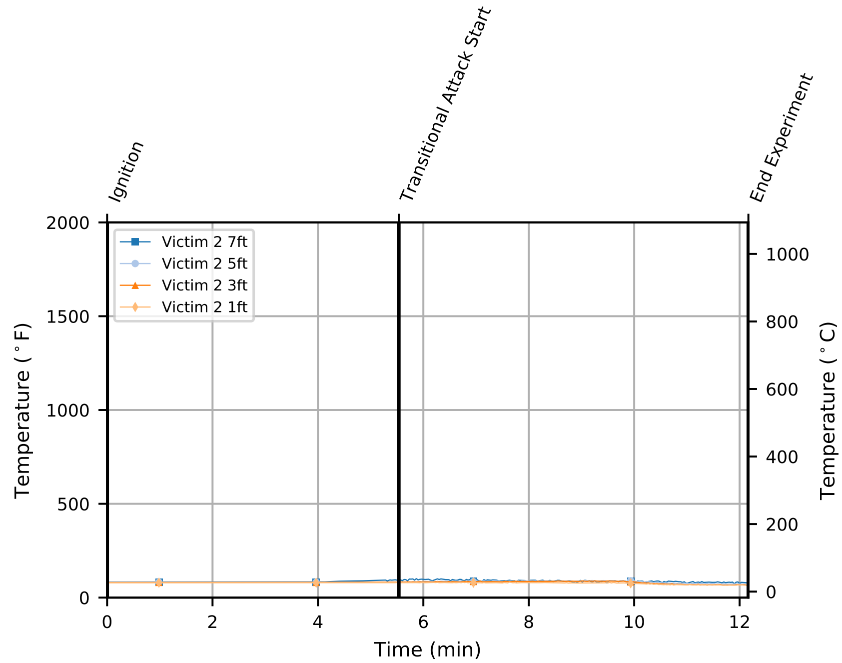


Figure E.676: Experiment 18 - Victim 2 Temps

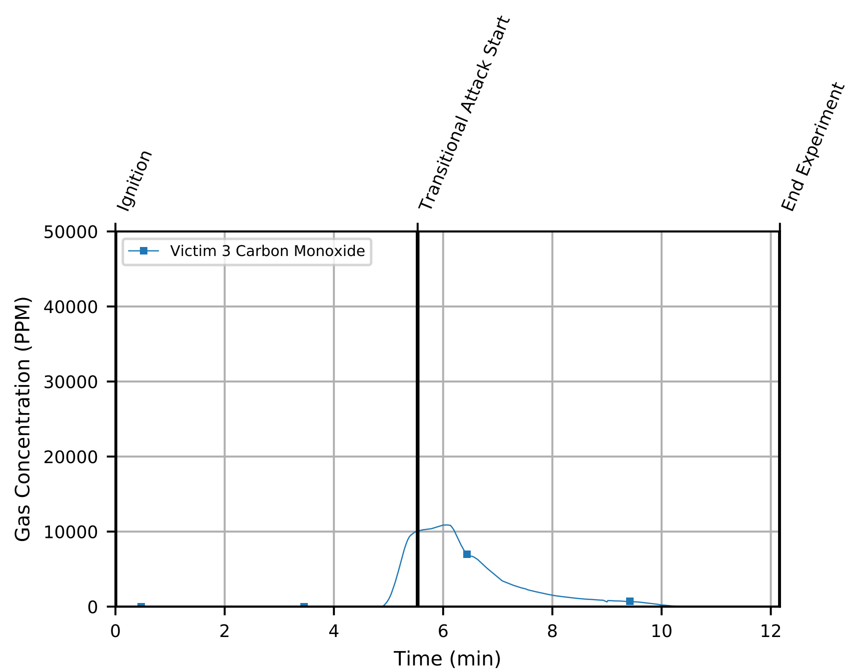


Figure E.677: Experiment 18 - Victim 3 Carbon Monoxide

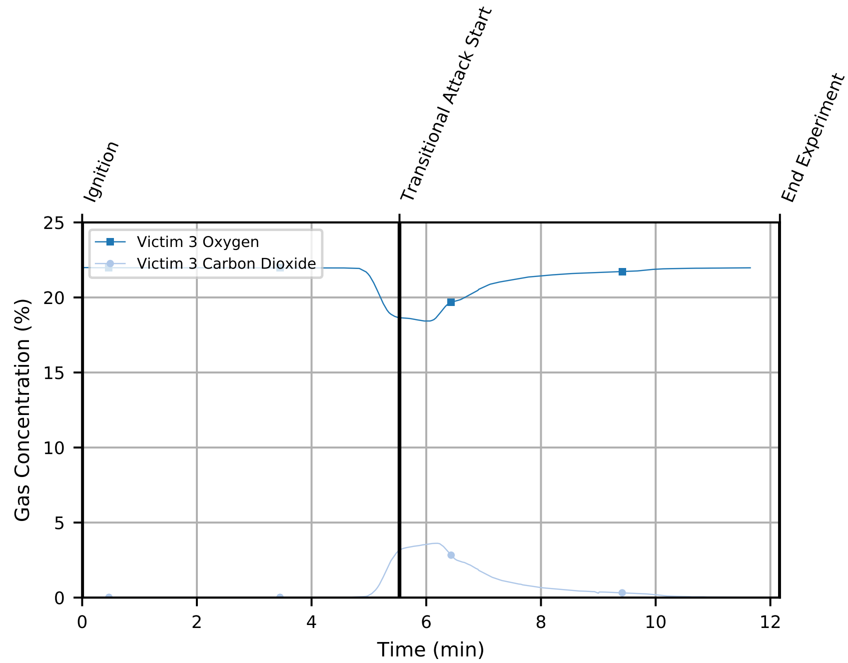


Figure E.678: Experiment 18 - Victim 3 Gas

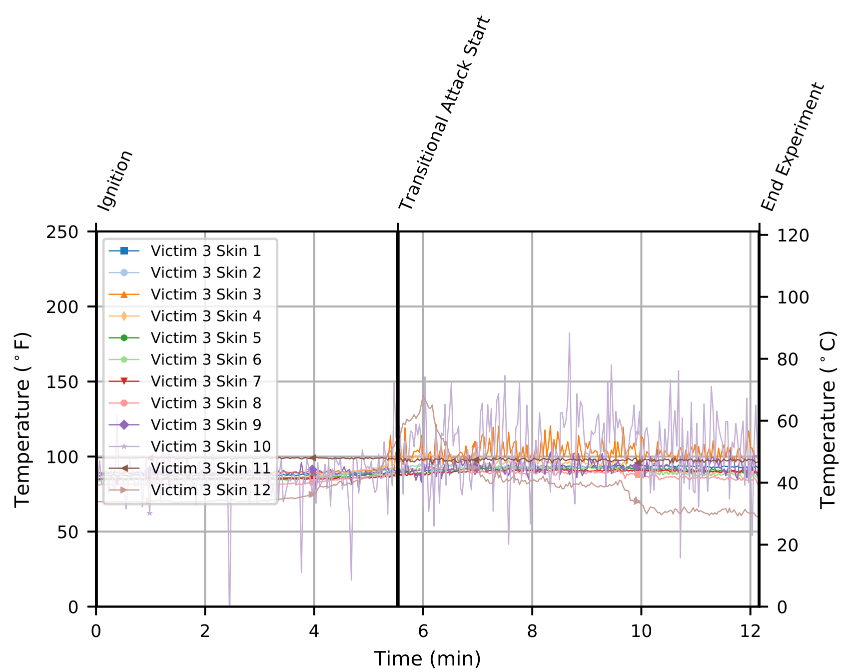


Figure E.679: Experiment 18 - Victim 3 Skin Temps

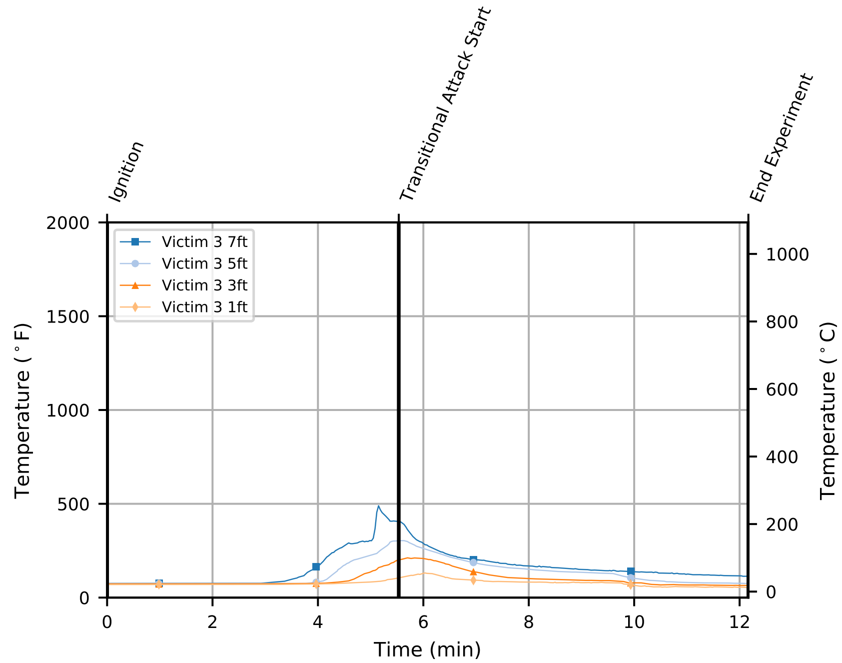


Figure E.680: Experiment 18 - Victim 3 Temps

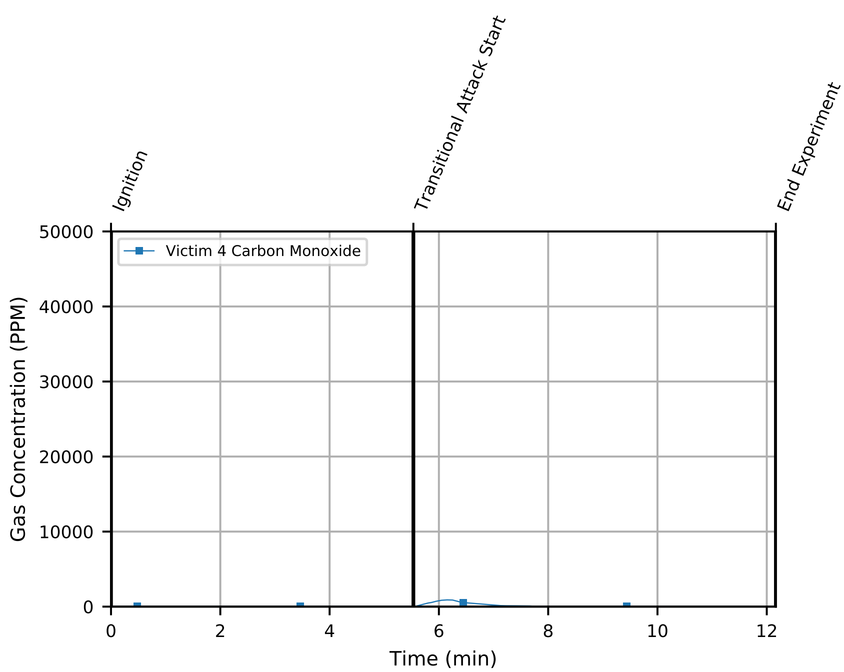


Figure E.681: Experiment 18 - Victim 4 Carbon Monoxide

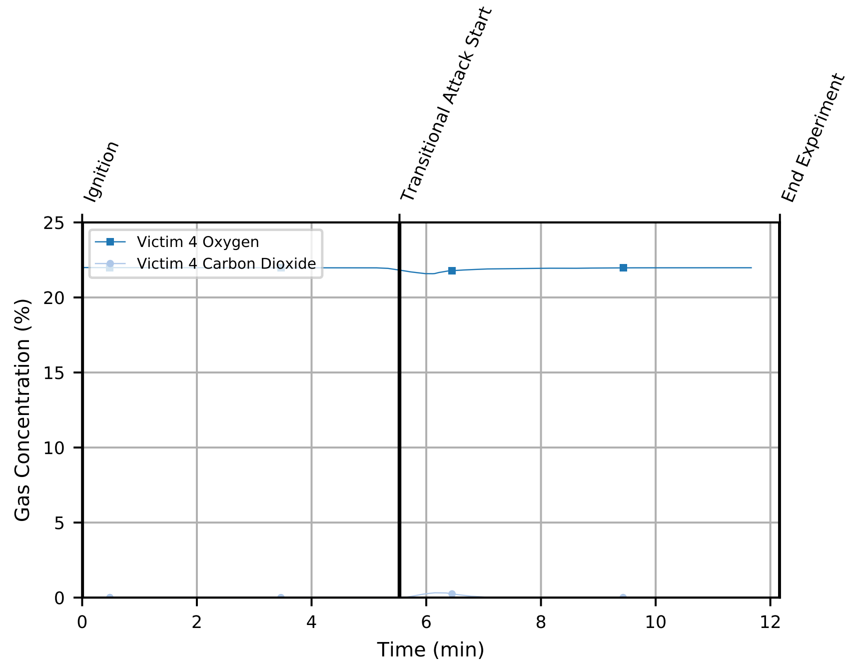


Figure E.682: Experiment 18 - Victim 4 Gas

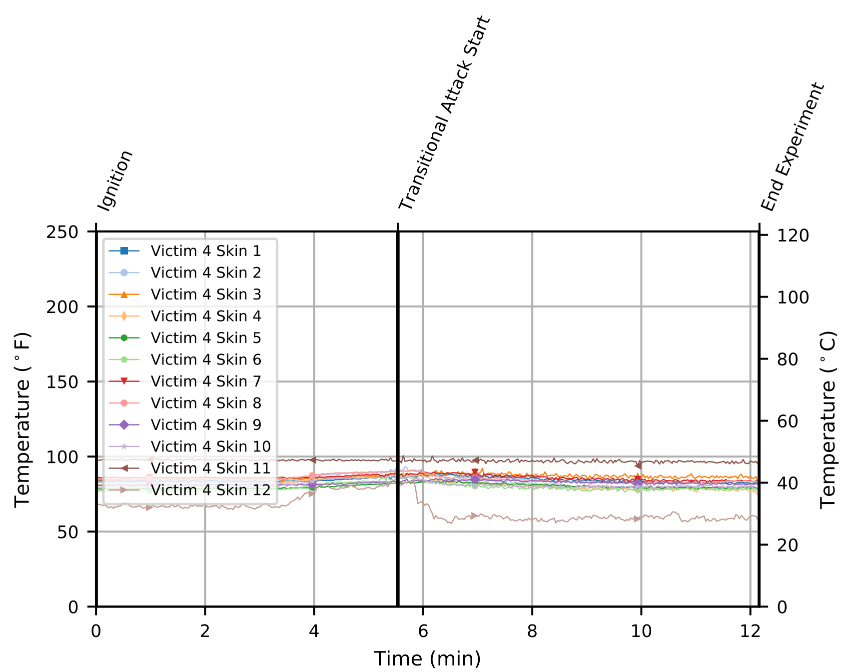


Figure E.683: Experiment 18 - Victim 4 Skin Temps

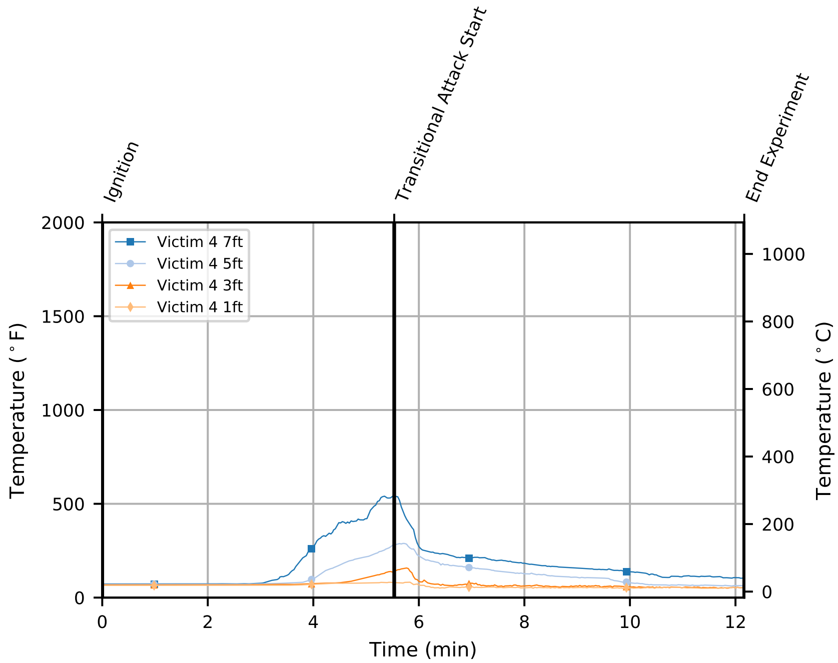


Figure E.684: Experiment 18 - Victim 4 Temps

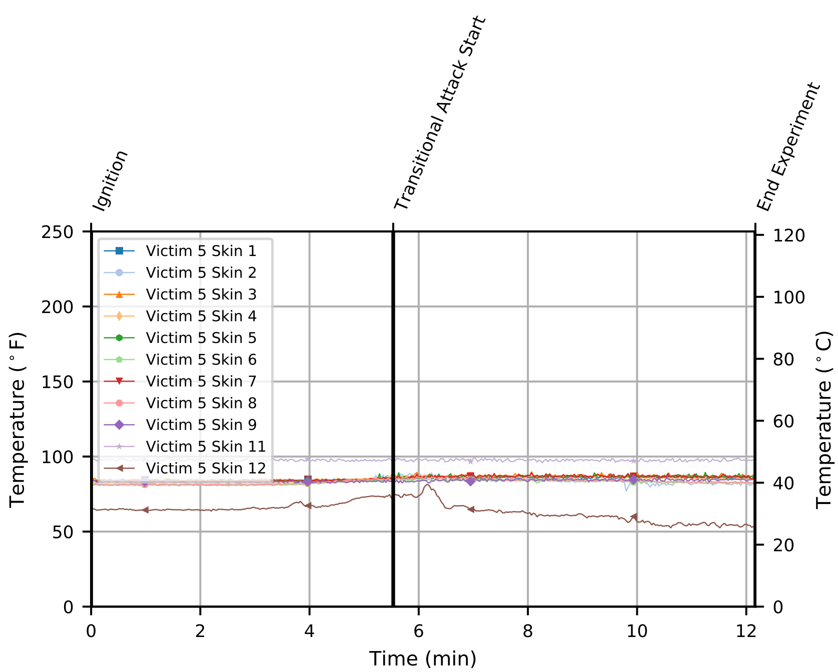


Figure E.685: Experiment 18 - Victim 5 Skin Temps

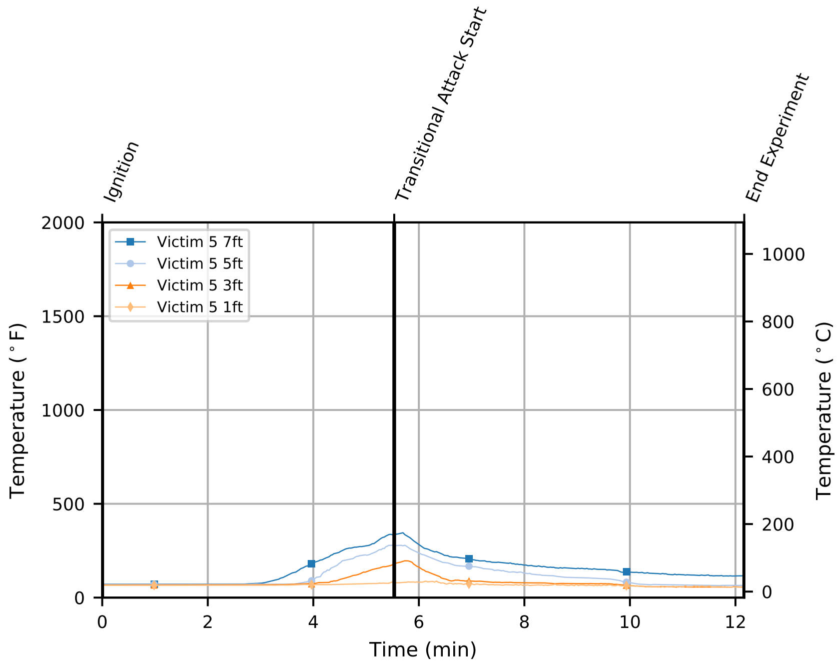


Figure E.686: Experiment 18 - Victim 5 Temps

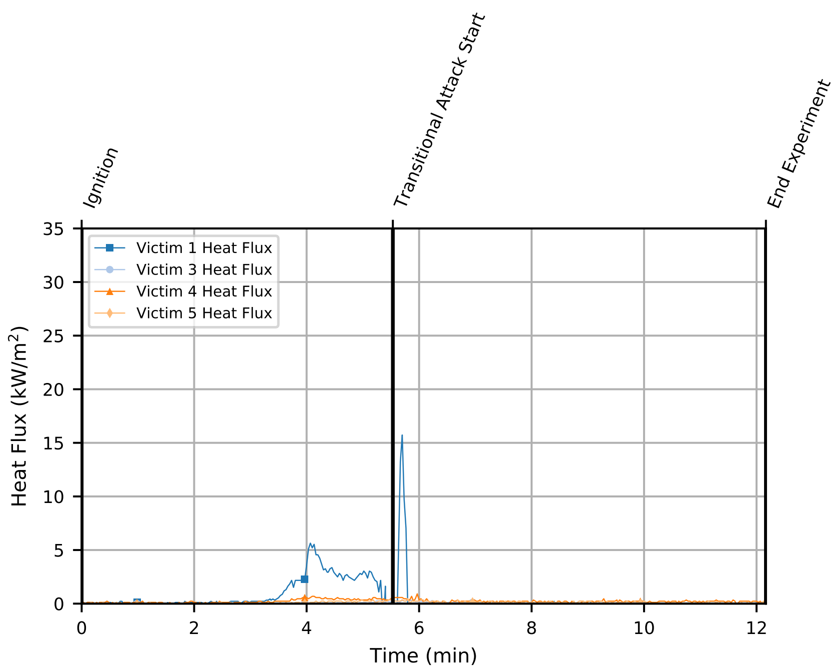


Figure E.687: Experiment 18 - Victim Heat Flux

E.19 Experiment 19 Data

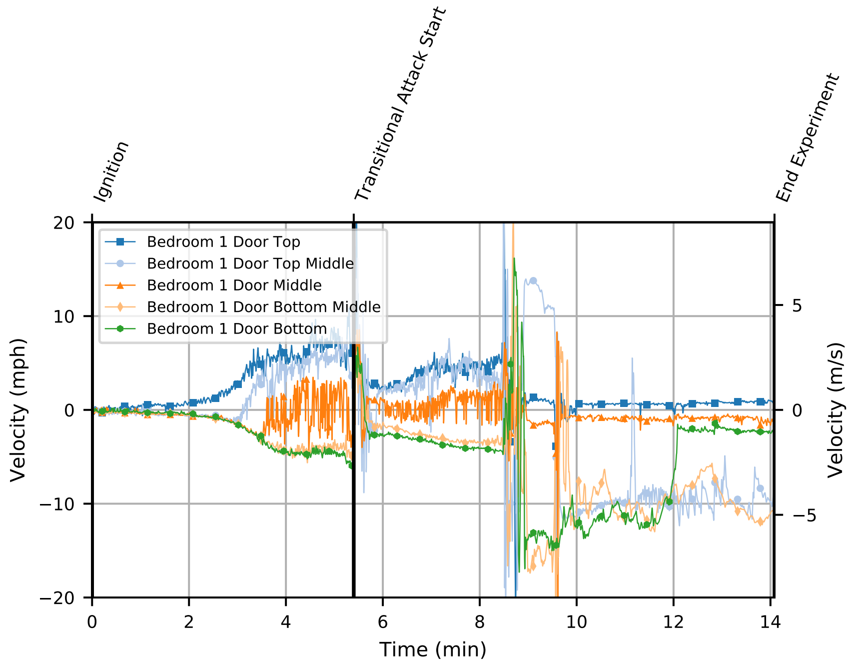


Figure E.688: Experiment 19 - Bedroom 1 Door

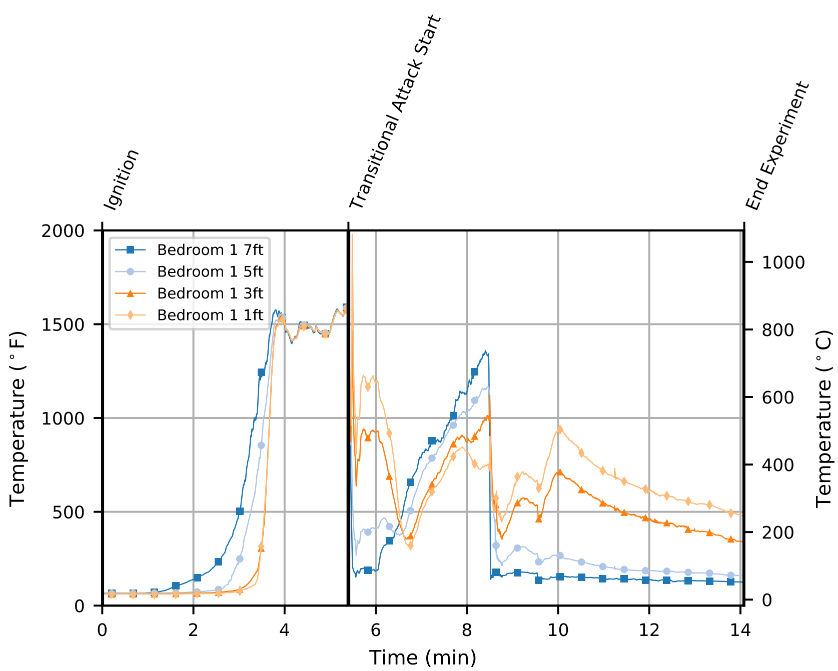


Figure E.689: Experiment 19 - Bedroom 1 Temps

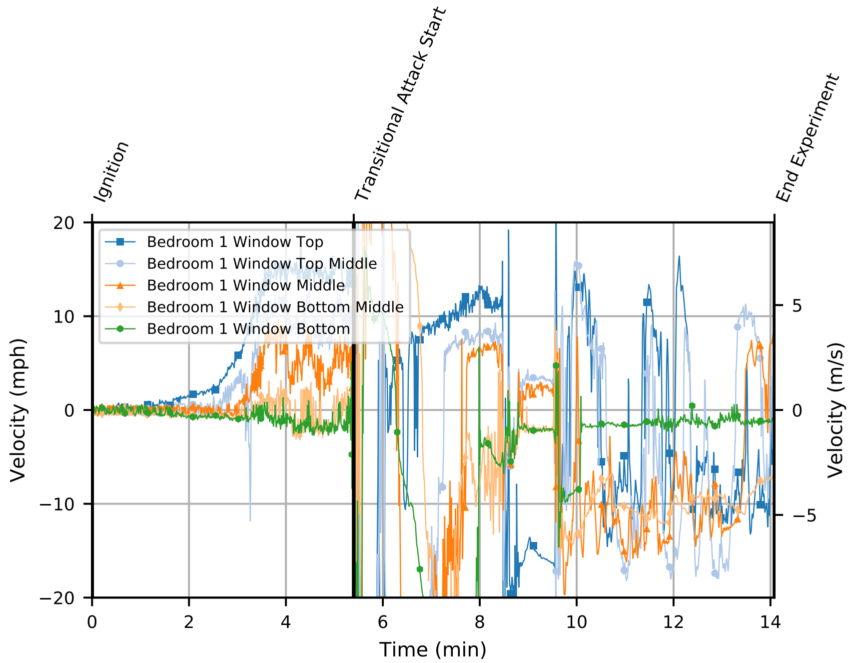


Figure E.690: Experiment 19 - Bedroom 1 Window

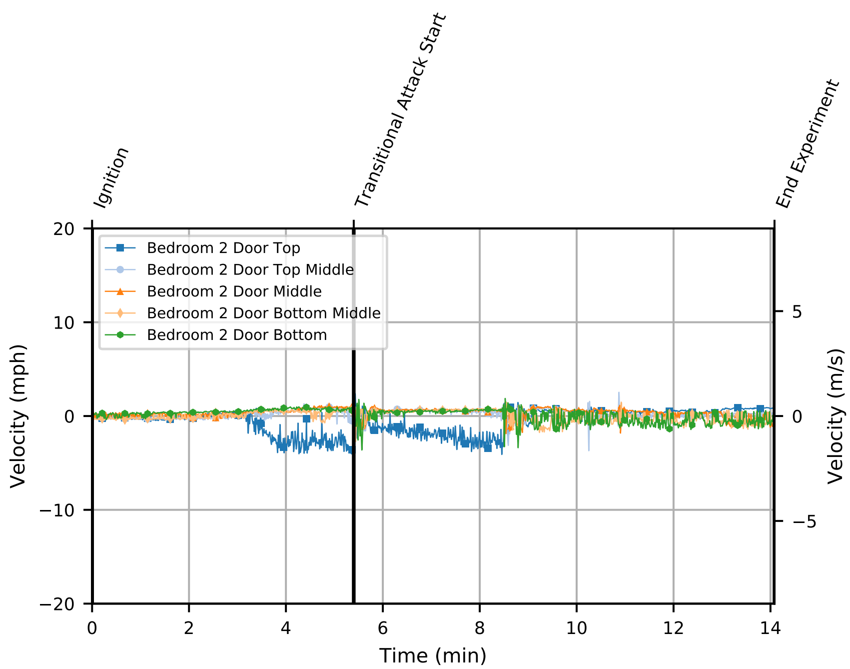


Figure E.691: Experiment 19 - Bedroom 2 Door

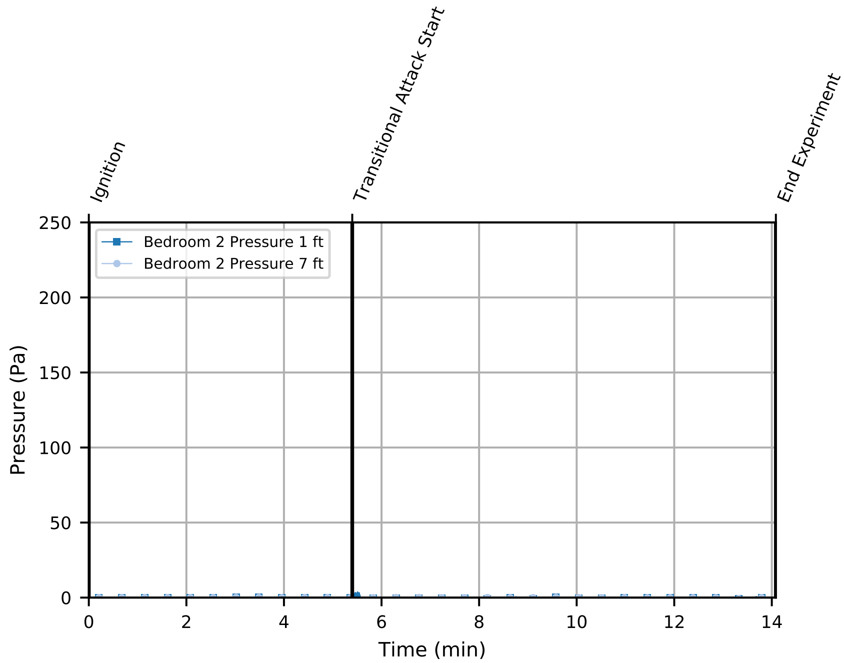


Figure E.692: Experiment 19 - Bedroom 2 Pressure

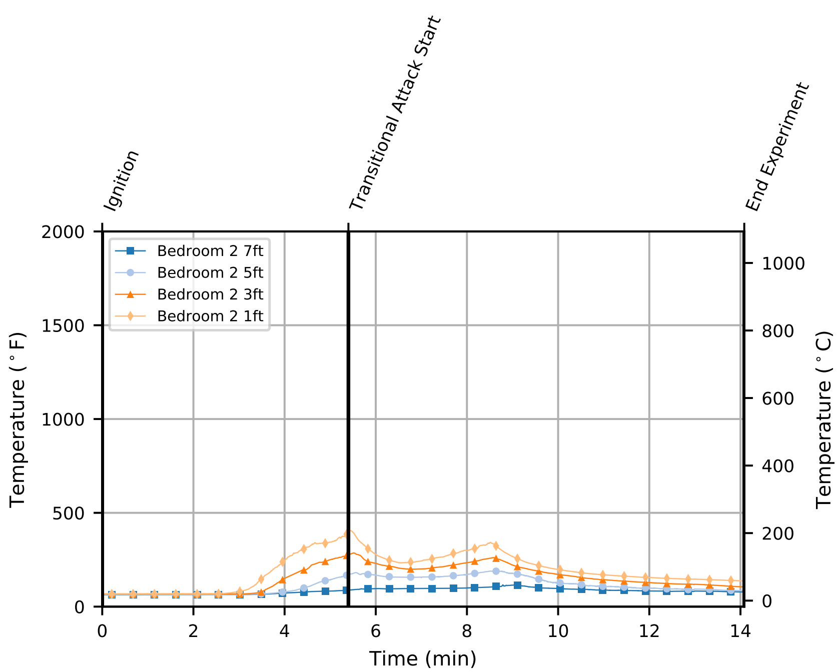


Figure E.693: Experiment 19 - Bedroom 2 Temps

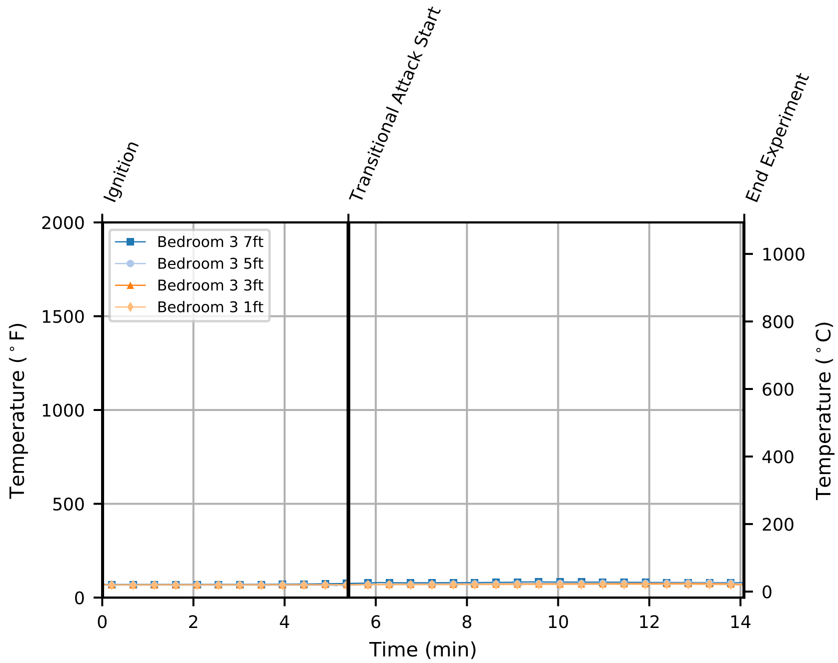


Figure E.694: Experiment 19 - Bedroom 3 Temps

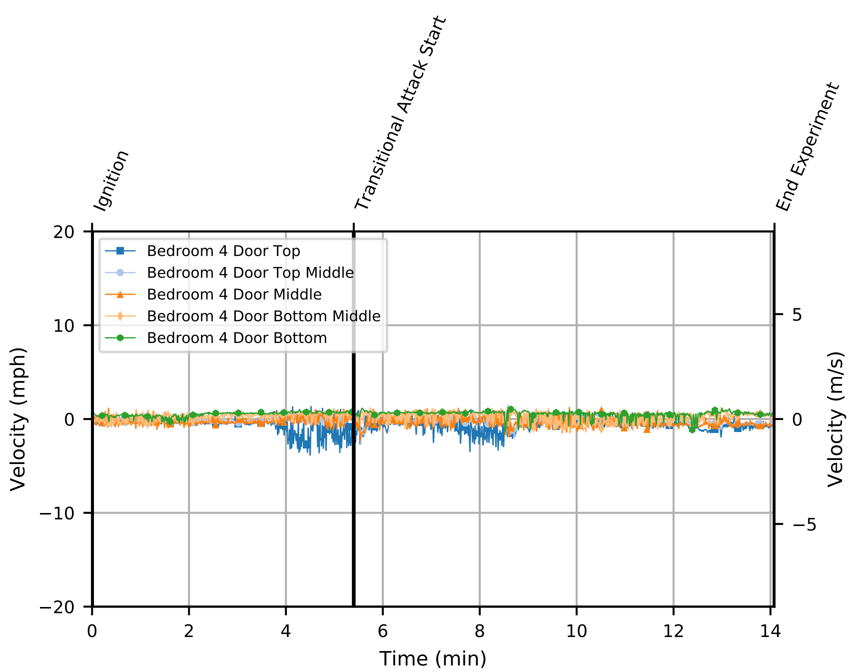


Figure E.695: Experiment 19 - Bedroom 4 Door

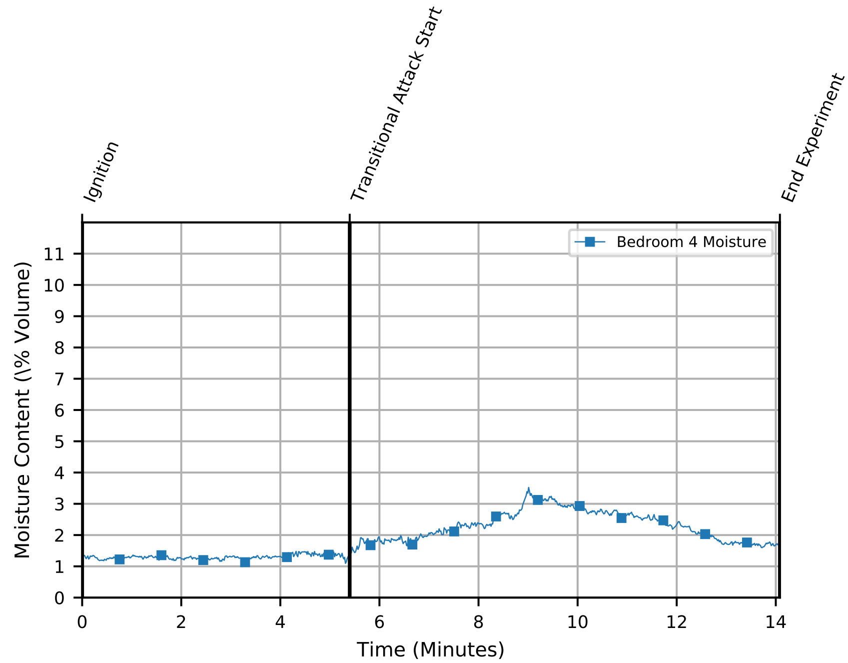


Figure E.696: Experiment 19 - Bedroom 4 Moisture

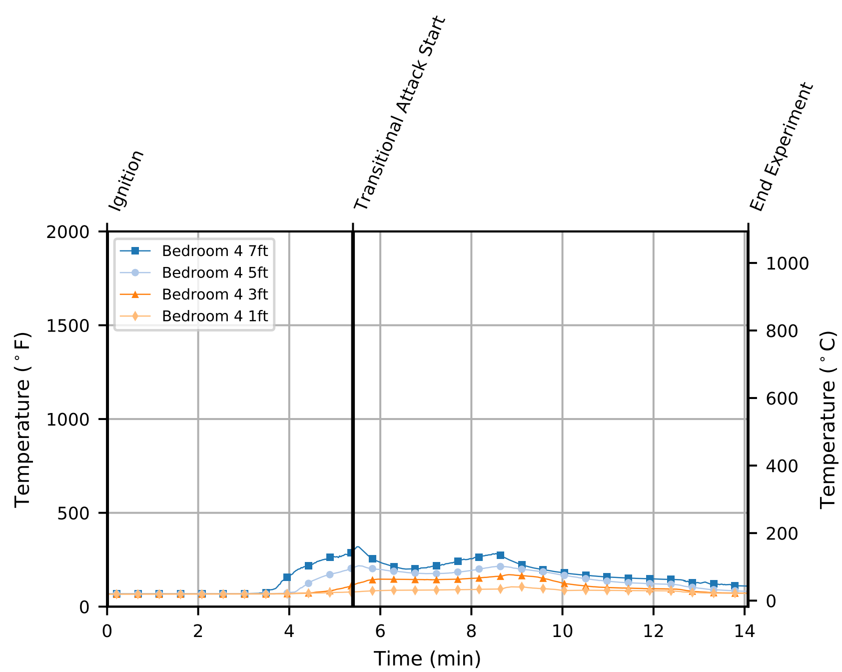


Figure E.697: Experiment 19 - Bedroom 4 Temps

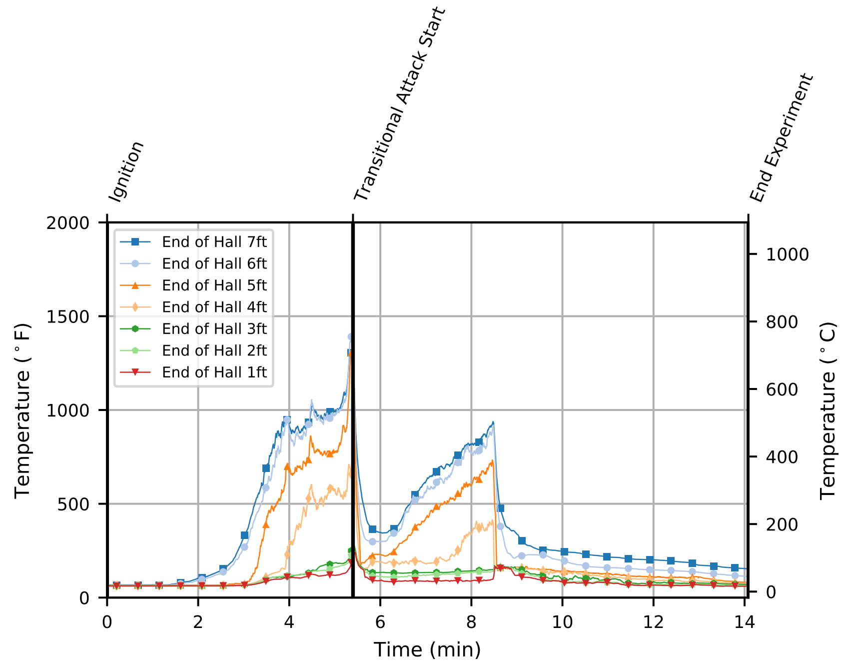


Figure E.698: Experiment 19 - End Hall Temps

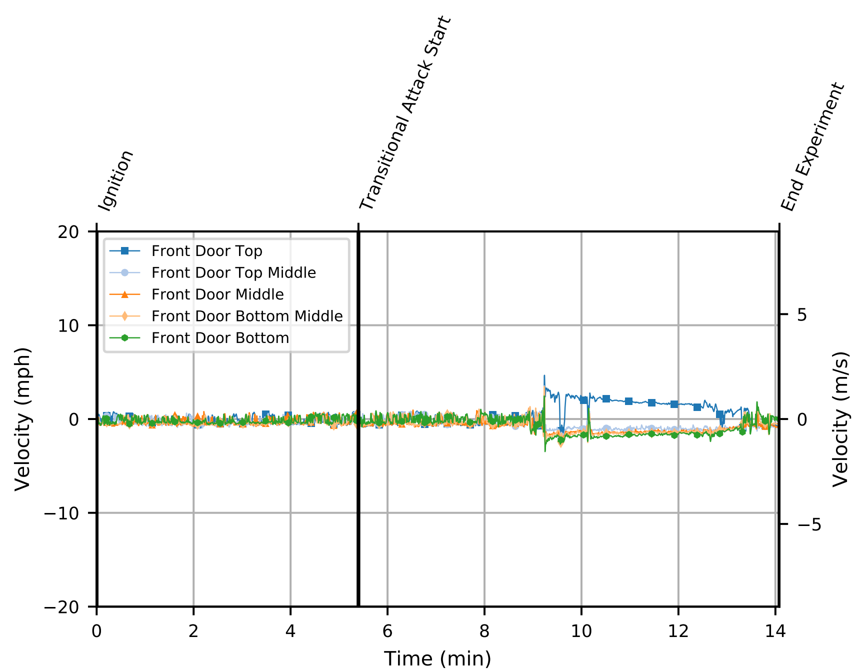


Figure E.699: Experiment 19 - Front Door Flow

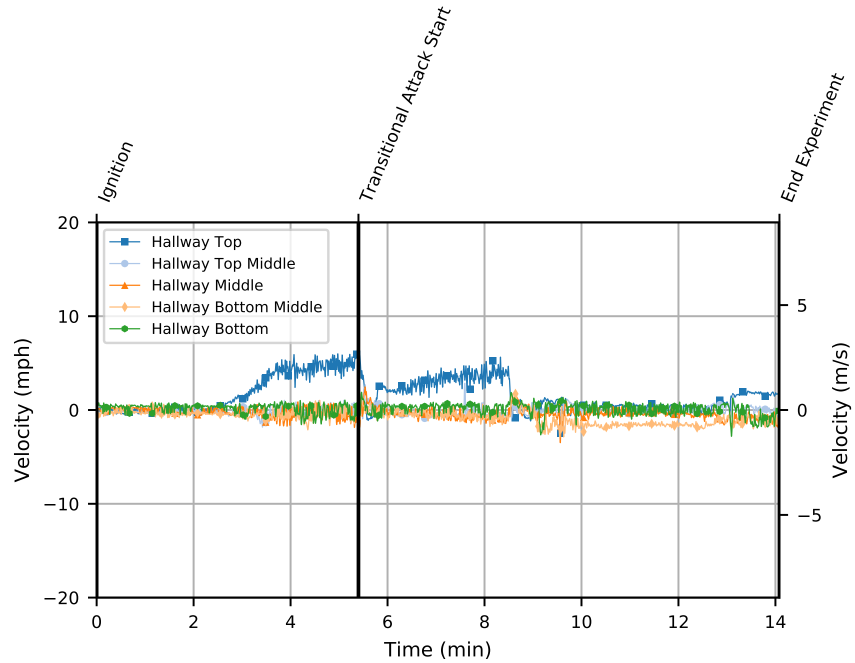


Figure E.700: Experiment 19 - Hallway Flow

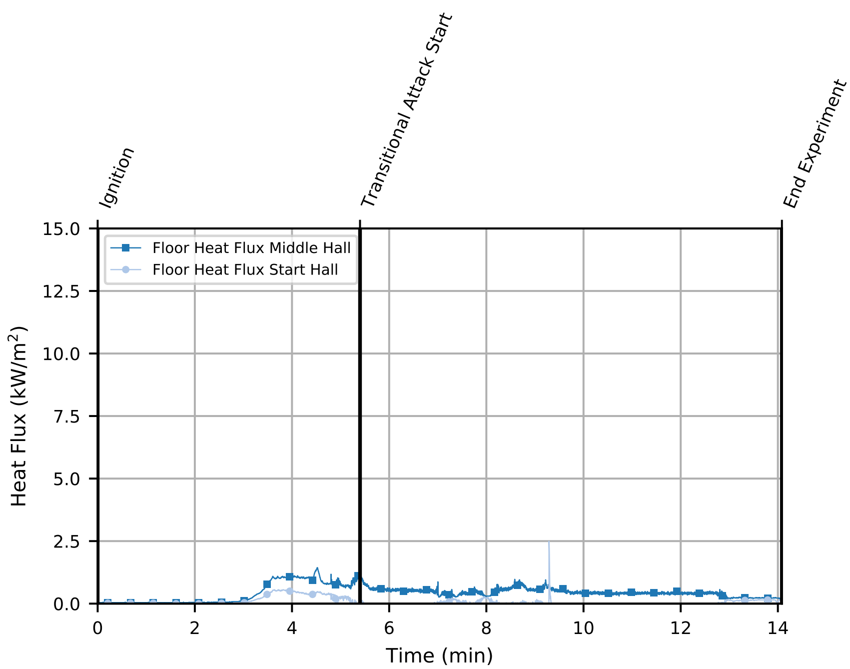


Figure E.701: Experiment 19 - Heat Flux Floor

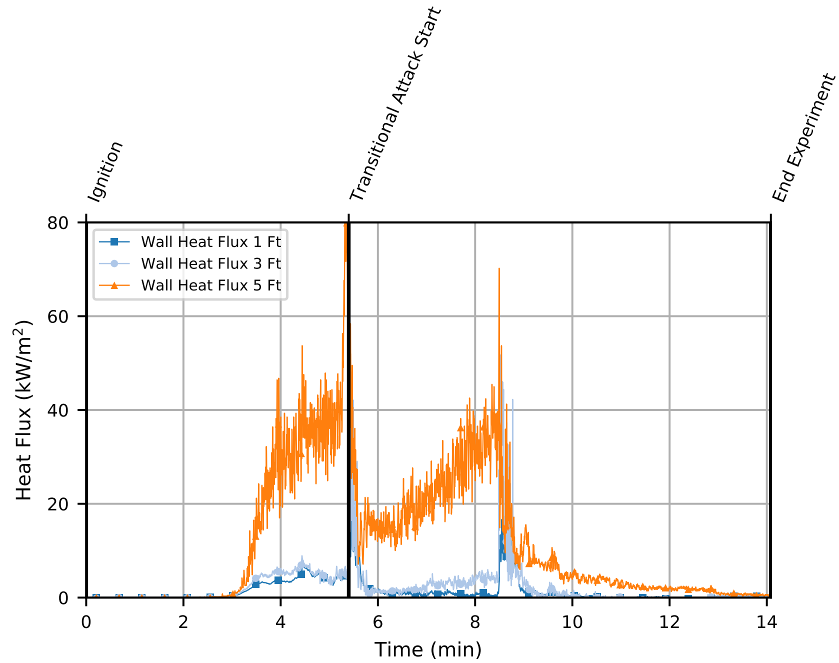


Figure E.702: Experiment 19 - Heat Flux Wall

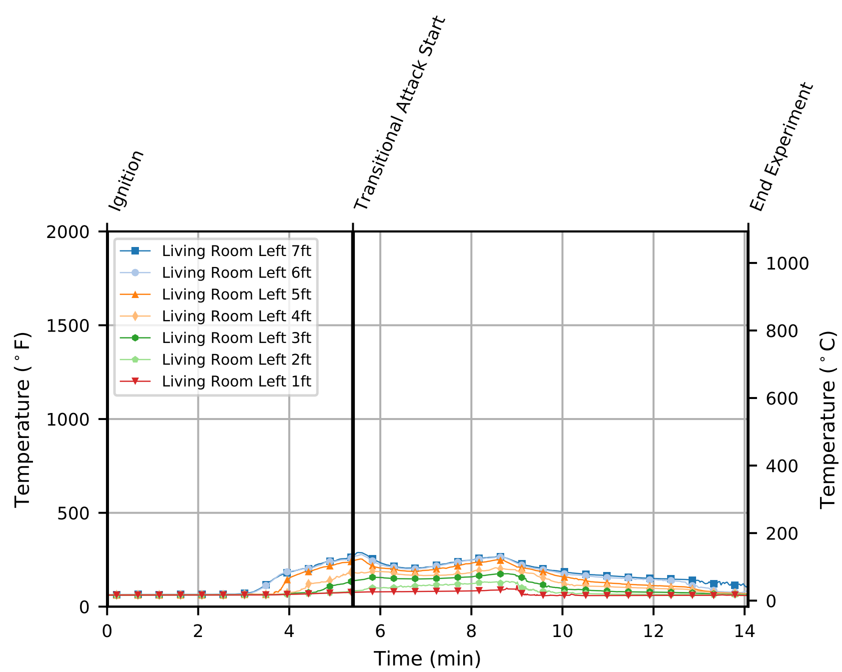


Figure E.703: Experiment 19 - Living Room Left Temps

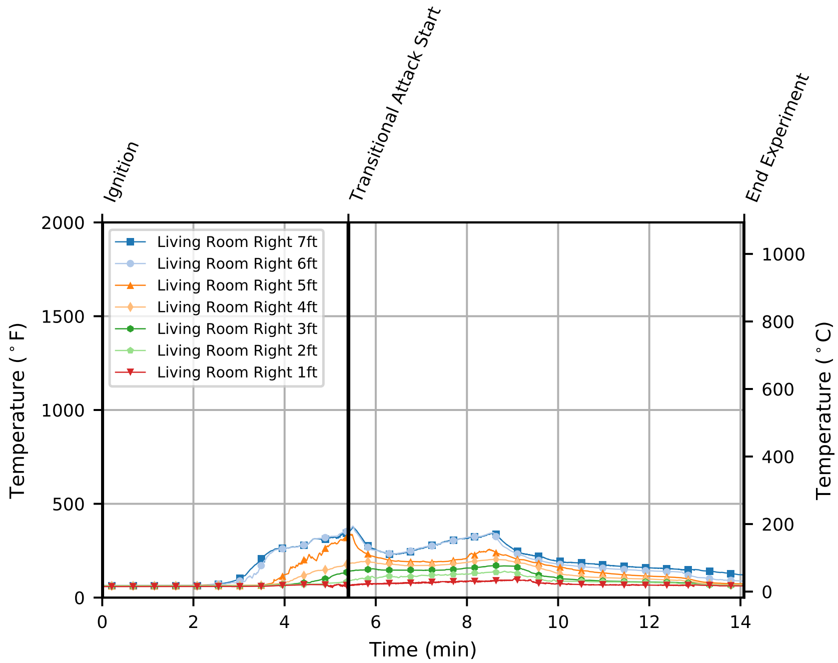


Figure E.704: Experiment 19 - Living Room Right Temps

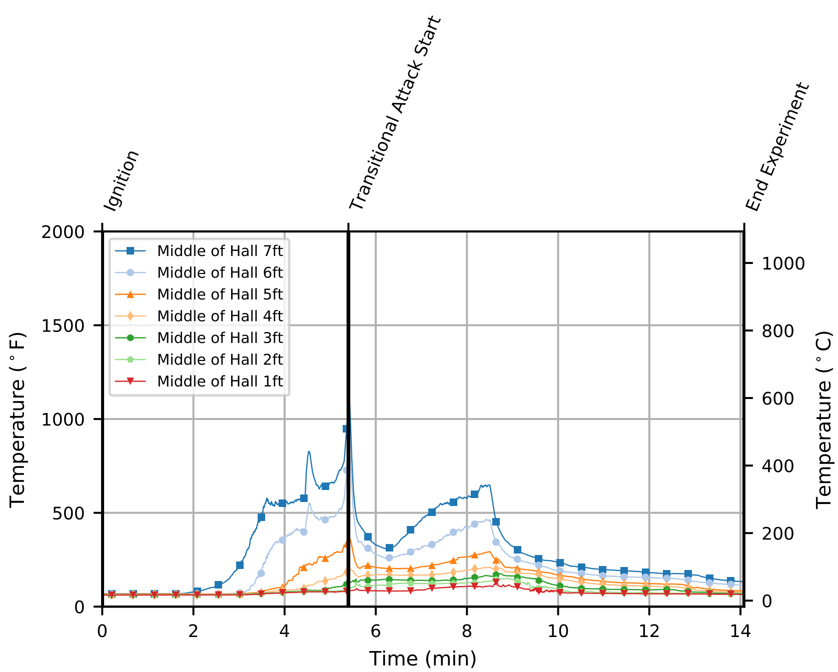


Figure E.705: Experiment 19 - Middle Hall Temps

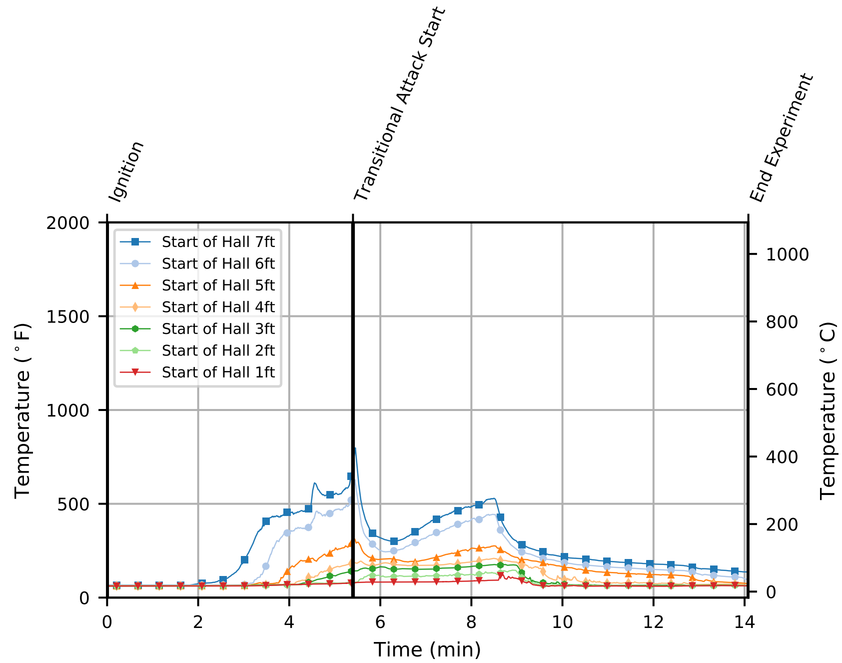


Figure E.706: Experiment 19 - Start Hall Temps

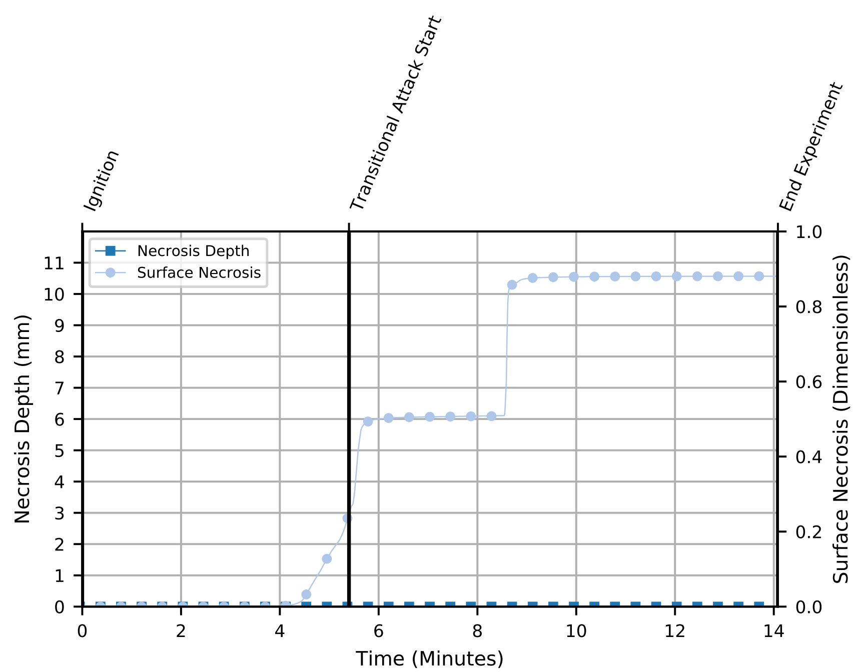


Figure E.707: Experiment 19 - Vic 1 Necrosis Depth

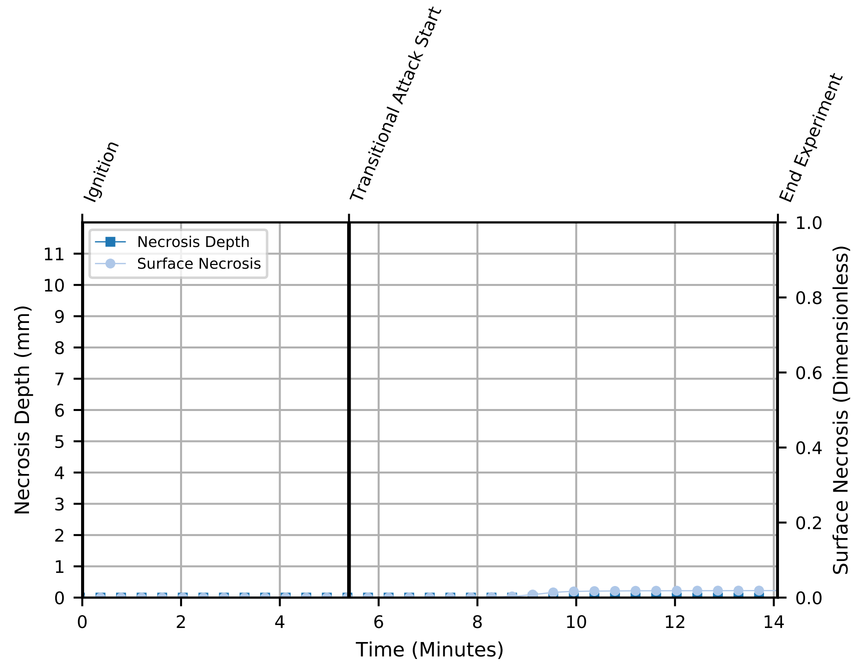


Figure E.708: Experiment 19 - Vic 3 Necrosis Depth

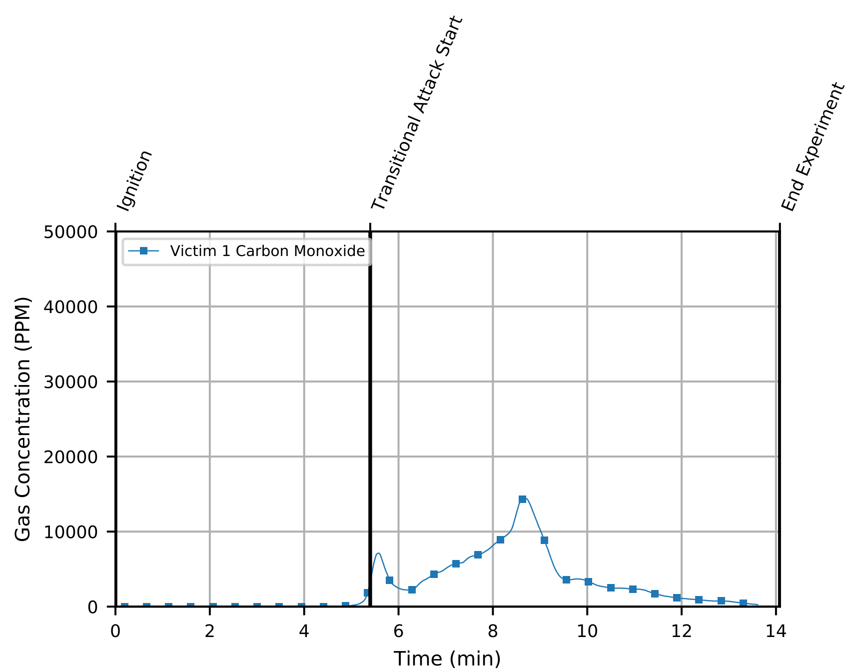


Figure E.709: Experiment 19 - Victim 1 Carbon Monoxide

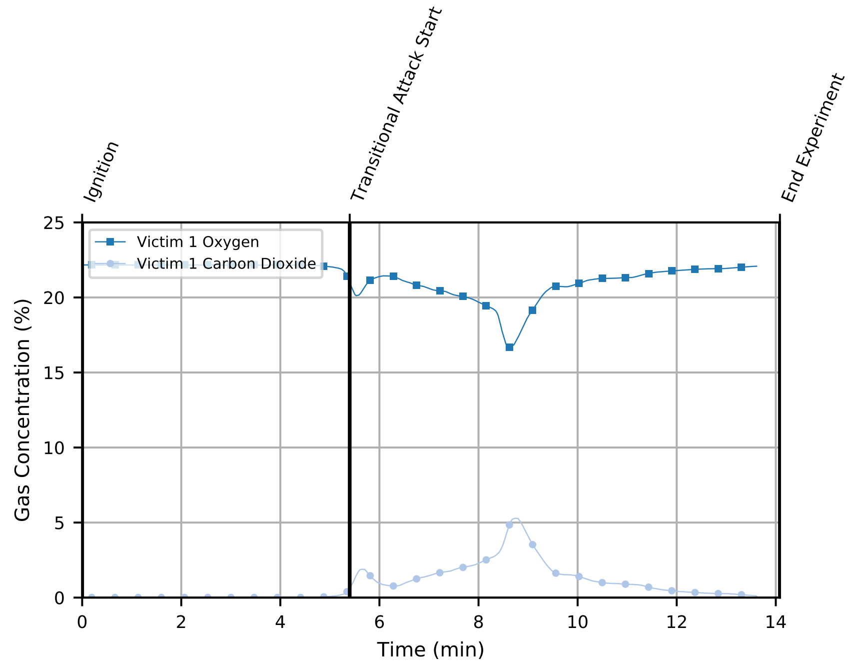


Figure E.710: Experiment 19 - Victim 1 Gas

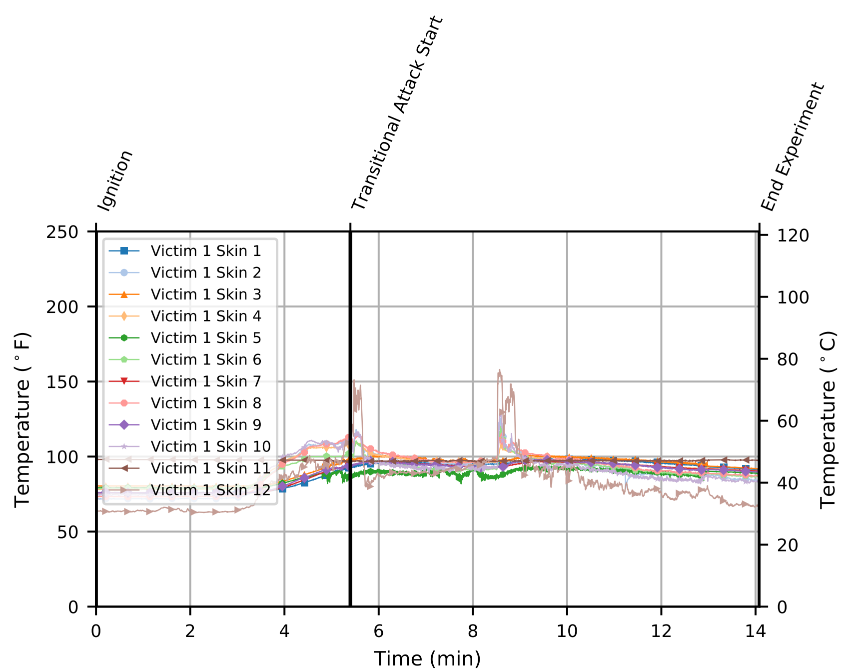


Figure E.711: Experiment 19 - Victim 1 Skin Temps

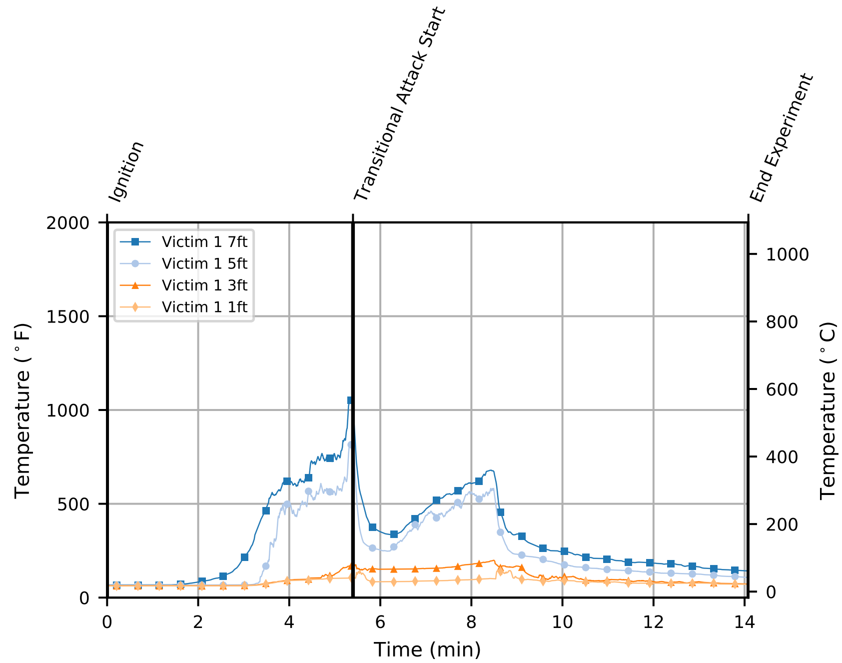


Figure E.712: Experiment 19 - Victim 1 Temps

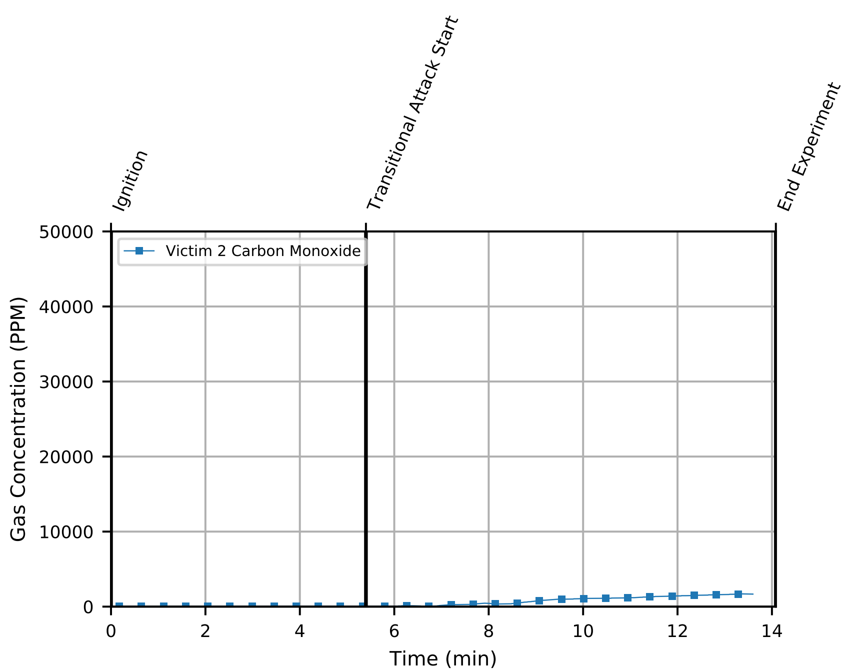


Figure E.713: Experiment 19 - Victim 2 Carbon Monoxide

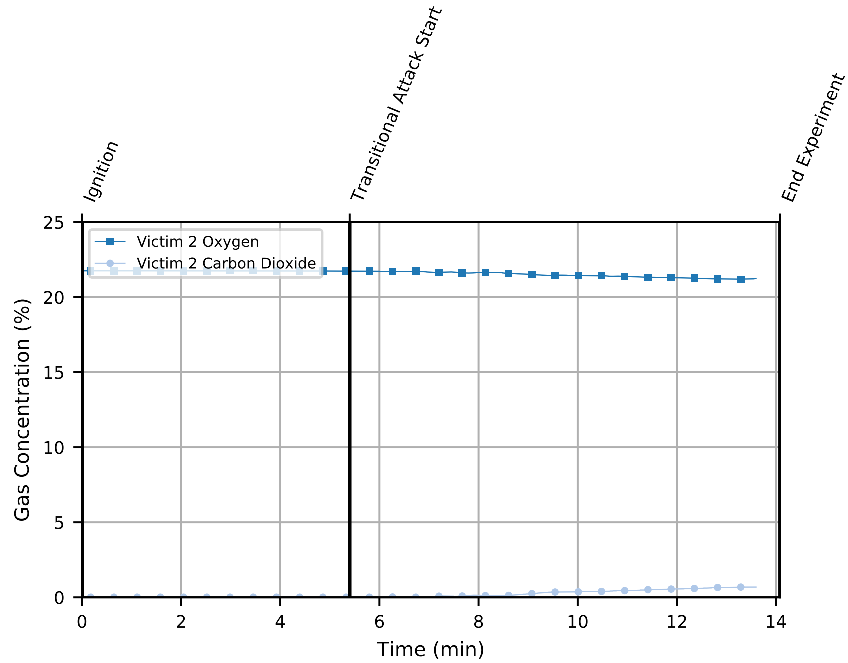


Figure E.714: Experiment 19 - Victim 2 Gas

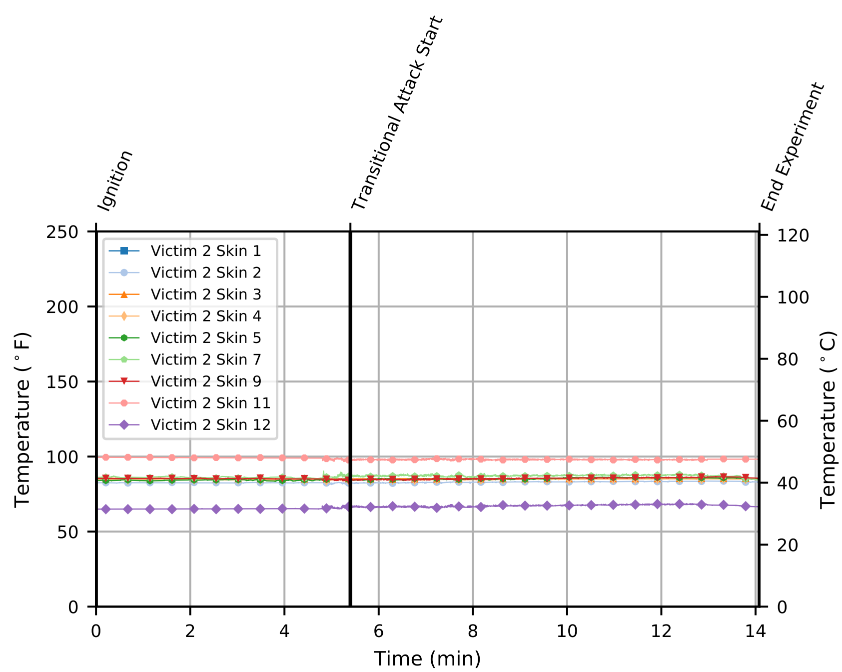


Figure E.715: Experiment 19 - Victim 2 Skin Temps

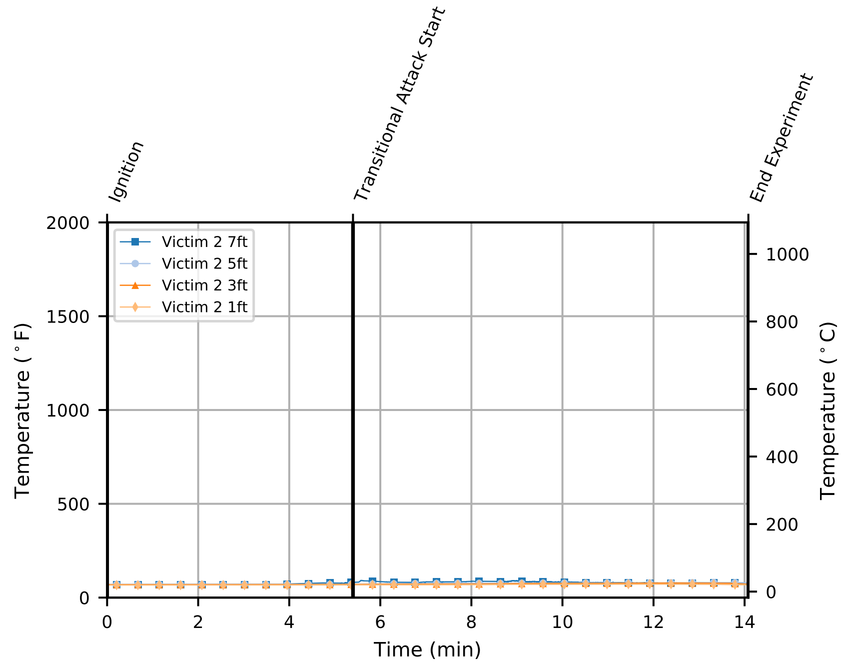


Figure E.716: Experiment 19 - Victim 2 Temps

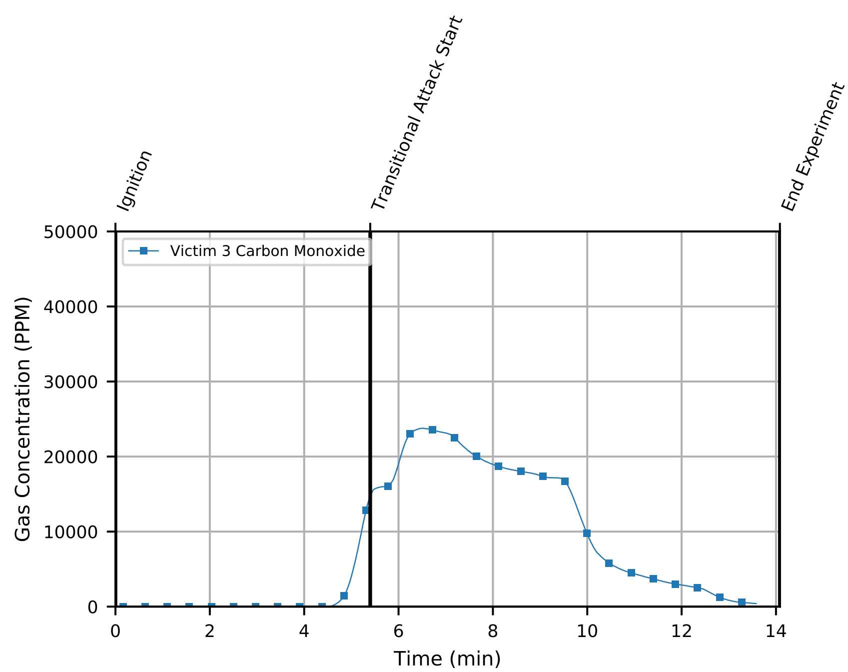


Figure E.717: Experiment 19 - Victim 3 Carbon Monoxide

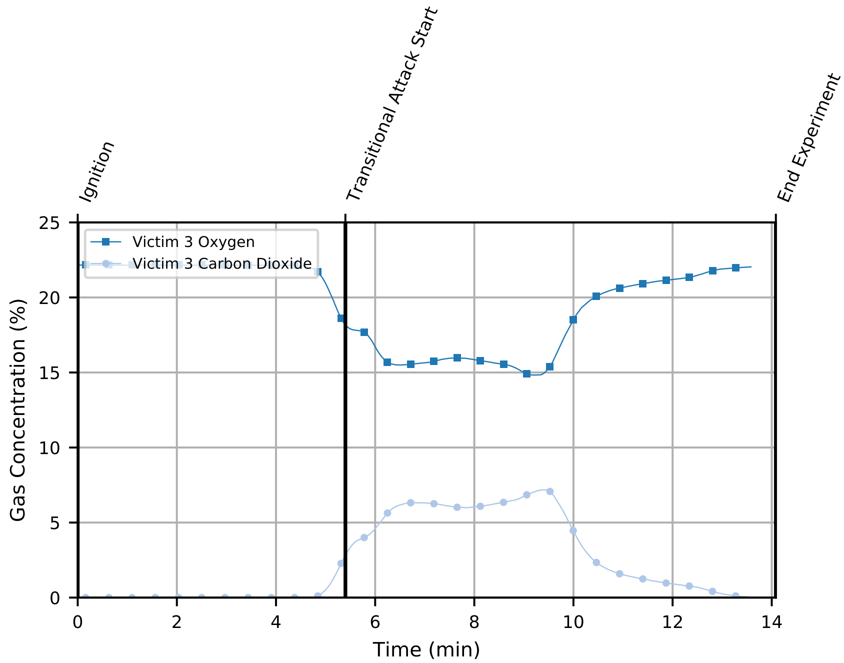


Figure E.718: Experiment 19 - Victim 3 Gas

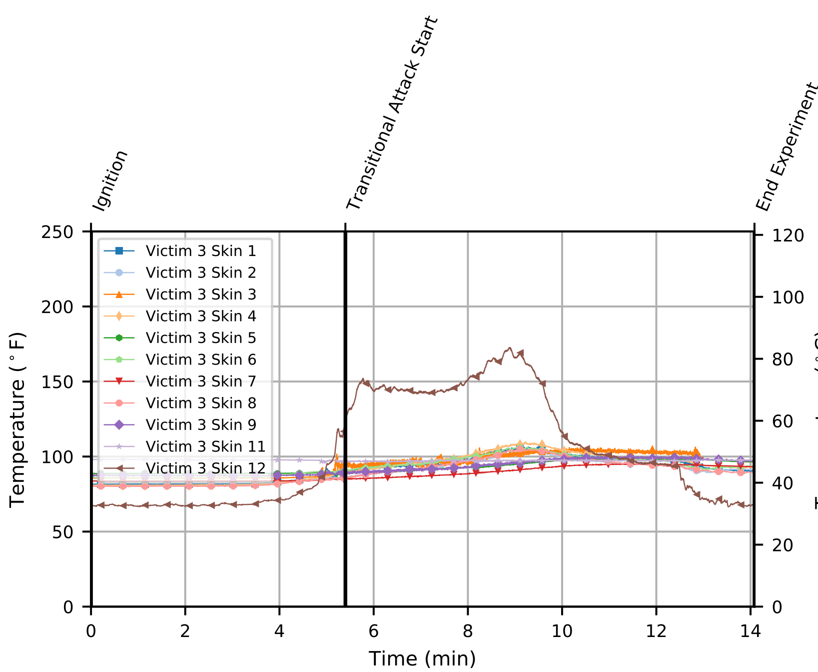


Figure E.719: Experiment 19 - Victim 3 Skin Temps

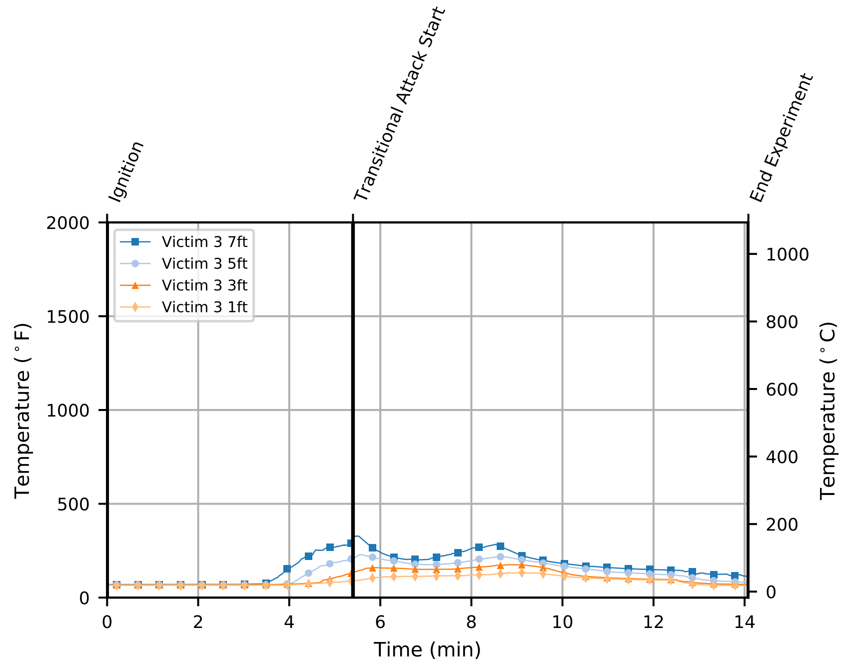


Figure E.720: Experiment 19 - Victim 3 Temps

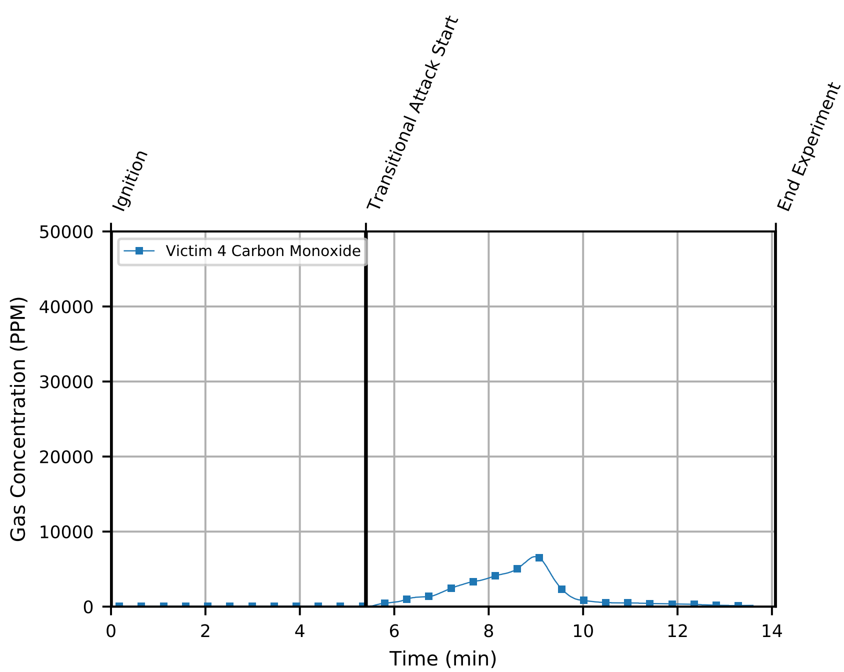


Figure E.721: Experiment 19 - Victim 4 Carbon Monoxide

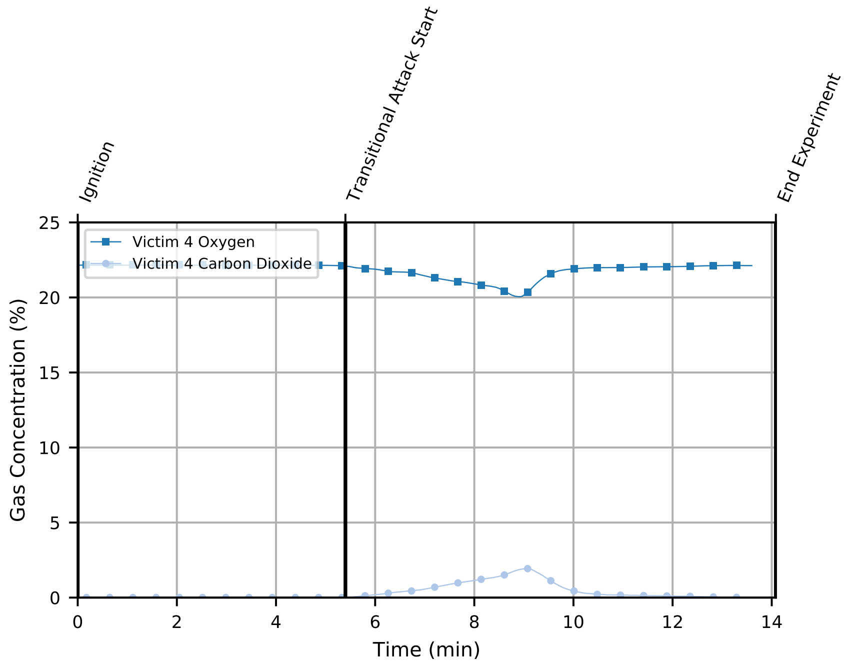


Figure E.722: Experiment 19 - Victim 4 Gas

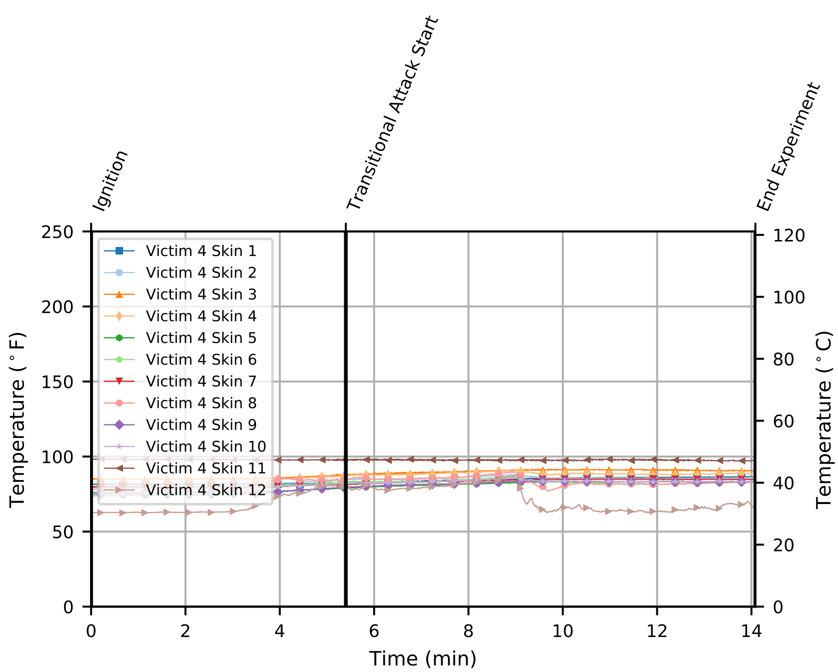


Figure E.723: Experiment 19 - Victim 4 Skin Temps

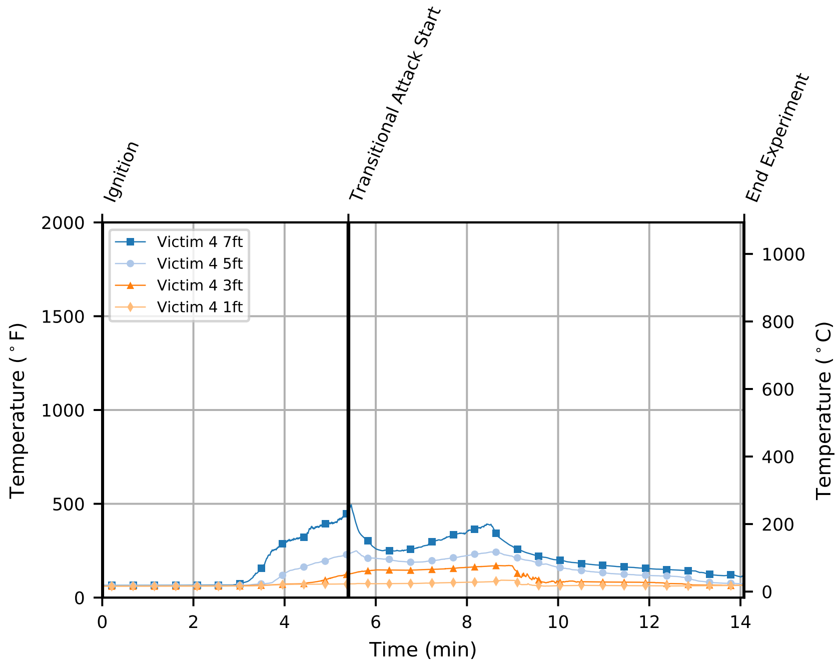


Figure E.724: Experiment 19 - Victim 4 Temps

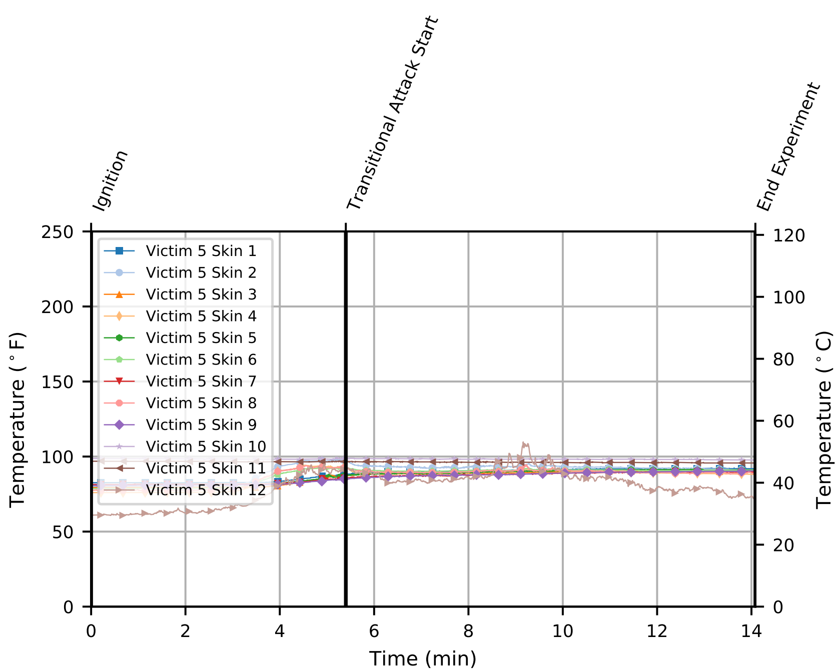


Figure E.725: Experiment 19 - Victim 5 Skin Temps

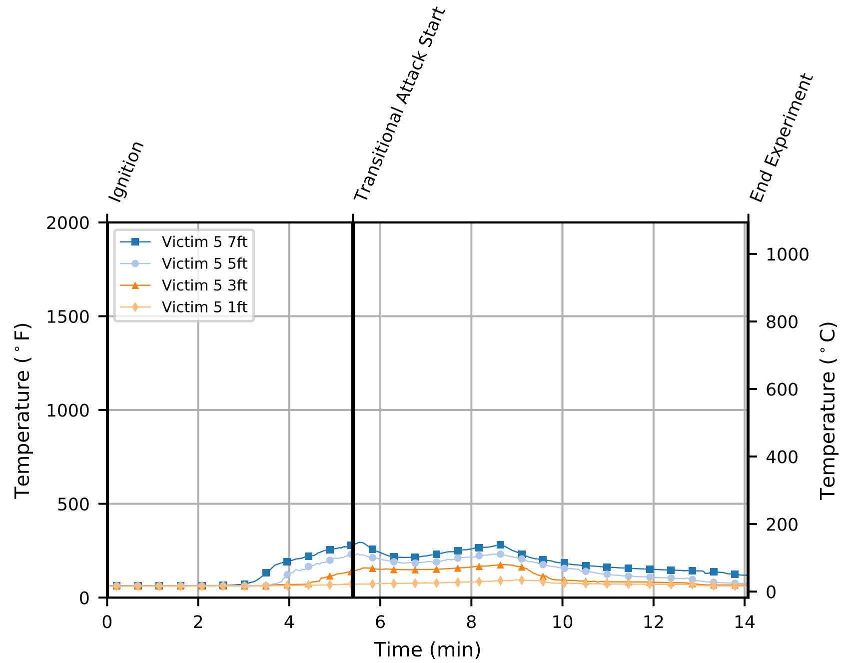


Figure E.726: Experiment 19 - Victim 5 Temps

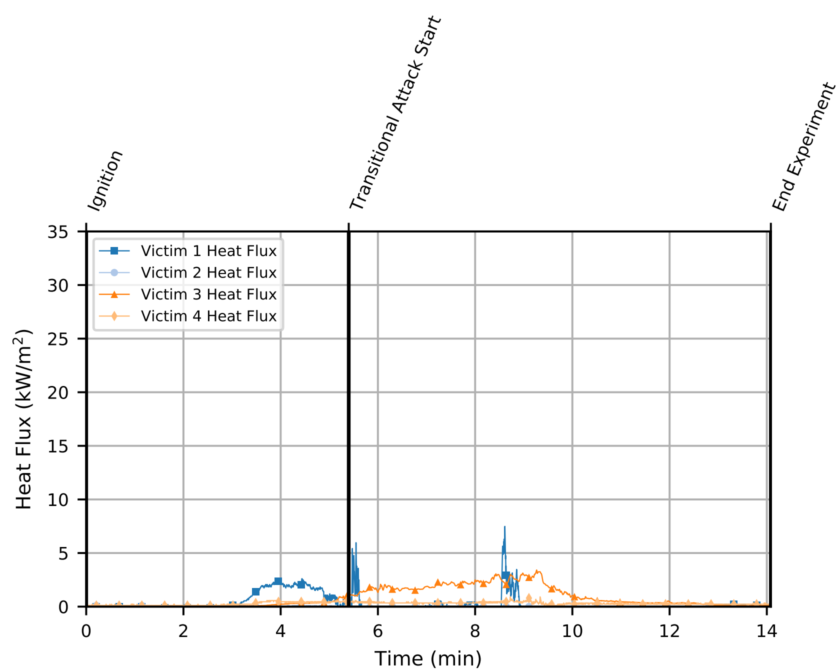


Figure E.727: Experiment 19 - Victim Heat Flux

E.20 Experiment 20 Data

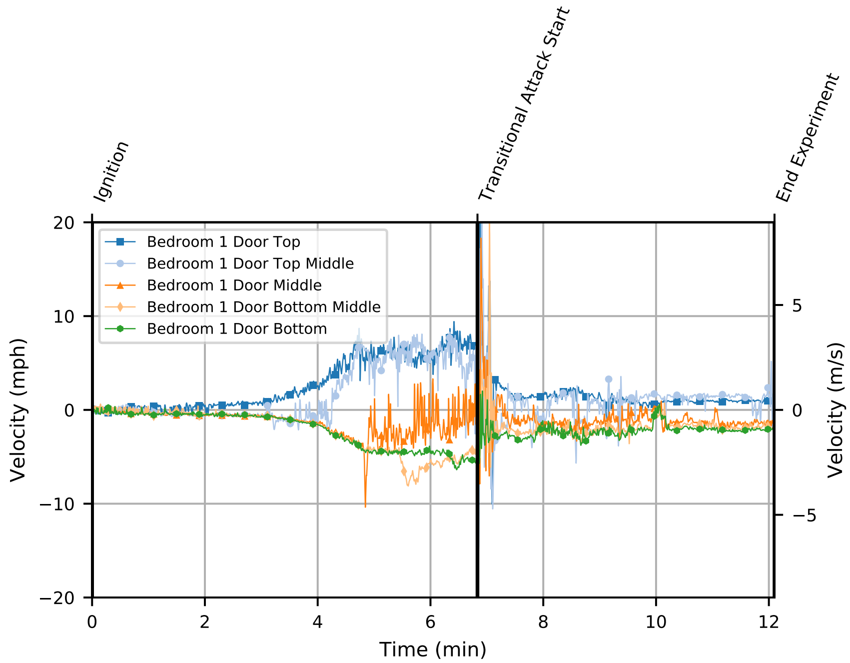


Figure E.728: Experiment 20 - Bedroom 1 Door

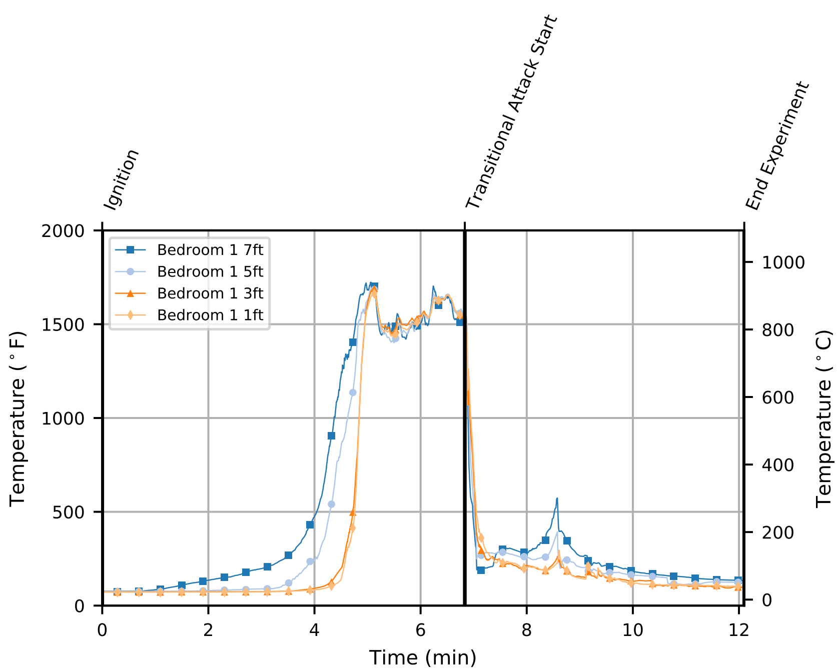


Figure E.729: Experiment 20 - Bedroom 1 Temps

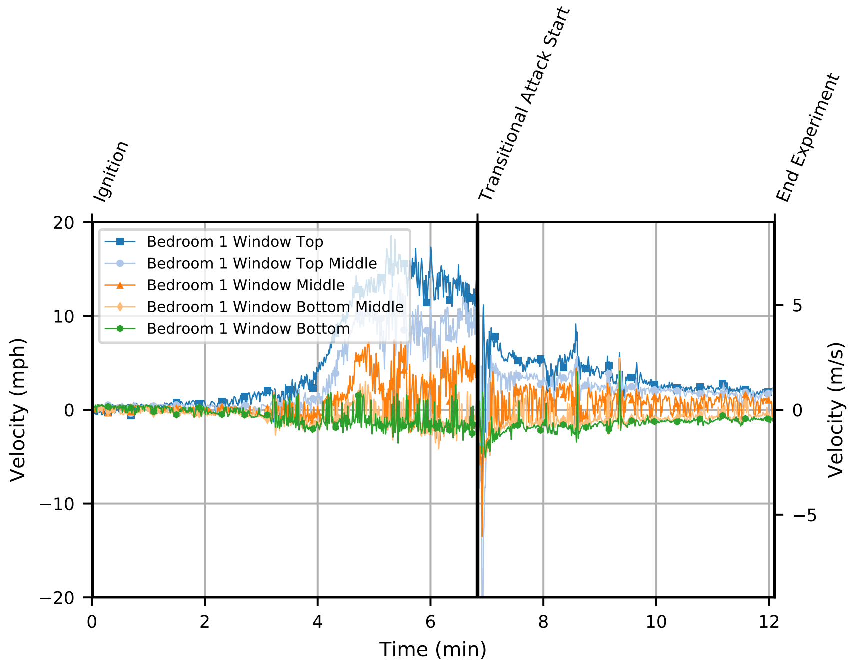


Figure E.730: Experiment 20 - Bedroom 1 Window

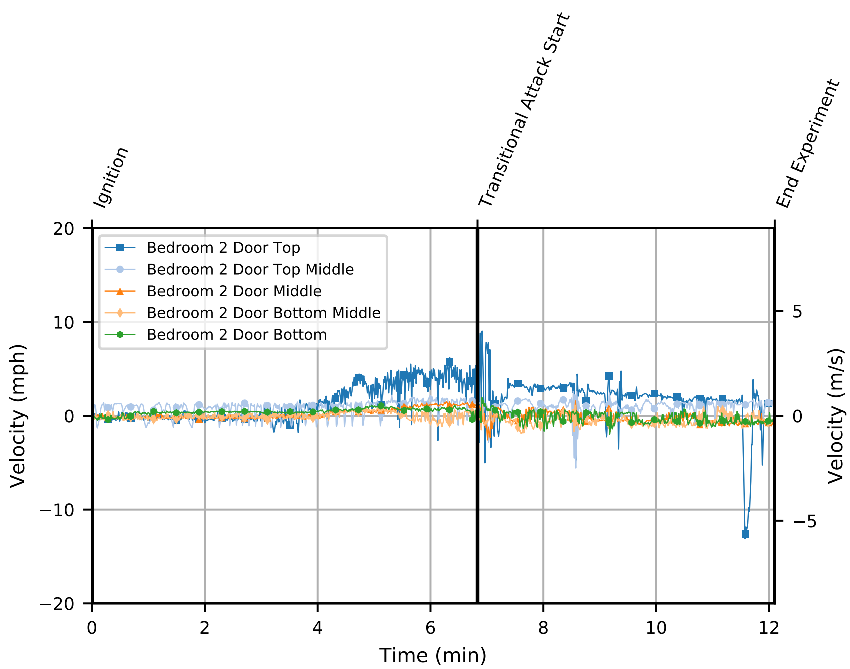


Figure E.731: Experiment 20 - Bedroom 2 Door

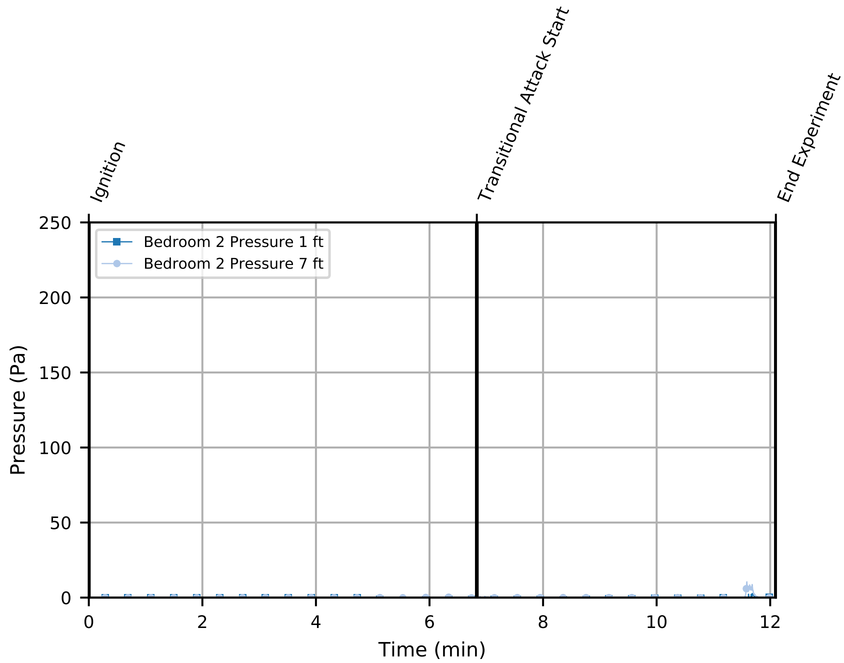


Figure E.732: Experiment 20 - Bedroom 2 Pressure

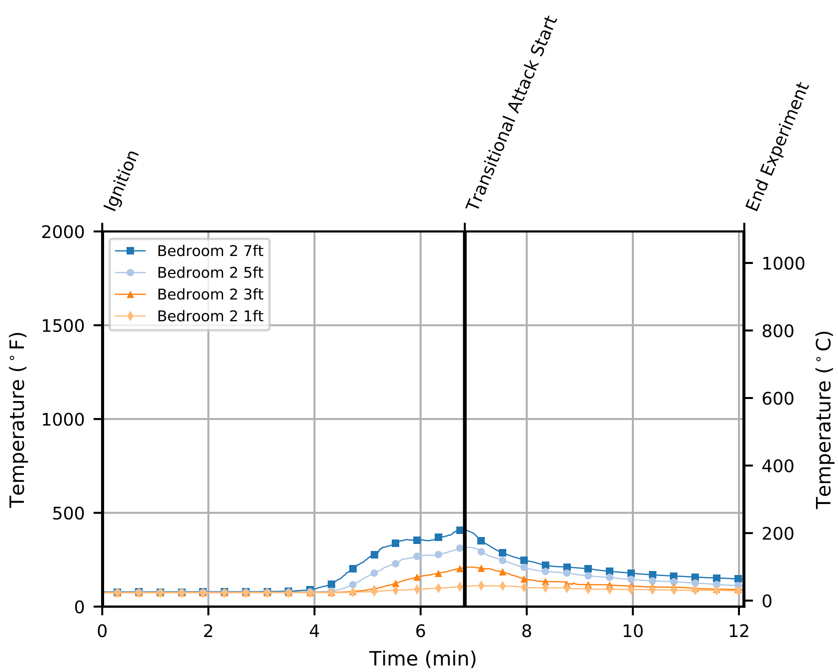


Figure E.733: Experiment 20 - Bedroom 2 Temps

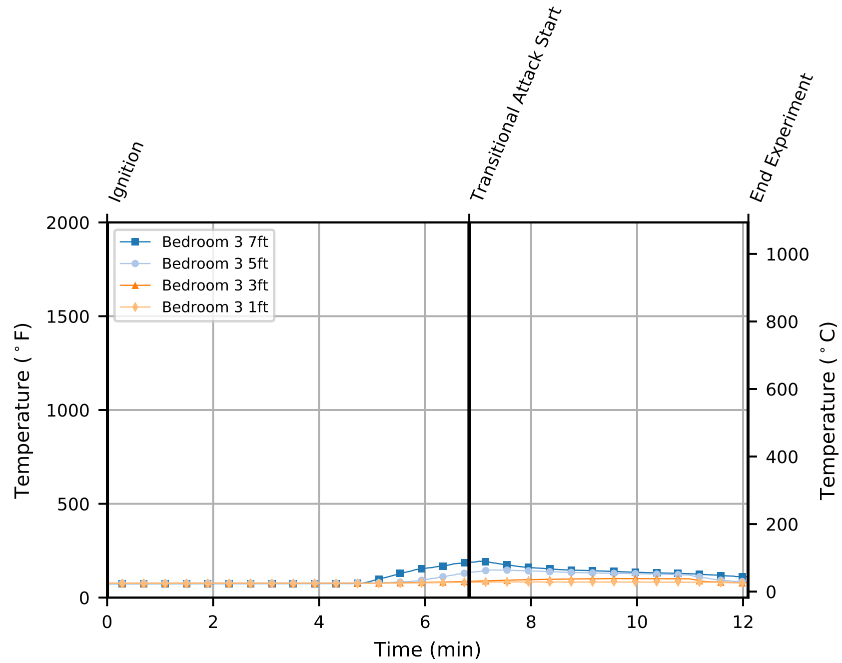


Figure E.734: Experiment 20 - Bedroom 3 Temps

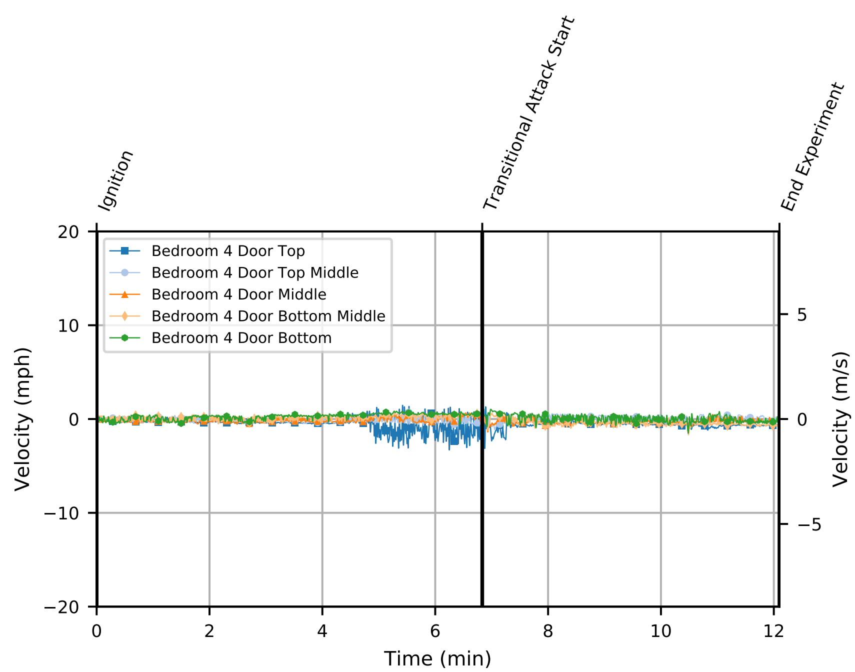


Figure E.735: Experiment 20 - Bedroom 4 Door

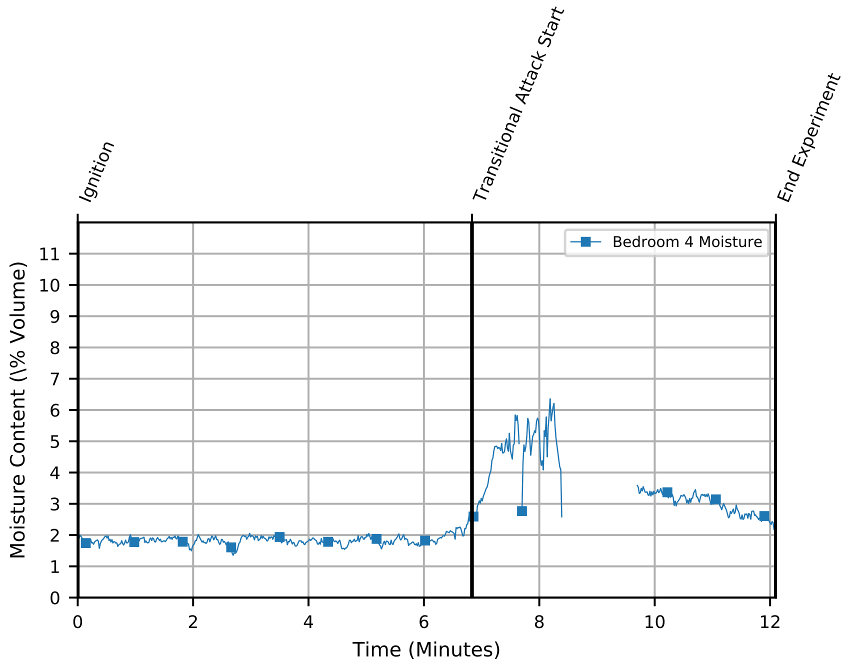


Figure E.736: Experiment 20 - Bedroom 4 Moisture

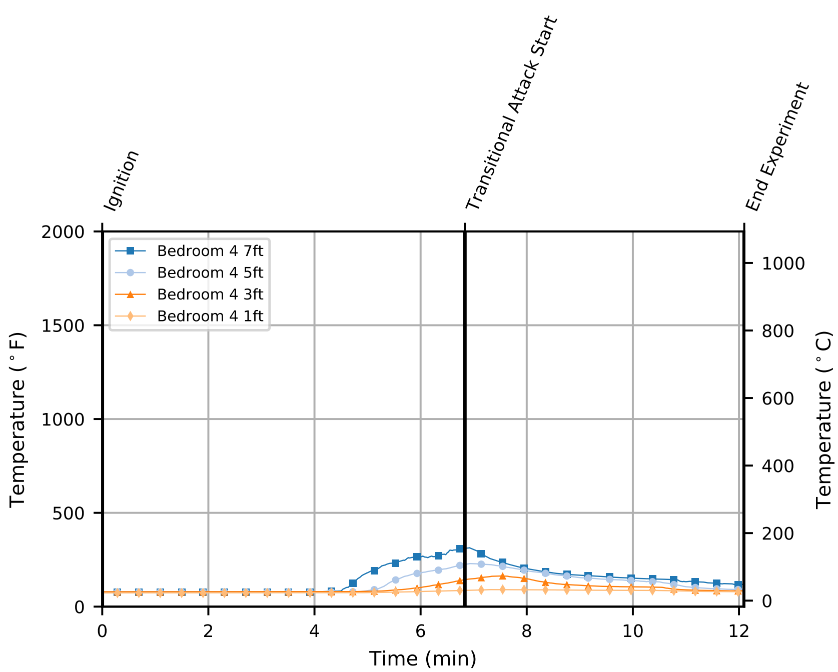


Figure E.737: Experiment 20 - Bedroom 4 Temps

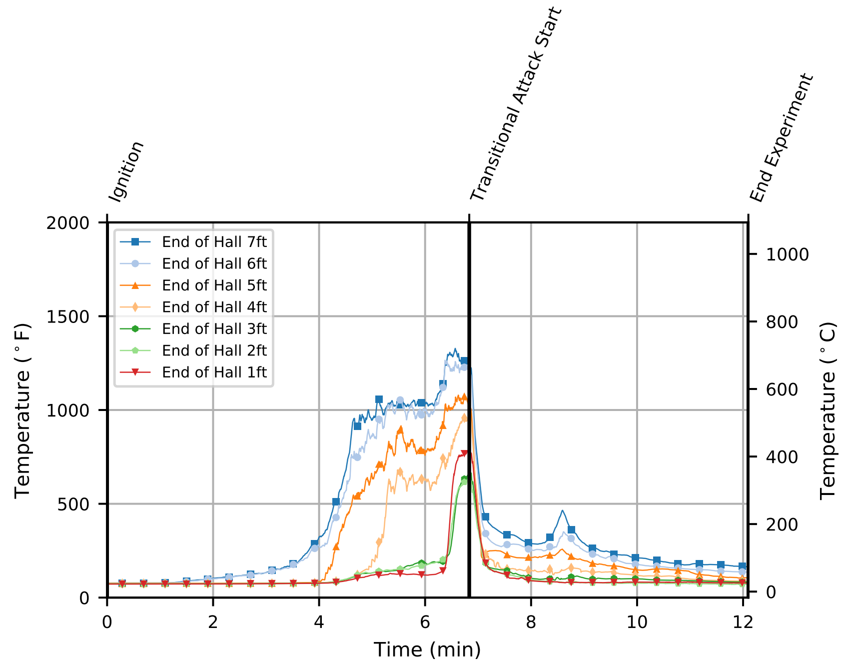


Figure E.738: Experiment 20 - End Hall Temps

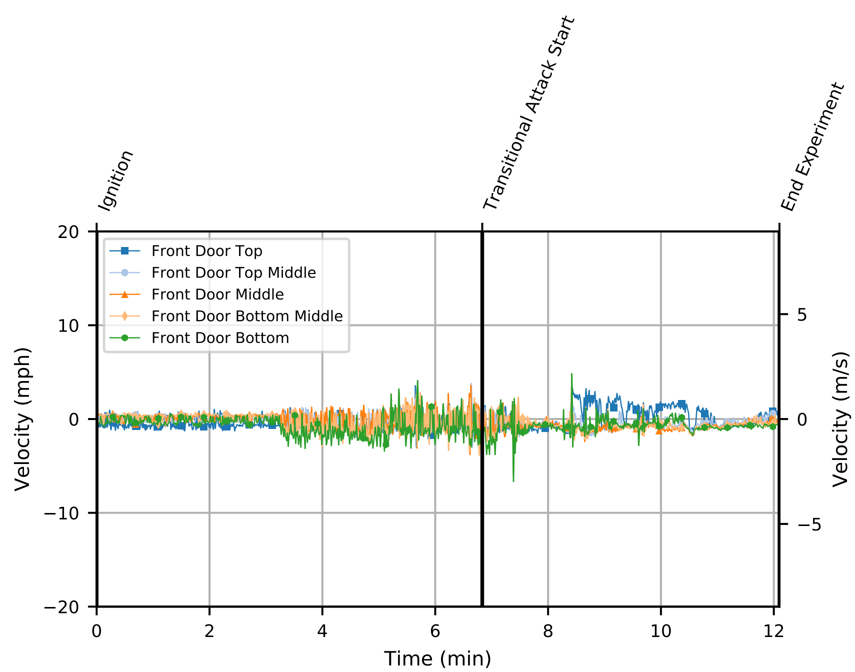


Figure E.739: Experiment 20 - Front Door Flow

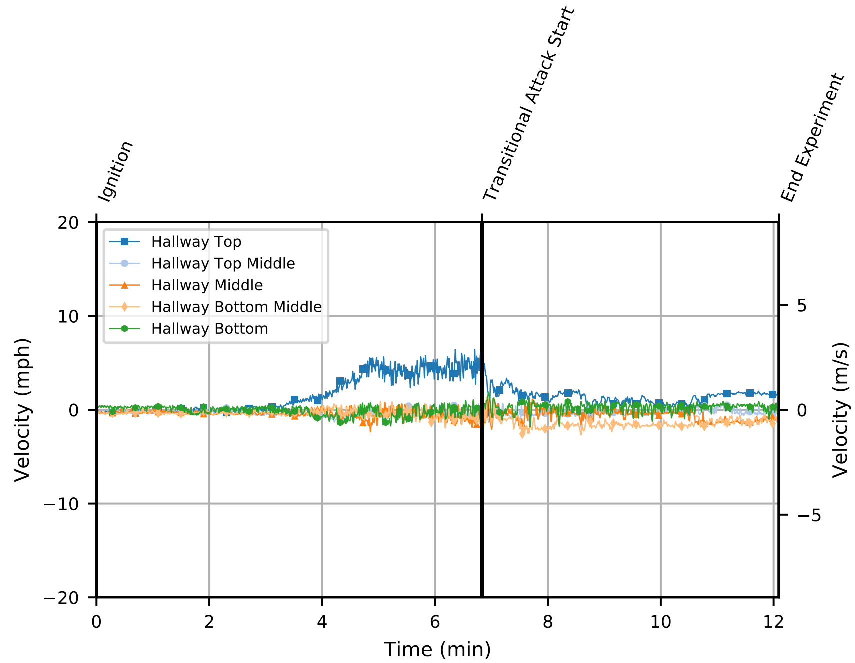


Figure E.740: Experiment 20 - Hallway Flow

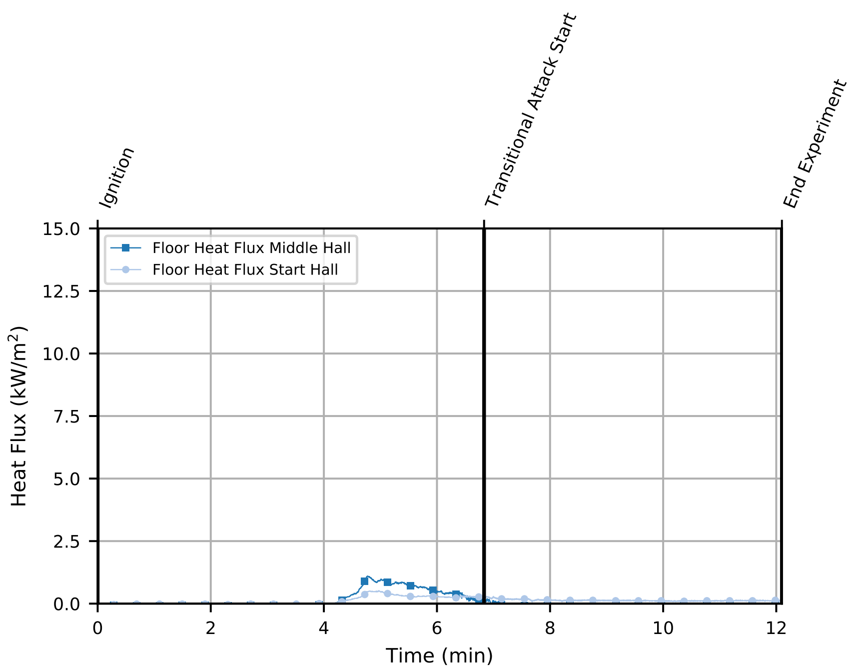


Figure E.741: Experiment 20 - Heat Flux Floor

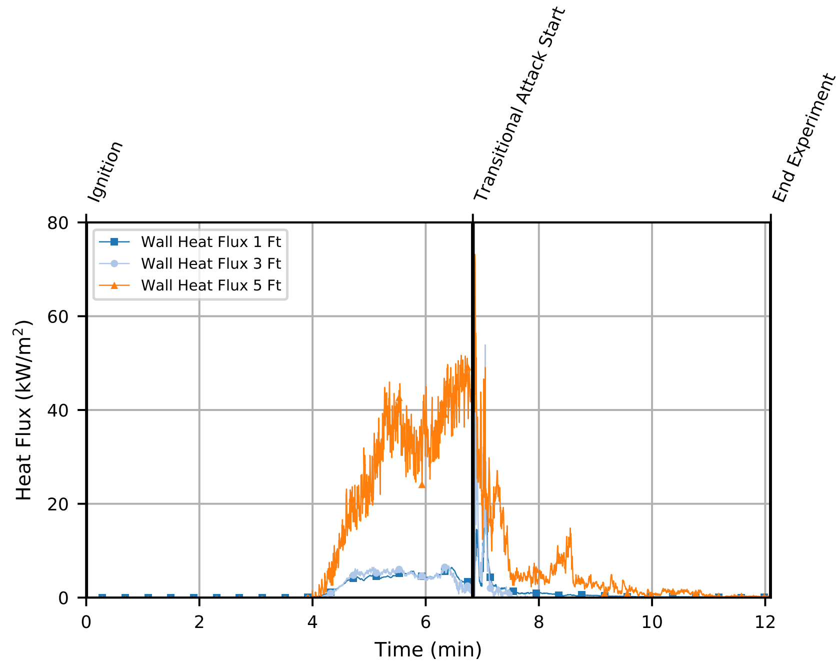


Figure E.742: Experiment 20 - Heat Flux Wall

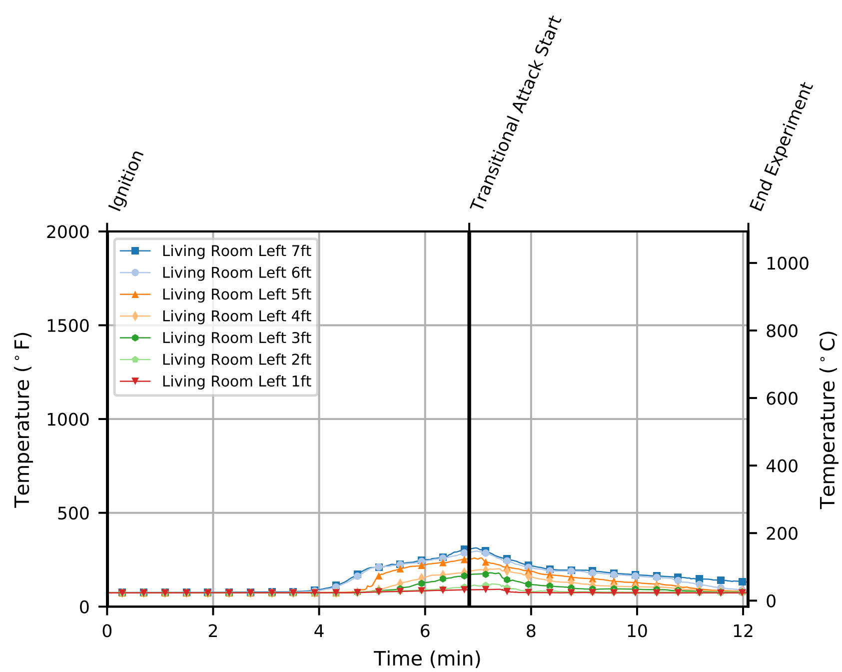


Figure E.743: Experiment 20 - Living Room Left Temps

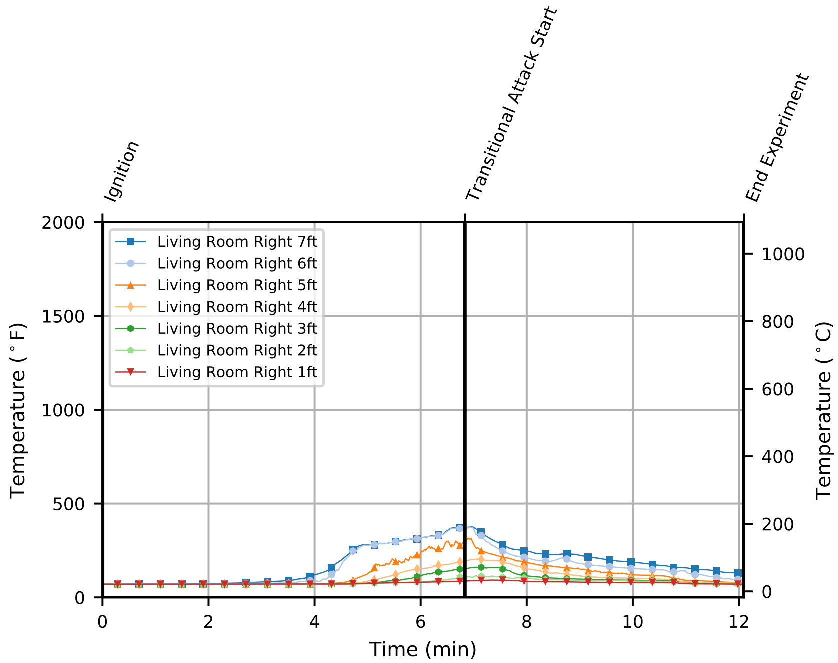


Figure E.744: Experiment 20 - Living Room Right Temps

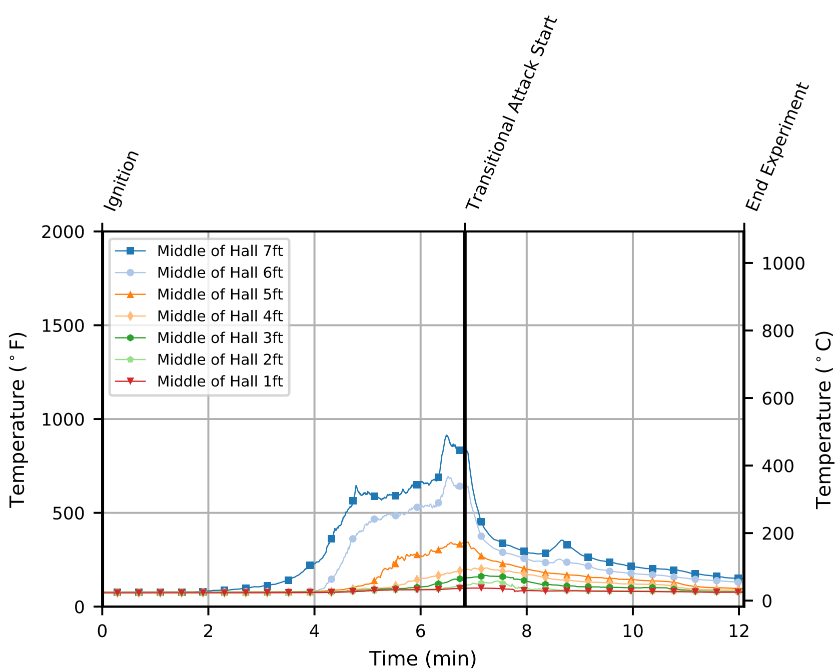


Figure E.745: Experiment 20 - Middle Hall Temps

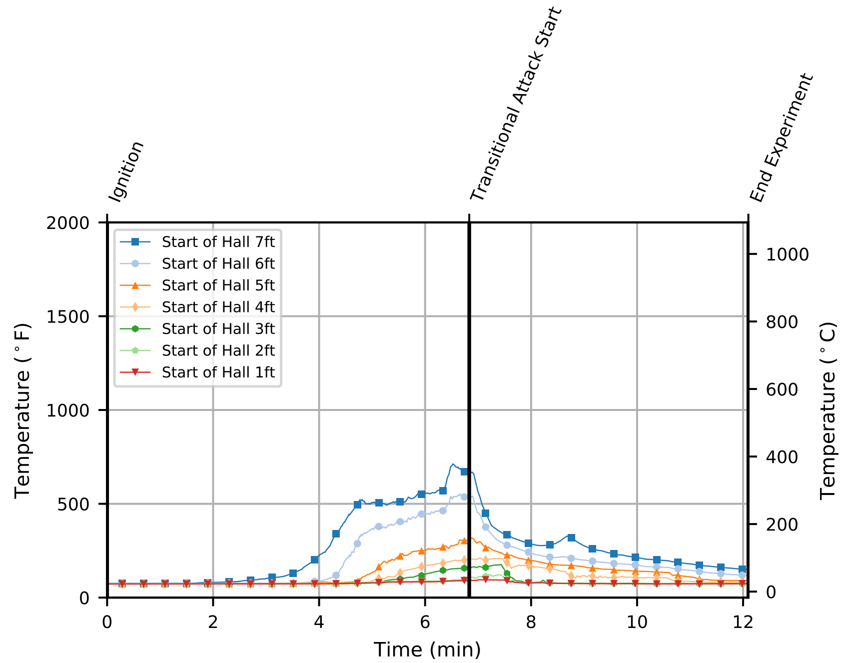


Figure E.746: Experiment 20 - Start Hall Temps

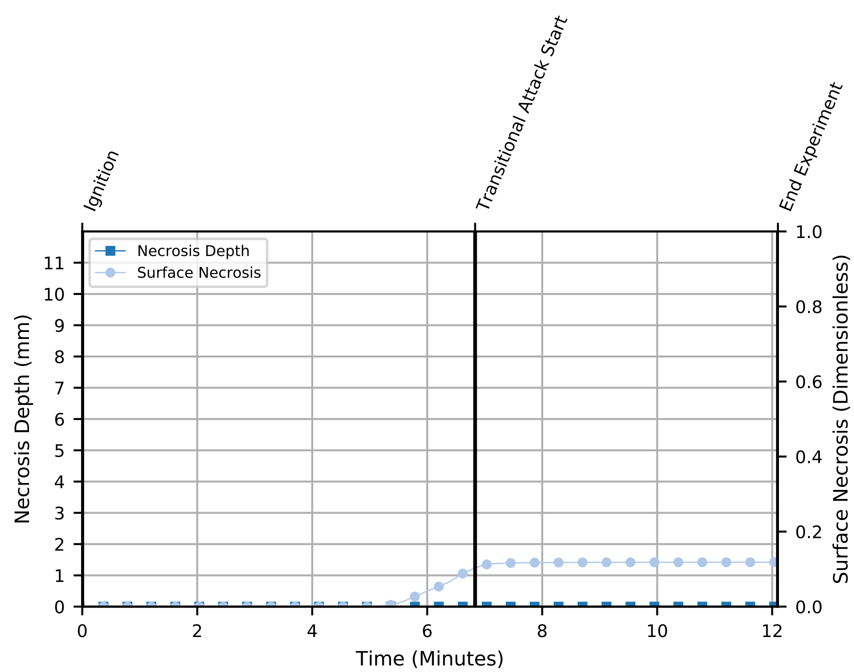


Figure E.747: Experiment 20 - Vic 1 Necrosis Depth

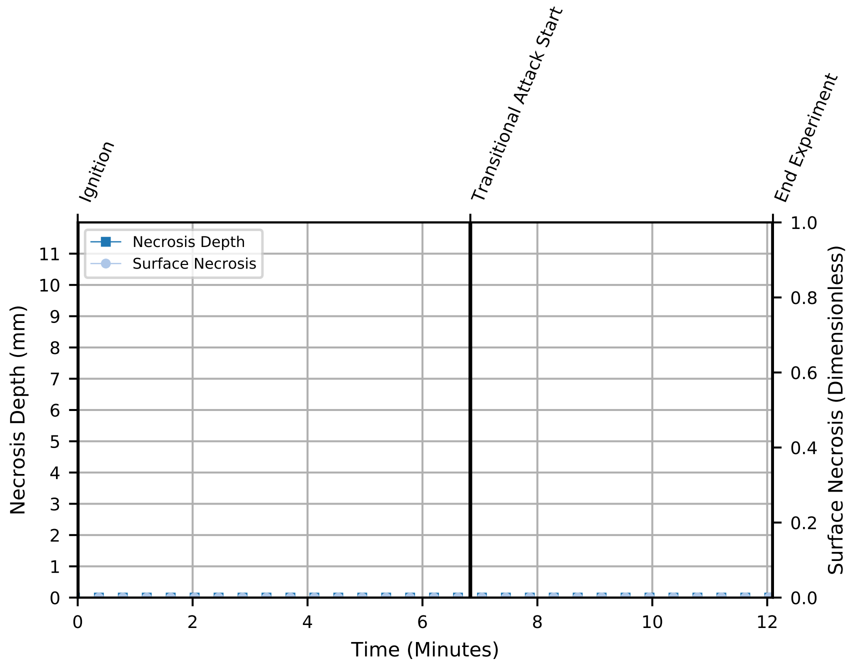


Figure E.748: Experiment 20 - Vic 3 Necrosis Depth

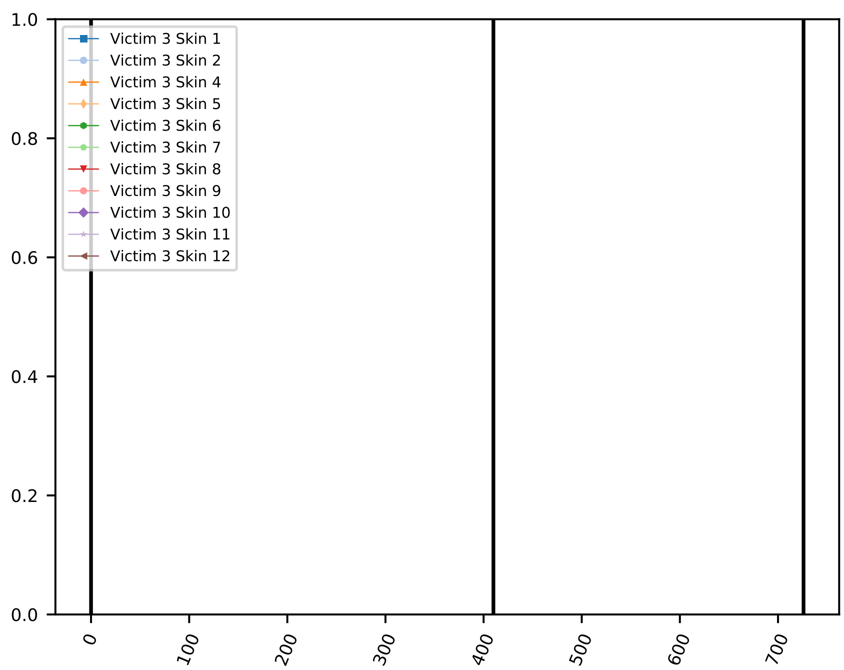


Figure E.749: Experiment 20 - Victim 1 Carbon Monoxide

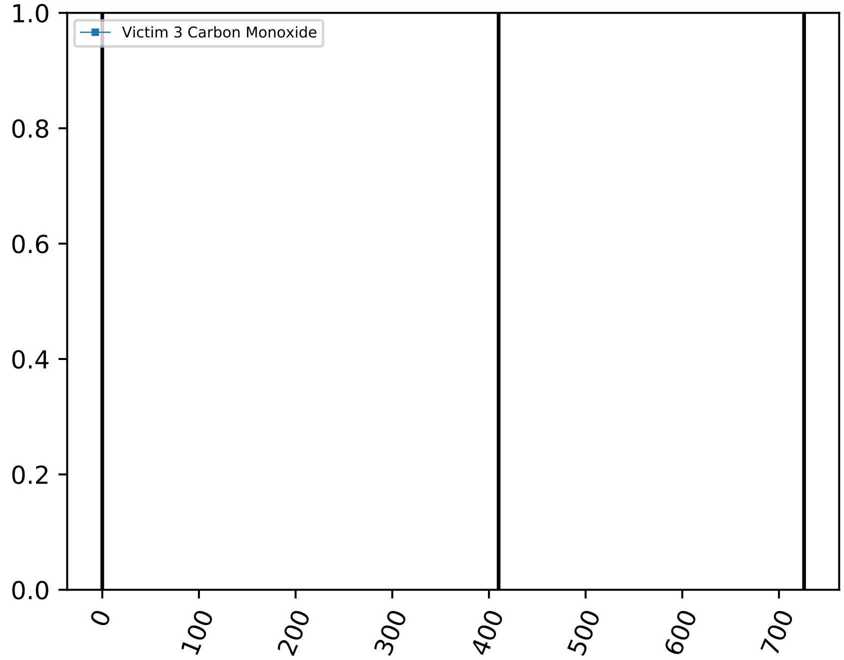


Figure E.750: Experiment 20 - Victim 1 Gas

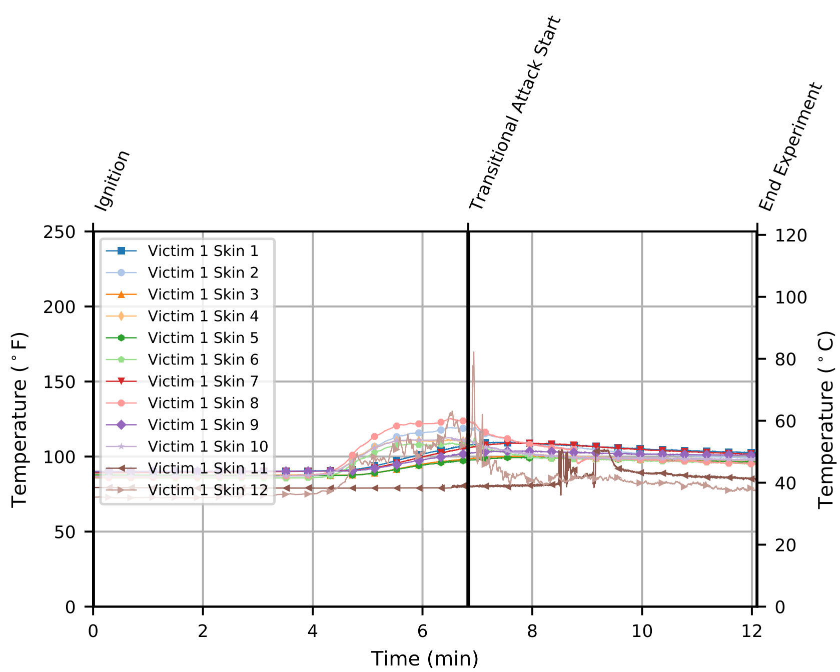


Figure E.751: Experiment 20 - Victim 1 Skin Temps

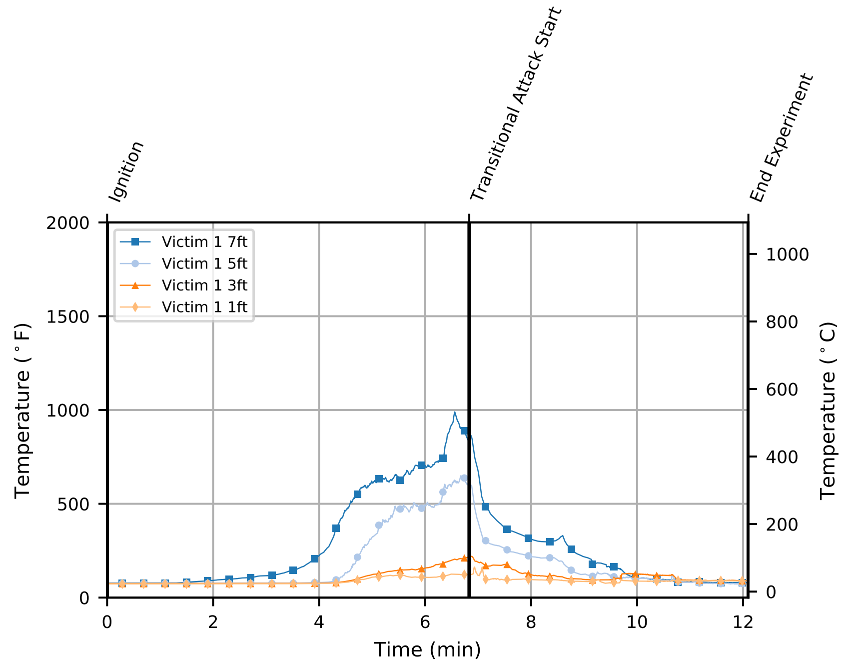


Figure E.752: Experiment 20 - Victim 1 Temps

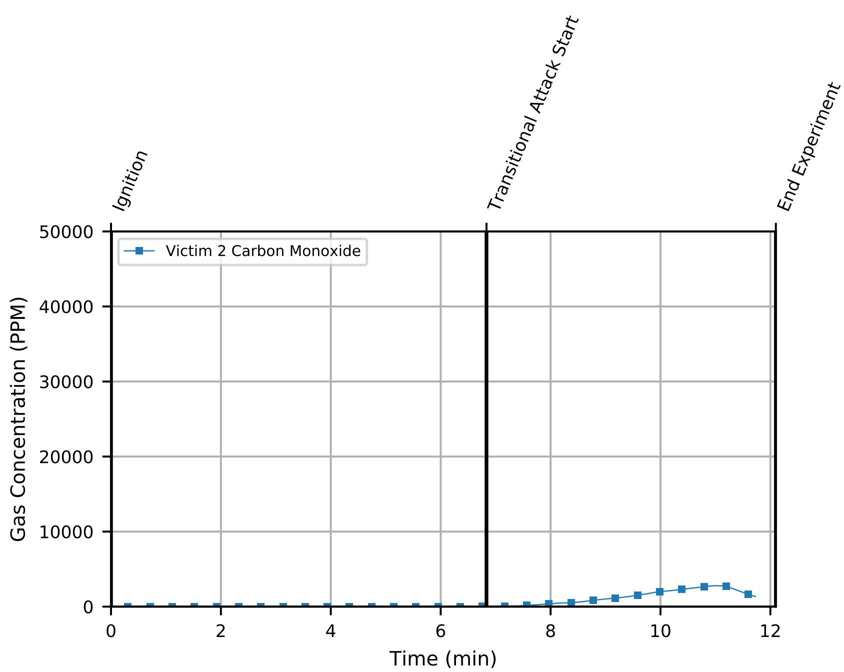


Figure E.753: Experiment 20 - Victim 2 Carbon Monoxide

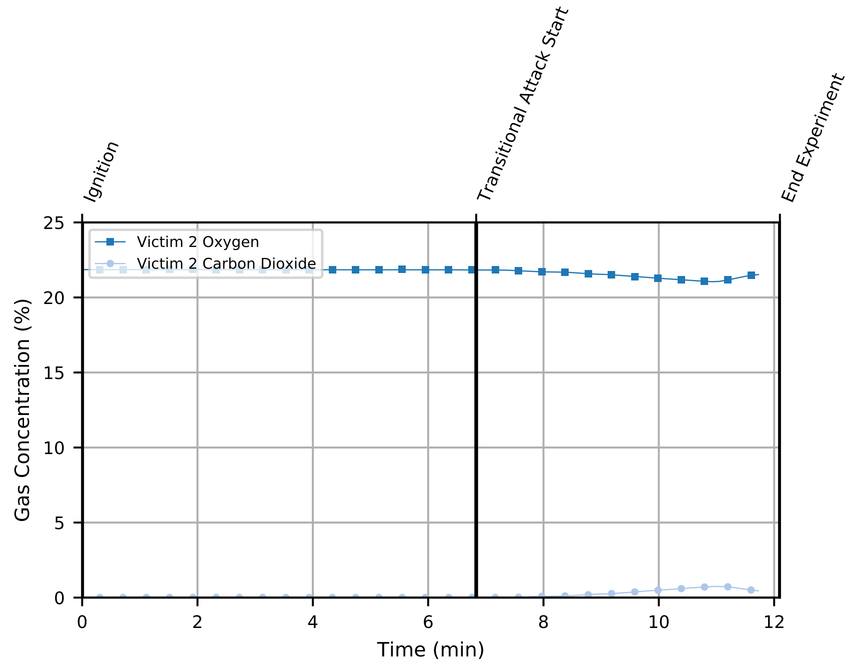


Figure E.754: Experiment 20 - Victim 2 Gas

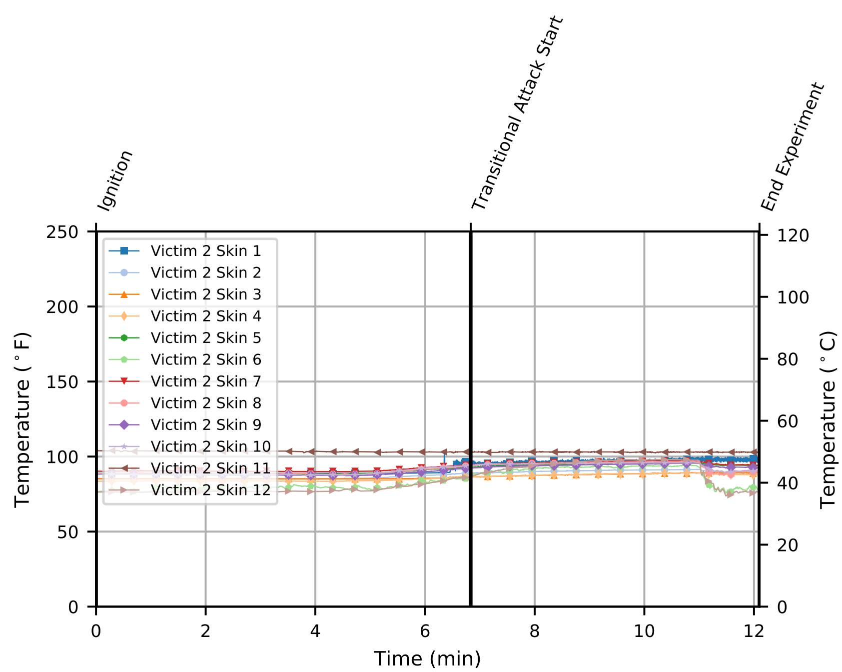


Figure E.755: Experiment 20 - Victim 2 Skin Temps

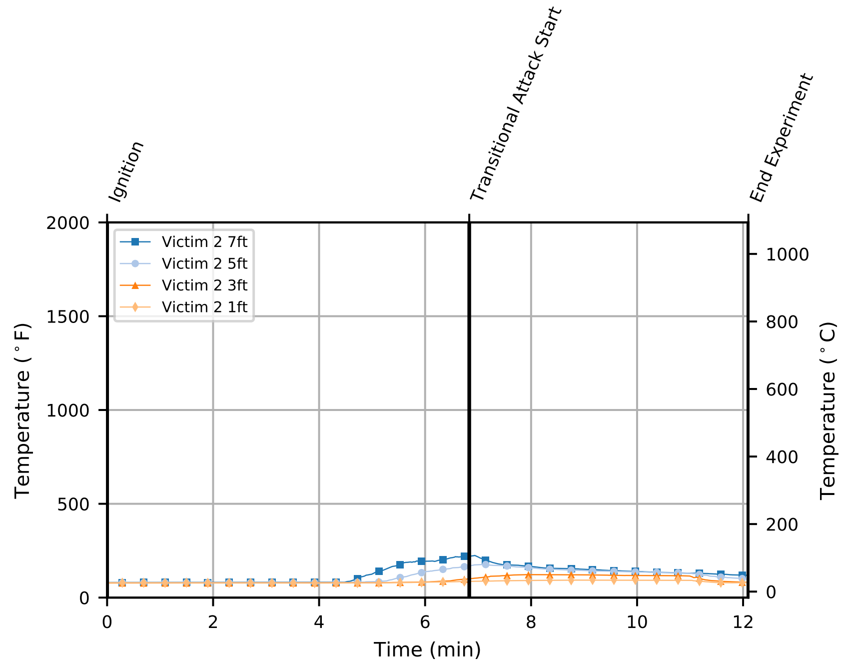


Figure E.756: Experiment 20 - Victim 2 Temps

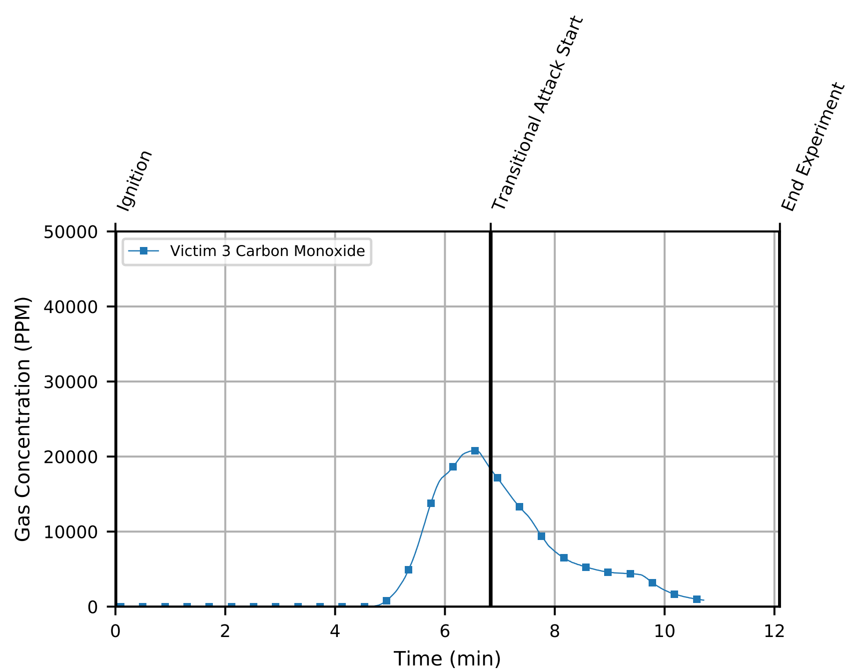


Figure E.757: Experiment 20 - Victim 3 Carbon Monoxide

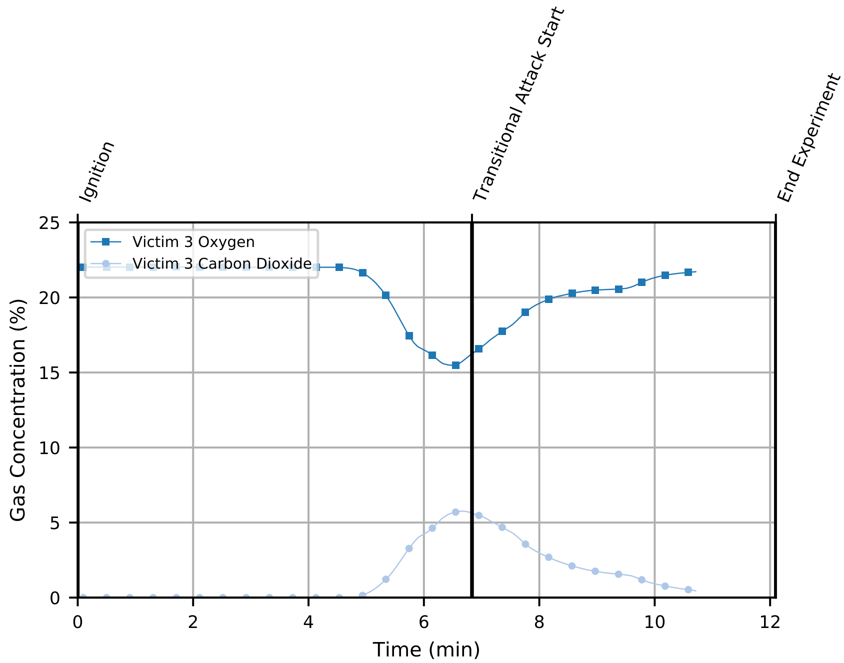


Figure E.758: Experiment 20 - Victim 3 Gas

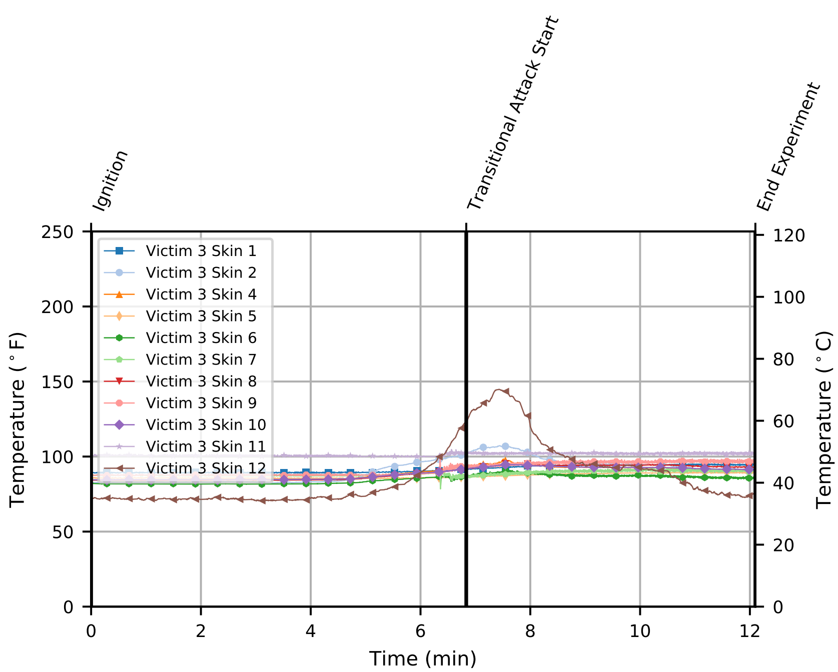


Figure E.759: Experiment 20 - Victim 3 Skin Temps

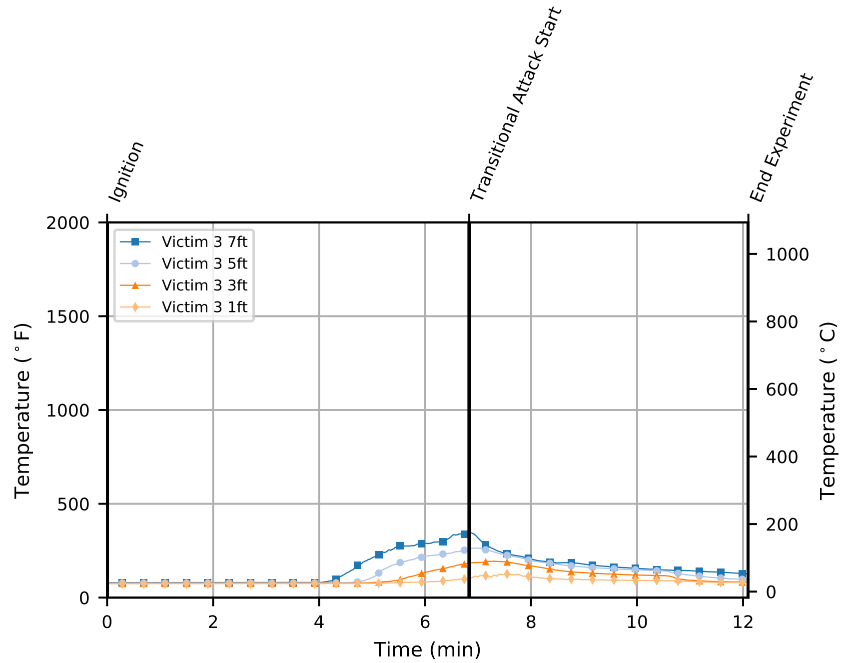


Figure E.760: Experiment 20 - Victim 3 Temps

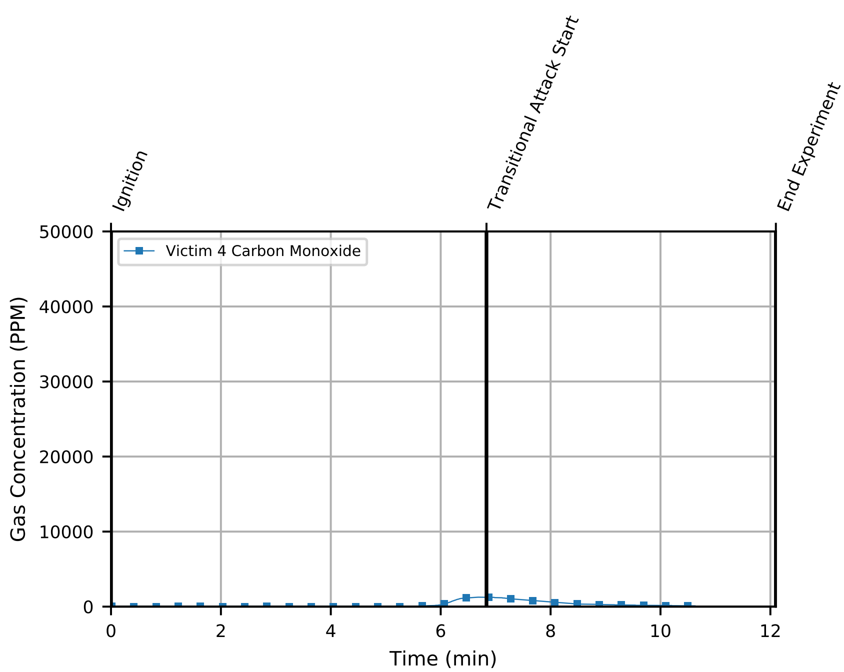


Figure E.761: Experiment 20 - Victim 4 Carbon Monoxide

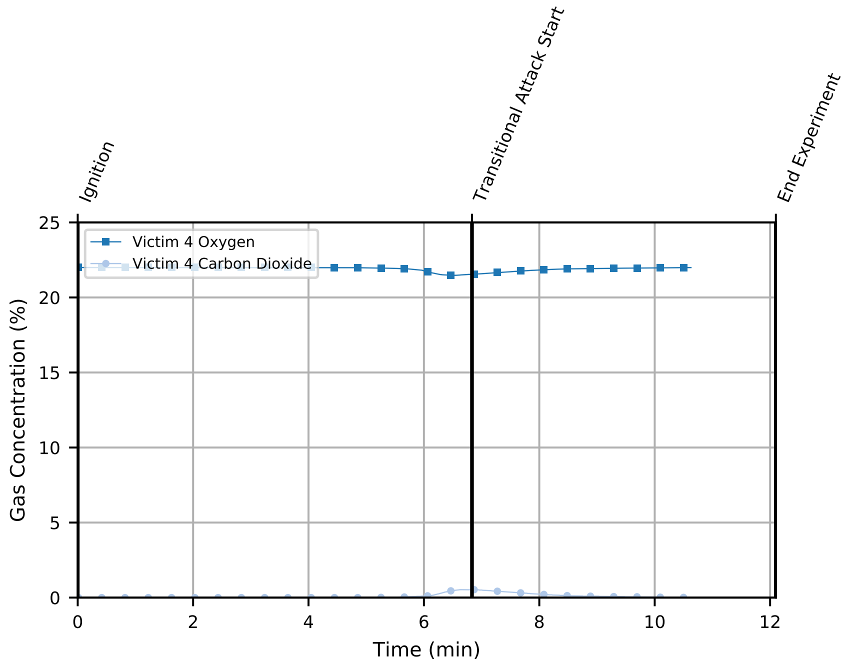


Figure E.762: Experiment 20 - Victim 4 Gas

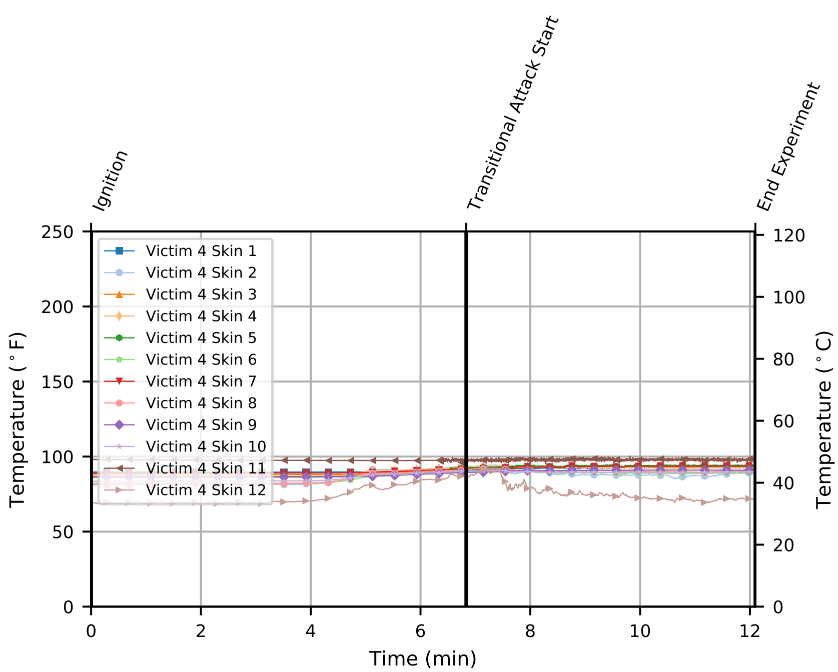


Figure E.763: Experiment 20 - Victim 4 Skin Temps

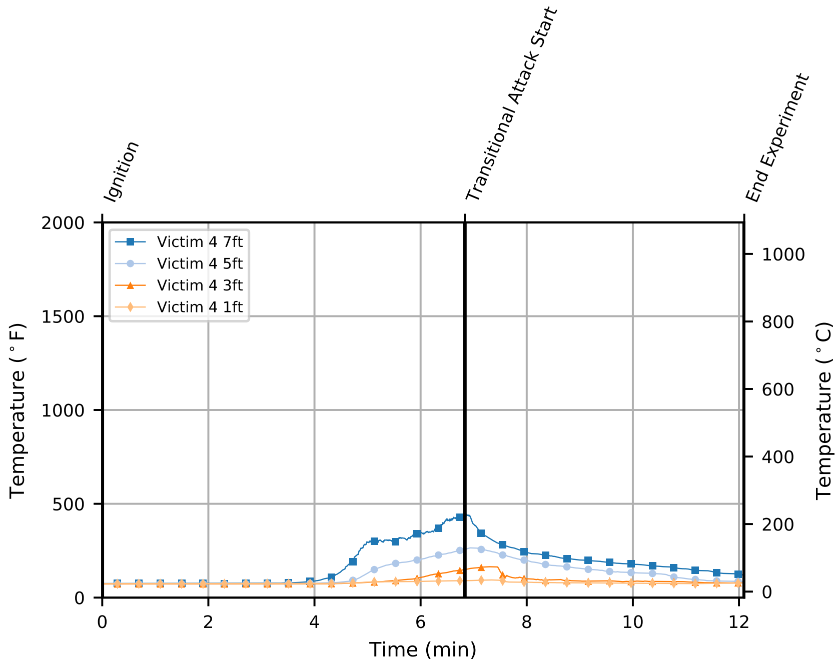


Figure E.764: Experiment 20 - Victim 4 Temps

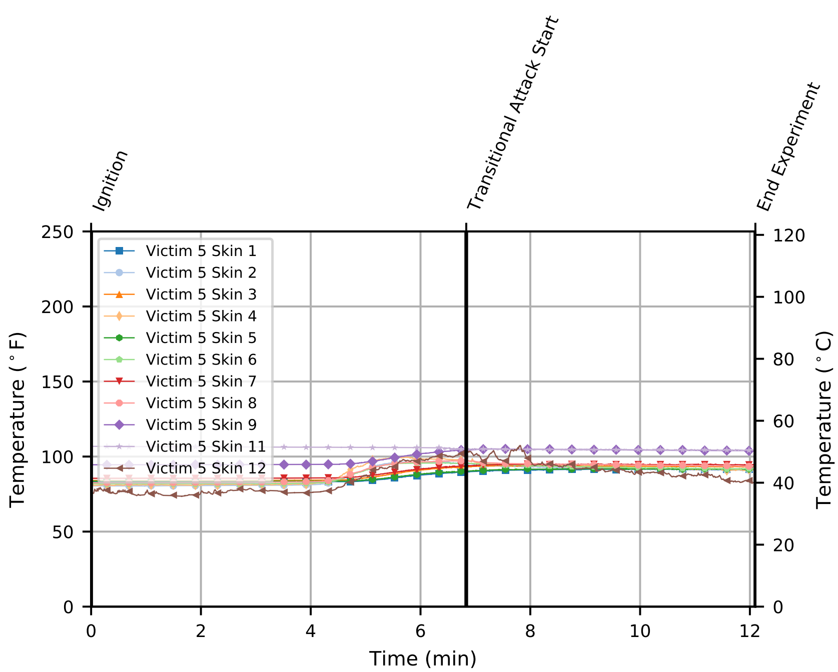


Figure E.765: Experiment 20 - Victim 5 Skin Temps

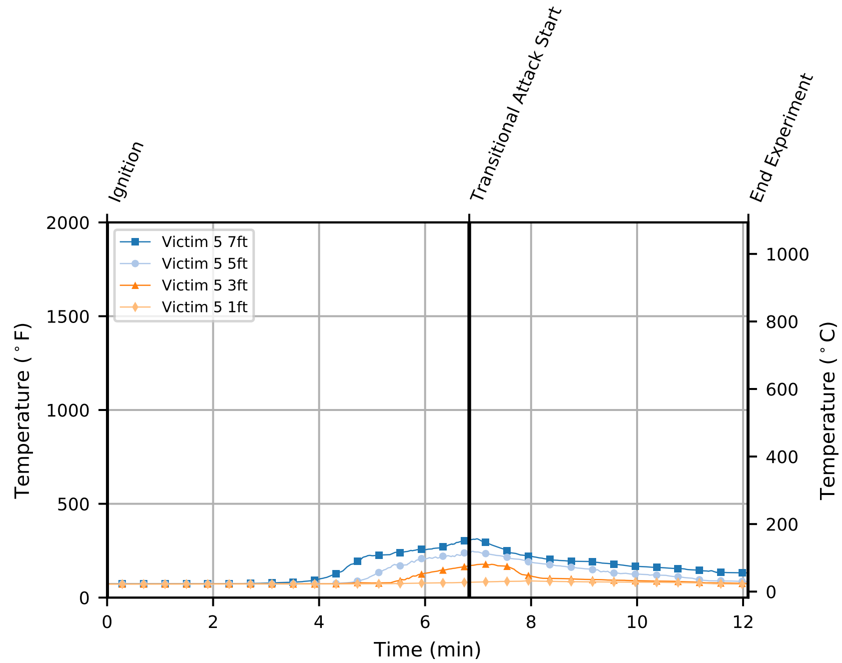


Figure E.766: Experiment 20 - Victim 5 Temps

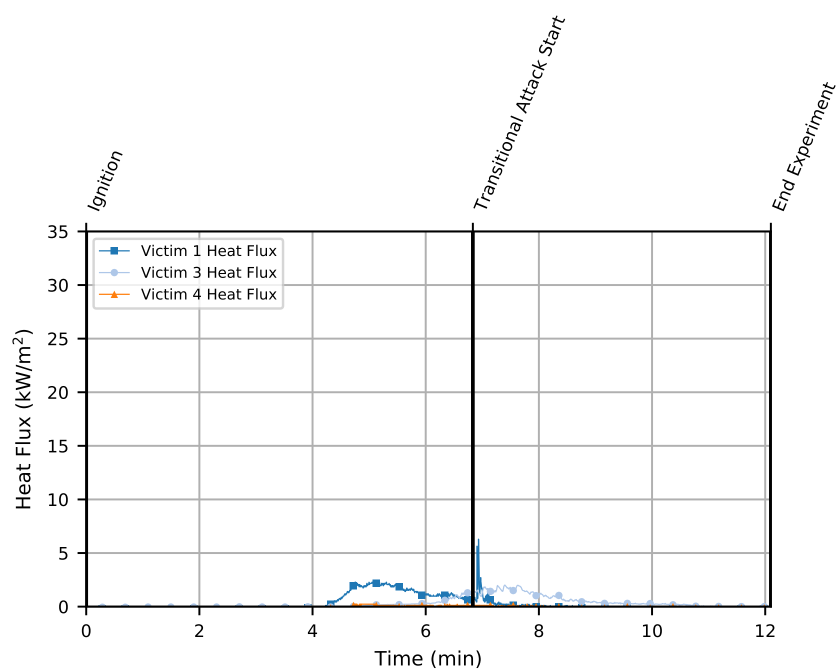


Figure E.767: Experiment 20 - Victim Heat Flux

E.21 Experiment 21 Data

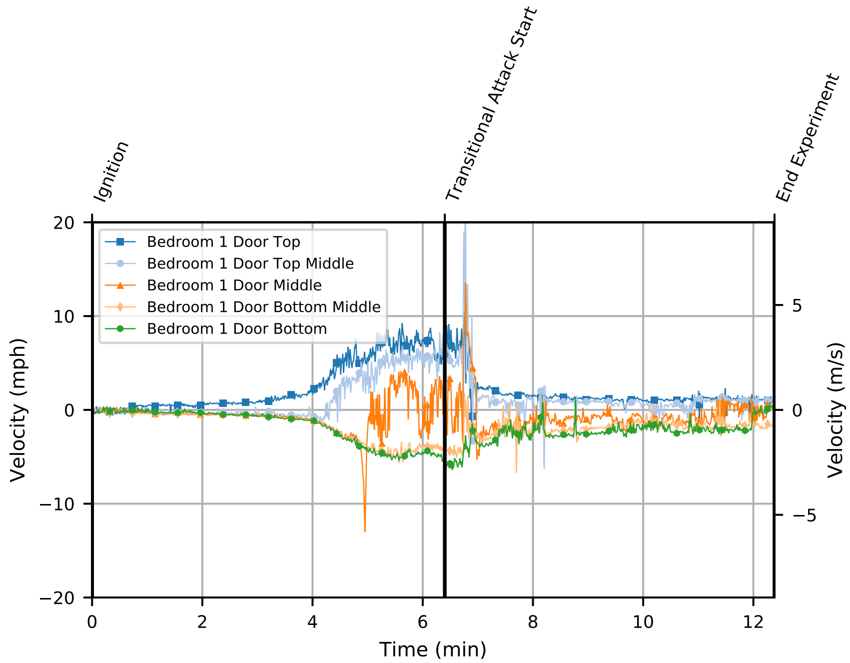


Figure E.768: Experiment 21 - Bedroom 1 Door

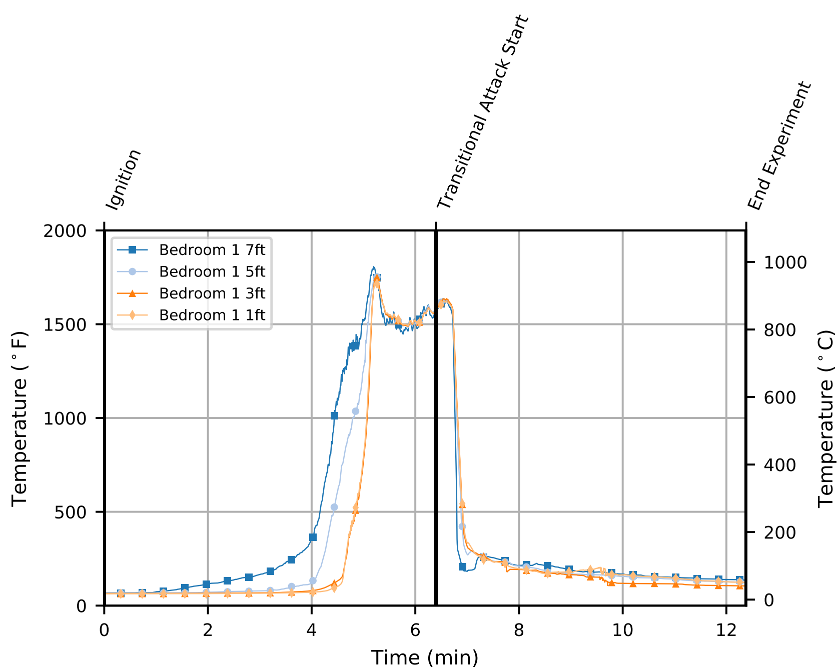


Figure E.769: Experiment 21 - Bedroom 1 Temps

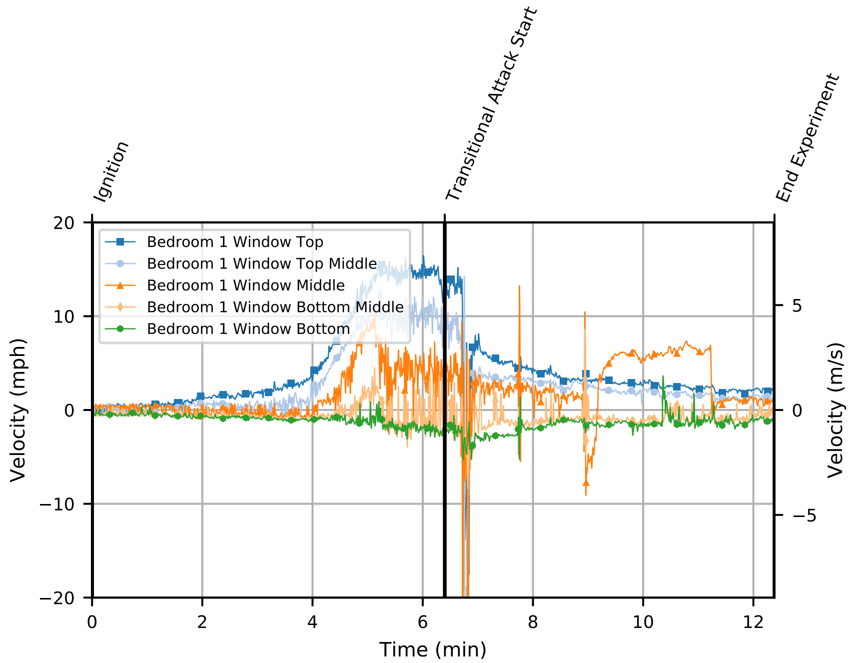


Figure E.770: Experiment 21 - Bedroom 1 Window

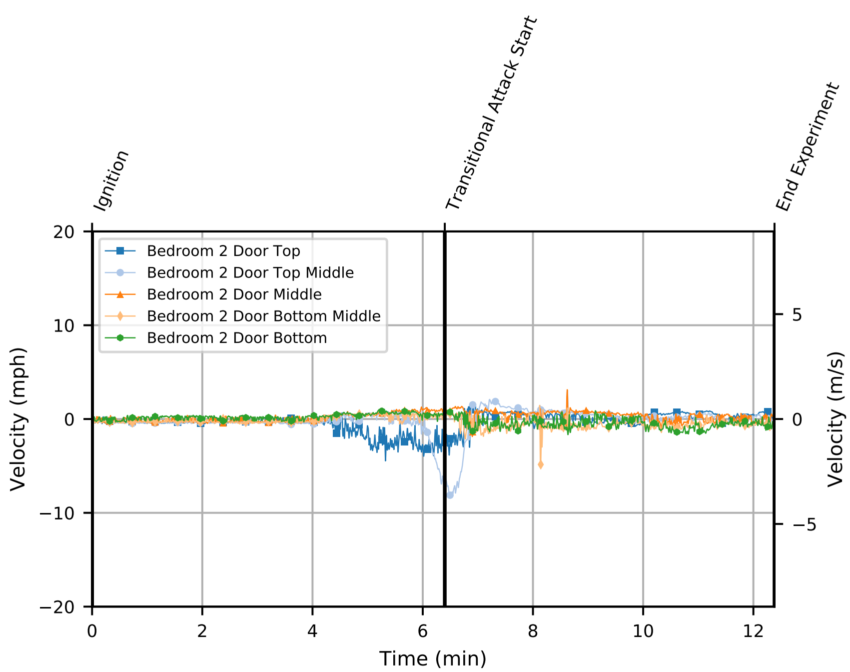


Figure E.771: Experiment 21 - Bedroom 2 Door

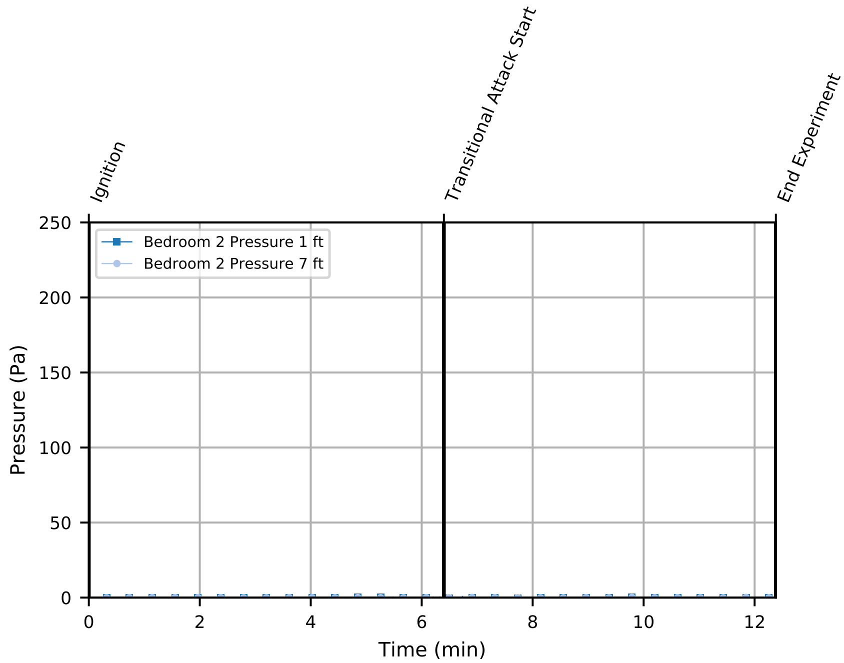


Figure E.772: Experiment 21 - Bedroom 2 Pressure

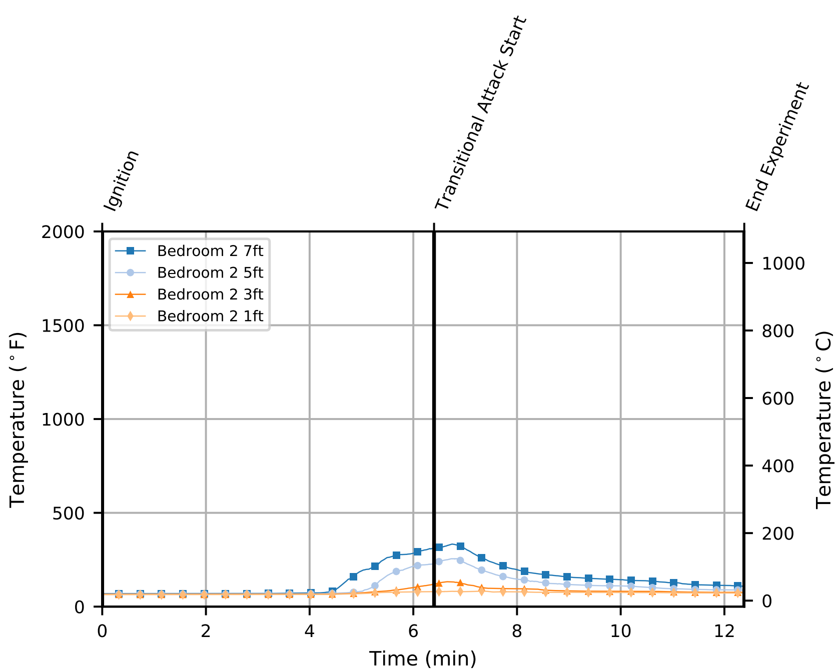


Figure E.773: Experiment 21 - Bedroom 2 Temps

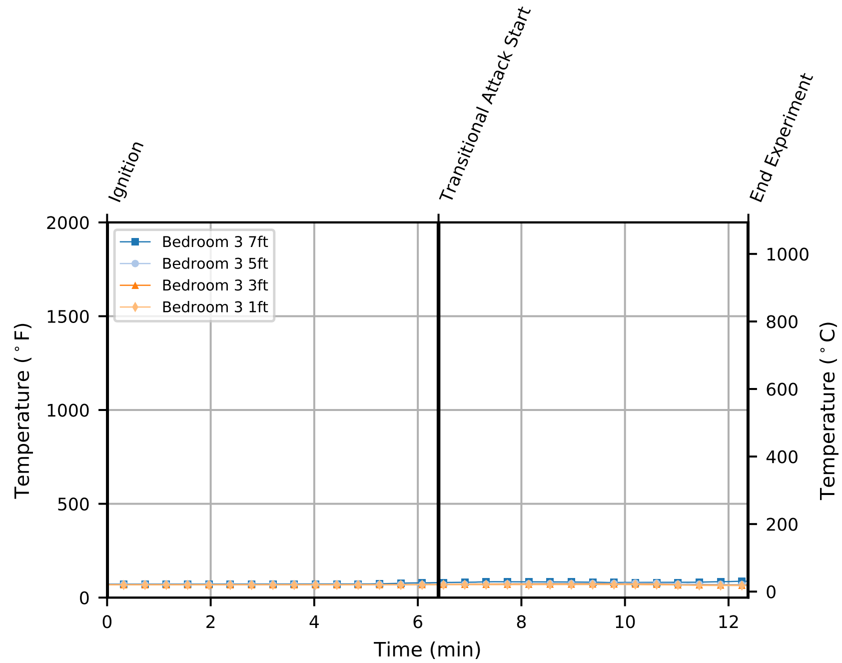


Figure E.774: Experiment 21 - Bedroom 3 Temps

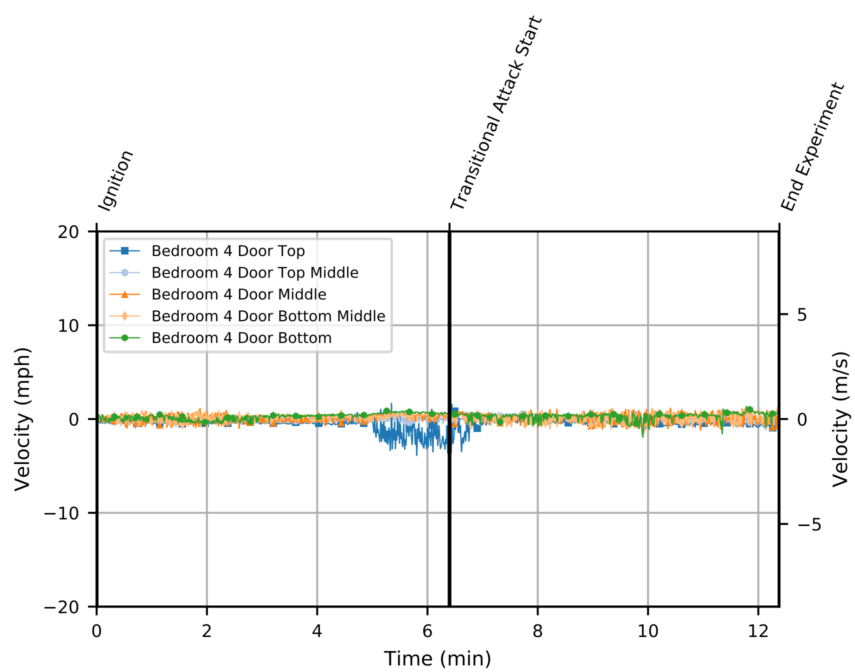


Figure E.775: Experiment 21 - Bedroom 4 Door

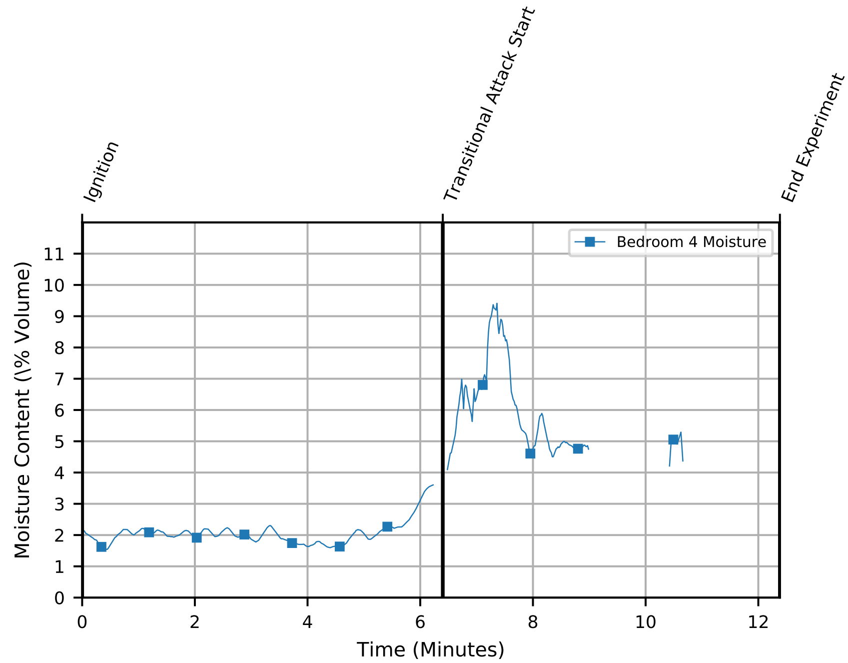


Figure E.776: Experiment 21 - Bedroom 4 Moisture

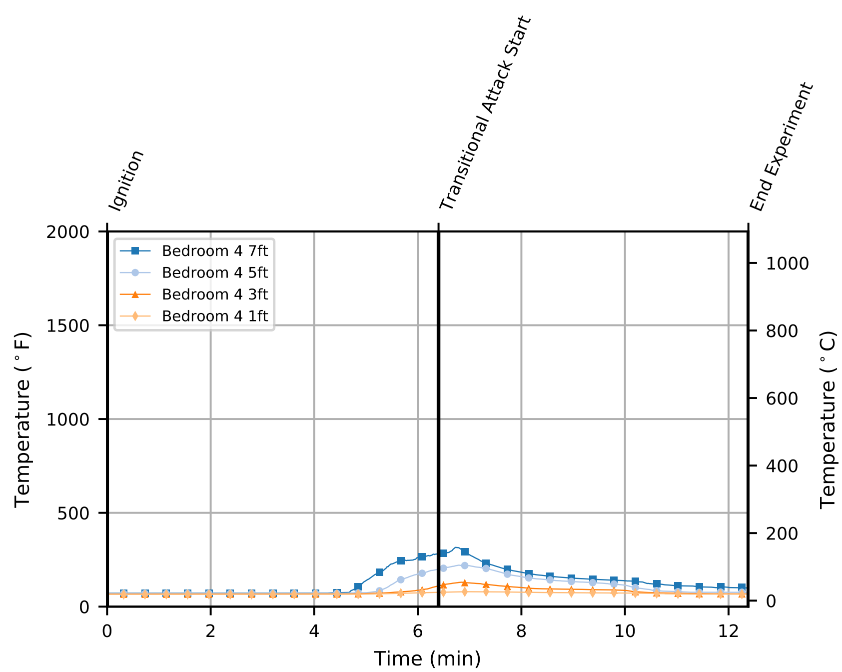


Figure E.777: Experiment 21 - Bedroom 4 Temps

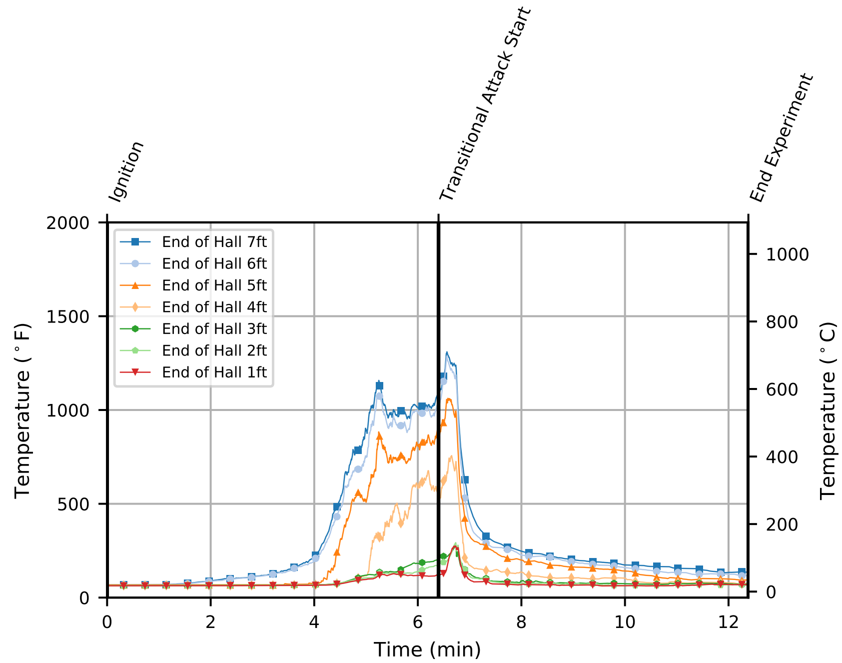


Figure E.778: Experiment 21 - End Hall Temps

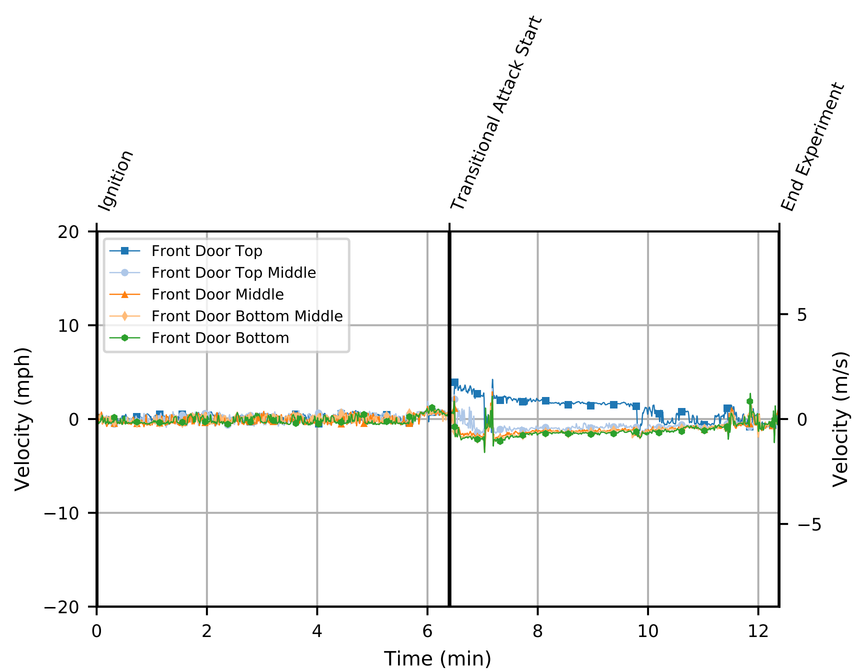


Figure E.779: Experiment 21 - Front Door Flow

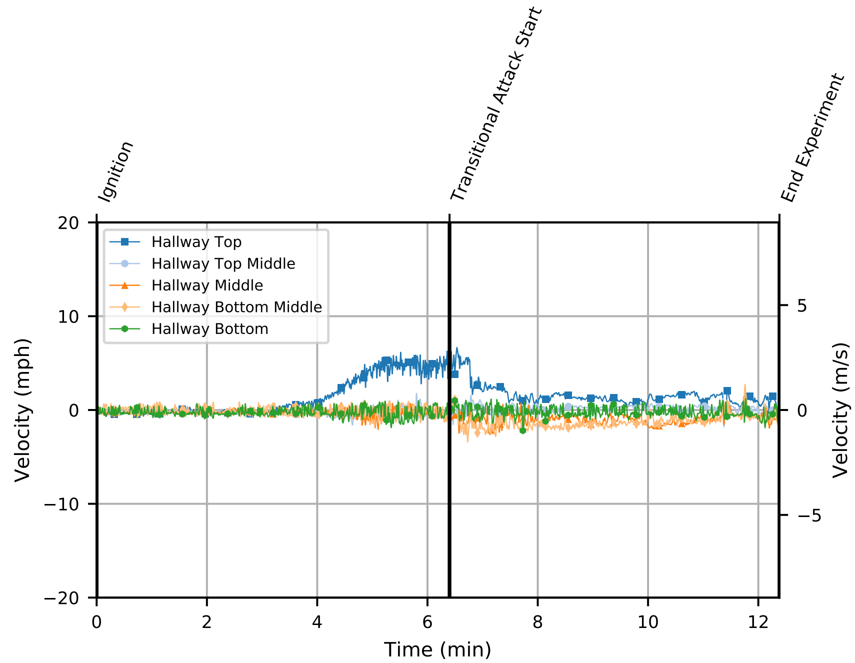


Figure E.780: Experiment 21 - Hallway Flow

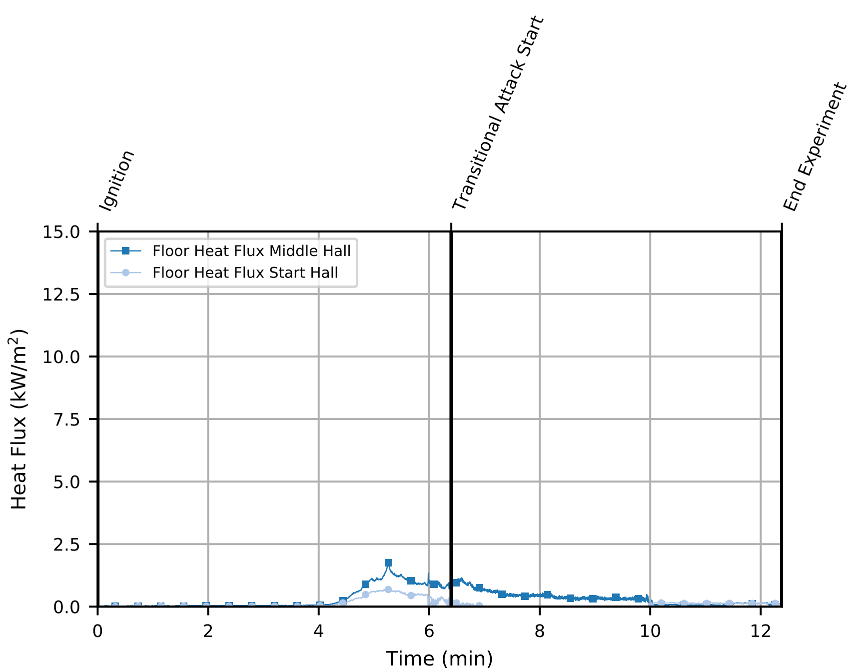


Figure E.781: Experiment 21 - Heat Flux Floor

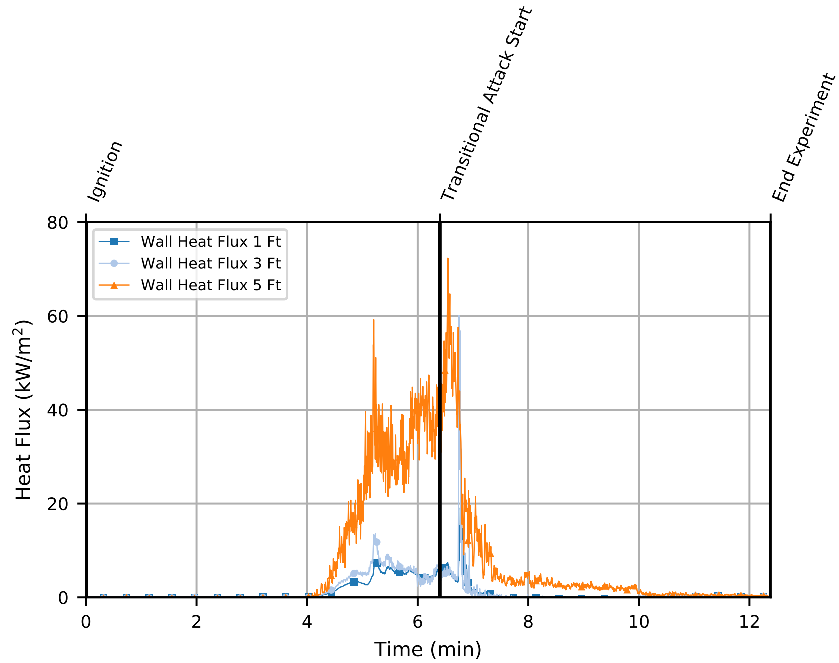


Figure E.782: Experiment 21 - Heat Flux Wall

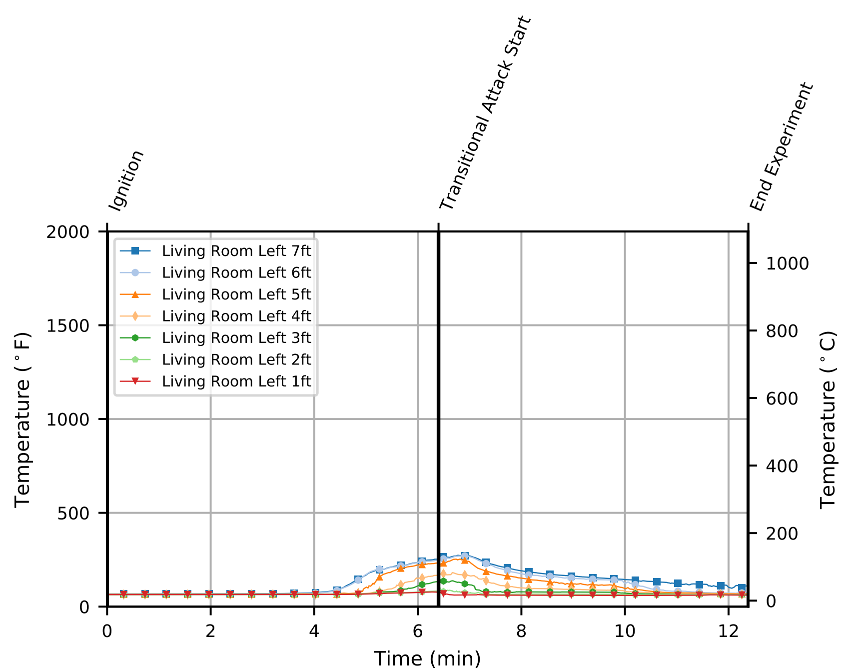


Figure E.783: Experiment 21 - Living Room Left Temps

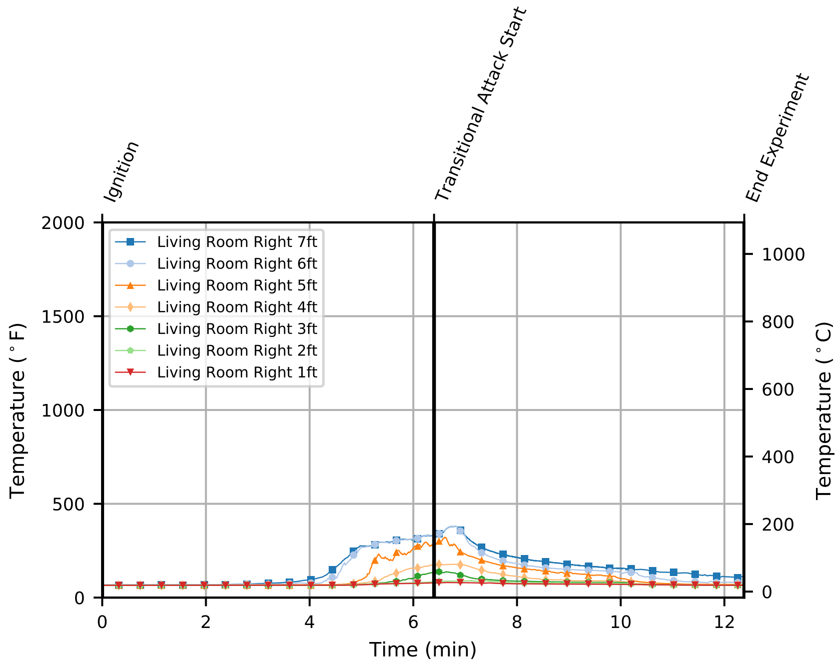


Figure E.784: Experiment 21 - Living Room Right Temps

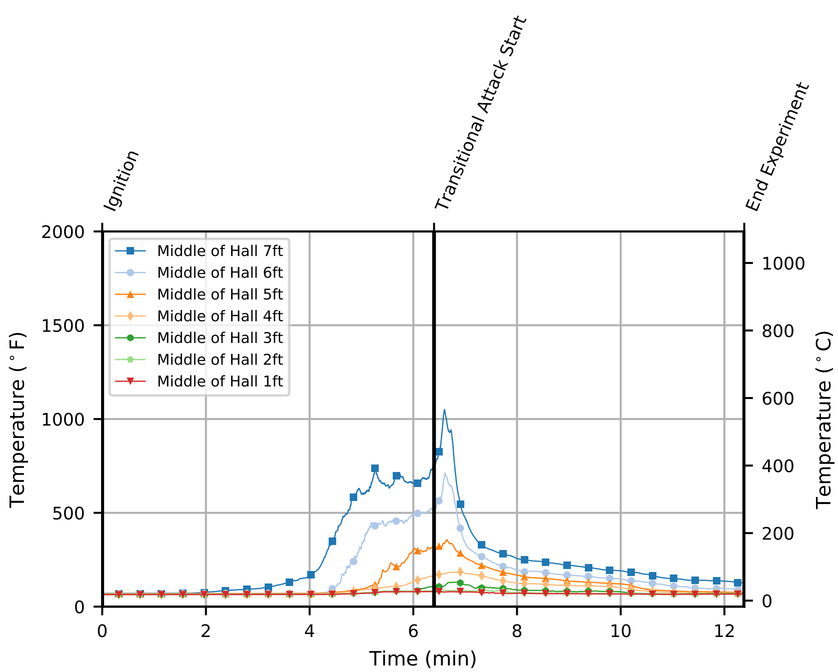


Figure E.785: Experiment 21 - Middle Hall Temps

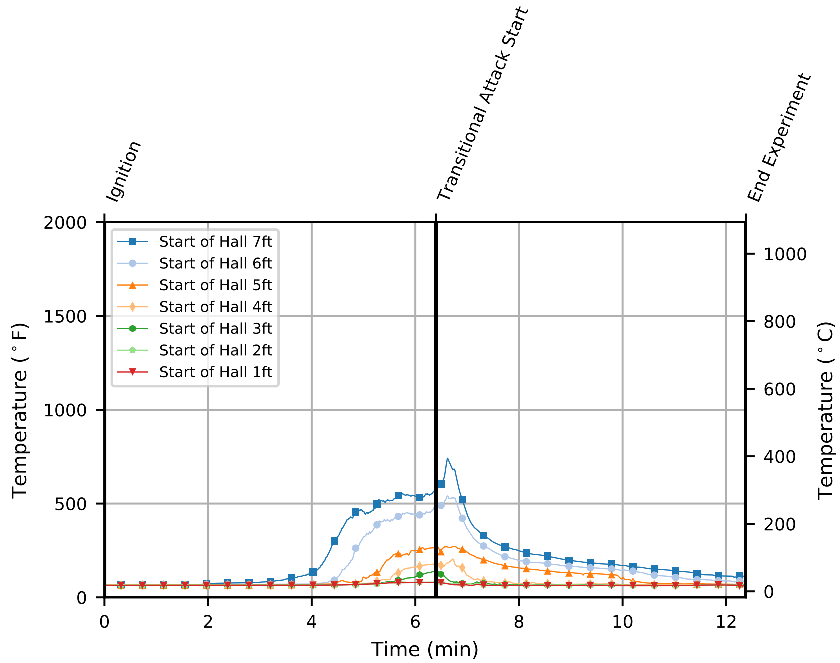


Figure E.786: Experiment 21 - Start Hall Temps

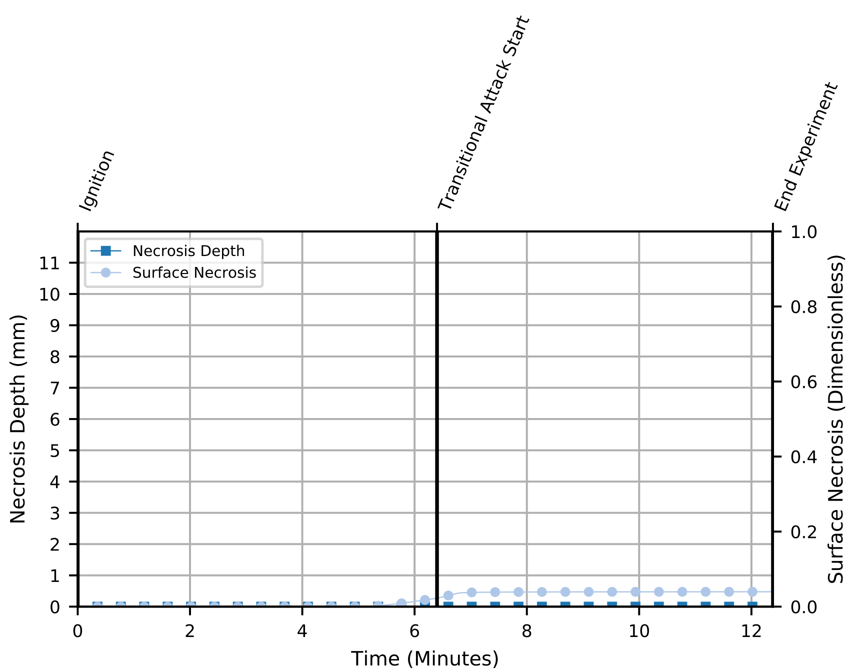


Figure E.787: Experiment 21 - Vic 1 Necrosis Depth

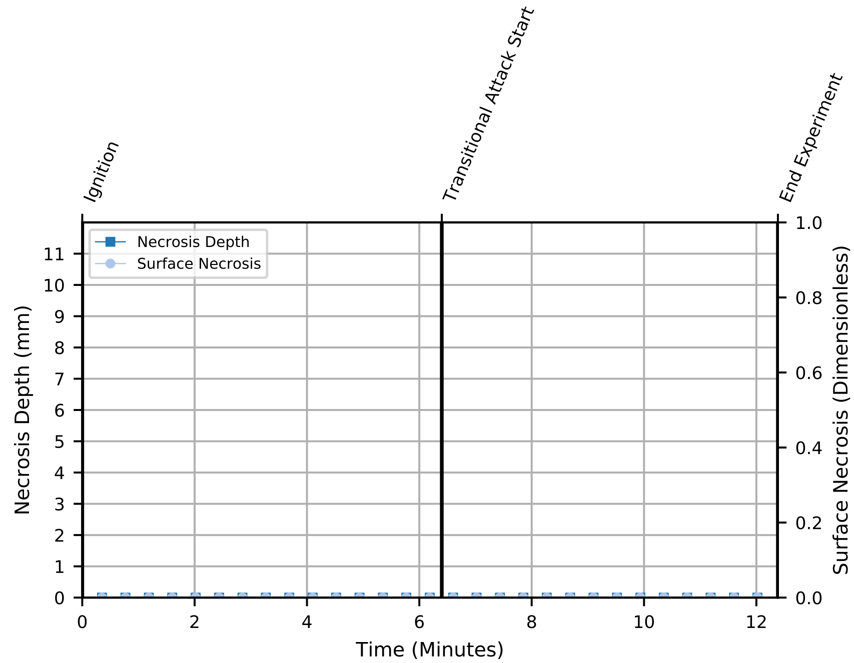


Figure E.788: Experiment 21 - Vic 3 Necrosis Depth

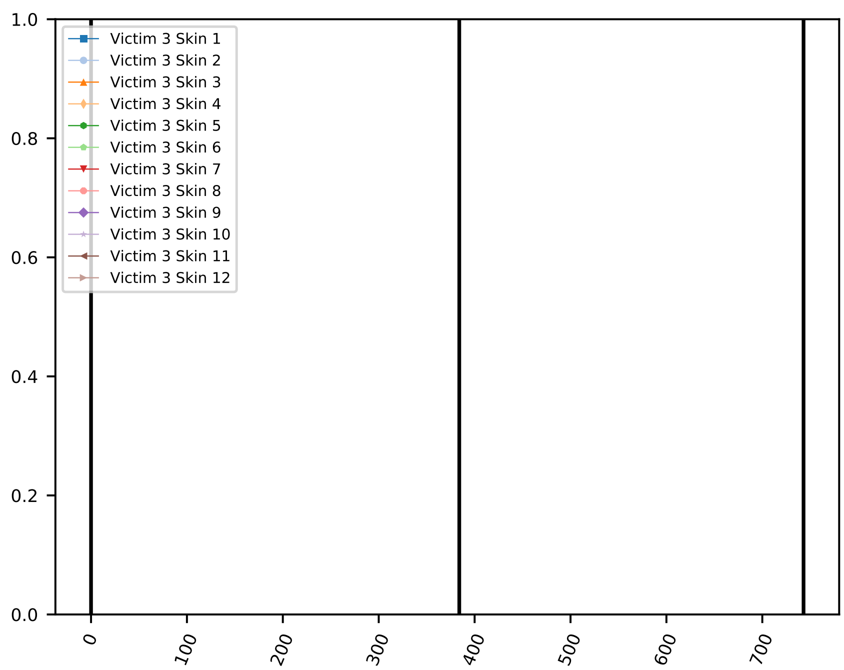


Figure E.789: Experiment 21 - Victim 1 Carbon Monoxide

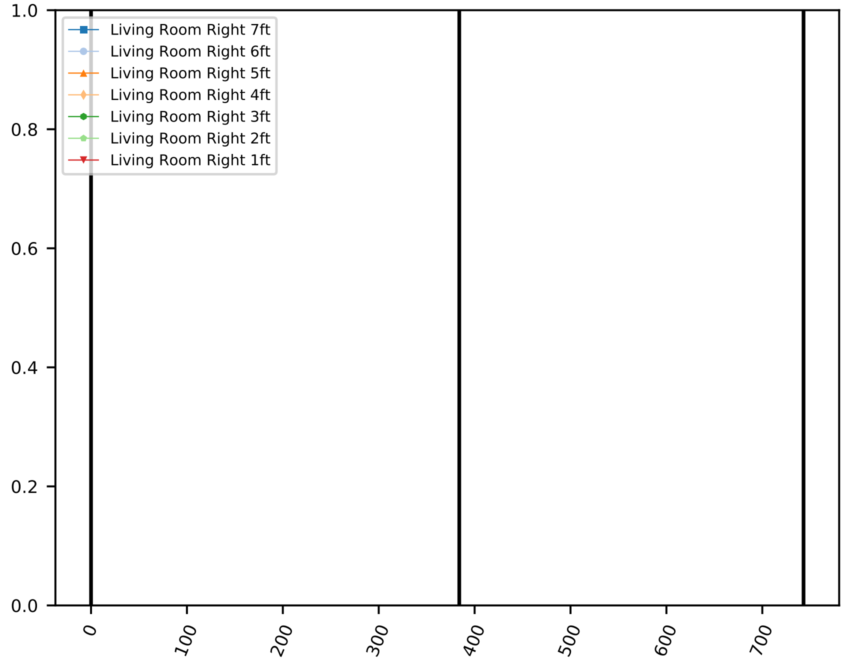


Figure E.790: Experiment 21 - Victim 1 Gas

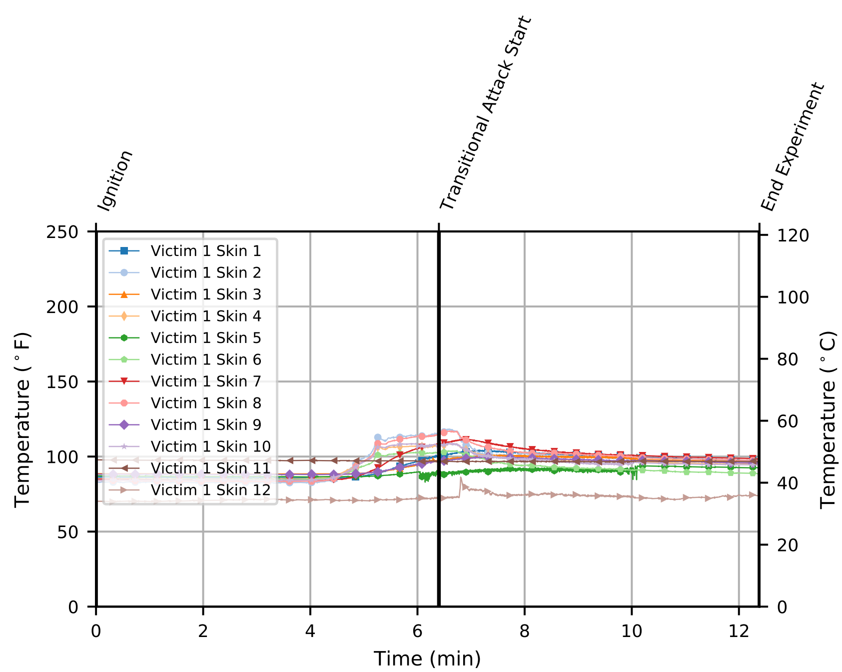


Figure E.791: Experiment 21 - Victim 1 Skin Temps

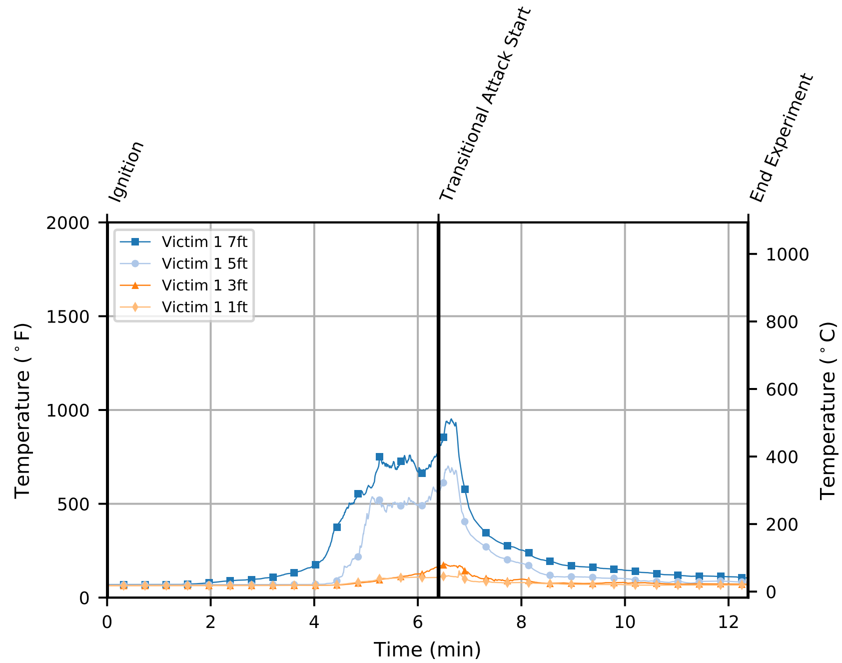


Figure E.792: Experiment 21 - Victim 1 Temps

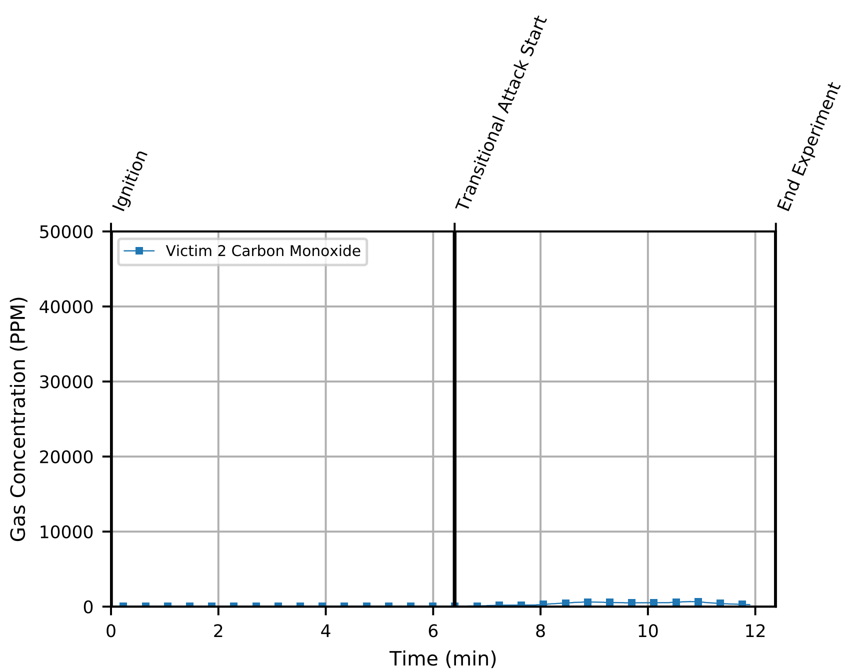


Figure E.793: Experiment 21 - Victim 2 Carbon Monoxide

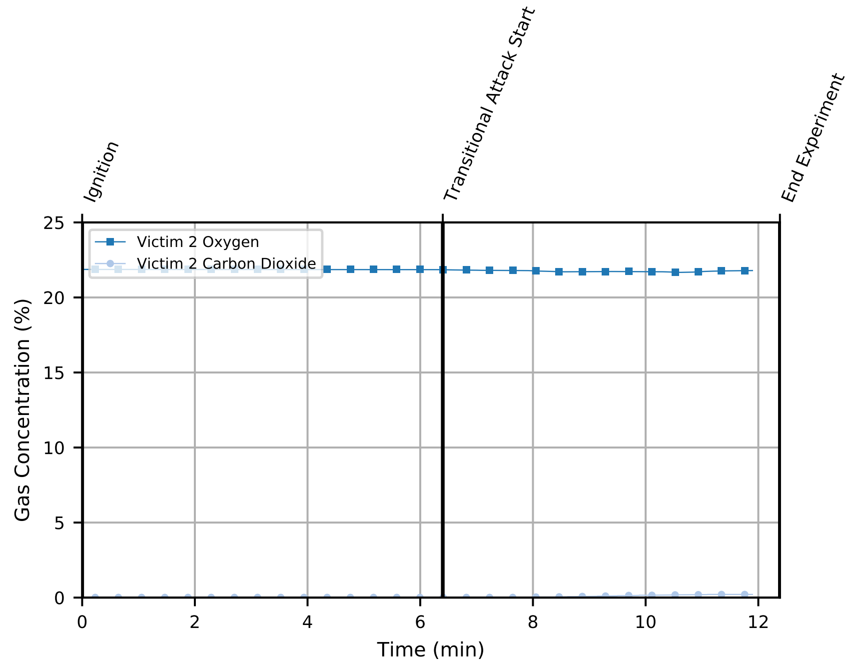


Figure E.794: Experiment 21 - Victim 2 Gas

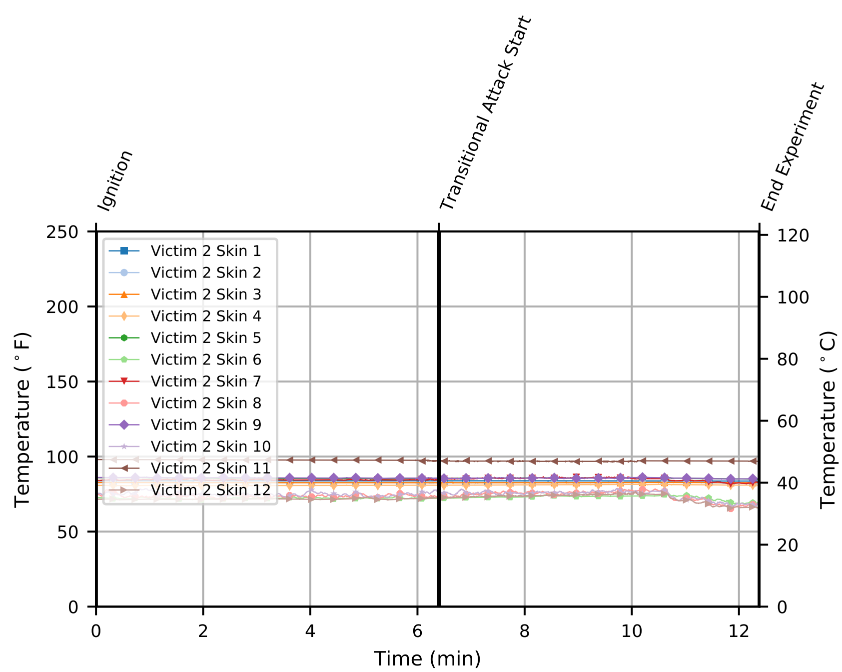


Figure E.795: Experiment 21 - Victim 2 Skin Temps

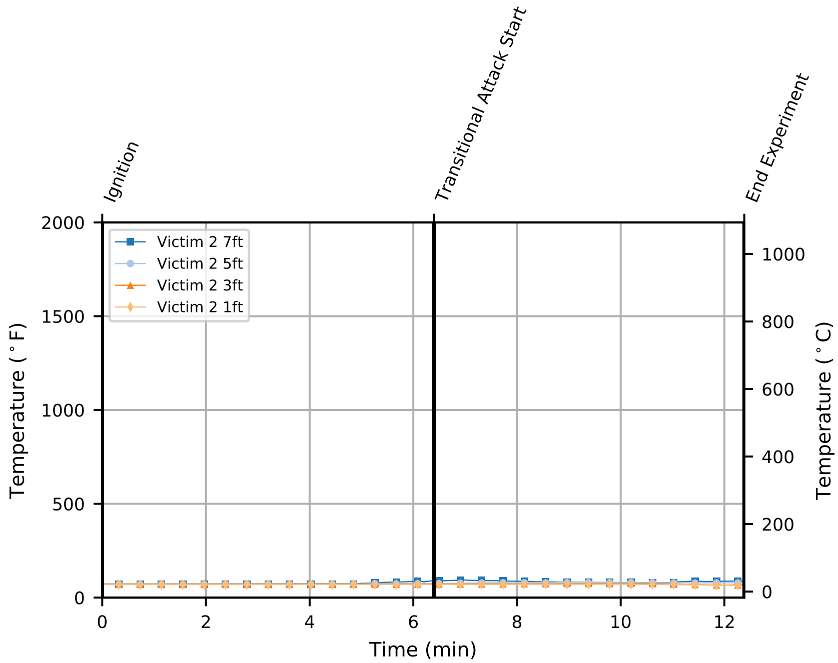


Figure E.796: Experiment 21 - Victim 2 Temps

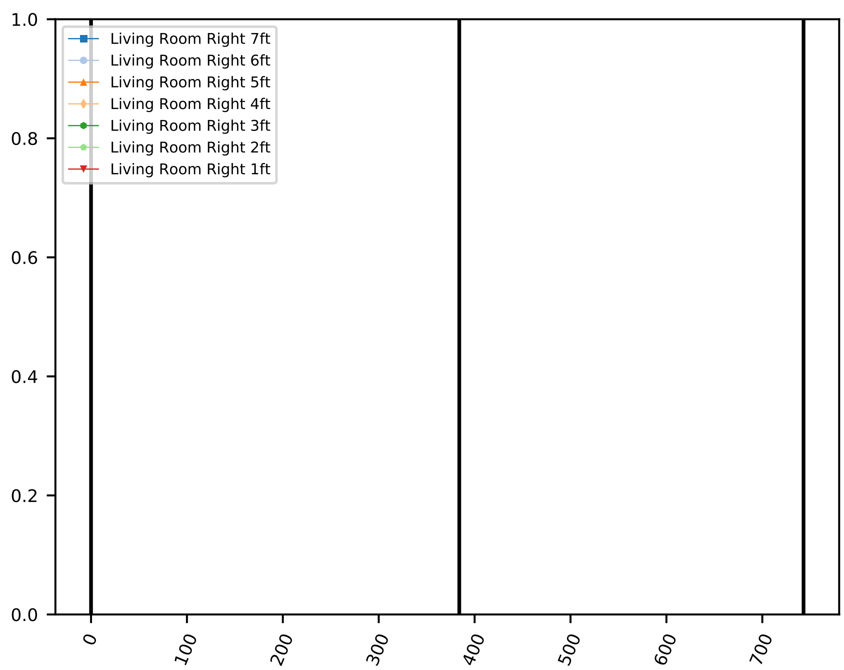


Figure E.797: Experiment 21 - Victim 3 Carbon Monoxide

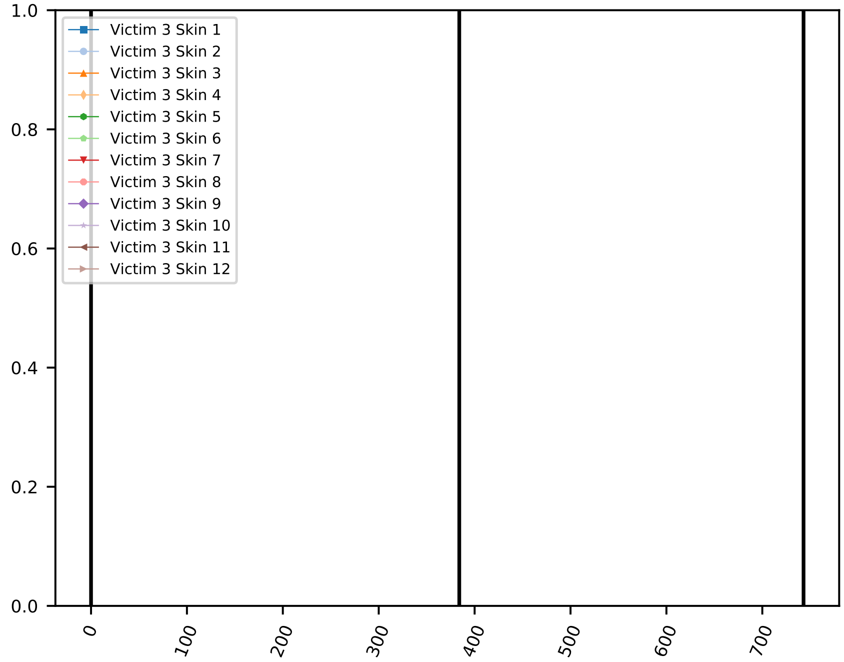


Figure E.798: Experiment 21 - Victim 3 Gas

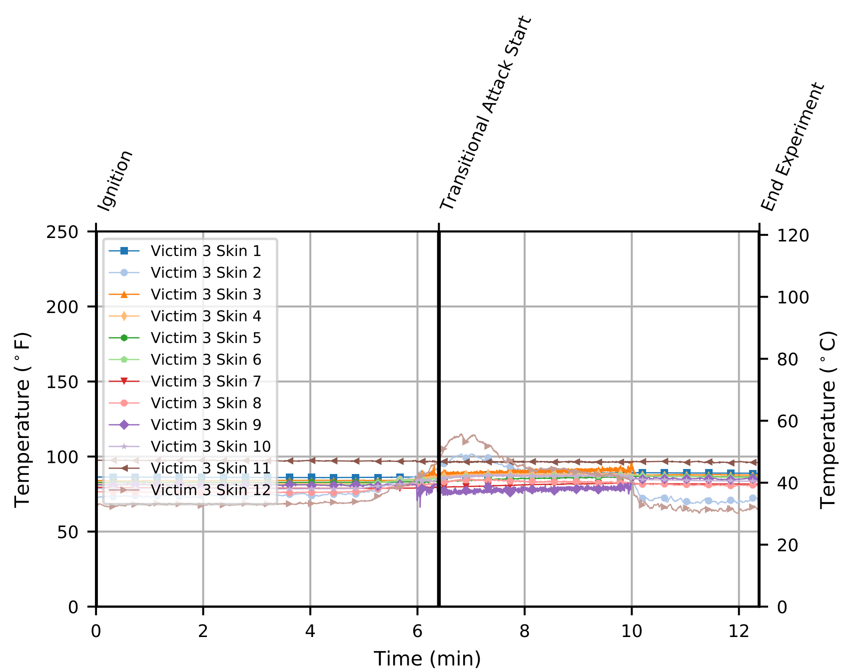


Figure E.799: Experiment 21 - Victim 3 Skin Temps

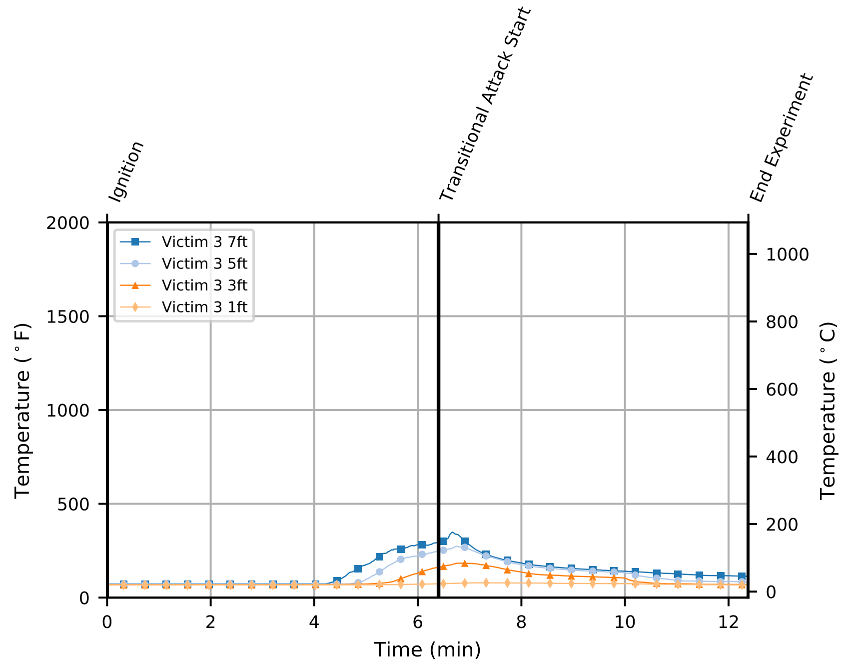


Figure E.800: Experiment 21 - Victim 3 Temps

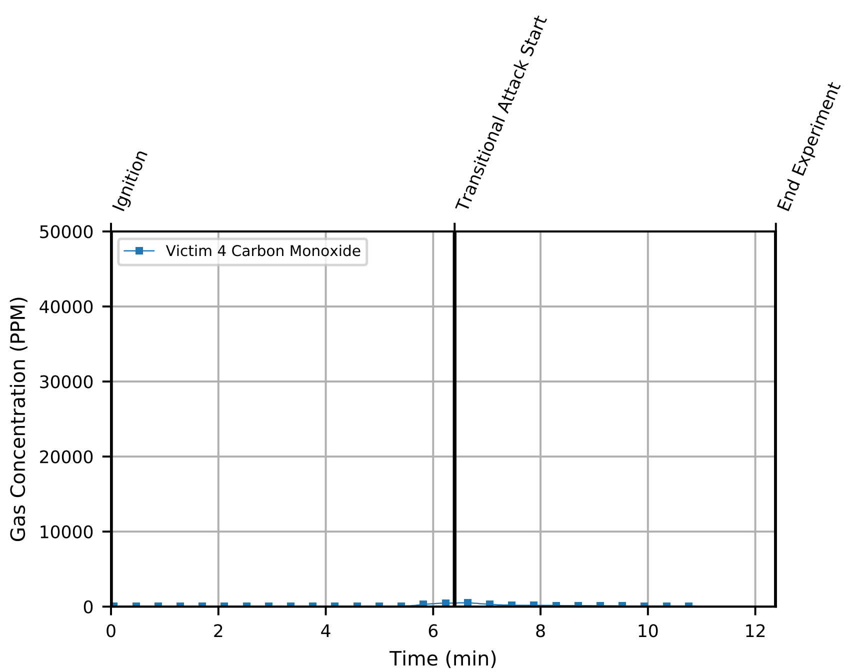


Figure E.801: Experiment 21 - Victim 4 Carbon Monoxide

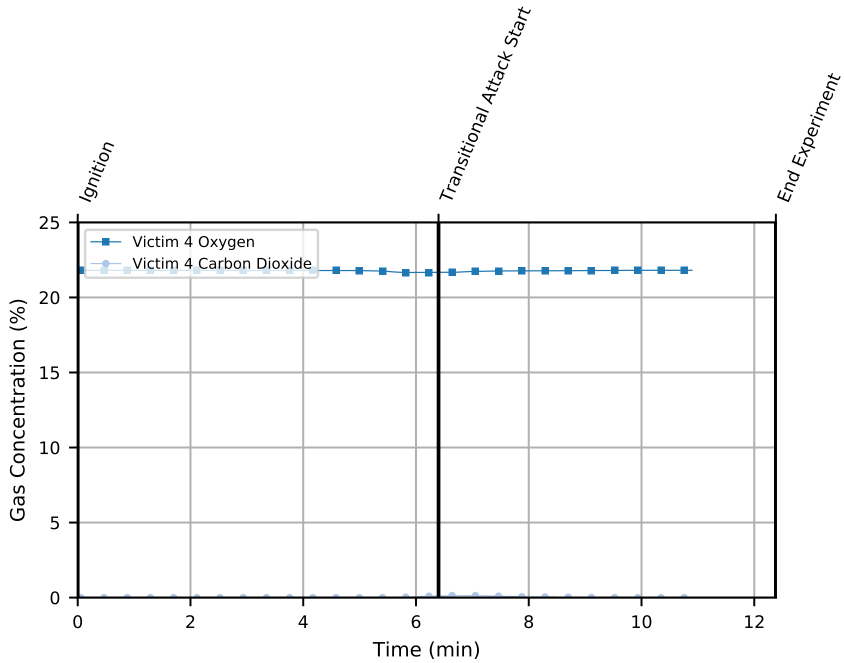


Figure E.802: Experiment 21 - Victim 4 Gas

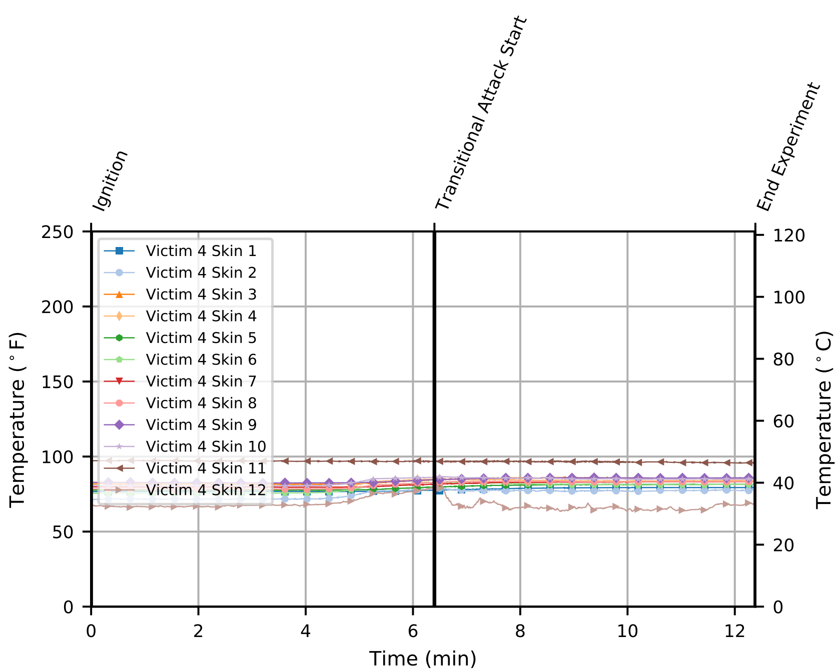


Figure E.803: Experiment 21 - Victim 4 Skin Temps

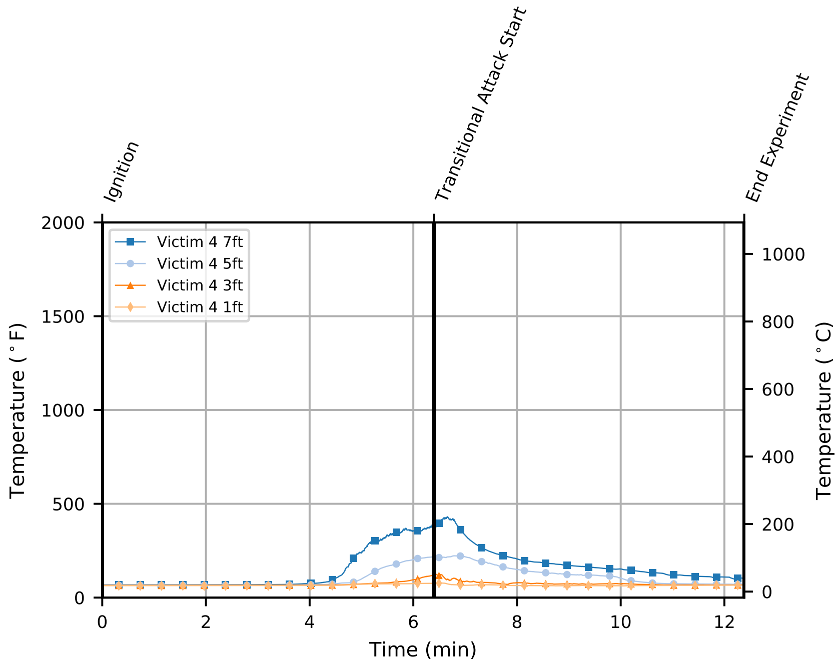


Figure E.804: Experiment 21 - Victim 4 Temps

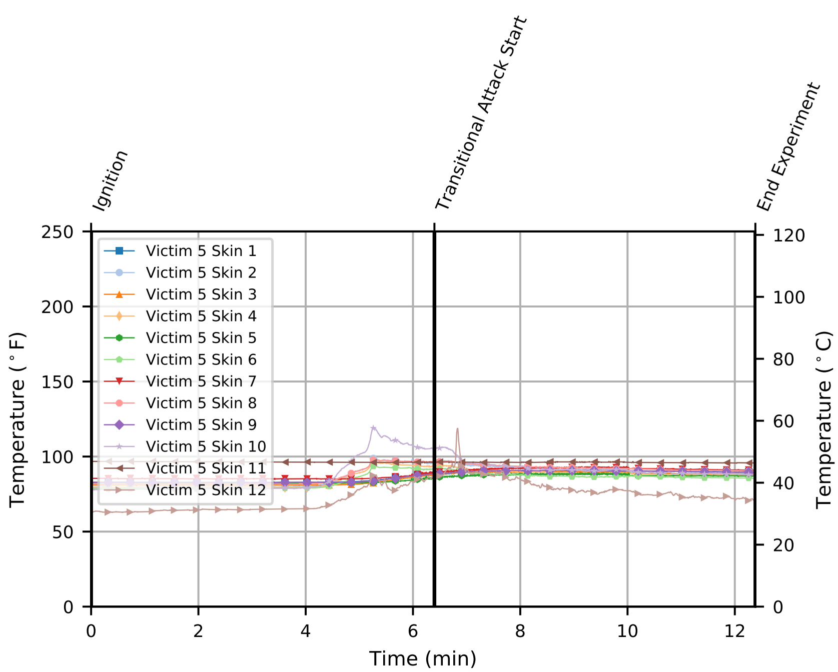


Figure E.805: Experiment 21 - Victim 5 Skin Temps

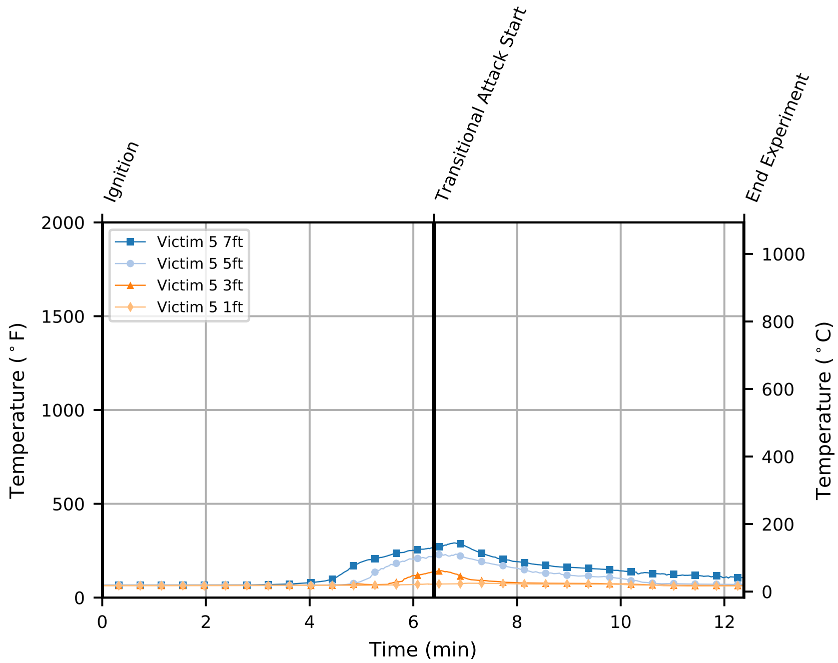


Figure E.806: Experiment 21 - Victim 5 Temps

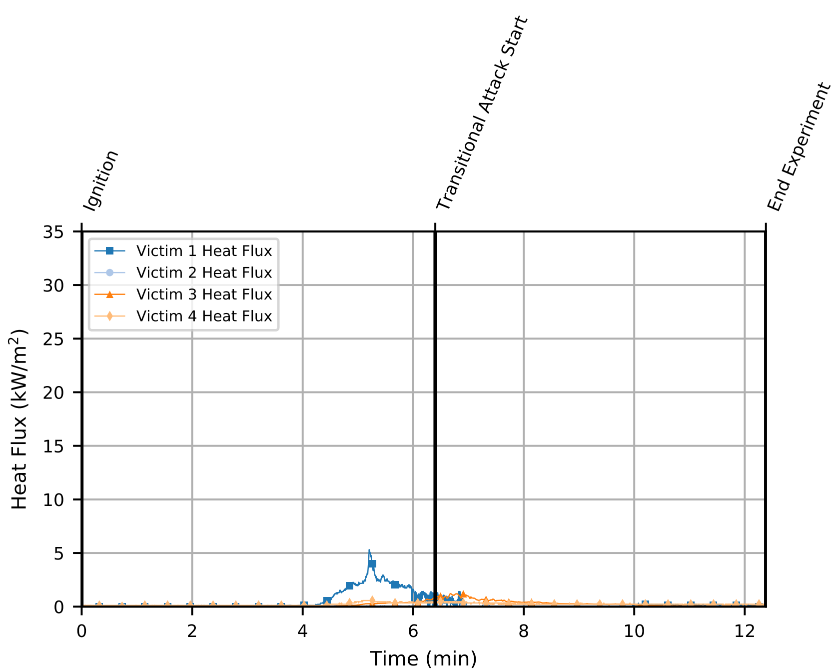


Figure E.807: Experiment 21 - Victim Heat Flux

E.22 Experiment 22 Data

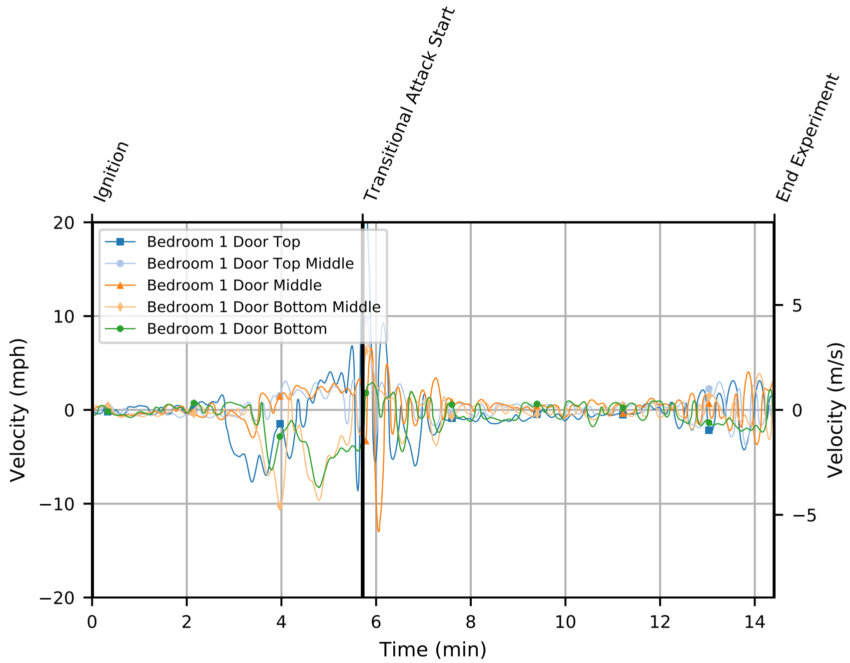


Figure E.808: Experiment 22 - Bedroom 1 Door

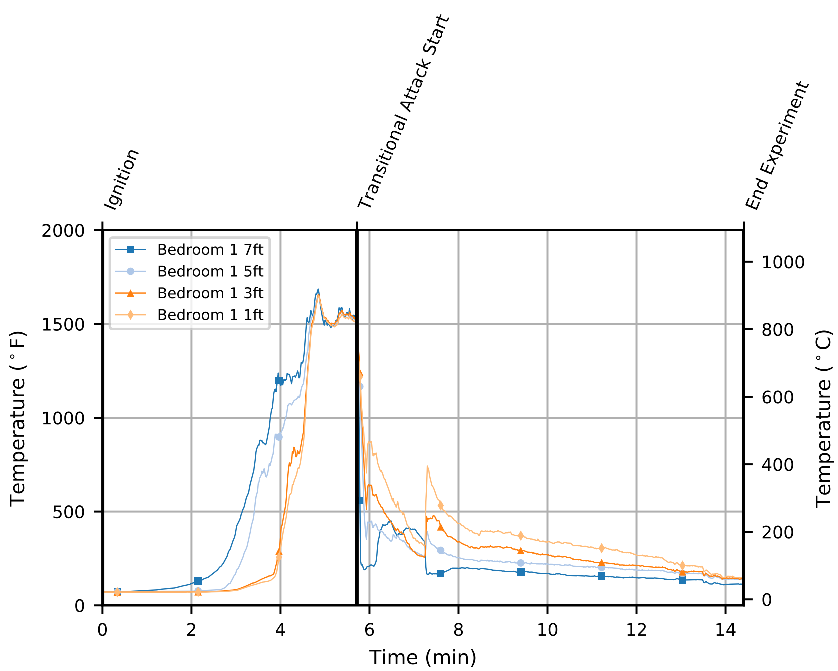


Figure E.809: Experiment 22 - Bedroom 1 Temps

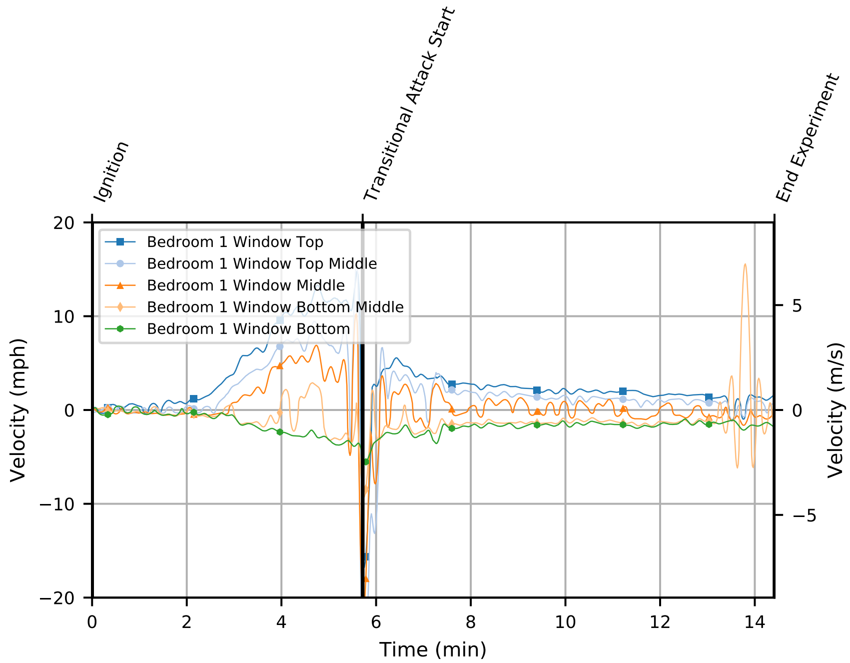


Figure E.810: Experiment 22 - Bedroom 1 Window

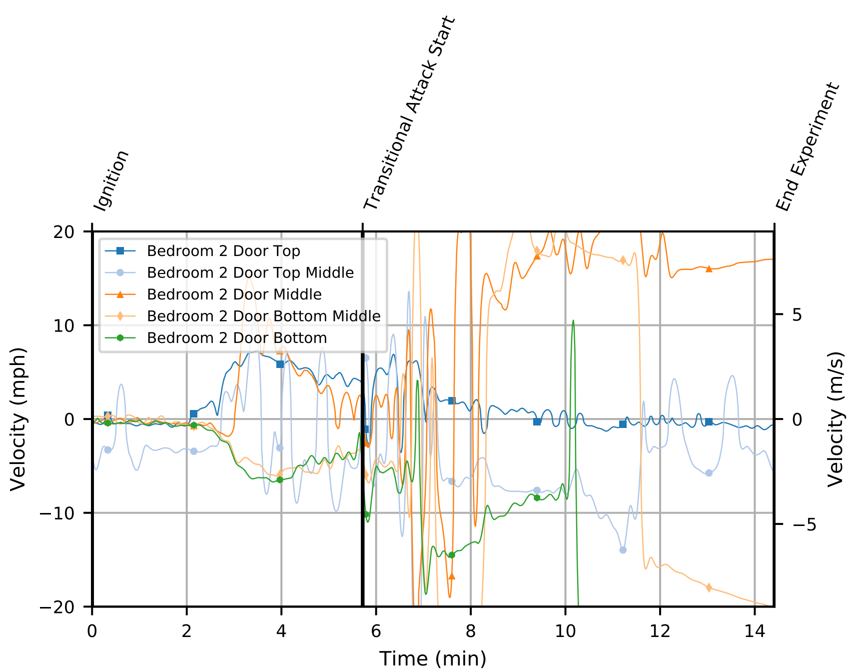


Figure E.811: Experiment 22 - Bedroom 2 Door

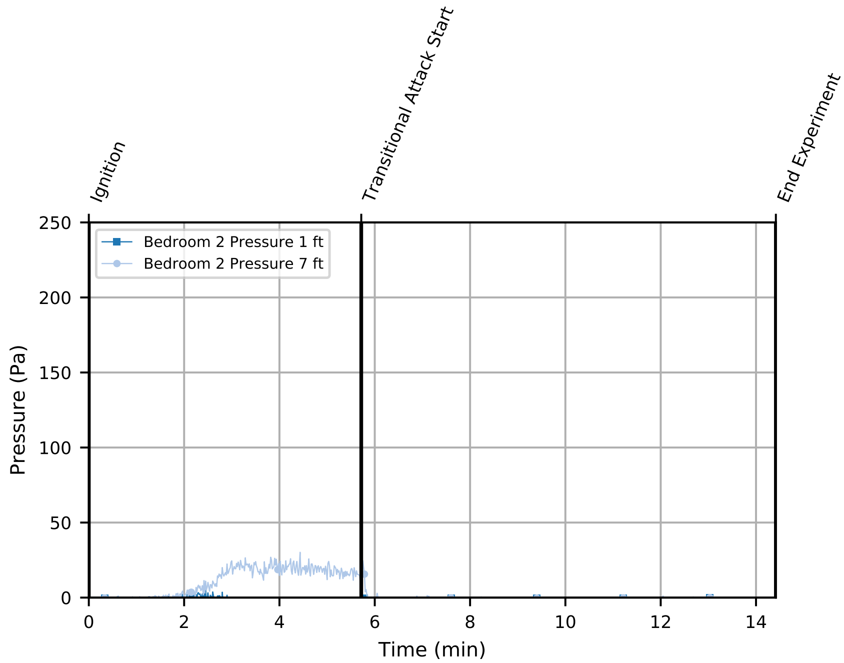


Figure E.812: Experiment 22 - Bedroom 2 Pressure

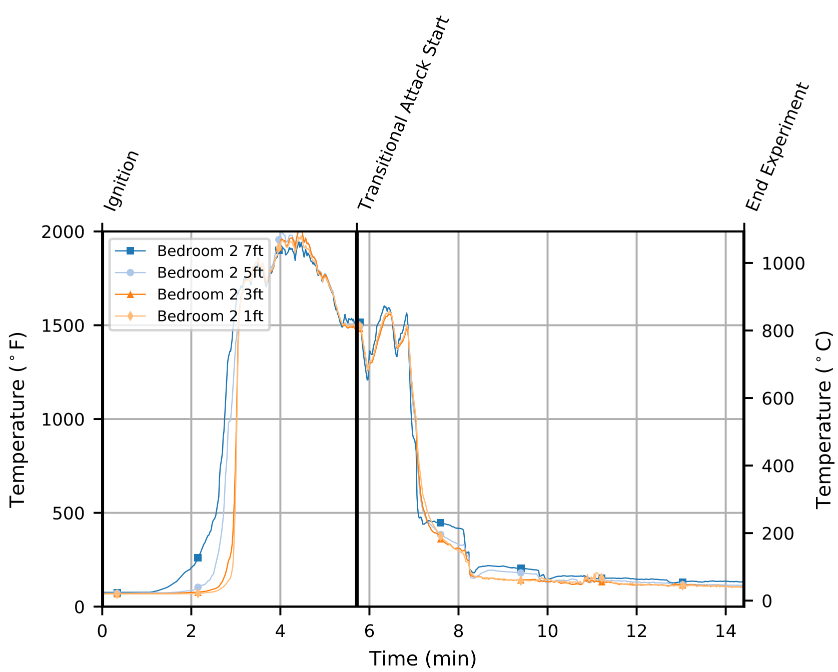


Figure E.813: Experiment 22 - Bedroom 2 Temps

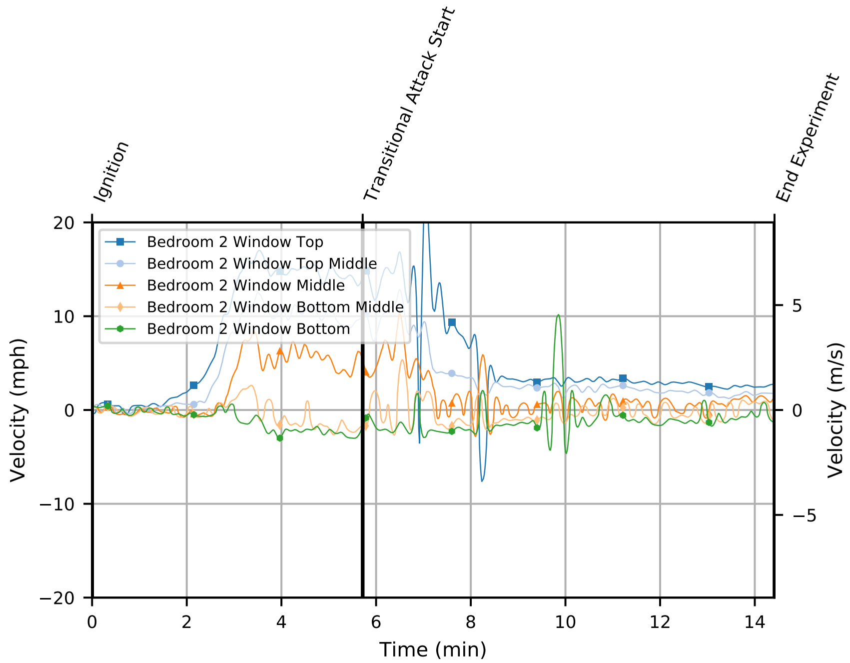


Figure E.814: Experiment 22 - Bedroom 2 Window

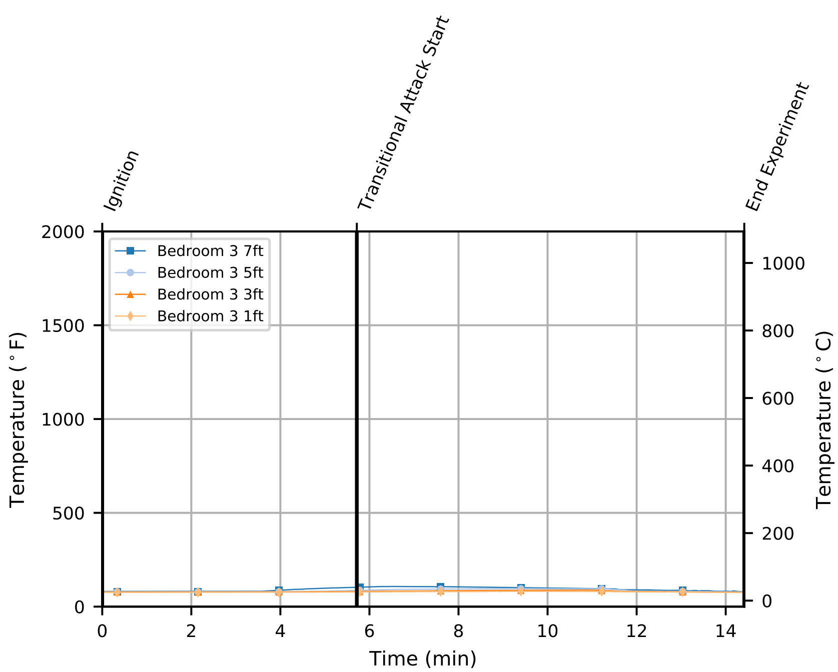


Figure E.815: Experiment 22 - Bedroom 3 Temps

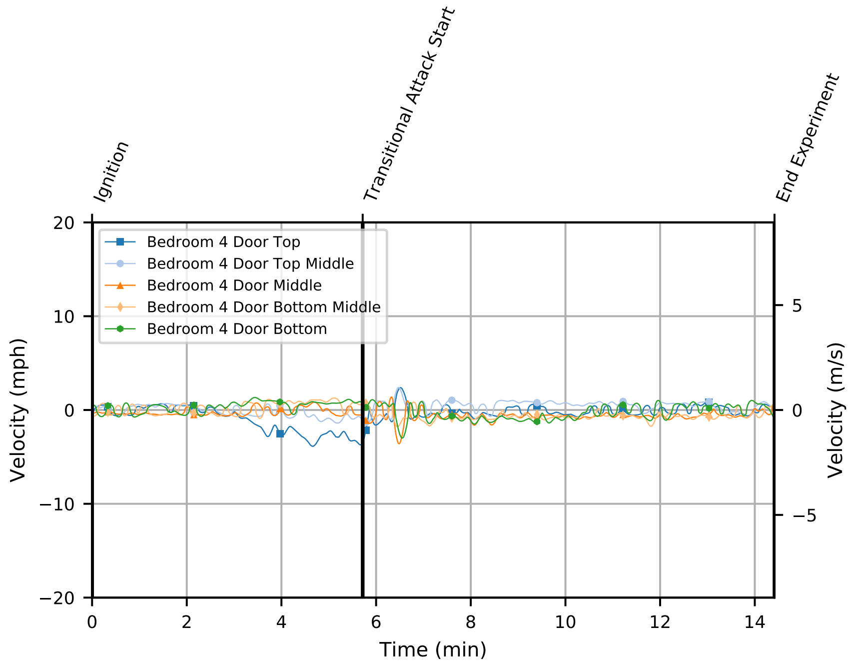


Figure E.816: Experiment 22 - Bedroom 4 Door

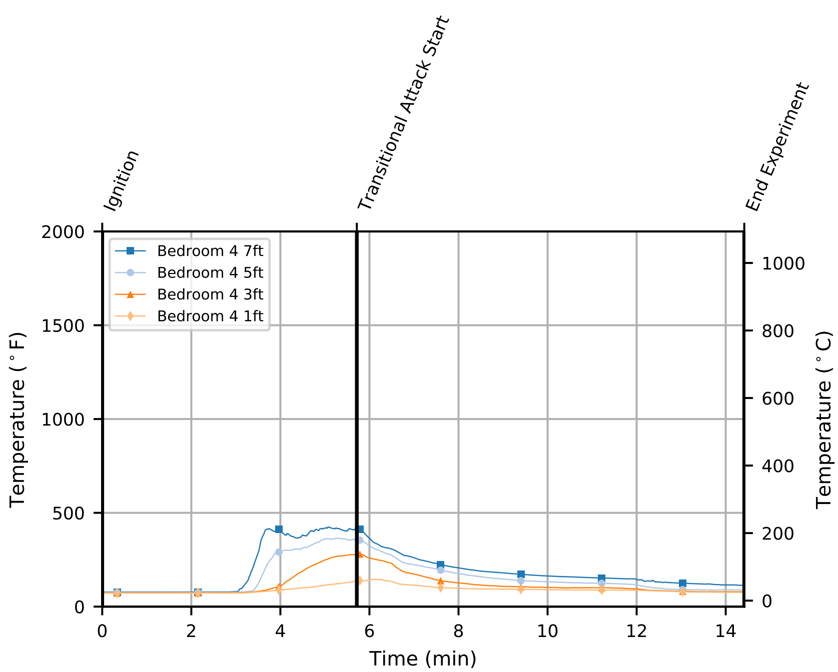


Figure E.817: Experiment 22 - Bedroom 4 Temps

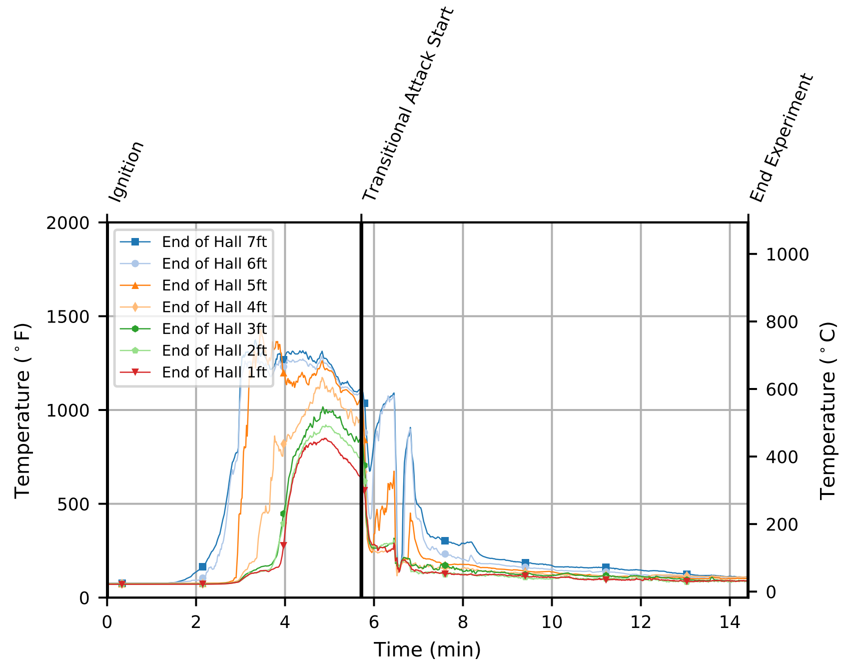


Figure E.818: Experiment 22 - End Hall Temps

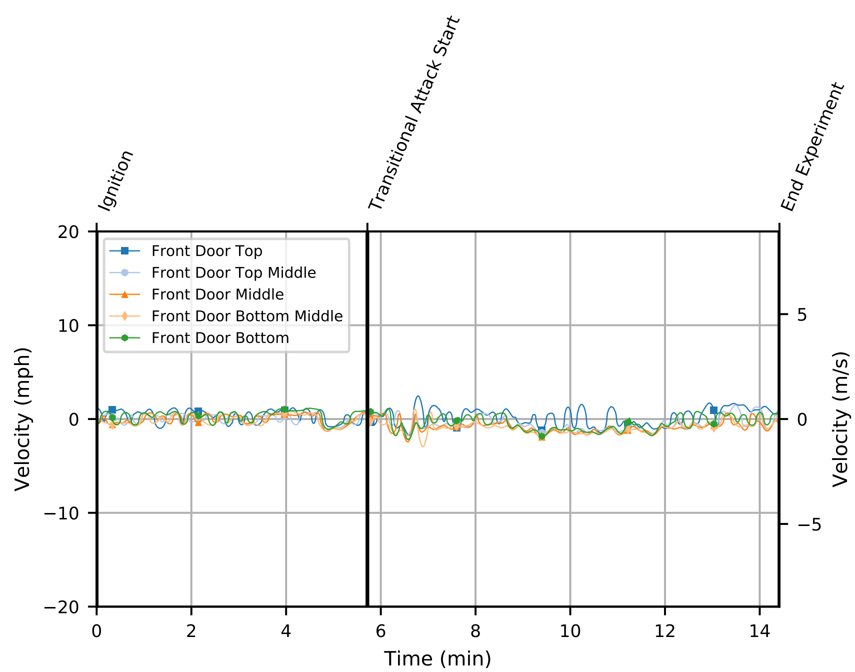


Figure E.819: Experiment 22 - Front Door Flow

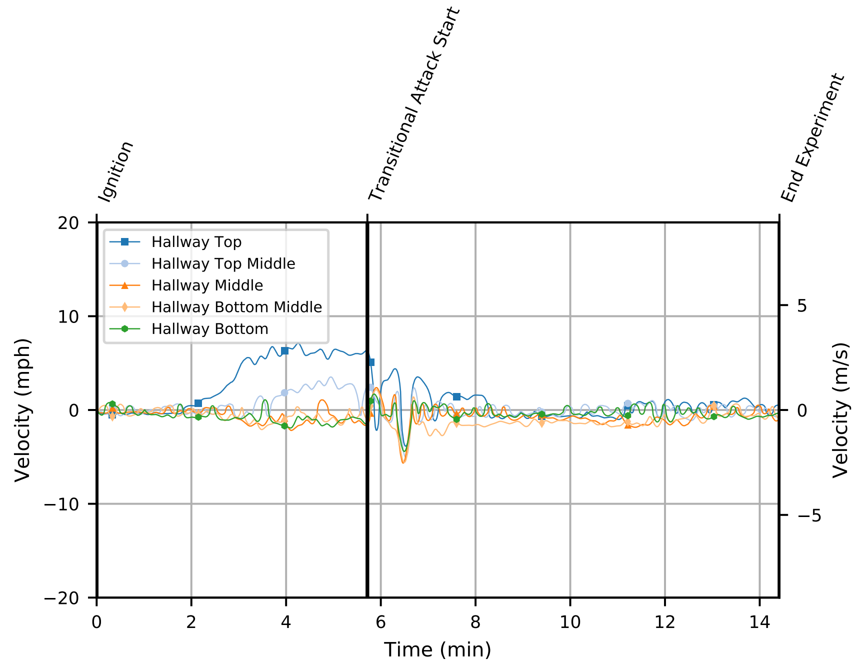


Figure E.820: Experiment 22 - Hallway Flow

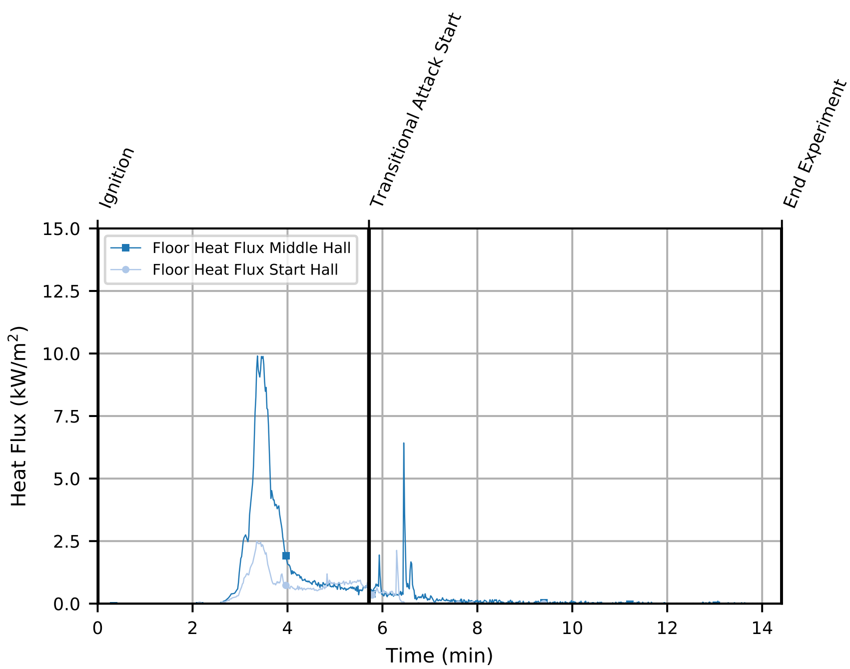


Figure E.821: Experiment 22 - Heat Flux Floor

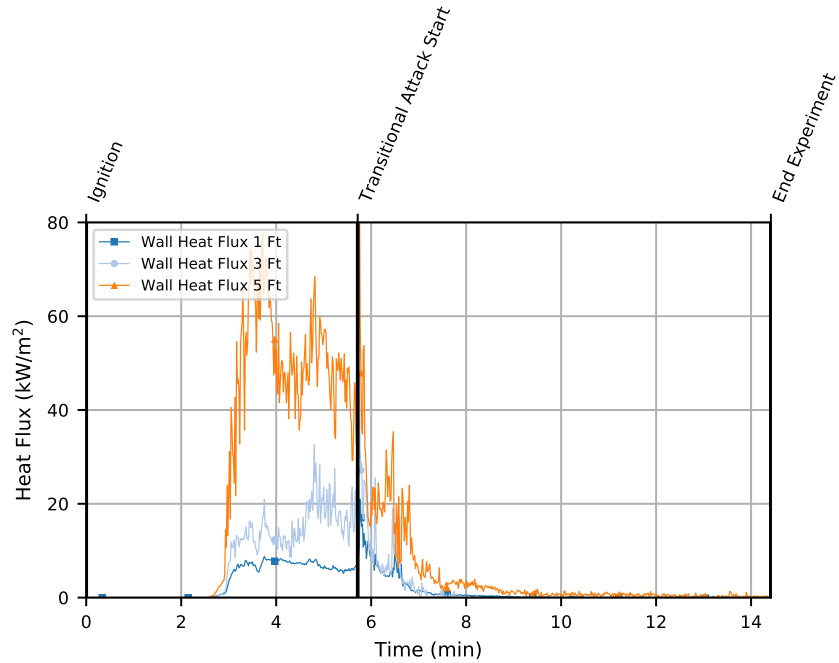


Figure E.822: Experiment 22 - Heat Flux Wall

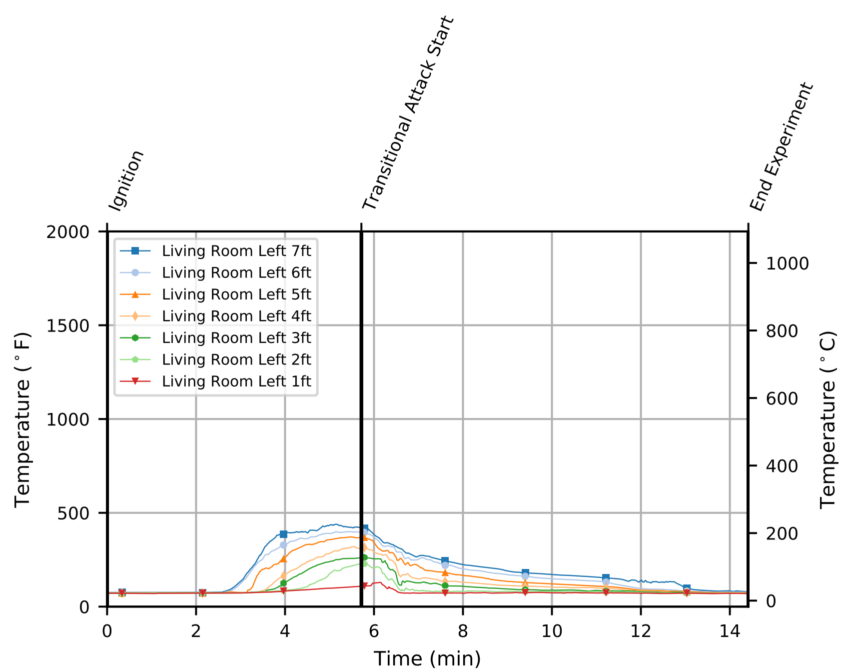


Figure E.823: Experiment 22 - Living Room Left Temps

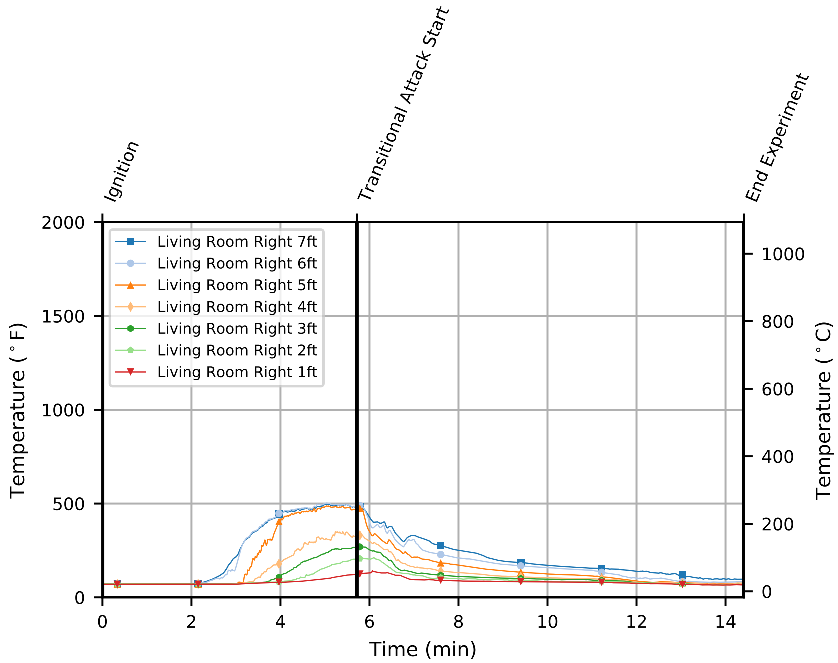


Figure E.824: Experiment 22 - Living Room Right Temps

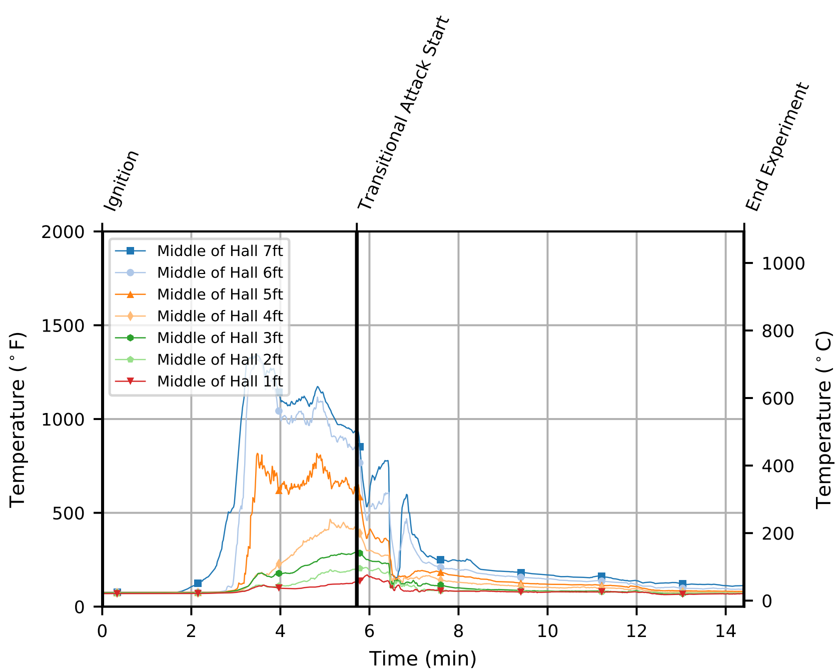


Figure E.825: Experiment 22 - Middle Hall Temps

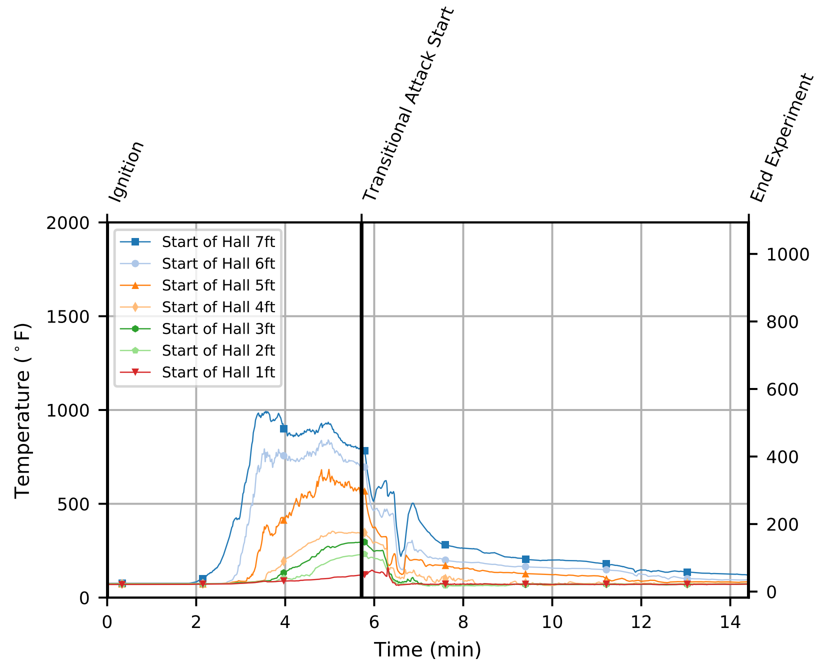


Figure E.826: Experiment 22 - Start Hall Temps

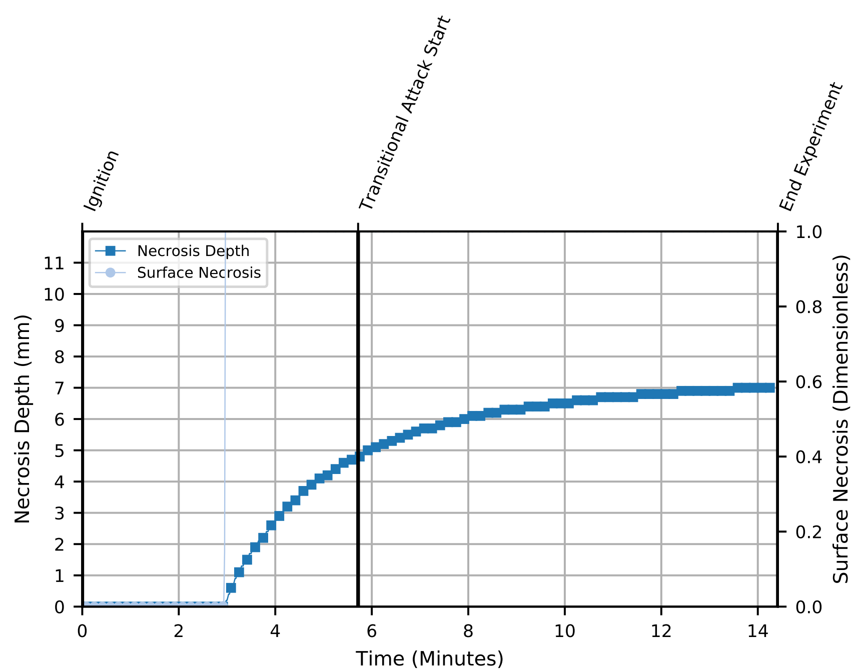


Figure E.827: Experiment 22 - Vic 1 Necrosis Depth

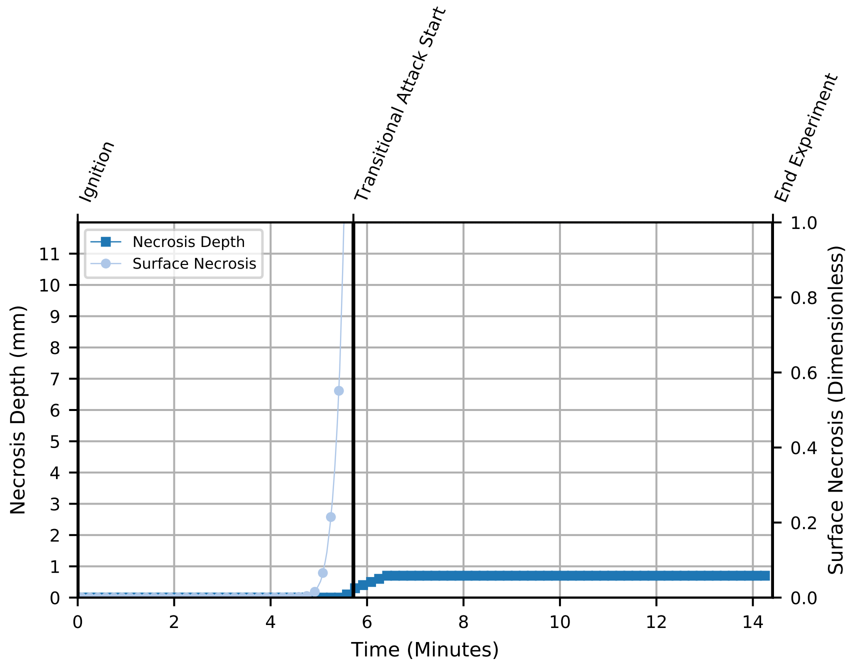


Figure E.828: Experiment 22 - Vic 3 Necrosis Depth

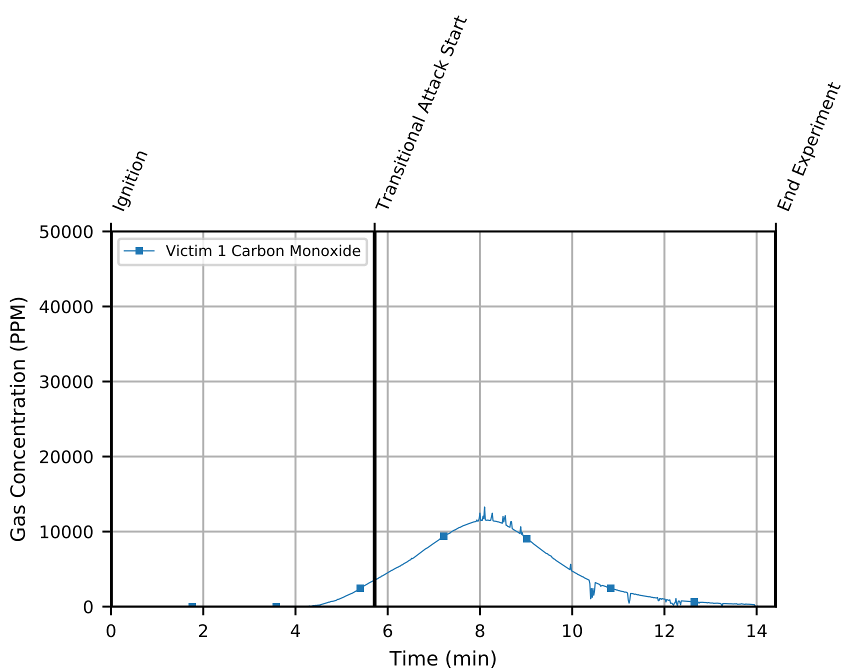


Figure E.829: Experiment 22 - Victim 1 Carbon Monoxide

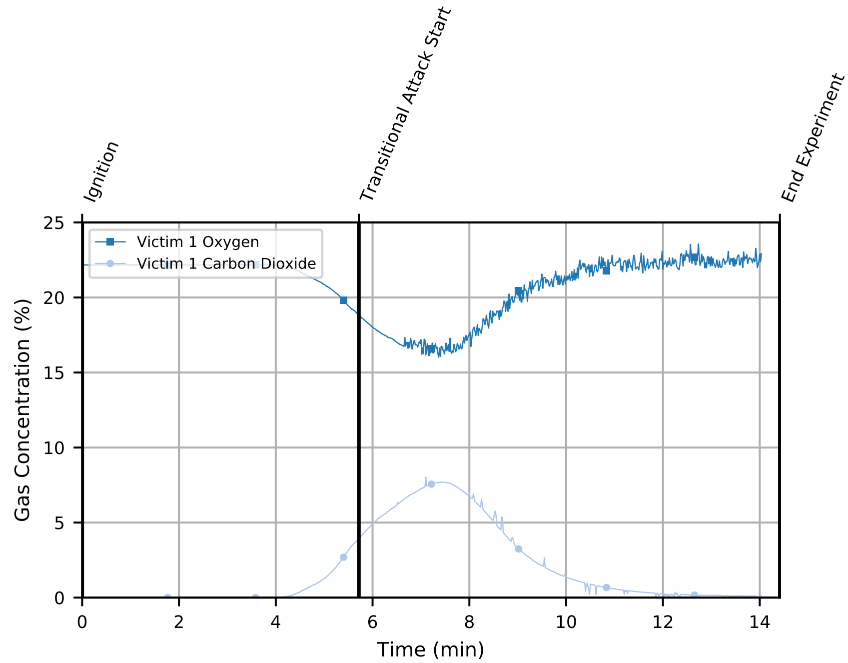


Figure E.830: Experiment 22 - Victim 1 Gas

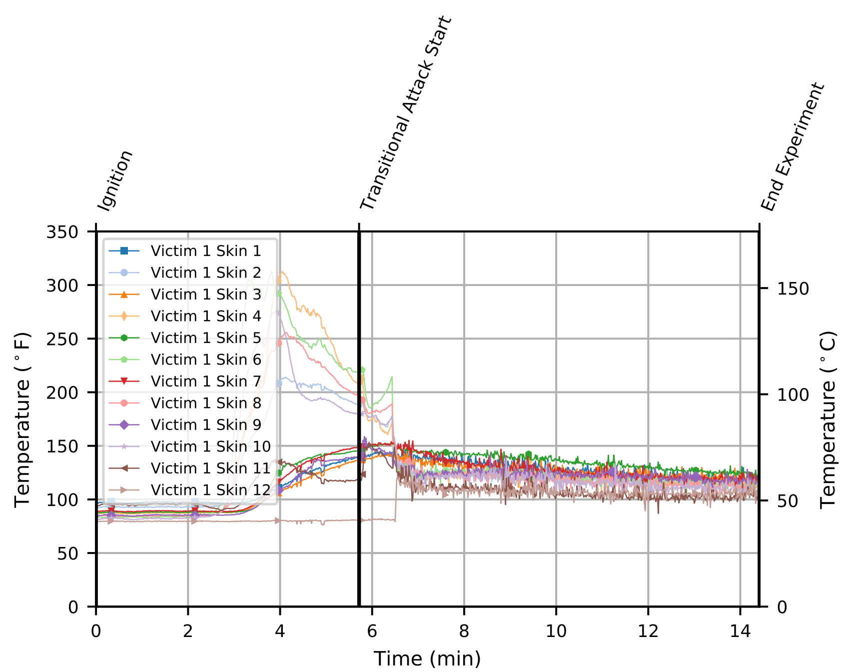


Figure E.831: Experiment 22 - Victim 1 Skin Temps

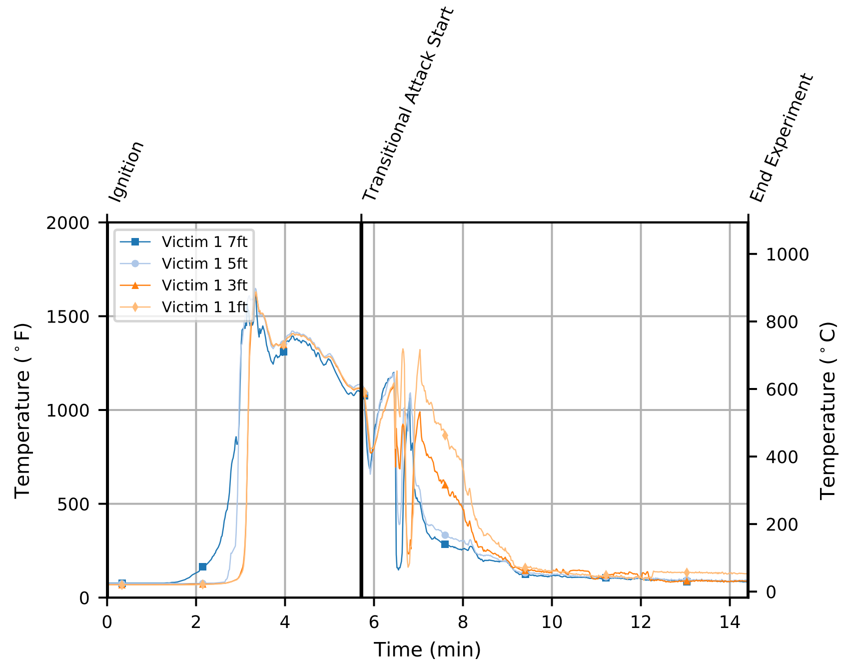


Figure E.832: Experiment 22 - Victim 1 Temps

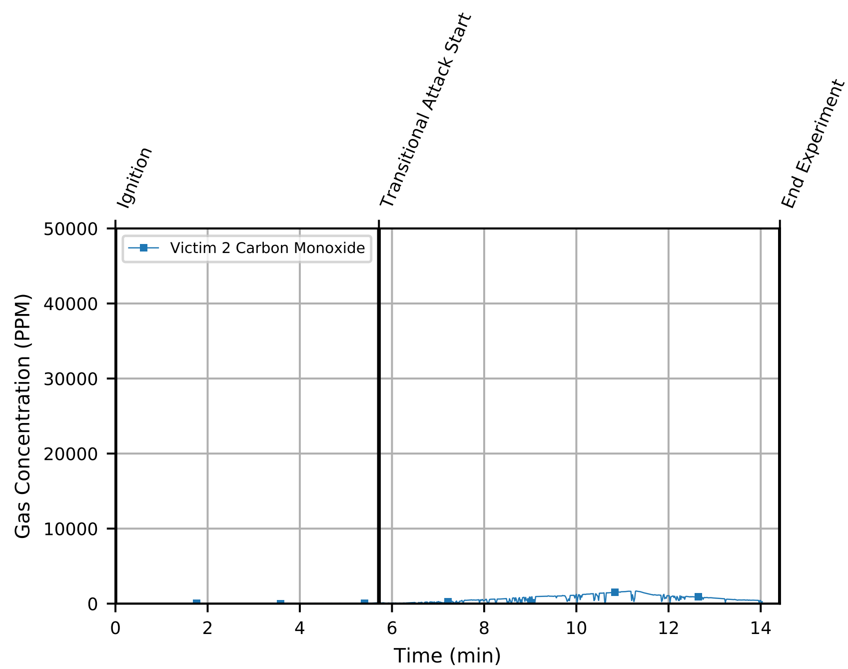


Figure E.833: Experiment 22 - Victim 2 Carbon Monoxide

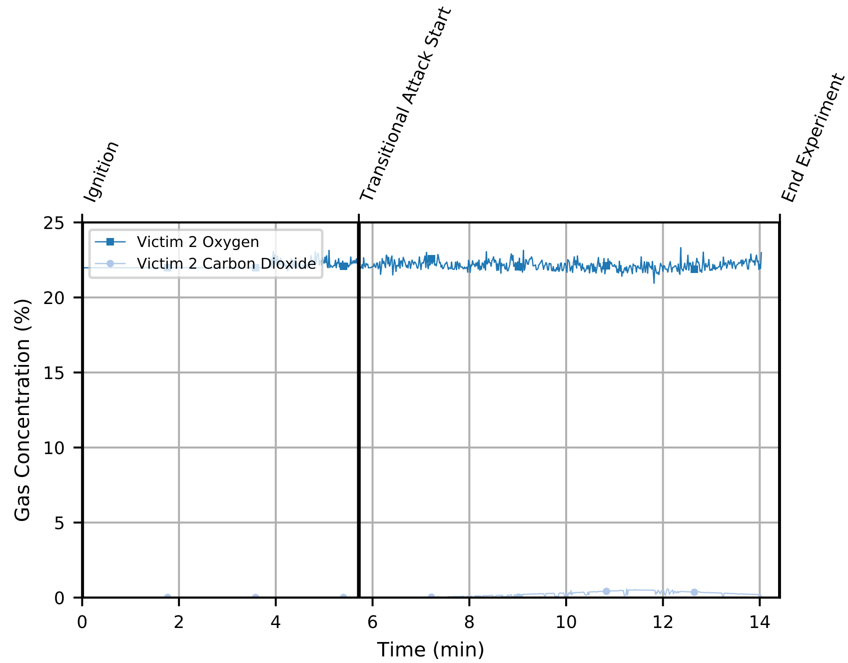


Figure E.834: Experiment 22 - Victim 2 Gas

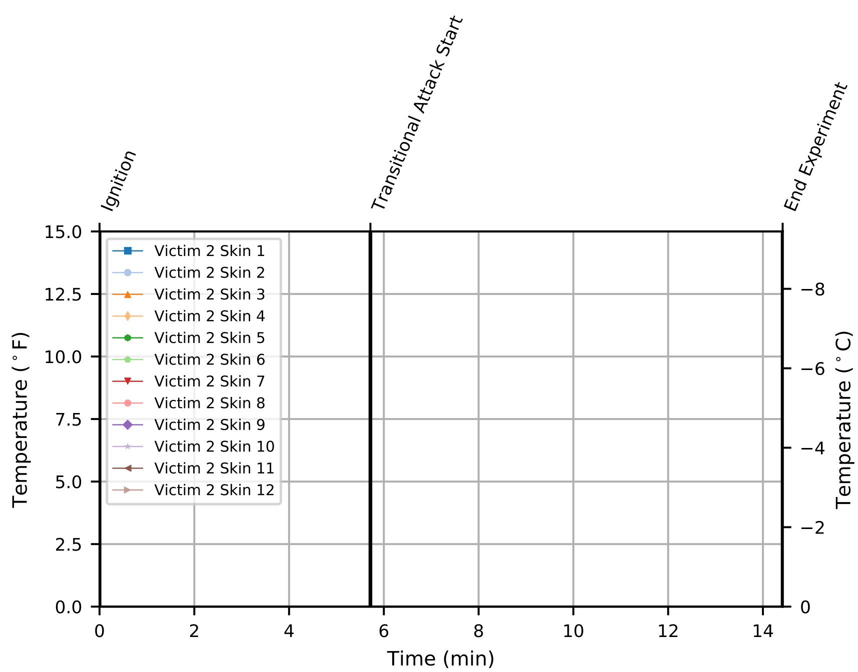


Figure E.835: Experiment 22 - Victim 2 Skin Temps

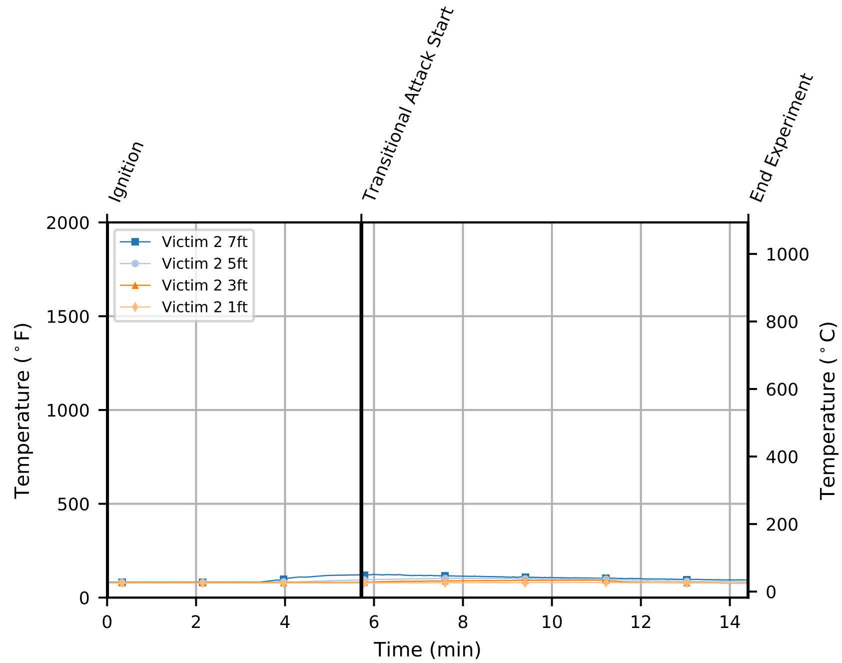


Figure E.836: Experiment 22 - Victim 2 Temps

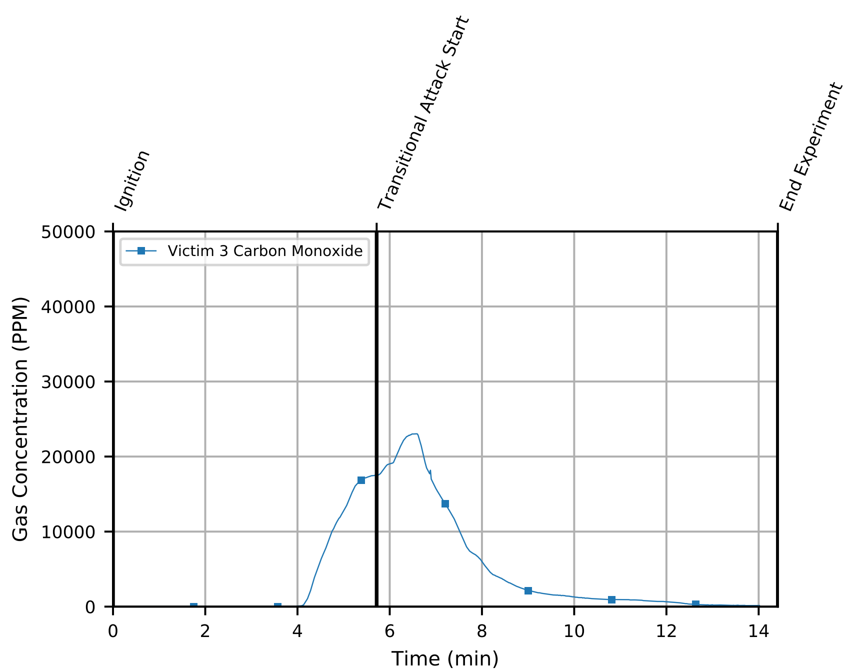


Figure E.837: Experiment 22 - Victim 3 Carbon Monoxide

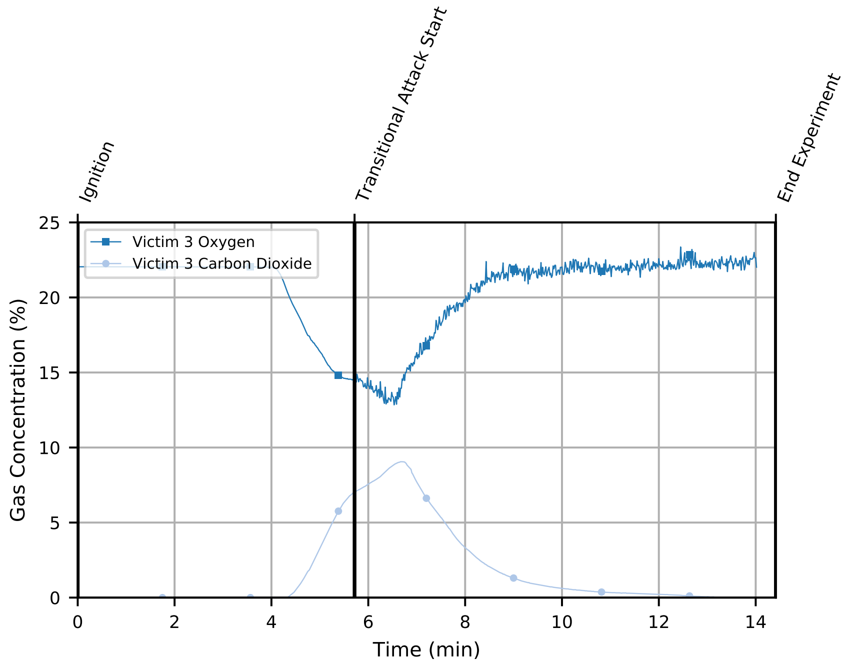


Figure E.838: Experiment 22 - Victim 3 Gas

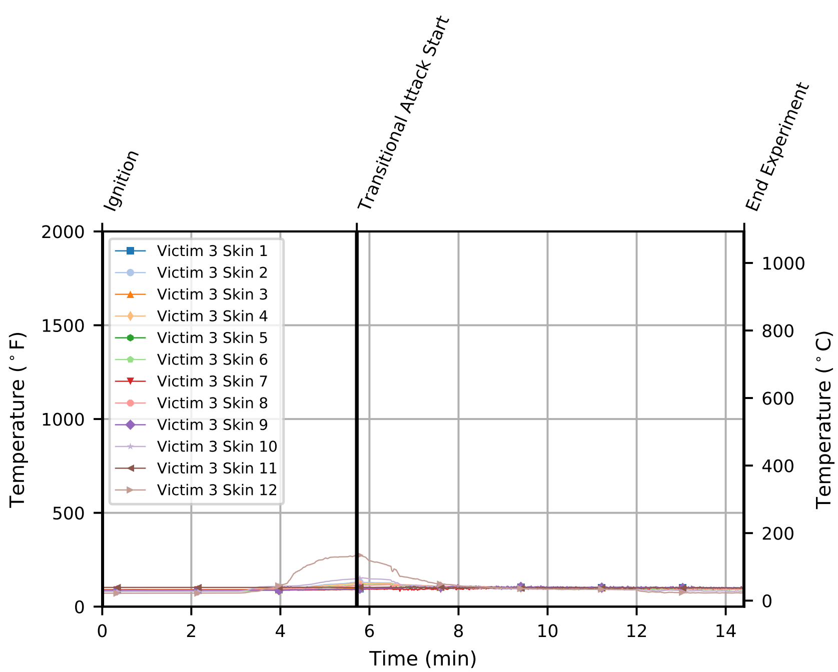


Figure E.839: Experiment 22 - Victim 3 Skin Temps

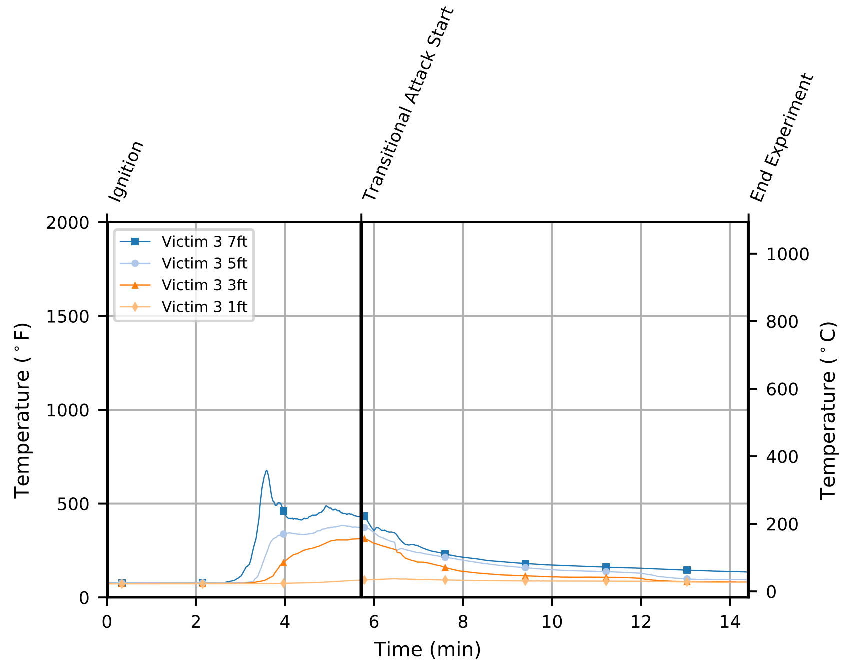


Figure E.840: Experiment 22 - Victim 3 Temps

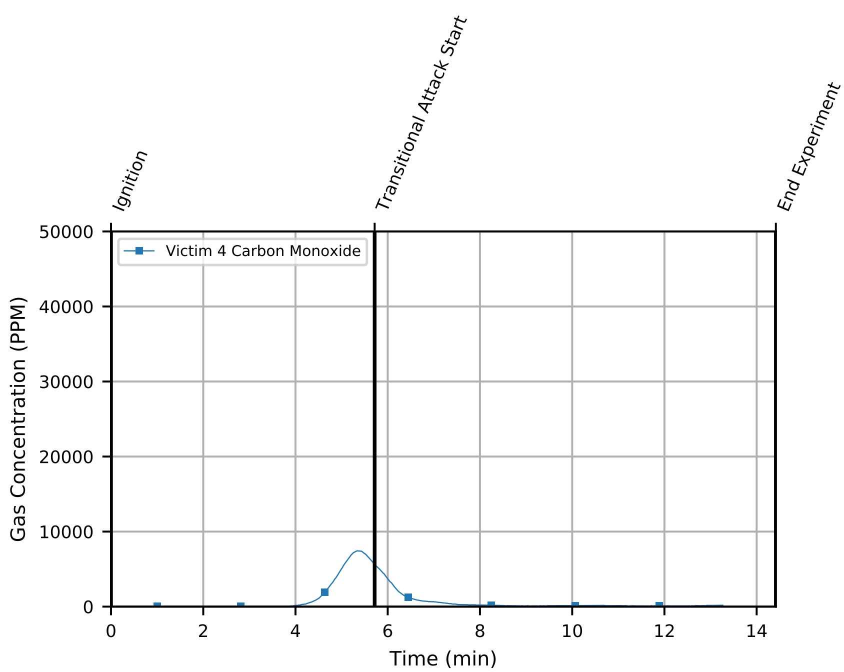


Figure E.841: Experiment 22 - Victim 4 Carbon Monoxide

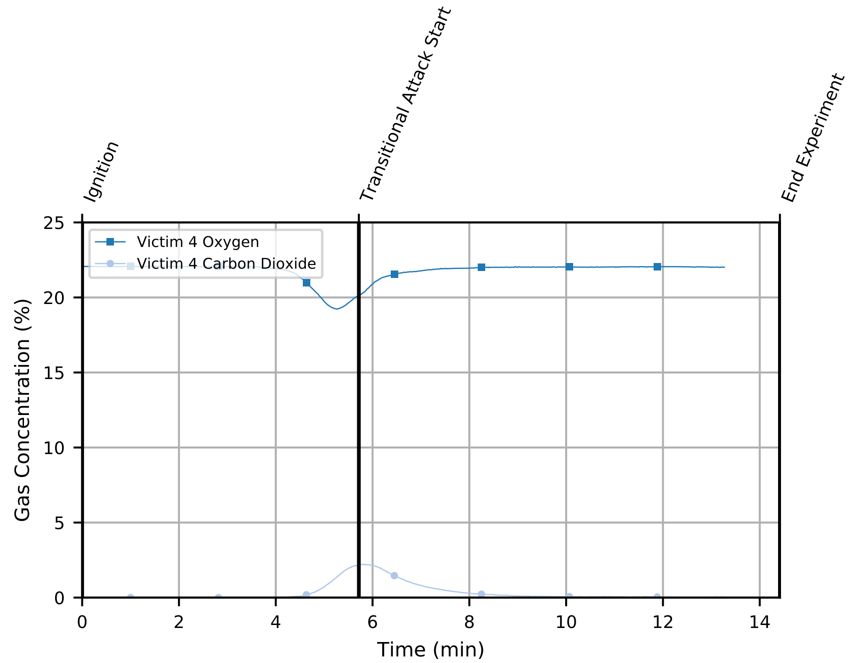


Figure E.842: Experiment 22 - Victim 4 Gas

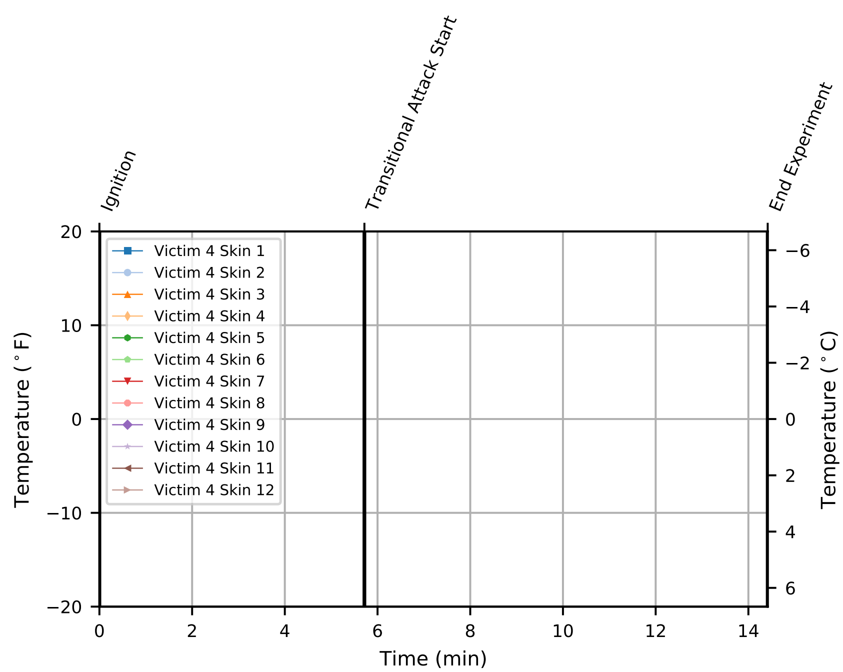


Figure E.843: Experiment 22 - Victim 4 Skin Temps

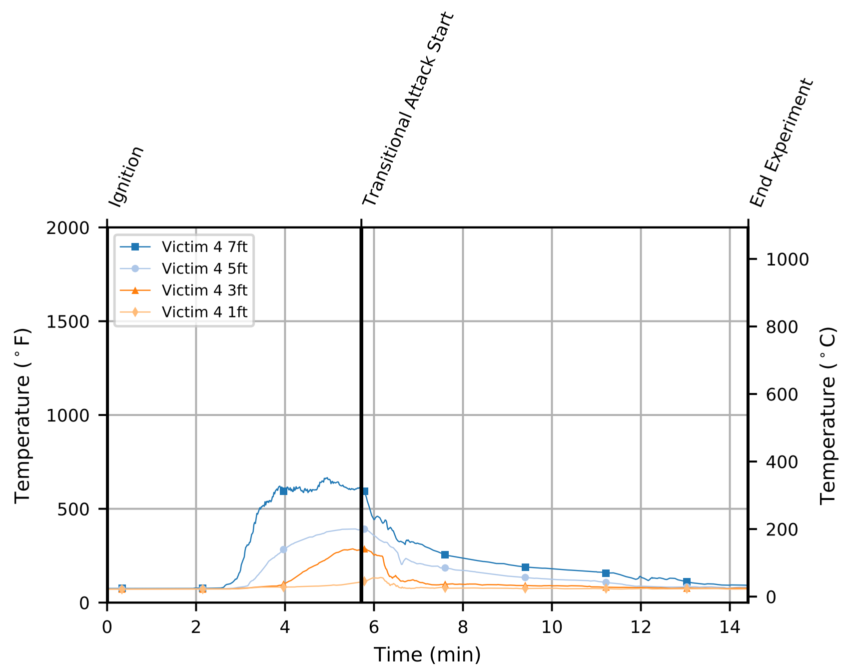


Figure E.844: Experiment 22 - Victim 4 Temps

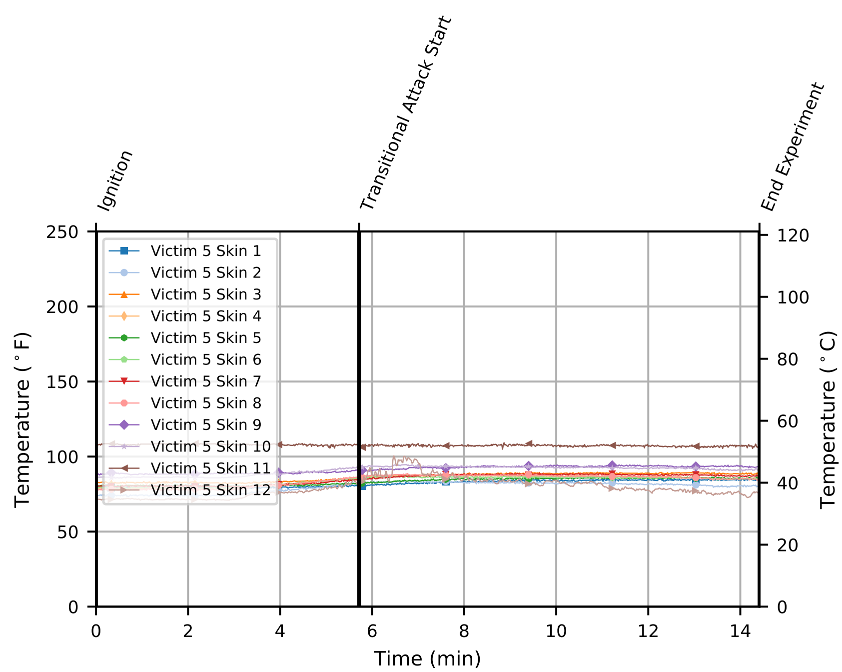


Figure E.845: Experiment 22 - Victim 5 Skin Temps

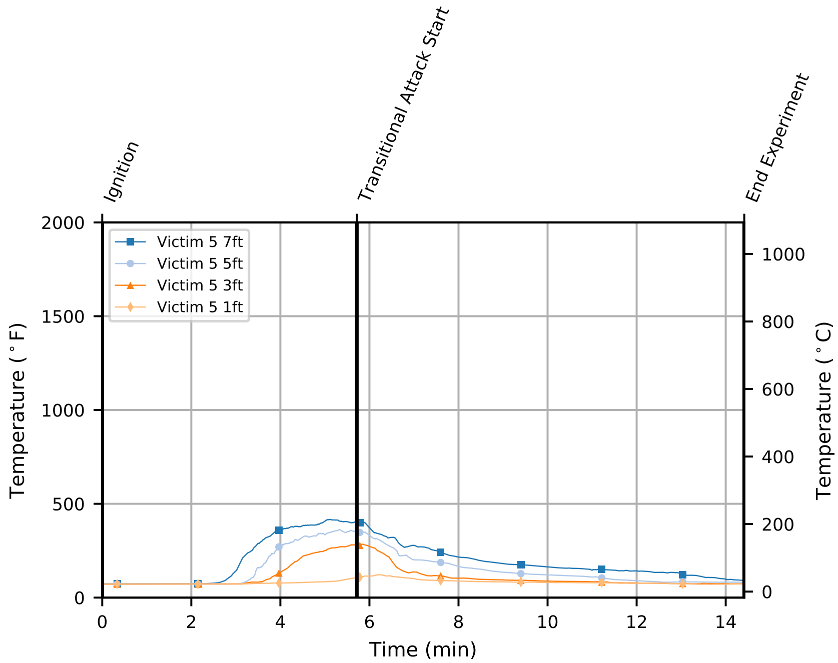


Figure E.846: Experiment 22 - Victim 5 Temps

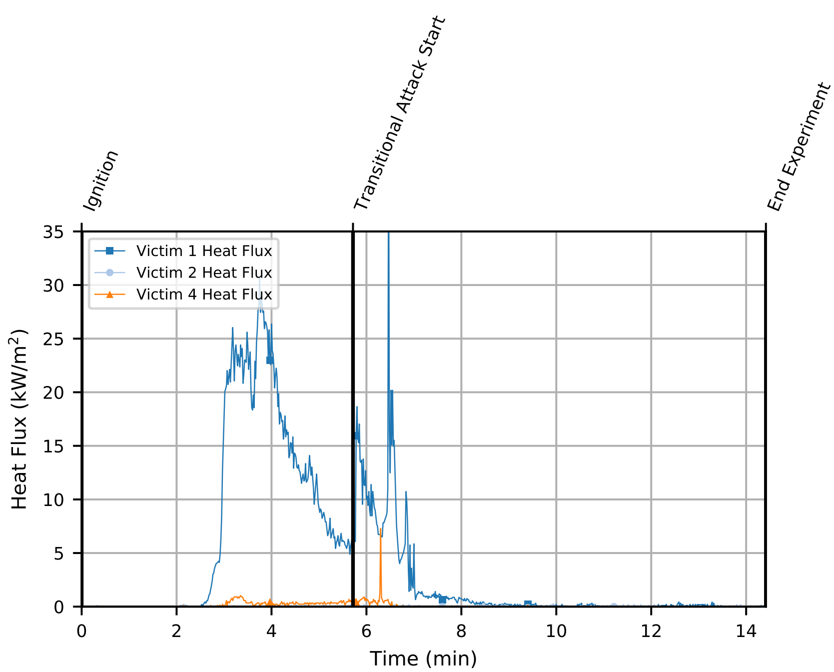


Figure E.847: Experiment 22 - Victim Heat Flux

E.23 Experiment 23 Data

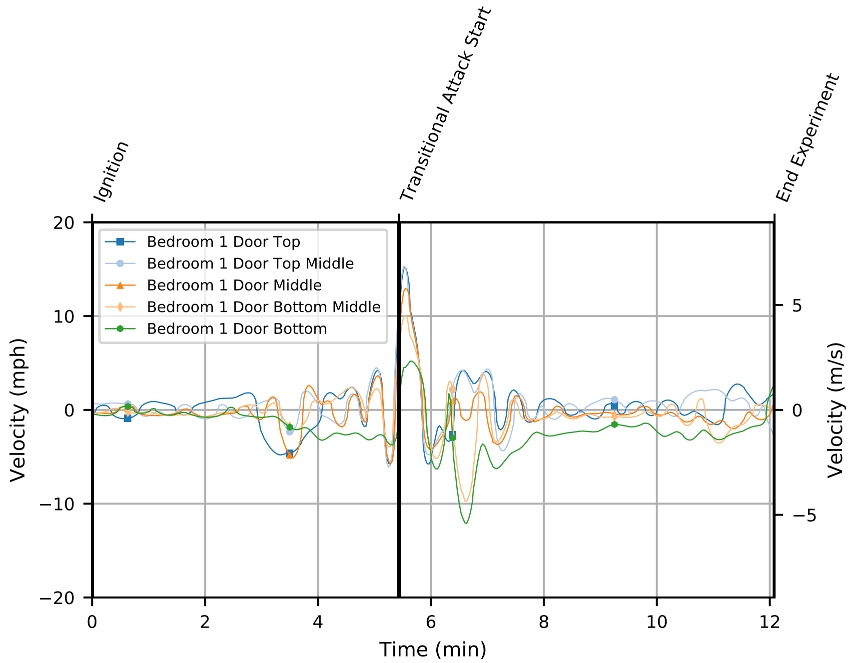


Figure E.848: Experiment 23 - Bedroom 1 Door

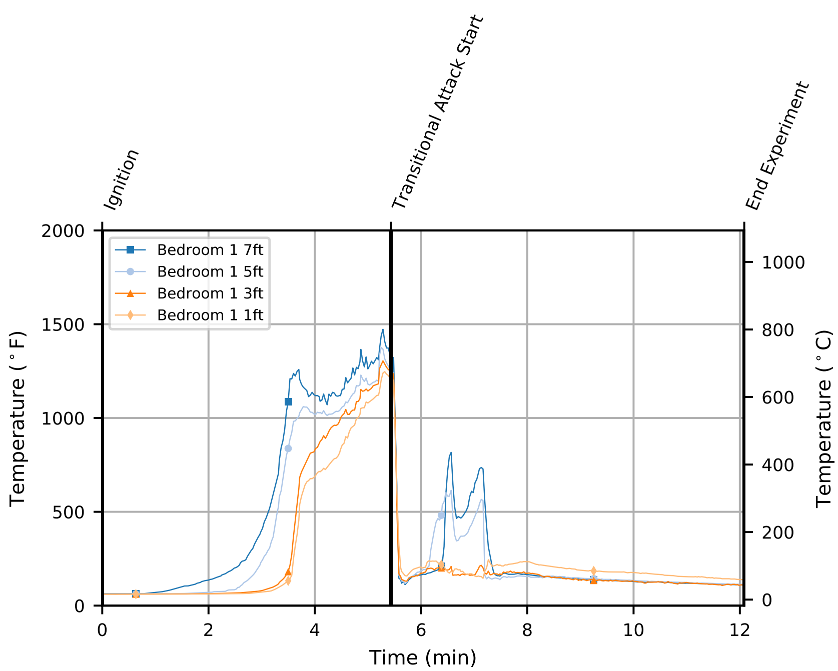


Figure E.849: Experiment 23 - Bedroom 1 Temps

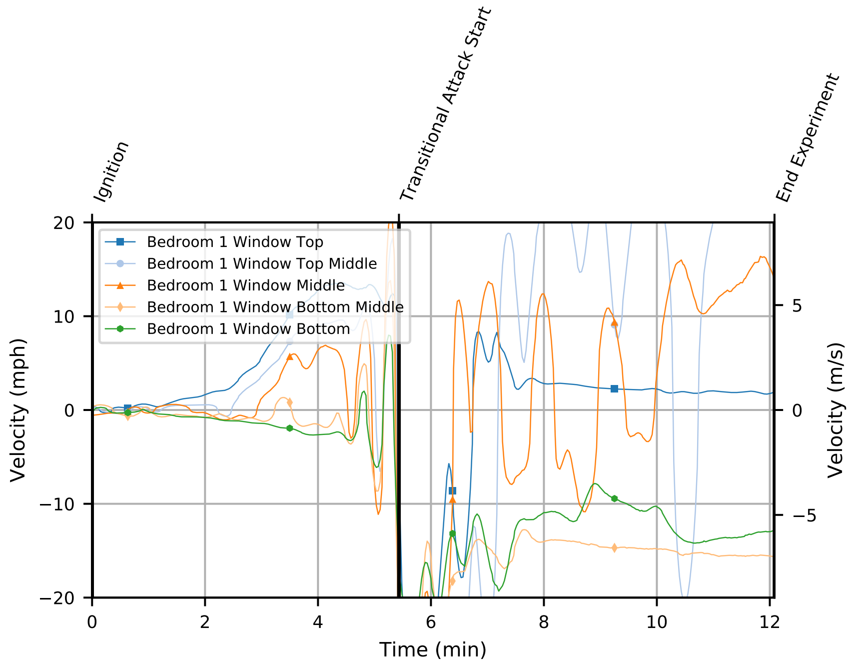


Figure E.850: Experiment 23 - Bedroom 1 Window

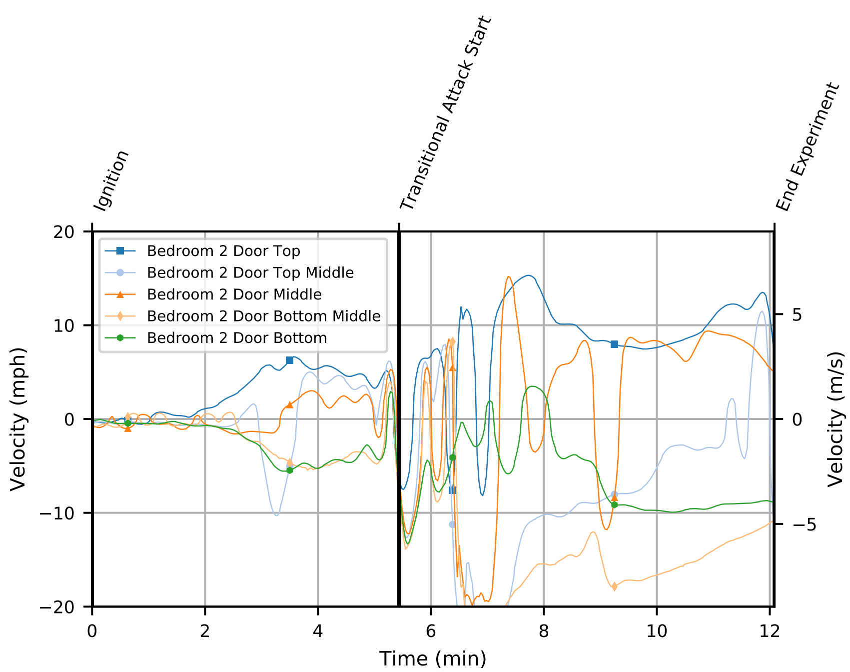


Figure E.851: Experiment 23 - Bedroom 2 Door

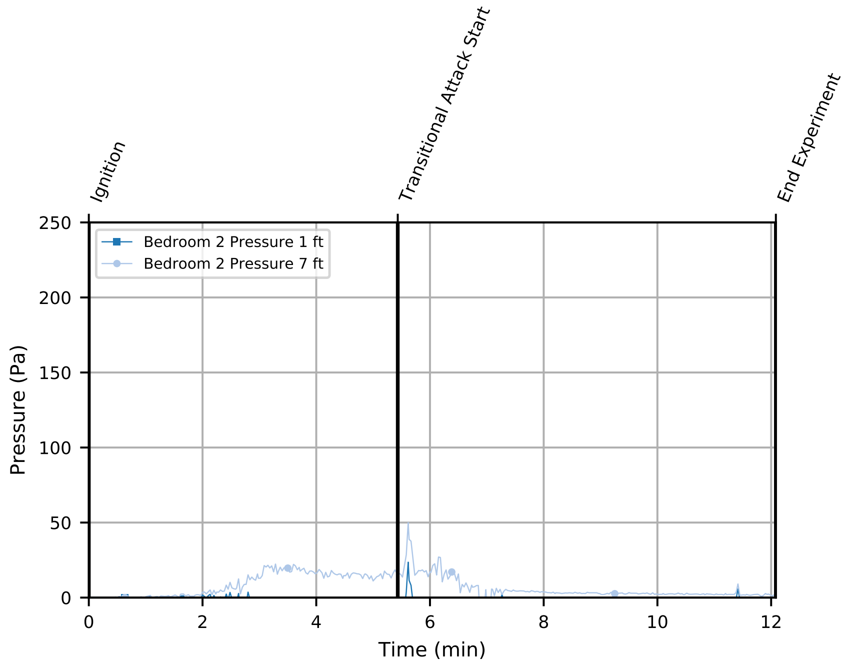


Figure E.852: Experiment 23 - Bedroom 2 Pressure

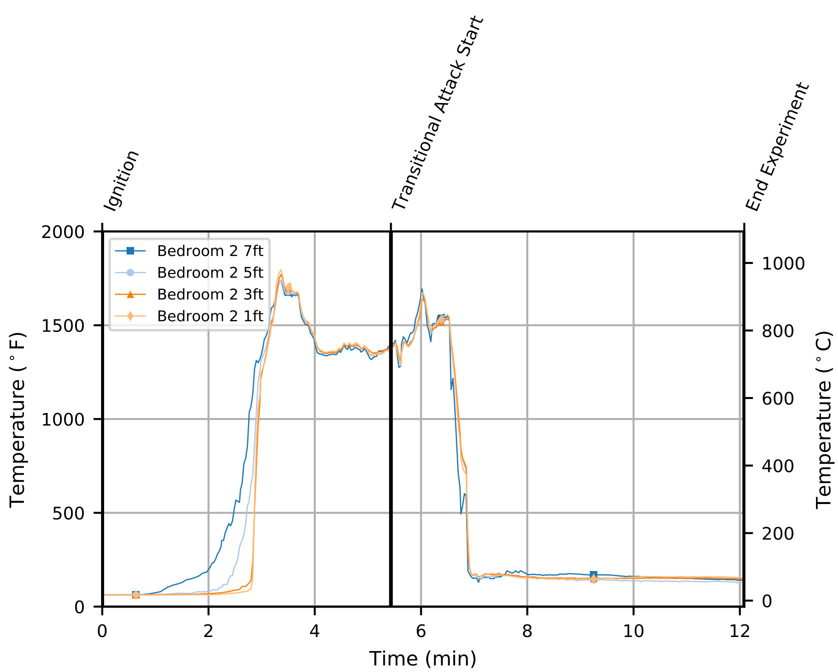


Figure E.853: Experiment 23 - Bedroom 2 Temps

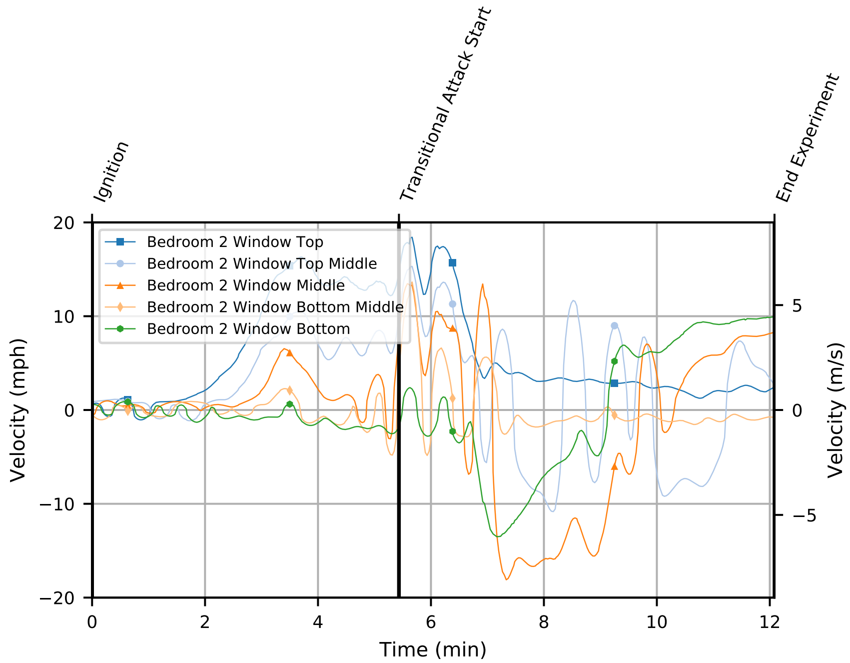


Figure E.854: Experiment 23 - Bedroom 2 Window

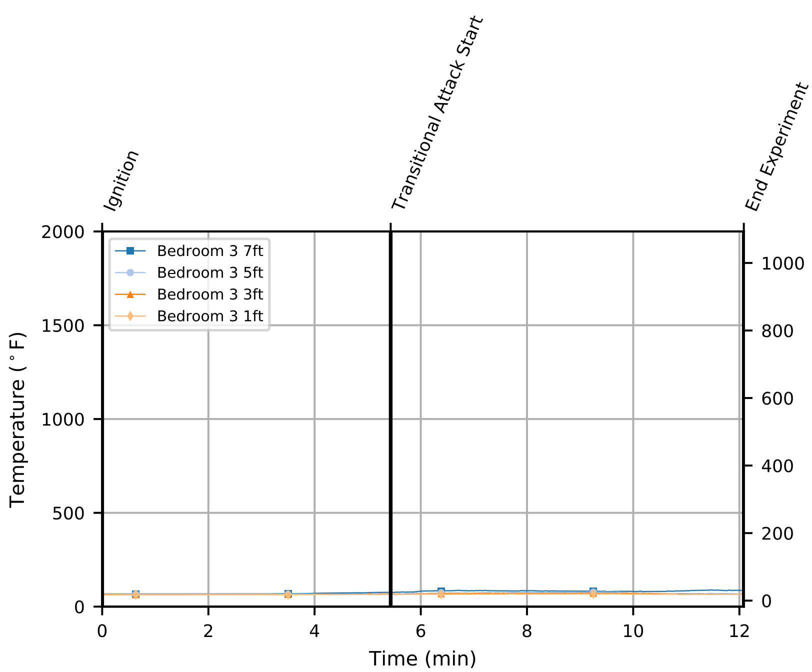


Figure E.855: Experiment 23 - Bedroom 3 Temps

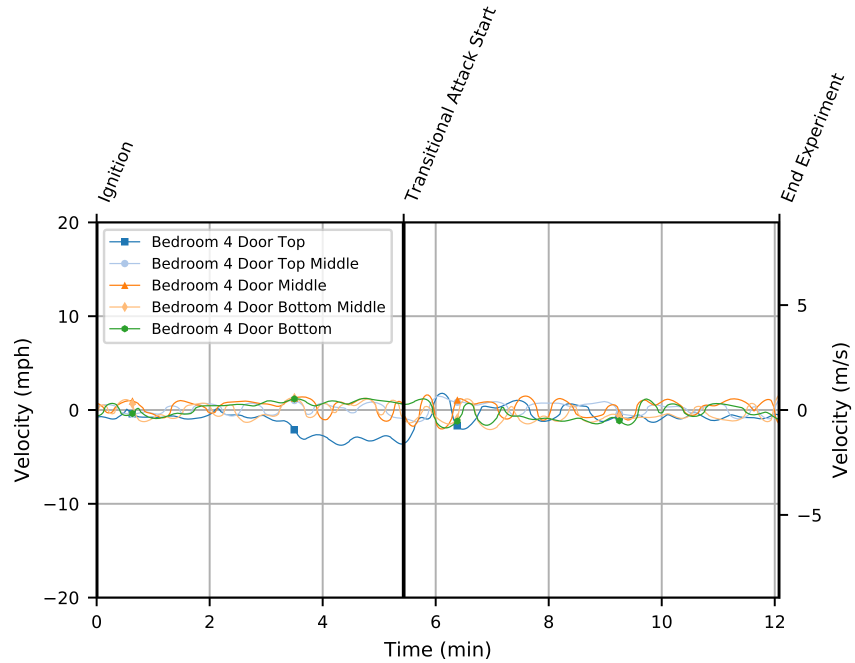


Figure E.856: Experiment 23 - Bedroom 4 Door

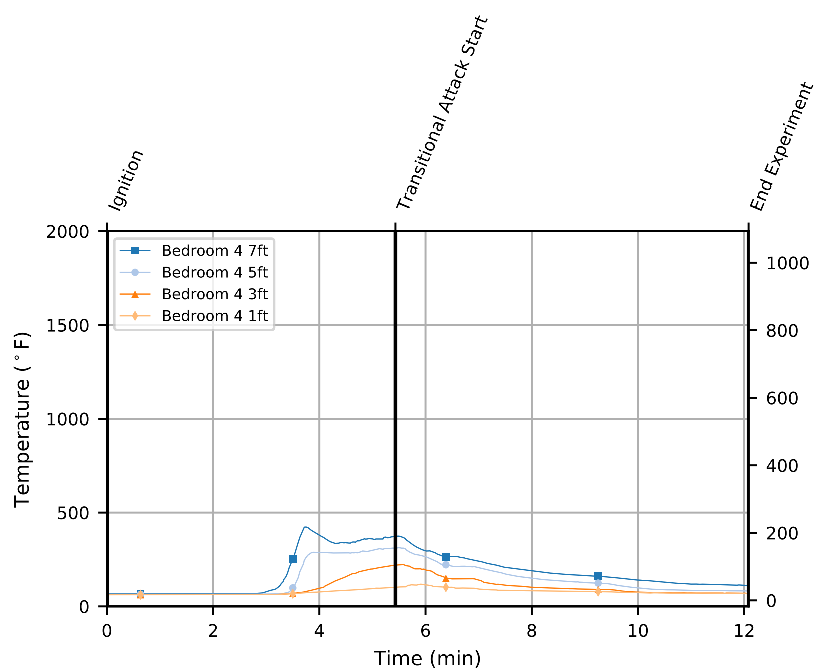


Figure E.857: Experiment 23 - Bedroom 4 Temps

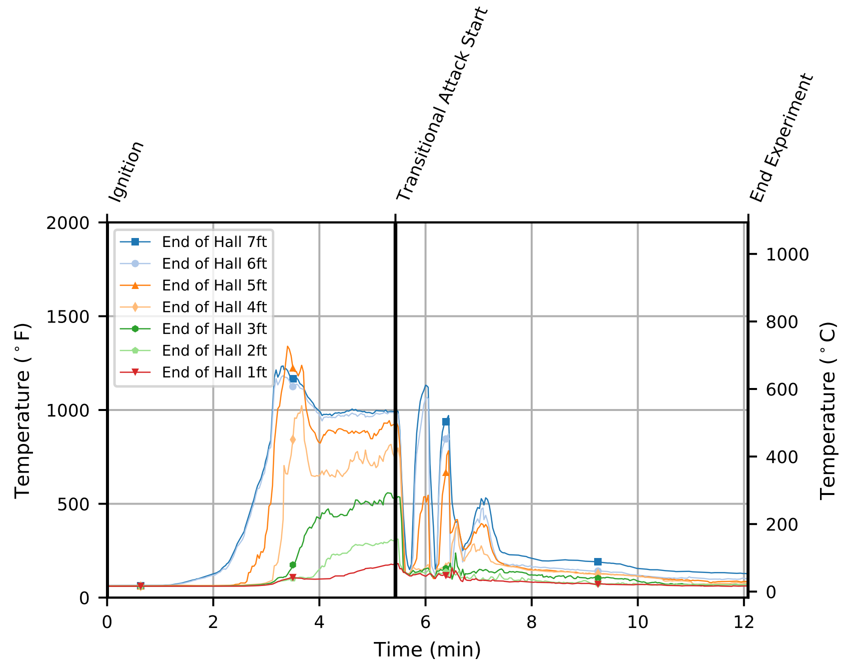


Figure E.858: Experiment 23 - End Hall Temps

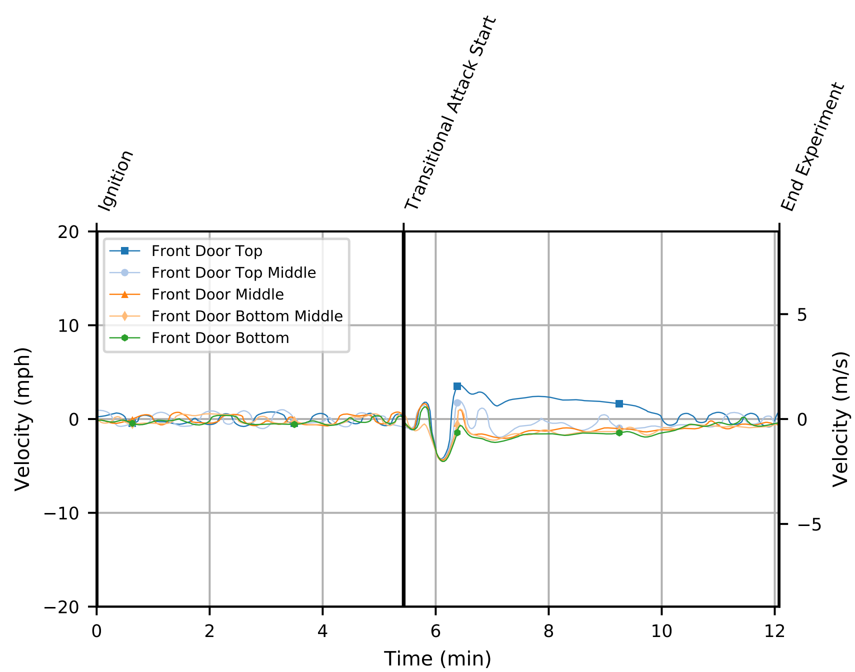


Figure E.859: Experiment 23 - Front Door Flow

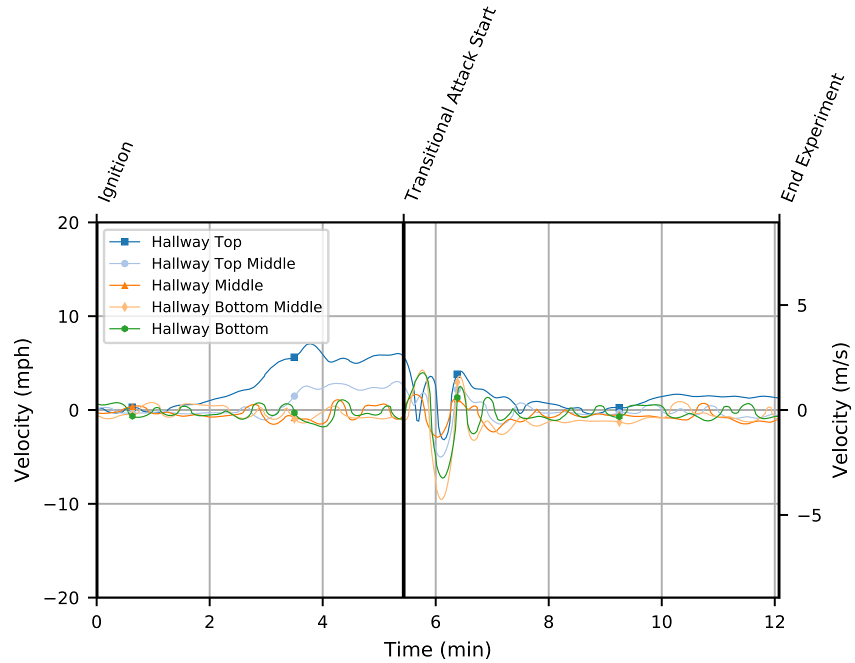


Figure E.860: Experiment 23 - Hallway Flow

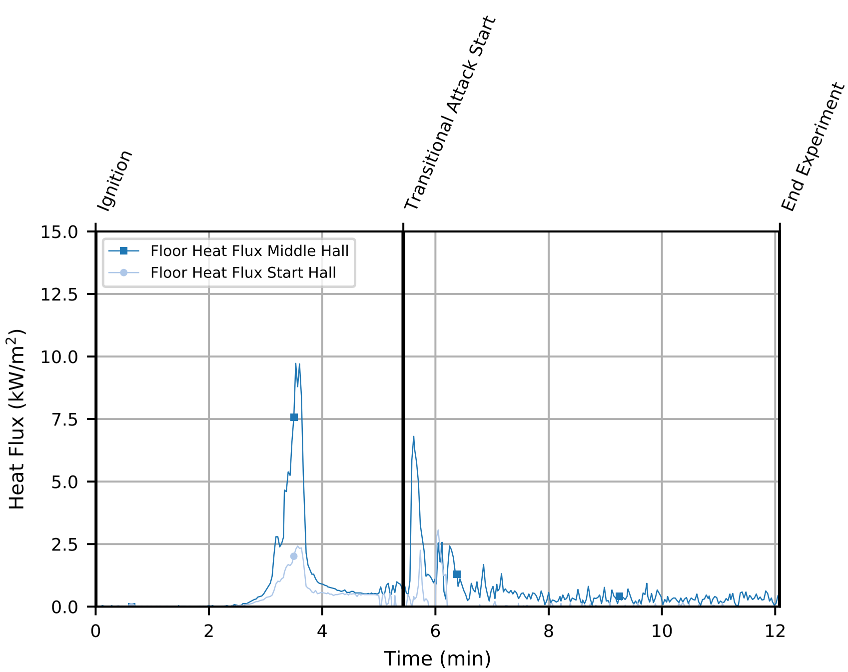


Figure E.861: Experiment 23 - Heat Flux Floor

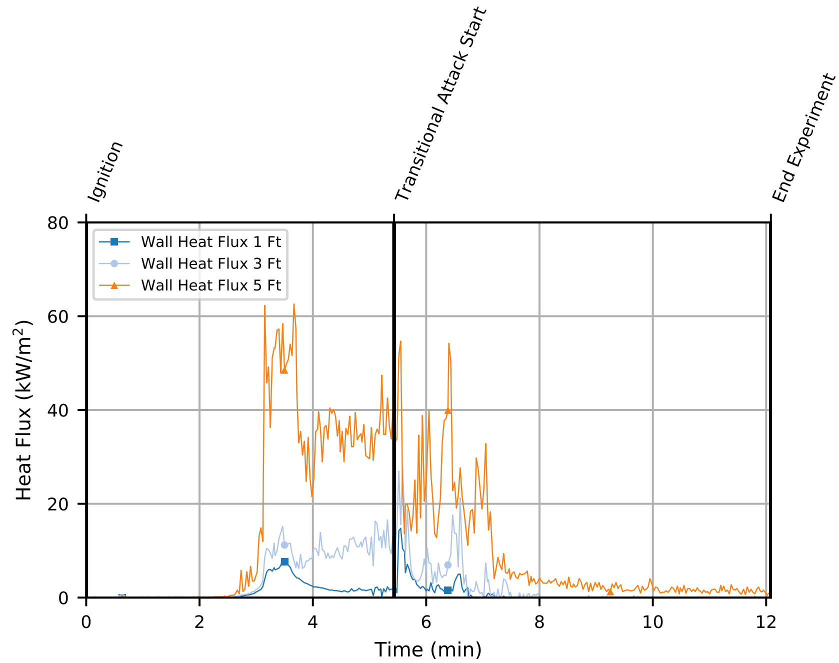


Figure E.862: Experiment 23 - Heat Flux Wall

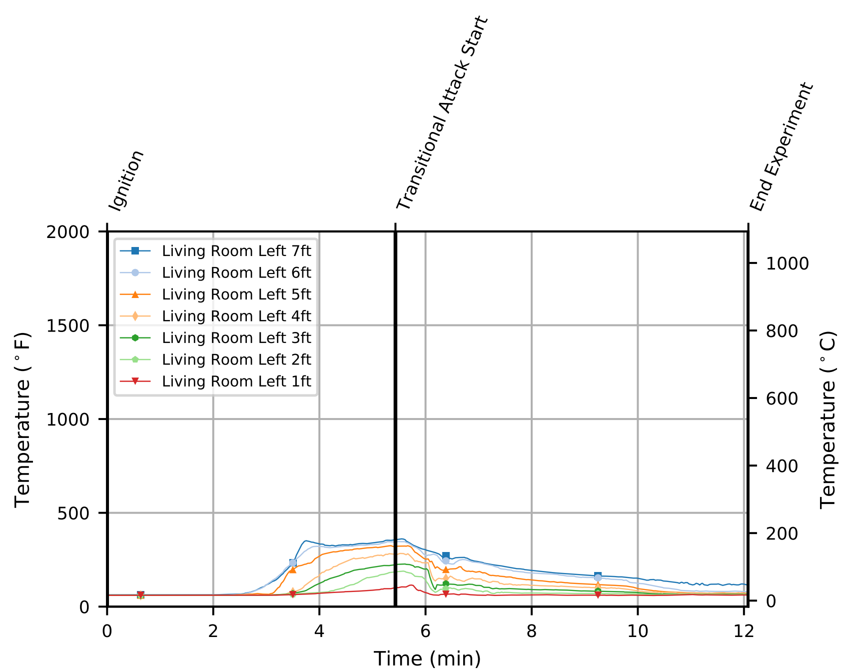


Figure E.863: Experiment 23 - Living Room Left Temps

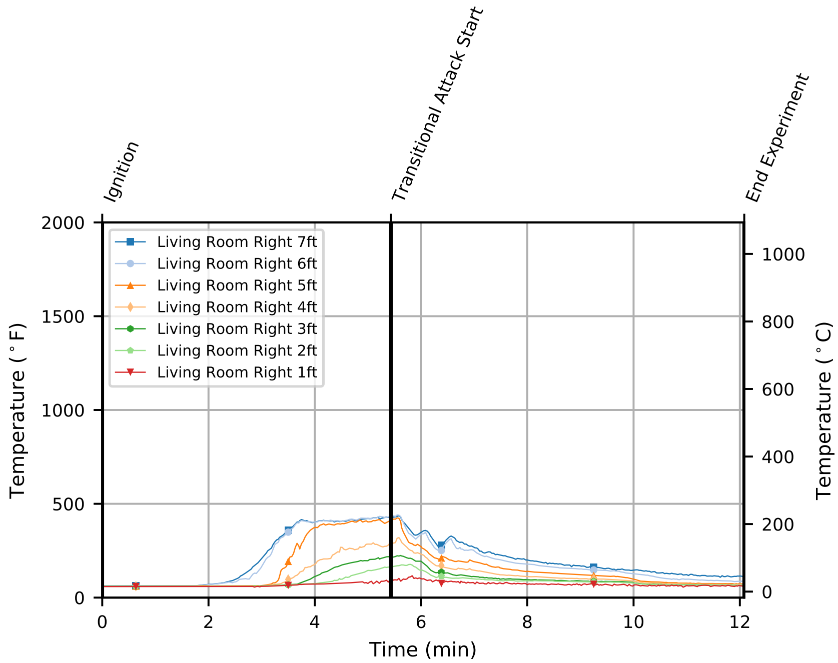


Figure E.864: Experiment 23 - Living Room Right Temps

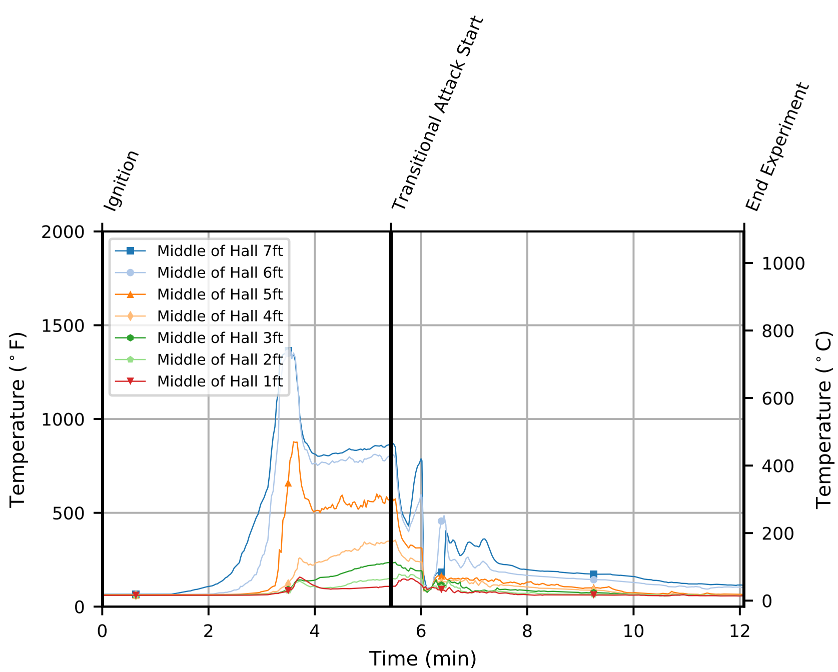


Figure E.865: Experiment 23 - Middle Hall Temps

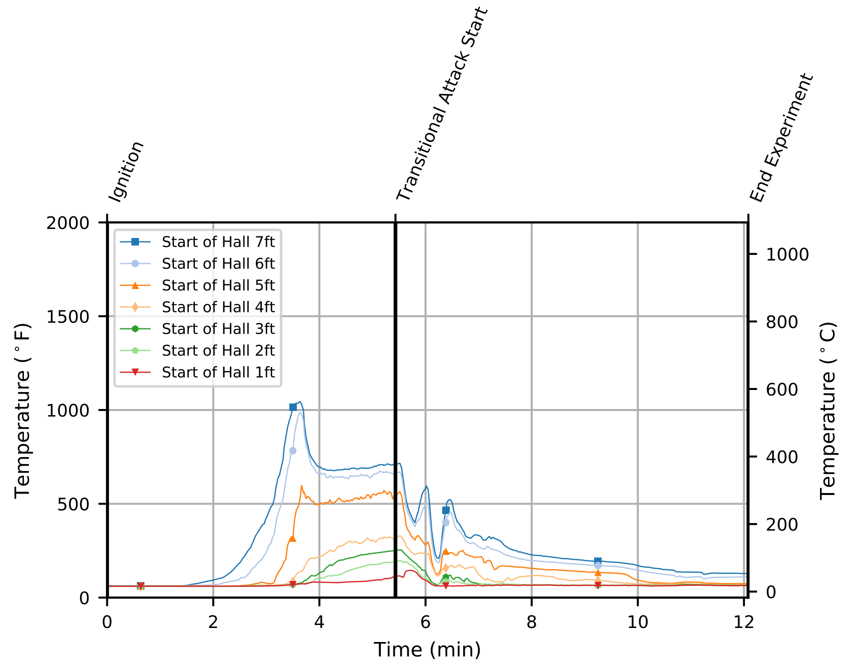


Figure E.866: Experiment 23 - Start Hall Temps

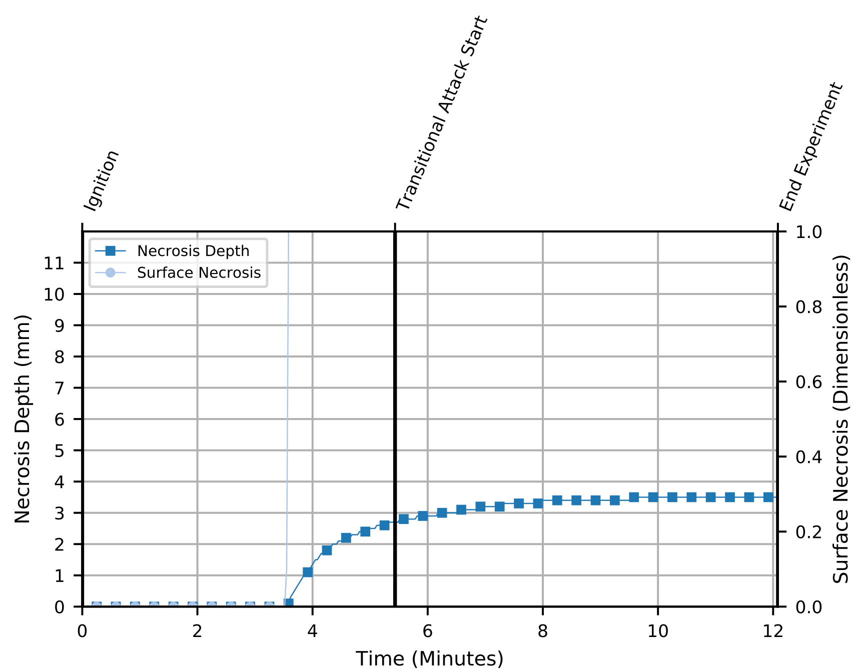


Figure E.867: Experiment 23 - Vic 1 Necrosis Depth

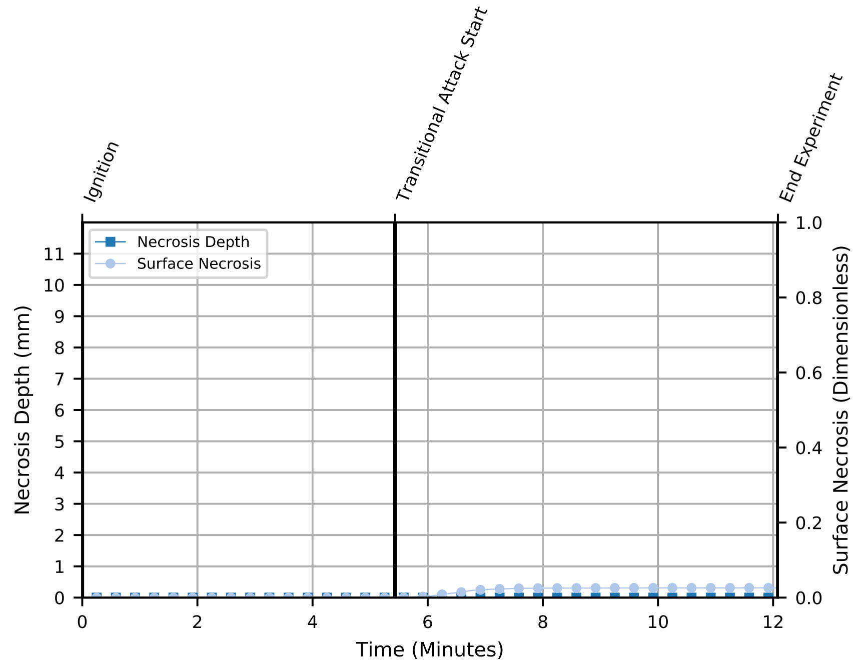


Figure E.868: Experiment 23 - Vic 3 Necrosis Depth

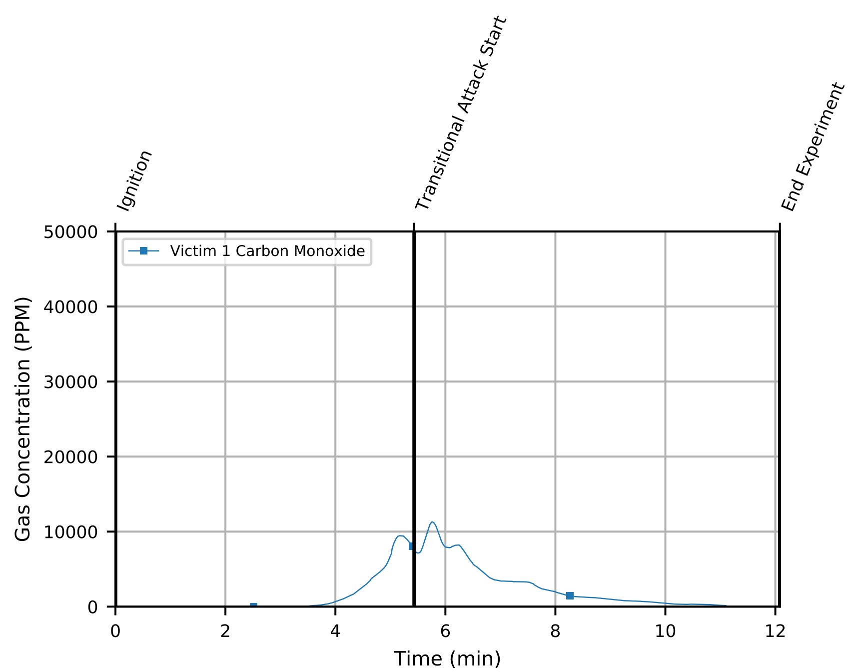


Figure E.869: Experiment 23 - Victim 1 Carbon Monoxide

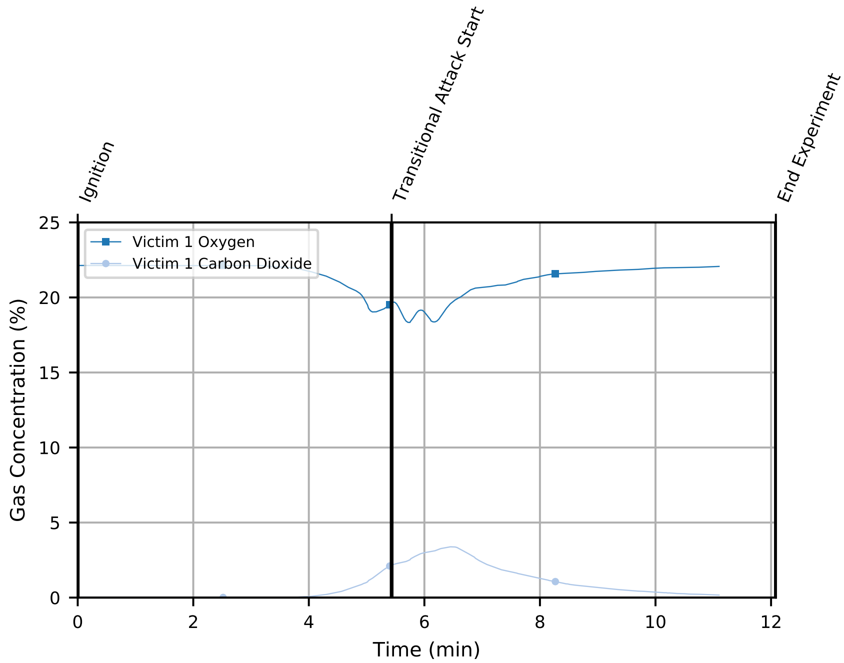


Figure E.870: Experiment 23 - Victim 1 Gas

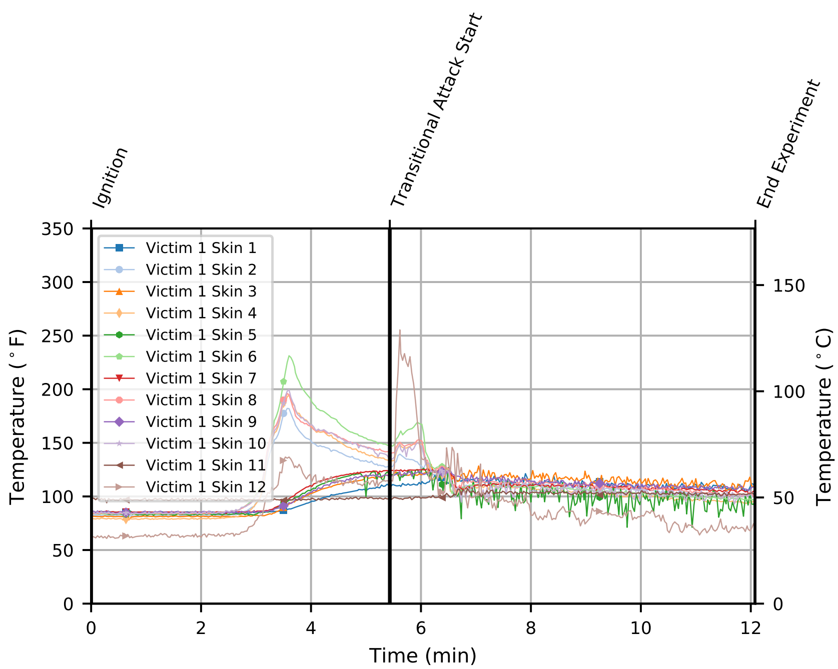


Figure E.871: Experiment 23 - Victim 1 Skin Temps

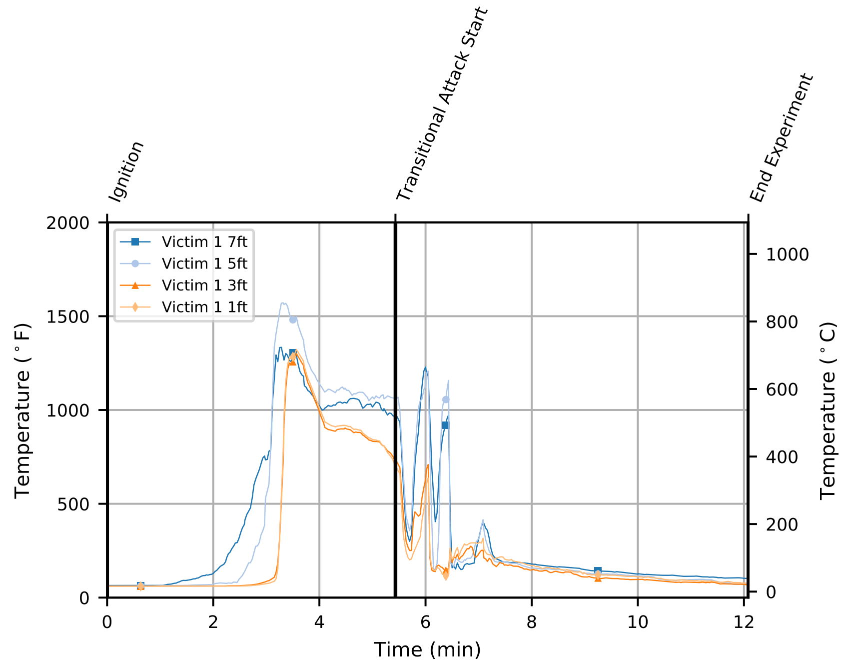


Figure E.872: Experiment 23 - Victim 1 Temps

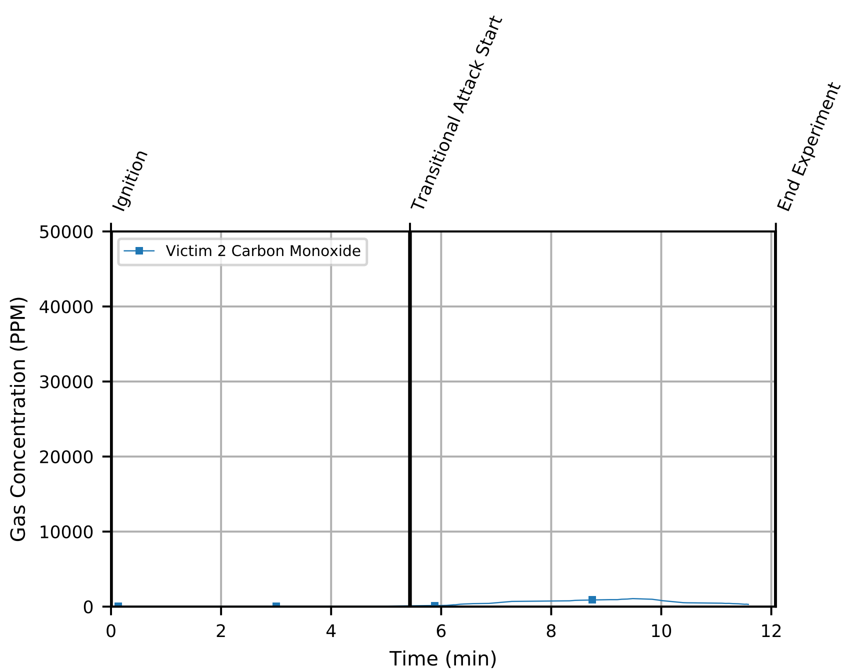


Figure E.873: Experiment 23 - Victim 2 Carbon Monoxide

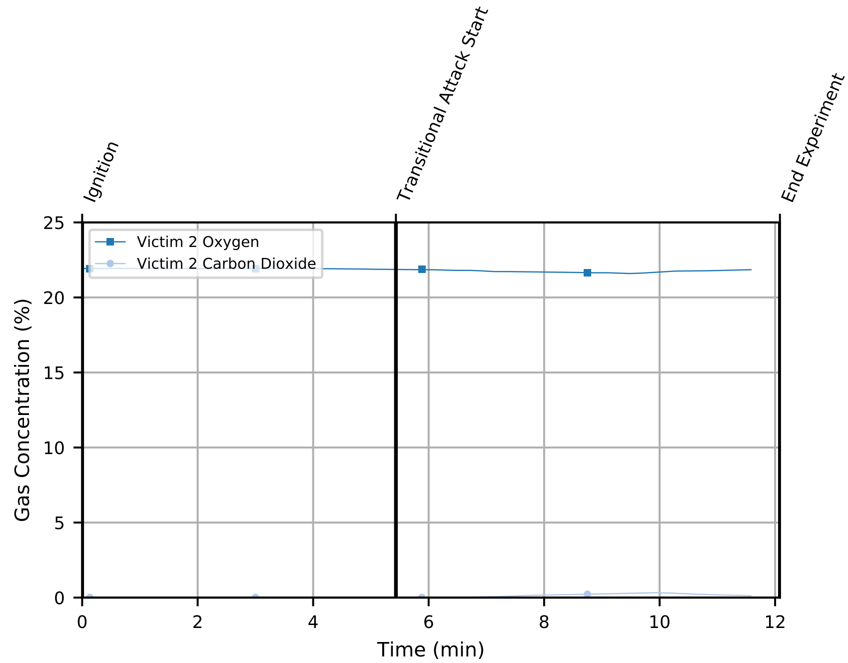


Figure E.874: Experiment 23 - Victim 2 Gas

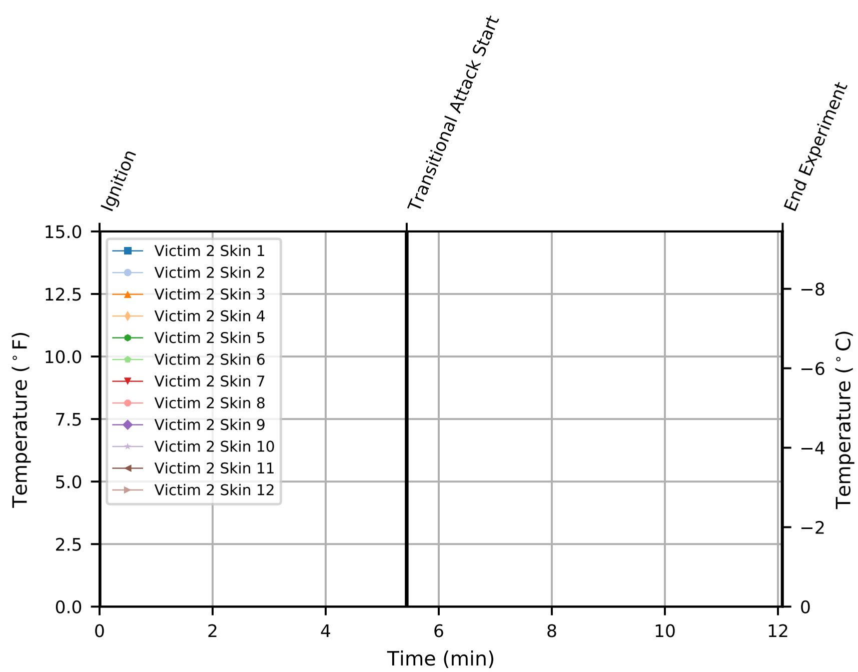


Figure E.875: Experiment 23 - Victim 2 Skin Temps

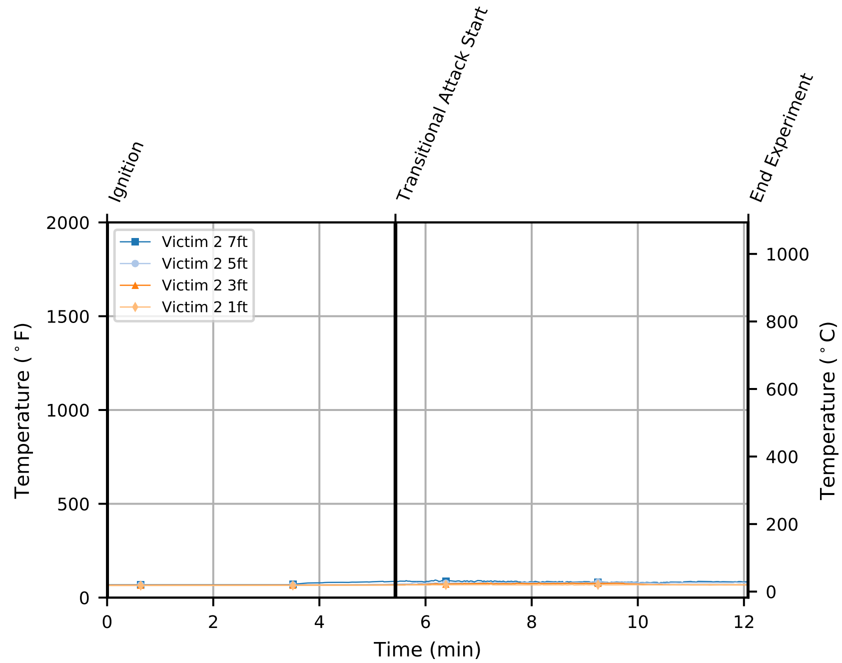


Figure E.876: Experiment 23 - Victim 2 Temps

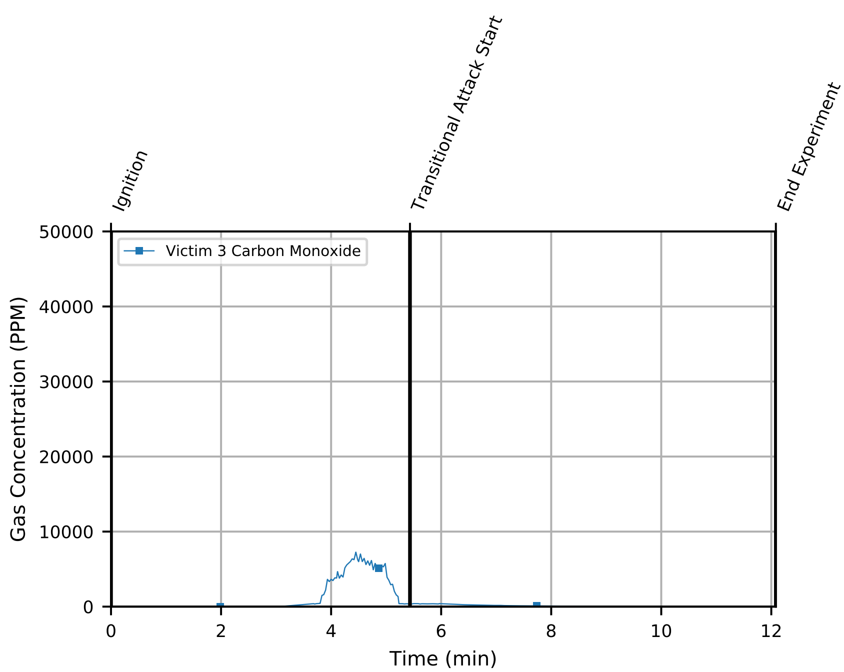


Figure E.877: Experiment 23 - Victim 3 Carbon Monoxide

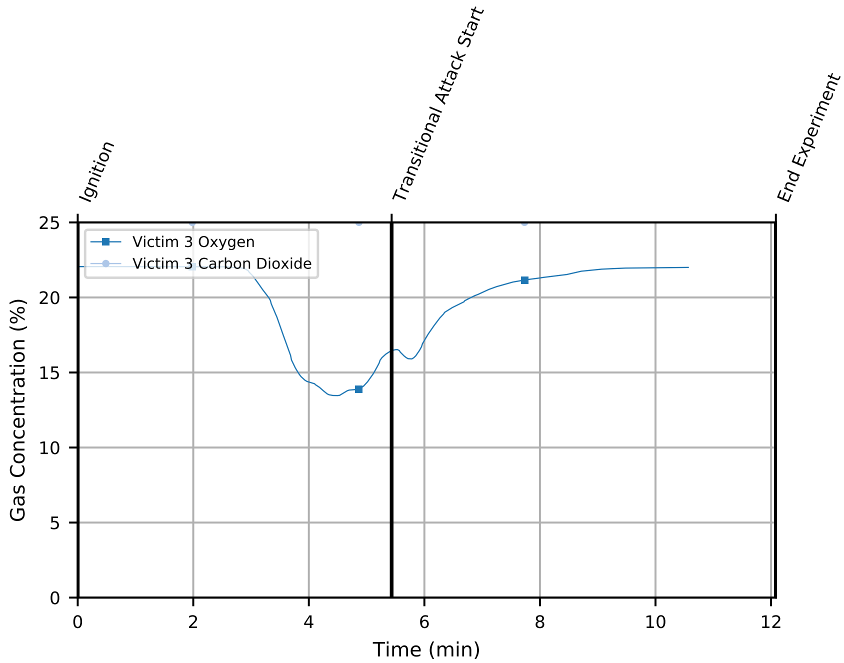


Figure E.878: Experiment 23 - Victim 3 Gas

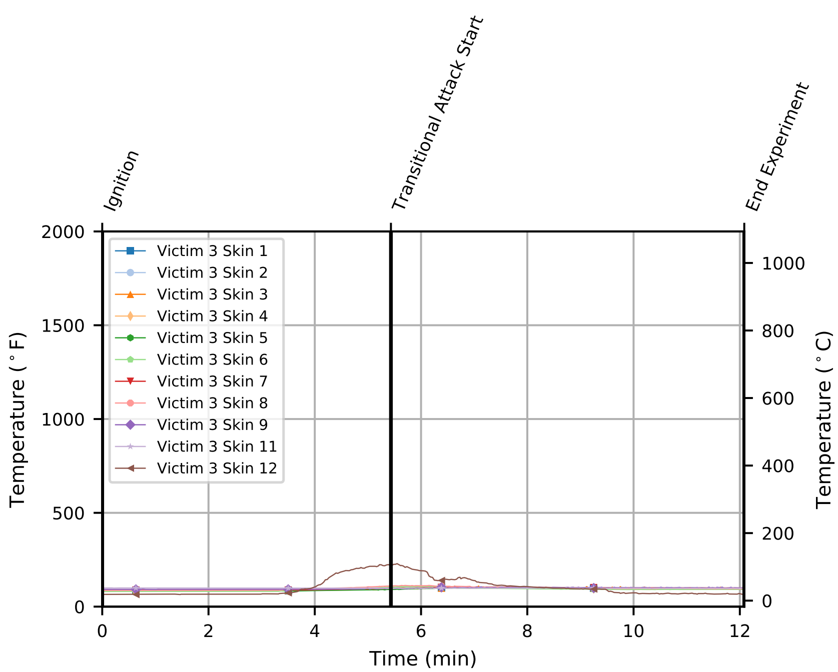


Figure E.879: Experiment 23 - Victim 3 Skin Temps

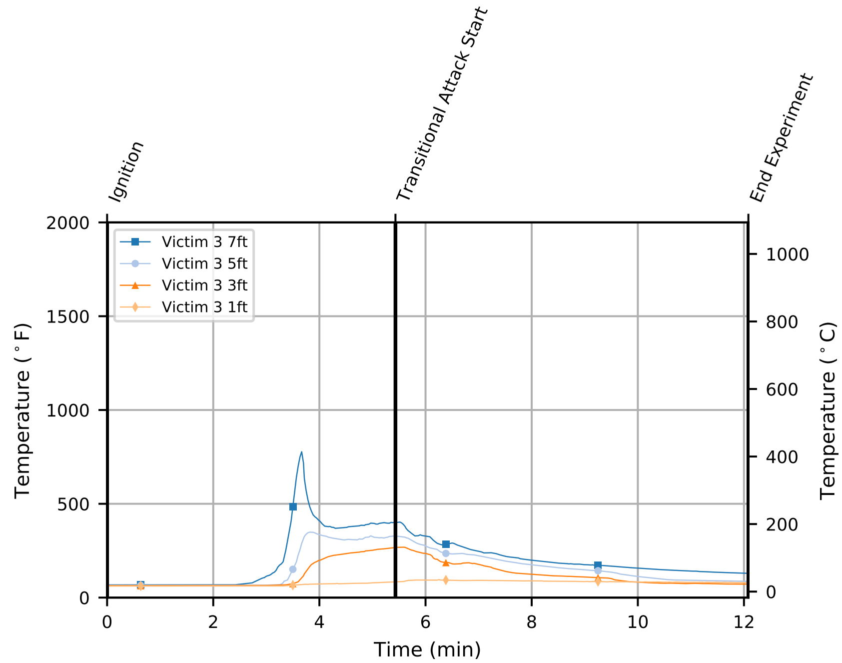


Figure E.880: Experiment 23 - Victim 3 Temps

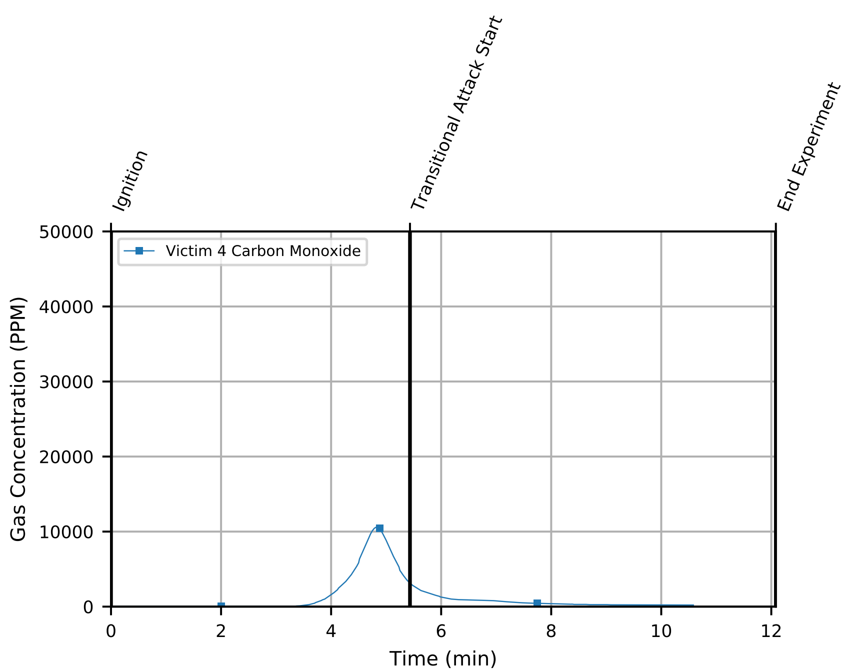


Figure E.881: Experiment 23 - Victim 4 Carbon Monoxide

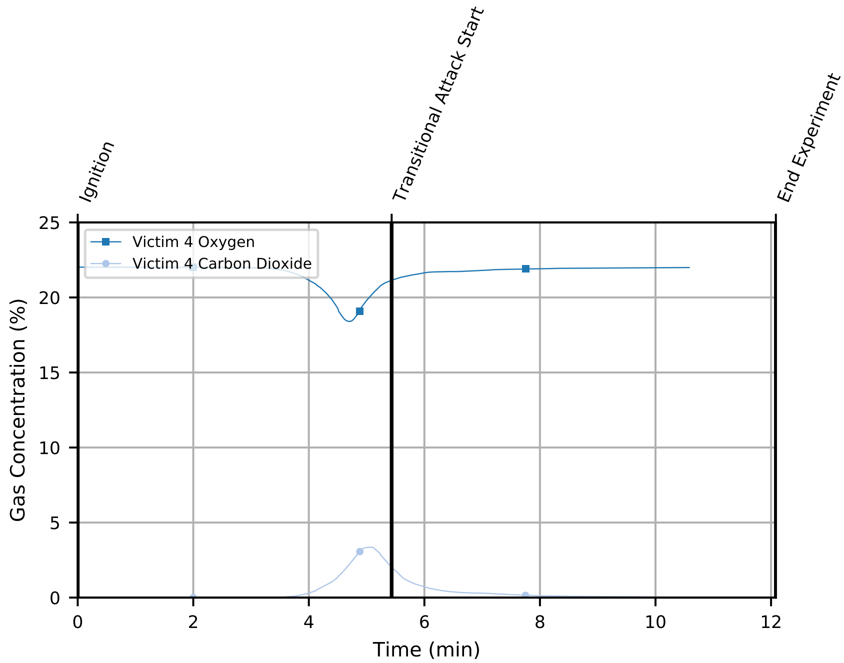


Figure E.882: Experiment 23 - Victim 4 Gas

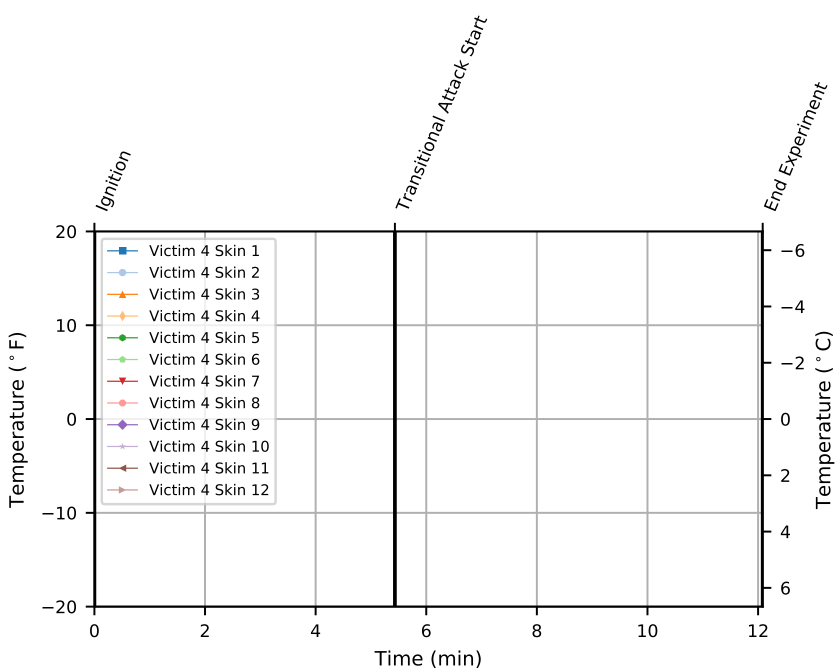


Figure E.883: Experiment 23 - Victim 4 Skin Temps

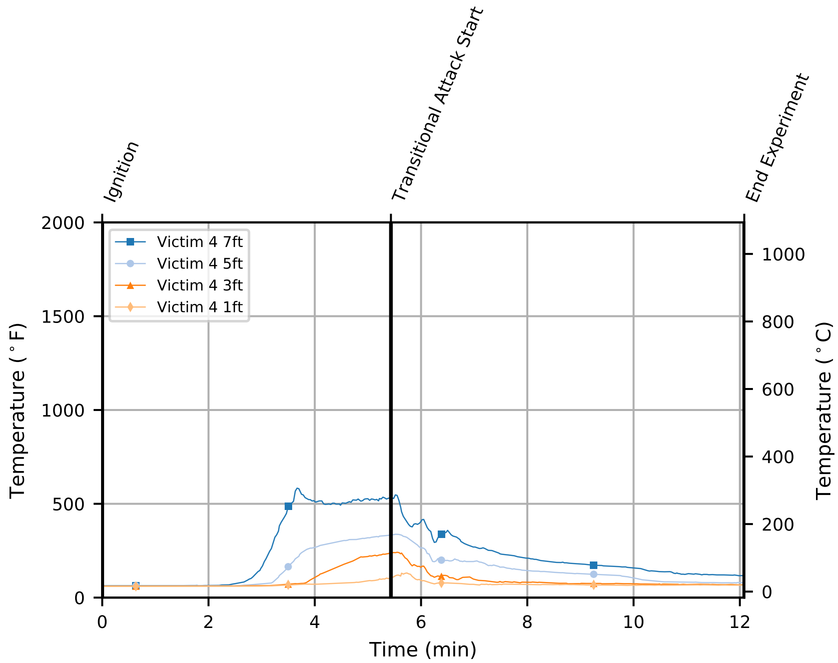


Figure E.884: Experiment 23 - Victim 4 Temps

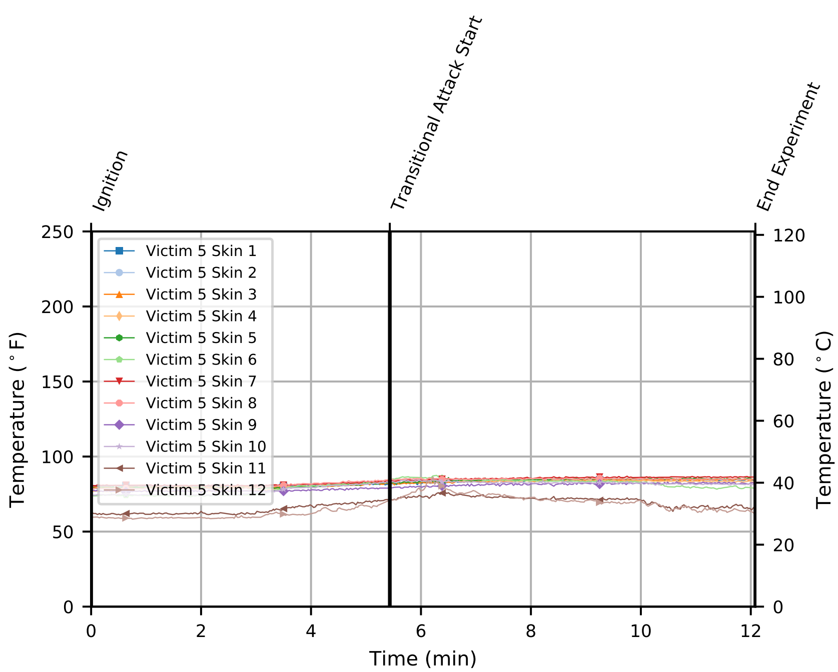


Figure E.885: Experiment 23 - Victim 5 Skin Temps

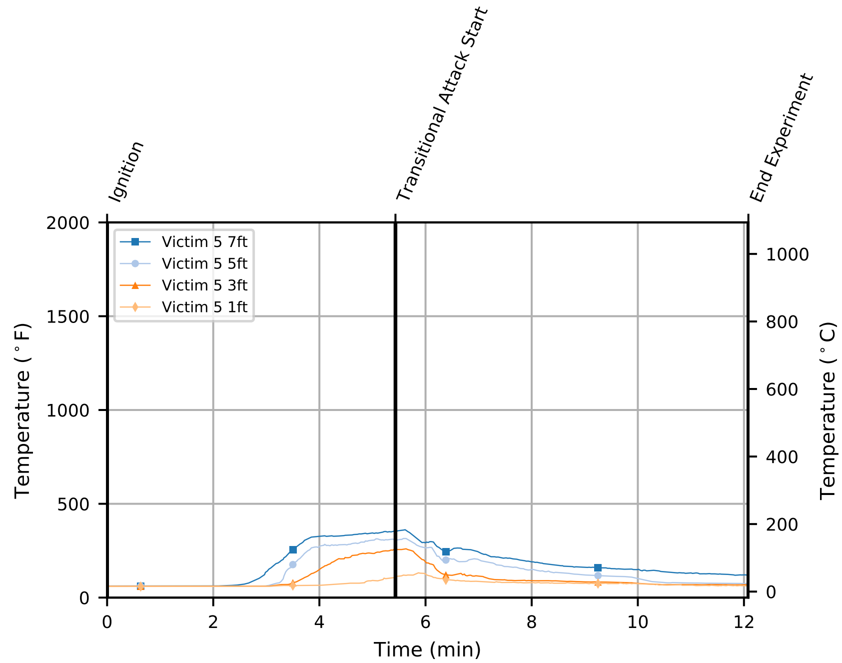


Figure E.886: Experiment 23 - Victim 5 Temps

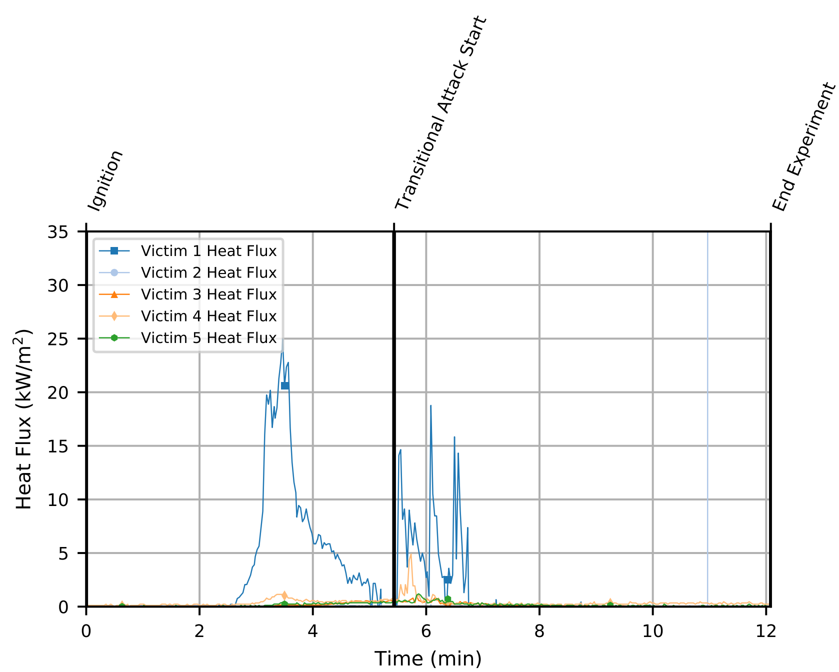


Figure E.887: Experiment 23 - Victim Heat Flux

E.24 Experiment 24 Data

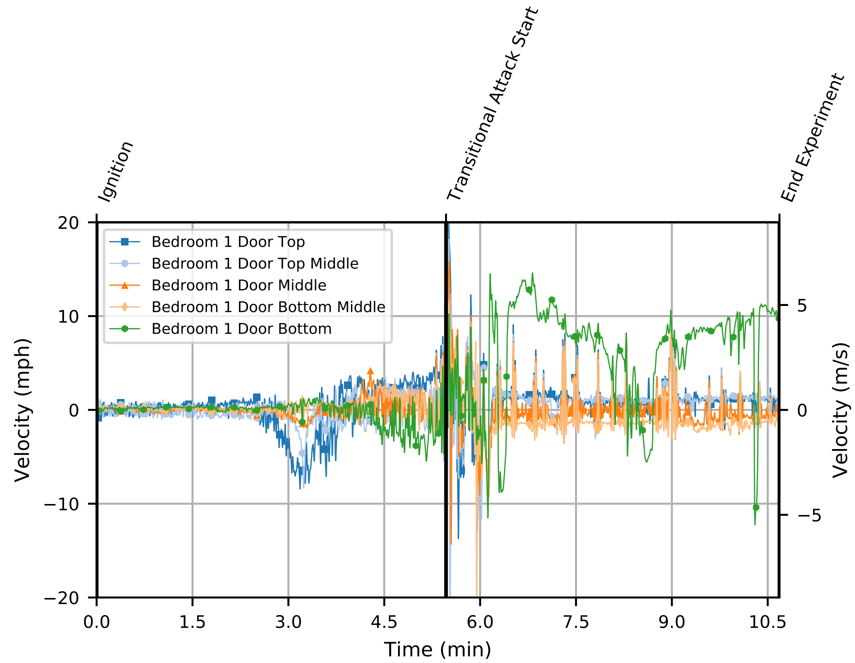


Figure E.888: Experiment 24 - Bedroom 1 Door

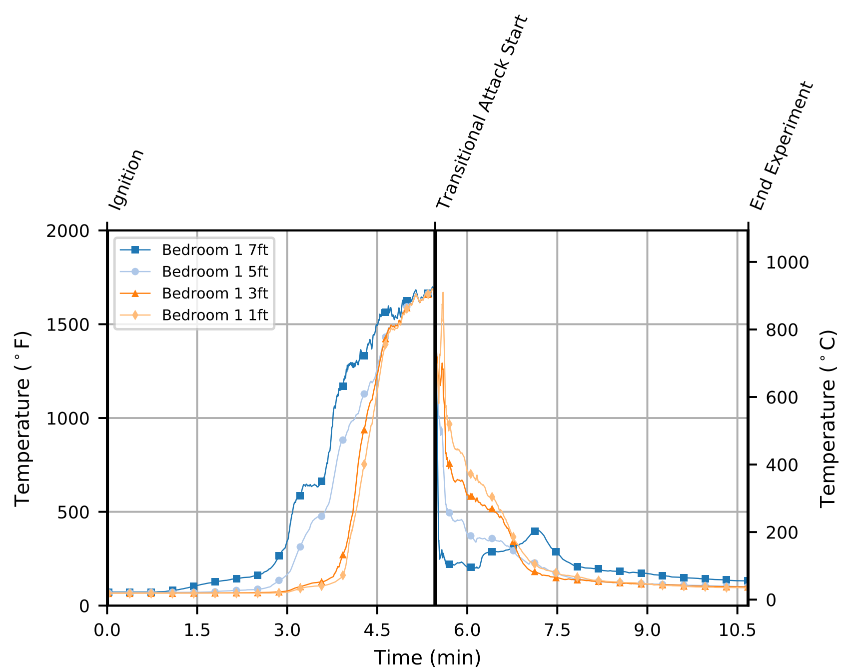


Figure E.889: Experiment 24 - Bedroom 1 Temps

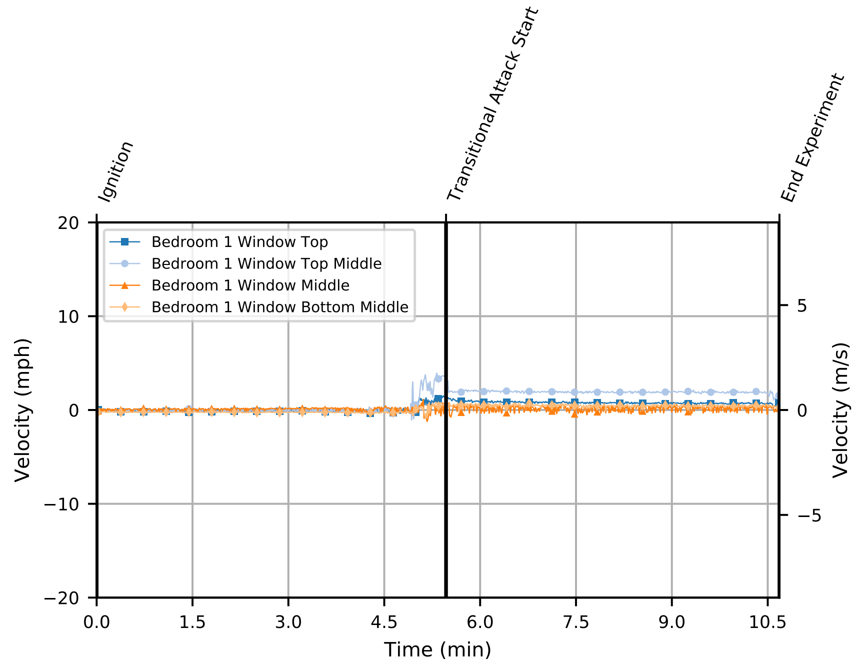


Figure E.890: Experiment 24 - Bedroom 1 Window

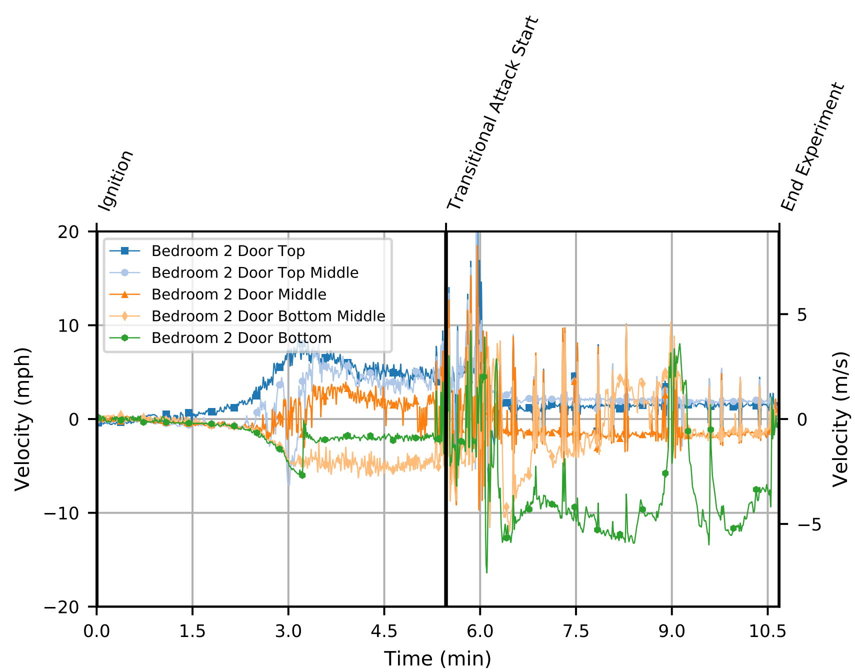


Figure E.891: Experiment 24 - Bedroom 2 Door

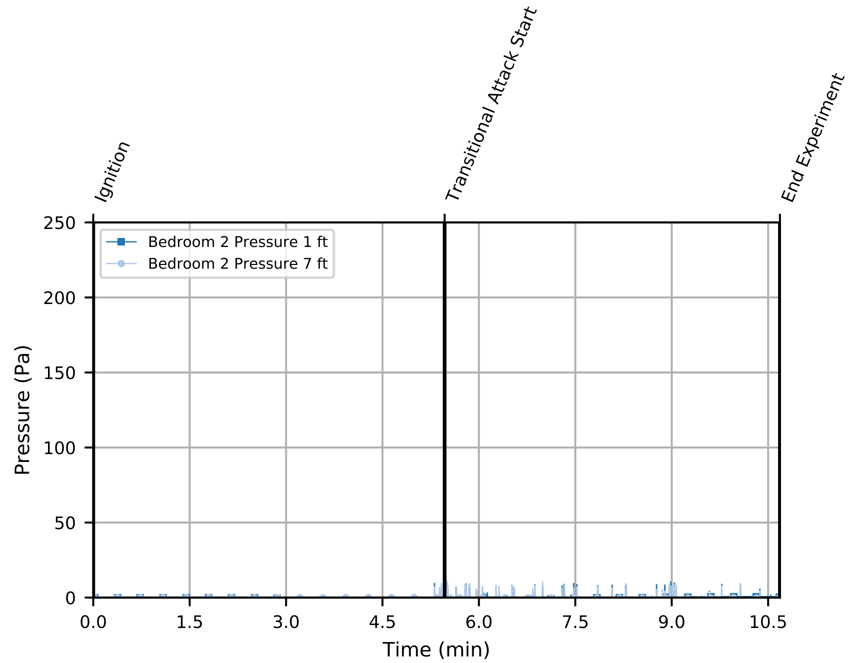


Figure E.892: Experiment 24 - Bedroom 2 Pressure

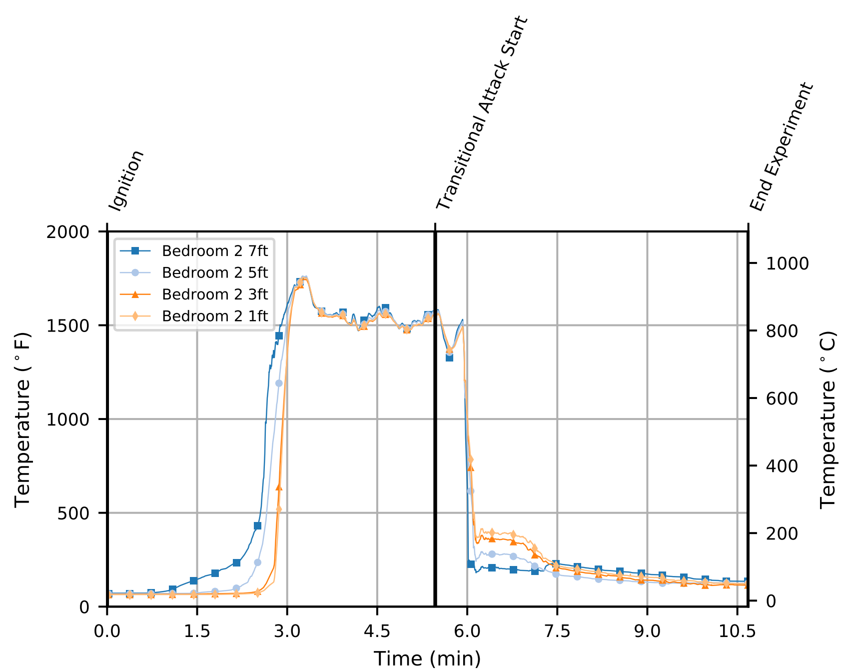


Figure E.893: Experiment 24 - Bedroom 2 Temps

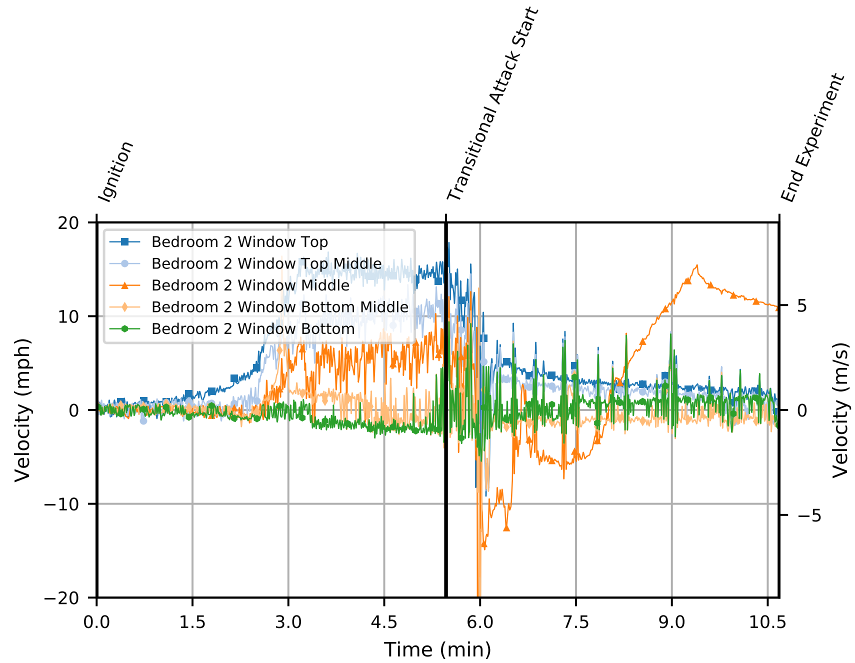


Figure E.894: Experiment 24 - Bedroom 2 Window

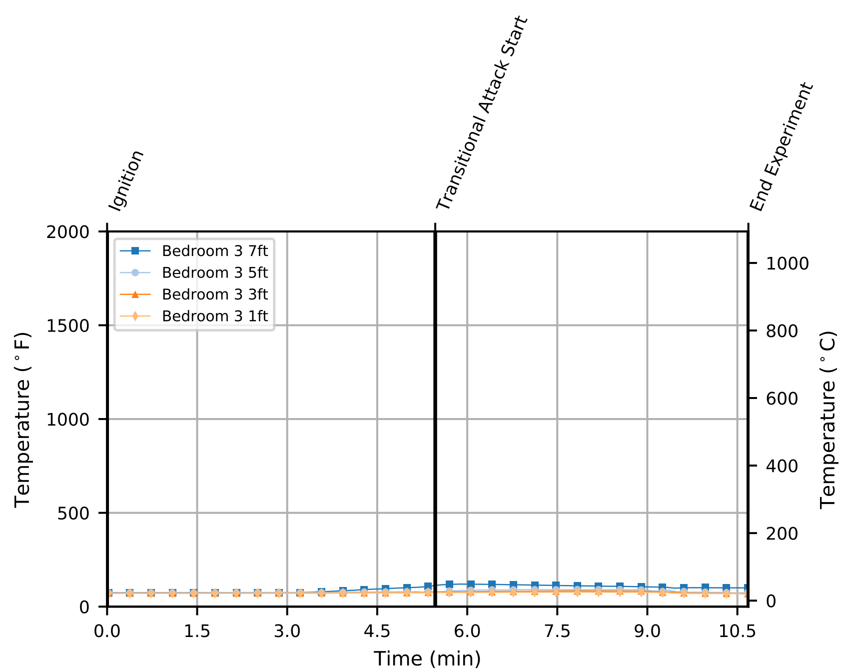


Figure E.895: Experiment 24 - Bedroom 3 Temps

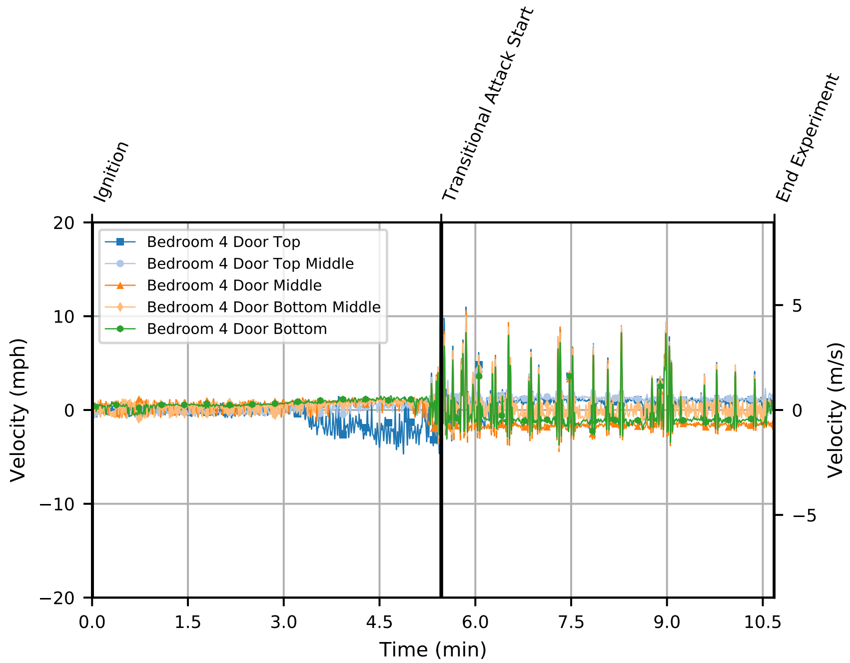


Figure E.896: Experiment 24 - Bedroom 4 Door

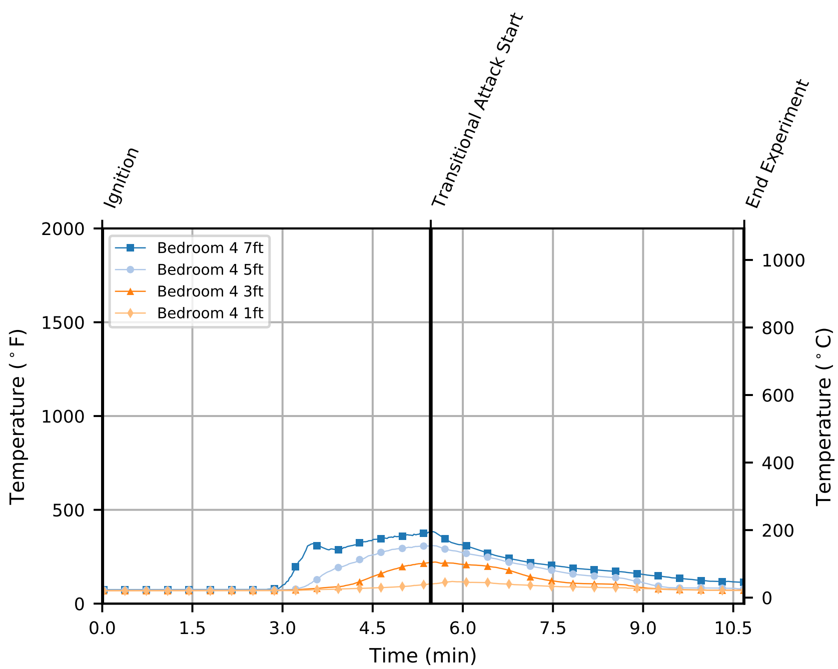


Figure E.897: Experiment 24 - Bedroom 4 Temps

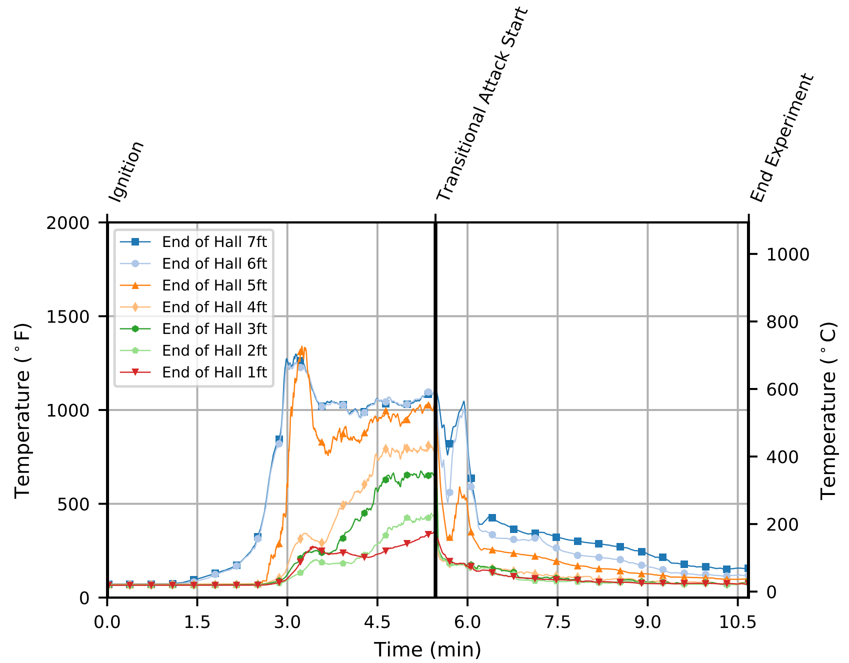


Figure E.898: Experiment 24 - End Hall Temps

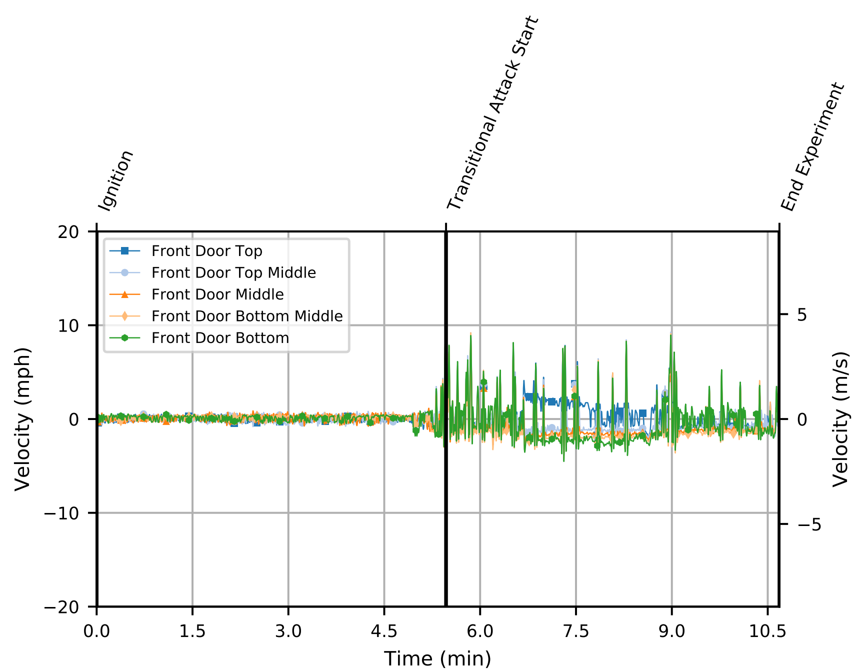


Figure E.899: Experiment 24 - Front Door Flow

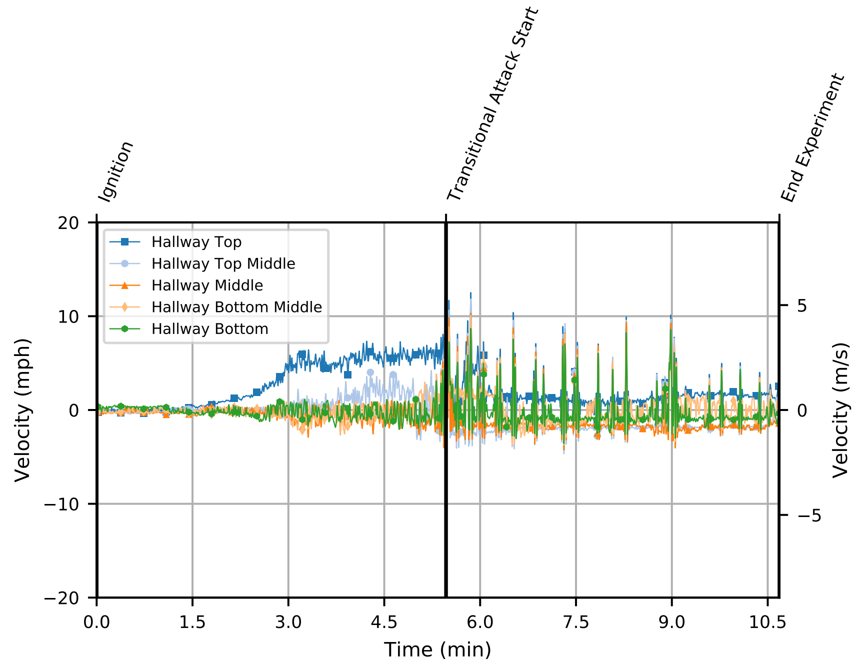


Figure E.900: Experiment 24 - Hallway Flow

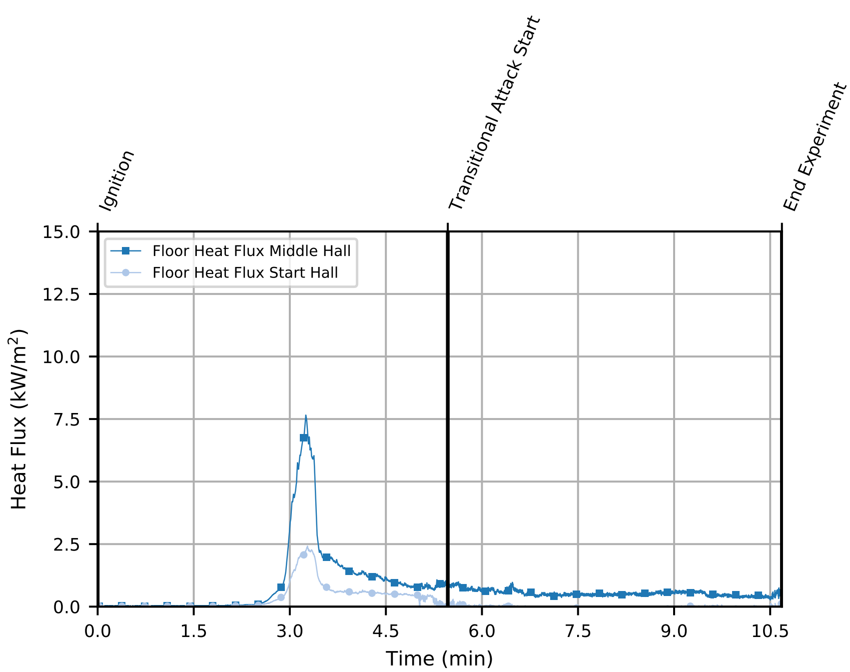


Figure E.901: Experiment 24 - Heat Flux Floor

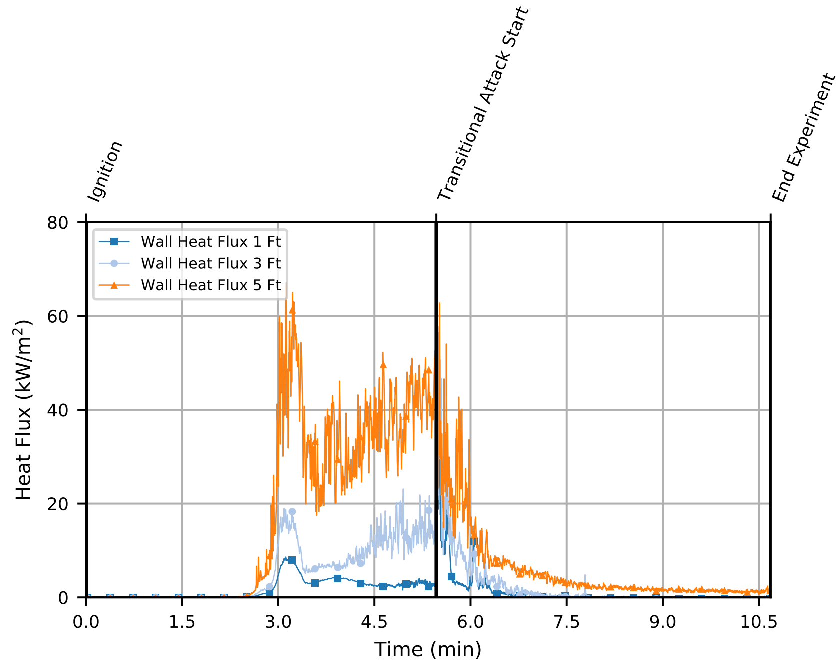


Figure E.902: Experiment 24 - Heat Flux Wall

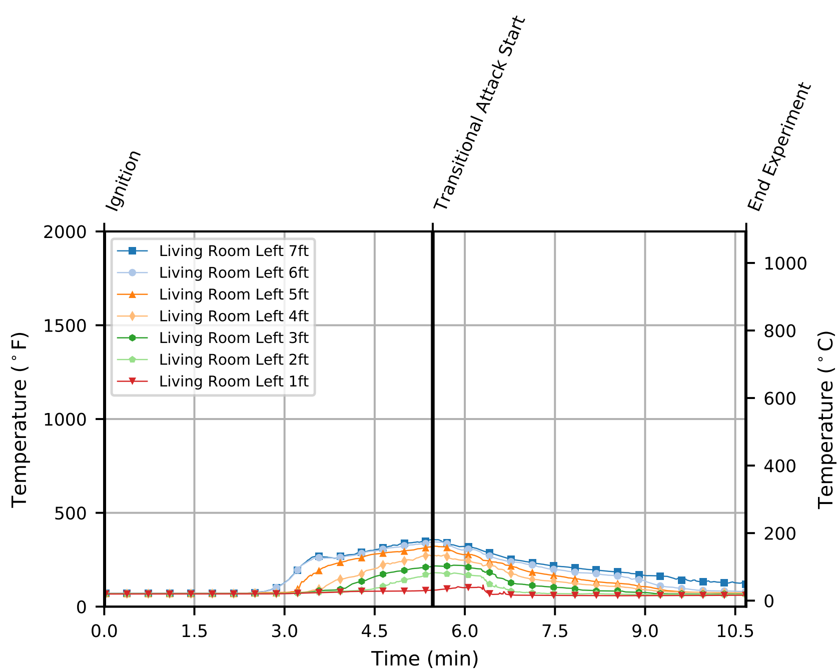


Figure E.903: Experiment 24 - Living Room Left Temps

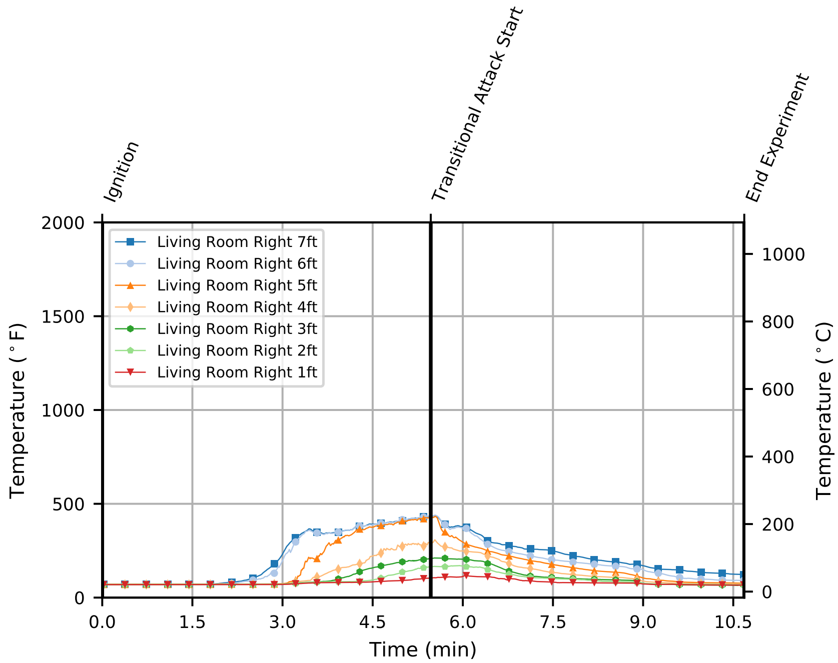


Figure E.904: Experiment 24 - Living Room Right Temps

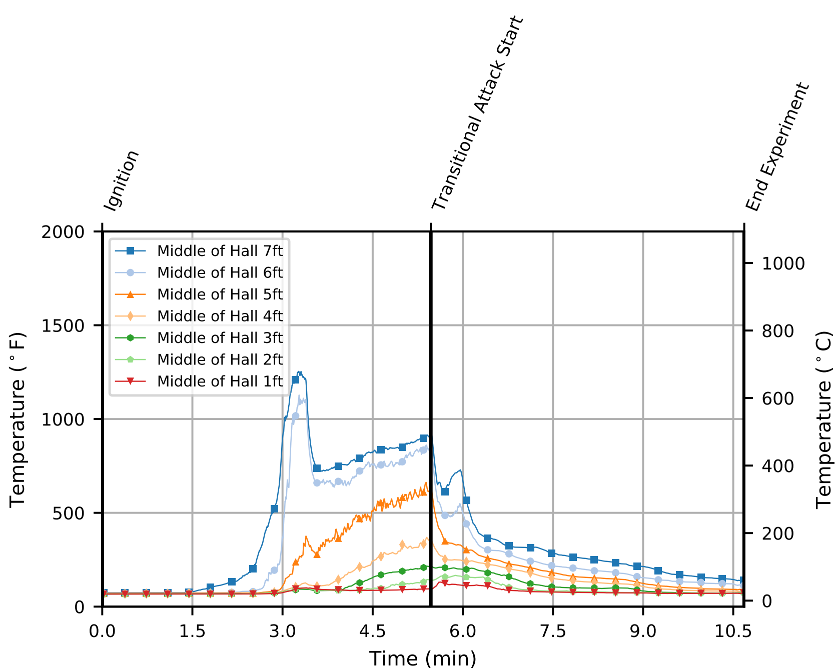


Figure E.905: Experiment 24 - Middle Hall Temps

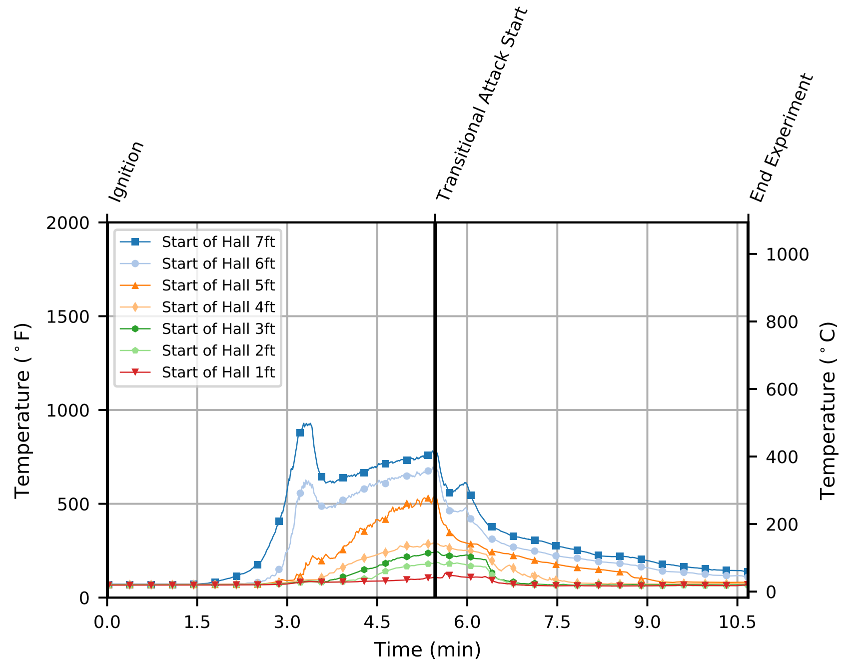


Figure E.906: Experiment 24 - Start Hall Temps

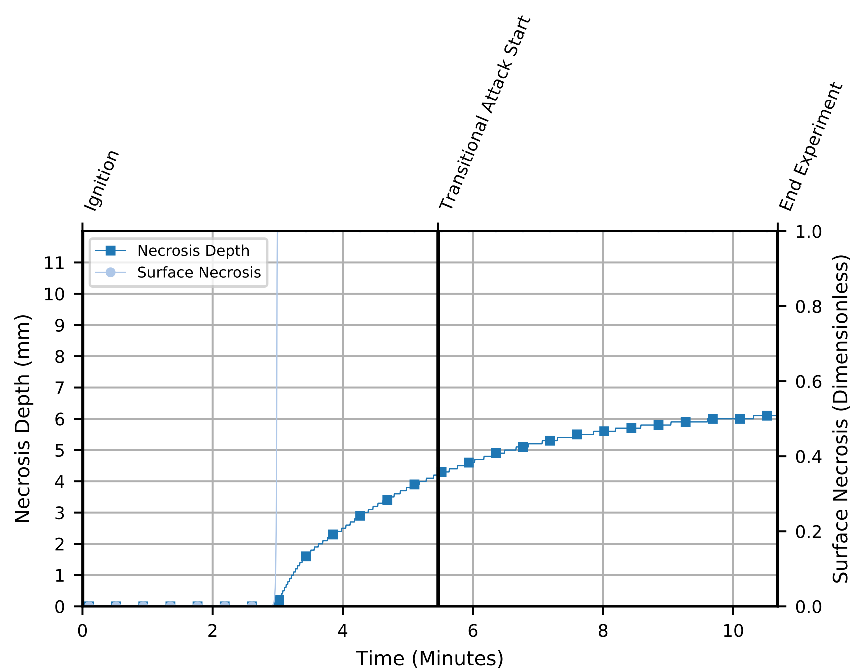


Figure E.907: Experiment 24 - Vic 1 Necrosis Depth

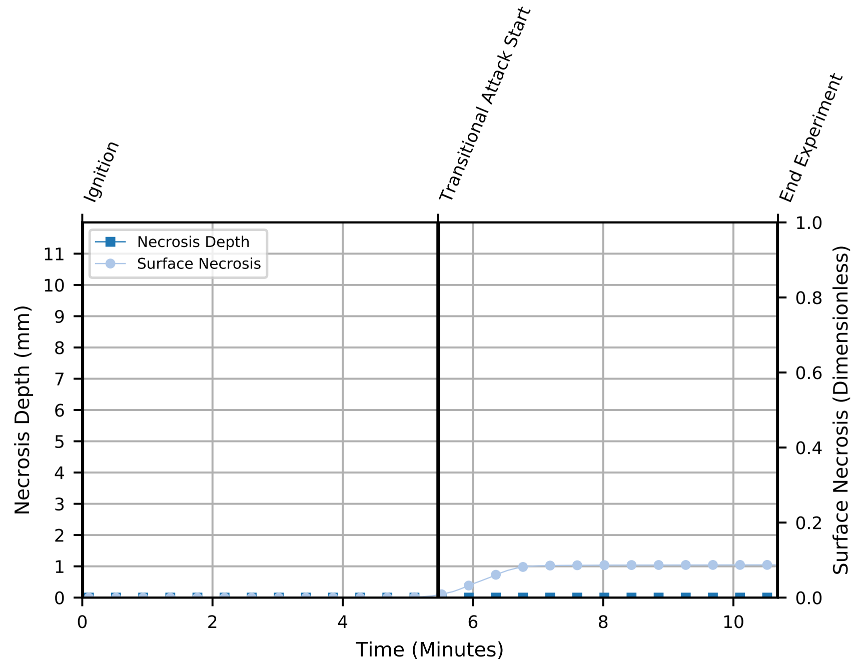


Figure E.908: Experiment 24 - Vic 3 Necrosis Depth

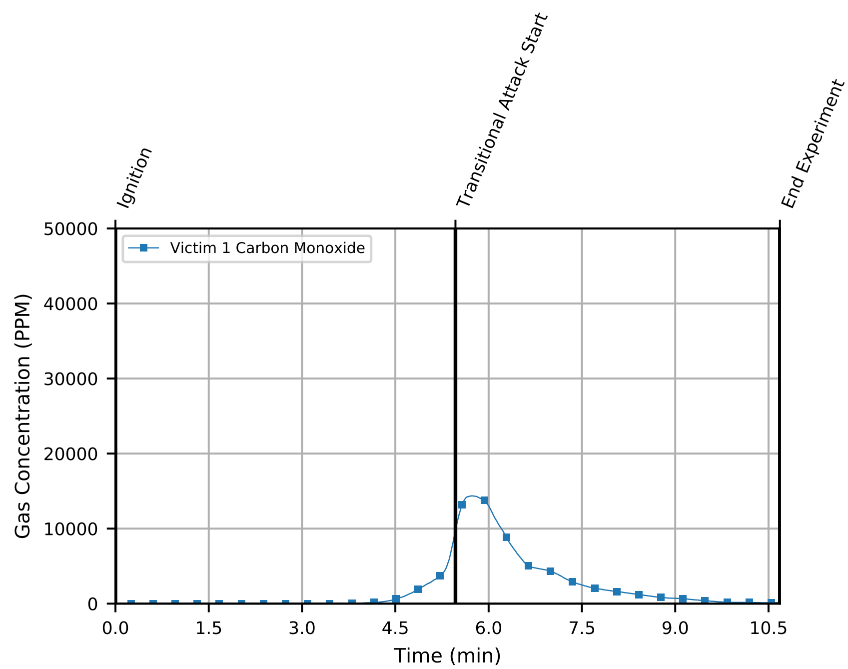


Figure E.909: Experiment 24 - Victim 1 Carbon Monoxide

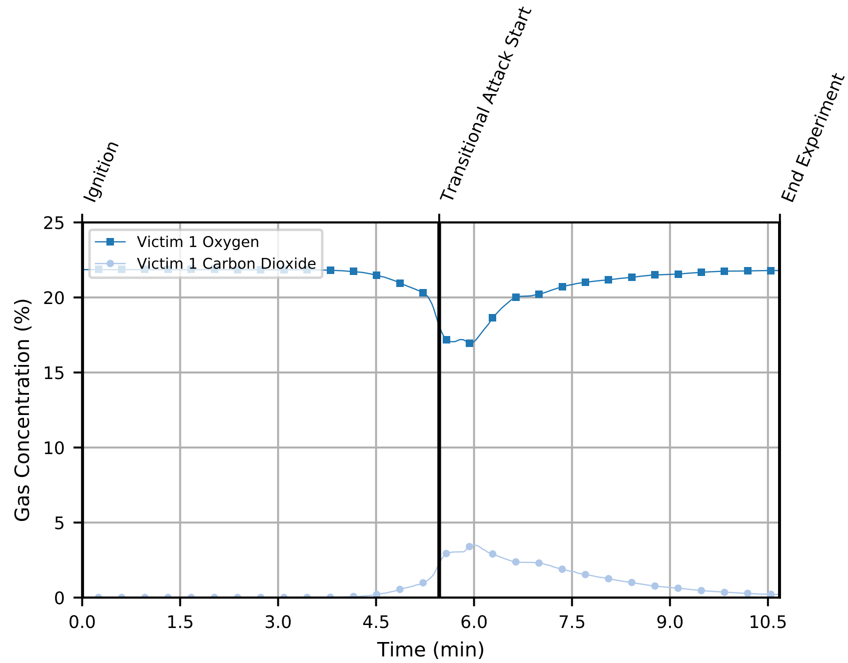


Figure E.910: Experiment 24 - Victim 1 Gas

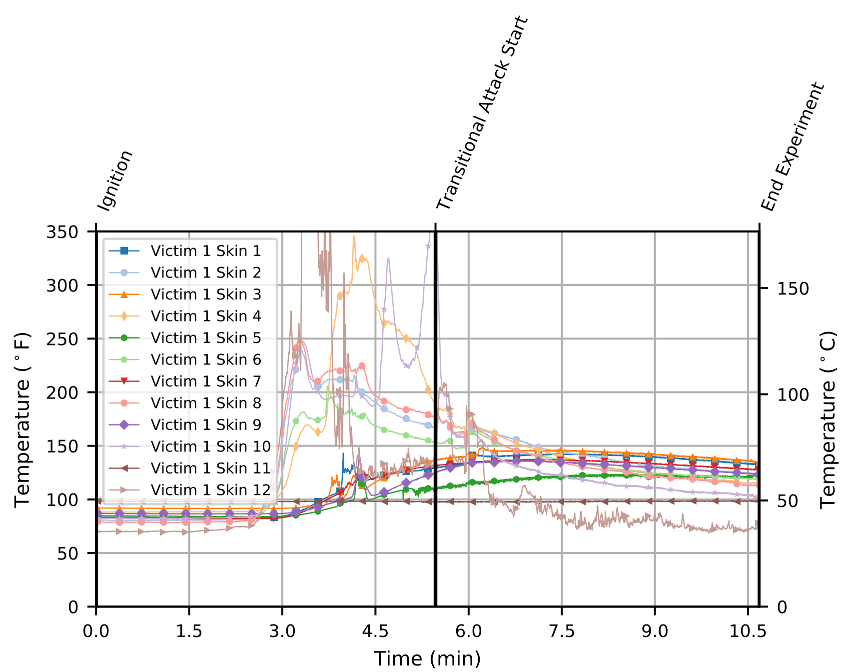


Figure E.911: Experiment 24 - Victim 1 Skin Temps

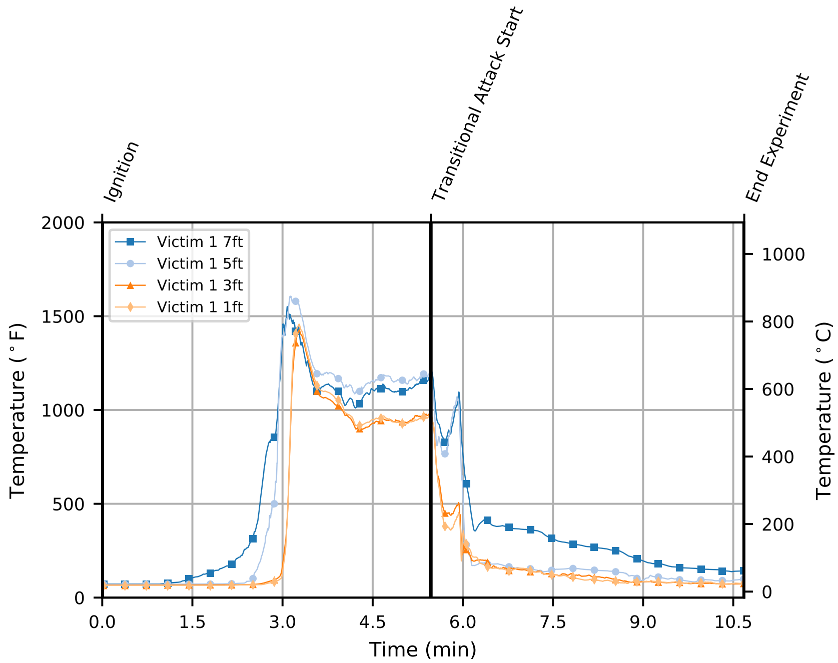


Figure E.912: Experiment 24 - Victim 1 Temps

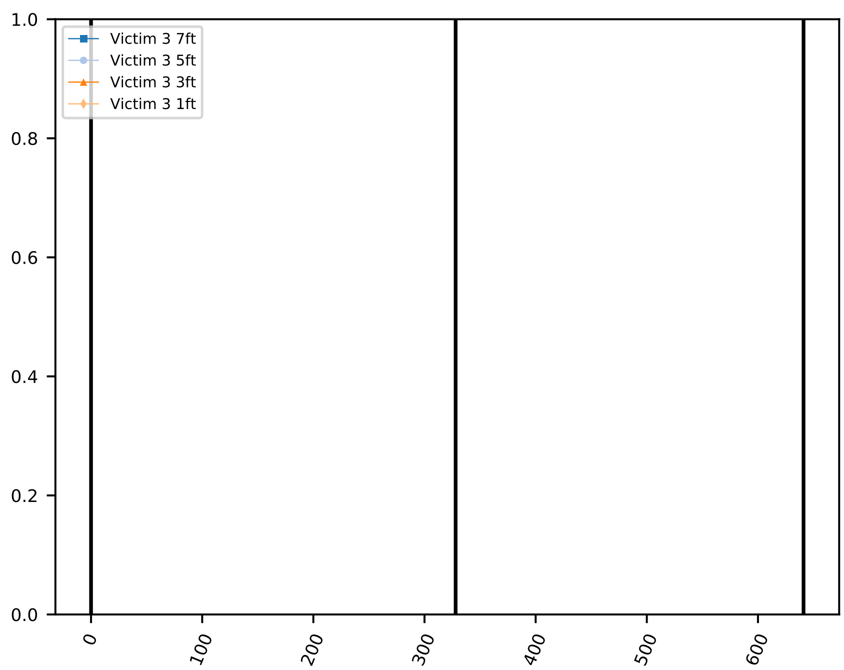


Figure E.913: Experiment 24 - Victim 2 Carbon Monoxide

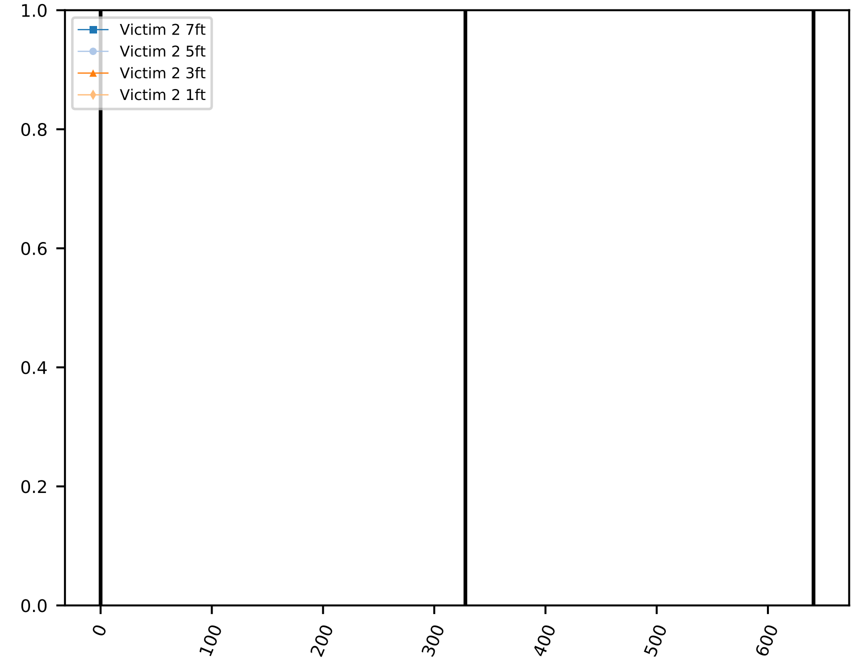


Figure E.914: Experiment 24 - Victim 2 Gas

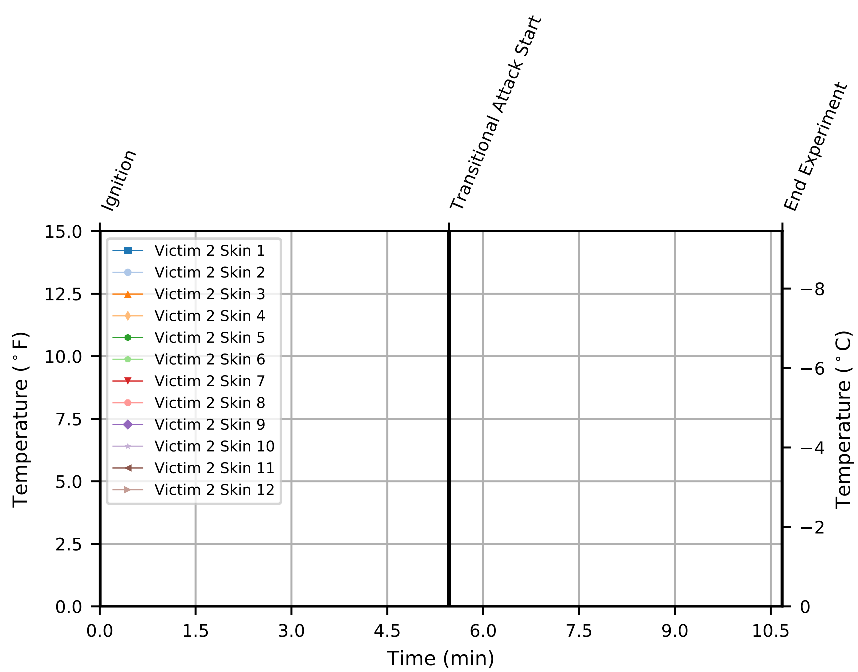


Figure E.915: Experiment 24 - Victim 2 Skin Temps

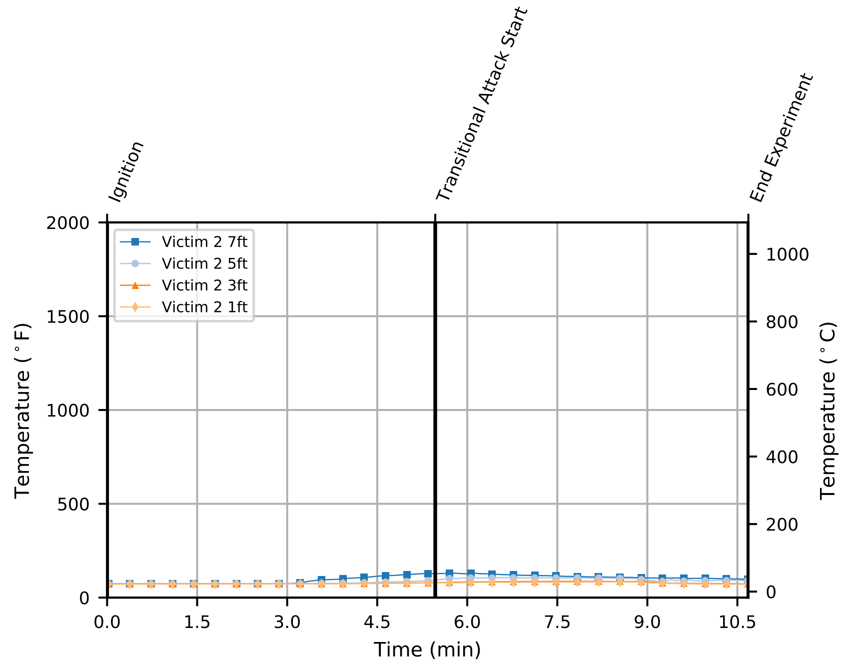


Figure E.916: Experiment 24 - Victim 2 Temps

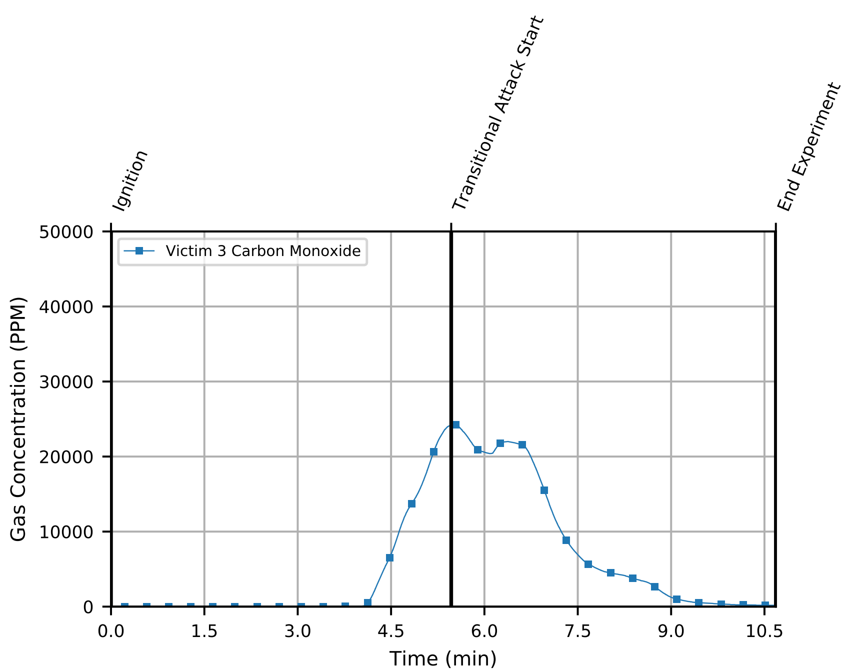


Figure E.917: Experiment 24 - Victim 3 Carbon Monoxide

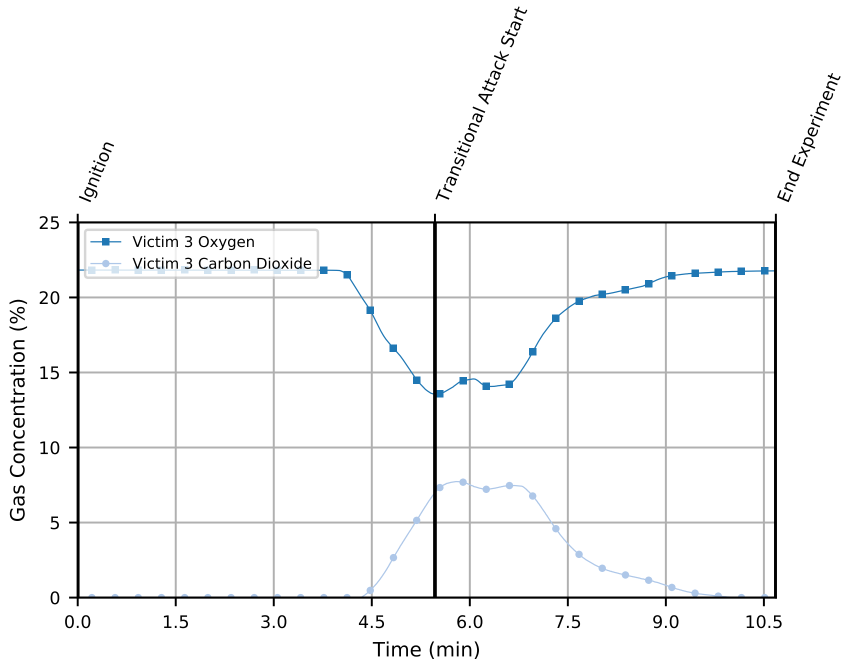


Figure E.918: Experiment 24 - Victim 3 Gas

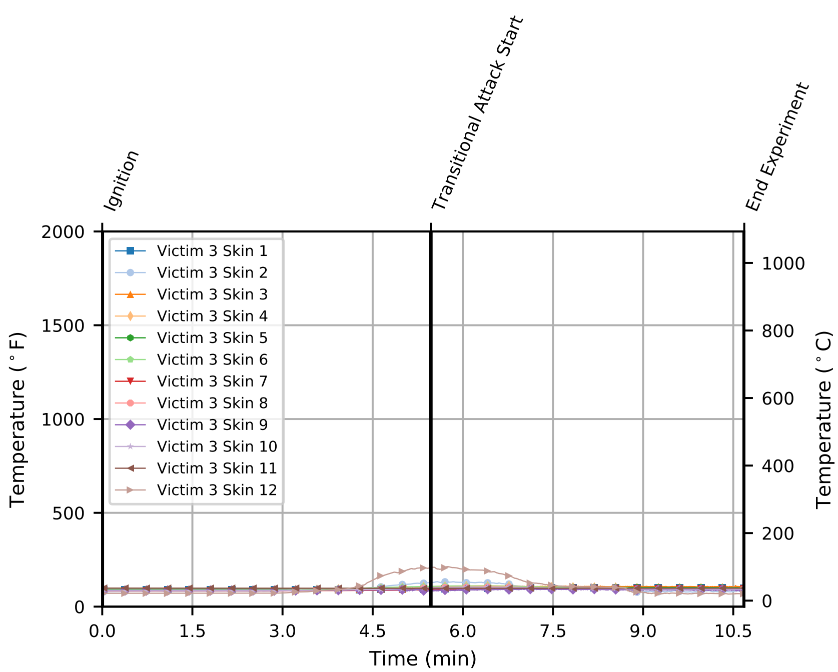


Figure E.919: Experiment 24 - Victim 3 Skin Temps

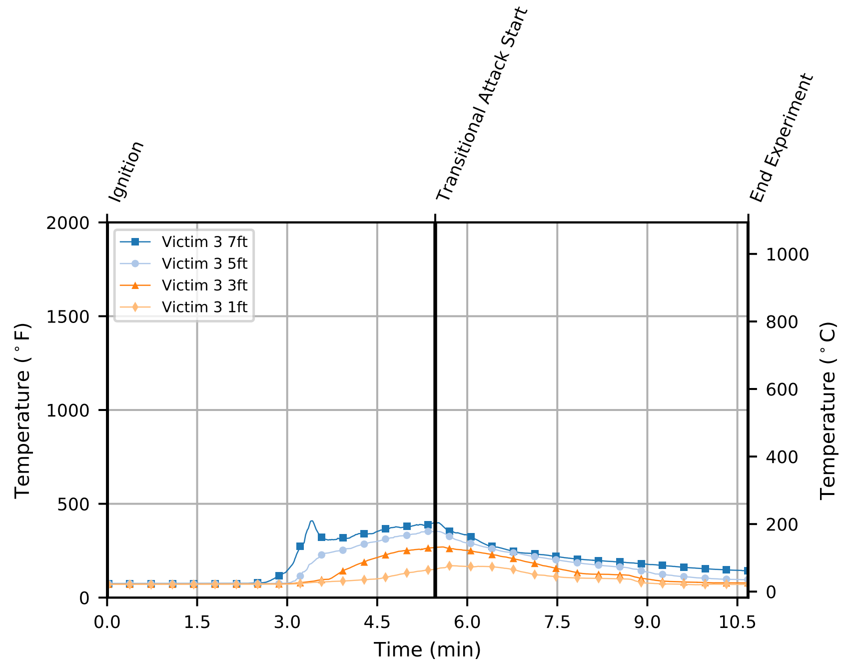


Figure E.920: Experiment 24 - Victim 3 Temps

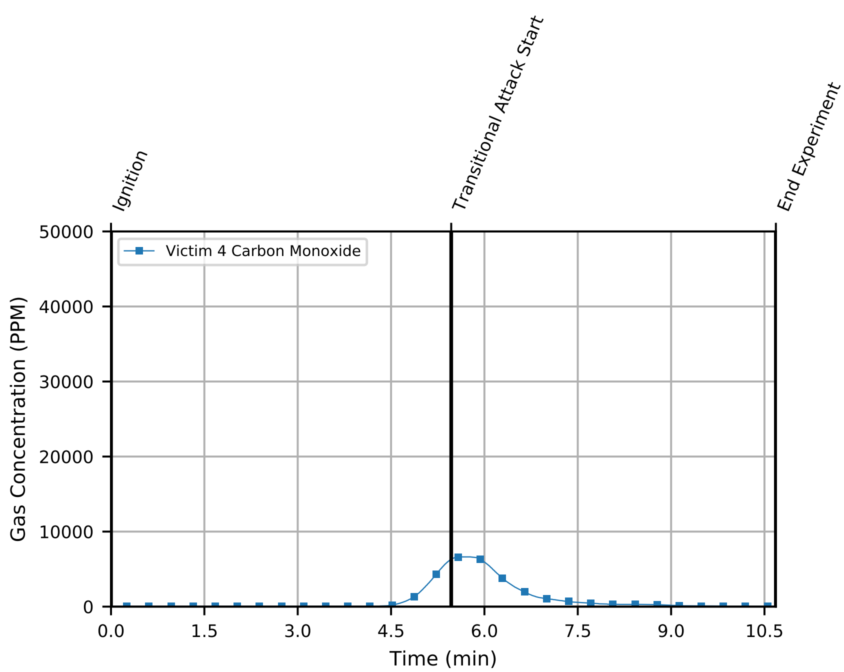


Figure E.921: Experiment 24 - Victim 4 Carbon Monoxide

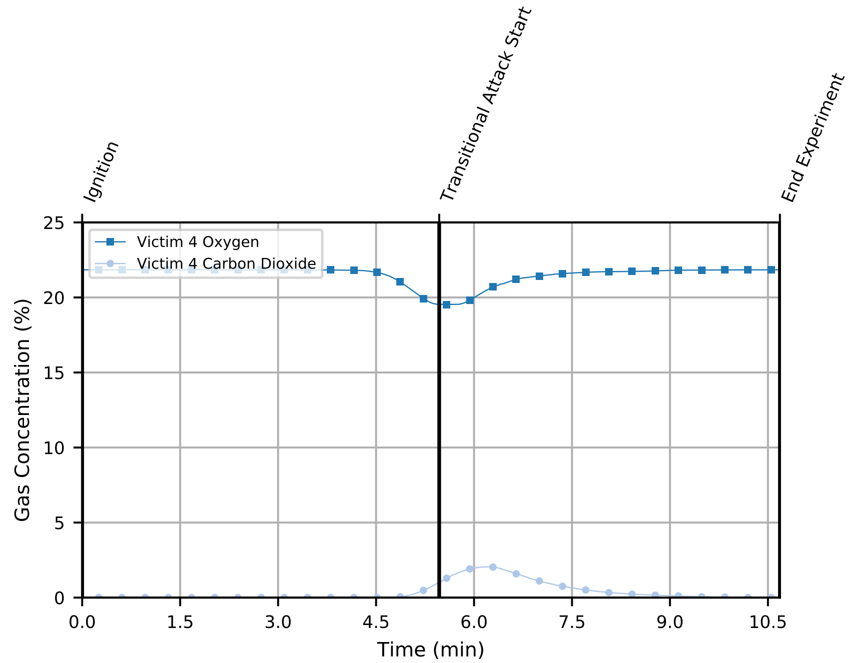


Figure E.922: Experiment 24 - Victim 4 Gas

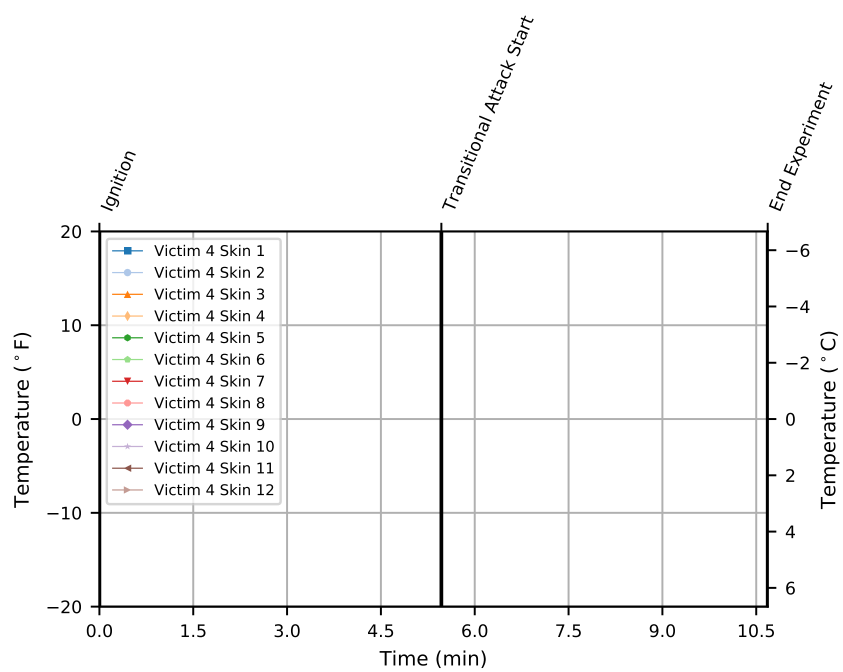


Figure E.923: Experiment 24 - Victim 4 Skin Temps

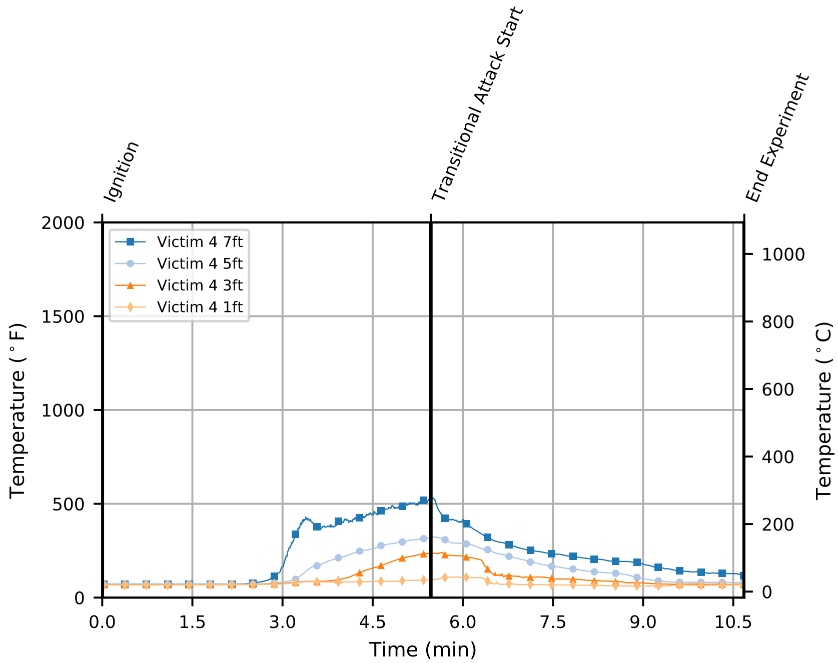


Figure E.924: Experiment 24 - Victim 4 Temps

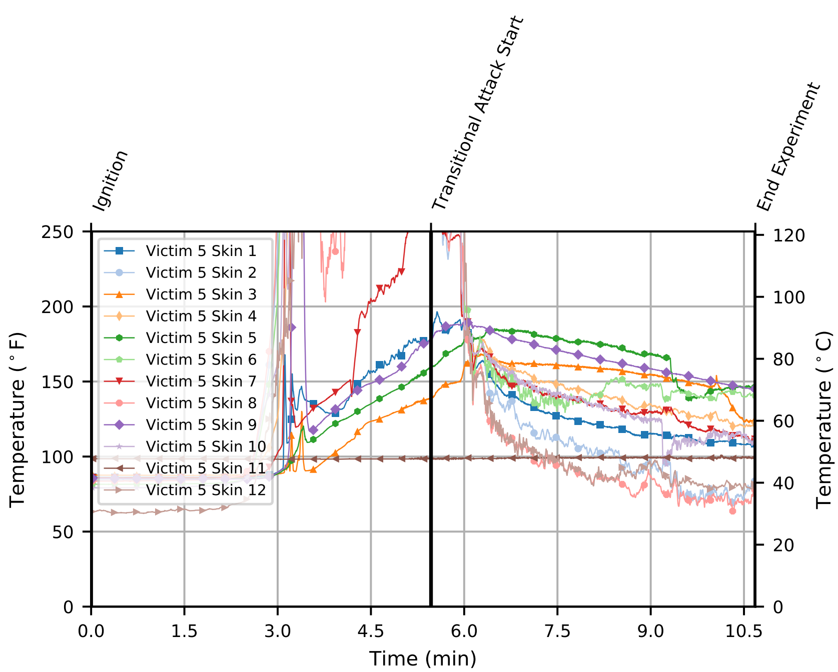


Figure E.925: Experiment 24 - Victim 5 Skin Temps

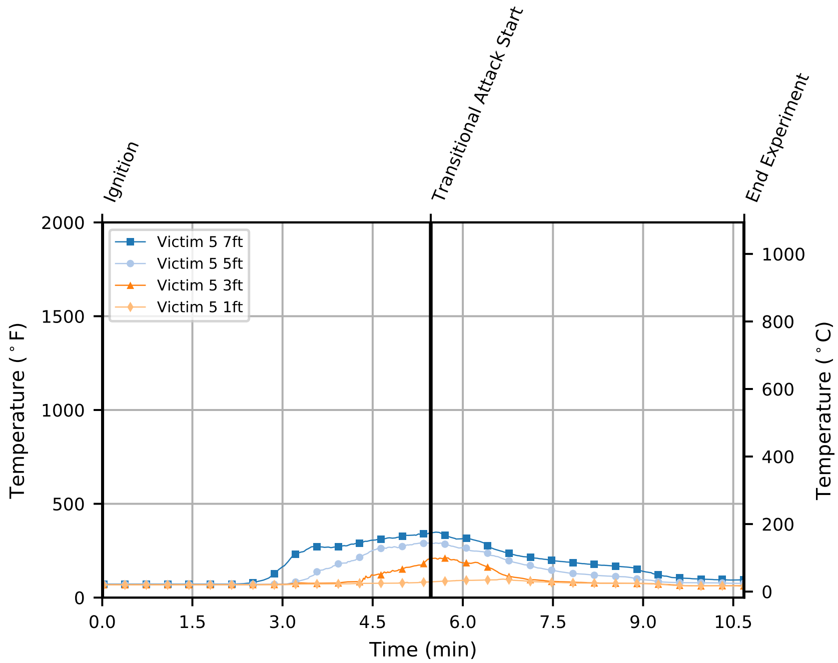


Figure E.926: Experiment 24 - Victim 5 Temps

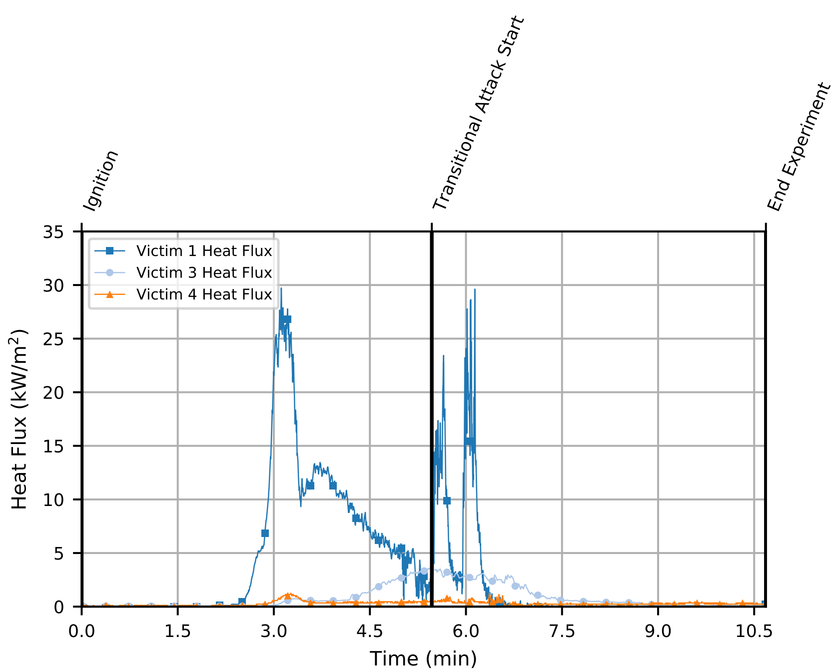


Figure E.927: Experiment 24 - Victim Heat Flux

E.25 Experiment 25 Data

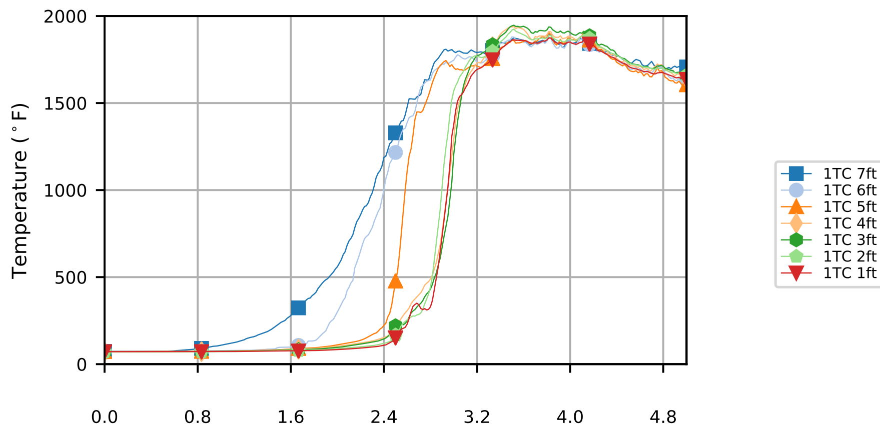


Figure E.928: Experiment 25 - 1 T C 0min to 5min

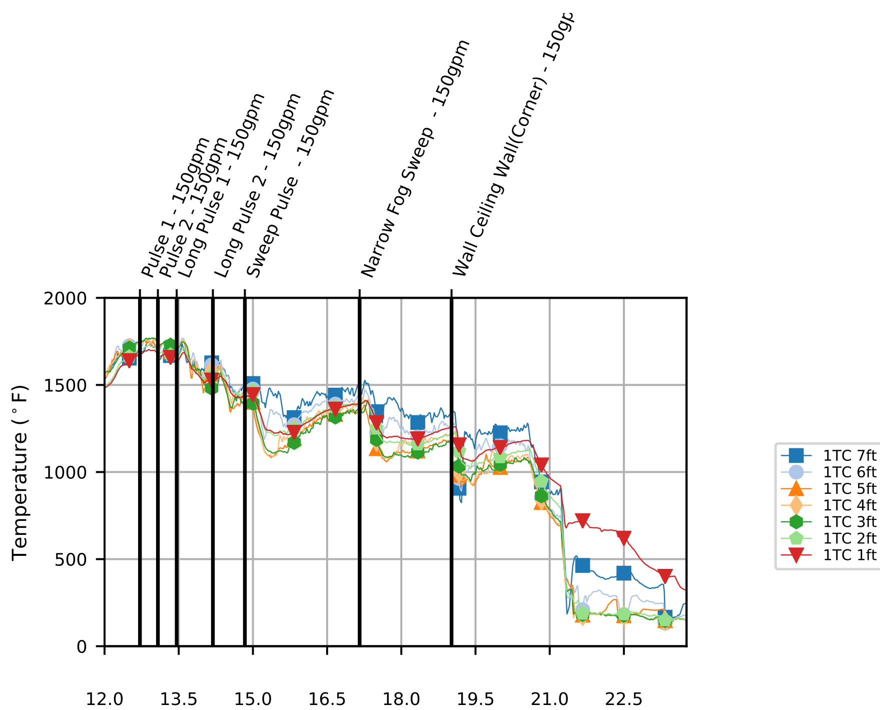


Figure E.929: Experiment 25 - 1 T C 1 2min to End

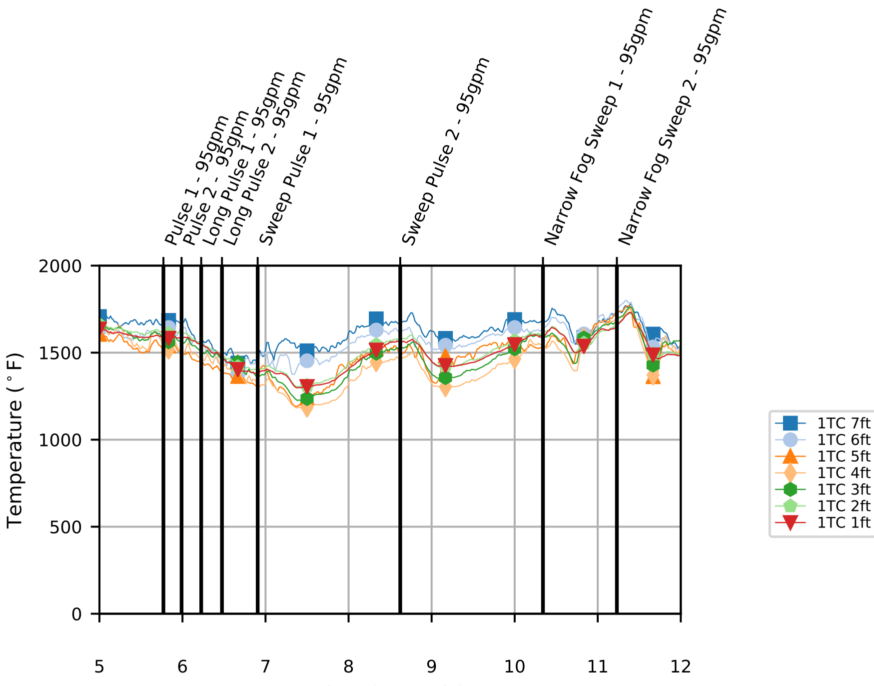


Figure E.930: Experiment 25 - 1 T C 5min to 1 2min

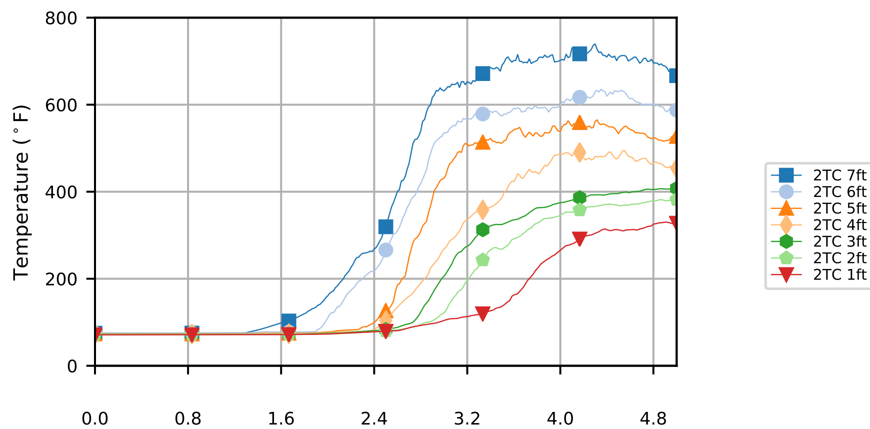


Figure E.931: Experiment 25 - 2 T C 0min to 5min

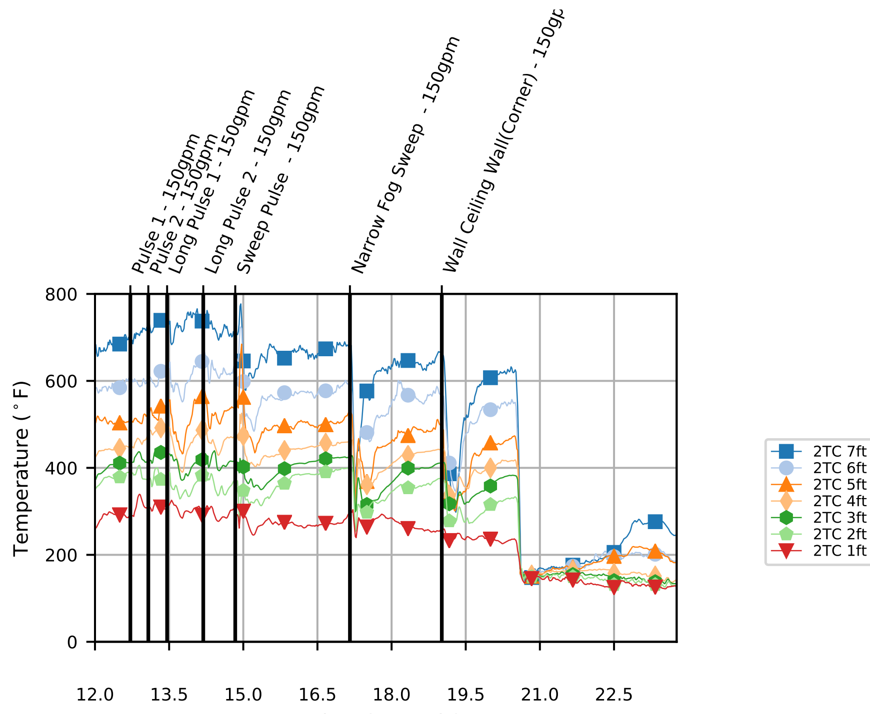


Figure E.932: Experiment 25 - 2 T C 1 2min to End

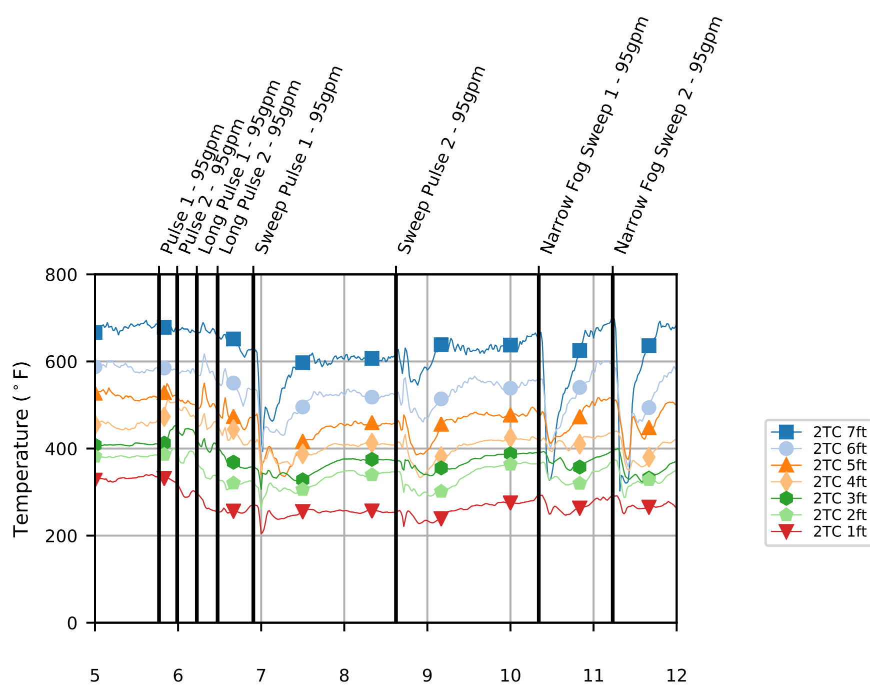


Figure E.933: Experiment 25 - 2 T C 5min to 1 2min

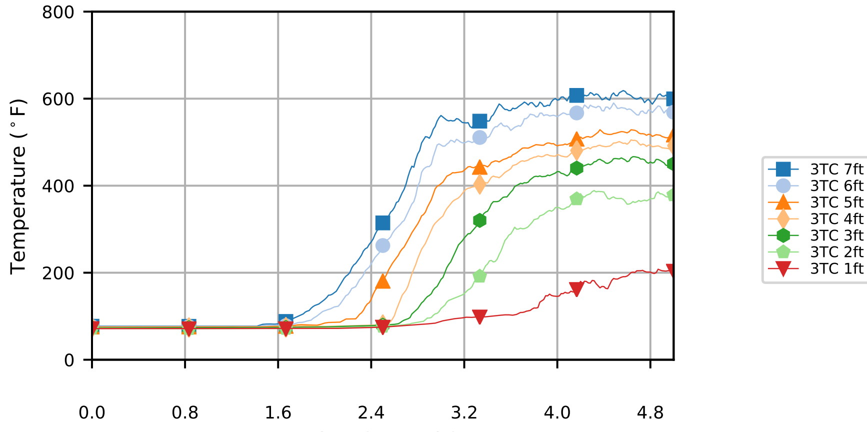


Figure E.934: Experiment 25 - 3 T C 0min to 5min

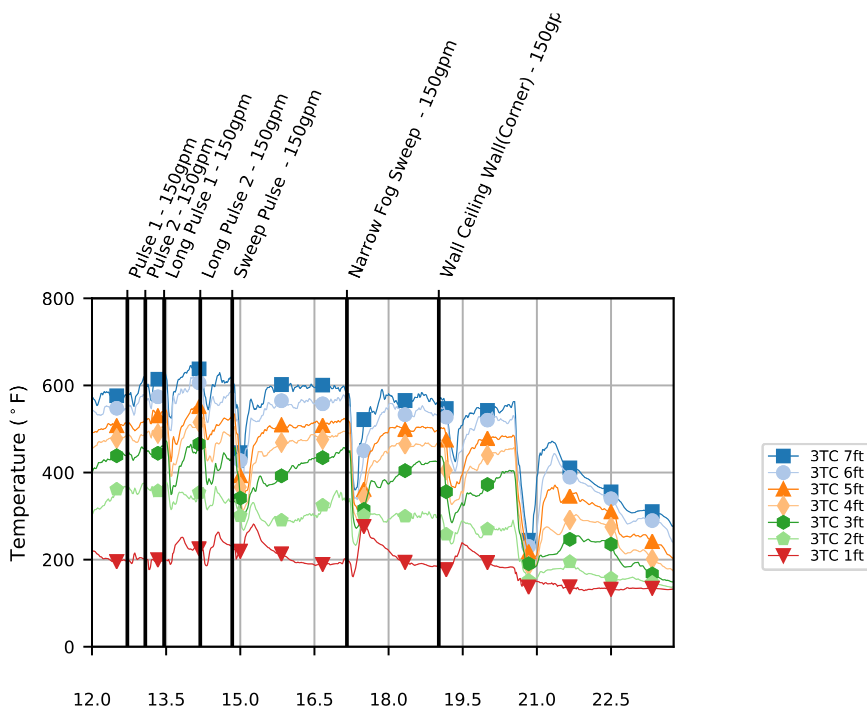


Figure E.935: Experiment 25 - 3 T C 1 2min to End

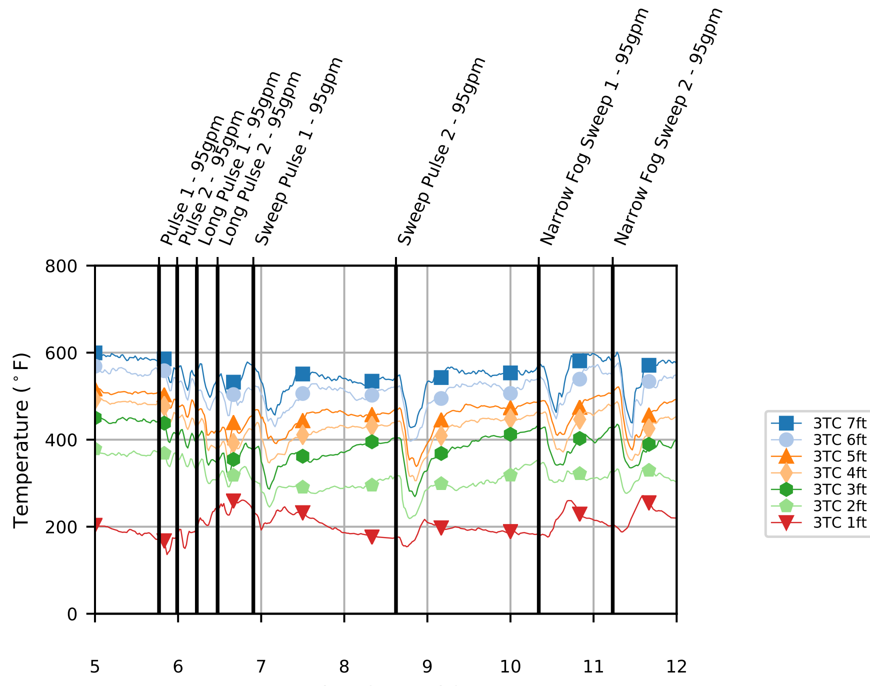


Figure E.936: Experiment 25 - 3 T C 5min to 1 2min

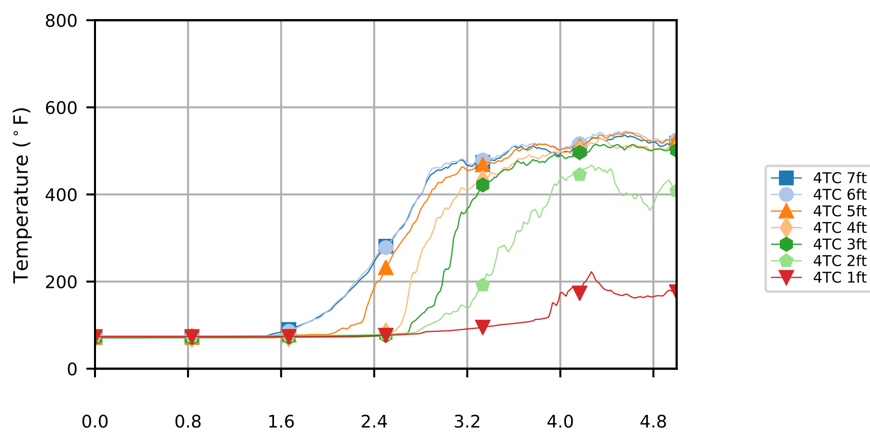


Figure E.937: Experiment 25 - 4 T C 0min to 5min

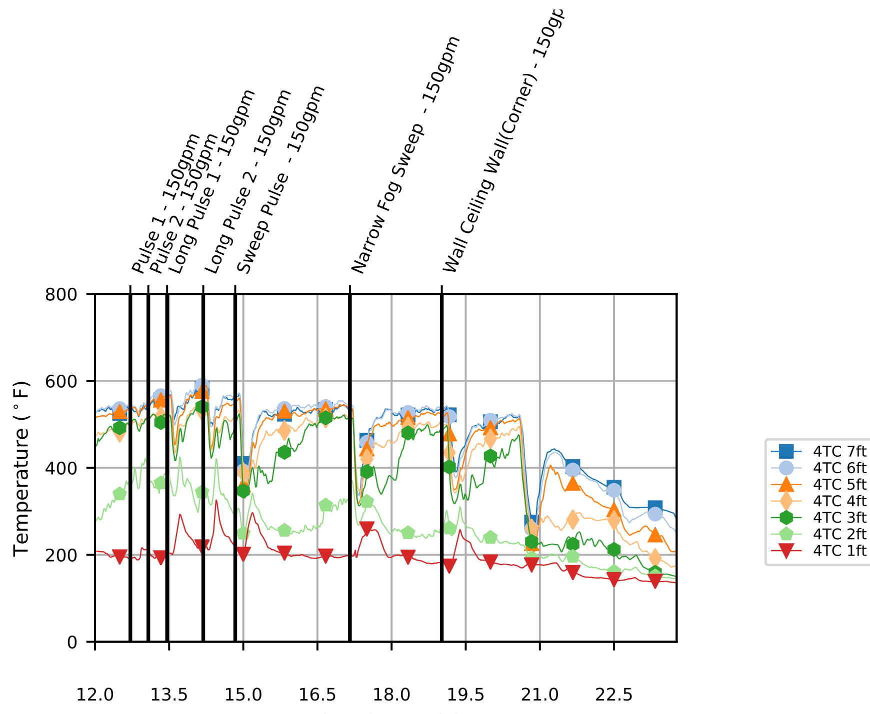


Figure E.938: Experiment 25 - 4 T C 1 2min to End

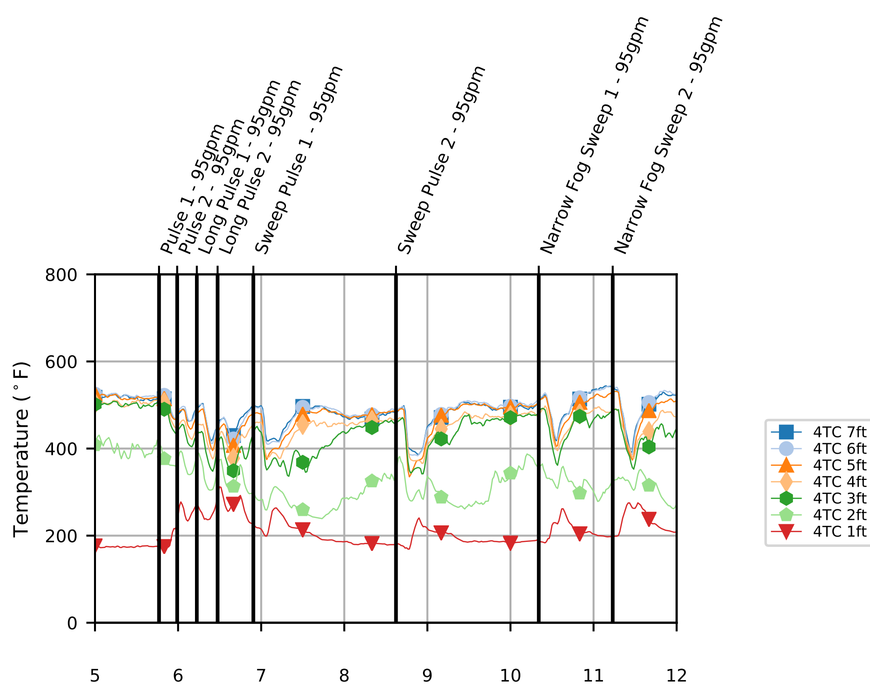


Figure E.939: Experiment 25 - 4 T C 5min to 1 2min

E.26 Experiment 26 Data

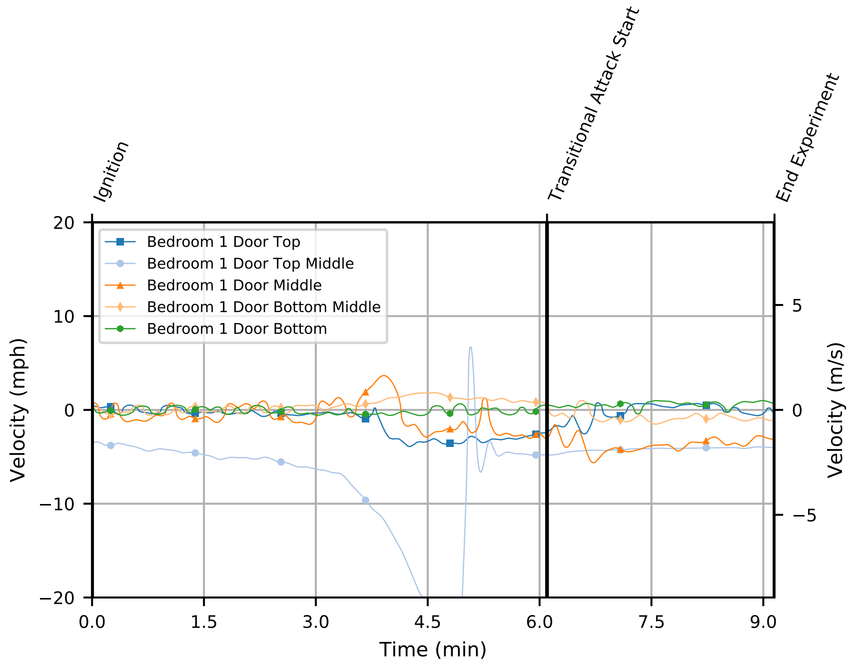


Figure E.940: Experiment 26 - Bedroom 1 Door

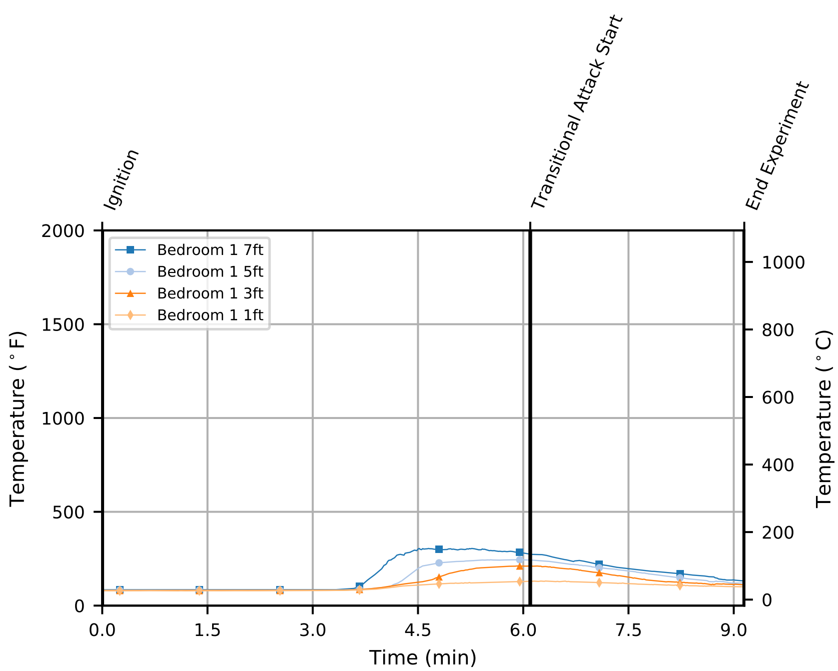


Figure E.941: Experiment 26 - Bedroom 1 Temps

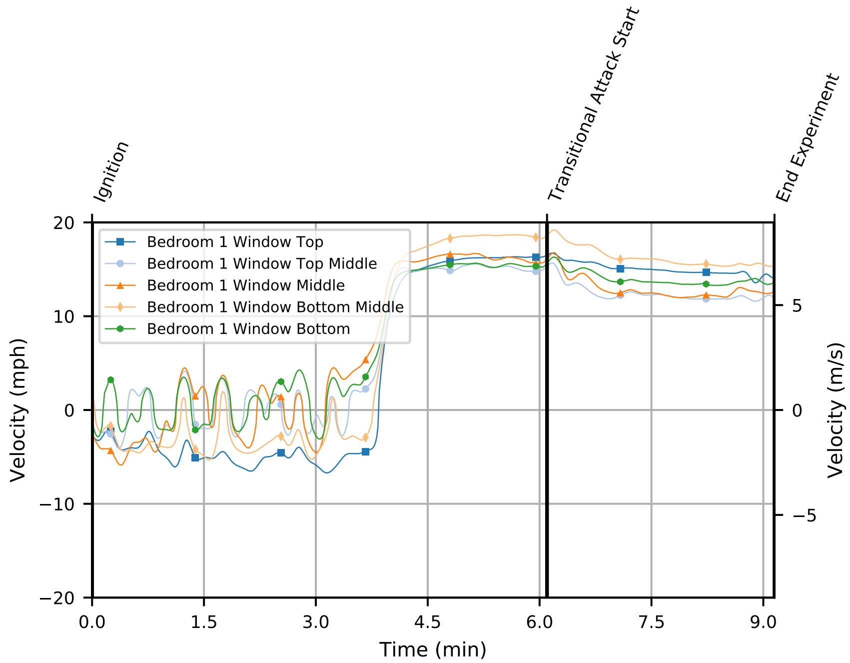


Figure E.942: Experiment 26 - Bedroom 1 Window

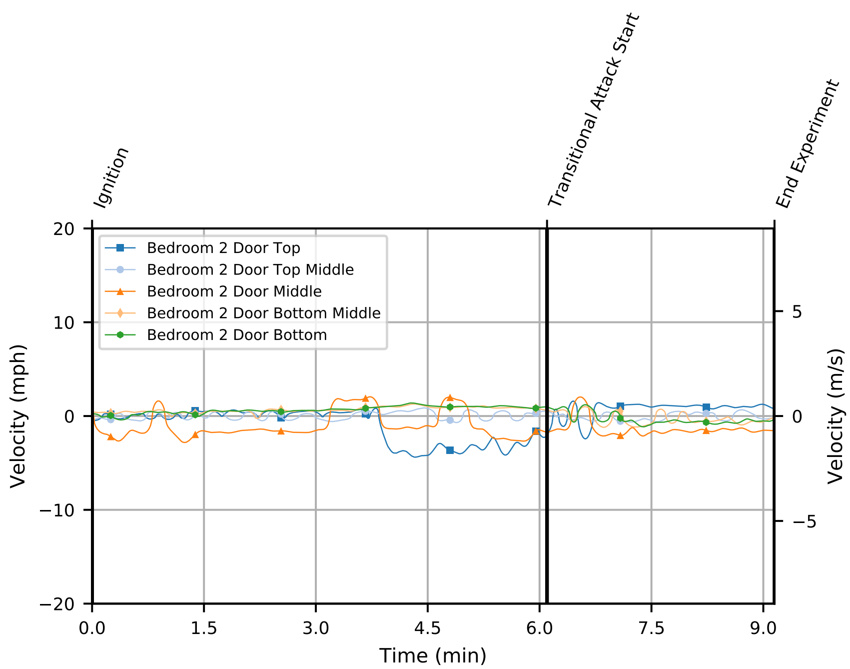


Figure E.943: Experiment 26 - Bedroom 2 Door

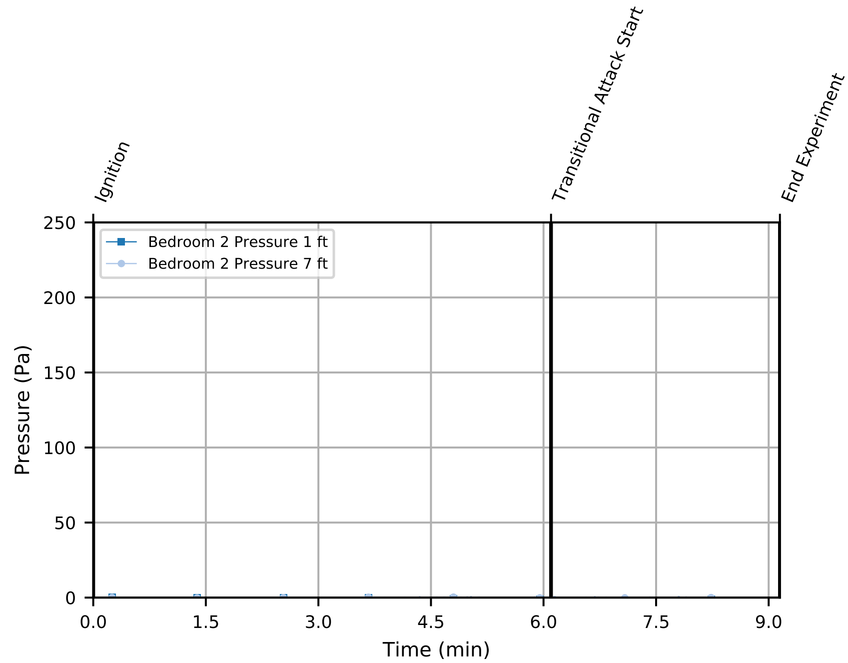


Figure E.944: Experiment 26 - Bedroom 2 Pressure

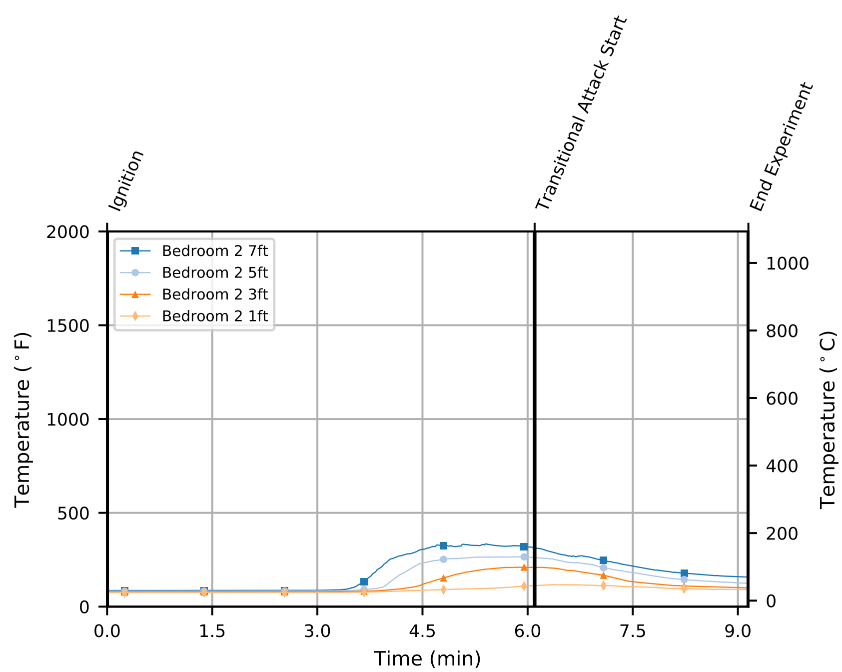


Figure E.945: Experiment 26 - Bedroom 2 Temps

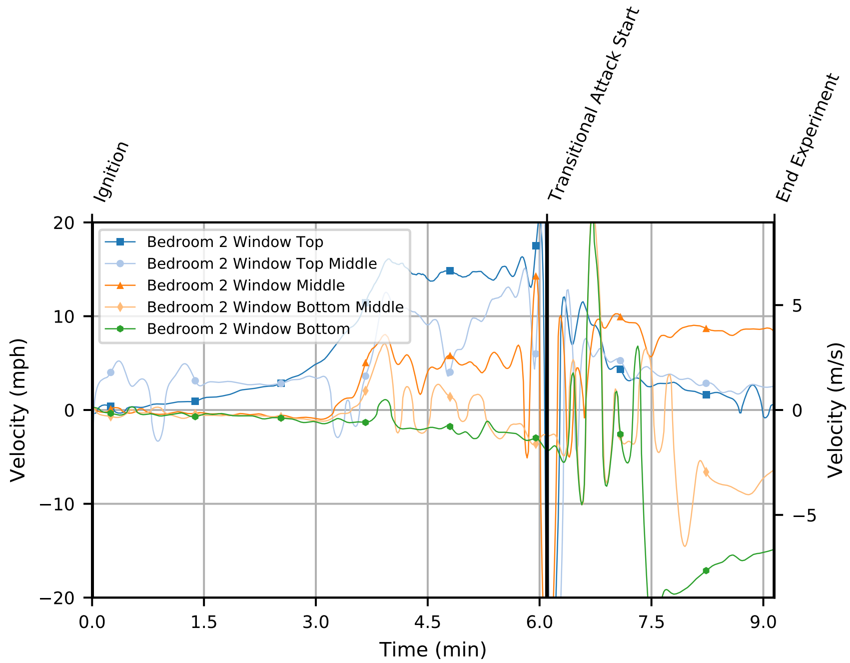


Figure E.946: Experiment 26 - Bedroom 2 Window

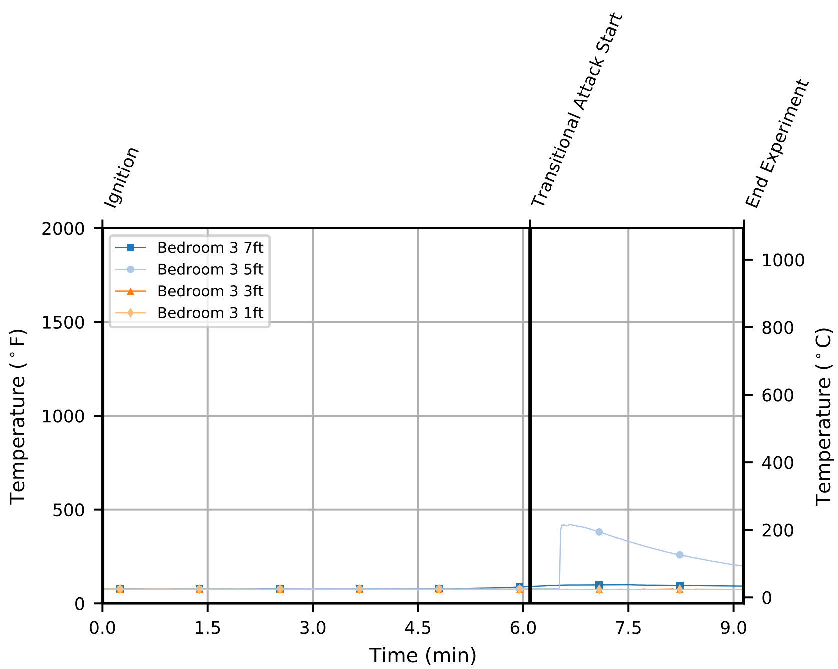


Figure E.947: Experiment 26 - Bedroom 3 Temps

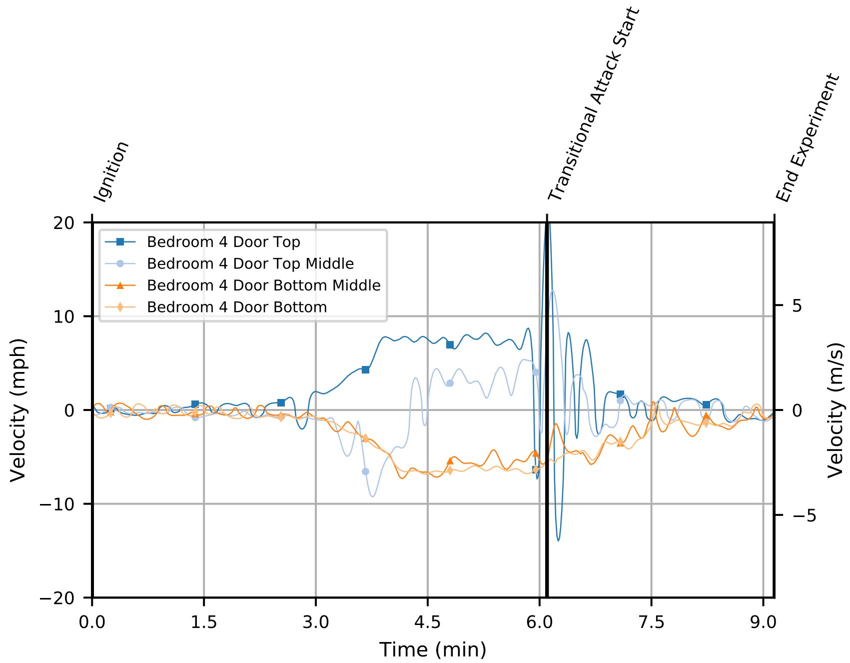


Figure E.948: Experiment 26 - Bedroom 4 Door

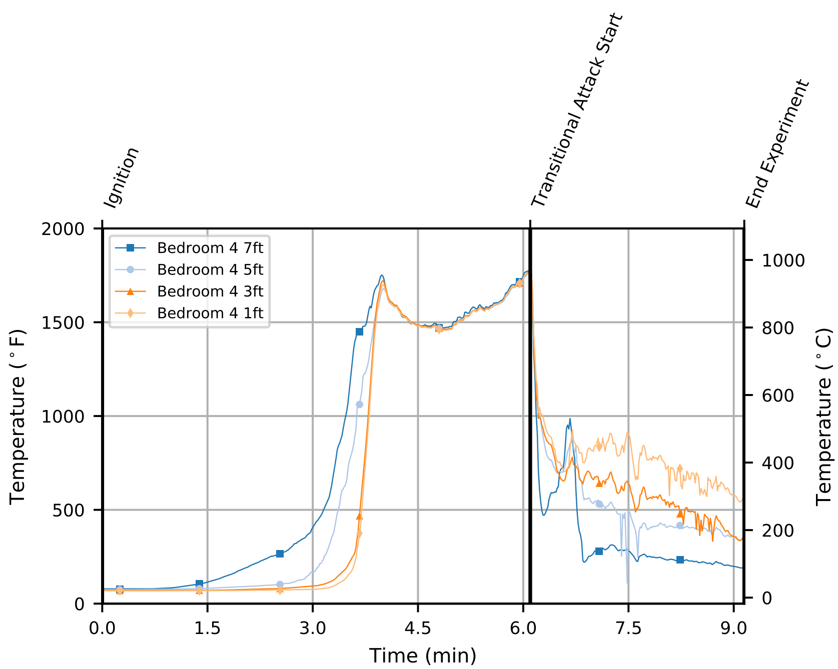


Figure E.949: Experiment 26 - Bedroom 4 Temps

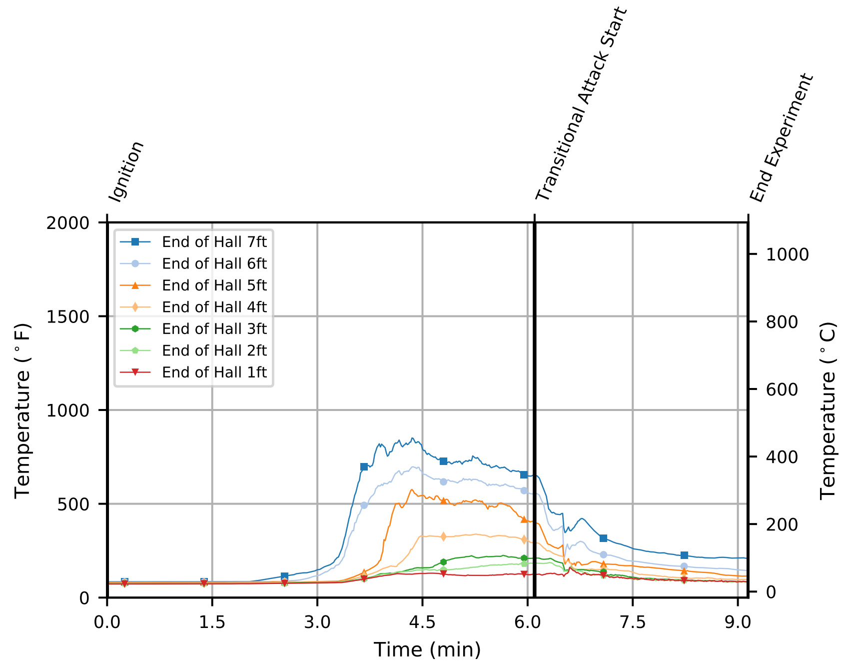


Figure E.950: Experiment 26 - End Hall Temps

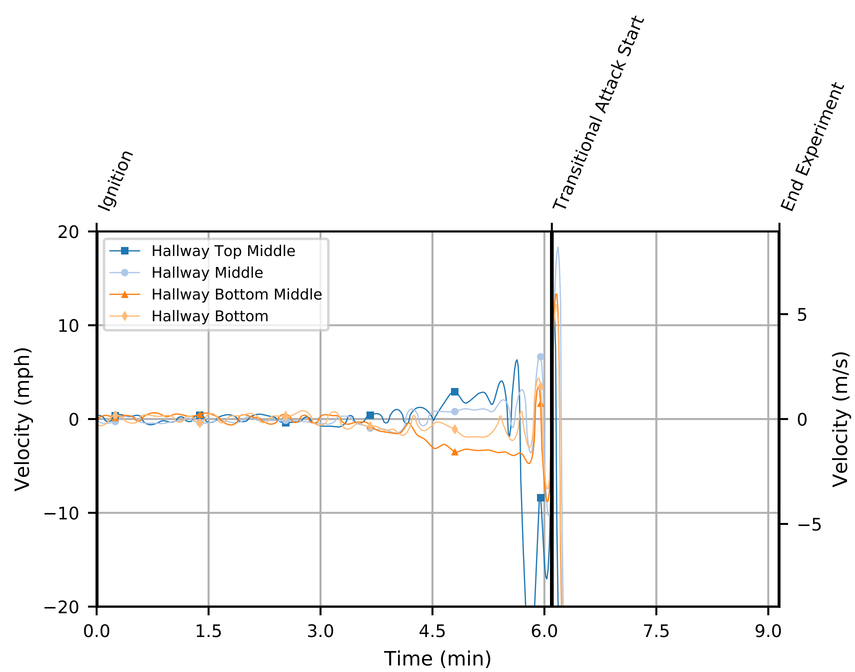


Figure E.951: Experiment 26 - Hallway Flow

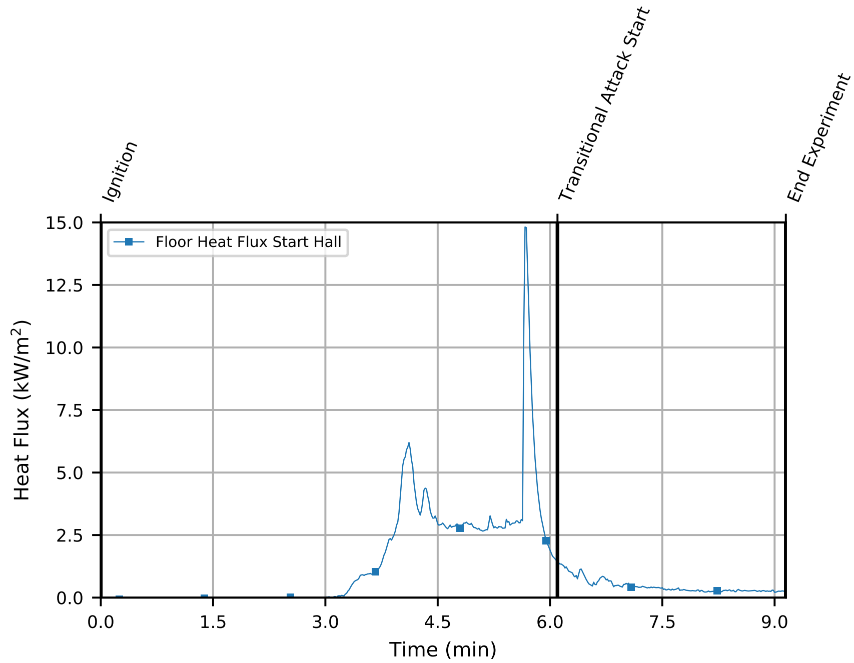


Figure E.952: Experiment 26 - Heat Flux Floor

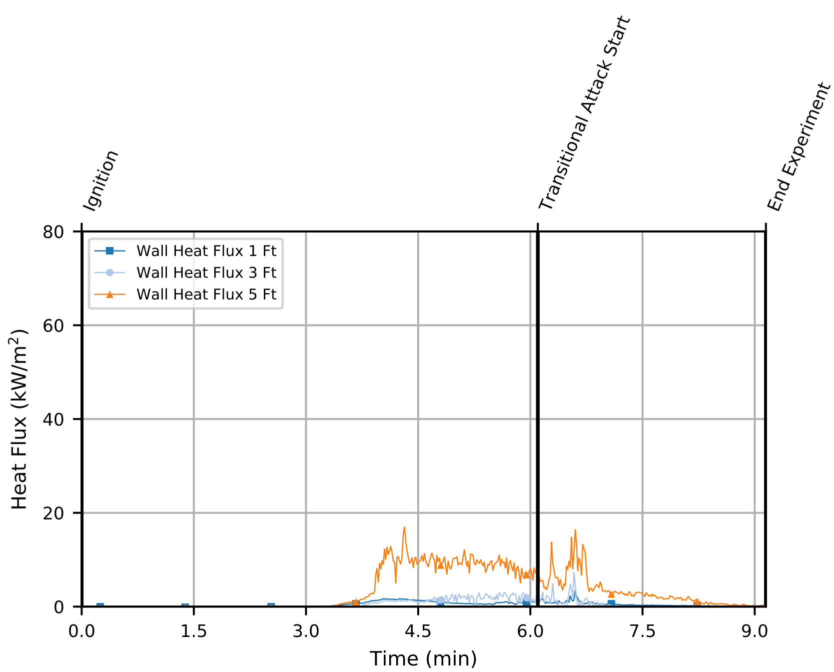


Figure E.953: Experiment 26 - Heat Flux Wall

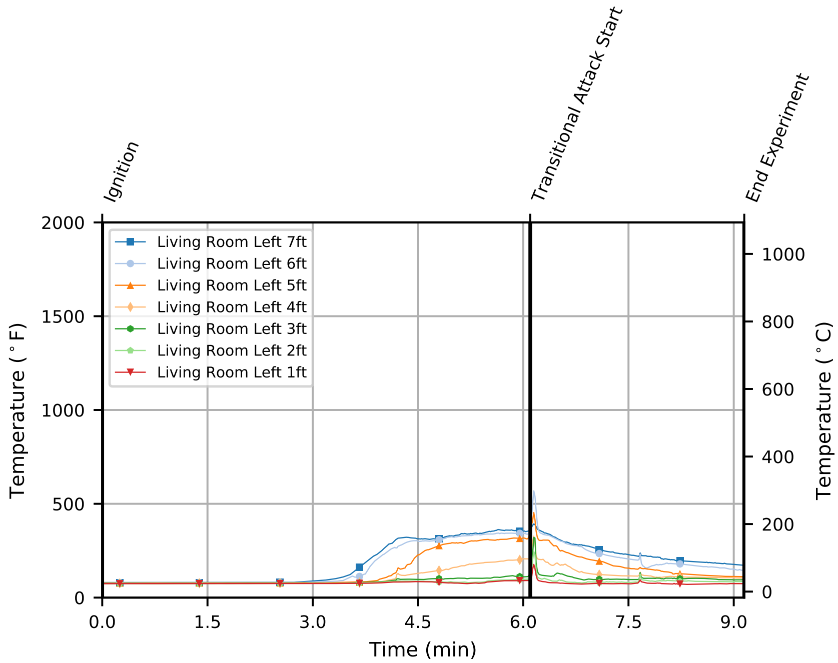


Figure E.954: Experiment 26 - Living Room Left Temps

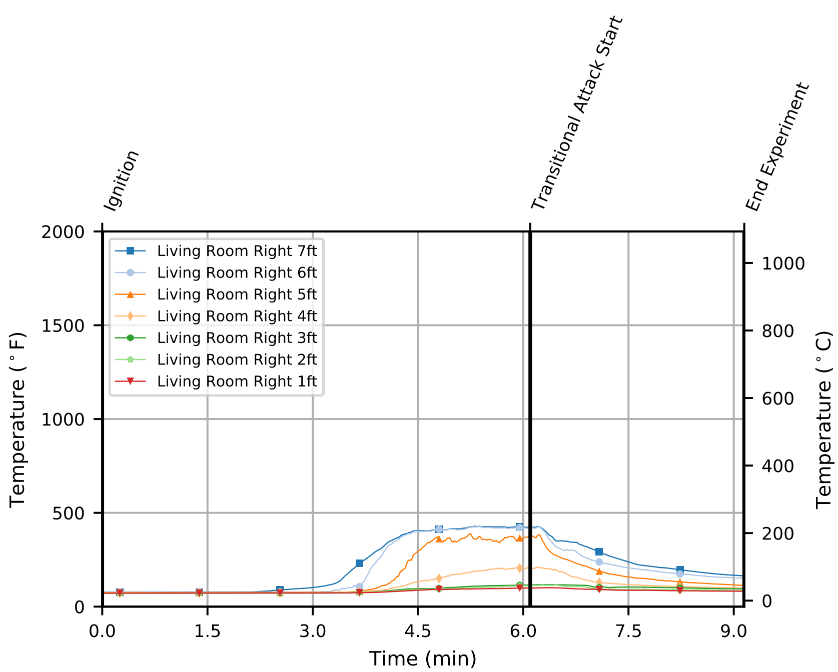


Figure E.955: Experiment 26 - Living Room Right Temps

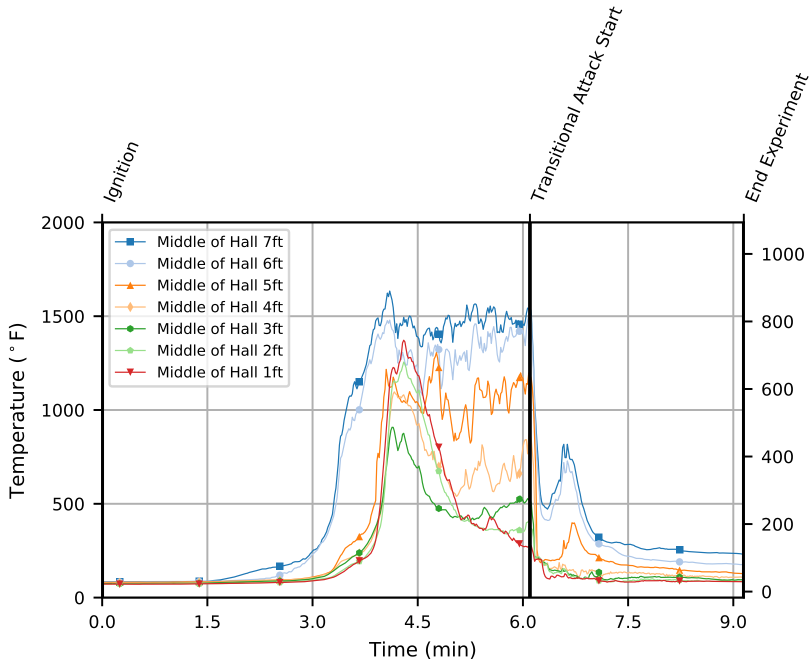


Figure E.956: Experiment 26 - Middle Hall Temps

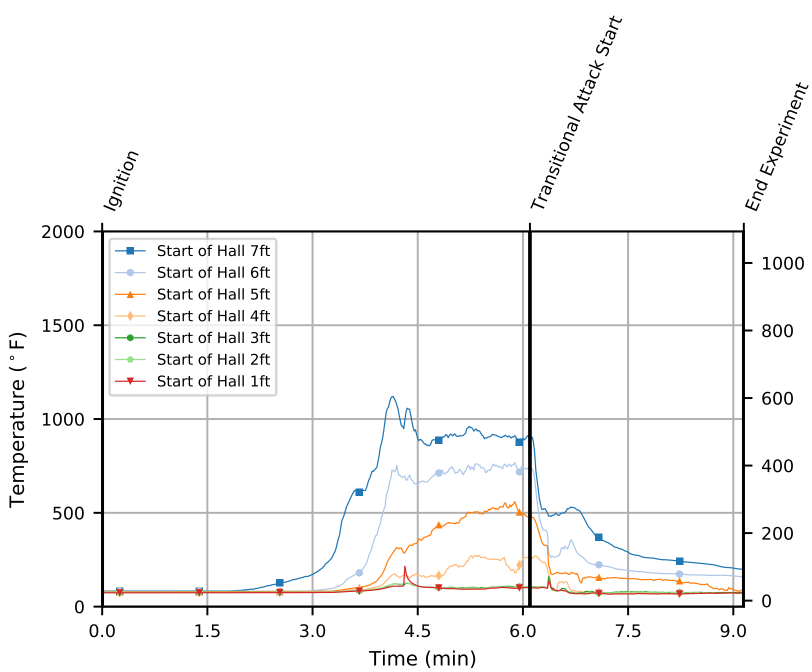


Figure E.957: Experiment 26 - Start Hall Temps

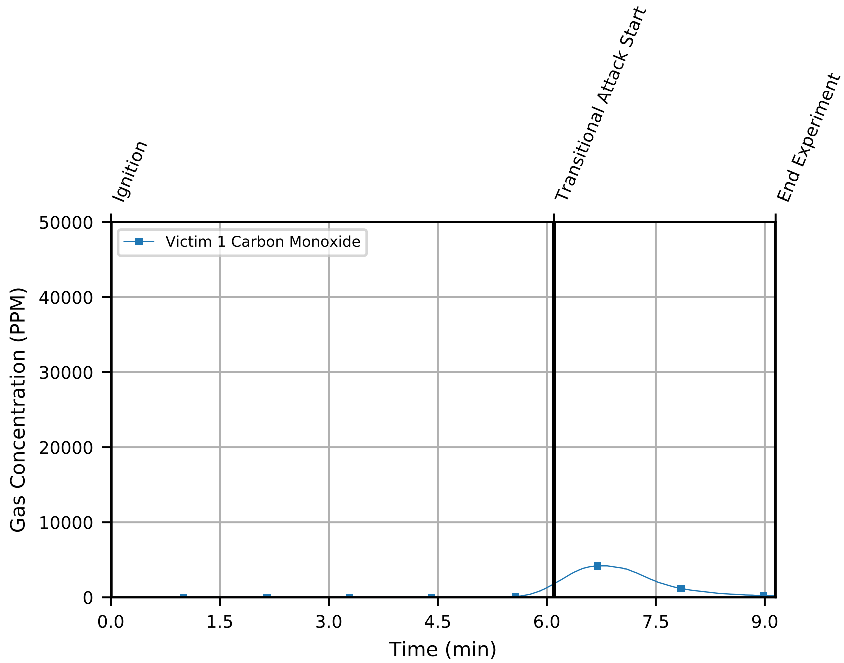


Figure E.958: Experiment 26 - Victim 1 Carbon Monoxide

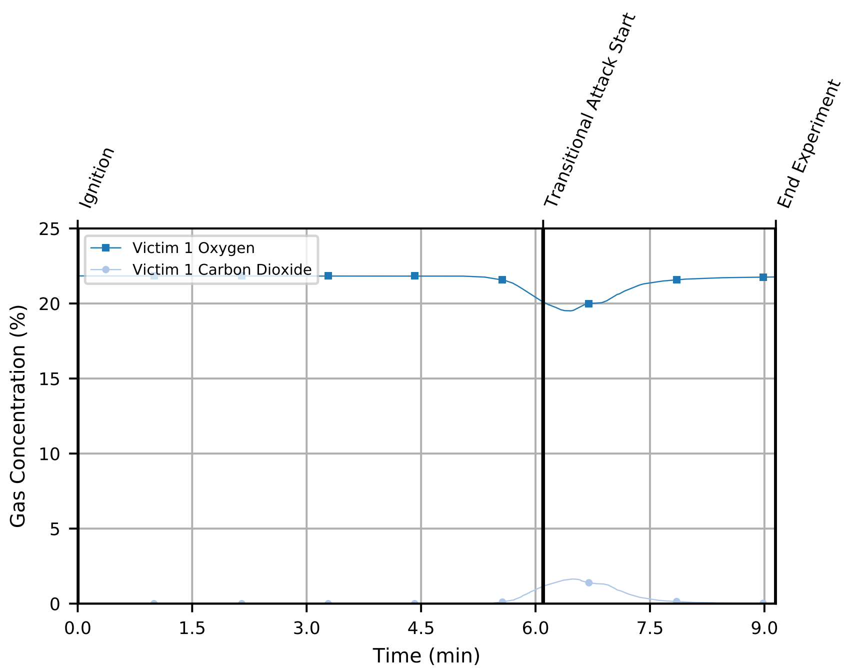


Figure E.959: Experiment 26 - Victim 1 Gas

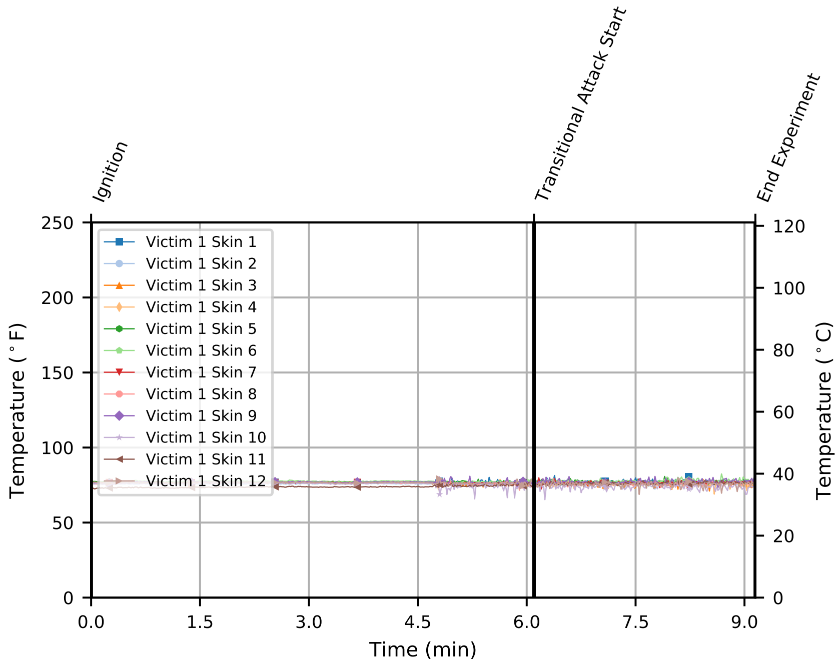


Figure E.960: Experiment 26 - Victim 1 Skin Temps

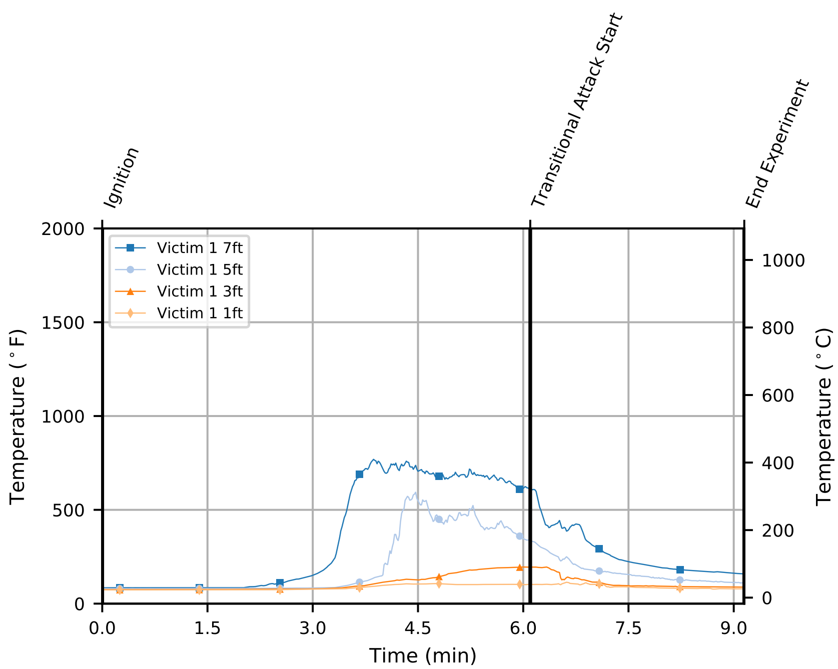


Figure E.961: Experiment 26 - Victim 1 Temps

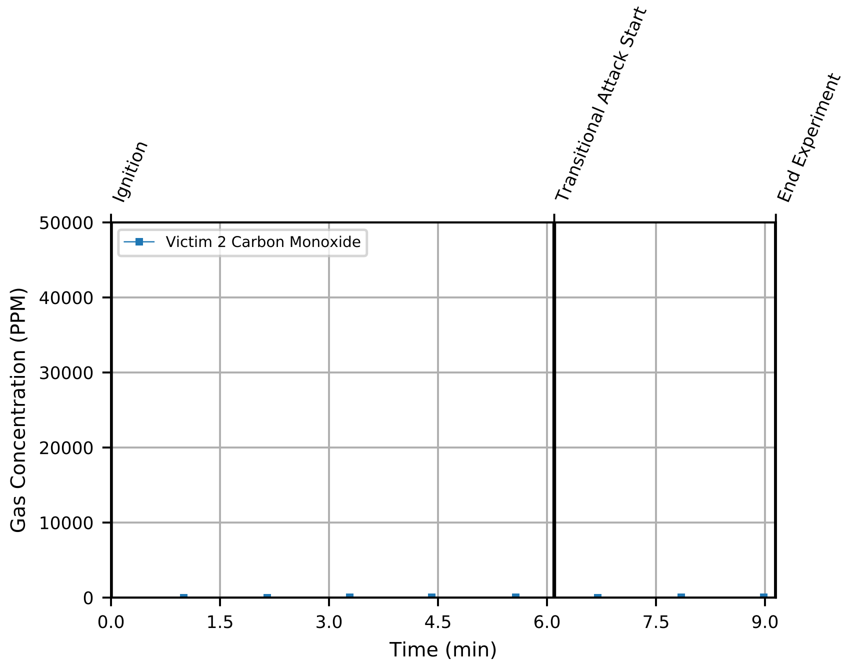


Figure E.962: Experiment 26 - Victim 2 Carbon Monoxide

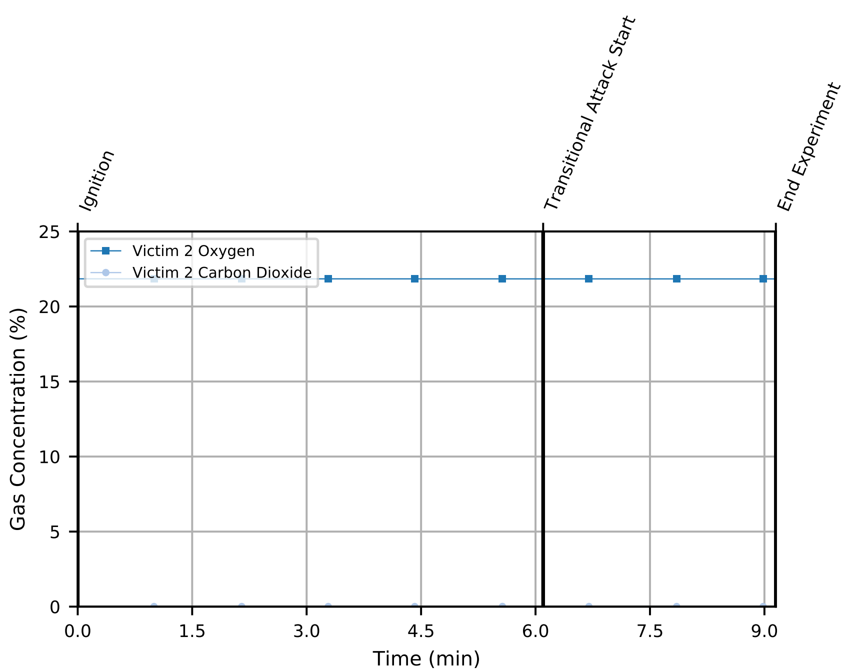


Figure E.963: Experiment 26 - Victim 2 Gas

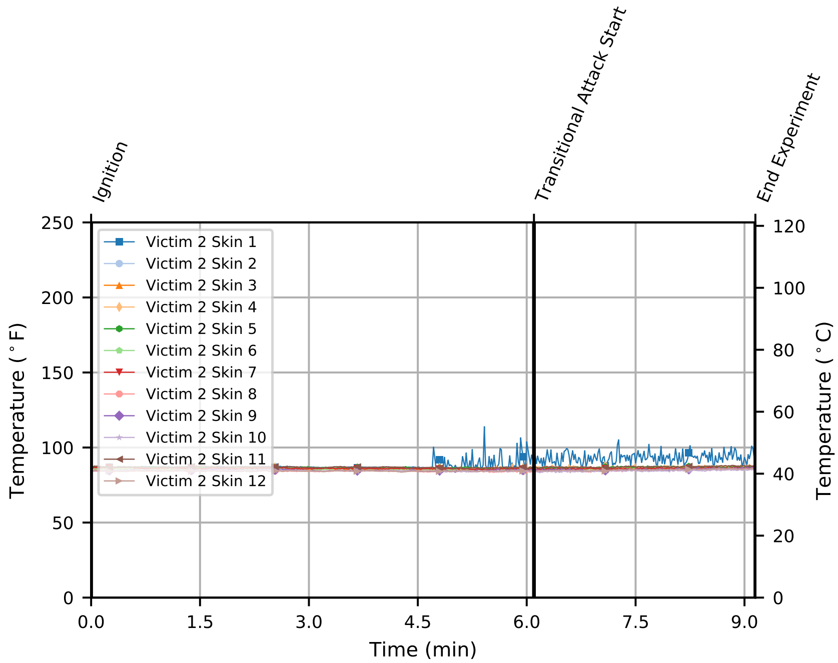


Figure E.964: Experiment 26 - Victim 2 Skin Temps

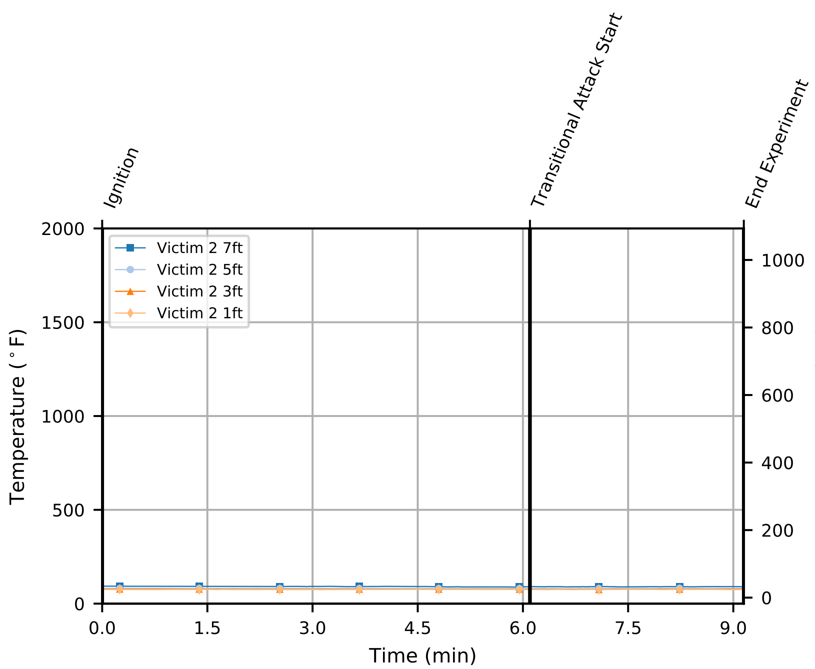


Figure E.965: Experiment 26 - Victim 2 Temps

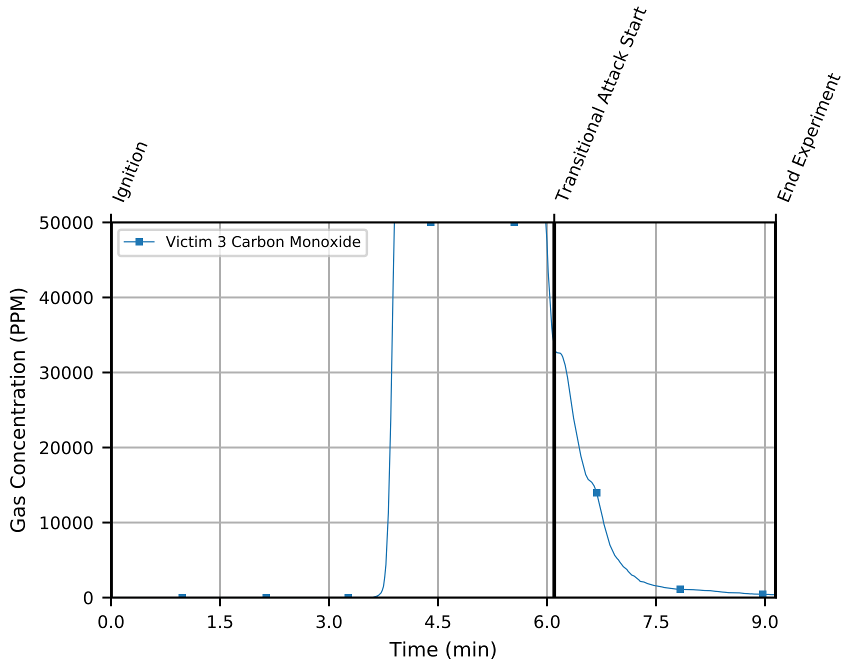


Figure E.966: Experiment 26 - Victim 3 Carbon Monoxide

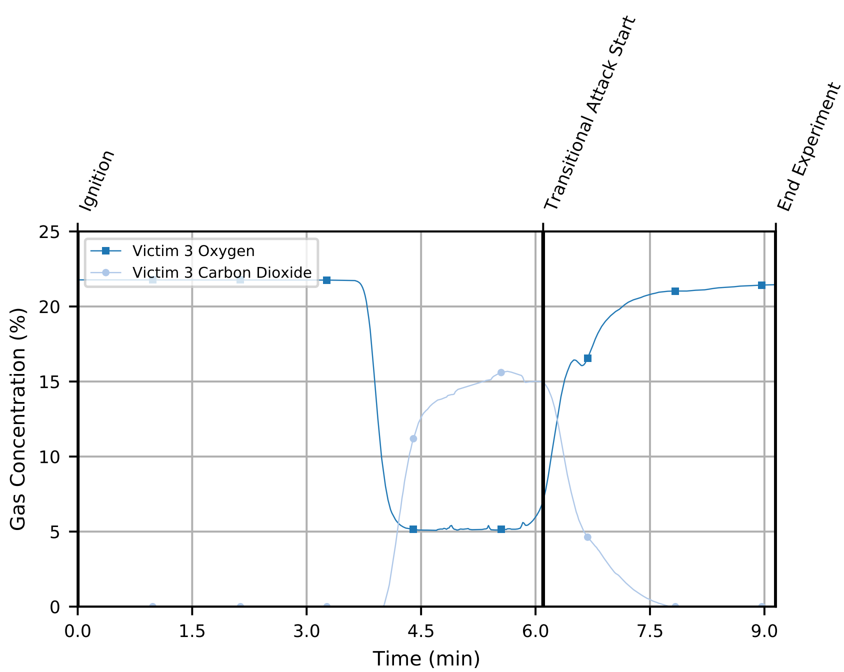


Figure E.967: Experiment 26 - Victim 3 Gas

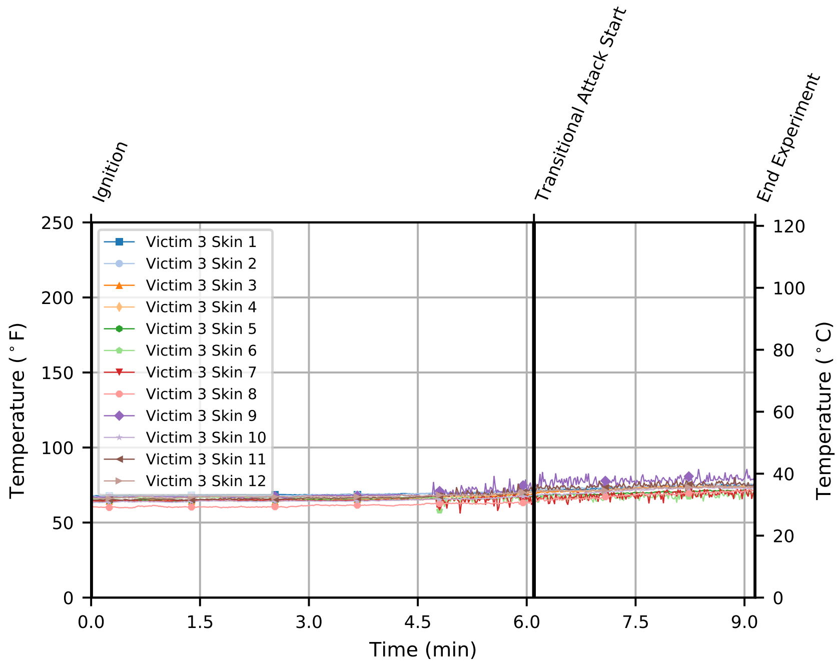


Figure E.968: Experiment 26 - Victim 3 Skin Temps

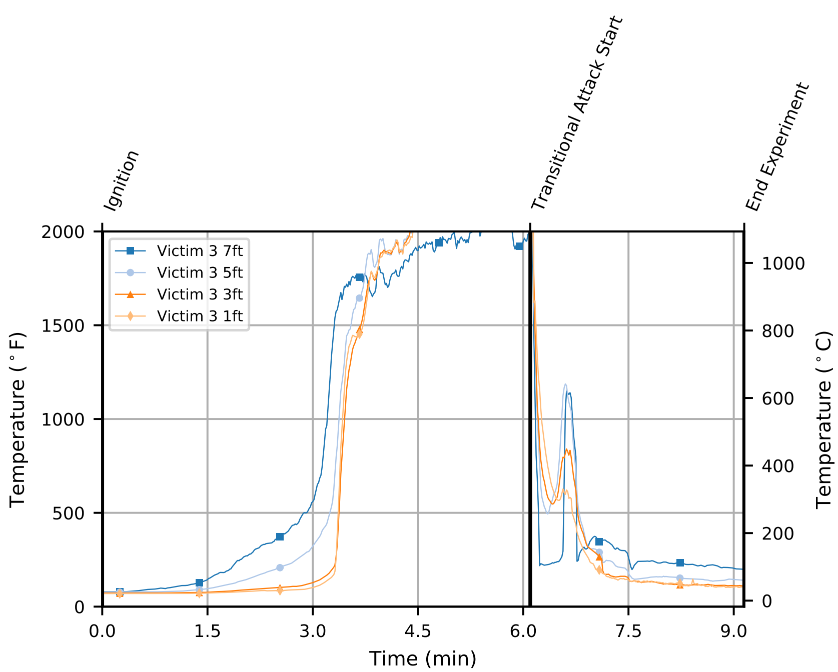


Figure E.969: Experiment 26 - Victim 3 Temps

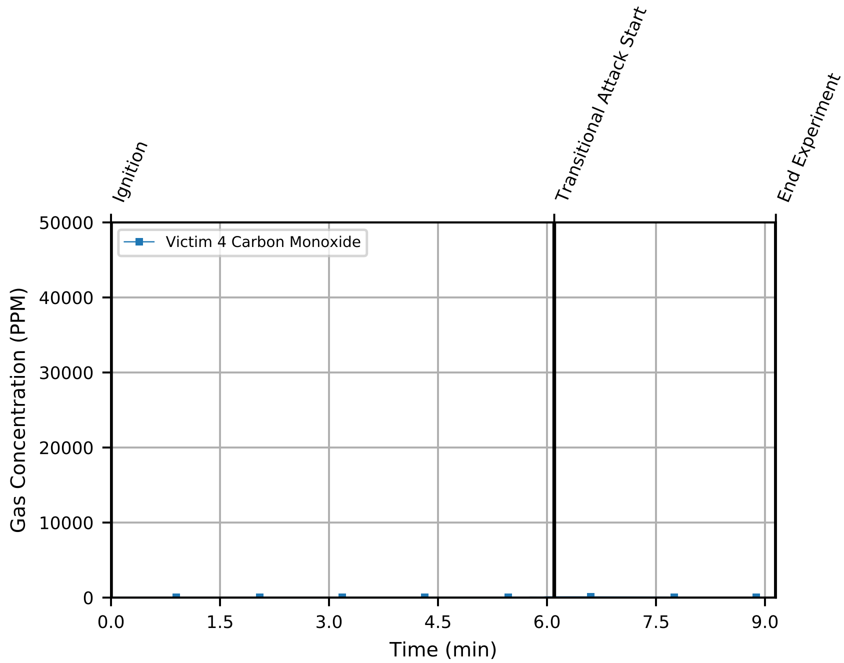


Figure E.970: Experiment 26 - Victim 4 Carbon Monoxide

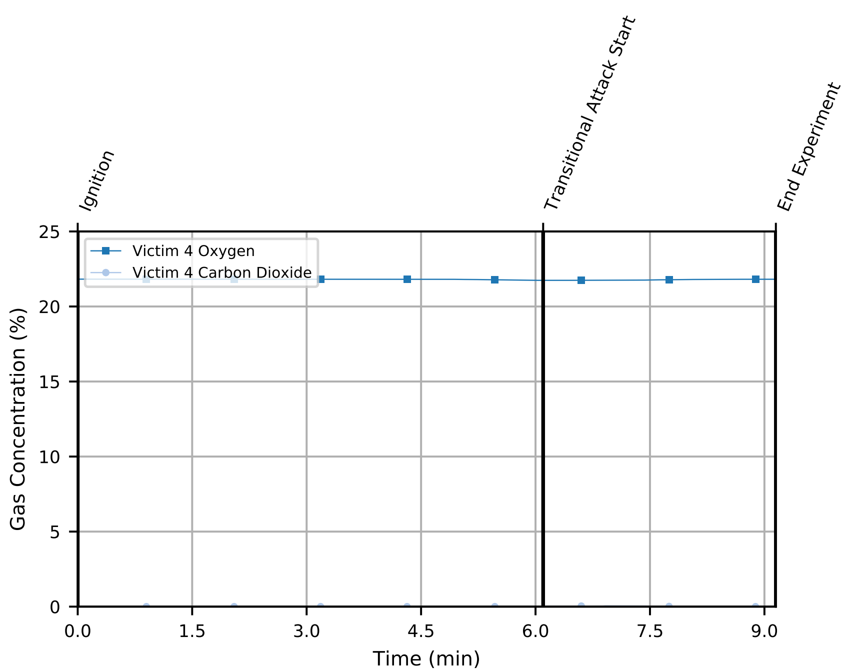


Figure E.971: Experiment 26 - Victim 4 Gas

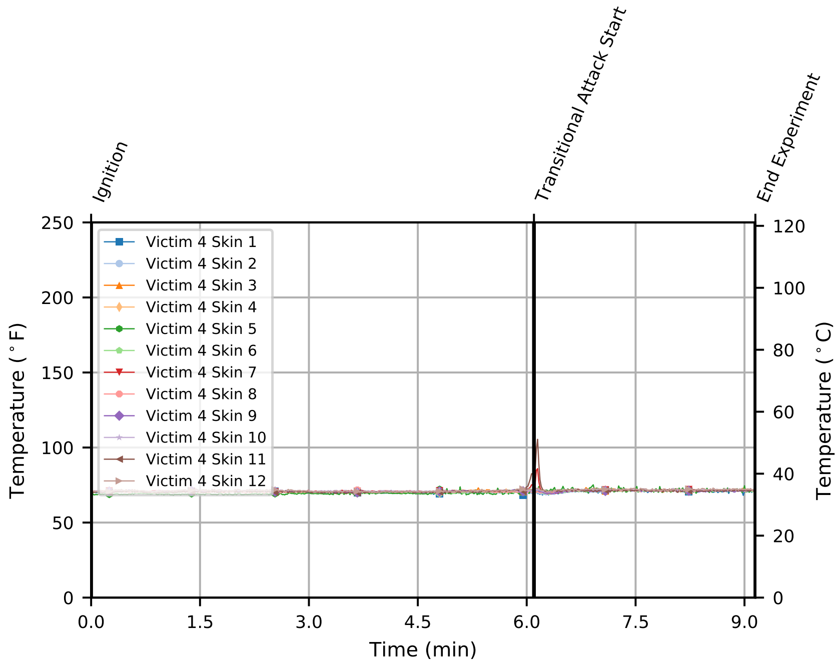


Figure E.972: Experiment 26 - Victim 4 Skin Temps

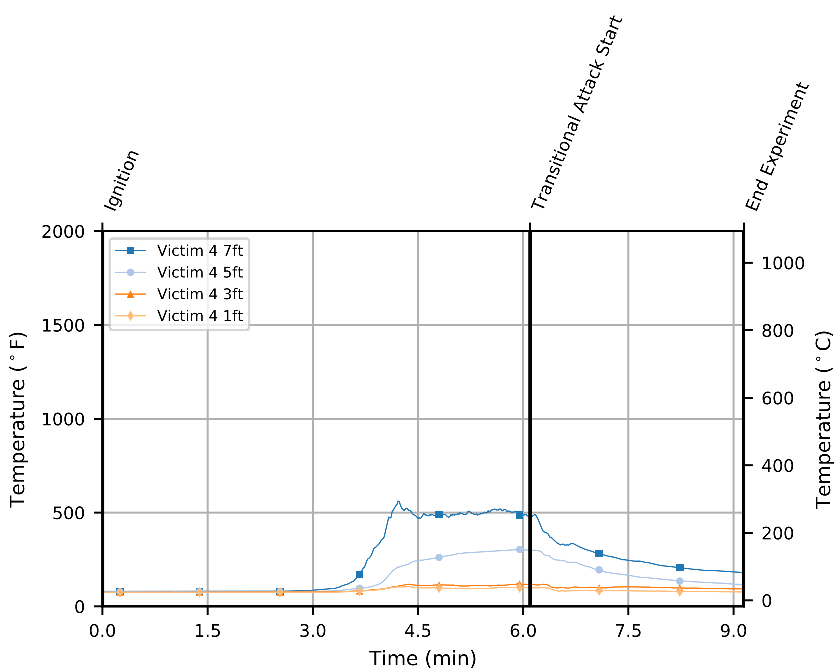


Figure E.973: Experiment 26 - Victim 4 Temps

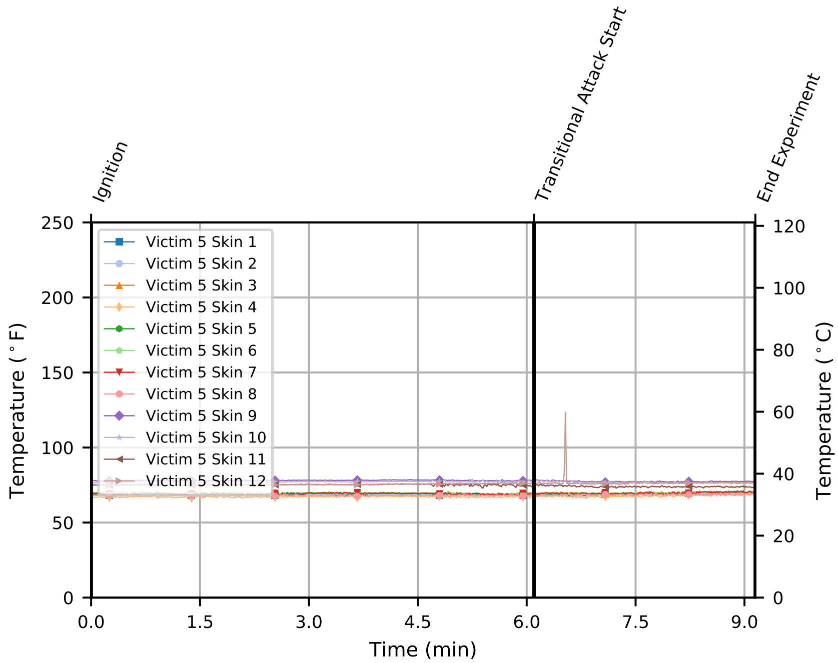


Figure E.974: Experiment 26 - Victim 5 Skin Temps

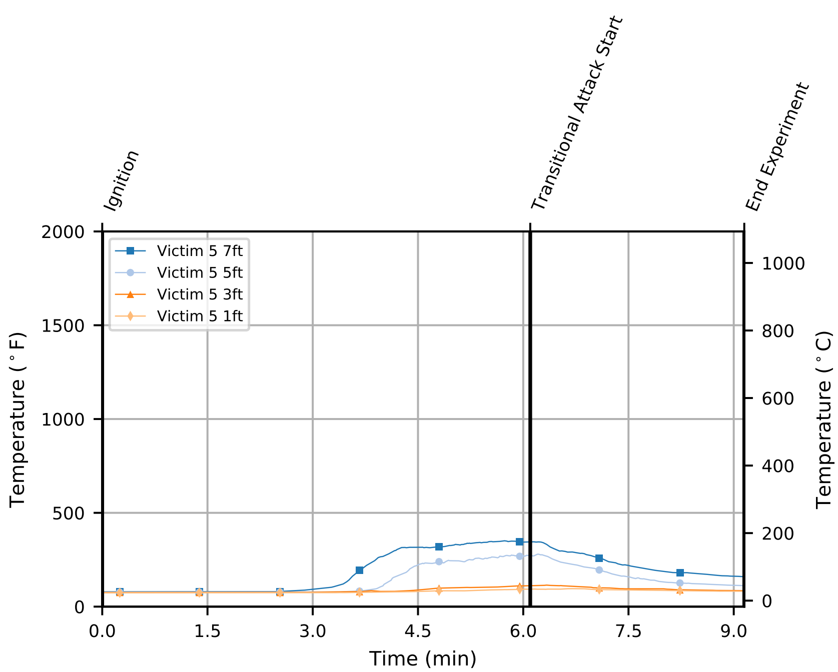


Figure E.975: Experiment 26 - Victim 5 Temps

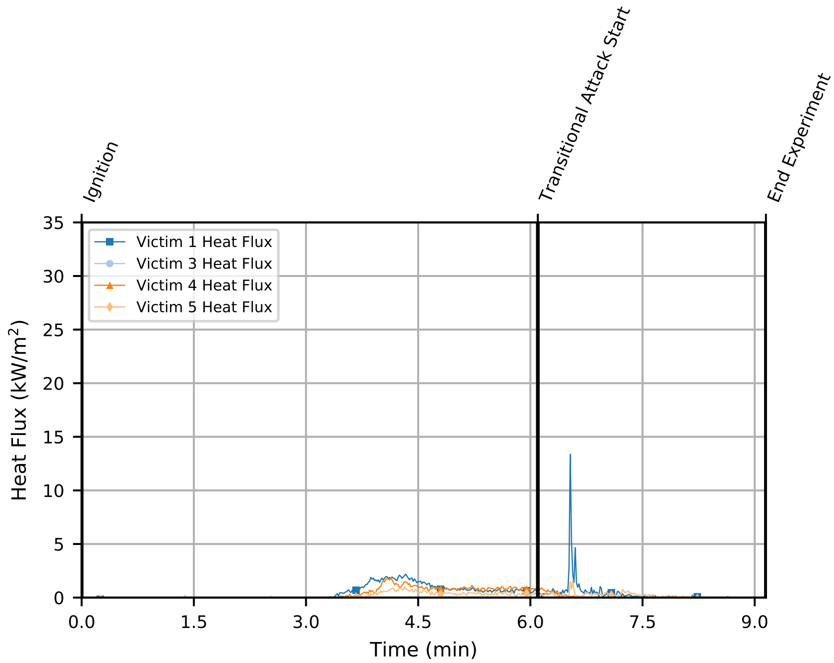


Figure E.976: Experiment 26 - Victim Heat Flux