the standard in safety

Underwriters Laboratories

Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction

Steve Kerber, PE
Research Engineer, Corporate Research

This publication is available free of charge from:
https://dx.doi.org/10.54206/102376/GIEQ2593

Issue Date: December 14, 2010

DOCUMENT INFORMATION

Release Type	ntial) ☑ External (Public)	
UL Distribution		
External Distribution	Department of Homeland Security	
Date: December 14, 2010	**Keywords:** Ventilation, Fire Behavior, Modern, Legacy	
Title: Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction		
Author(s)	**Department**	**Phone**
Steve Kerber	Corporate Research	
Reviewer(s)	**Department**	**Phone**
Thomas Fabian	Corporate Research	
Pravinray Gandhi	Corporate Research	

EXECUTIVE SUMMARY

Under the United States Department of Homeland Security (DHS) Assistance to Firefighter Grant Program, Underwriters Laboratories examined fire service ventilation practices as well as the impact of changes in modern house geometries. There has been a steady change in the residential fire environment over the past several decades. These changes include larger homes, more open floor plans and volumes and increased synthetic fuel loads. This series of experiments examine this change in fire behavior and the impact on firefighter ventilation tactics. This fire research project developed the empirical data that is needed to quantify the fire behavior associated with these scenarios and result in immediately developing the necessary firefighting ventilation practices to reduce firefighter death and injury.

Two houses were constructed in the large fire facility of Underwriters Laboratories in Northbrook, IL. The first of two houses constructed was a one-story, 1200 ft^2, 3 bedroom, 1 bathroom house with 8 total rooms. The second house was a two-story 3200 ft^2, 4 bedroom, 2.5 bathroom house with 12 total rooms. The second house featured a modern open floor plan, two-story great room and open foyer. Fifteen experiments were conducted varying the ventilation locations and the number of ventilation openings. Ventilation scenarios included ventilating the front door only, opening the front door and a window near and remote from the seat of the fire, opening a window only and ventilating a higher opening in the two-story house. One scenario in each house was conducted in triplicate to examine repeatability.

The results of these experiments provide knowledge for the fire service for them to examine their thought processes, standard operating procedures and training content. Several tactical considerations were developed utilizing the data from the experiments to provide specific examples of changes that can be adopted based on a departments current strategies and tactics.

The tactical considerations addressed include:

- **Stages of fire development**: The stages of fire development change when a fire becomes ventilation limited. It is common with today's fire environment to have a decay period prior to flashover which emphasizes the importance of ventilation.

- **Forcing the front door is ventilation**: Forcing entry has to be thought of as ventilation as well. While forcing entry is necessary to fight the fire it must also trigger the thought that air is being fed to the fire and the clock is ticking before either the fire gets extinguished or it grows until an untenable condition exists jeopardizing the safety of everyone in the structure.

- **No smoke showing:** A common event during the experiments was that once the fire became ventilation limited the smoke being forced out of the gaps of the houses greatly diminished or stopped all together. No some showing during size-up should increase awareness of the potential conditions inside.

- **Coordination:** If you add air to the fire and don't apply water in the appropriate time frame the fire gets larger and safety decreases. Examining the times to untenability gives the best case scenario of how coordinated the attack needs to be. Taking the average time for every experiment from the time of ventilation to the time of the onset of firefighter untenability conditions yields 100 seconds for the one-story house and 200 seconds for the two-story house. In many of the experiments from the onset of firefighter untenability until flashover was less than 10 seconds. These times should be treated as being very conservative. If a vent location already exists because the homeowner left a window or door open then the fire is going to respond faster to additional ventilation opening because the temperatures in the house are going to be higher. Coordination of fire attack crew is essential for a positive outcome in today's fire environment.

- **Smoke tunneling and rapid air movement through the front door:** Once the front door is opened attention should be given to the flow through the front door. A rapid in rush of air or a tunneling effect could indicate a ventilation limited fire.

- **Vent Enter Search (VES):** During a VES operation, primary importance should be given to closing the door to the room. This eliminates the impact of the open vent and increases tenability for potential occupants and firefighters while the smoke ventilates from the now isolated room.

- **Flow paths:** Every new ventilation opening provides a new flow path to the fire and vice versa. This could create very dangerous conditions when there is a ventilation limited fire.

- **Can you vent enough?:** In the experiments where multiple ventilation locations were made it was not possible to create fuel limited fires. The fire responded to all the additional air provided. That means that even with a ventilation location open the fire is still ventilation limited and will respond just as fast or faster to any additional air. It is more likely that the fire will respond faster because the already open ventilation location is allowing the fire to maintain a higher temperature than if everything was closed. In these cases rapid fire progression if highly probable and coordination of fire attack with ventilation is paramount.

- **Impact of shut door on occupant tenability and firefighter tenability:** Conditions in every experiment for the closed bedroom remained tenable for temperature and oxygen concentration thresholds. This means that the act of closing a door between the occupant and the fire or a firefighter and the fire can increase the chance of survivability. During firefighter operations if a firefighter is searching ahead of a hoseline or becomes separated from his crew and conditions deteriorate then a good choice of actions would be to get in a room with a closed door until the fire is knocked down or escape out of the room's window with more time provided by the closed door.

- **Potential impact of open vent already on flashover time:** All of these experiments were designed to examine the first ventilation actions by an arriving crew when there are no ventilation openings. It is possible that the fire will fail a window prior to fire department arrival or that a door or window was left open by the occupant while exiting. It is important to understand that an already open ventilation location is providing air to the fire, allowing it to sustain or grow.

- **Pushing fire:** There were no temperature spikes in any of the rooms, especially the rooms adjacent to the fire room when water was applied from the outside. It appears that in most cases the fire was slowed down by the water application and that external water application had no negative impacts to occupant survivability. While the fog stream “pushed” steam along the flow path there was no fire “pushed”.

- **No damage to surrounding rooms:** Just as the fire triangle depicts, fire needs oxygen to burn. A condition that existed in every experiment was that the fire (living room or family room) grew until oxygen was reduced below levels to sustain it. This means that it decreased the oxygen in the entire house by lowering the oxygen in surrounding rooms and the more remote bedrooms until combustion was not possible. In most cases surrounding rooms such as the dining room and kitchen had no fire in them even when the fire room was fully involved in flames and was ventilating out of the structure.

TABLE OF CONTENTS

1. Introduction

There is a continued tragic loss of firefighters' and civilian lives, as shown by fire statistics. It is believed that one significant contributing factor is the lack of understanding of fire behavior in residential structures resulting from natural ventilation and use of ventilation as a firefighter practice on the fire ground. The changing dynamics of residential fires as a result of the changes in construction materials, building contents and building size and geometry over the past 50 years add complexity to the influence of ventilation on fire behavior. UL conducted a series of 15 full-scale residential structure fires to examine this change in fire behavior and the impact of firefighter ventilation tactics.

NFPA estimates[1] that from 2003-2007, U.S. fire departments responded to an average of 378,600 residential fires annually. These fires caused an estimated annual average of 2,850 civilian deaths and 13,090 civilian injuries. More than 70% of the reported home fires and 84% of the fatal home fire injuries occurred in one- or two- family dwellings, with the remainder in apartments or similar properties. For the 2001-2004 period, there were an estimated annual average 38,500 firefighter fire ground injuries in the U.S.[2] The rate for traumatic firefighter deaths when occurring outside structures or from cardiac arrest has declined, while at the same time, firefighter deaths occurring inside structures has continued to climb over the past 30 years.[3] Ventilation is believed to be one significant factor that is contributing to this continued climb in firefighter deaths.

Ventilation is frequently used as a firefighting tactic to control and fight fires. In firefighting, ventilation refers to the tactic of creating a draft with an opening above or opposite the entry point so that heat and smoke will be released, permitting the firefighters to locate and attack the fire. If used properly, ventilation improves visibility and reduces the chance of flashover or back draft. If a fire is not properly ventilated, not only will it be much harder to fight, but it could also build up enough smoke to create a back draft or smoke explosion, or enough heat to create flashover. However, poorly placed or timed ventilation may increase the air supply to the fire, causing it to rapidly grow and spread. Used improperly, ventilation can cause the fire to grow in intensity and potentially endanger the lives of fire fighters who are between the fire and the ventilation opening.

While no known studies compile statistics on ventilation induced fire injuries and fatalities, the following are examples of recent ventilation induced fires that resulted in fire fighter injuries and fatalities.

1) A NIOSH fatality investigation report, 98-FO7 involved "offensive entry (that) was not coordinated with ventilation that was complete and effective" that resulted in a firefighter fatality[4];

2) A January 27, 2000 Texas residential fire resulted in one firefighter death as a result of venting through the front door causing "a thermal heat column"[5];

3) A February 29, 2008 duplex fire resulted in 1 firefighter death and 1 resident death as a result of, among other factors, "lack of coordinated ventilation". NIOSH report conclusion states "This contributory factor (tactical ventilation) points to the need for training on the influence of tactical operations (particularly ventilation) on fire behavior".[6] ;

4) A November 20, 2008 residential fire in Prince Georges County, Maryland resulted in "two firefighters involved in this incident were seriously injured. The crew from the truck company donned their PPE and SCBA and entered the structure to begin ventilation by removing windows. As additional arriving firefighters stretched another hoseline into position, flashover occurred."[7];

5) NIOSH fatality investigation report F2007-29 reports of a fire in a residential structure and states "…Horizontal and vertical ventilation was conducted and a powered positive pressure ventilation fan was utilized at the front door but little smoke was pushed out. Minutes later, heavy dark smoke pushed out of the front door…. Two victims (firefighters) died of smoke inhalation and thermal injuries.";

6) While not a residential fire, the Charleston, SC fire on June 18, 2008 that resulted in 9 firefighter deaths reported that misuse of ventilation was one contributing factor. The recent NIOSH report on this event stated "A vent opening made between the fire fighter or victims and their path of egress could be fatal if the fire is pulled to their location or cuts off their path of egress"[8];

7) Most recently a residential fire in Homewood, IL claimed the life of a young firefighter and injured another. The NIOSH fatality investigation report, F2010-10 recommends, "Fire departments should ensure that fire fighters and officers have a sound understanding of fire behavior and the ability to recognize indicators of fire development and the potential for extreme fire behavior, and, Fire departments should ensure that incident commanders and fire fighters understand the influence of ventilation on fire behavior and effectively coordinate ventilation with suppression techniques to release smoke and heat.[9]"

An alliance of the Department of Homeland Security, International Association of Fire Chiefs and the International Association of Fire Fighters created a website, www.firefighternearmiss.com, to track fire fighter near miss incidents. The National Fire Fighter Near-Miss Reporting System is a voluntary, confidential, non-punitive and secure reporting system with the goal of improving fire fighter safety. Submitted reports are reviewed by fire service professionals. Identifying descriptions are removed to protect people's identities. The report is then posted on the web site for other fire fighters to use as a learning tool. Countless reports indicate that ventilation, rapid fire progression and flashover are responsible for near miss situations. Some excerpts of the reports include:

- "While progressing further into the living area, the temperature of the room, which was about 350 degrees F, rapidly climbed to approximately 800 degrees. Smoke conditions rapidly darkened, and we proceeded to immediately exit the structure. Heat conditions worsened and I began to feel burning on my arms, legs and neck. I turned around and noticed a wall of orange flame as the room began to flash. The firefighter and I made it to the hallway and rapidly exited the structure.[10]"

- "We tracked the sound to a door that was leading to a converted garage with 15 foot ceilings. The windows were blackened, giving us a clear indication that there were possible backdraft conditions in that room. I called on the radio for ventilation to be coordinated with our fire attack. Command sent crews to the wrong set of windows.

When we opened the door and began to advance, I noticed that the entire room was burning around us. Just as I was ordering crews to retreat and regroup, a wall of flame came rushing toward us and the force of the flame knocked three 225 pound men flat on their backs. We were fortunate to be retreating when the flashover occurred. Although we all suffered minor first and second degree burns, it could have been a lot worse.[11]"

- "On arrival at a two-story house fire, we found heavy smoke coming from the 2nd. floor of the house and no visible fire. We entered with a 1 3/4" line, using the stairway. We went to the second floor to do a primary search and search for a confined fire. We advised command that we needed ventilation and a back-up on the second floor. Suddenly, smoke and heat conditions increased, and we were driven down to the landing of the stairway. My officer then told me to take the landing window out, which I did without thinking. Suddenly an explosive event occurred that knocked us down the stairway to the first floor followed by a large fire ball.[12]"

- "Arrive on scene of a 2 story 3000 square foot residential structure…Ventilation needed to take place. The ventilation occurred at the rear of the structure. I opened the front door and the smoke was rapidly being sucked back into the building. I was on my knees and looking inside the door to see what I could see. I decided to crawl inside to see where the fire was coming from. As I got to a couch that was about 8 foot inside the door, I stopped as heavy embers of fire were dropping on the floor. I found the smoke had lightened and I could see the roof. All I saw was fire. The gas vapor at the highest level of the structure was burning. I immediately retreated to the exterior of the structure through the doorway. As I turned from the front porch and looked back at the door, the fire was lapping out of the front door about 12 feet. The second line was deployed to knock that fire down and give me a chance to get farther away from the structure. When I regained my position, both hand lines were deployed at the door and the front window. The entire living room was on fire from flashover.[13]"

- "We backed out, advised the IC of the situation, and requested ventilation be performed. Two large windows were broken out behind the wood stove in the same room. The smoke layer lifted 3-4 feet. We advanced again inside just past our earlier position when the entire home flashed over. My nozzle man disappeared in flames except for his feet. I could barely see the doorway we entered but was otherwise surrounded by fire. I began dragging my partner by the feet back to the door. Initially he was resistant to this due to the fact he had rolled to his back and opened the nozzle without any apparent effect on the fire. The backup crew assisted as we exited the door. They saw that the fire had blown out the windows on our side and was impinging on both hose lines in the breezeway leading to the door connecting to the garage.[14]"

As fire grows from the initial ignited item to other objects in the room of fire origin, it may become ventilation controlled depending on how well the fire compartment (i.e., home) is sealed. During this incipient stage both the fire growth and power (heat release rate) are limited by available ventilation. If the compartment is tightly sealed, the fire may ultimately self-extinguish due to insufficient oxygen. However, if ventilation is increased, either through tactical action of firefighters or unplanned ventilation resulting from effects of the fire (e.g., failure of a window) or human action (e.g., door opened) heat release will increase, potentially resulting in ventilation induced flashover conditions. These ventilation induced fire conditions are sometimes unexpectedly swift providing little time for firefighters to react and respond.

Compounding the problem with ventilation is the changing dynamics of residential fires due to the changes in contemporary home construction including recently developed building materials and construction practices, contents, size and geometry of new homes. Many contemporary homes are larger than older homes built before 1980. Based on United States Census data homes have increased in average square footage from approximately 1600 ft^2 in 1973 to over 2500 ft^2 in 2008[15]. Newer homes tend to incorporate open floor plans, with large spaces that can contribute to rapid fire spread. The challenge of rapid fire spread is exacerbated by the use of building contents that have changed significantly in recent years, contributing to the decrease in time to untenable (life threatening) conditions. Changes include: a) the increased use of more flammable synthetic materials such as plastics and textiles, b) the increased quantity of combustible materials and c) the use of goods with unknown composition and uncertain flammability behavior.

2. Objectives and Technical Plan

The objectives of this research study are to:

- Improve firefighter safety by providing an enhanced understanding of ventilation (naturally induced and as a firefighting tactic) in residential structures.
- Demonstrate the impact on fire behavior of changes in residential construction such as those created by window types and furnishings.
- Develop tactical considerations based on the experimental results that can be incorporated into firefighting standard operating guidelines.

The objectives were accomplished through the technical plan depicted in Figure 1. The literature review was conducted to determine the gaps in research and to develop the details of the panel furnace window and door experiments, heat release rate experiment and the modern and legacy room fire experiments. The results of the panel furnace window and door experiments and the heat release rate experiment were used to develop the timeline and fuel load for the full-scale house experiments. All of the experiments were documented for the technical report and the technical report is the basis for the web based outreach program and the dissemination of the results to the key stakeholders such as the Department of Homeland Security, the fire service and other organizations in the fire protection community.

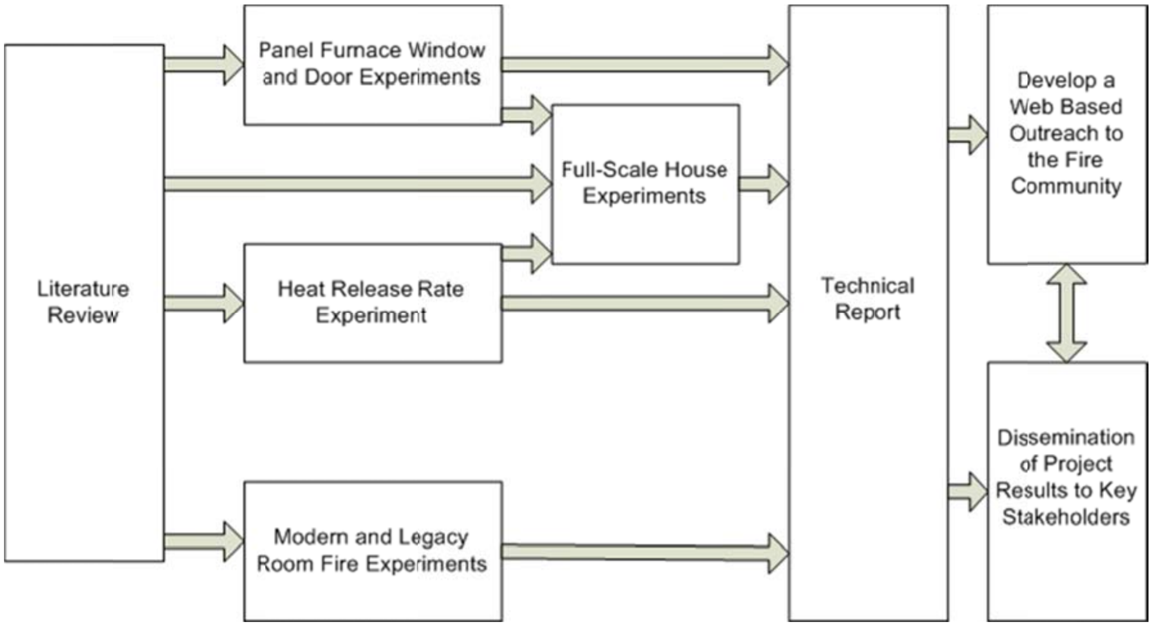


Figure 1. Project Technical Plan

3. Project Technical Panel

A technical panel of fire service and research experts was assembled based on their previous experience with research studies, ventilation practices, scientific knowledge, practical knowledge, professional affiliations and dissemination to the fire service. They provided valuable input into all aspects of this project such as experimental design and identification of tactical considerations. The panel made this project relevant and possible for the scientific results to be applicable to firefighters and officers of all levels. The panel consisted of:

- Charles Bailey, Captain, Montgomery County Fire Department (MD)
- John Ceriello, Lieutenant, Fire Department of New York
- James Dalton, Coordinator of Research, Chicago Fire Department
- Richard Edgeworth, Director of Fire Training, Chicago Fire Department
- Ed Hartin, Fire Chief, Central Whidbey Island Fire Rescue Department
- Otto Huber, Fire Chief, Loveland – Symmes Fire Department
- Dan Madrzykowski, Fire Protection Engineer, National Institute of Standards and Technology
- Mark Nolan, Fire Chief, City of Northbrook (IL)
- Stefan Svensson, Research and Development Engineer, Swedish Civil Contingencies Agency

4. Previous Literature

Prior to the start of the experimentation three topics were researched for previous studies that have been conducted, window failure, ventilation research and fire service ventiation publications.

4.1. Research on Window Failure

There have been quite a few studies done on the failure of windows. Many of these studies had very different objectives such as windows exposed to room fires, windows exposed to outside fires, glass cracking temperatures, glass fall out temperatures, thick glass windows, multi-glazed windows, radiant exposure of windows, small-scale windows, vinyl, aluminum and wood frame windows, floating glass experiments, speacial types of glass, etc. An analysis was done by Vytenis Babrauskas in 2005[16] that compiled 21 studies on glass breakage in fires. He highlights the challenges with the lack of repeatability as it pertains to glass fall out. Similar to the house experiments, glass breakage is not important if there is never glass fallout to provide oxygen to the ventilation limited fire.

Many of the studies used 4 mm to 6 mm glass which is representative of commercial applications[17,18,19,20,21]. This study utilized residential windows with glass thicknesses of 2.2 mm to 2.9 mm. Another topic that was researched was wildland fire exposure to the outside of the windows[22,23]. Two studies examined the impact of frame type[24,25]. The first study states that they had vinyl frame failure prior to the falling-out of the glazing which was not witnessed in these experiments. The only studies that utilized double glazing were also studies that utilized thick glass so their conclusions provide little importance to our needs.

The Building Research Institute of Japan[26] conducted a series of experiments on 3 mm thick window glass in a large muffle furnace. They concluded that the mean temperature of glass breaking and falling out was 340 °C (640 °F) with a standard deviation of 50 °C (120 °F).

This review concludes that factors such as window size, frame type, glass thickness, glass defects and vertical tremperature gradiant may all be expected to have an effect on glass fall-out. This study will examine many of these variables in Section 0.

Another series of experiments was conducted in 2009[27] to try to develop inputs for FDS for glass breakage and fall-out. The experiments utilized 6 mm thick glass in a compartment fire with up to a 680 kW fire and concluded that glass fall-out temperature was around 450 °C (840 °F).

An article by a fire chief in 1992[28] examines the impact of “Energy Efficient Windows” to firefighting. He explains that the negative impacts include that they keep the heat and smoke in the fire building, they are difficult to break and they severly limit firefighter egress. The author states that the windows allow for faster flashover times and pose a real problem for the fire service. A second article by a fire chief in 2008[29] restates many of the previous articles concerns. The first concern is the interference with the size-up process. Heat inside the structure is masked by the windows. The article also identifies that energy efficient windows are harder to break and harder to clean out for safe passage.

4.2. Research on Ventilation

There has been some research on ventilation but no studies on full-scale houses that examined horizontal ventilation for the fire service. To date most scientific studies focus on a single room or a couple rooms. Some studies have been done in full-scale fire training structures or single fires have been examined in acquired structures. Additional ventilation studies are done with computer models and have no supporting experiments.

Six studies were found that address fire service ventilation. The first was "Experimental Study of Fire Ventilation During Fire Fighting Operations," by Svensson in 2001[30]. This study compared natural ventilation to positive pressure ventilation in a simulated 3 room apartment in a concrete fire training faility. Fifteeen tests were conducted using a pan of heptane as the fuel source. The tests show an increased burning rate with ventilation but all of the conclusions focused on the use of positive pressure ventilation. It is concluded that coordination of different measures at the fire scene is crucial.

The second study was ""Exploratory Experiments on Backdraft in a Full Residential Scale Compartment, " by Fleischmann in 1995.[31] This study utilizes a single room to try to create backdraft conditions as the result of fire service ventilation operations. The fuel used for the experiments was methane and 18 experiments were conducted. They conclude that they were able to replicate small scale experiments but there were no conclusions about ventilation procedures.

Another study was conducted to examine backdraft conditions titled, "Some Theoretical and Practical Aspects on Fire-Fighting Tactics in a Backdraft Situation", by Gojkovic in 2001. No experiments were conducted but SOFIE computational fluid dynamics (CFD) models were run to examine underventilated fires and the impact of firefighter operations. Four tactics were examined, search and rescue, natural ventilation, positive pressure ventilation and use of the cutting extinguisher. They conclude that the choice of tactic depends on whether or not there are people left in the building, the risks one is willing to take and what resources are available.

A second study utilizing CFD modeling was conducted by Saber titled, "CFD simulation for fully-developed fires in a room under different ventilation conditions."[32] This study examined the impact of different ventilation scenarios on heat release rate, fuel total mass loss, temperature, airflow distribution, and fire duration in a single room with a sofa. Ventilation was provided by a door and window. These openings were varied in size and location during the 11 configurations. The study concludes that when the door and window were on the same wall the window size was not significant but when on opposite walls the window size had a significant impact on fire behavior. Additionally, the results showed that the location of the fire load in the room had a significant effect on the fire characteristics. There were no tactical conclusions for the fire service.

The next study, "Effect of Positive Pressure Ventilation on a Room Fire," by Kerber completed in 2005[33], was a comparison of natural and positive pressure ventilation (PPV) in a bedroom with attached hallway. Examining the natural experiment only, when the window was ventilated the heat release rate increased from approximately 2 MW to 12 MW in seconds. After ventilation, the temperatures rapidly increased from 800 °C (1470 °F) to the maximum temperature of 1050 °C (1890 °F). While most of the conclusions deal with the use of PPV the study does highlight the rapid change in conditions and the need for firefighting crews to be coordinated.

The final study by the same authoras the previous study, "Full-Scale Evaluation of Positive Pressure Ventilation In a Fire Fighter Training Building" was completed in 2006[34]. This study also was focused on PPV but half of the experiments were naturally ventilated. The fire training building the experiments were conducted in was to simulate a two story house. The fuel was wooden pallets and straw and the fires were all ventilation limited prior to ventilation. Fourteen different ventilation configurations were examined including, near the seat of the fire, remote from the seat of the fire and several different fire locations. The data suggested that natural ventilation created lower temperatures and the low elevations in the rooms. In these tests the fire did transition back to a fuel limited fire rather quickly because of the heat absorption of the concrete walls of the fire training building and the wood product fuel load. The study concludes that the growth of the fire after ventilation was influenced by the path the outside air traveled to provide oxygen to the fire. When the ventilation window was in proximity of the fire, usually in the correct ventilation scenarios as defined in the report, the initial fire growth was more rapid in the naturally ventilated tests. The average rate of temperature increase for the naturally ventilated tests was 1.91 °C/s (3.44 °F/s).

4.3. Fire Service Ventilation Publications

There are several fire service training publications and many fire service magaine articles that address ventilation. Most of the training publications are based on the criteria put forth by NFPA 1001, the standard for "Fire Fighter Professional Qualifications."[35] This standard outlines the requisite knowledge needed by the firefighter should include: Perform horizontal ventilation on a structure operating as part of a team, given an assignment, personal protective equipment, ventilation tools, equipment, and ladders, so that the ventilation openings are free of obstructions, tools are used as designed, ladders are correctly placed, ventilation devices are correctly placed, and the structure is cleared of smoke. Additional knowledge is needed on the principles, advantages, limitations, and effects of horizontal, mechanical, and hydraulic ventilation; safety considerations when venting a structure; fire behavior in a structure; the products of combustion found in a structure fire; the signs, causes, effects, and prevention of backdrafts; and the relationship of oxygen concentration to life safety and fire growth.

There are three main publications that provide firefighters with the requisite knowledge outlined above. Each of them teaches ventilation differently and each of them has their own definition of what ventilation is. International Fire Service Training Association (IFSTA) defines ventilation as, "Systematic removal of heated air, smoke, and airborne contaminants from a structure and replacing them with fresh air." Jones and Bartlett define ventilation as, "The process of removing smoke, heat, and toxic gases from a burning structure and replacing them with clean air." Delmar defines ventilation as, "the planned, methodical, and systematic removal of pressure, heat, smoke, gases, and in some cases, even flame from an enclosed area through predetermined paths." All of these definitions are generally the same, with subtle differences. One point to highlight is the inclusion of words that hint at coordination such as, systematic, process, planned, and methodical. The other important point is the mention of fresh air and clean air in the first two definitions and no mention in the third definition. The ability of air to enter during ventilation is a significant component of ventilation. Each of these publishers also generates their own training material based on the opinions, experience and practical knowledge of the committees or authors that get assembled to write them. Unfortunately, there have not been a lot of experiments done to answer many of the topics that need to be covered to meet the NFPA 1001 standard.

Of the many fire service magazine articles on ventilation, ten of them will be included in this literature review because of their relevance to horizontal ventilation and fire behavior. Much like the training books described above these articles are written based on the experience or opinion of the author. The difference in this case is that the article is written by a single author and not a committee of fire fighters.

The first of these magazine articles is Vincent Dunn's "The Danger of Outside Venting."[36] This Fire Engineering Magazine article from 1989 is written by a retired Deputy Chief of the Fire Department of New York. He had 42 years as a member of FDNY with 26 years as a chief officer. He has written numerous books and countless articles, all based on the knowledge he gained through his experiences.

In his article he describes a fire where a firefighter assigned to ventilate the rear of a two story house is met by a mother in the front yard that is panicked saying her baby is in the bedroom next to the kitchen. The firefighter ventilates the bedroom window, crawls in and saves the baby. After this dramatic story that ends in heroism Chief Dunn goes on to teach the importance of ventilation. He says, "outside venting shows that it requires knowledge, skill and determination." To prove his point he describes the hazards of operating alone, dangers around the perimeter of the structure, dangers of working off of ground ladders, dangers of window removal, the possibility of being cut off from egress by flames such as those on a fire escape and the hazards of entering the structure to search after ventilating. After these topics he defines flashover and says that signs of flashover are high temperatures in smoke filled rooms or intermittent flames at the ceiling of the room. He suggests taking your glove off, raise it to check for heat and if it is too hot to raise then flashover is possible. Dunn mentions that flashover creates temperatures of 1000 F to 1500 F and that "tests" show that skin has extreme pain at 280 F to 320 F. He says that due to the speed a firefighter can crawl, he can only be in the structure 5 to 10 feet and safely escape a flashover.

This article is typical of ventilation articles in that it explains a lot about how to ventilate and what to look out for when doing so but does not talk about why a firefighter would ventilate and what impact it would have on the conditions in the structure. It mentions flashover but does not say why flashover could occur. This highlights a significant gap in the knowledge of the US fire service. As a general rule firefighters are taught practical knowledge with little scientific foundation to support their training. Another important question that should be asked by the reader which is often not is, how valid is the knowledge in this article to me? No one would question that Chief Dunn does not have significant experience or practical knowledge, but how does his experience relate to the reader as far as available resources, types of structures, or training level. Very few places have the resources, structures or training of FDNY so is Chief Dunn's knowledge always applicable and what hazards does that cause? There are not one set of tactics or rules of thumb that apply to all fires but all fires do have to follow the rules of physics.

A second article by Comstock and Maxwell, "Firefighters' 10 Deadly Sins of the Fireground"[37] contains a discussion of 3 critical issues which are relevant to this research. "Ignoring Size-up" is the first issue which discusses the importance of looking at the type of structure, especially modern construction techniques as they may provide information about fire spread and length of time a fire has been burning. "Ignoring changing fire conditions" is the next relevant issue. The authors highlight roll-over and flameover and the importance of understanding that smoke can ignite when mixing with air. The third issue is "Ventilating late or not at all." This supports that ventilation needs to be studied and understood. It goes on to say that ventilation helps trapped occupants and helps advance the hoseline but does not mention the ability of ventilation to increase the size of the fire. Coordinating ventilation is mentioned as waiting for the hoseline to be in place.

A Fire Engineering Magazine article titled "First Due Without a Clue: Don't Let it Happen to You"[38] also discussed construction and horizontal ventilation. The authors say that the use of thermal pane windows contributes greatly to the development of flashover conditions by not allowing heat to exit the building. They reference the NFPA code on fire investigation to highlight the changes in heat release rate of natural material chair (290 to 370 kW) and newer polyurethane foam padded chair (1350 to 1990 kW). They use this information and relate it to other contents such as upholstered furniture, mattresses and electronics to make up the "ingredients for a fire scene disaster." They go on to say, "proper, well-timed venting techniques will greatly reduce the chances for flashover and backdraft. By using these, we can aggressively and more safely perform our interior attack and searches, and any trapped occupants will have increased survival time." However they don't define what proper or well-timed means.

In August 2008, Battalion Chief Ed Hartin had an article, "Flashover Fundamentals"[39] published in Fire Rescue Magazine. This article points out many of the questions we aim to answer with our study. He states, "For many years firefighters have been taught that ventilation reduces the potential for flashover…When a fire is ventilation controlled, heat release rate is limited by the available oxygen. Under ventilation-controlled conditions, increased air supply (ventilation) results in increased heat release rate and establishes a path for fire travel, which may result in flashover." He reviews several case studies that discuss this phenomena and provides guidance to identify the ventilation profile of the structures. He explains how changes in ventilation will impact that profile. Chief Hartin advises that controlling the air track will limit the potential for flashover and that an access point is also a ventilation opening.

The fifth article included in this review is "Getting the Most from Horizontal Ventilation" by Wolfe, published in Fire Engineering Magazine in 2009[40]. Wolfe compares vertical ventilation with horizontal ventilation. He argues that without preexisting openings in the roof such as skylights or scuttles that vertical ventilation takes too long and the focus should be on using horizontal ventilation to relieve interior crews and save the occupants. The coordination of crews is highlighted, "knowing when the attack team has a charged hoseline in place and is ready for ventilation will ease the operation and prevent any premature actions by the attack or ventilation team." The author concludes that horizontal ventilation hasn't been used to its fullest potential and that operations can be made safer and less destructive if used. There is no mention in this article about the impact of improper timed or located ventilation. No attention is given to the air entering the structure in this analysis.

"Gone With the Wind? Ventilation Fundamentals" was an article published in National Fire and Rescue Magazine in 2001[41]. It highlights the need to understand "systematic" ventilation by knowing the location of the fire, type of building construction, occupancy and pre-fire plan. The author, Peltier, emphasizes that for operations to be carried out effectively, there must be a person specifically in charge of the ventilation crew and the command to vent should be coordinated and come from the incident commander. Another important point is made in that "check to make sure there is a charged hoseline in place before the opening operation takes place." Peltier describes horizontal ventilation as letting smoke and hot gases out but never talks about the fresh air allowed into the structure and its potential effects.

FDNY Lieutenant Tom Donnely wrote an article, "Primary Ventilation: A Review" in Fire Engineering Magazine in 2007[42]. He focuses on the hazard that single family dwelling fires pose and that horizontal ventilation coupled with an aggressive search should be the primary firefighting tactics. He emphasizes communication and coordination as keys to a safe operation and that venting is done for 2 reasons:

- Venting for fire is done to "facilitate the movement of the hoseline attack into the fire area. We do this by releasing the products of combustion – heat and the highly flammable, toxic gases and smoke – to decrease the flame spread to reduce the possibility of flashover, backdraft or smoke explosion."
- Venting for life is defined as, "during an aggressive search effort, we vent to improve conditions for known life hazard while knowing that we may escalate the fire condition."

Another Fire Engineering Magazine article by a FDNY firefighter, Tom Brennan, was published in 2006[43]. The article titled, "Still Talking in the Kitchen…" focuses on the tactics associated with the most well-trained operations that support aggressive structural firefighting. Brennan mentions horizontal ventilation and that a mistake that is rarely detected or talked about is venting without a plan basd on size-up factors and interior aggressive offensive operations. He also describes two types of ventilation, accounting for human life and ensuring effective firefighting. "Venting for life is to open anything that will keep the interior search going-or allow entry and search of areas behind the fire before water or fans start." "Venting horizontally for fire control is to open the fire floor methodically depending on the fire location, movement of the handline, wind conditions and auto-exposure. This usually means, where the fire is going to be pushed by the nozzle, the flanks of the enclosure that the nozzle is trying to pass through and at the side that the nozzle entered from, if necessary."

The ninth fire service article is titled "Ventilation in Wood-Frame Structures" by Buffalo Fire Department Captain Peter Kertzie[44]. He shares that putting water on the fire is the most important task but ventilation makes that easier. He goes on to say that venting too early does not occur often because hoselines are put in place quickly and venting too late is dangerous and irresponsible. He adds that random breaking of windows is not right and "systematic" ventilation is what is needed. This should be based on sound firefighting essentials, fire and weather conditions, standard operating procedures, and the use of trained and experienced firefighters. Another point made is that smoke removal gets confused with ventilation and the two should be thought of as being very different. Kertzie says, " the goal of ventilation is to poke a big enough hole in the structure to let out as much heat, smoke and steam as possible." He compares ventilation to opening a bag of popcorn. The caveat he provides is that ventilation must be carried out simultaneously with the advancement of charged hoselines to save life and property. While the author mentions coordination he does not mention the fact that the fire can get larger due to the addition of air to the fire.

The final article, "When to Break the Windows" by John Carlin, Volunteer Safety Officer, was published in Fire Engineering Magazine in 2001[45]. He explains there are many types of ventilation but horizontal is the most effective on house fires, easiest to perform and least time consuming. Carlin explains that he had adverse fire conditions in a number of fires because of lack of ventilation; they were "cooked like lobsters." They learned that "beginning the ventilation process by simply breaking the right window at the right time resulted in a much more positive outcome." Again the coordination of ventilation is emphasized. He goes on to say that the window closest to the fire or in the fire area should be broken. Further the crew will have to have a charged hoseline and be ready to advance into the fire area and that premature ventilation can cause problems that are detrimental to the outcome of the firefight by increasing the intensity of the fire or pull the fire into uninvolved areas. Carlin advises, “flames can be drawn to open windows. Therefore, if you break a window in an unburned area, you can pull the fire to that area, causing greater damage.” He warns, “if the hoseline crew does not have adequate water or is not advancing into the fire area, do not break the window.” Also, “remember that a building on fire is not a green light to randomly smash every window in sight.”

From this literature search the following gaps were identified:

- Window failure data for residential windows is lacking.
- The ventilation research fell short on creating experiments that give the fire service the necessary details to ventilate intelligently.
- The fire service publications provide a lot of practical knowledge about ventilation but there are many holes to be filled, especially what is the role of the air allowed into the house during ventilation on fire growth.
- How ventilation differs in different types of houses and different house geometries.

5. Panel Furnace Window and Door Experiments

Fire performance experiments were conducted to identify and quantify the self-ventilation performance of windows, comparing legacy to modern, in a fire event prior to fire service arrival. An additional experiment was conducted to examine interior door performance. The object of this investigation was to evaluate the reaction to fire of six different window assemblies and three different door assemblies, by means of fire endurance experiments with the furnace temperatures controlled in accordance with the time-temperature curve presented in the Standard, "Fire Tests of Window Assemblies," UL 9, 8th Edition dated July 2, 2009 for windows or “Positive Pressure Fire Tests of Door Assemblies,” UL 10C, 2nd Edition dated January 26, 2009 for doors. Window performance measurements included: extent of and mechanism of failure indicated by time of initial glass breakage and size of opening; catastrophic frame failure; and other fire performance characteristics of varying window structures comparing legacy and modern windows. Each window had thermocouples inside and outside the furnace, in the center of the panes as well as near the frame. Heat flux was measured at the face of the window inside the furnace and 1 m (3 ft) back from the window outside the furnace.

Different window construction parameters assessed include: 1) wood frame and vinyl frame construction; 2) single and multi-pane designs and 3) single and multi-glazed designs. Different door construction parameters assessed include: 1) Hollow and solid core construction; and 2) different wood types. This data demonstrates and compares window and interior door performance parameters between legacy and modern window and door types. Modern windows are defined as windows that are able to be easily purchased new and that are typically found in houses constructed post the year 2000. The legacy windows used in these experiments were purchased used and are meant to be representative of windows that would be found on houses built between the years 1950 and 1970. These results were used to design specific ventilation parameters for the full-scale house fire experiments.

5.1. Full-Scale Vertical Fire Furnace

The full-scale vertical fire furnace (panel furnace) is one of three major furnaces used to evaluate the fire endurance characteristics of representative building sections. When the fire has spread and engulfed an entire room or floor, it becomes necessary to contain the fire. The building materials coupled with building construction techniques help resist the long-term effects of the fire.

Fire testing of building materials started in the early 1900s. Prior to that time, fire separations were achieved by allowing builders to use only specific materials known to hold up under fire conditions. Around the turn of the century, several new and innovative materials and construction techniques were developed. As a result, it was necessary to develop a testing procedure that evaluated these new innovations. The same basic test procedure has been used ever since.

The panel furnace (Figure 2) was originally developed to determine the fire endurance rating of wall assemblies. A representative section of a wall, 10 by 10-ft, is constructed. One side of the assembly is heated to temperatures up to 2000 °F for up to 4 hours. During the test, the wall must contain the fire and limit the temperature rise on the unheated side of the assembly. After the fire test, a water hose stream test is conducted to determine a wall's ability to resist damage from mechanical and thermal stresses. Water is flowed onto the wall using a hose to apply a uniform force to the entire wall assembly and to cool the assembly rapidly. The wall may not develop any holes during this test.

Figure 2. The Panel Furnace

5.2. Experimental Samples

Table 1 describes the designations, descriptions and dimensions of the 6 windows and 3 door samples used for the experiments. Figure 3 through Figure 11 show the samples prior to the experiments. Modern windows are defined as windows that are able to be easily purchased new and that are typically found in houses constructed post the year 2000. The legacy windows used in these experiments were purchased used and are meant to be representative of windows that would be found on houses built between the years 1950 and 1970.

Table 1. Sample Descriptions

Designation	Description	Legacy (L) or Modern (M)	Size Width (in). x Height (in.) / Glass thickness (in)
A	Wooden Frame, Two Pane, Single Glazed, Storm	(L)	30 x 46 1/2 / .093
B	Vinyl Clad Wood Frame, Two Pane, Double Glazed	(M)	30 1/2 x 56 7/8 / .087
C	Wood/Metal Frame / Nine Pane over One Pane, Single Glazed	(L)	25 5/8 x 59 1/2 / .115
D	Premium Plastic Frame, Two Pane, Double Glazed	(M)	28 x 54 / .087
E	Plastic Frame, Two Pane, Double Glazed	(M)	28 1/2 x 54 1/2 / .088
F	Premium Wooden Frame, Two Pane, Double Glazed	(M)	29 x 57 / .089
1	Door – Flush Oak, Hollow Core	N/A	30 x 80
2	Door – Six Panel Molded, Hollow Core	N/A	30 x 80
3	Door – Six Panel Pine, Solid Core	N/A	30 x 80

Figure 3. Sample A

Figure 4. Sample B

Figure 5. Sample C

Figure 6. Sample D

Figure 7. Sample E

Figure 8. Sample F

Figure 9. Sample 1

Figure 10. Sample 2

Figure 11. Sample 3

5.3. Construction of the Experimental Assemblies

Three assemblies were installed into a wood stud and drywall plug. The plug was then installed into a masonry wall. The plug was 145 3/4 in. wide and 85 3/4 in. high; the three openings for the window assemblies were framed with 2 by 4 dimensional lumber, 32 in. wide and 62 1/2 in. high. These openings were located 19 in. apart and 12 in. off the bottom edge. A 2 x 6 header was the top edge of the opening. Figure 12 provides details for this assembly. The exposed surface was covered with 1/2 in. non-rated gypsum wallboard. The masonry wall was constructed on a 4 in. concrete sill with solid block and a steel lintel. The wall had an opening 146 in. wide and 86 in. high with two 8 in. wide by 16 in. long columns built flush with the exterior of the exposed side. The columns served to split the opening into thirds. An experimental assembly is presented in Figure 13.

The experimental samples were installed into the plug opening so that the samples were flush on the exposed surface with the drywall. A 3 in. drywall frame was attached to protect any exposed lumber needed for the custom fit of each window. The windows were orientated such that the furnace exposed side would be the interior side of the window.

After the completion of the window experiments, one of the window plugs was modified to fit three, 3 ft. x 7 ft. pre-hung doors with wood frames for the last and final experiment. The door openings were created by removing portions of each window slot that included the removal of the window header and vertical supports. The pre-hung doors were latched closed with passage type locksets and were hung with the hinges provided by the door and frame manufacturer. The wood door frames were secured to the stud wall with fasteners through the each jamb. Strips of non-rated gypsum wallboard were then used to simulate the casement trim around the door opening.

Upon completion, the frame was lifted into the masonry opening. The frame was drilled and then secured to the wall with screws through the frame and metal plates. The metal plates were attached to the masonry wall.

Figure 12. Unexposed Side of Frame

Figure 13. Exposed Side of Frame

5.4. Instrumentation

Each window was instrumented with eight - 0.5 mm (0.02 in) nominal diameter type K bare bead thermocouples and two Schmidt-Boelter heat flux gauges. Each window pane had a thermocouple in the center and in the lower left corner, on both sides of the glass to measure the temperature difference between the inside and outside of the glass. It also measured the difference in temperature between the center of the window pane and near the frame. The thermocouples were bent so that they touched the glass but they were not glued or fixed to the glass in any way. A heat flux gauge was installed 10 in. below each window such that the face was flush with the gypsum board on the exposed side of the furnace to measure the heat flux the windows or doors were exposed to. An additional heat flux gauge was placed centered on the top pane of the window, 36 in. back from the face of the wood stud wall. This gauge measured the heat flux transmitted through the upper window pane (Figure 14).

Each door was instrumented with 4 - 0.5 mm (0.02 in) nominal diameter type K bare bead thermocouples and 1 Schmidt-Boelter heat flux gauges. Thermocouples were placed in the top center of the door and bottom center of the door, both on the exposed and unexposed side. The thermocouples were bent so that they touched the door but they were not glued or fixed to the door in any way. A heat flux gauge was placed centered on the top half of the door, 36 in. back from the face of the wood stud wall. This gauge measured the heat flux transmitted through the door at failure (Figure 15).

Video cameras were placed with a field of view that focused on each window or door. A thermal imaging camera was placed to look at the entire frame.

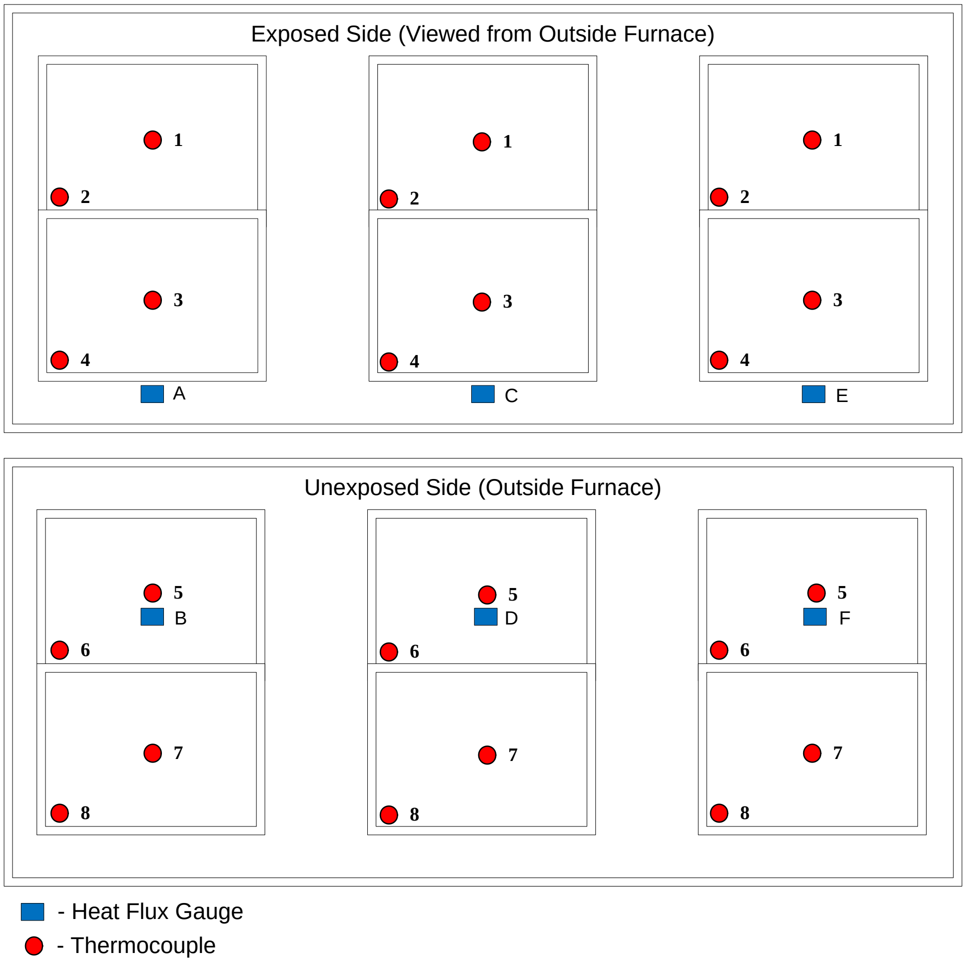


Figure 14. Window Instrumentation locations

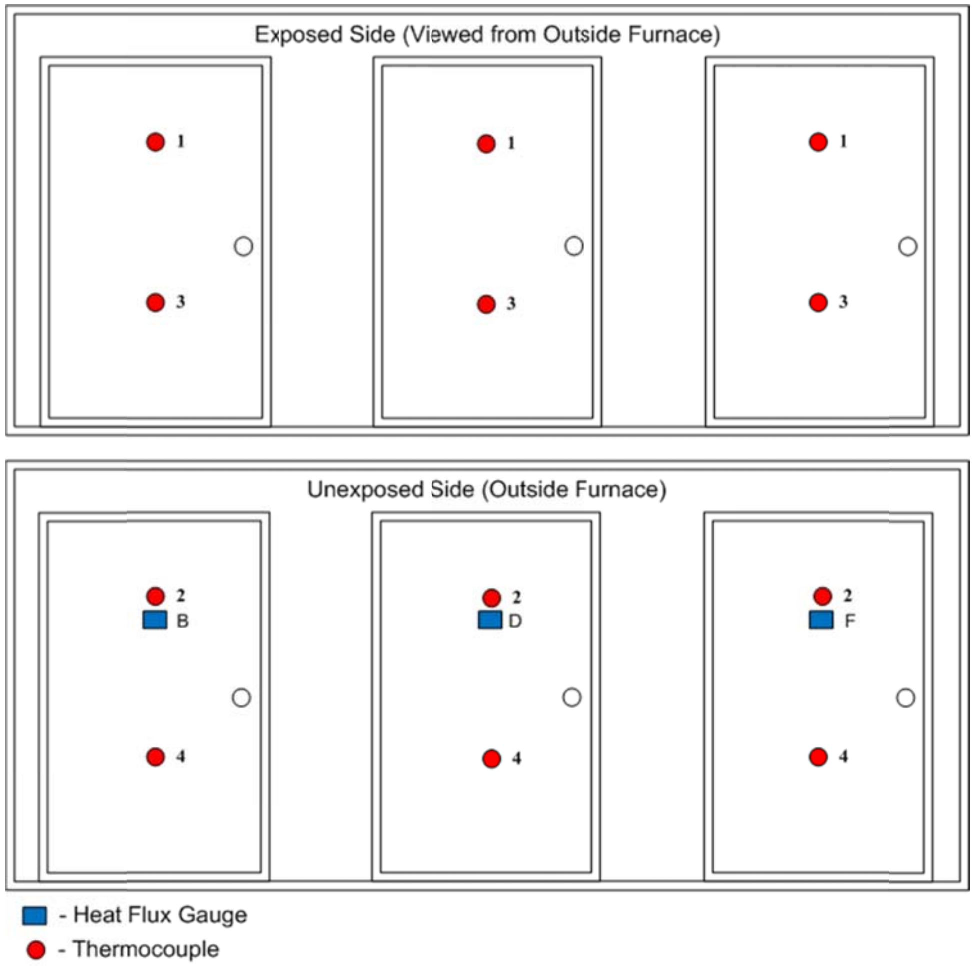


Figure 15. Door Instrument Locations

5.5. Experimental Methodology

The first 3 experiments were conducted with samples A, B and C. In each experiment, the windows were rotated to the next slot in the frame until every window was tested in each location (A-B-C, C-A-B, B-C-A). Experiments 4 through 6 were conducted with samples D, E and F and were rotated just as the first 3 were (D-E-F, F-D-E, E-F-D).

The furnace temperatures were controlled in accordance with the time-temperature curve presented in the Standard, "Fire Tests of Window Assemblies," UL 9, 8th Edition dated July 2, 2009 for windows. The furnace temperatures followed for the door experiment is presented in the standard "Positive Pressure Fire Tests of Door Assemblies," UL 10C, 2nd Edition dated January 26, 2009 for doors. The furnace temperatures were measured with twelve thermocouples symmetrically located in the furnace chamber positioned approximately 6 in. (152 mm) from the exposed face of the assembly.

Throughout the experiments, observations were made to note the character of the fire and its control, the condition of the exposed and unexposed surfaces and of all developments pertinent to the fire performance of the assembly with particular reference to window melting, cracking, breaking and falling out, heat transmission, passage of flame and generation of smoke.

5.6. Window and Door Experiment Results

5.6.1. Experiment 1

The appearance of the unexposed surface of the assembly before the fire endurance experiment is shown in Figure 16. The assembly had, from right to left on the unexposed side of the same, experimental windows A – B – C.

Observations during Experiment 1 are detailed in Table 2. Observations are from the unexposed side unless otherwise noted. The average furnace temperature is graphed versus time in Figure 17. Window temperatures are graphed in Figure 18 through Figure 20. The heat flux for all three windows is graphed versus time in Figure 21.

Figure 16. Experiment 1 Setup

Table 2. Experiment 1 Observations

Time (min:sec)	Observations
0:00	Gas on
1:00	Sample C, the top panes had begun to crack.
1:30	Sample C, smoke had begun to emit from the crack.
1:45	Sample B, top exposed internal pane had broken out.
2:00	Sample B, developed a crack on the top exterior pane.
2:40	Samples A and C, developed a hole in the bottom pane.
4:07	Sample B, top interior pane had broken out.
4:24	Sample B, top exterior pane had broken out.
5:30	Sample C, center sash had started to burn on the exterior.
6:34	Sample A, the bottom pane had broken out.
7:10	Sample B, the top of the exterior frame had ignited.
7:40	Sample B, a hole had developed in the bottom pane.
9:00	Sample C, the entire exposed surface of the top wood muntins were burning.
11:49	Sample C, top sash had slid down to the bottom of the window assembly.
12:00	Gas off.
12:08	Sample C, the top sash, which had slid to the bottom, had fallen out of the assembly

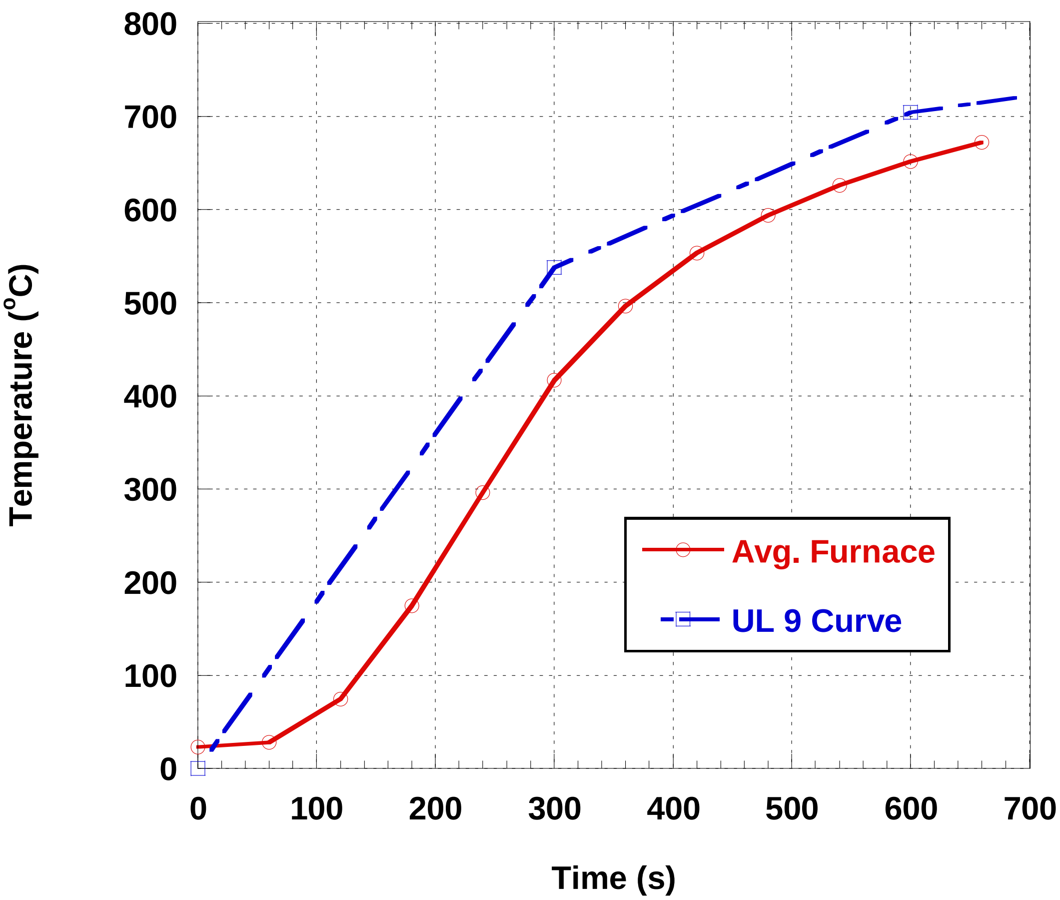


Figure 17. Average Furnace Temperature

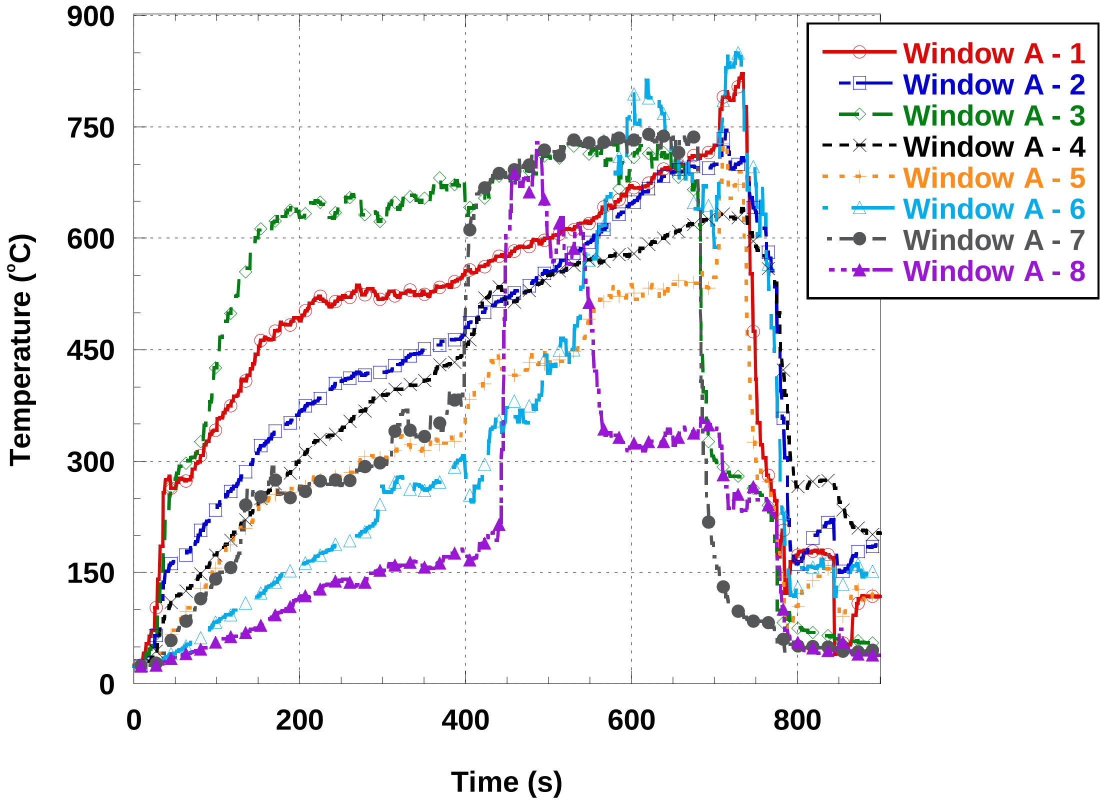


Figure 18. Window A Temperatures

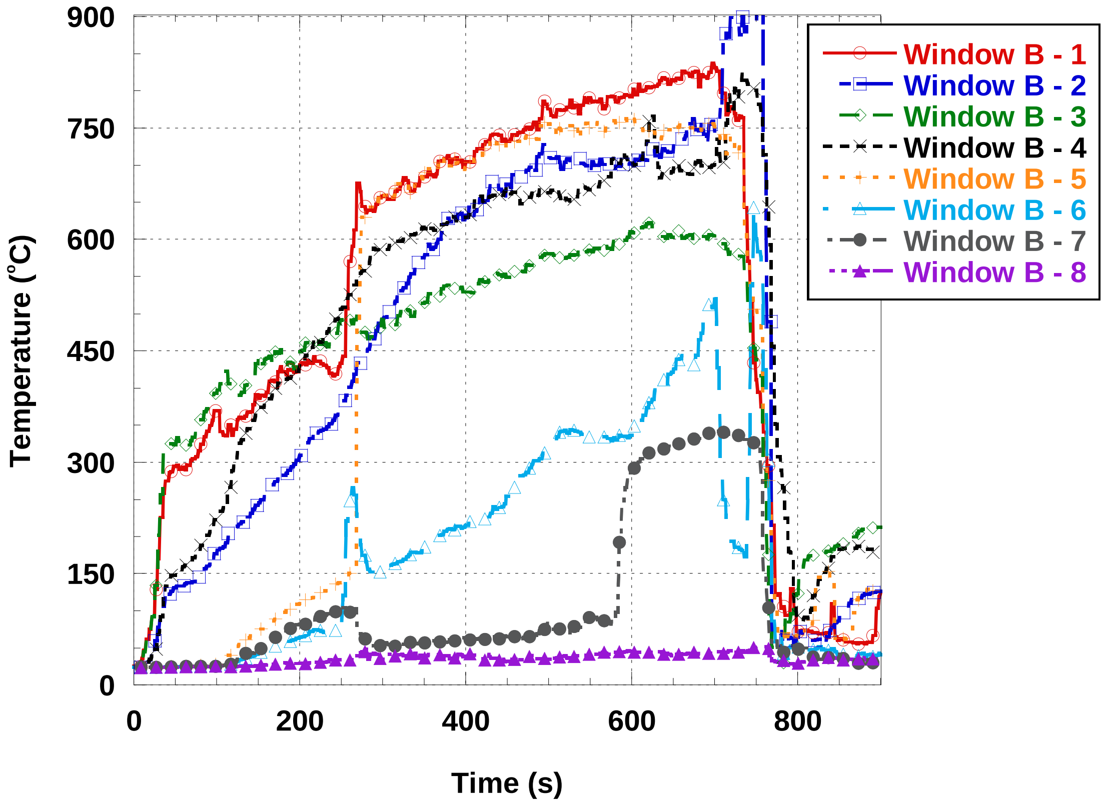


Figure 19. Window B Temperatures

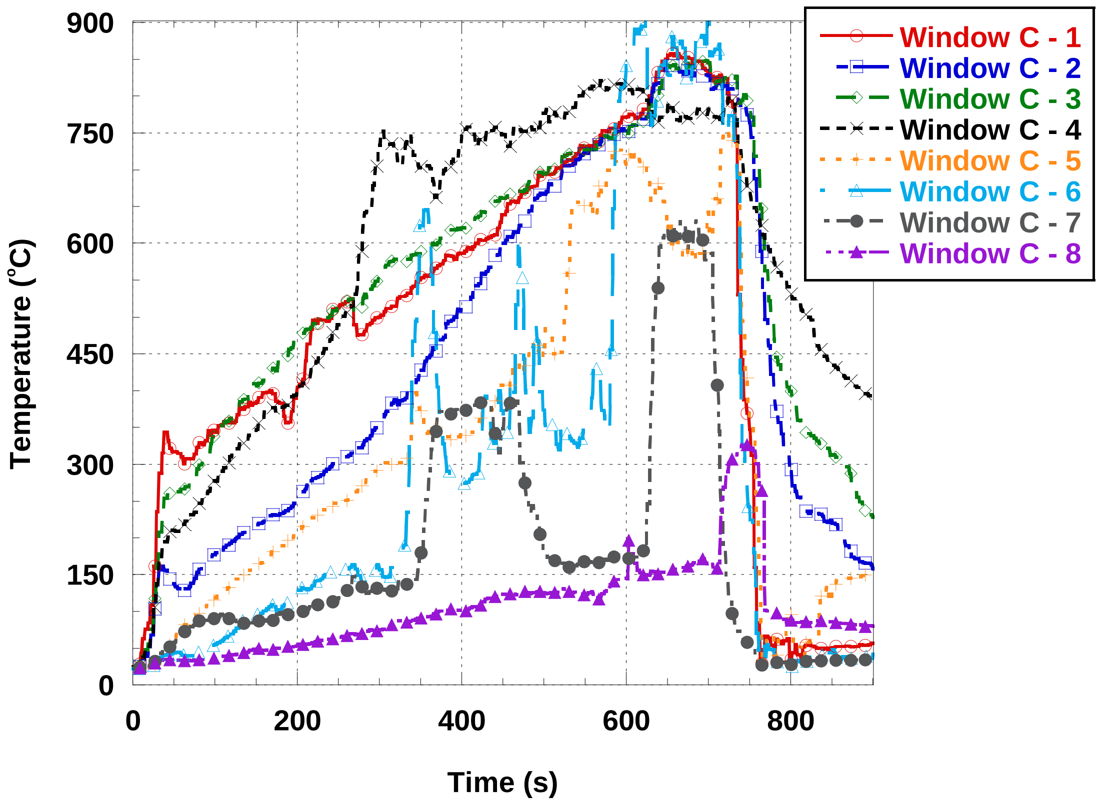


Figure 20. Window C Temperatures

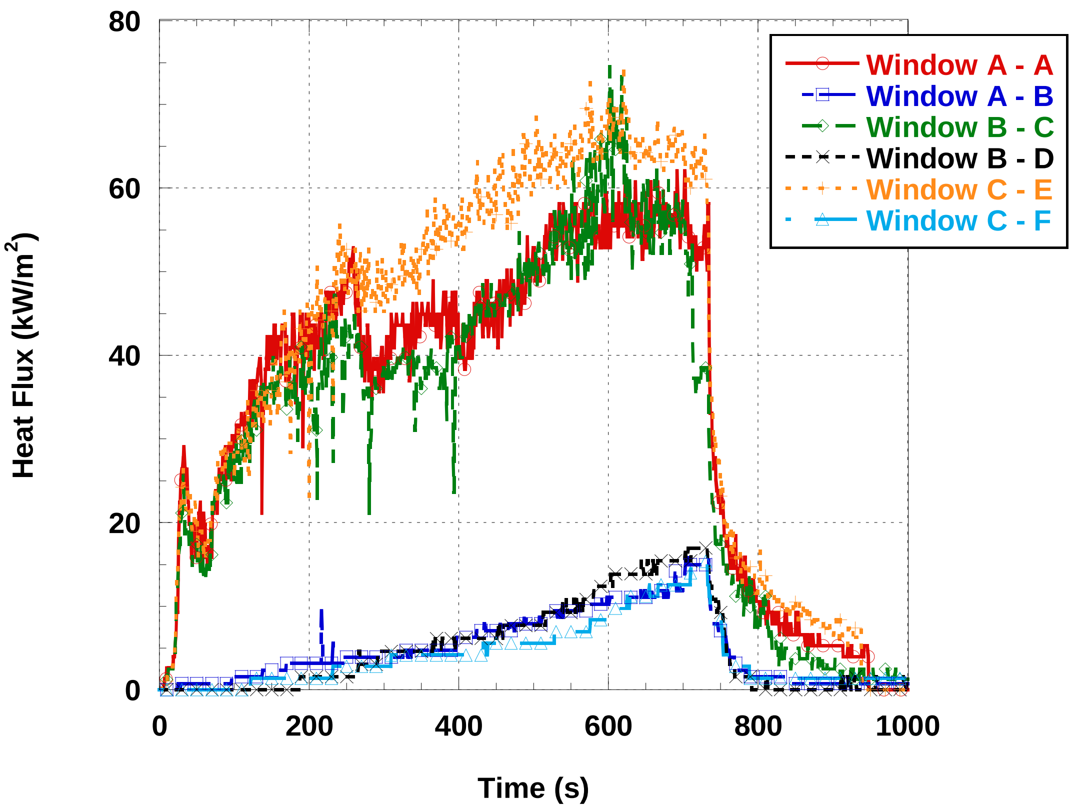


Figure 21. Experiment 1 Heat Flux

5.6.2. Experiment 2

The appearance of the unexposed surface of the assembly before the fire endurance experiment is shown in Figure 22. The assembly had, from right to left from looking from the unexposed side of the same, experimental windows C – A – B.

Observations during Experiment 2 are detailed in Table 3. Observations are from the unexposed side unless otherwise noted. The average furnace temperature is graphed versus time in Figure 23. Window temperatures are graphed in Figure 24 through Figure 26. The heat flux for all three windows is graphed versus time in Figure 27.

.

Figure 22. Experiment 2 Setup

Table 3. Experiment 2 Observations

Time (min:sec)	Observations
0:00	Gas on
0:45	Sample B, had begun to smoke.
1:14	Samples A and C, had begun to crack on the top panes.
1:33	Sample B, top exposed internal pane had broken out.
1:47	Sample B, interior top pane had fallen into the furnace.
1:51	Sample B, interior bottom pane had fallen into the furnace.
4:38	Sample B, top exterior pane had broken out.
6:41	Sample B, bottom exterior pane had broken out.
8:00	Sample A, entire circumference of the frame had begun to burn.
10:06	Sample A, the top pane had broken out.
10:46	Sample C, top sash had stated to slip downwards.
12:15	Sample A, the bottom pane had broken out.
14:00	Sample C, the top sash had slid down approximately 25%.
15:00	Gas off.

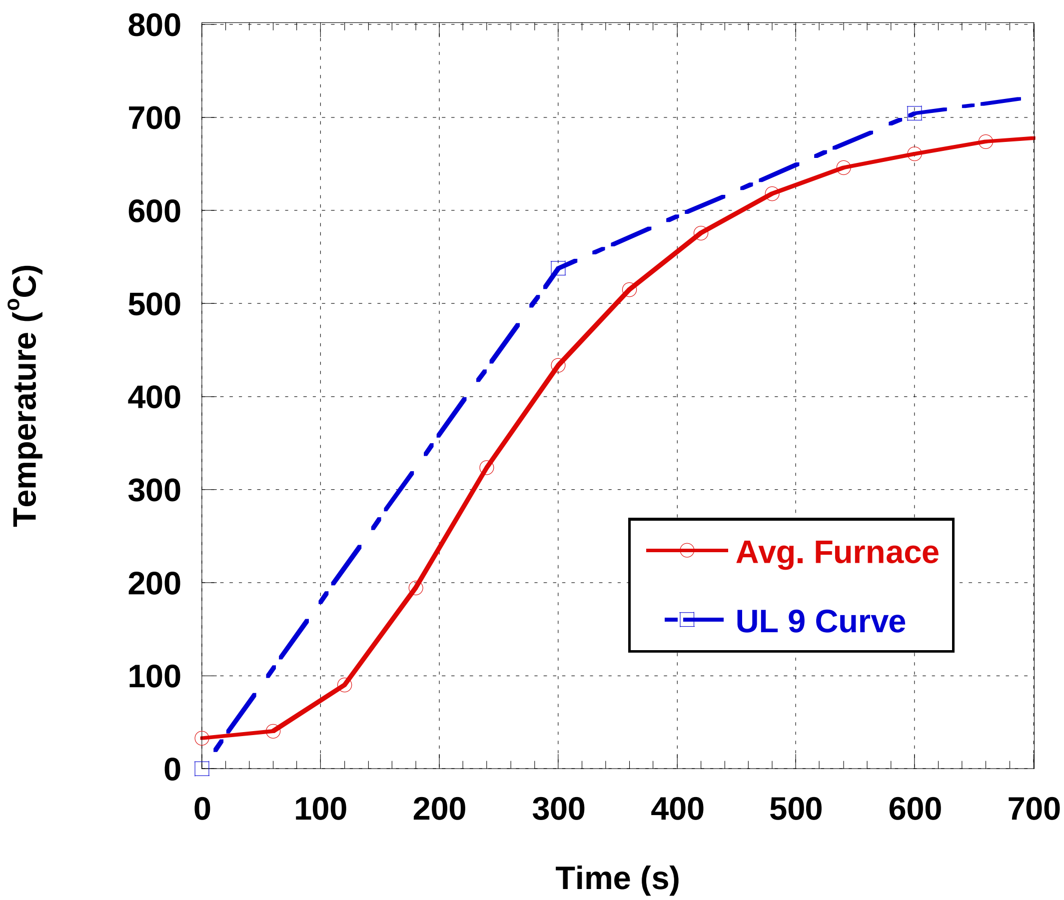


Figure 23. Average Furnace Temperature

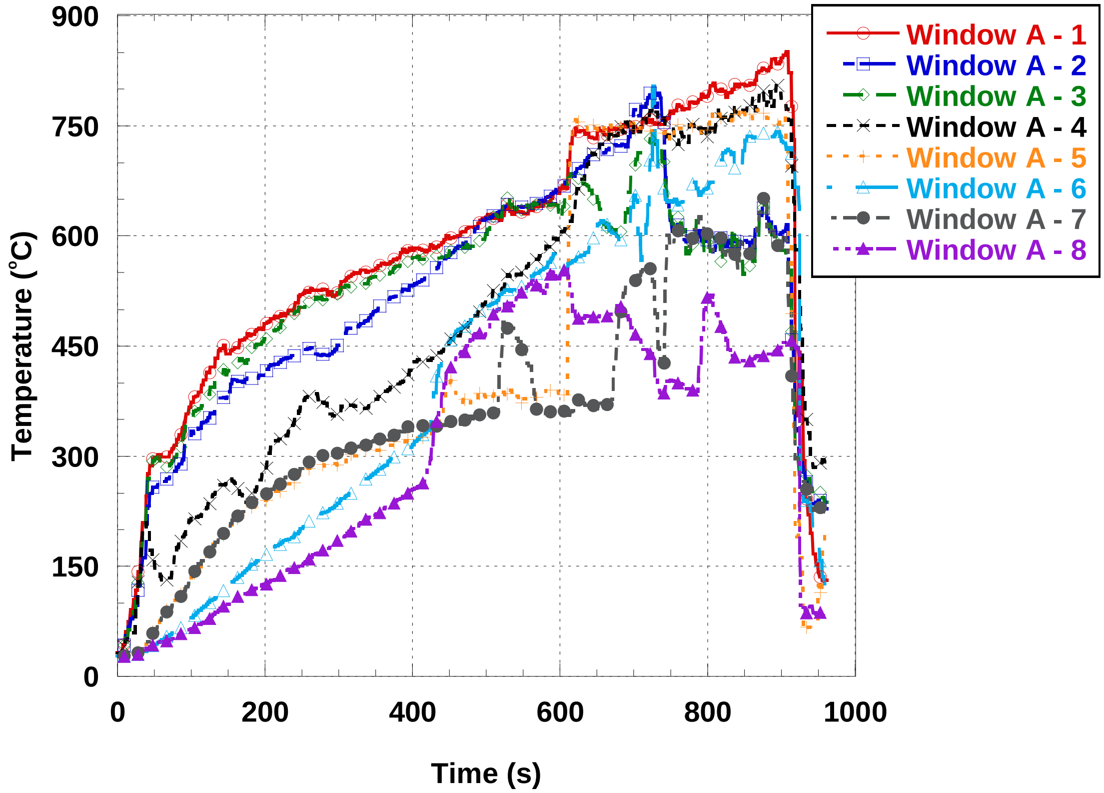


Figure 24. Window A Temperatures

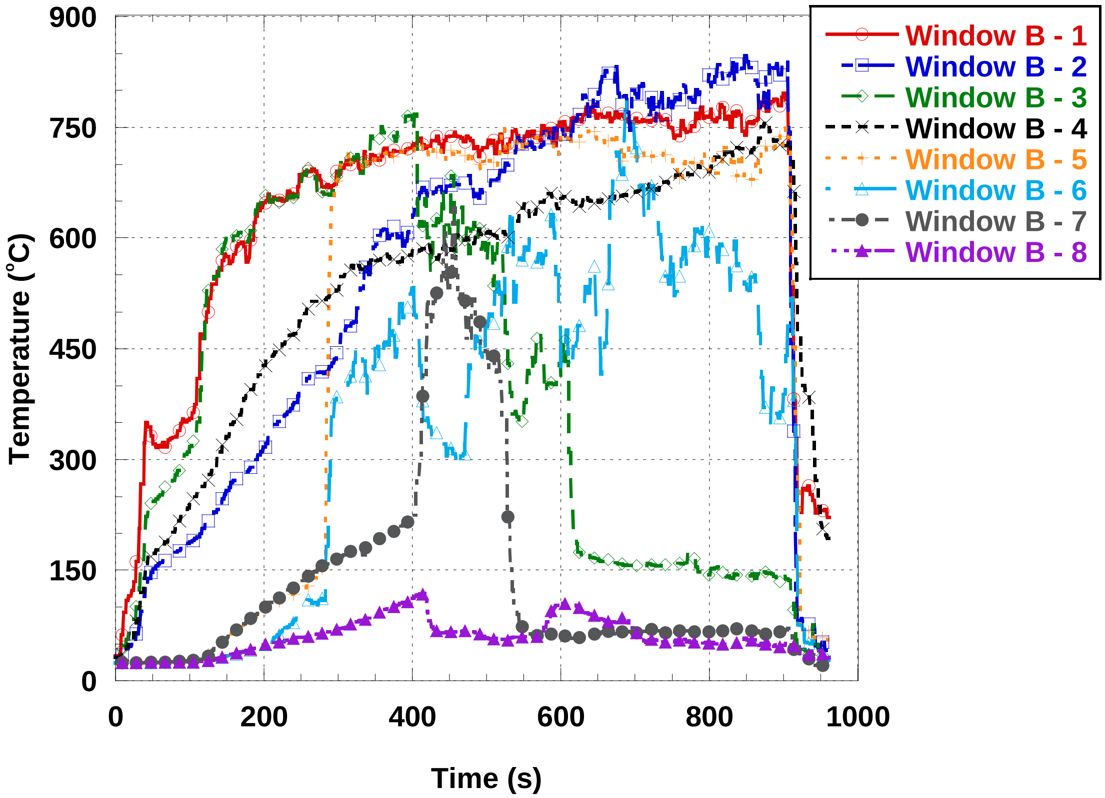


Figure 25. Window B Temperatures

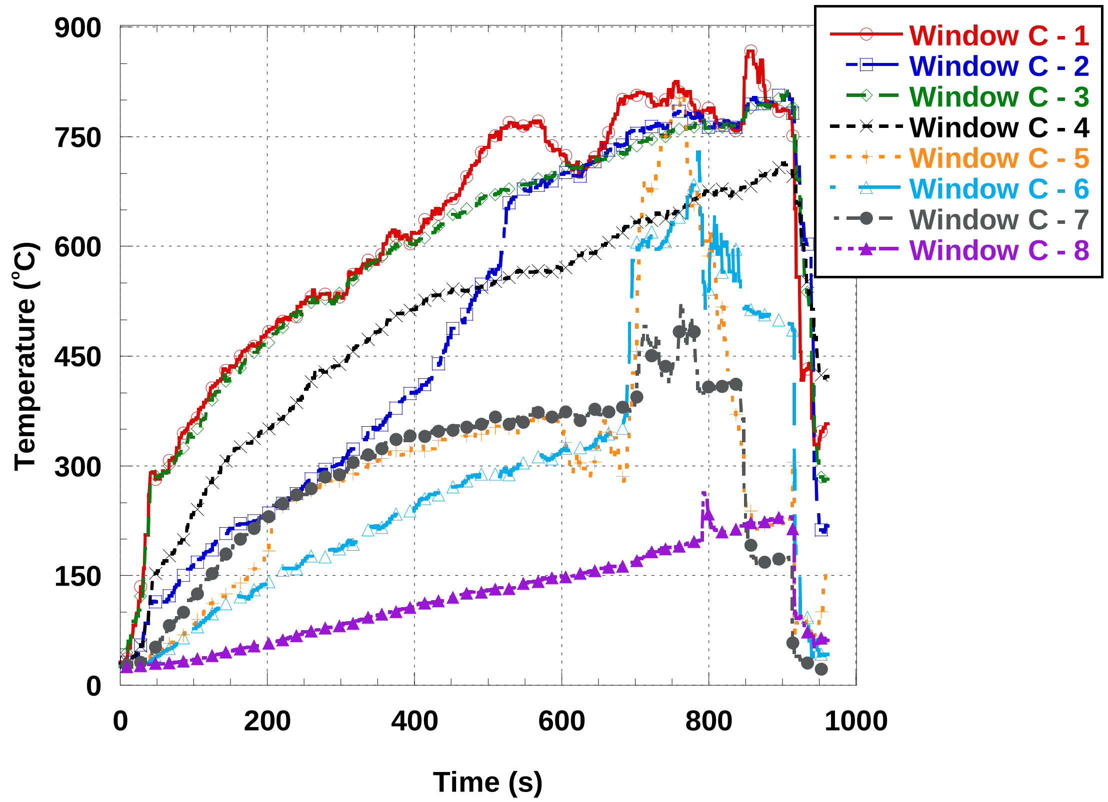


Figure 26. Window C Temperatures

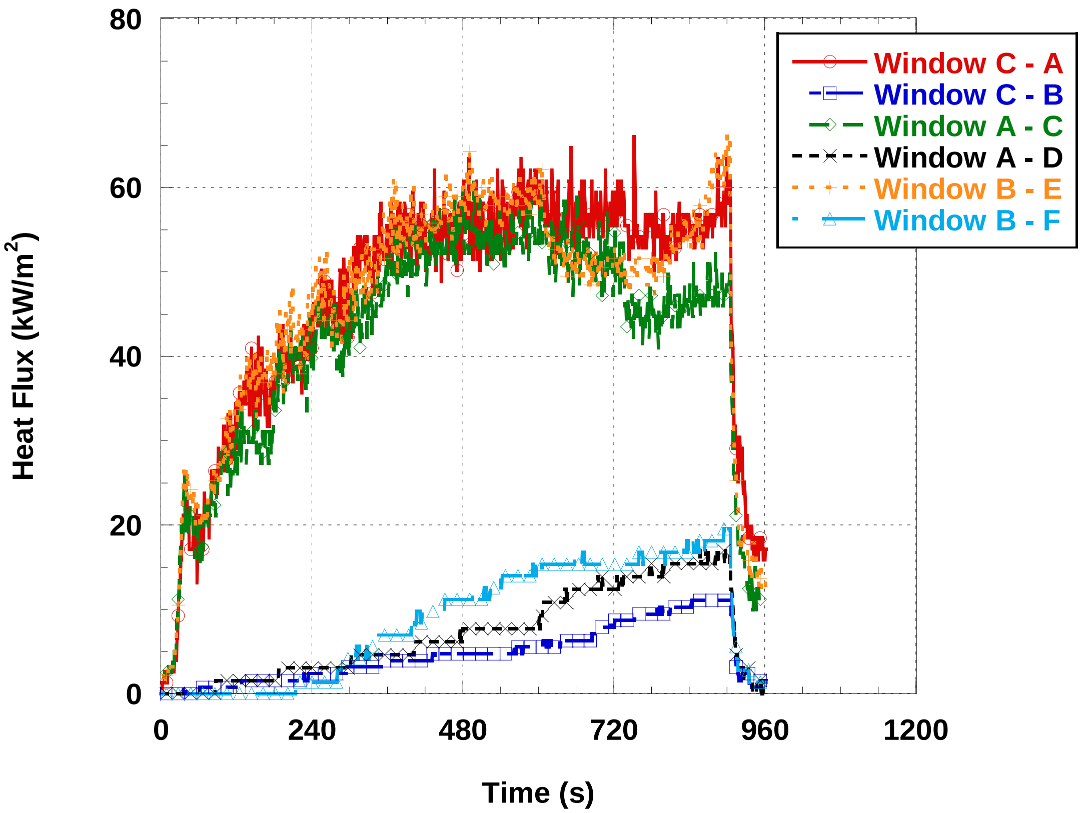


Figure 27. Expriment 2 Heat Flux

5.6.3. Experiment 3

The appearance of the unexposed surface of the assembly before the fire endurance experiment is shown in Figure 28. The assembly had, from right to left from looking from the unexposed side of the same, experimental windows B – C – A.

Observations during Experiment 3 are detailed in Table 4. Observations are from the unexposed side unless otherwise noted. The average furnace temperature is graphed versus time in Figure 29. Window temperatures are graphed in Figure 30 through Figure 32. The heat flux for all three windows is graphed versus time in Figure 33.

Figure 28. Experiment 3 Setup

Table 4. Experiment 3 Observations

Time (min:sec)	Observations
0:00	Gas on
1:00	Samples A and C, had begun to crack.
1:22	Sample B, had begun to crack.
1:44	Sample B, bottom exposed internal pane had broken out.
1:48	Sample B, top exposed internal pane had broken out.
3:56	Sample B, top external pane had broken out.
4:07	Sample B, top interior had pane broken out.
4:24	Sample B, top exterior had pane broken out.
7:00	Sample B, top sash had started to slide downwards.
7:46	Sample B, the bottom pane had developed openings.
10:25	Sample A, the top panel had developed an opening
10:46	Sample B, the bottom pane had broken out.
11:42	Sample A, the unexposed, exterior frame had ignited.
12:04	Sample C, the unexposed, exterior frame had ignited.
12:11	Sample A, the top pane had broken out.
14:19	Sample A, the bottom pane had broken out.
15:00	Gas off.

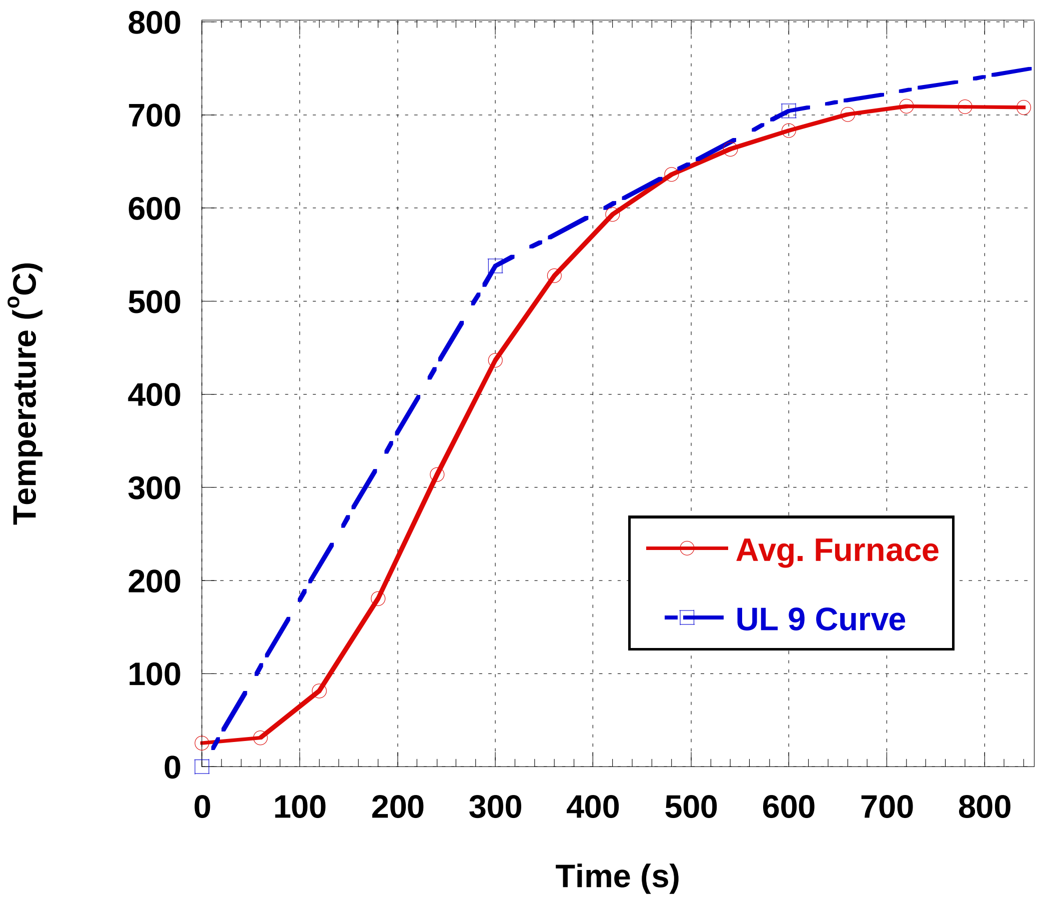


Figure 29. Average Furnace Temperature

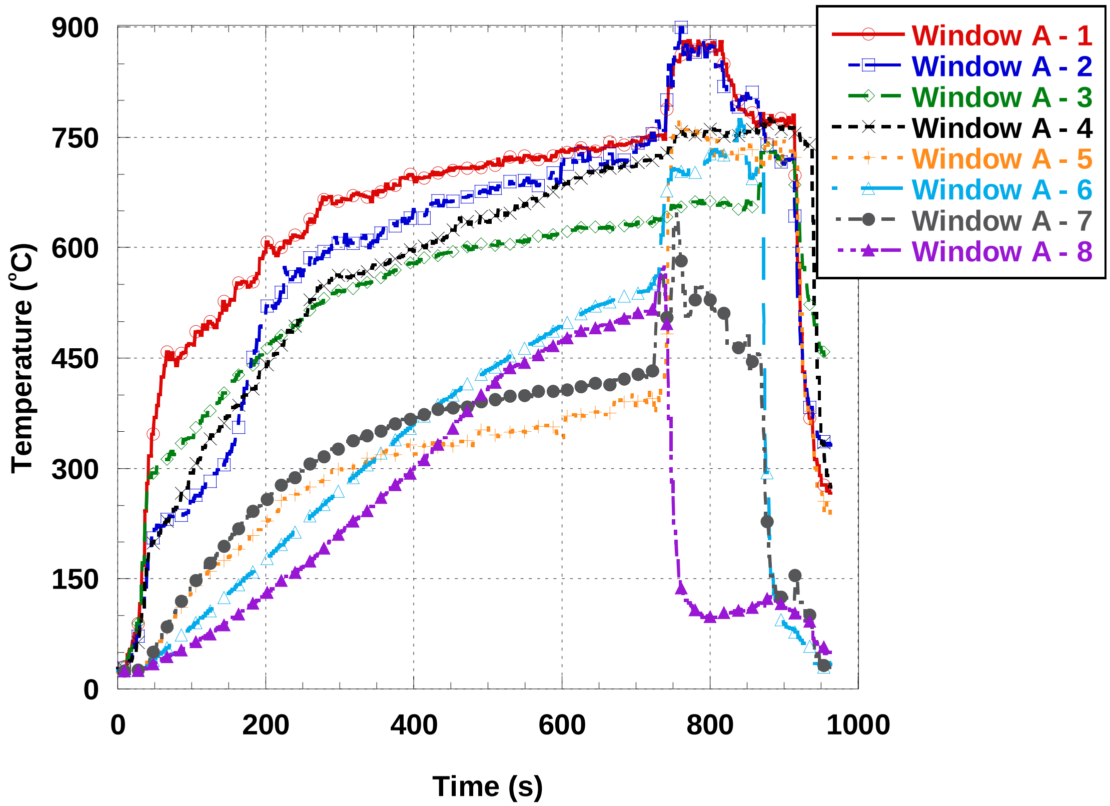


Figure 30. Window A Temperatures

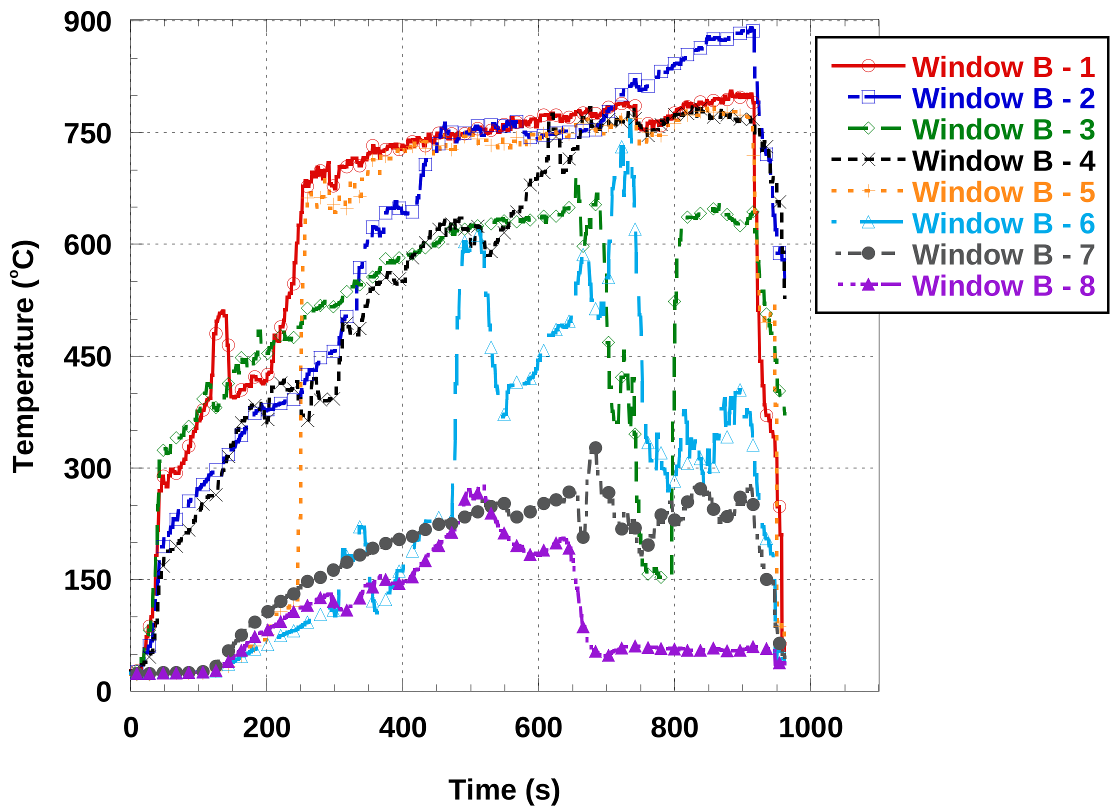


Figure 31. Window B Temperatures

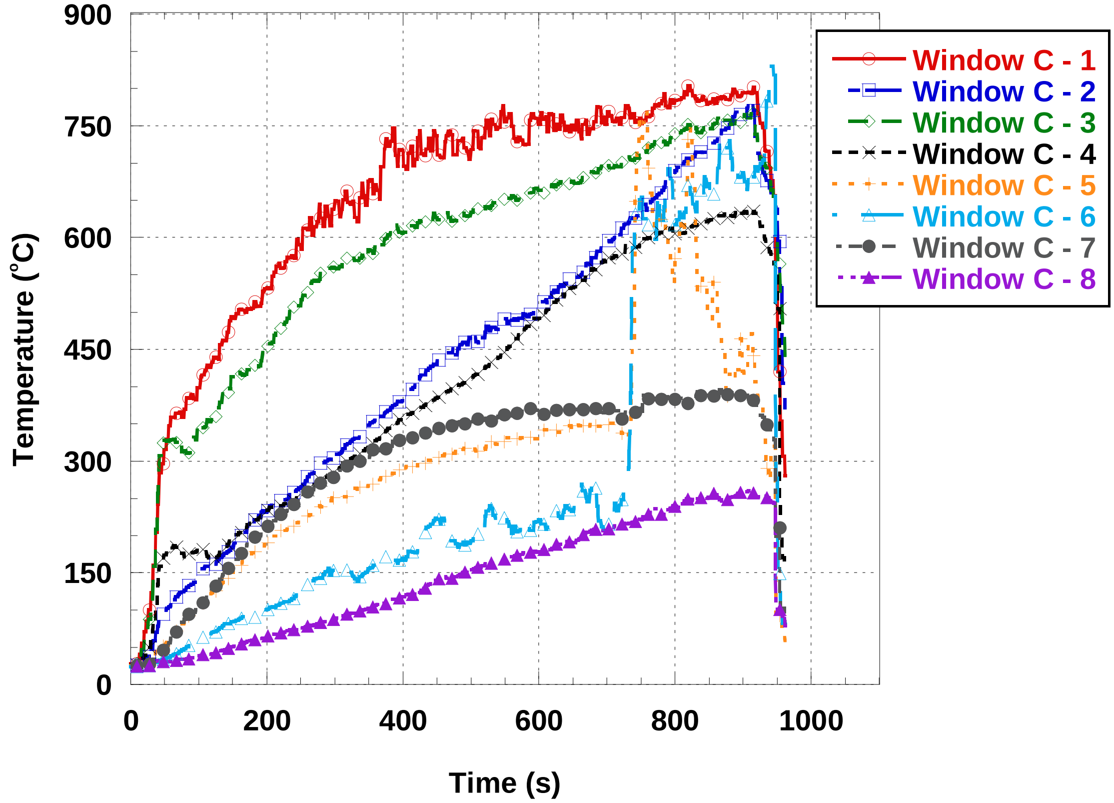


Figure 32. Window C Temperatures

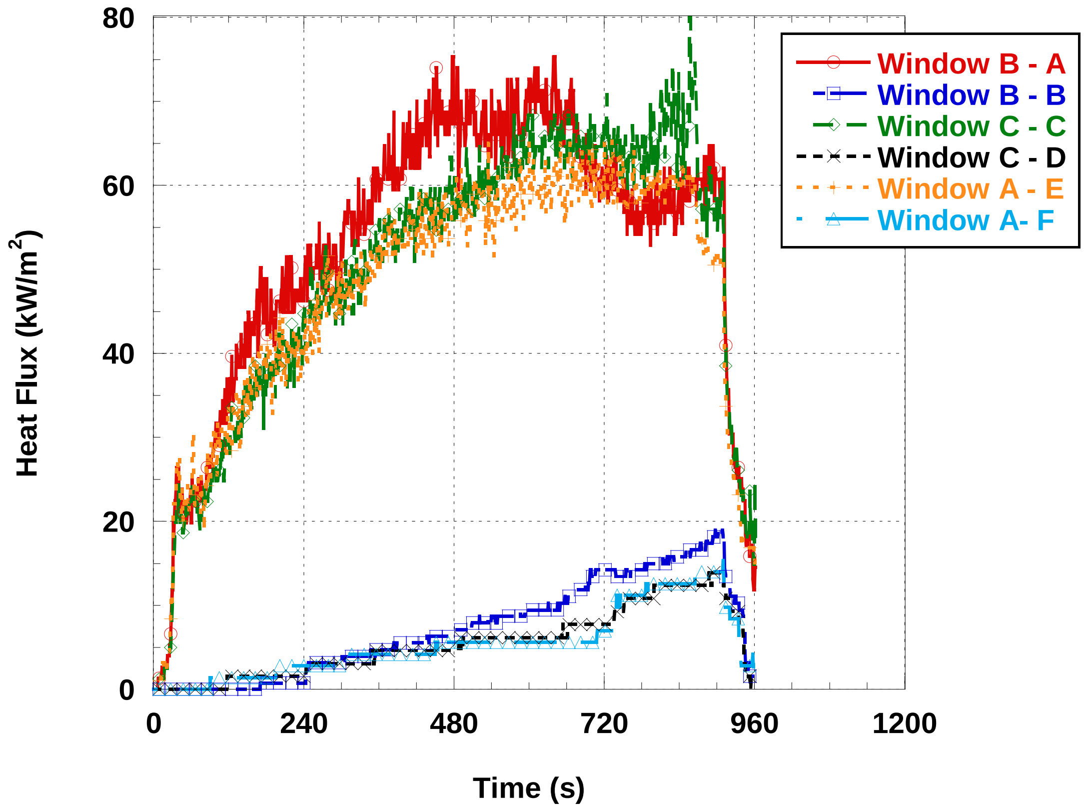


Figure 33. Experiment 3 Heat flux

5.6.4. Experiment 4

The appearance of the unexposed surface of the assembly before the fire endurance experiment is shown in Figure 34. The assembly had, from right to left from looking from the unexposed side of the same, experimental windows D – E – F.

Observations during Experiment 4 are detailed in Table 5. Observations are from the unexposed side unless otherwise noted. The average furnace temperature is graphed versus time in Figure 35. Window temperatures are graphed in Figure 36 through Figure 38. The heat flux for all three windows is graphed versus time in Figure 39.

Figure 34. Experiment 4 Setup

Table 5. Experiment 4 Observations

Time (min:sec)	Observations
0:00	Gas on
0:57	Sample F, had begun to crack.
1:10	Sample E, had begun to crack.
1:15	Sample D, top exposed internal pane had broken out.
1:35	Sample F, top exposed internal pane had broken out.
2:12	Sample D, bottom exposed internal pane had broken out.
2:39	Sample E, bottom exposed internal pane had broken out.
3:39	Sample F, bottom external pane had broken out.
3:58	Sample D, top external pane had broken.
5:10	Sample F, top sash had started to slide downwards.
5:15	Sample D, top sash had started to slide downwards.
5:16	Sample E, bottom external pane had broken out.
5:25	Sample D, the top sash had fallen out of the track.
5:26	Sample E, top exposed internal pane had broken out.
5:47	Sample E, top external pane had broken out. Sample D, bottom exterior pane had broken out.
6:23	Sample D, the bottom pane had broken out.
8:30	Gas off.

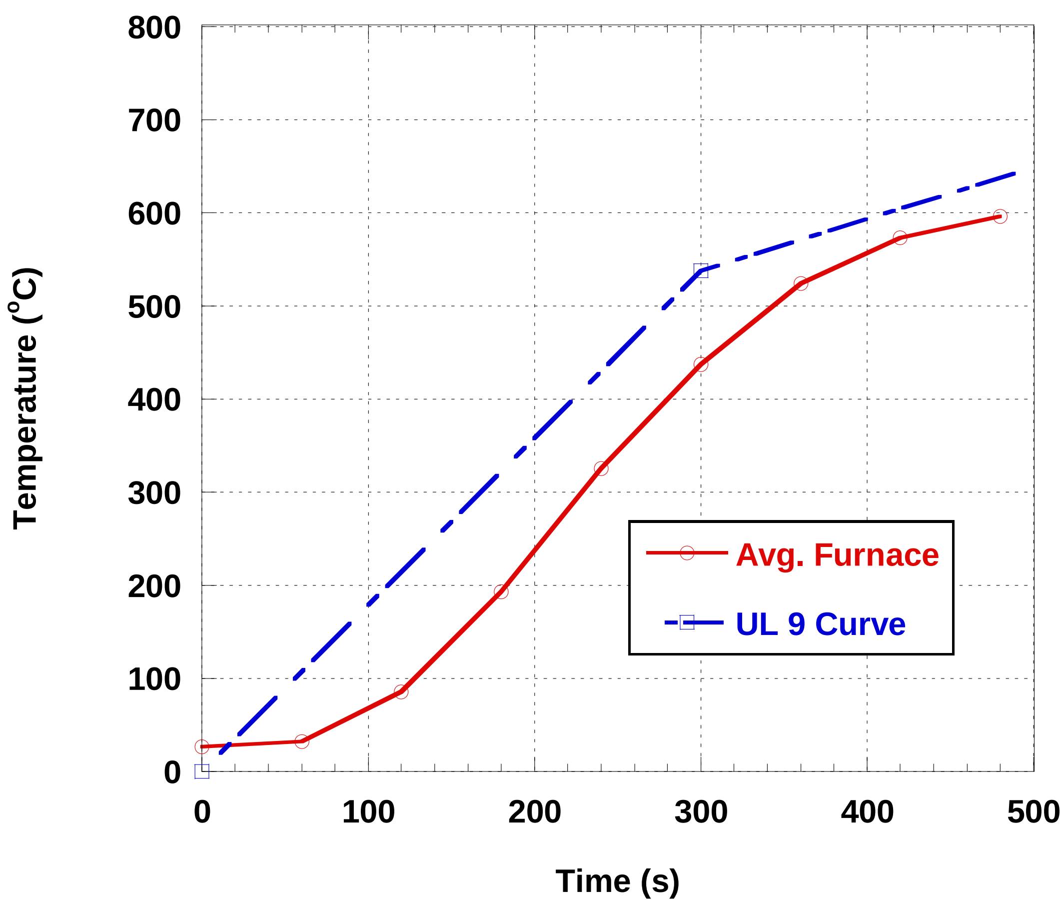


Figure 35. Average Furnace Temperature

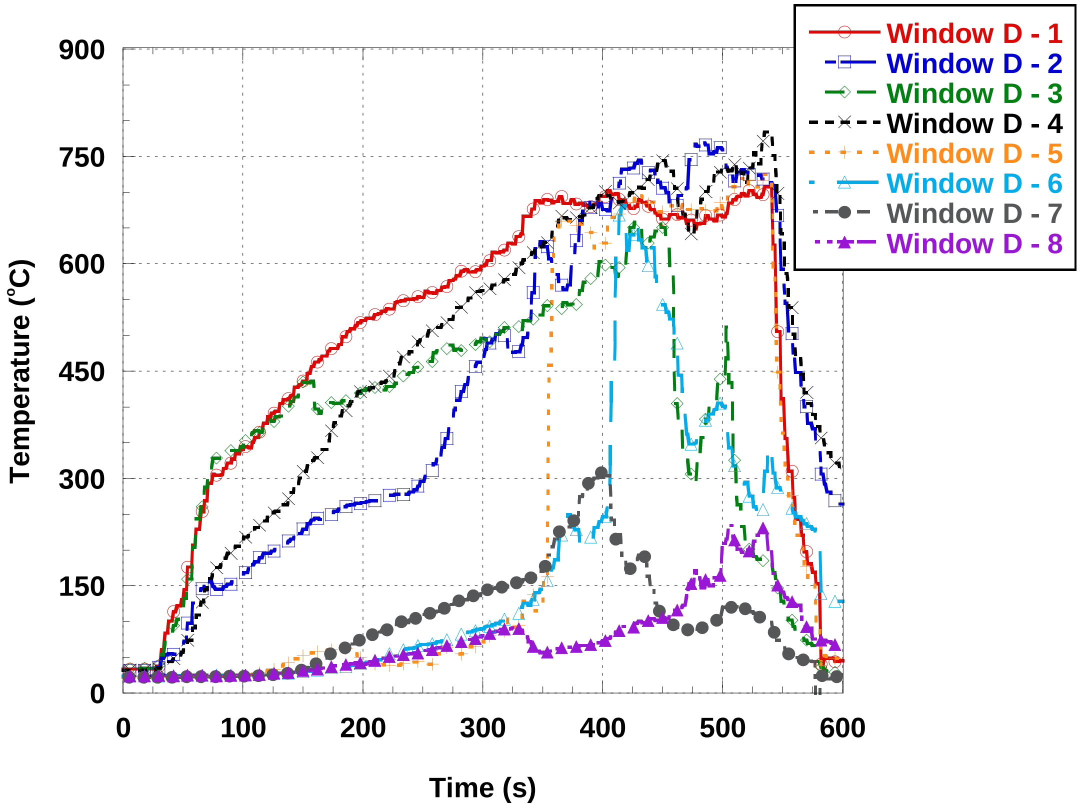


Figure 36. Window D Temperature

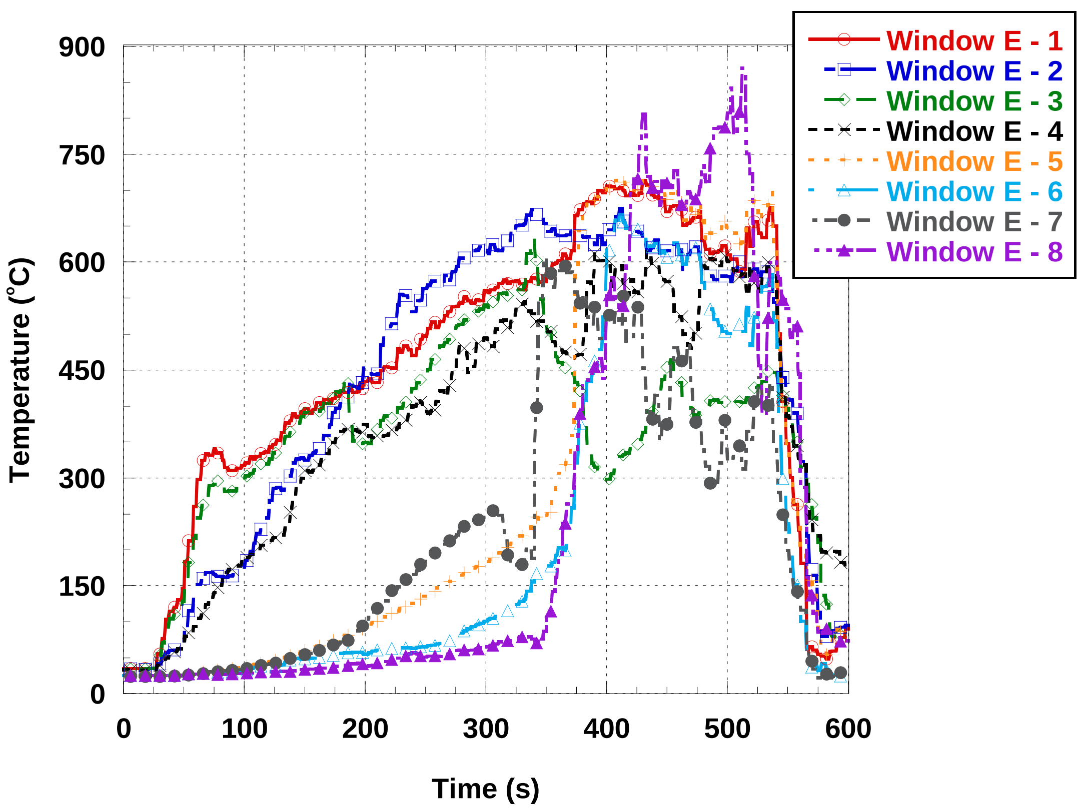


Figure 37. Window E Temperature

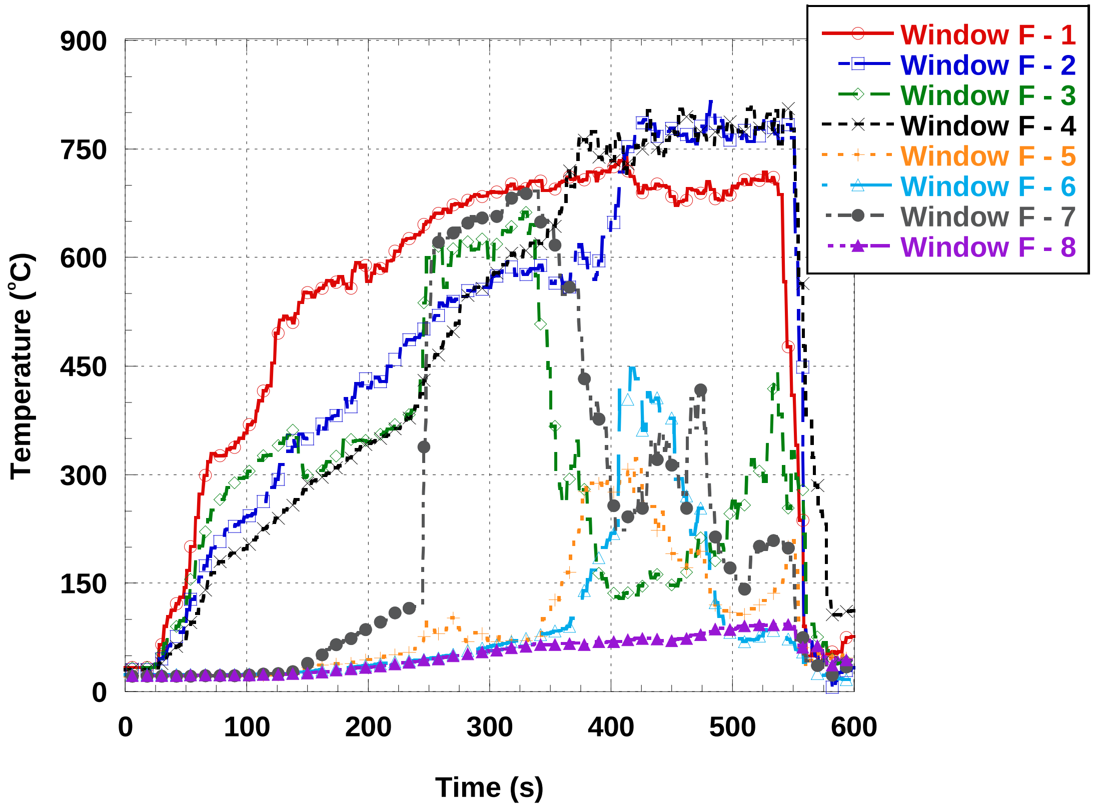


Figure 38. Window F Temperature

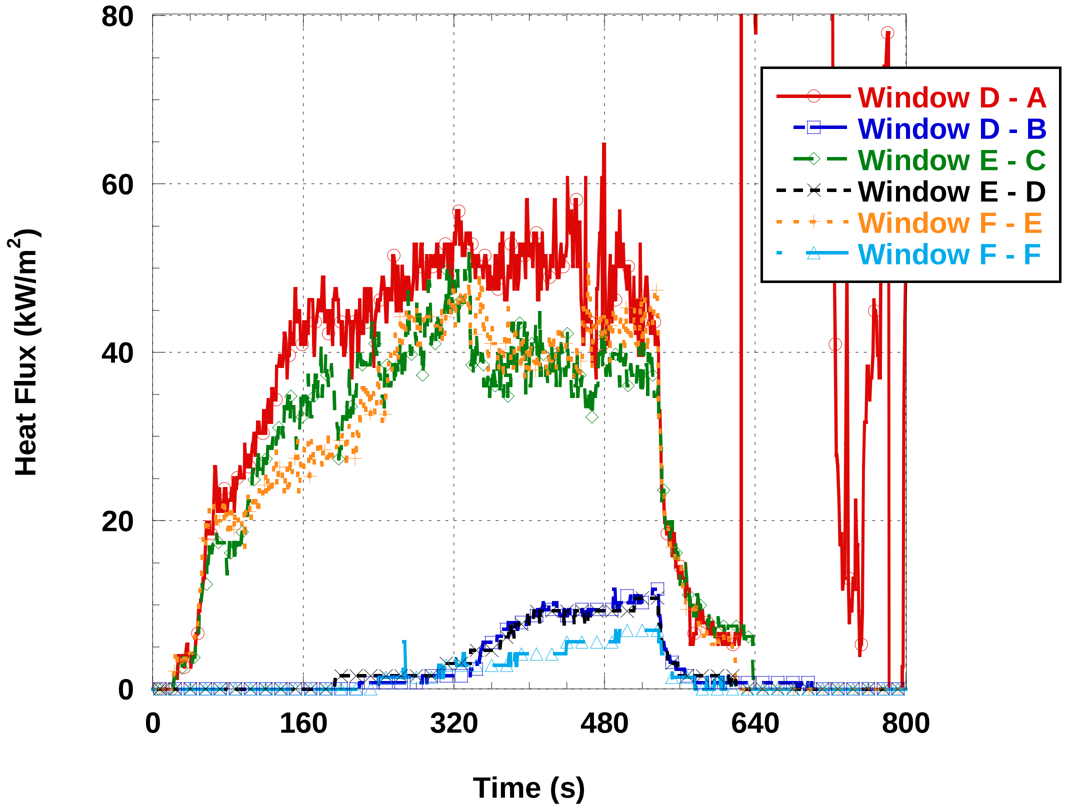


Figure 39. Experiment 4 Heat Flux

5.6.5. Experiment 5

The appearance of the unexposed surface of the assembly before the fire endurance experiment is shown in Figure 40. The assembly had, from right to left from looking from the unexposed side of the same, experimental windows F – D – E.

Observations during Experiment 5 are detailed in Table 6. Observations are from the unexposed side unless otherwise noted. The average furnace temperature is graphed versus time in Figure 41. Window temperatures are graphed in Figure 42 through Figure 44. The heat flux for all three windows is graphed versus time in Figure 45.

Figure 40. Experiment 5 Setup

Table 6. Experiment 5 Observations

Time (min:sec)	Observations
0:00	Gas on
1:00	Sample F, D, E, had begun to crack.
1:27	Sample F, bottom exposed internal pane had broken out.
2:00	Sample F, top exposed internal pane had broken out.
2:30	Sample D, top sash had started to slide downwards.
2:39	Sample E, bottom exposed internal pane had broken out.
3:39	Sample D, top sash had slid all the way down. Some internal pane breakage had occurred.
4:26	Sample E, top external pane and bottom exterior pane had broken out.
4:36	Sample D, bottom external pane had broken out.
5:45	Sample E, top external pane had broken out.
5:49	Sample F, bottom external pane had broken out.
7:00	Gas off.

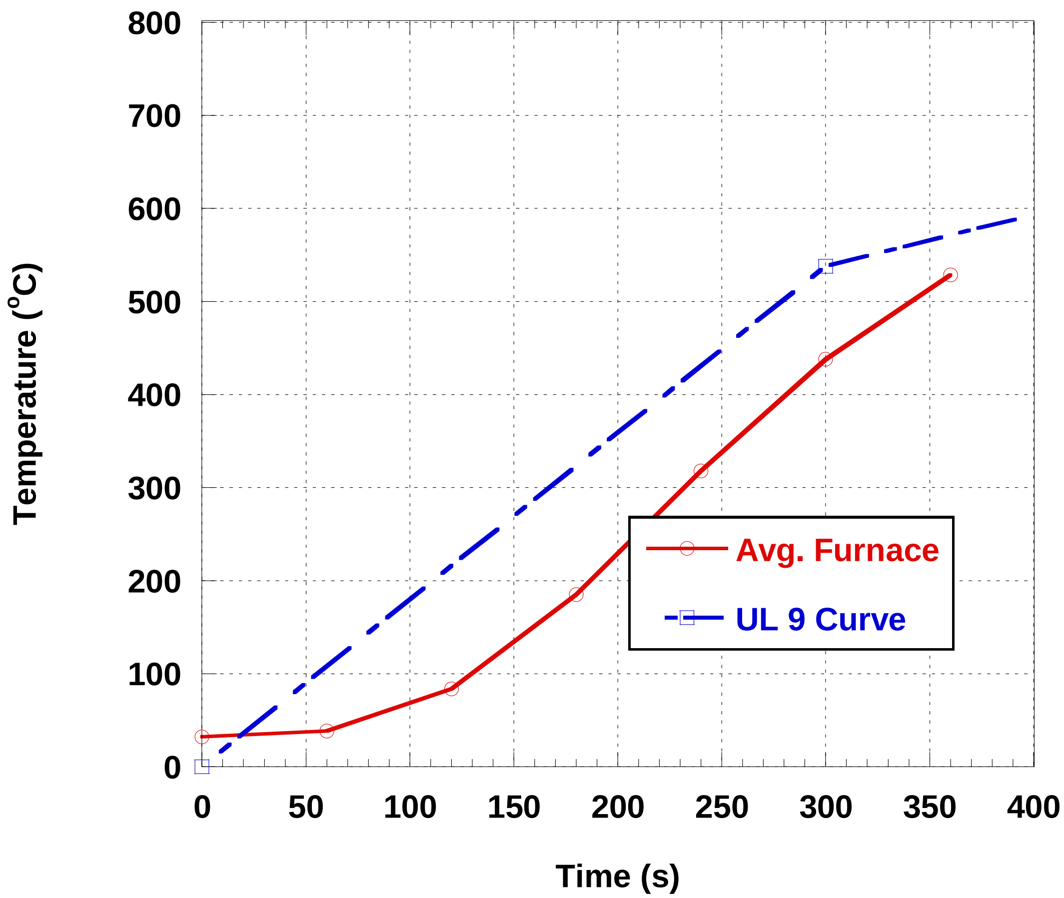


Figure 41. Average Furnace Temperatures

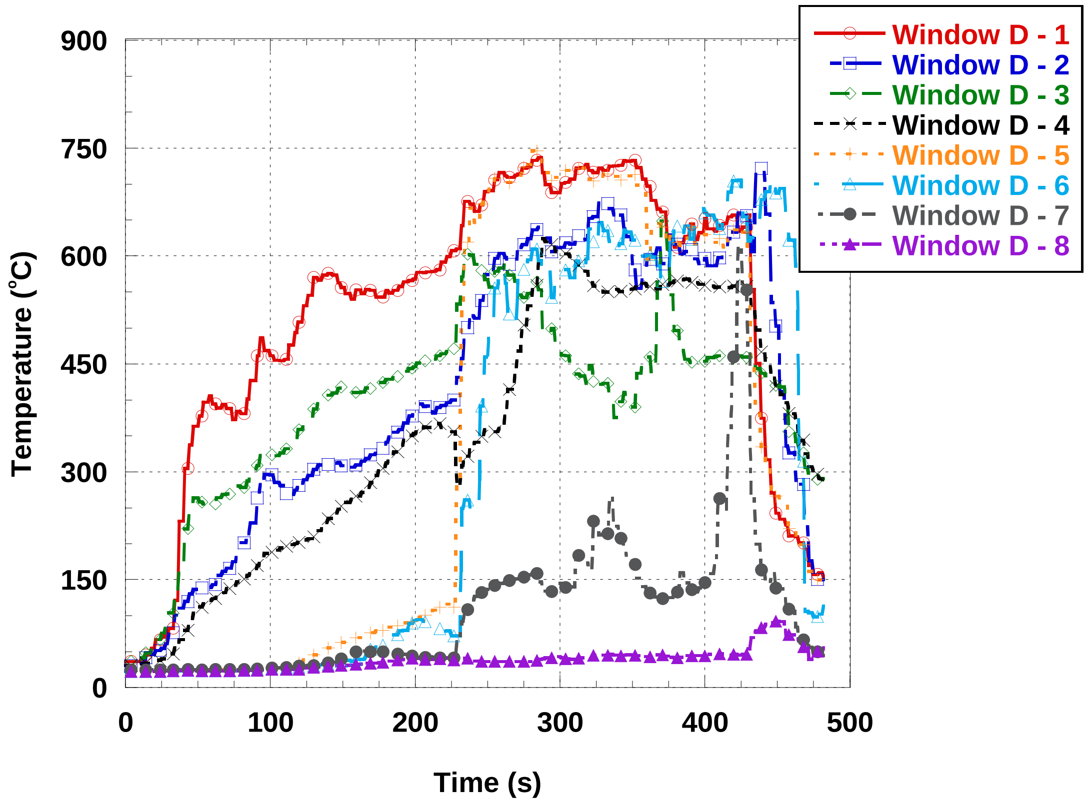


Figure 42. Window D Temperatures

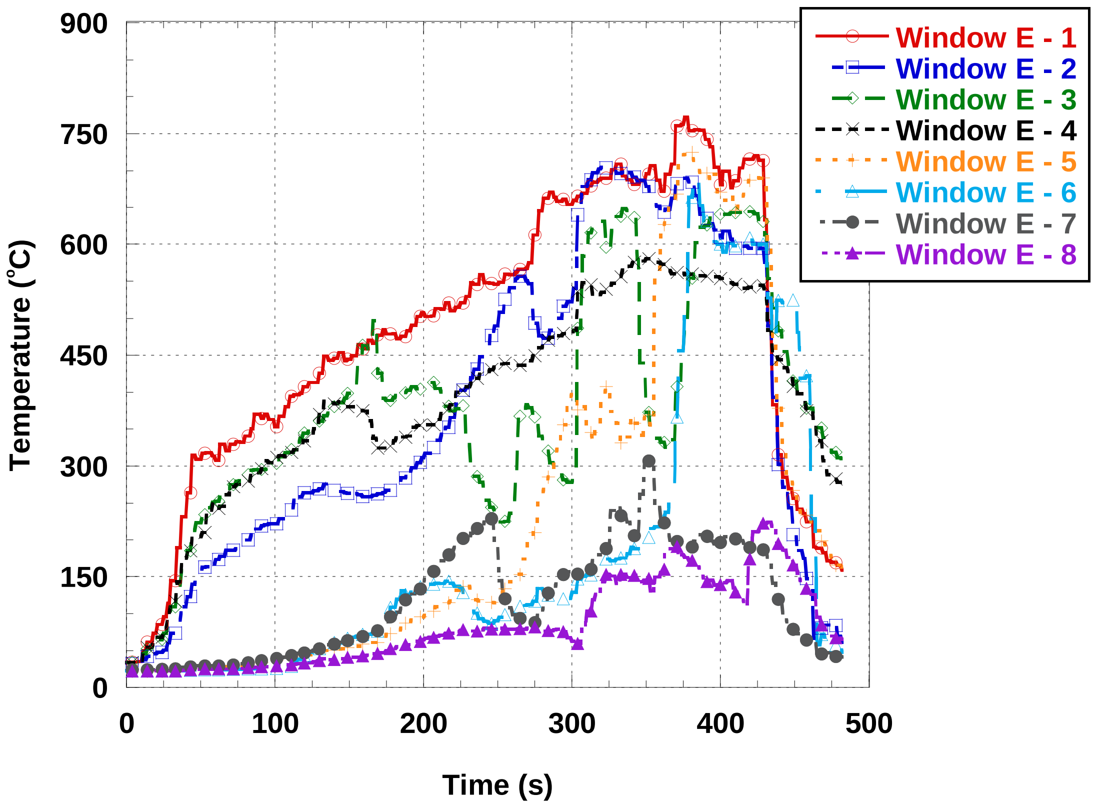


Figure 43. Window E Temperatures

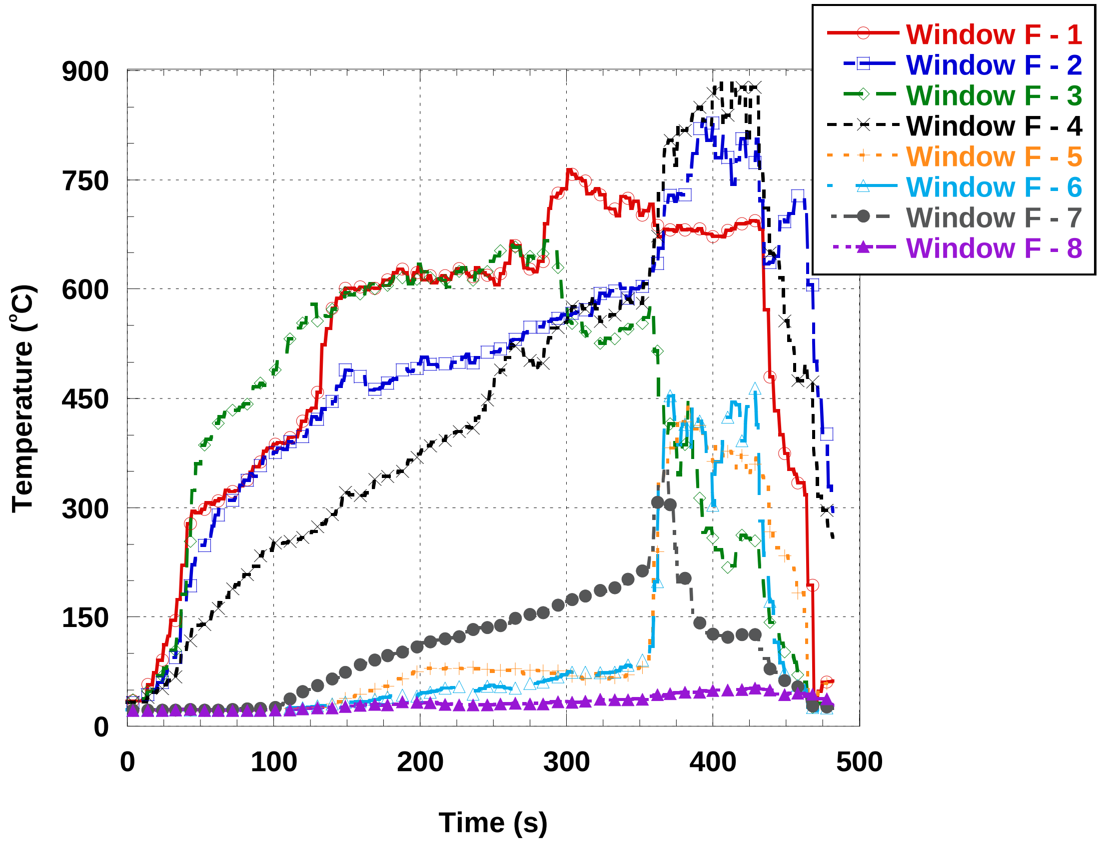


Figure 44. Window F Temperatures

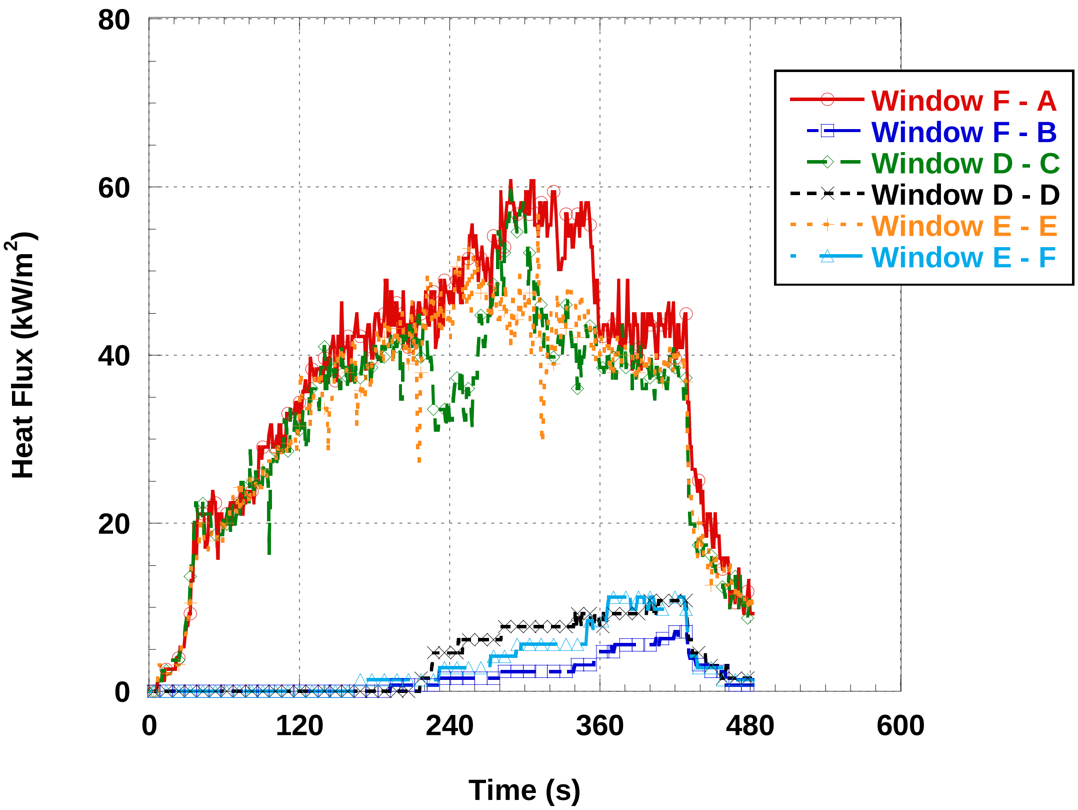


Figure 45. Experiment 5 Heat Flux

5.6.6. Experiment 6

The appearance of the unexposed surface of the assembly before the fire endurance experiment is shown in Figure 46. The assembly had, from right to left from looking from the unexposed side of the same, experimental windows E – F – D.

Observations during Experiment 6 are detailed in Table 7. Observations are from the unexposed side unless otherwise noted. The average furnace temperature is graphed versus time in Figure 47. Window temperatures are graphed in Figure 48 through Figure 50. The heat flux for all three windows is graphed versus time in Figure 51.

Figure 46. Experiment 6 Setup

Table 7. Experiment 6 Observations

Time (min:sec)	Observations
0:00	Gas on
1:05	Sample F, D, E, had begun to crack.
1:40	Sample F, top exposed internal pane had broken out.
2:12	Sample D, top exposed internal pane had broken out.
2:20	Sample F, bottom exposed internal pane had broken out.
3:51	Sample E, bottom exposed internal pane had broken out.
4:02	Sample F, bottom external pane had broken out.
4:22	Sample F, top external pane had broke and had created an opening.
5:05	Sample D, top sash had slid all the way down.
5:12	Sample D, bottom external pane had broken out.
5:22	Sample D, top external pane had started to break out.
5:55	Sample E, bottom external pane had broken out.
6:01	Sample F, top external pane had fallen from the sash.
6:27	Sample E, top external pane had broken out.
7:00	Gas off.

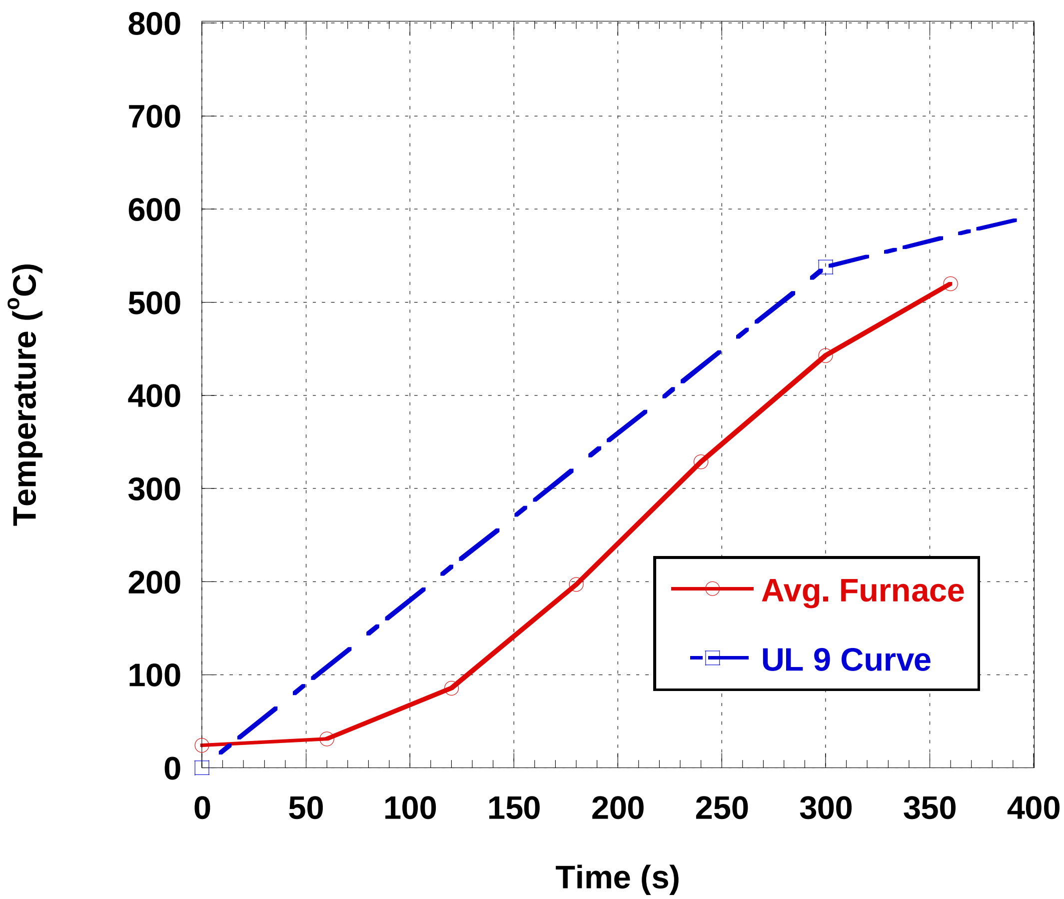


Figure 47. Average Furnace Temperatures

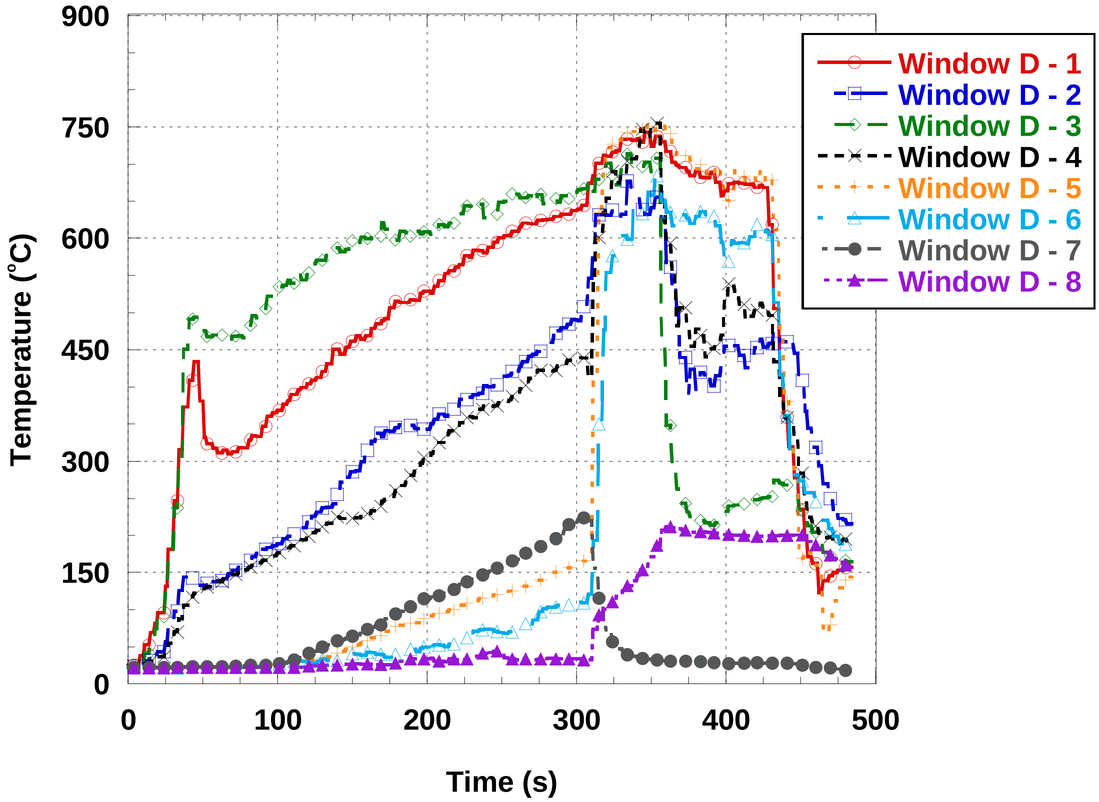


Figure 48. Window D Temperatures

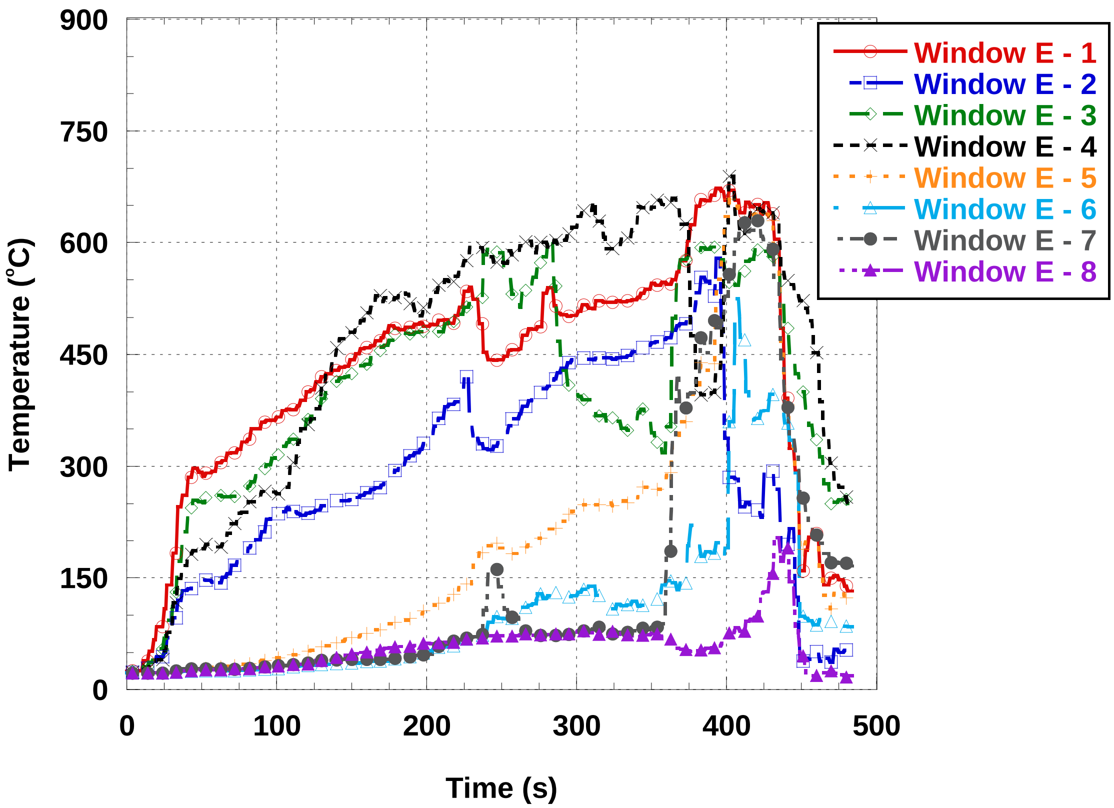


Figure 49. Window E Temperatures

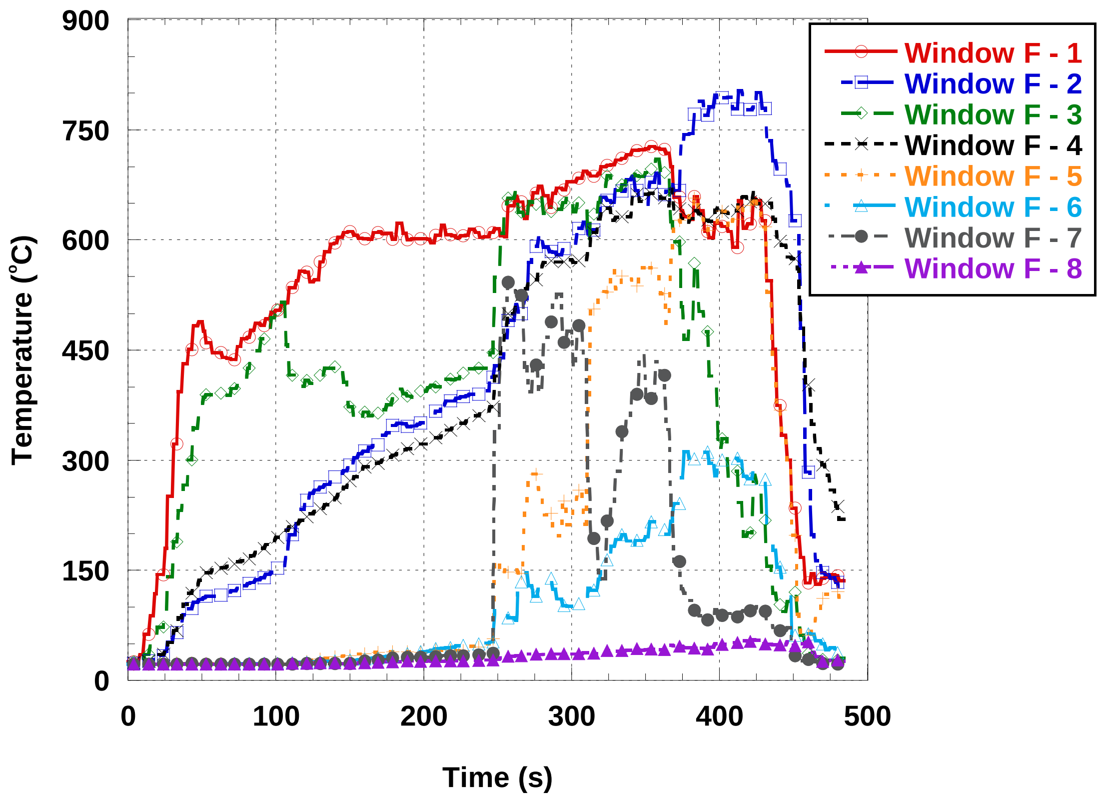


Figure 50. Window F Temperatures

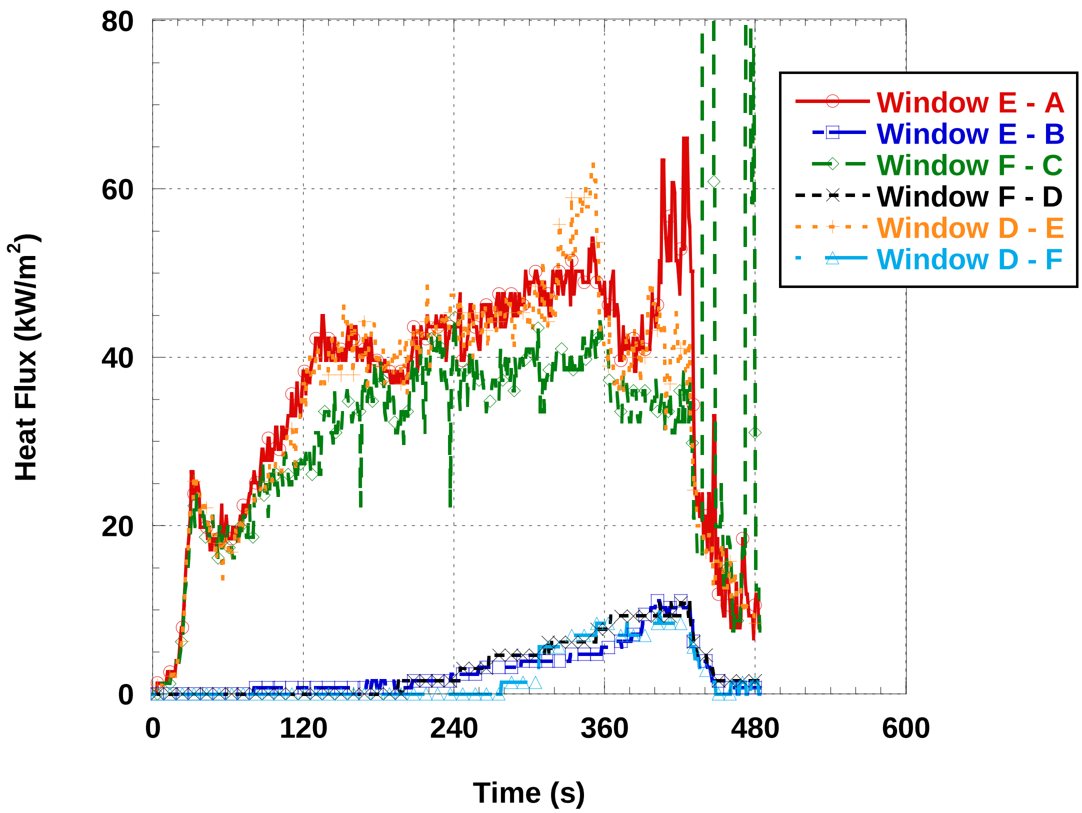


Figure 51. Experiment 6 Heat Flux

5.6.7. Experiment 7

The appearance of the unexposed surface of the assembly before the fire endurance experiment is shown in Figure 52. The assembly had, from right to left from looking from the unexposed side of the same, experimental doors 1 – 2 – 3.

Observations during Experiment 7 are detailed in Table 8. Observations are from the unexposed side unless otherwise noted. The average furnace temperature is graphed versus time in Figure 53. Door temperatures are graphed in Figure 54 through Figure 56. The heat flux for all three doors is graphed versus time in Figure 57.

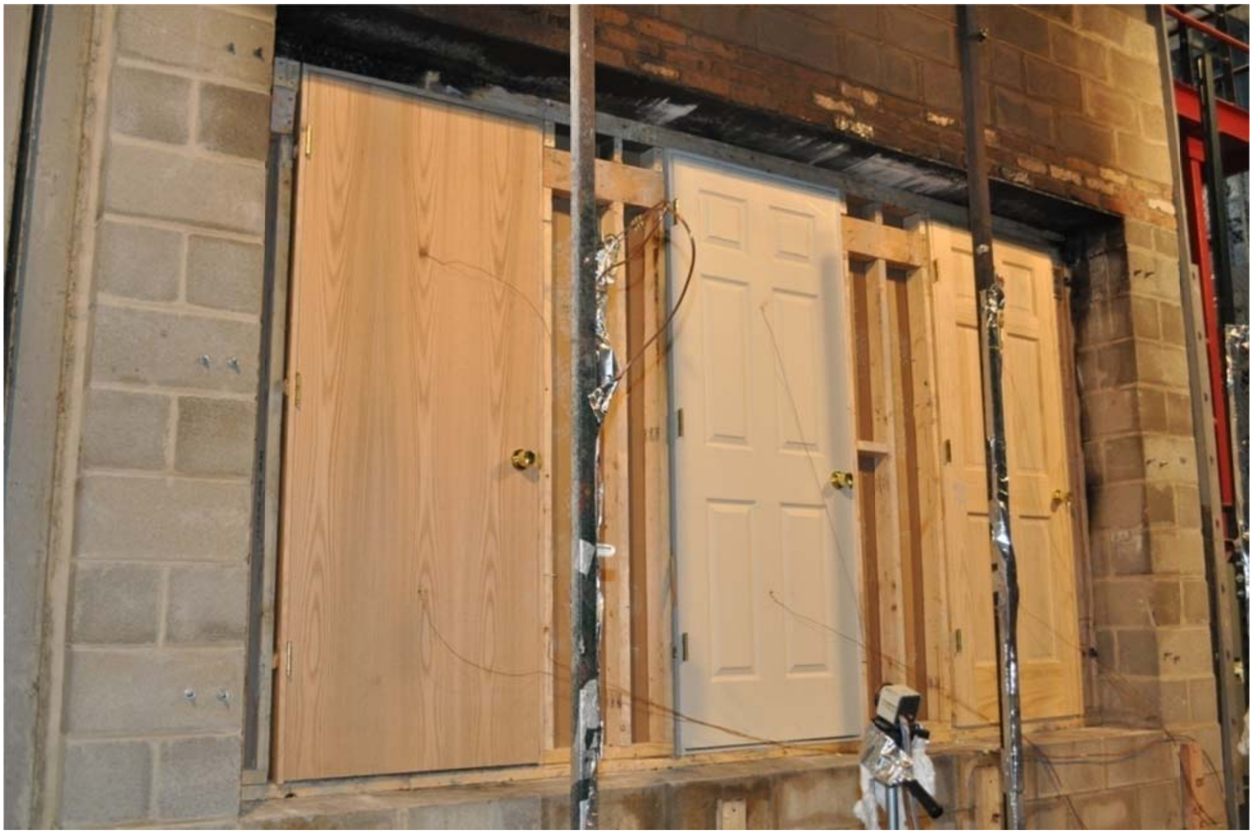


Figure 52. Experiment 7 Setup

Table 8. Experiment 7 Observations

Time (min:sec)	Observations
0:00	Gas on
1:00	All three assemblies had emitted light smoke from the top.
2:00	All three assemblies had emitted heavy smoke from the top.
2:20	Door 1, had developed a bubble on the unexposed surface.
2:26	Door 3, flaming had occurred along the leading edge.
3:00	All three assemblies had bowed outwards from the furnace.
3:28	Door 3, flaming had occurred along the top of the frame.
3:41 and 4:36	Door 3, flaming had re-occurred along the leading edge.
3:47	Door 2, flash of flame occurred along the hinge edge.
5:02	Door 3, the unexposed surface of the door had begun to burn.
5:12	Door 1, the unexposed surface of the door had begun to burn.
5:15	Door 2, the unexposed surface of the door had begun to burn.
5:20	Doors 1 and 2, entire surface of doors had ignited.
5:45	Door 1, had been consumed.
5:51	Door 2, had been consumed.
6:07	Door 3, the door had burned through at the six panel locations.
7:05	Gas off.

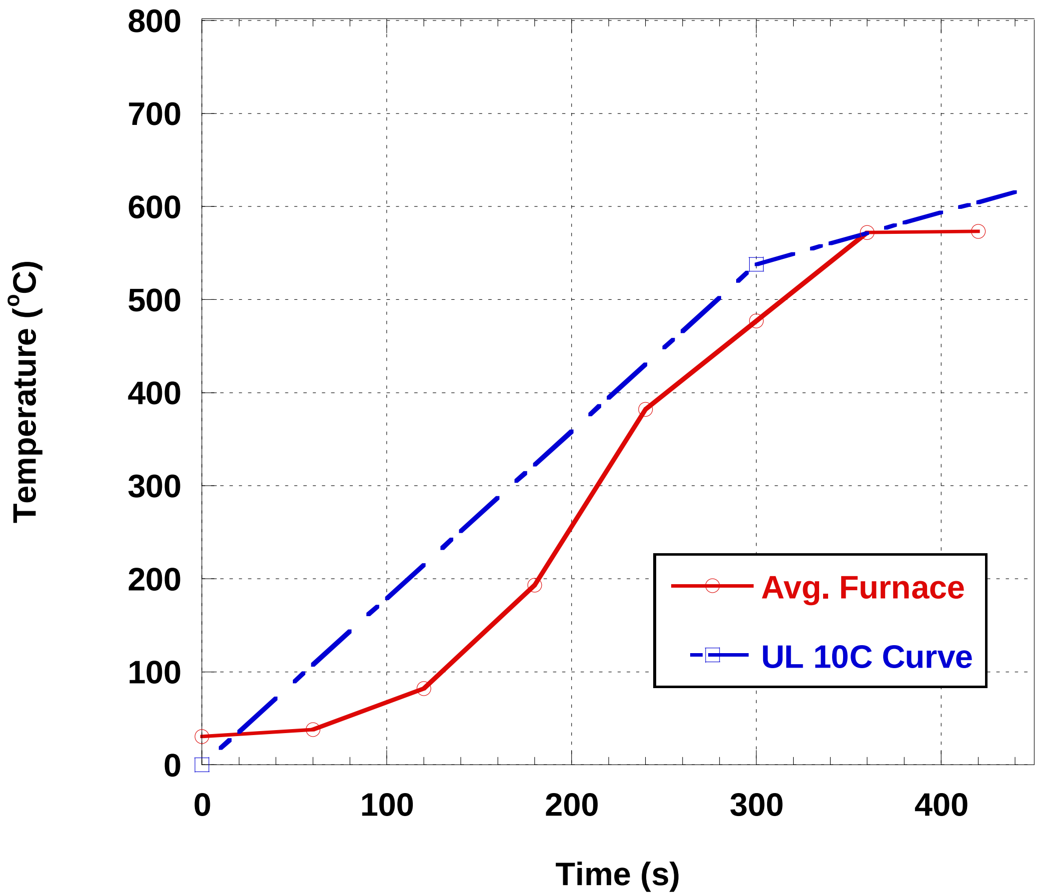


Figure 53. Average Furnace Temperature

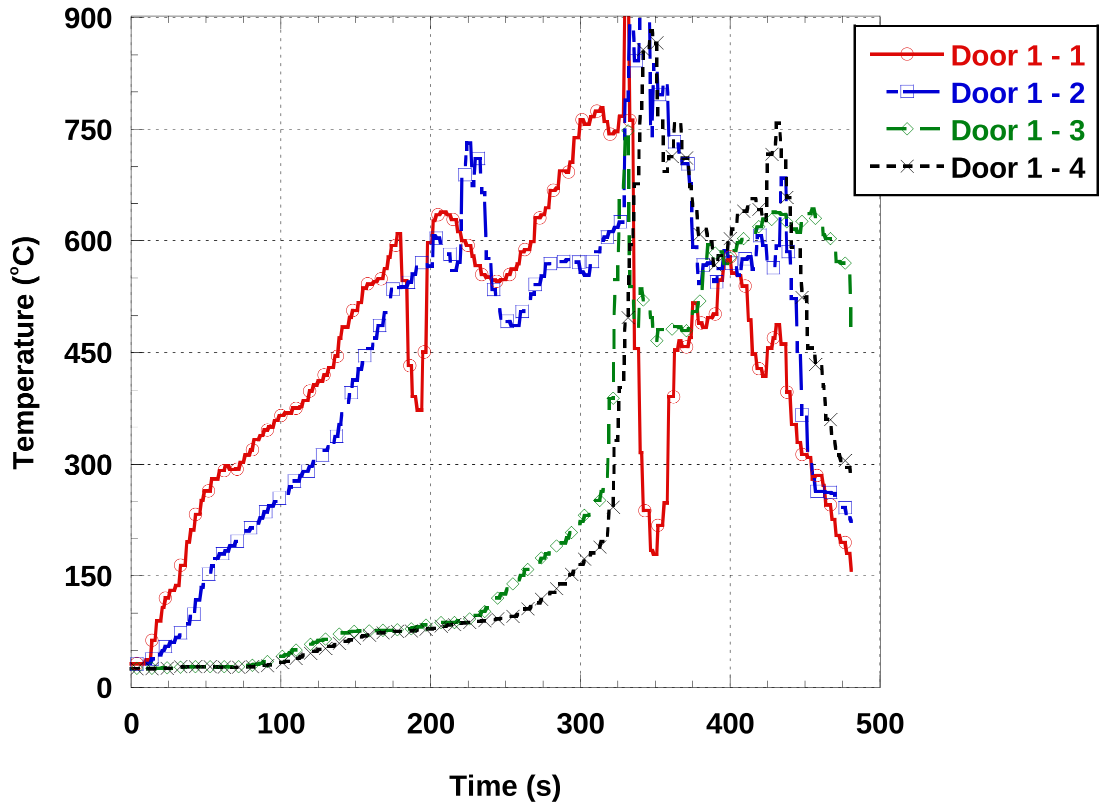


Figure 54. Door 1 Temperatures

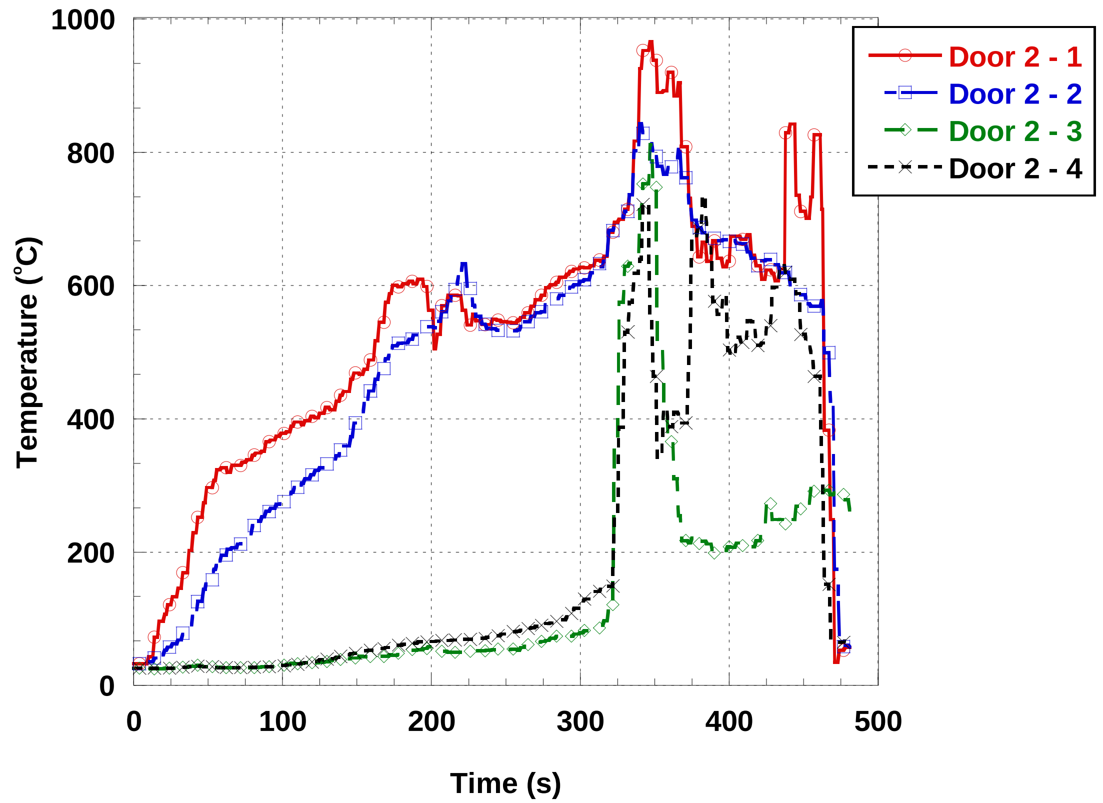


Figure 55. Door 2 Temperatures

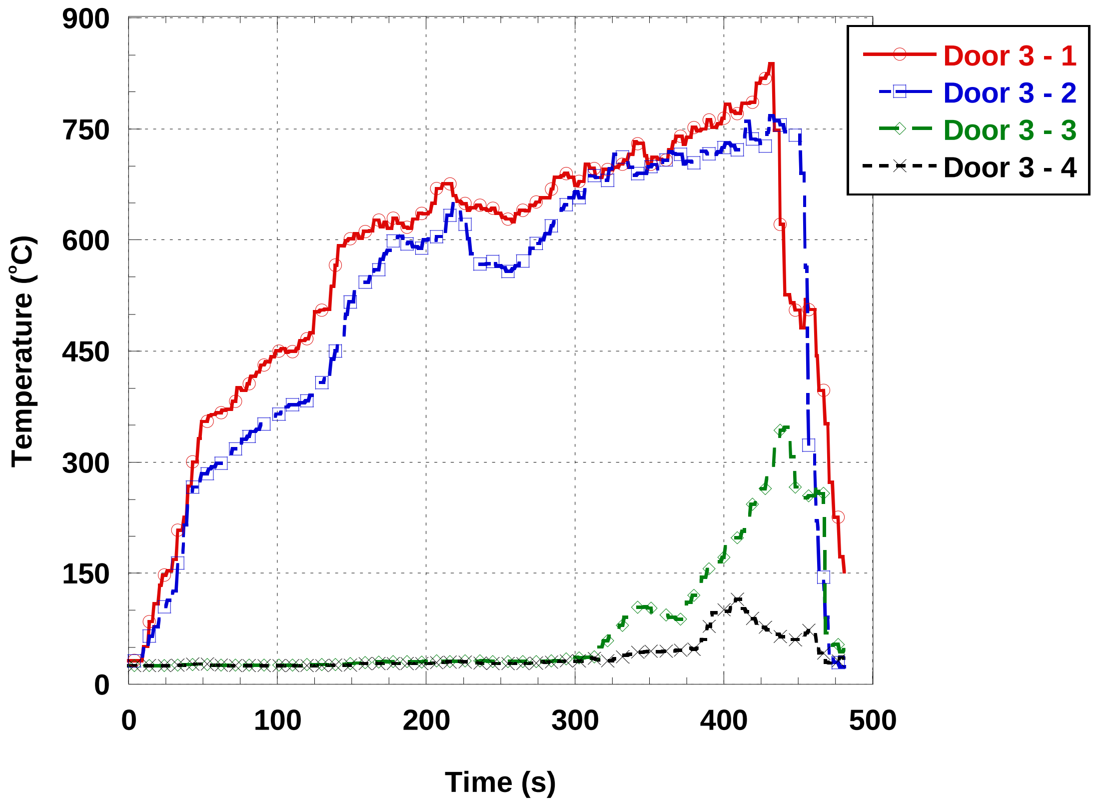


Figure 56. Door 3 Temperatures

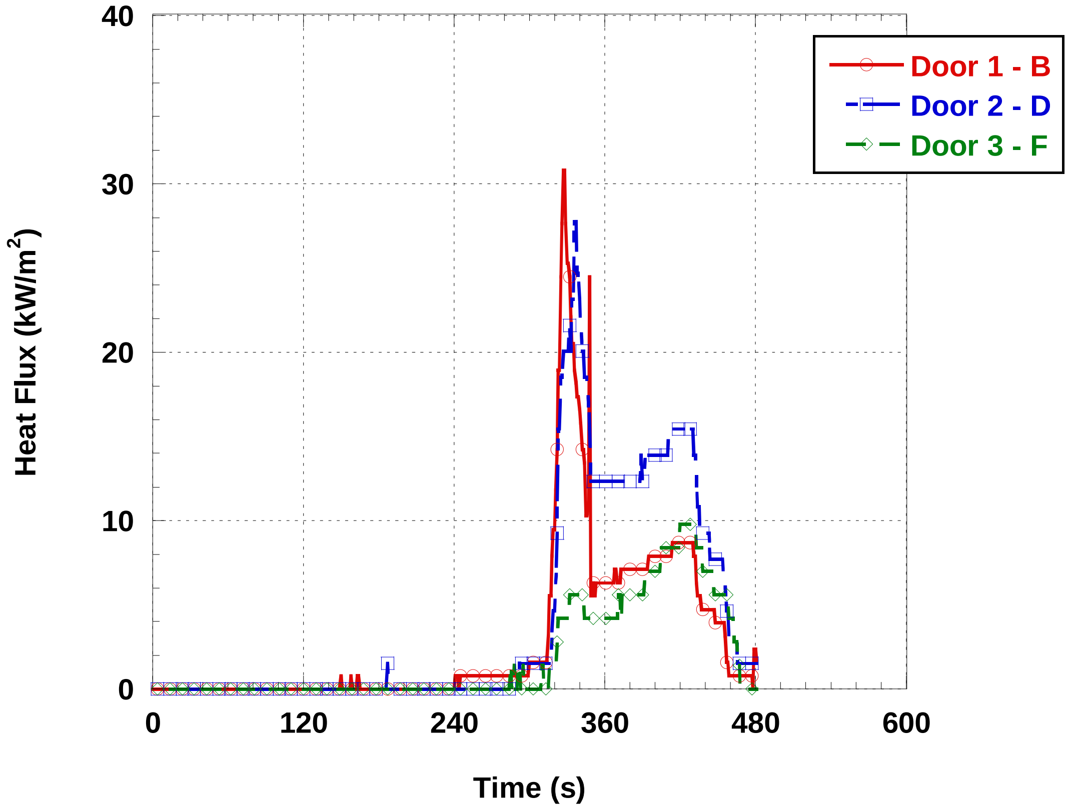


Figure 57. Experiment 7 Heat Flux

5.7. Window and Door Experiment Discussion

5.7.1. Window Furnace Exposure Repeatability

It was not possible to perform a large number of experiments and to optimize resources, 3 windows were tested at once. To improve repeatability the windows were rotated between bays in the frame so that each window was in each location once. Pillars were built into the furnace between windows to decrease the impact of one window failing on the exposure of the other windows. Figure 58 shows the furnace temperature for each window experiment versus time. The average furnace temperatures were within 20% for the first 3 minutes, 10% from minute 3 to 5 and 6% for the remainder.

Another measure of repeatability used was the heat flux to the window assemblies. Figure 59 through Figure 61 show the heat flux for the gauges that were located 10 inches below the windows for every experiment. These graphs show good repeatability between experiments. Figure 62 shows the average heat flux for the same 3 gauges. Heat flux gauge A had the highest average while heat flux gauges C and E had very similar fluxes. The heat fluxes for all of the gauges for every experiment are within 20%.

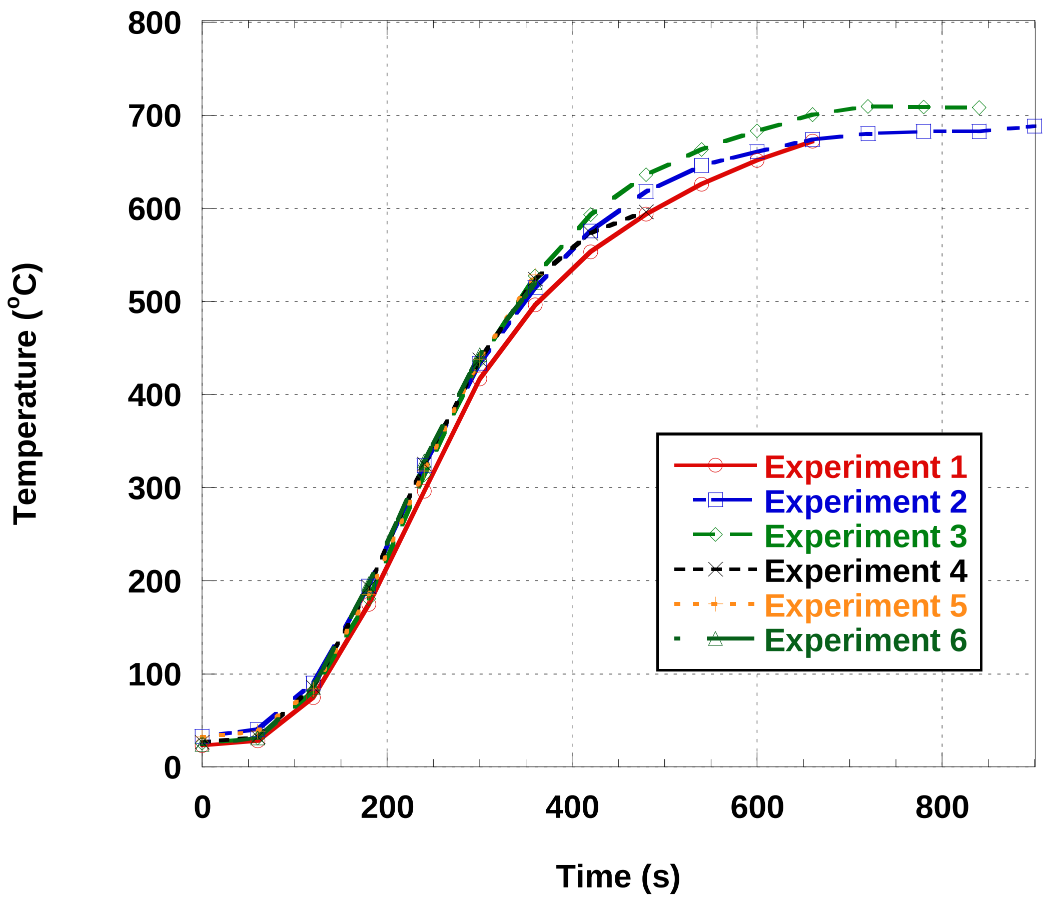


Figure 58. Furnace Temperature Comparison

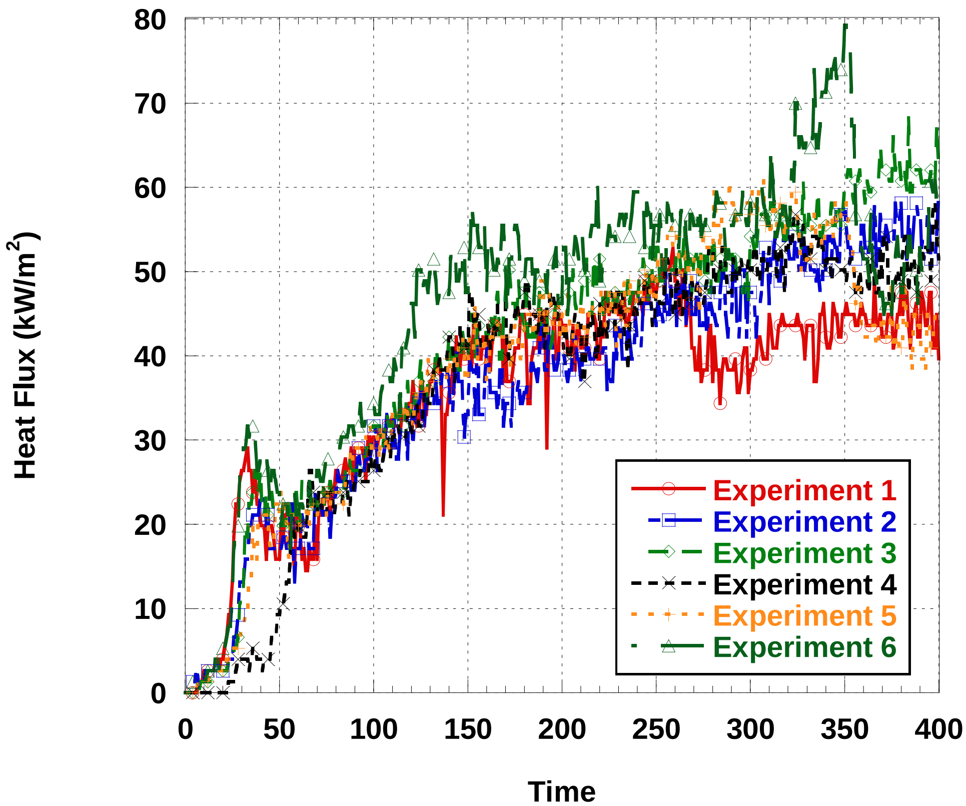


Figure 59. Heat Flux Gauge A

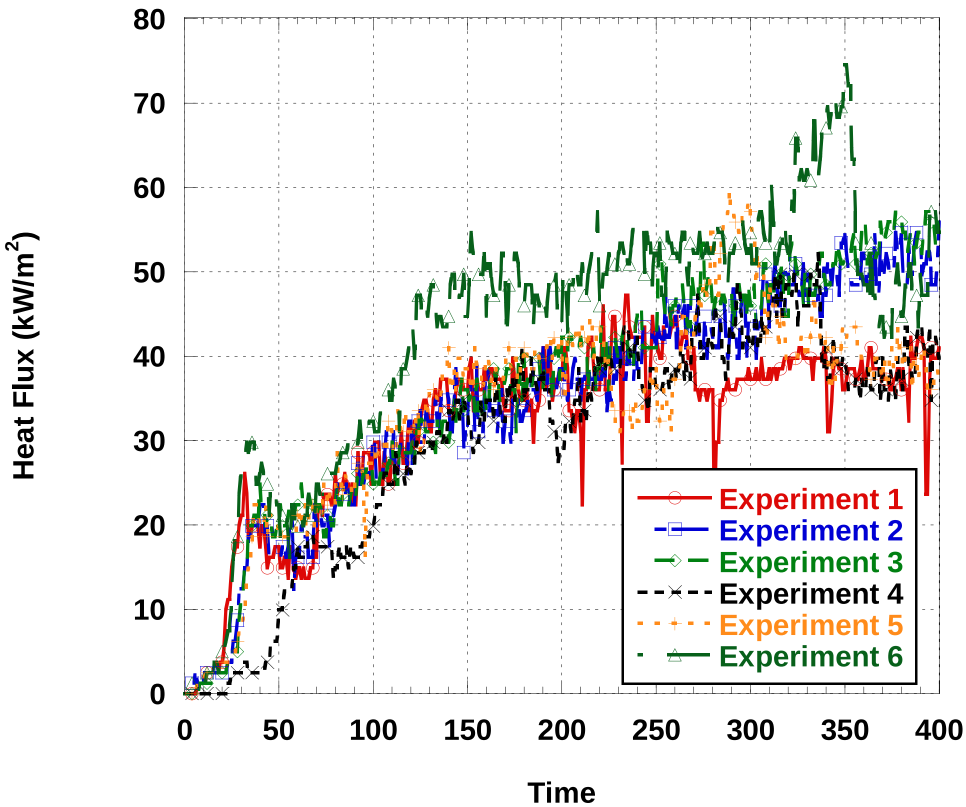


Figure 60. Heat Flux Gauge C

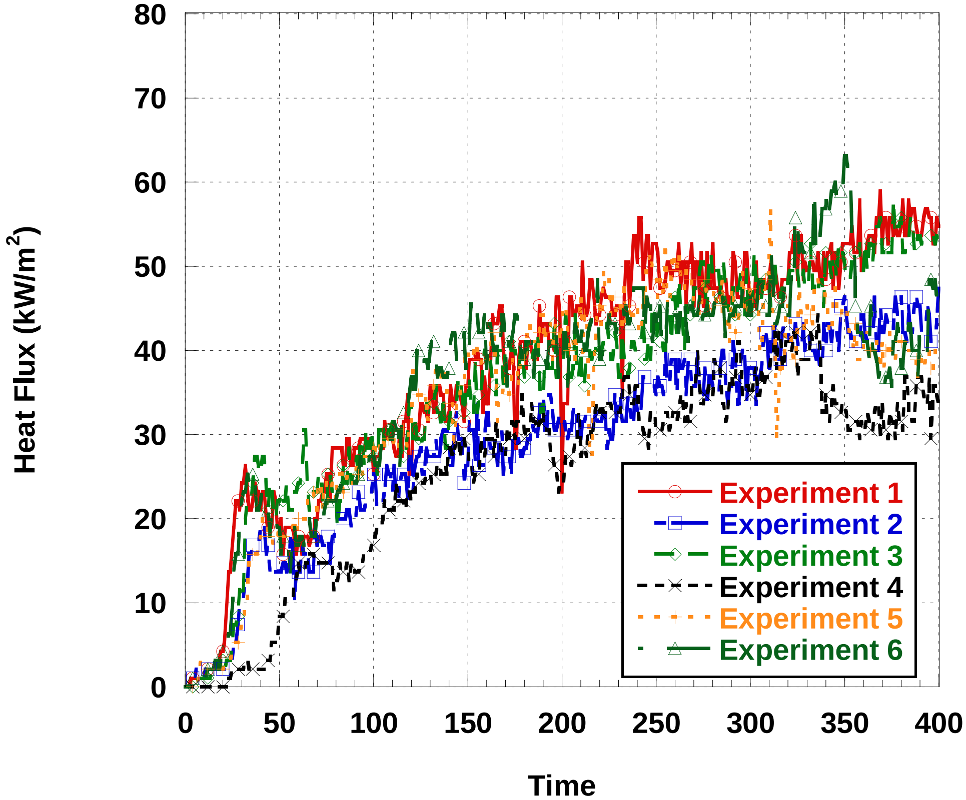


Figure 61. Heat Flux Gauge E

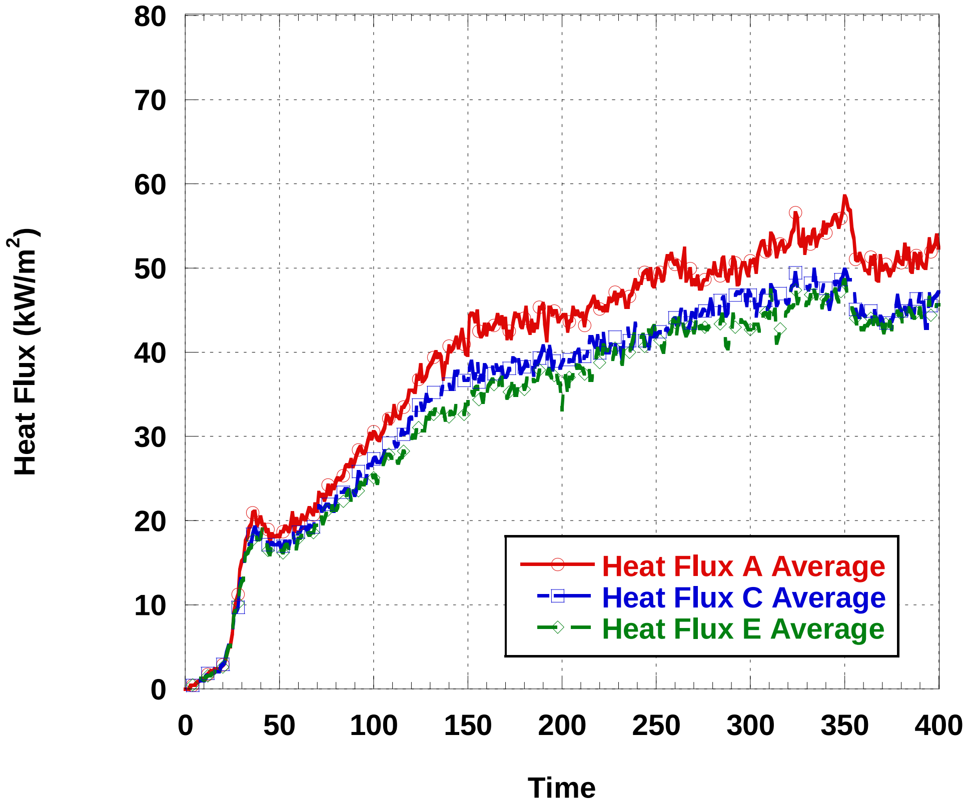


Figure 62. Average Heat Flux for Experimental Series

5.7.2. Window Failure

There were a number of different window failure mechanisms and degrees of failure observed during the experiments. In order to have an impact on the fire growth there has to be a passage for air to enter the structure, therefore the failure of interest was the breaking out of the glass as opposed to the cracking of the glass. Failure is defined as a passage through the window of 25% or more of the total glass area. In most cases this was the failure of the top or bottom pane(s) of the window but in some cases the top window sash moved downward, opening the window 25% or more. The two legacy windows with single glazing failed later than the four modern windows with double glazing. The two legacy windows failed at 577 s and 846 s respectively while the modern windows failed at 259 s, 254 s, 312 s, and 270 s respectively. Images of the experimental assemblies showing post-experiment damage are in Figure 63 through Figure 74.

In addition to time, the temperatures at which failure occurred were analyzed. Table 10 shows the average gas temperatures just inside and just outside the upper pane of each window just prior to failure. Similar to time, the temperatures for the legacy windows were higher than those of the modern windows. The legacy windows failed when the furnace side temperature was between 650 °C (1200 °F) and 790 °C (1450 °F), while the modern windows failed between 540 °C (1000 °F) and 650 °C (1200 °F). The corresponding outside of the glass temperature was between 370 °C (700 °F) and 380 °C (720 °F) for the legacy window and between 80 °C (180 °F) and 205 °C (400 °F) for the modern windows.

Table 9. Window Failure Times

	Window [mm:ss (sec)]		
Experiment	**A (L)**	**B (M)**	**C (L)**
1	6:34 (394)	4:24 (264)	11:49 (709)
2	10:06 (606)	4:38 (278)	14:30 (870)
3	12:11 (731)	3:56 (236)	16:00 (960)
Average	9:37 (577)	4:19 (259)	14:06 (846)
	D (M)	**E (M)**	**F (M)**
4	3:58 (238)	5:16 (316)	3:39 (219)
5	3:39 (219)	4:26 (266)	5:49 (349)
6	5:05 (305)	5:55 (355)	4:02 (242)
Average	4:14 (254)	5:12 (312)	4:30 (270)

Figure 63. Exp. 1 Post experiment, Unexposed side

Figure 64. Exp. 1 Post experiment, Exposed side

Figure 65. Exp. 2 Post experiment, Unexposed side

Figure 66. Exp. 2 Post experiment, Exposed side

Figure 67. Exp. 3 Post experiment, Unexposed side

Figure 68. Exp. 3 Post experiment, Exposed side

Figure 69. Exp. 4 Post experiment, Unexposed side

Figure 70. Exp. 4 Post experiment, Exposed side

Figure 71. Exp. 5 Post experiment, Unexposed side

Figure 72. Exp. 5 Post experiment, Exposed side

Figure 73. Exp. 6 Post experiment, Unexposed side

Figure 74. Exp. 6 Post experiment, Exposed side

Table 10. Top Pane Failure Temperatures

	Window		
	A (L)	**B (M)**	**C (L)**
Average Inner Temperature	650 °C (1200 °F)	540 °C (1000 °F)	790 °C (1450 °F)
Average Outer Temperature	370 °C (700 °F)	150 °C (300 °F)	380 °C (720 °F)
	D (M)	**E (M)**	**F (M)**
Average Inner Temperature	650 °C (1200 °F)	565 °C (1050 °F)	650 °C (1200 °F)
Average Outer Temperature	140 °C (280 °F)	205 °C (400 °F)	80 °C (180 °F)

5.7.3. Door failure

There was only one door failure experiment conducted and the failure times are shown in Table 11. Failure was defined to have occurred when the unexposed surface of the door sustained burning. All of the doors failed at approximately 300 s. There was very little difference between the two hollow core doors (1 and 2). The fire ignited the unexposed side and quickly consumed what was left of the door. The solid core door (3) had a similar failure time but the mechanism was different. Door 3 was a six panel door so where the panels were located on the door burned through because of its reduced thickness. The thicker portions of the door remained intact at the termination of the experiment (Figure 75). This experiment shows the fire containment ability of interior doors during a well ventilated compartment fire is approximately 5 minutes. For the doors evaluated in this experiment it can also be concluded that the type of wood had no noticeable impact on failure time.

Table 11. Door Failure Times

	Door		
Experiment	**1**	**2**	**3**
7	5:12 (312)	5:15 (315)	5:02 (302)

Figure 75. Post experiment photo of the doors

5.8. Window and Door Experiment Conclusions

These experiments demonstrated a significant difference in legacy and modern windows exposed to fire conditions. In this series of experiments the legacy single glazed windows outperformed the modern double glazed windows in terms of longer failure times. It is proposed that this occurred for two reasons. First the legacy windows had thicker glazing than the modern windows. The legacy windows had glass thicknesses of 0.093 in and 0.11 in., while the modern window thicknesses were 0.087 in. Second, the method the glass was fixed into the frame differed greatly between the two eras. The legacy window glass was held in place with putty like substance and there was room in the frame for expansion of the glass. The modern glass was fixed very tightly into the frame with an air tight gasket and metal band, to provide better thermal insulation. This configuration did not allow for much expansion and therefore stressed the glass as it heated and expanded.

The doors evaluated in this experiment demonstrated that the type of wood had no noticeable impact on failure time. The failure time was dictated by the thickness of the door. The hollow core doors had the same overall wood thickness as the panels of the solid core door and therefore the fire breached them at very similar times.

5.9. Future Research Needed

Future research is needed to examine the impact of uneven heating and the impact of soot deposited on the glass. The furnace exposes the windows to a uniform temperature and flux exposure while windows exposed to actual fire conditions most likely would be heated on a gradient as the hot gas layer moves toward the floor as the fire increases in intensity. The furnace also utilizes a fire condition that has minimal soot production. It has been observed in other experiments that the soot deposited on the glass of a window will protect it from fire exposure for a period of time.

Additional door experiments would also be insightful, especially for a solid core door with no panels. Additional experiments could also examine failure mechanisms such as fire breaching around or under the door assembly as opposed to burn through and total containment failure.

5.10. Fire Service Tactical Consideration

During window experiments 1-3 it was noticed in the thermal imaging camera view that the modern window hid the fact that there was a fire behind it for a significant period of time as compared to the legacy windows. This is anticipated due to the energy efficient design of the modern window. Figure 76 shows the thermal imaging view of the three windows 7 seconds after ignition. The heat from the furnace immediately is conducted to the exterior of the legacy windows but is not visible in the modern window. The image at one minute and 30 seconds shows that the modern window allows as much heat through as the gypsum board on the inside of the assembly, while temperatures above 150 °C (300 °F) are detected on the legacy windows (Figure 77). Figure 78 shows that heat is now visible through the window and the first crack has developed through the outer, upper pane. At 4 minutes and 27 seconds the modern window upper pane has failed and the temperature registers the same as that of the still intact legacy windows (Figure 79).

The temperature inside the modern window at 1 minute and 30 seconds is in excess of 315°C (600 °F) but is not detectible on the outside with a thermal imaging camera. This is important to understand for thermal imaging cameras being used for "size-up" of structure fires. The first elevated temperature (red in the images) detected by the thermal imaging camera came after window failure. Even slight temperature differentials noticed with the camera when looking at modern windows may be indicative of elevated temperatures in the structure.

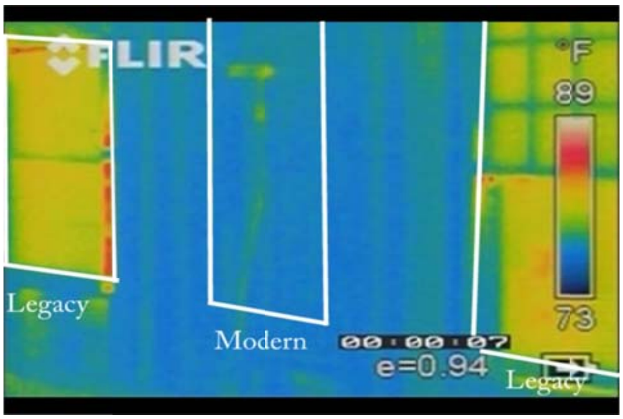


Figure 76. 7 seconds after ignition

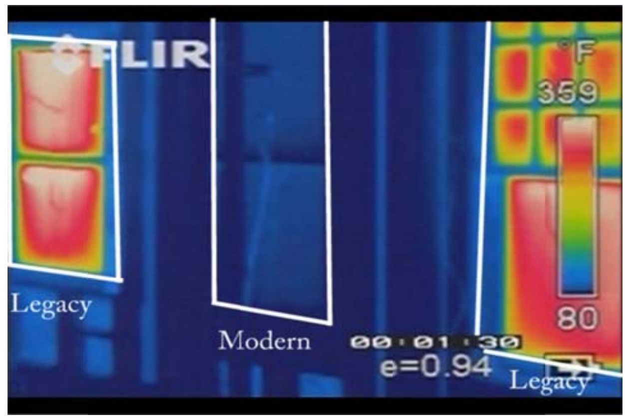


Figure 77. 1 minute 30 seconds after ignition

Figure 78. 4 minutes 7 seconds after ignition

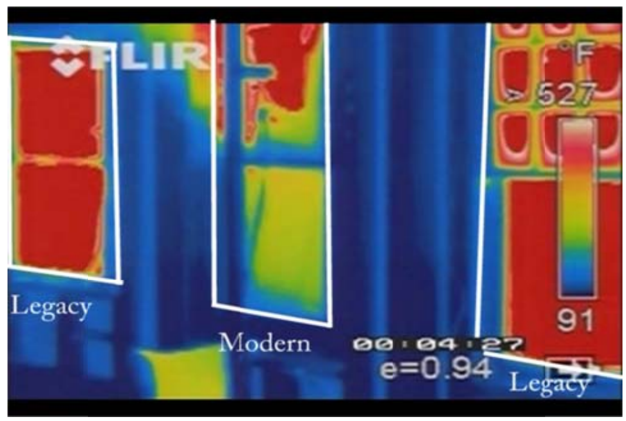


Figure 79. 4 minutes 27 seconds after ignition

6. Modern vs. Legacy Room Furnishings Fire Comparisons

Two experiments were conducted to examine the changes in fire development in modern room's contents versus that that may have been found in a house in the mid-20th century. The modern rooms utilized synthetic contents that were readily available new at various retail outlets, and the legacy rooms utilized contents that were purchased used from a number of second hand outlets.

6.1. Experiment 1

An experiment was conducted with two side by side living room fires. The purpose was to develop comparative data on modern and legacy furnishings. The rooms measured 12 by 12 ft, with an 8 ft ceiling and had an 8 ft wide by 7 ft tall opening on the front wall. Both rooms contained similar types and amounts of like furnishings.

6.1.1. Experimental Set-up and Furnishings

The modern room (Figure 80 through Figure 85) was lined with a layer of ½ inch painted gypsum board and the floor was covered with carpet and padding. The furnishings included a polyester microfiber covered polyurethane foam filled sectional sofa, engineered wood coffee table, end table, television stand and book case. The sofa had a polyester throw placed on its right side. The end table had a lamp with polyester shade on top of it and a wicker basket on its lower shelf. The coffee table had six color magazines, a television remote and a synthetic plant on it. The television stand had a color magazine and a 37 inch flat panel television. The book case had two small plastic bins, two picture frames and two glass vases on it. The right rear corner of the room had a plastic toy bin, a plastic toy tub and four stuffed toys. The rear wall had polyester curtains hanging from a metal rod and the side walls had wood framed pictures hung on them.

The legacy room (Figure 86 through Figure 91) was lined with a layer of ½ inch painted cement board and the floor was covered with unfinished hardwood flooring. The furnishings included a cotton covered, cotton batting filled sectional sofa, solid wood coffee table, two end tables, and television stand. The sofa had a cotton throw placed on its right side. Both end tables had a lamp with polyester shade on top of them. The one on the left side of the sofa had two paperback books on it. A wicker basket was located on the floor in front of the right side of the sofa at the floor level. The coffee table had three hard-covered books, a television remote and a synthetic plant on it. The television stand had a 27 inch tube television. The right front corner of the room had a wood toy bin, and multiple wood toys. The rear wall had cotton curtains hanging from a metal rod and the side walls had wood framed pictures hung on them.

Figure 80. Modern room corner

Figure 81. Modern room front

Figure 82. Modern sofa and coffee table

Figure 83. Modern end table and toys

Figure 84. Modern LCD television and stand

Figure 85. Modern book case

Figure 86. Legacy corner view

Figure 87. Legacy front view


Figure 88. Legacy end table


Figure 89. Legacy sofa and coffee table


Figure 90. Legacy television and stand


Figure 91. Legacy toys

6.1.2. Experimental Procedure

Both rooms were ignited simultaneously by placing a lit candle on the right side of the sofa. The fires were allowed to grow until flashover and maintain flashover for a short period of time. The fire was then extinguished.

6.1.3. Instrumentation

Temperatures were measured with an inconel thermocouple array placed two feet out of the right rear corner of the room. Measurements locations were every foot in elevation from the floor to the ceiling.

6.1.4. Results

The fire in the modern room grew slowly for the first minute as the candle flame extended to the polyester throw blanket and sofa cushion. At two minutes the fire had spread to the back cushion of the sofa and a black smoke layer developed in the top two to three feet of the room. At three minutes approximately one half of the sofa is involved in the fire, the carpet has begun to burn and the hot gas layer is thickening and flowing out of the top third of the room opening. The modern room transitioned to flashover in 3 minutes and 30 seconds (Figure 92 through **Figure 96**).

The fire in the legacy room also grew slowly in the first minute as the candle flame spread to the cotton throw blanket and sofa cushion. At five minutes the fire involved the arm of the sofa and extended to the curtains behind the sofa.   At ten minutes the fire has spread to approximately one-third of the sofa. From ten minutes to twenty minutes the pictures are darkened because the smoke from the modern room has obscured the lights in the laboratory that are tweny feet above the floor, however the fire continued to spread across the sofa and begin to develop a hot gas layer in the room. The legacy room transitioned to flashover at 29 minutes and 30 seconds after ignition (Figure 97 through Figure 103).

The modern room temperature peaked at approximately 1300 °C (2370 °F) while the legacy room temperature peaked at approximately 1200 °C (2190 °F) (Figure 104 and Figure 105).

Figure 92. 1 minute after ignition

Figure 93. 2 minutes after ignition

Figure 94. 3 minutes after ignition

Figure 95. 3 minutes 30 seconds after ignition

Figure 96. 4 minutes after ignition

Figure 97. 1 minute after ignition

Figure 98. 5 minutes after ignition

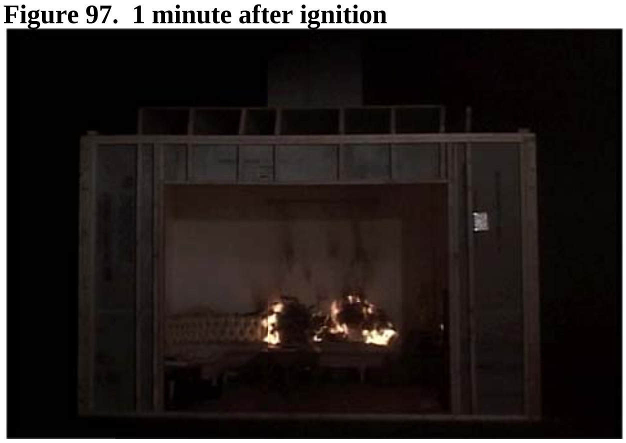


Figure 99. 10 minutes after ignition

Figure 100. 15 minutes after ignition

Figure 101. 20 minutes after ignition

Figure 102. 25 minutes after ignition

Figure 103. 29 minutes 30 seconds after ignition

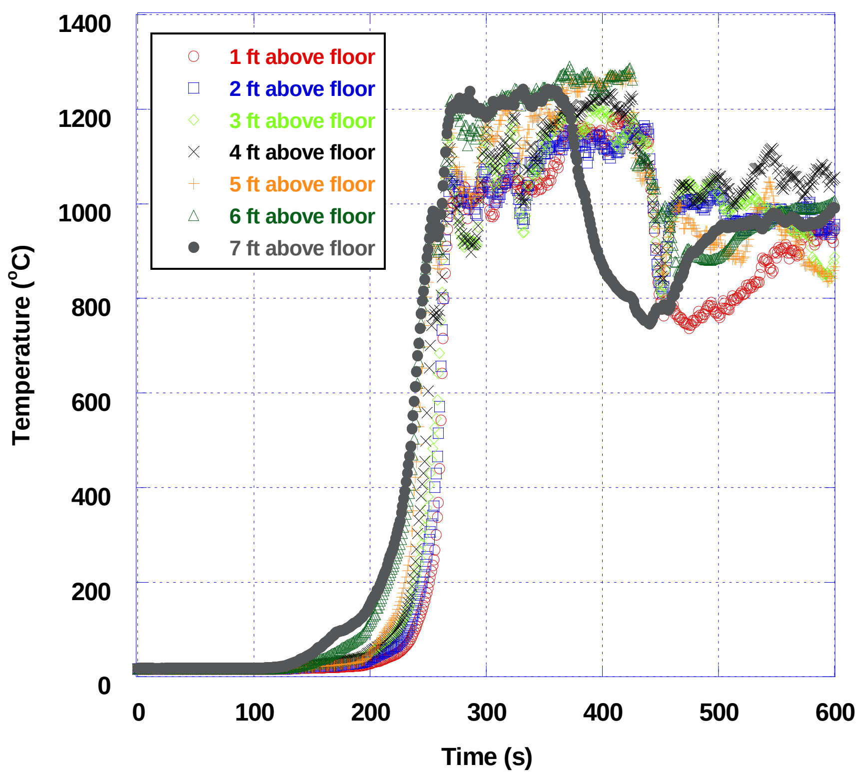


Figure 104. Modern room temperatures

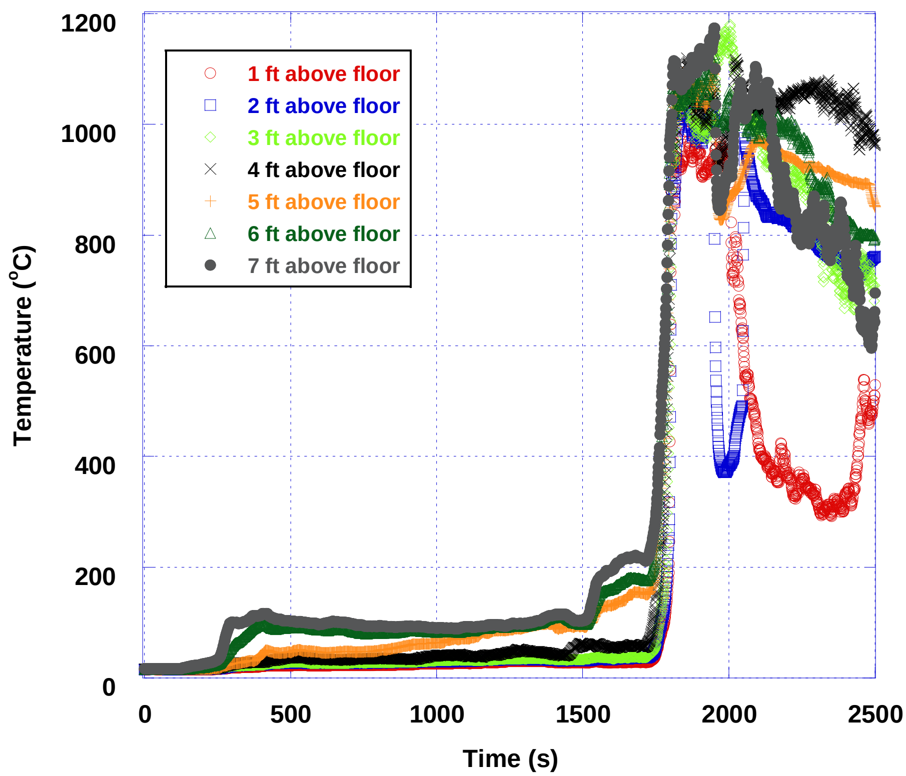


Figure 105. Legacy room temperatures

6.2. Experiment 2

A second experiment was conducted with two side by side living room fires. The purpose was the same, to gain knowledge on the difference between modern and legacy furnishings. Additionally the room size was increased to examine that impact. The rooms measured 13 ft by 18 ft, with an 8 ft ceiling and had a 10 ft wide by 7 ft tall opening on the front wall. Both rooms contained similar amounts of like furnishings (Figure 106 through Figure 113). All furnishings were weighed before being placed in the rooms. Both the modern room and legacy room had a fuel loading of approximately 2.3 lb/ft^2.

6.2.1. Experimental Set-up and Furnishings

The modern room was lined with a layer of ½ inch painted gypsum board and the floor was covered with nylon carpet and polyurethane padding. The furnishings included a polyester microfiber covered polyurethane foam filled sofa, two matching chairs, engineered wood coffee table, end table, television stand and book case. The sofa had a polyester throw placed on its left side and two polyfill pillows, one on each side. The end table had a lamp with polyester shade on top of it. The coffee table had three color magazines, a wicker basket and a synthetic plant on it. The television stand had two picture frames and a 32 inch flat panel television. The book case had a plastic basket on it. The right rear corner of the room had a plastic toy bin, a plastic toy tub and four stuffed toys. The rear wall had polyester curtains hanging from a metal rod and the side walls had wood framed pictures hung on them.

The legacy room was lined with a layer of ½ inch painted gypsum board and the floor was covered with finished hardwood flooring. The furnishings included a cotton covered, cotton batting filled sofa, two matching chairs, solid wood coffee table, two end tables, and television stand. The sofa had a cotton throw placed on its left side. Both end tables had a lamp with glass shade on top of them and a wicker basket. The coffee table had a wicker basket filled with five books and two glass vases. The television stand had a 13 inch tube television with a plant on top of it. The right rear corner of the room had a wood/wicker toy bin, and multiple wood toys. The rear wall had cotton curtains hanging from a metal rod and the side walls had wood framed pictures hung on them.

Figure 106. Front of Modern Room

Figure 107. Left wall of modern room

Figure 108. Back wall of modern room

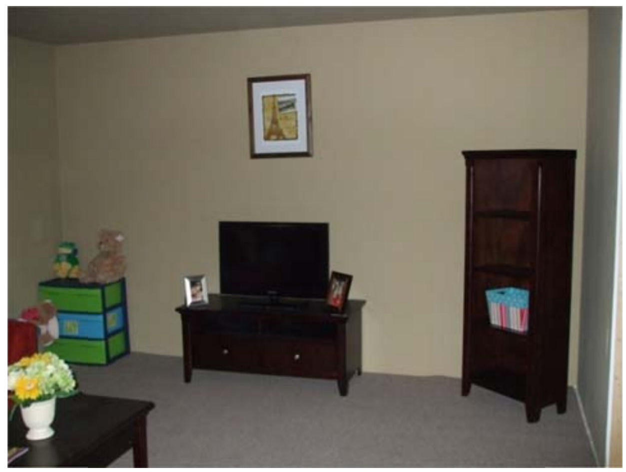


Figure 109. Right wall of modern room

Figure 110. Front of legacy room

Figure 111. Left wall of legacy room

Figure 112. Back wall of legacy room

Figure 113. Right wall of legacy room

6.2.2.Experimental Procedure

Both rooms were ignited simultaneously by placing a lit candle on the left side of the sofa. The fires were allowed to grow until flashover and maintain flashover for a short period of time. The fire was then extinguished.

6.2.3.Results

The modern room was ignited and the fire spread to the sofa cushion and pillow by the one minute mark. By two minutes the fire involved approximately one third of the top of the sofa and spread to the lamp shade. At three minutes the top of the entire sofa was on fire and the carpet began to burn adjacent to the sofa. The modern room transitioned to flashover in 3 minutes and 20 seconds (Figure 114 through Figure 117). The legacy room sofa was also ignited on the left side and it spread to the throw blanket and sofa cushion by one minute. By five minutes the fire involved the left side of the sofa and spread to the curtains burning the left panel away. At ten minutes the entire surface of the sofa was burning and by fifteen minutes the fire involved the entire sofa including the underside. The flames reached the ceiling but did not extend to the adjacent furnishings. The fire burned down and never transitioned to flashover so it was extinguished at thirty minutes after ignition (Figure 118 through Figure 124).

Figure 114. 1 minute after ignition

Figure 115. 2 minutes after ignition

Figure 116. 3 minutes after ignition

Figure 117. 3 minutes 30 seconds after ignition

Figure 118. 1 minute after ignition

Figure 119. 5 minutes after ignition


Figure 120. 10 minutes after ignition


Figure 121. 15 minutes after ignition


Figure 122. 20 minutes after ignition


Figure 123. 25 minutes after ignition


Figure 124. 30 minutes after ignition

6.3. Discussion

Comparing the two experiments, the times to flashover are very similar even though the room size and front opening was varied (Table 12). Even though the second modern room was 90 ft^2 larger and had a 14 ft^2 larger front opening a similar fuel load was able to flash the room over in the same time. The second legacy experiment did not transition to flashover because it did not have enough fuel burning at the same time to create significant heat in the upper gas layer to ignite items not adjacent to the sofa. The chairs on the left side of the room and the television and bookcase of the right side of the room were never heated to their ignition temperatures. The legacy sectional sofa in the first experiment was able to accomplish this heat generation because of its additional surface area as compared to the second experiments regular sofa. The chairs' being a few feet away was enough to not allow them to ignite.

Table 12. Comparison flashover times

Experiment	Modern	Legacy
1	3:30	29:30
2	3:20	Not Achieved

6.4. Conclusion

The modern rooms and the legacy rooms demonstrated very different fire behavior. It was very clear that the natural materials in the legacy room burned slower and produced less energy and smoke than the fast burning synthetic furnished modern room. The times to flashover show that the a flaming fire in a room with modern furnishings leaves significantly less time for occupants to escape the fire. It also demonstrates to the fire service that in most cases the fire has either transitioned to flashover prior to their arrival or became ventilation limited and is waiting for a ventilation opening to increase in burning rate.

7. Heat Release Rate Experiment

Prior to conducting the full-scale house experiments a fuel load needed to be determined. In order to achieve ventilation limited fire conditions during the experiments, the fuel load must consume more oxygen than is available in the houses. To measure this an 18 ft by 13 ft room was constructed in UL's large fire test building (Figure 125).

7.1. Experimental Set-up and Furnishings

The experimental room dimensions, 18 ft wide by 13 ft deep by 8 ft tall, were similar to those of the living rooms in the experimental houses. The opening on the front of the room measured 12 ft wide by 7 ft tall. This opening was meant to simulate multiple openings to adjacent rooms such as in the one-story house. The furniture was chosen to represent a common compliment of furnishings including two sofas, end table, lamp, stuffed chair, armoire, television, carpet and carpet padding. All furnishings in the room were positioned similar to that of the rooms in the houses. For more details on the furniture and their positioning refer to Section 7.3.

7.2. Experimental Procedure

Ignition took place remotely using stick matches on the left side of the sofa facing the opening of the room. The fire was allowed to grow unimpeded through flashover and the decay stages of the fire. The fire was suppressed once the furnishings burned to a pile of glowing embers.

7.3. Instrumentation

The room was positioned in the nominal 50 by 50-ft. fire test cell equipped with a 25-ft. diameter heat release rate measurement hood (Figure 126). Four inlet ducts provide make up air in the test facility and are located at the walls 5 ft. above the test floor to minimize any induced drafts during the fire tests.

The heat release calorimeter is equipped with convective and total heat release instrumentation. The convective instrumentation calculates the heat release rate from the energy rise of the products of combustion entering the calorimeter. The total heat release instrumentation calculates fire size using oxygen consumption techniques. The heat release calorimeter is calibrated up to a 10 MW fire size. Heat release rate data beyond the calibrated value may reflect inaccuracies which are resultant from products of combustion overflowing the collection hood.

Temperatures were measured with an inconel thermocouple array placed two feet out of the left rear corner of the room. Measurements locations were every foot in elevation from the floor to the ceiling.

7.4. Results

Figure 127 through Figure 136 show each minute for the first ten minutes of the experiment. Flashover occurred at approximately five minutes after ignition. The peak heat release rate was 11.5 MW at approximately six minutes after ignition (Figure 137). The peak temperature measured 1 ft from the ceiling was approximately 1100 °C (2010 °F) eight minutes after ignition (Figure 138).

7.5. Discussion

To determine the ability to achieve ventilation limited conditions in both houses with this fuel package, the available oxygen needed to be compared to the oxygen consumed during the heat release rate experiment. First the interior volume of the houses was calculated and the volume of interior walls, stairs and floors was subtracted. The volume of the furnishings was disregarded to remain conservative. The percentage of oxygen (21%) was multiplied by the resulting volume to calculate the volume of oxygen.

One-Story: 7,600 ft^3 x 0.21 = 1,596 ft^3 O_2
Two-Story: 20,350 ft^3 x 0.21 = 4,273 ft^3 O_2

The volume of oxygen above was converted to mass and multiplied by the mass of oxygen in each house and the theoretical value of 13.1 kJ/g. Using this theoretical value of energy produced by the consumption of oxygen[46], a theoretical amount of maximum energy produced can be calculated for each house.

0.001429 g/cm^3 x 3.5315×10^{-5} cm^3/ft^3 = 40.46 g/ft^3 of oxygen

One-Story: 40.46 g/ft^3 x 1596 ft^3 = 64,582 g
Two-Story: 40.46 g/ft^3 x 4273 ft^3 =172,886 g

One-Story: 64,582 g x 13.1 kJ/g = 846,204 kJ
Two-Story: 172,886 g x 13.1 kJ/g = 2,264,801 kJ

The amount of energy produced during the heat release rate experiment was calculated by integrating the area under the curve of the heat release rate versus time plot. This value was 3,647,010 kJ over the 19 minute experiment. Focusing on the time before ventilation in the house experiments the energy released during the first 10 minutes was calculated to be 2,268,436 kJ. This value is greater than that for both houses, so in theory the fire can consume all of the oxygen in the houses prior to ventilation.

7.6. Conclusion

The heat release measurement confirms that the fuel package selected is sufficient to generate ventilation limited conditions in both houses. This fuel package and fuel layout will be utilized for the full-scale house experiments in the following section.

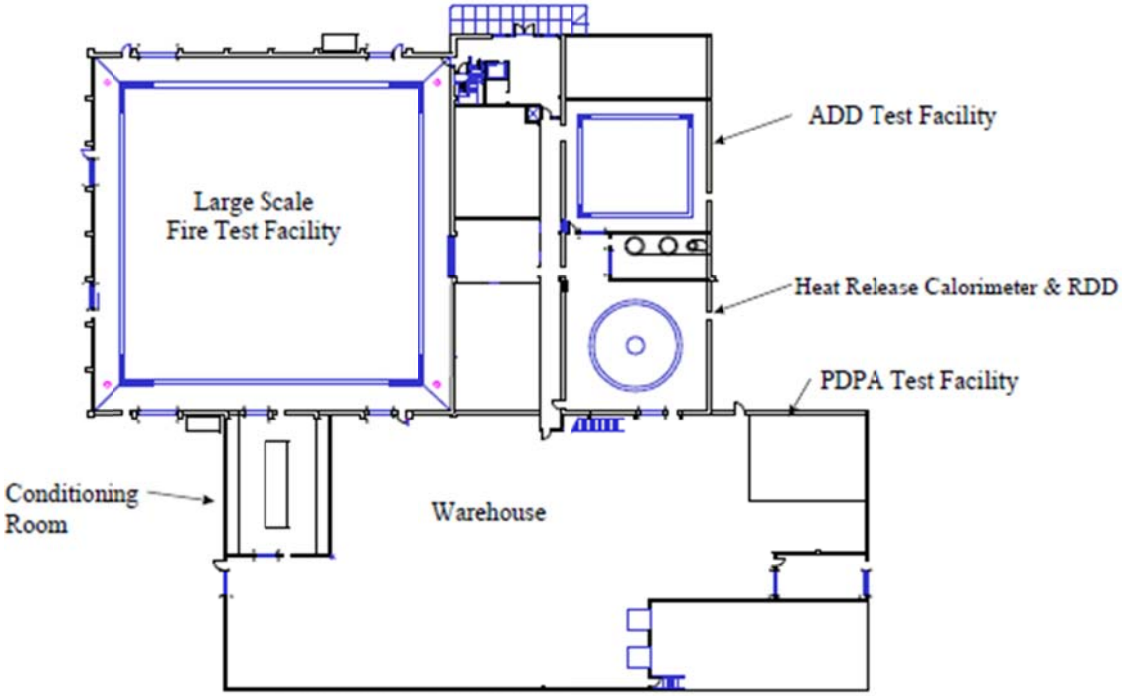


Figure 125. UL's Large-Scale Fire Test Building

Figure 126. Heat Release Rate Experimental Set-up

Figure 127. 1 minute after ignition

Figure 128. 2 minutes after ignition

Figure 129. 3 minutes after ignition

Figure 130. 4 minutes after ignition

Figure 131. 5 minutes after ignition

Figure 132. 6 minutes after ignition

Figure 133. 7 minutes after ignition

Figure 134. 8 minutes after ignition

Figure 135. 9 minutes after ignition

Figure 136. 10 minutes after ignition

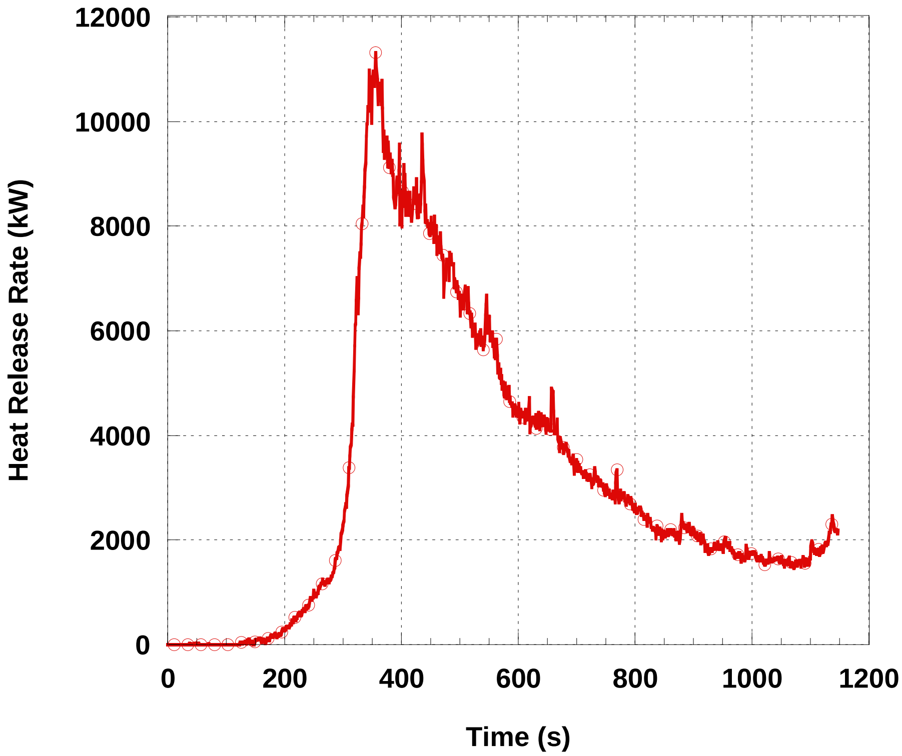


Figure 137. Heat release rate versus time

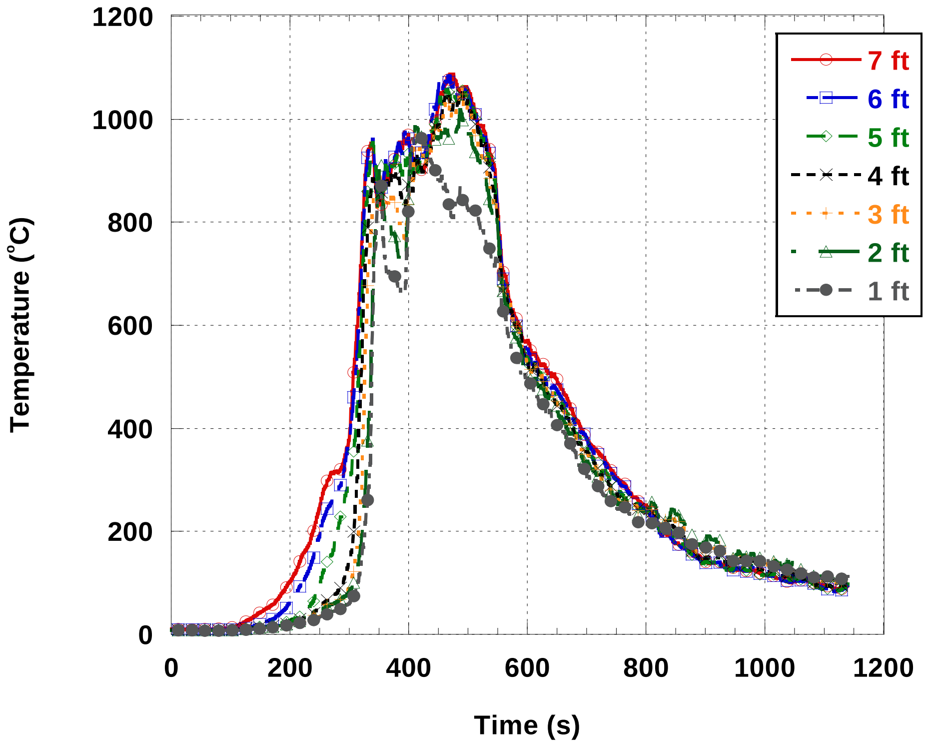


Figure 138. HRR Experiment room temperatures

8. Full-Scale House Experiments

To examine ventilation practices as well as the impact of changes in modern house geometries, two houses were constructed in the large fire facility of Underwriters Laboratories in Northbrook, IL. Fifteen experiments were conducted varying the ventilation locations and the number of ventilation openings (Table 13). Ventilation scenarios included ventilating the front door only, opening the front door and a window near and remote from the seat of the fire, opening a window only and ventilating a higher opening in the two-story house. One scenario, each for the one-story and two-story structures were conducted in triplicate to examine repeatability. Details of the structures, instrumentation, fuel load and results follow in this section. To assist with understanding the results, Appendix A contains firefighter reference scales for temperature and carbon monoxide levels.

Table 13. Experimental Series

Experiment #	Structure	Location of Ignition	Ventilation Parameters
1	1-Story	Living Room	Front Door
2	2-Story	Family Room	Front Door
3	1-Story	Living Room	Front Door + Living Room Window (Window near seat of the fire)
4	2-Story	Family Room	Front Door + Family Room Window (Window near seat of the fire)
5	1-Story	Living Room	Living Room Window Only
6	2-Story	Family Room	Family Room Window Only
7	1-Story	Living Room	Front Door + Bedroom 2 Window (Window remote from fire)
8	2-Story	Family Room	Front Door + Bedroom 3 Window (Window remote from fire)
9	1-Story	Living Room	Front Door + Living Room Window (Repeat Exp. 3)
10	2-Story	Family Room	Front Door + Family Room Window (Repeat Exp. 4)
11	2-Story	Family Room	Front Door + Family Room Window (Repeat Exp. 4)
12	1-Story	Living Room	Front Door + Living Room Window (Repeat Exp. 3)
13	2-Story	Family Room	Front Door + Upper Family Room Window
14	1-Story	Living Room	Front Door + 4 Windows (LR, BR1, BR2, BR3)
15	2-Story	Family Room	Front Door + 4 Windows (LR, Den, FR1, FR2)

8.1. One-Story Structure

Seven of the experiments took place in the one-story house. The house was designed by a residential architectural company to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 8 ft ceilings. The experiments aim to examine the fire dynamics in a structure of this type and to further understand the impact of different types of ventilation on tenability throughout the structure.

The one-story house had an area of 1200 ft^2, with 3 bedrooms, 1 bathroom and 8 total rooms (Figure 139 through Figure 141). The home was a wood frame, type 5 structure lined with two layers of gypsum board (Base layer 5/8 in, Surface layer ½ in.) The roof was truss construction but not sheathed because the fires were content fires only and not structure fires. The front and rear of the structure were covered with cement board to limit exterior fire spread. Figure 142 is a 3D rendering of the house with the roof cut away to show the interior layout with furniture and floor coverings. The tan floor shows the carpet placement and the grey shows the cement floor or simulated tile locations.

Figure 139. One-story front

Figure 140. One-story rear

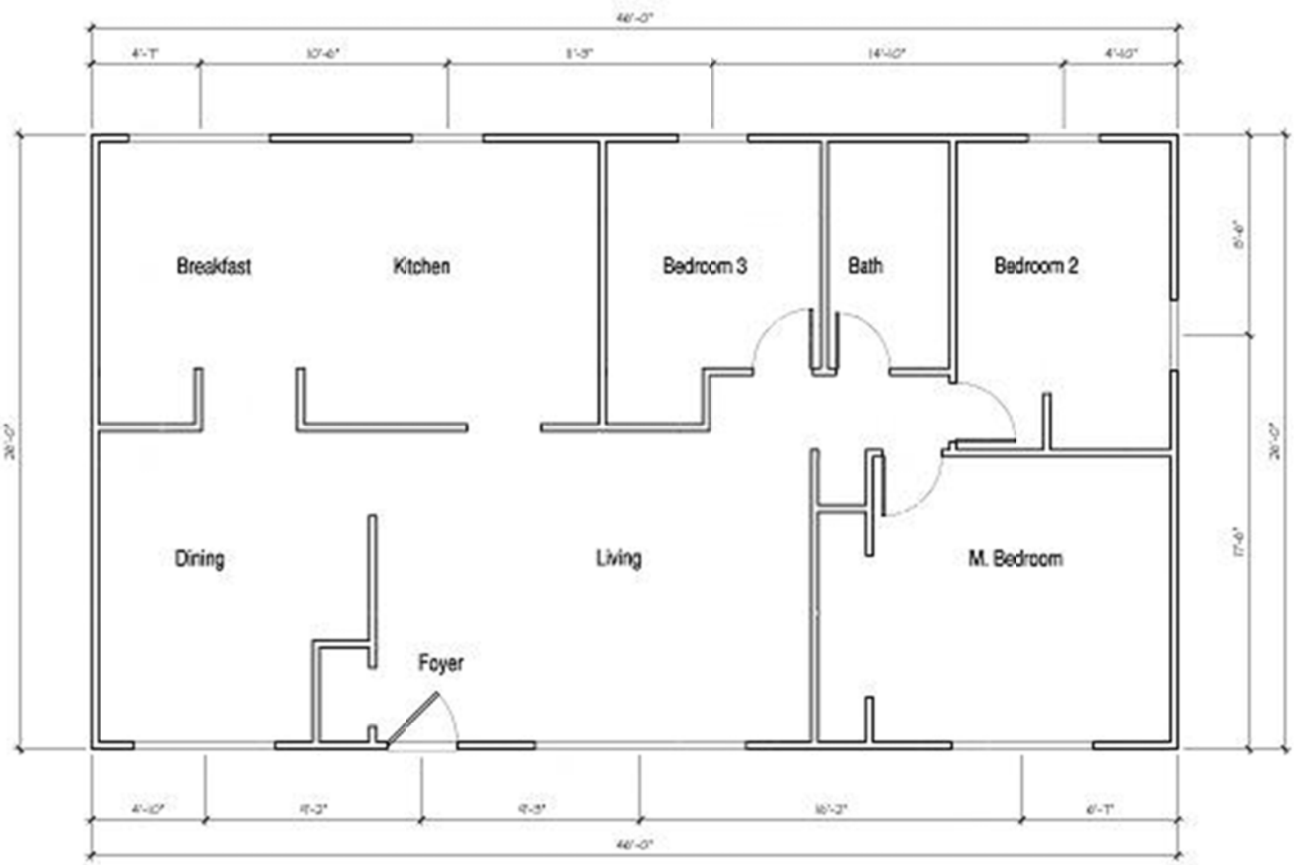


Figure 141. One-Story House Floor Plan

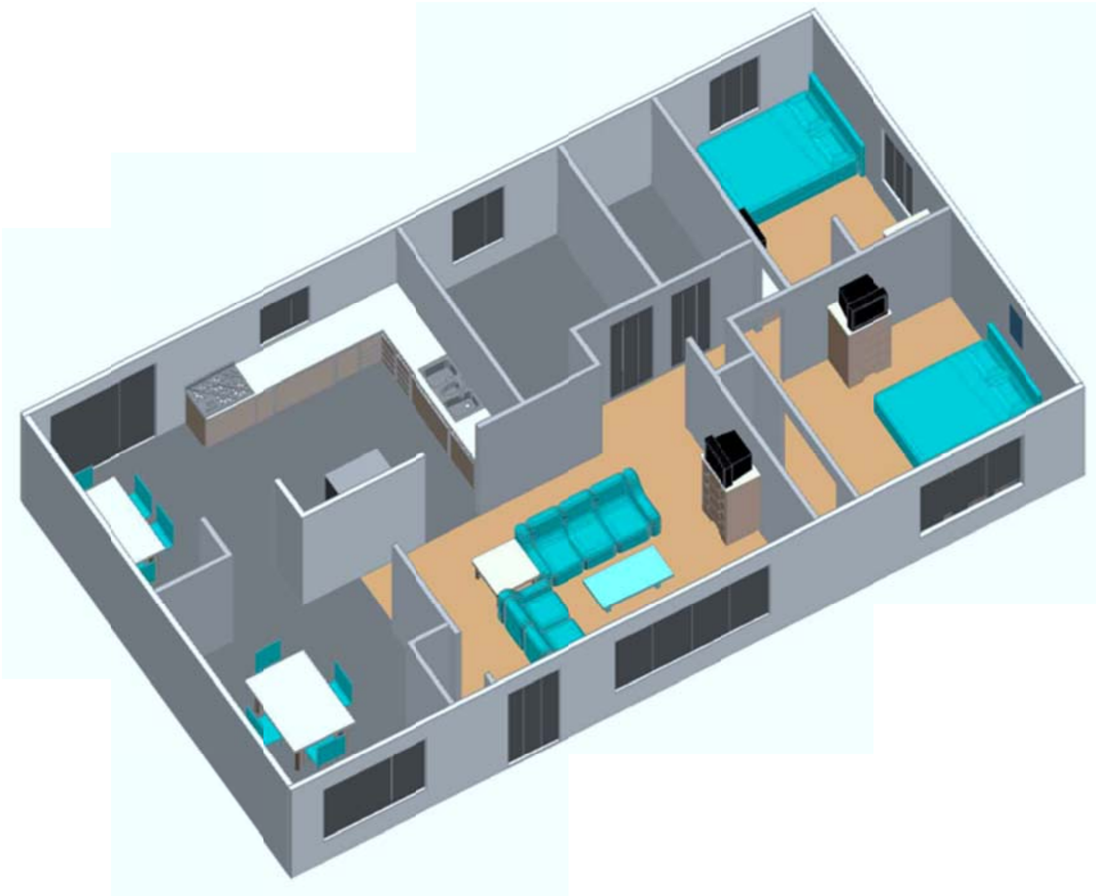


Figure 142. 3D Rendering of the One-Story House from the Front

8.2. Two-Story Structure

The two-story house had an area of 3200 ft^2, with 4 bedrooms, 2.5 bathrooms house and 12 total rooms (Figure 143 through Figure 148). The home was also a wood frame, type 5 structure lined with two layers of gypsum board (Base layer 5/8 in, Surface layer ½ in.) The roof was truss construction but not sheathed because the fires were content fires only and not structure fires. The front and rear of the structure were covered with cement board to limit exterior fire spread.

Figure 143. Two-Story front

Figure 144. Two-Story Rear

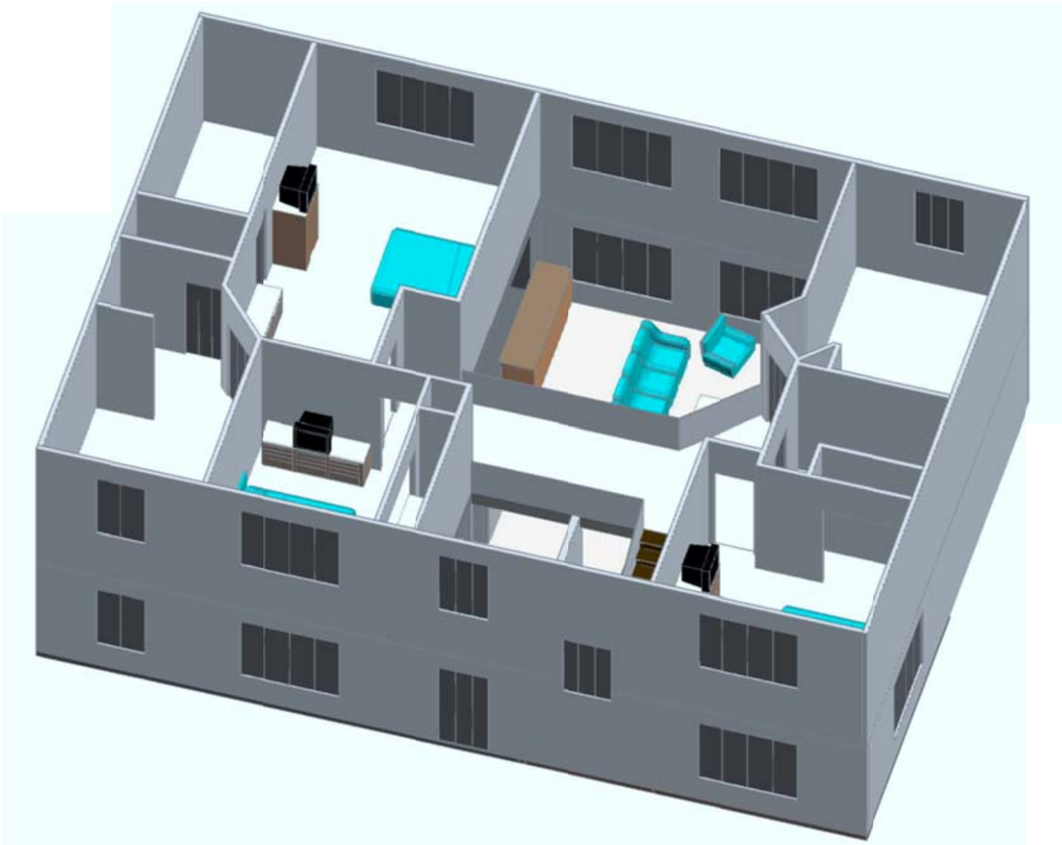


Figure 145. 3D Rendering of the 2-Story House from the Front

Figure 146. 3D Rendering of the 2-Story House from the Back

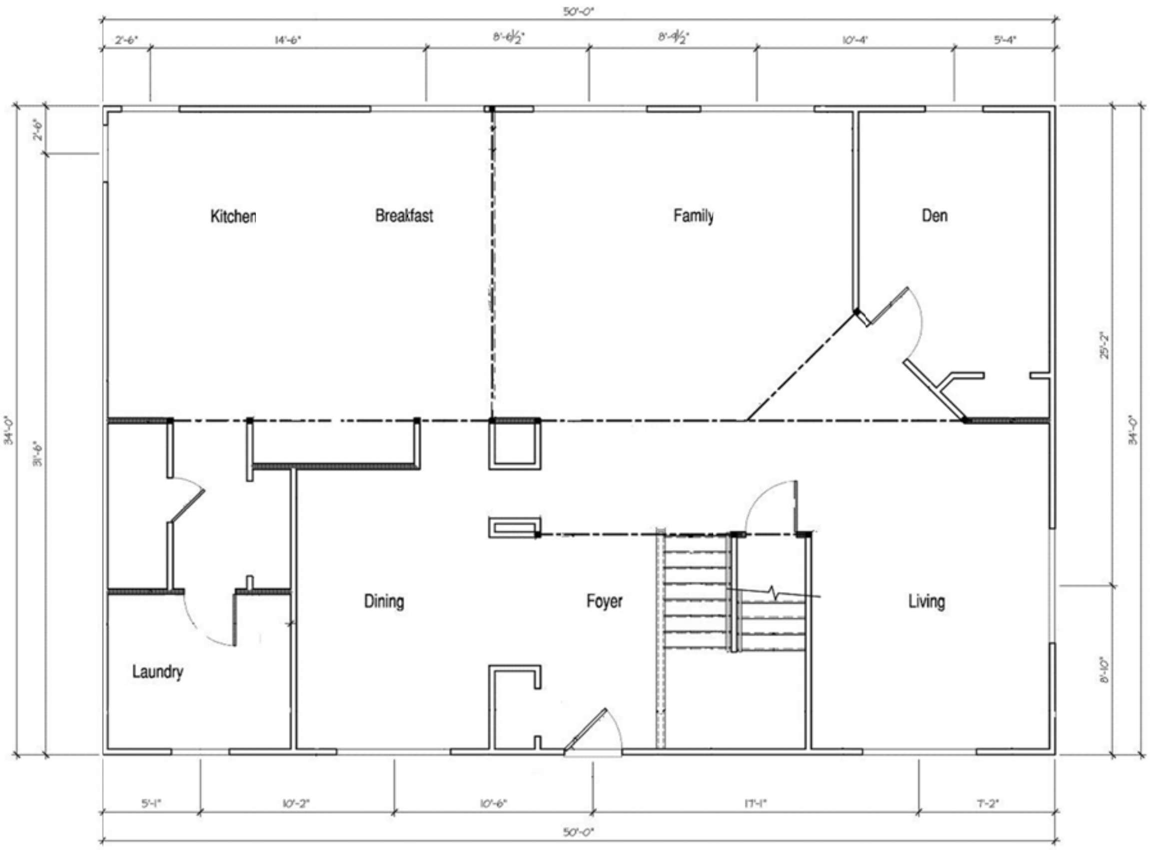


Figure 147. Two-Story House First Floor Plan

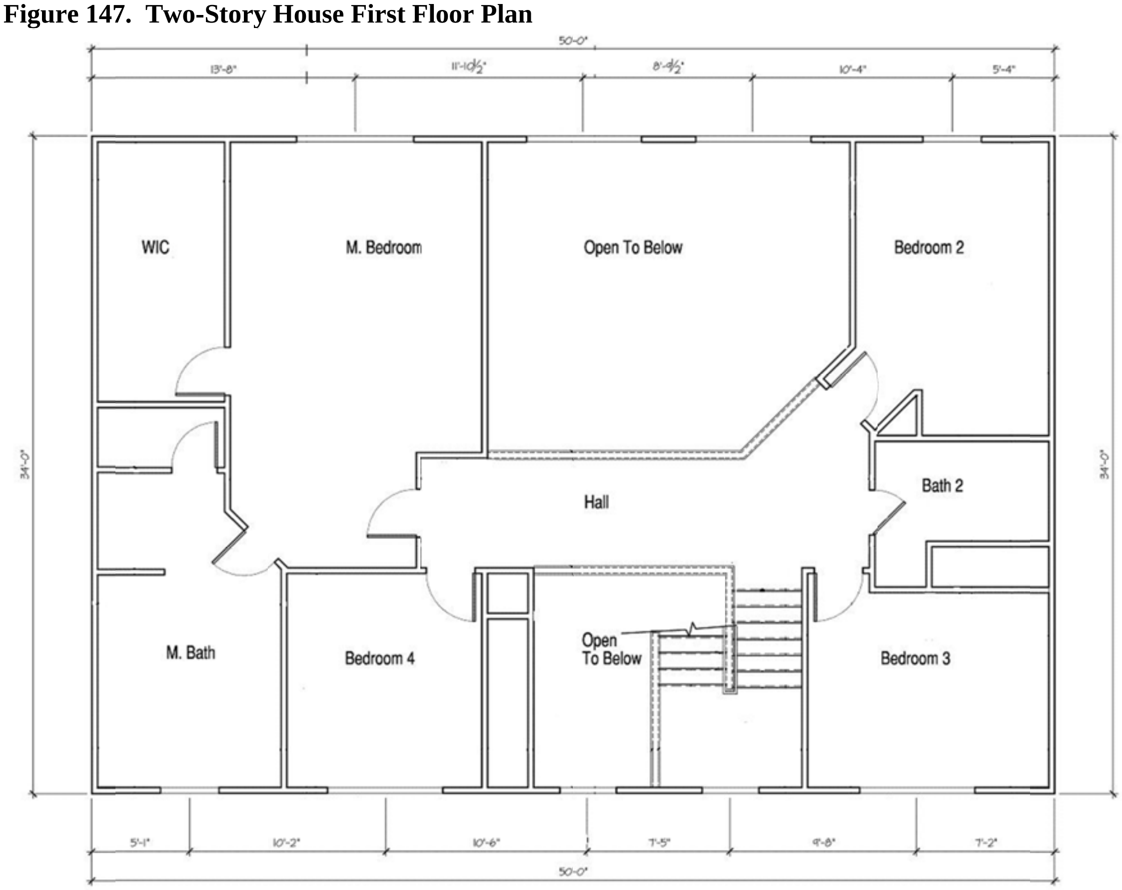


Figure 148. Two-Story House Second Floor Plan

8.3. Fuel Load

Furniture was acquired for the experiments such that each room of furniture was the same from experiment to experiment. Descriptions, dimensions and weights for all of the furniture are in Table 14. The living room in the one-story house, the family room and the living room in the two-story house were furnished similarly with two sofas, armoire, television, end table, coffee table, chair, two pictures, lamp with shade and two curtains (Figure 149 through Figure 151). The floor was covered with polyurethane foam padding and polyester carpet. These were also the same furnishings used in the heat release rate experiment in Section 7.

The master bedroom in both houses was furnished with a queen bed comprised of a mattress, box spring, wood frame, two pillows and comforter. The rest of the room had a dark brown dresser, armoire and television. The floor was covered with polyurethane foam padding and polyester carpet (Figure 152 and Figure 153). The remainder of the bedrooms in both houses was furnished with the same bed, armoire, television and flooring compliment as well as a light brown dresser, headboard, framed mirror (Figure 154 and Figure 155).

The dining room of both houses was furnished with a solid wood table and four upholstered chairs (Figure 156). The kitchens were furnished with the same table and chairs as the dining room, a dishwasher, stove, refrigerator and simulated OSB base cabinets with cement board counters. The floors of both rooms were also cement board to simulate a tile floor (Figure 157 and Figure 158). The two-story house also had a den on the first floor in which a tan stuffed chair was placed as a target fuel.

Table 14. Furnishings

Item	General Description	Depth (in)	Width (in)	Height (in)	Weight (lb)
Armoire	Medium brown, with TV	28	41	79	285
Sofa	Patterned sleeper sofa	36	72.5	33	171
Chair	Solid light tan patterened chair with padded arms	35	32.5	32.5	60
End Table	Solid wood	24	27	24.25	23
Coffee Table	Solid wood	20	36	19.5	30
Television	25 in. screen, tube	24	27	24	72
Picture	brass wood frame	30	1	26	8.6
Picture	blue wood frame	38.5	1	21.5	9.4
Lamp Shade	Plastic cloth	20	10	9.5	0.6
Curtains	weighed as a pair				6.5
Mattress	queen	60	78	7.5	65.5
Box Spring	queen	60	78	7.5	63
Dresser	Light brown, mainly particle board	19	71.5	23.25	140
Dresser	Dark brown, mostly solid wood	20	71.75	24	131
Mirror	Particle board frame	28	1	46.5	25
Headboard	Particle board	1.25	60.5	20	35
Dining Room Table	Solid wood	44	60	30.5	147
Dining Room Chair	Upholstered	20	22.5	36	24.3

Item	General Description	Depth (in)	Width (in)	Height (in)	Weight (lb)
Refrigerator	White – 1 story	29	36	70	NA
Oven	White – 1 story	27	30	46.75	NA
Dishwasher	White – 1 story				NA
Refrigerator	Stainless Steel - 2 story	27.5	36.25	70.25	NA
Oven	White - 2 Story	26.5	30	46.5	NA
Dishwasher	Stainless Steel - 2 story	27	24	34	NA
Island	2 Story only	24	96	36	160.2
Counter	Both ranch and 2 story	24	96	36	102.4
Chair	Light brown, slight pattern with padded arms	34	29	34	63.2
Comforter	Full/queen	2	86	92	5.1
Pillows	Twin size	6	20	26	1.1

Figure 149. One-Story Living Room

Figure 150. Two-Story Family Room

Figure 151. Two-Story Living Room

Figure 152. Two-Story Master Bedroom


Figure 153. One-Story Master Bedroom


Figure 154. Two-Story Bedroom 2


Figure 155. Bedroom Fuel Load


Figure 156. Dining Room Fuel Load


Figure 157. One-Story Kitchen


Figure 158. Two-Story Kitchen

8.4. Instrumentation

The measurements taken during the experiments included gas temperature, gas velocity, gas concentrations and video recording. Detailed measurement locations can be found in Appendix A and B. Gas temperature was measured with bare-bead, Chromel-Alumel (type K) thermocouples, with a 0.5 mm (0.02 in) nominal diameter. Thermocouple arrays were located in every room. The thermocouple locations in the living room and hallway had an array of thermocouples with measurement locations of 0.03 m, 0.3 m, 0.6 m, 0.9 m, 1.2 m,1.5 m, 1.8 m and 2.1 m (1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft) below the ceiling (Figure 159). The thermocouple locations in the dining room, kitchen, and bedrooms had an array of thermocouples with measurement locations of 0.3 m, 0.9 m, 1.5 m, and 2.1 m (1 ft, 3 ft, 5 ft, and 7 ft) below the ceiling.

Gas velocity was measured utilizing differential pressure transducers connected to bidirectional velocity probes (Figure 160 through Figure 162). These probes were located in the front doorway and the window used for ventilation. There were five probes on the vertical centerline of each doorway located at 0.3 m (1 ft) from the top of the doorway, the center of the doorway and 0.3 m (1 ft) from the bottom of the doorway. Thermocouples were co-located with the bidirectional probes to complete the gas velocity measurement. Positive measurements are flows out of the houses while negative velocity measurements are into the houses.

Gas concentrations of oxygen, carbon monoxide and carbon dioxide were measured in 4 locations in the structure. Concentrations were measured at 1 ft and 5 ft from the floor in the living room and at 5 ft from the floor in bedrooms 2 and 3 (Figure 163 and Figure 164). Gas concentration measurements after water flow into the structure may not be accurate due to the impact of moisture on the gas measurement equipment.

Video cameras were placed inside and outside the building to monitor both smoke and fire conditions throughout each experiment (Figure 165). Eight video camera views were recorded during each experiment. The views recorded are detailed in Table 15.

Table 15. Video camera views

One-Story	Two-Story
Outside front	Outside front
Outside rear	Outside rear
Inside front door	Inside front door
From dining room looking into the living room	From hallway looking down into the family room
From kitchen looking into the living room	From kitchen looking into the family room
Bedroom 3 looking at closed door	From living room looking toward family room
Bedroom 2 looking toward hallway	Bedroom 2 looking toward hallway
Master bedroom looking toward hallway	From master bedroom looking toward hallway

Figure 159. Thermocouple Array

Figure 160. Doorway Velocity Probes


Figure 161. Window Velocity Probes


Figure 162. Pressure Transducers


Figure 163. Gas Sampling Tubes


Figure 164. Gas Sampling Instruments


Figure 165. Interior Video Camera

8.5. Experimental Methodology

All of the experiments began with all of the exterior doors and windows closed and all of the interior doors in the same locations, either open or closed, for every experiment. The fire was ignited in a sofa in the living room of the one story house (Figure 166) and in a sofa in the family room for the two story house (Figure 167) using a remote ignition device comprised of three stick matches (Figure 168). This ignition device used a thin wire which was energized to heat the match heads to create a small flaming ignition.

The flaming fire was allowed to grow until ventilation operations were simulated by making openings. The one story house was ventilated at 8 minutes after ignition. This was determined based on three factors, time to achieve ventilation limited conditions in the house, potential response and intervention times of the fire service and window failure times from the window experiments. The ventilation time for the two story house was 10 minutes for the same reasons as the one story house and the additional time enabled ventilation limited conditions, as the larger volume needed a longer time to consume the oxygen.

Ventilation scenarios included ventilating the front door only, opening the front door and a window near and remote from the seat of the fire, opening a window only and ventilating a higher opening in the two-story house. When more than one ventilation opening was created in an experiment, such as opening the door and a window, the subsequent openings were made in 15 second intervals. This time was arrived at by assuming well timed and efficient ventilation independent of the ventilation scenario.

After ventilation the fire was allowed to grow until flashover or perceived maximum burning rate based on the temperatures, observation of exterior conditions and monitoring of the internal video. Once the fire maintained a peak for a period of time, with respect given to wall lining integrity, a hose stream was flowed in through an external opening.

At the conclusion of every experiment a stream of water was directed into a ventilation opening for 10 seconds. The hose line used was a 1 ¾ inch with a combination nozzle with approximately 100 psi nozzle pressure (Figure 169). Two types of flow patterns were used during the experiments, straight stream and fog. During straight stream application the nozzle was adjusted to a straight stream pattern and directed toward the ceiling through the opening at about a 30 to 45 degree angle (Figure 170). During the fog stream application the nozzle was adjusted to create an approximate 30 degree fog pattern and also direct the stream 30 to 45 degrees above parallel to the ground (Figure 171). The flow rate of the nozzle was 100 gpm which means that approximately 17 gallons of water were delivered through the opening into the house during the 10 second flow. The purpose of this flow was not to extinguish the fire but to suppress the burning gases and to see if there was an impact to the surrounding rooms as it pertains to "pushing fire", which will be addressed in the tactical considerations section. This would allow the potential fire attack crew to slow the fire down prior to making entry and therefore make entry into a safer environment. The experiment was terminated approximately one minute after the hose stream, and suppression was completed by a deluge sprinkler system and the firefighting crew.

Ignition Locations

Figure 166. One Story House Ignition Location

Figure 167. Two Story House Ignition Location

Figure 168. Remote Ignition Device

Figure 169. Suppression Nozzle

Figure 170. Straight stream application

Figure 171. Fog stream application

8.6. One-Story Experimental Results

Seven experiments were conducted in the one story structure (Table 16). Each experiment's purpose will be described and a figure is provided to show the fire and ventilation locations. The experimental timeline is developed to show the time of ventilation and suppression changes. Data graphs are provided for temperatures throughout the structure at multiple elevations, gas concentrations at four locations and gas velocities at the opening(s) for each experiment. Each graph has the events labeled on the top with a vertical line indicating when they occurred.

Table 16. One-Story Experimental Outline

Experiment #	Structure	Location of Ignition	Ventilation Parameters
1	1-Story	Living Room	Front Door
3	1-Story	Living Room	Front Door + Living Room Window (Window near seat of the fire)
5	1-Story	Living Room	Living Room Window Only
7	1-Story	Living Room	Front Door + Bedroom 2 Window (Window remote from fire)
9	1-Story	Living Room	Front Door + Living Room Window (Repeat Exp. 3)
12	1-Story	Living Room	Front Door + Living Room Window (Repeat Exp. 3)
14	1-Story	Living Room	Front Door + 4 Windows (LR, BR1, BR2, BR3)

8.6.1. Experiment 1

Experiment 1 was designed to simulate a crew making entry by opening the front door. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 8 minutes after ignition at which time the front door was opened (Table 17). The fire again was allowed to grow until 12:30, post-flashover condition, when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. At 13:30 another 10 seconds of water was flowed out of the same nozzle in a fog pattern. At 14:15 the left half of the living room window was opened allowing more air into the living room. The experiment was terminated at 15:30 and was extinguished by the suppression crew. Figure 173 through Figure 180 show the front of the house during the experiment.

Table 17. Experiment 1 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	8:00
Straight Stream into Front Door	12:30-12:40
Fog Stream into Front Door	13:30-13:40
Left Half of Living Room Window Opened	14:15
End of Experiment	15:30

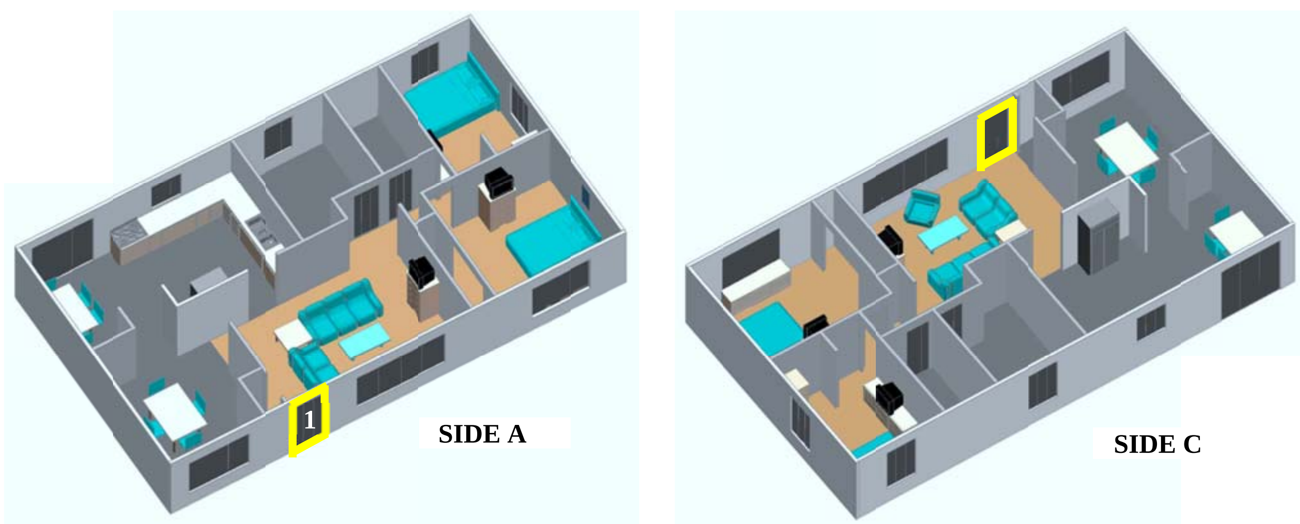


Figure 172. House graphic highlighting ventilation location

Figure 173. Experiment 1 - 0:00

Figure 174. Experiment 1 - 5:00

Figure 175. Experiment 1 - 8:05

Figure 176. Experiment 1 - 10:48

Figure 177. Experiment 1 - 12:36

Figure 178. Experiment 1 - 13:33

Figure 179. Experiment 1 - 14:15

Figure 180. Experiment 1 - 15:00

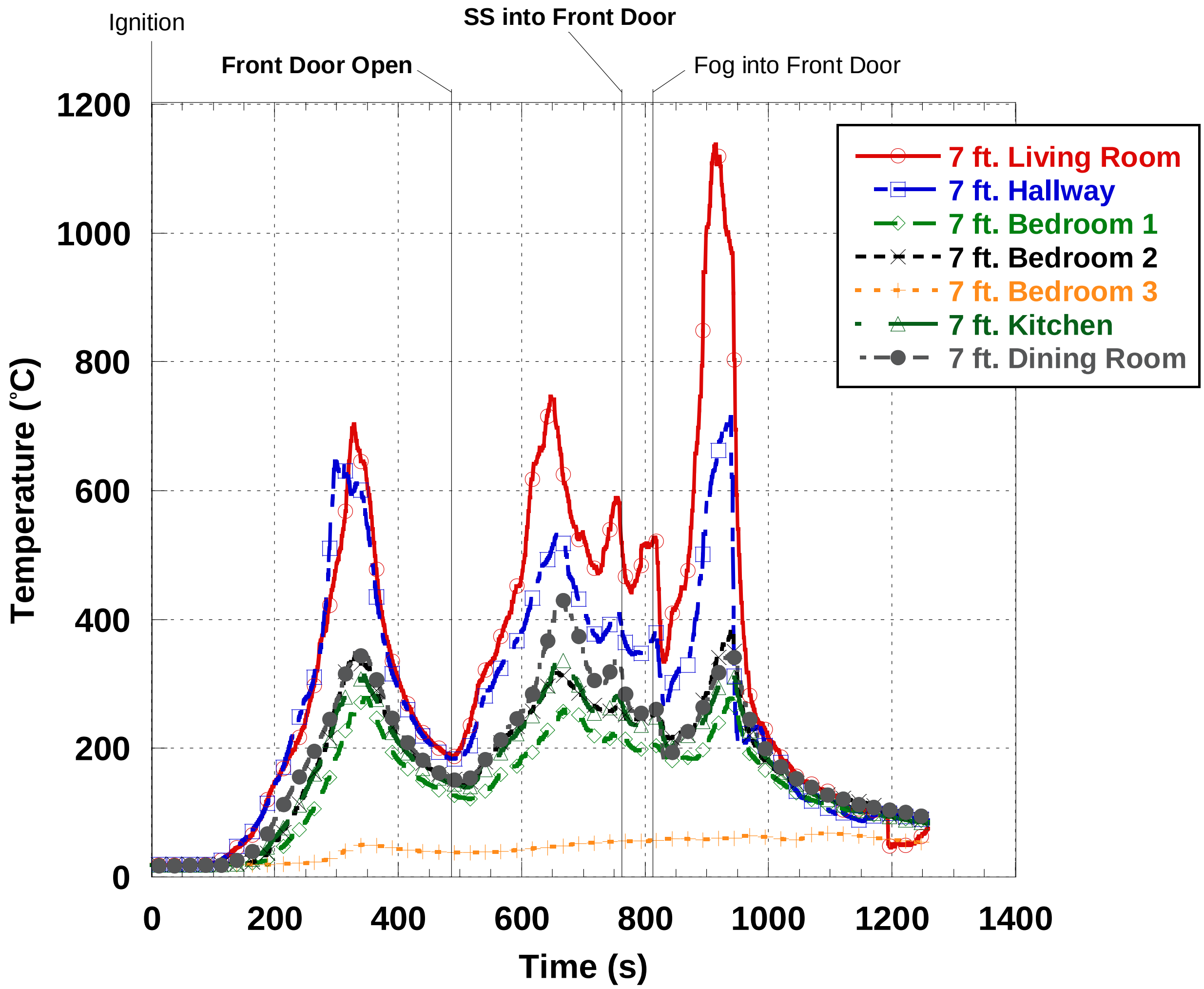


Figure 181. Experiment 1- 7ft. Temperatures

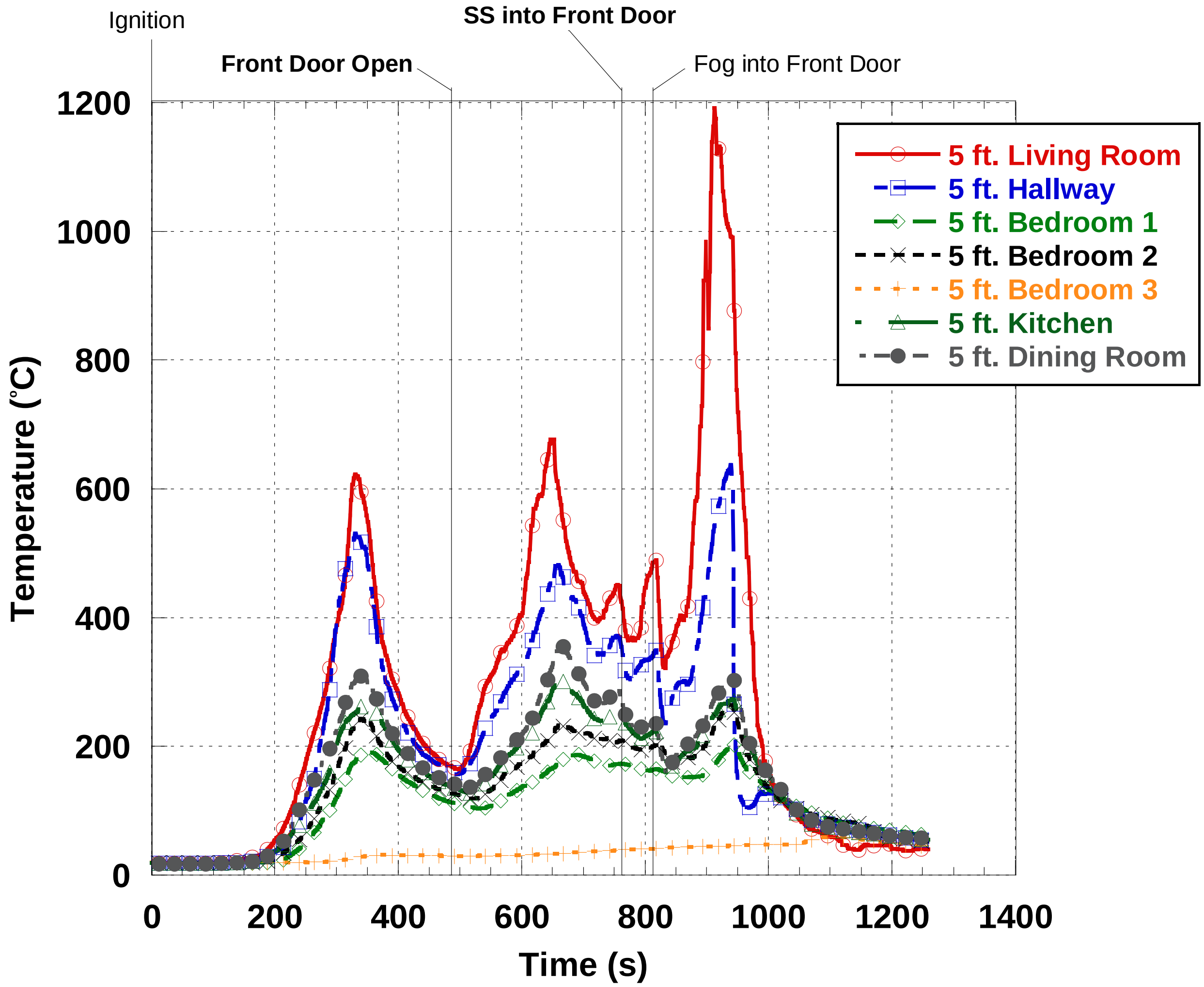


Figure 182. Experiment 1- 5ft. Temperatures

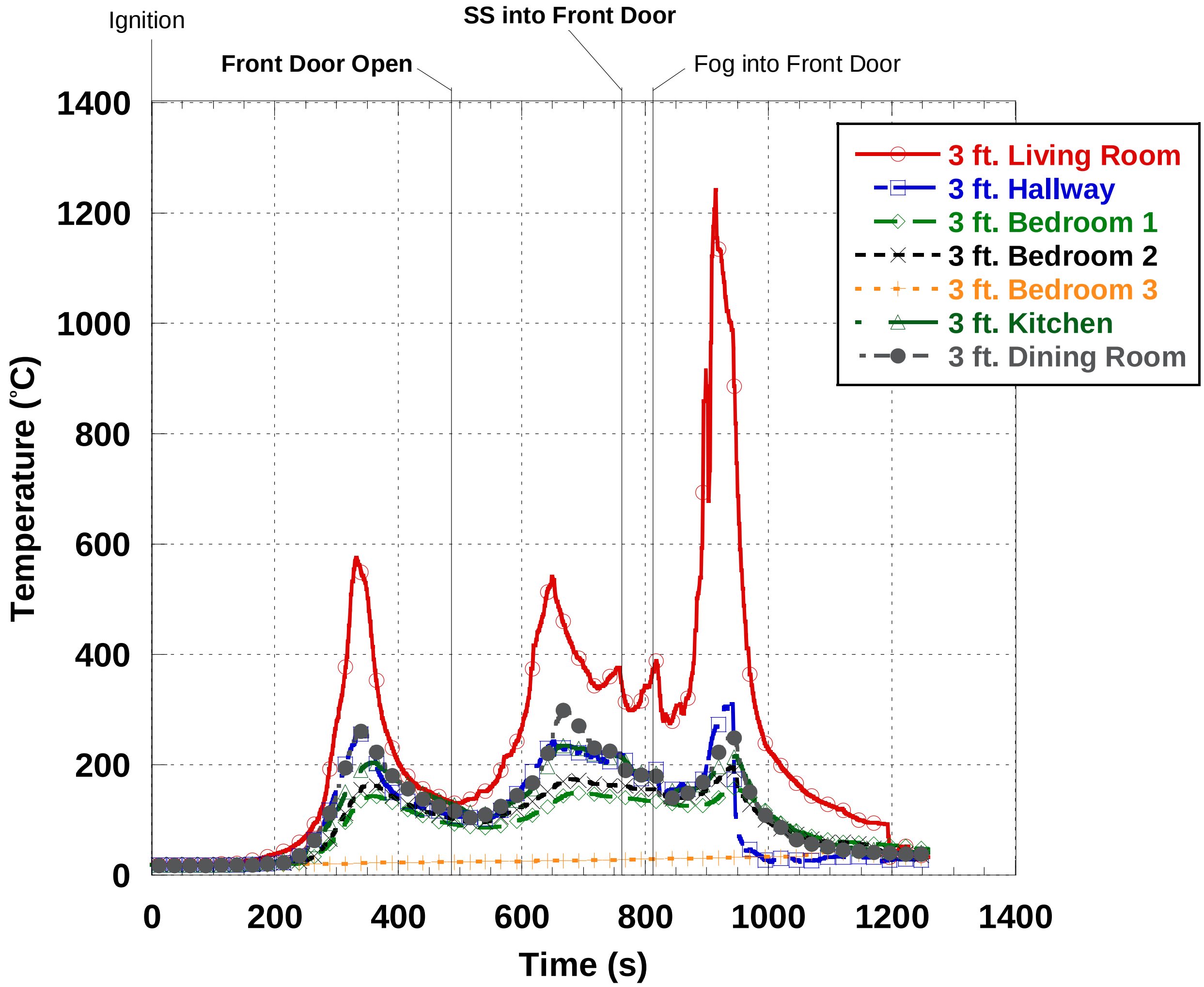


Figure 183. Experiment 1- 3ft. Temperatures

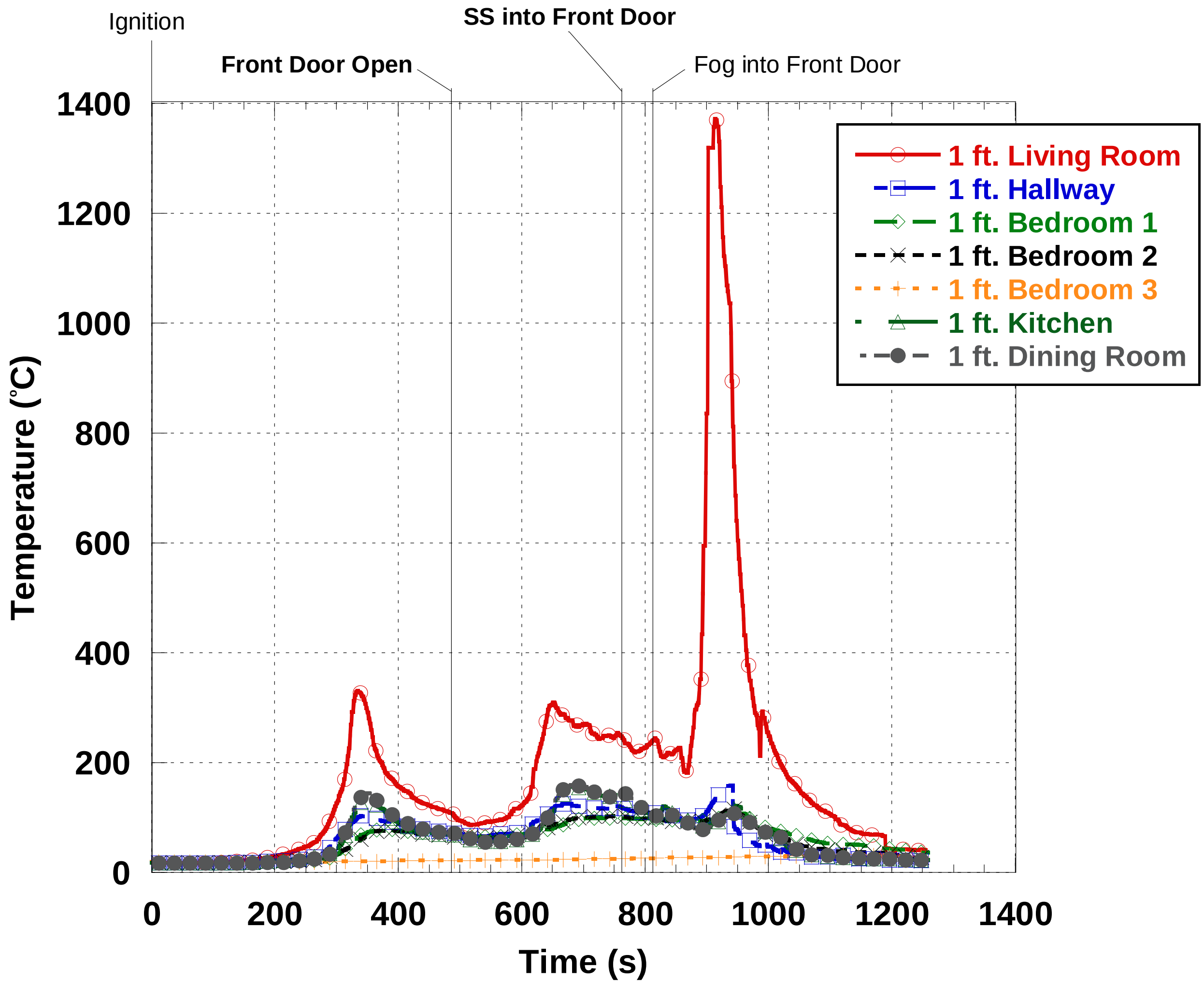


Figure 184. Experiment 1- 1ft. Temperatures

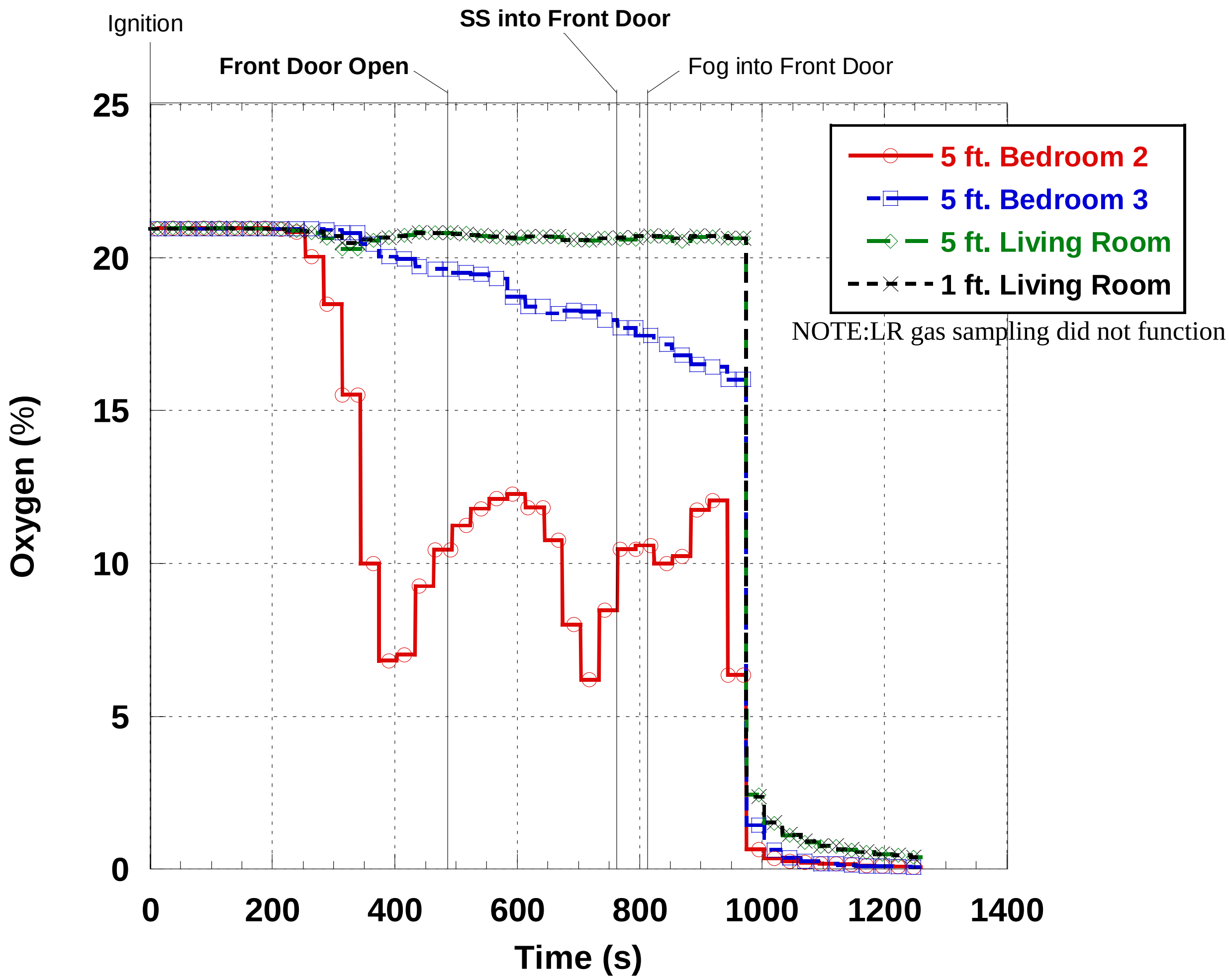


Figure 185. Experiment 1- Oxygen Concentrations

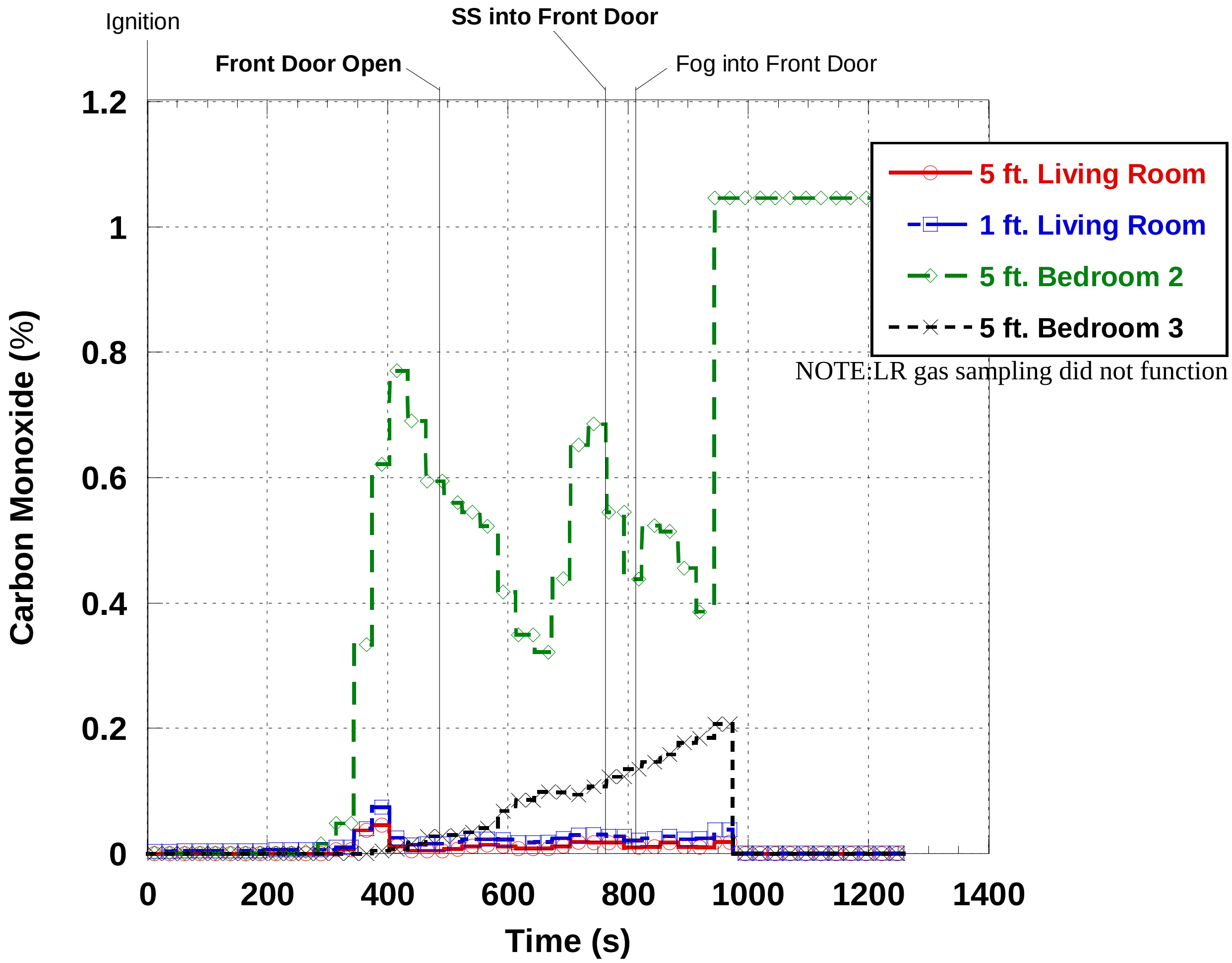


Figure 186. Experiment 1 - CO Concentrations

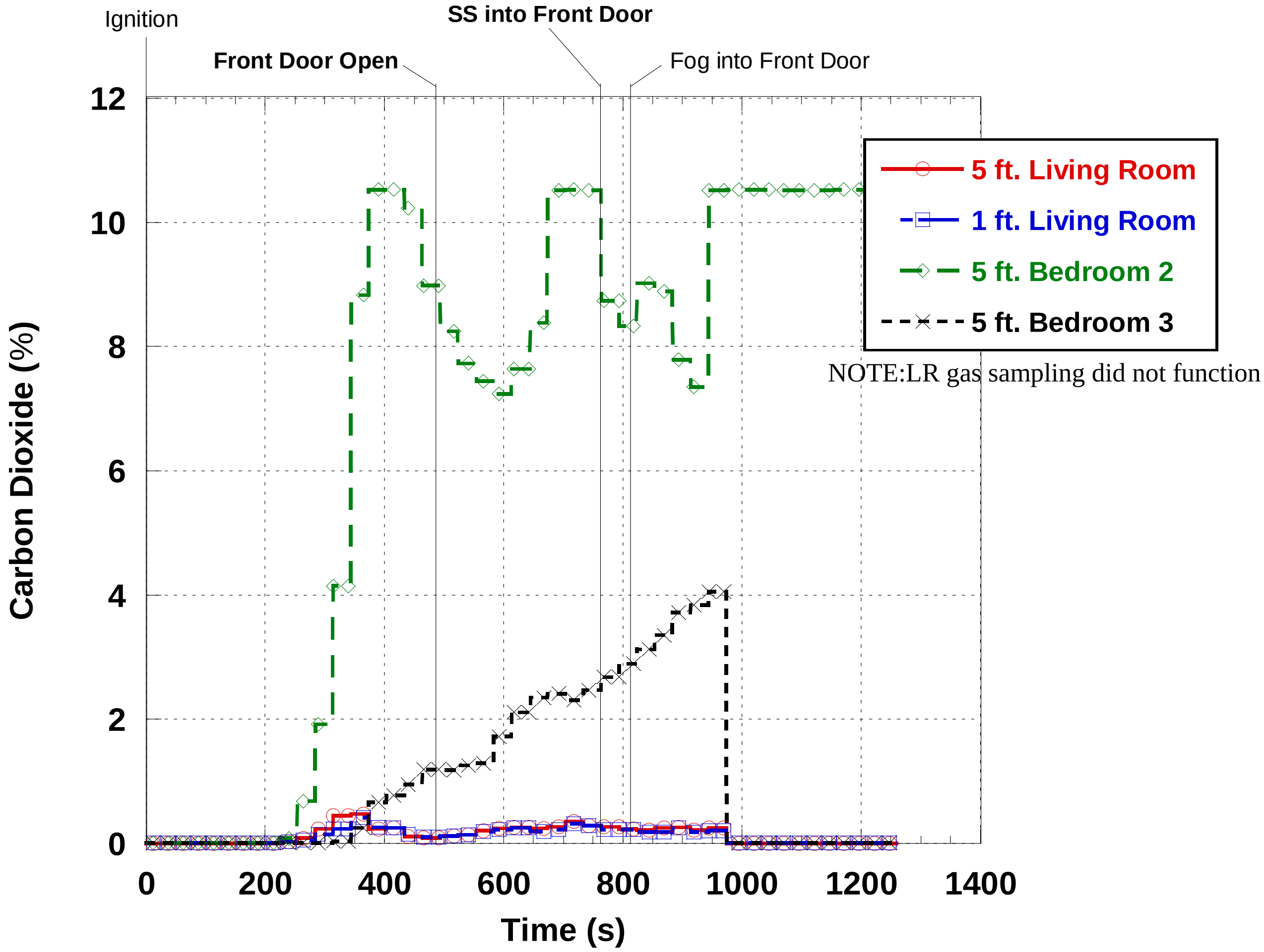


Figure 187. Experiment 1 - CO_2 Concentrations

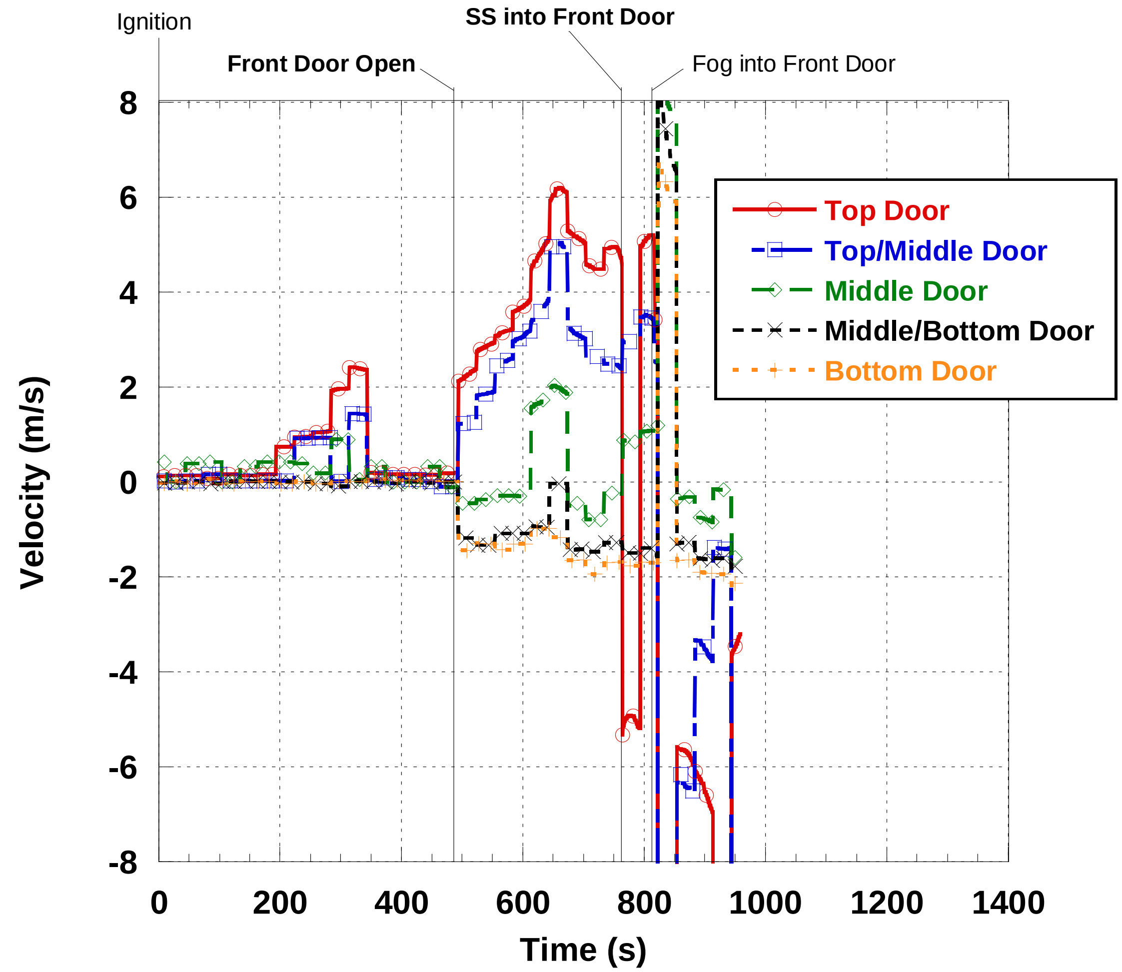


Figure 188. Experiment 1 – Front Door Velocities

8.6.2. Experiment 3

Experiment 3 was conducted in the one-story house. This experiment was designed to simulate a crew making entry through the front door and having a ventilation opening made shortly after near the seat of the fire. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 8 minutes after ignition at which time the front door was opened. Fifteen seconds later the front window to the living room was opened (Table 18). The fire again was allowed to grow until 10:22 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 11:30 and was extinguished by the suppression crew. Figure 190 through Figure 196 show the front of the house during the experiment.

Table 18. Experiment 3 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	8:00
Living Room Window Open	8:15
Straight Stream into Living Room Window	10:22-10:32
End of Experiment	11:30

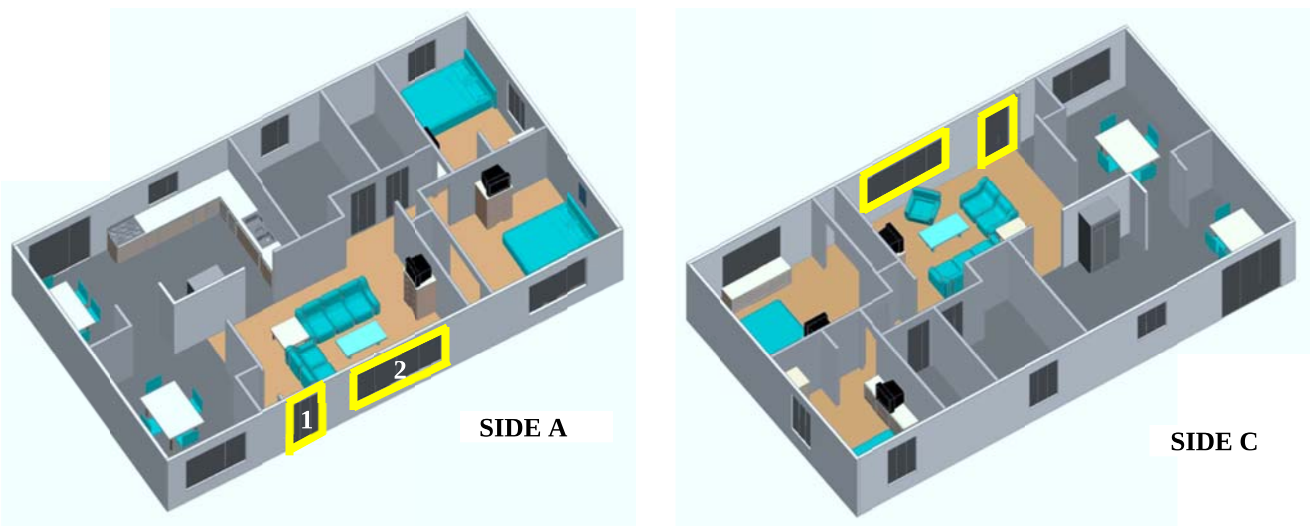


Figure 189. House graphic highlighting ventilation locations


Figure 190. Experiment 3 - 0:00

Figure 191. Experiment 3 - 5:00

Figure 192. Experiment 3 - 8:05

Figure 193. Experiment 3 - 8:17

Figure 194. Experiment 3 - 10:00

Figure 195. Experiment 3 - 10:25

Figure 196. Experiment 3 - 11:00

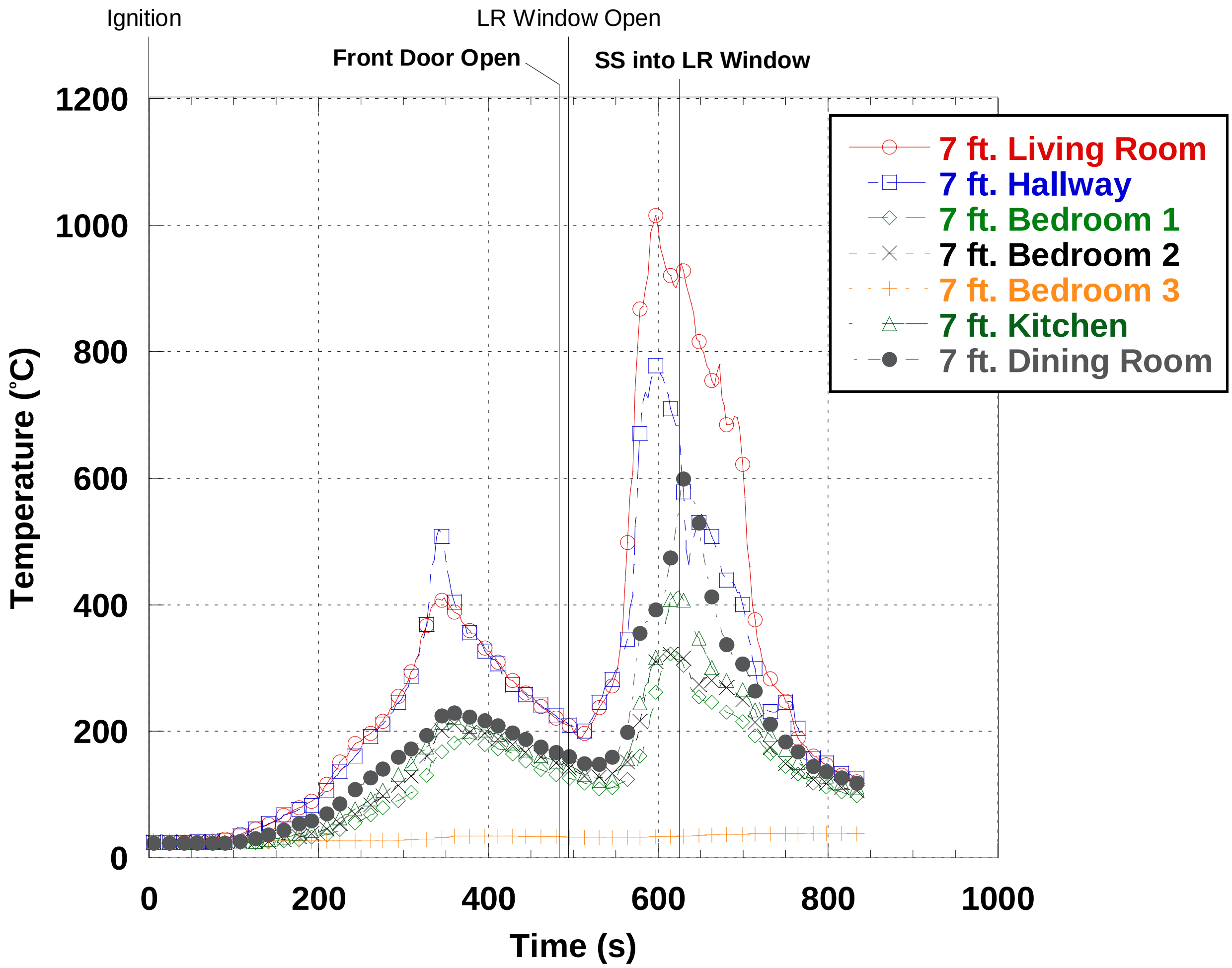


Figure 197. Experiment 3- 7ft. Temperatures

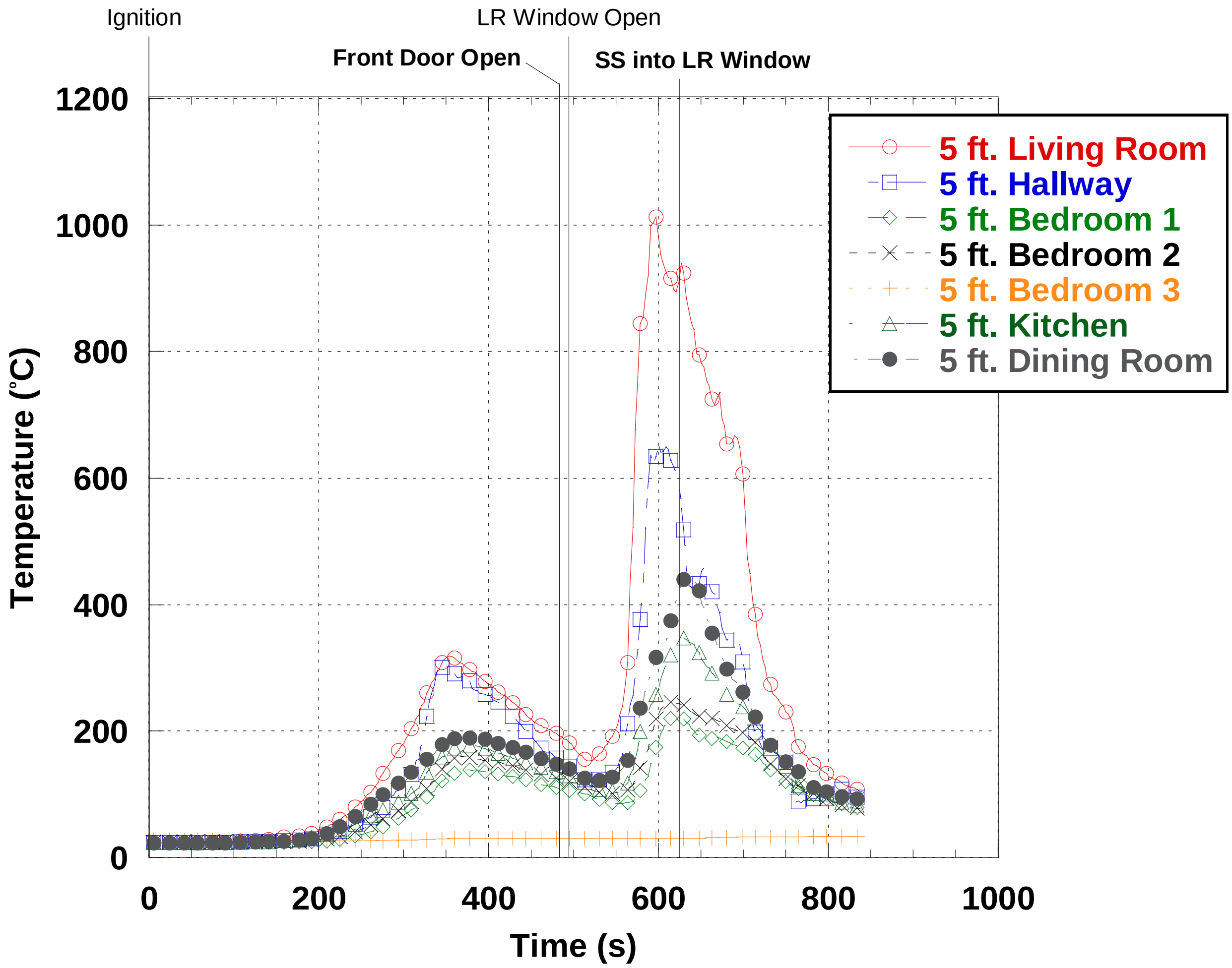


Figure 198. Experiment 3- 5ft. Temperatures

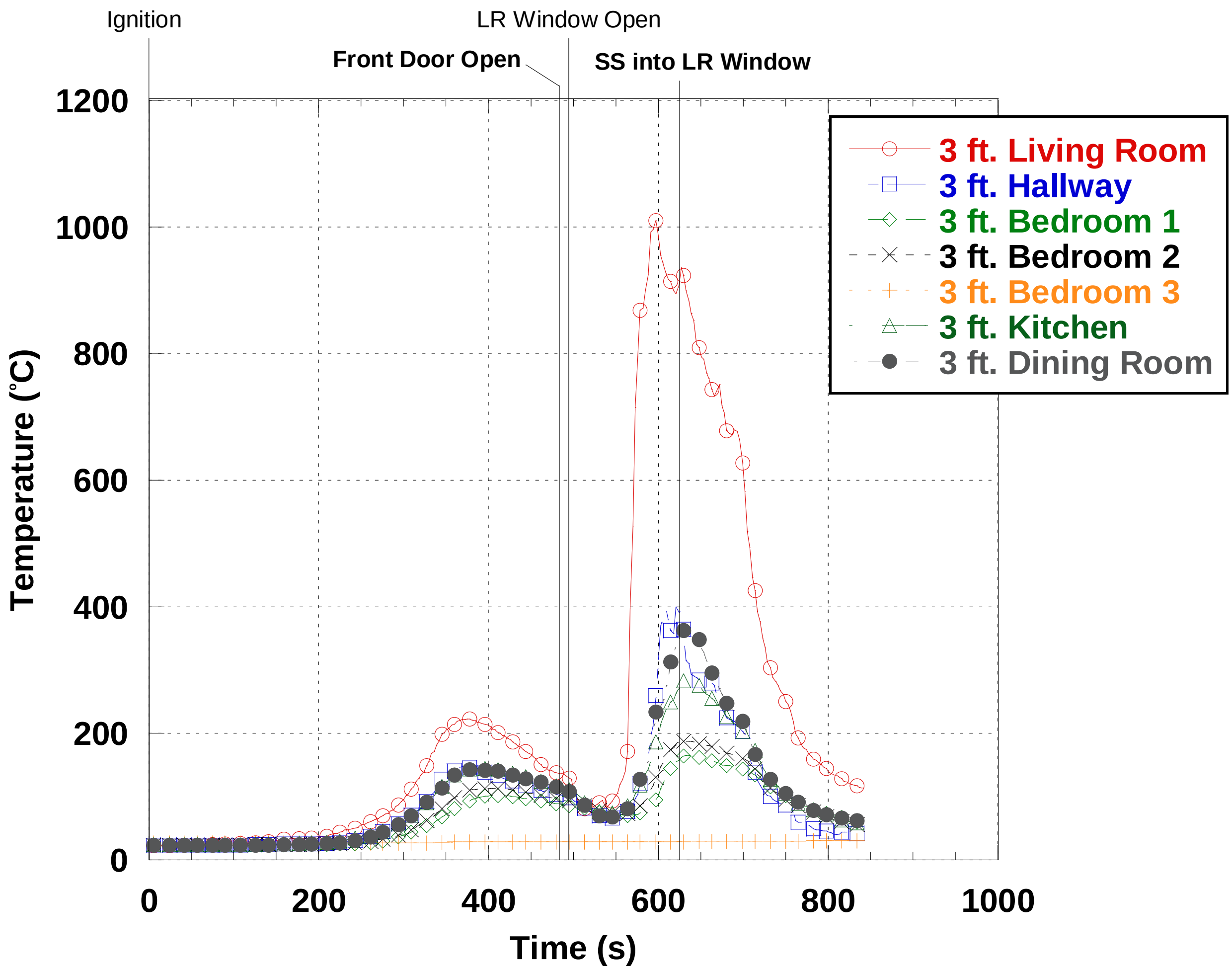


Figure 199. Experiment 3- 3ft. Temperatures

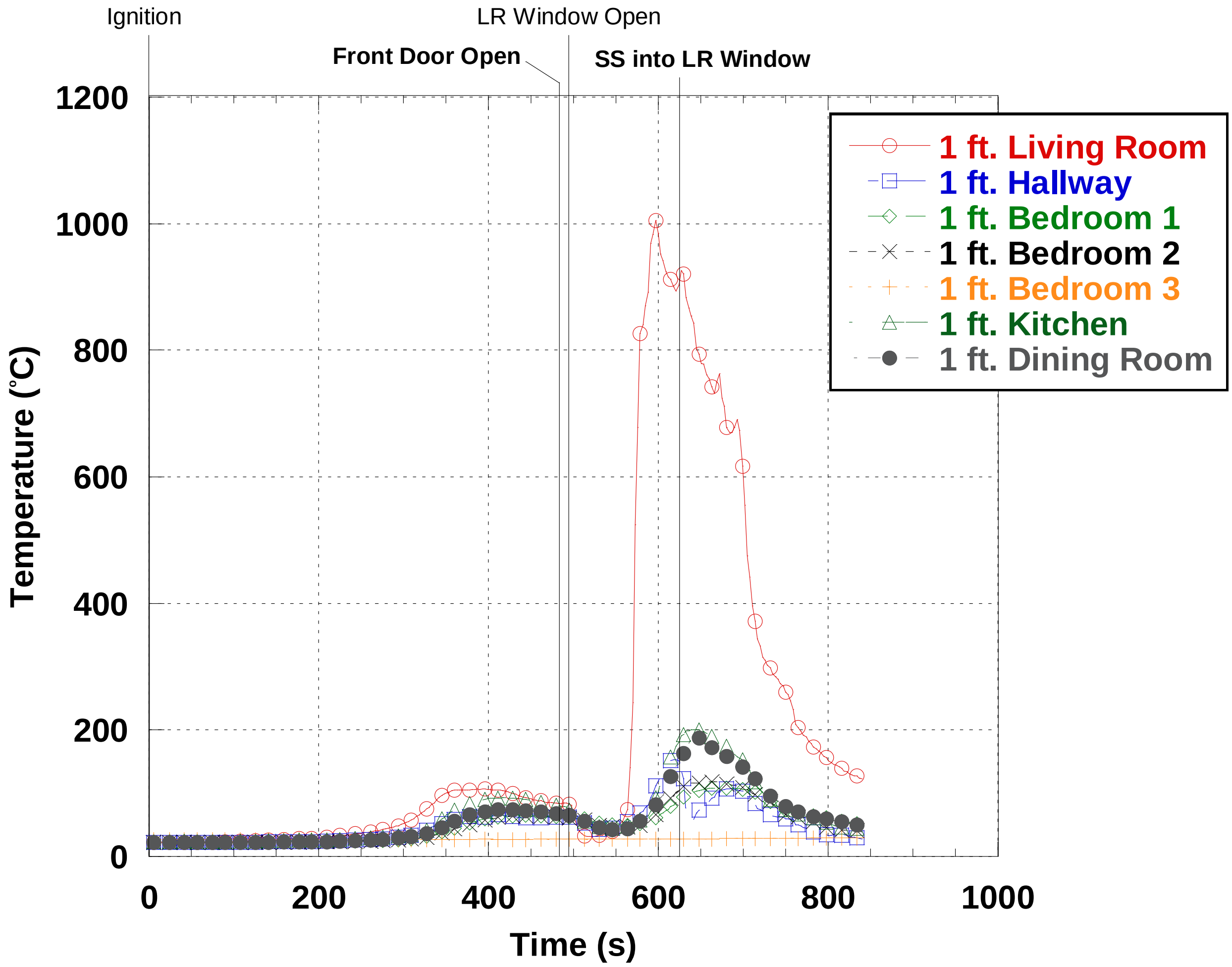


Figure 200. Experiment 3- 1ft. Temperatures

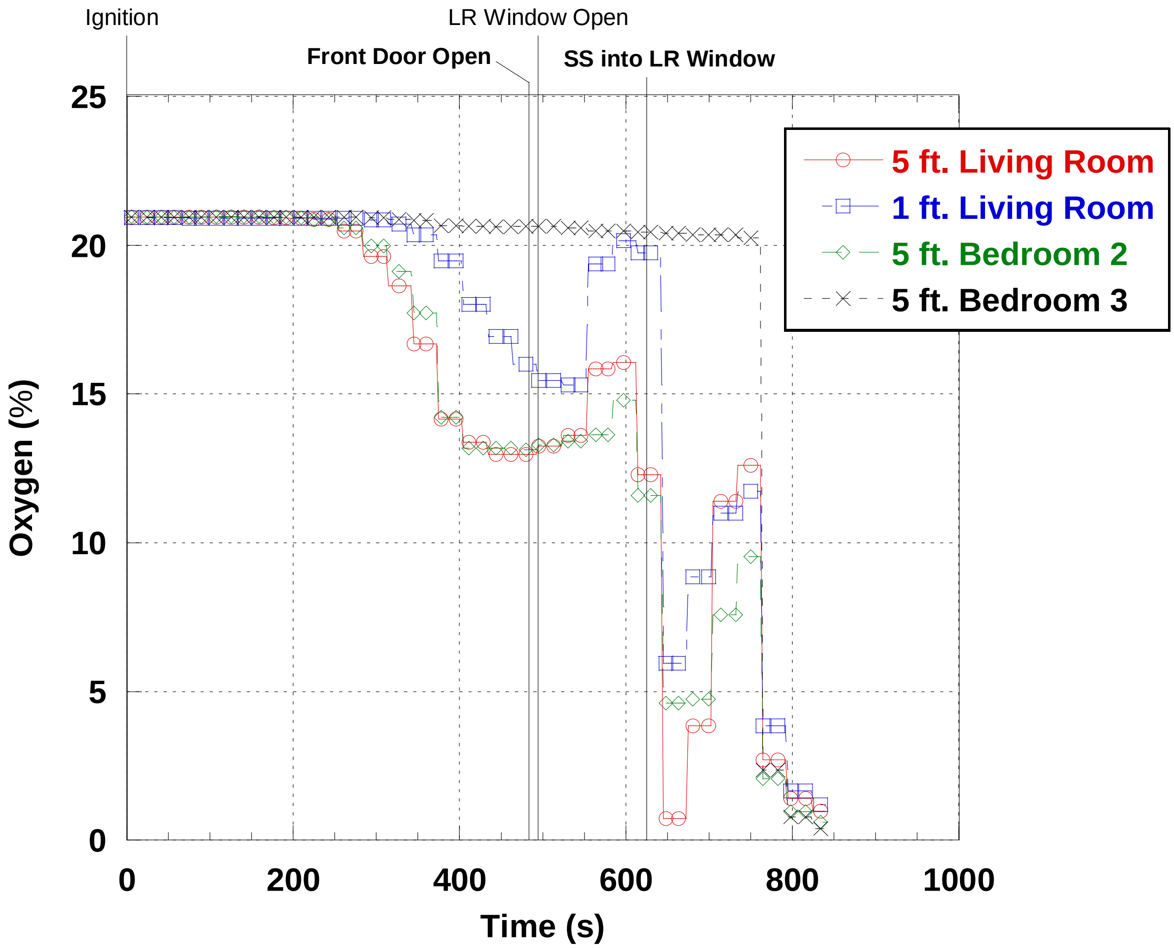


Figure 201. Experiment 3 - Oxygen Concentrations

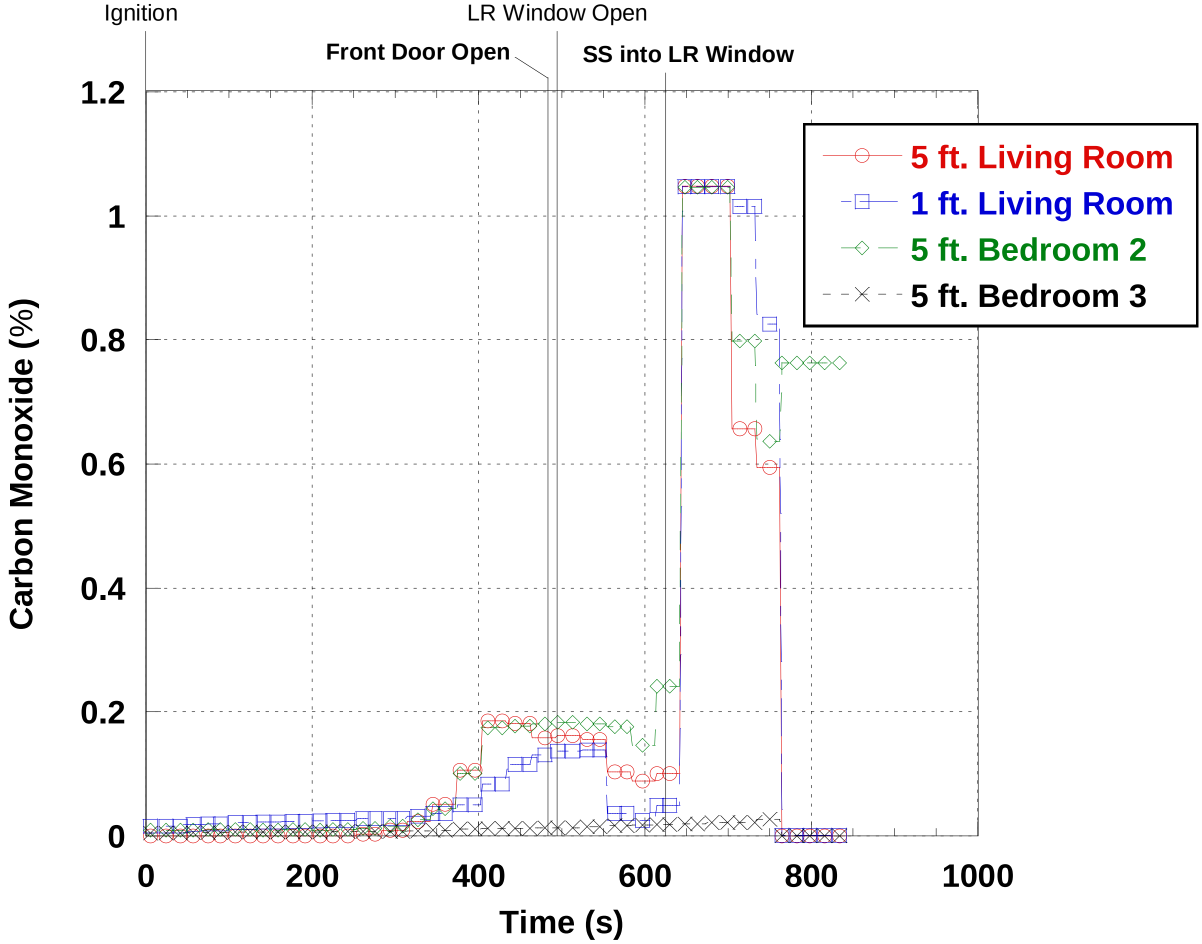


Figure 202. Experiment 3 - CO Concentrations

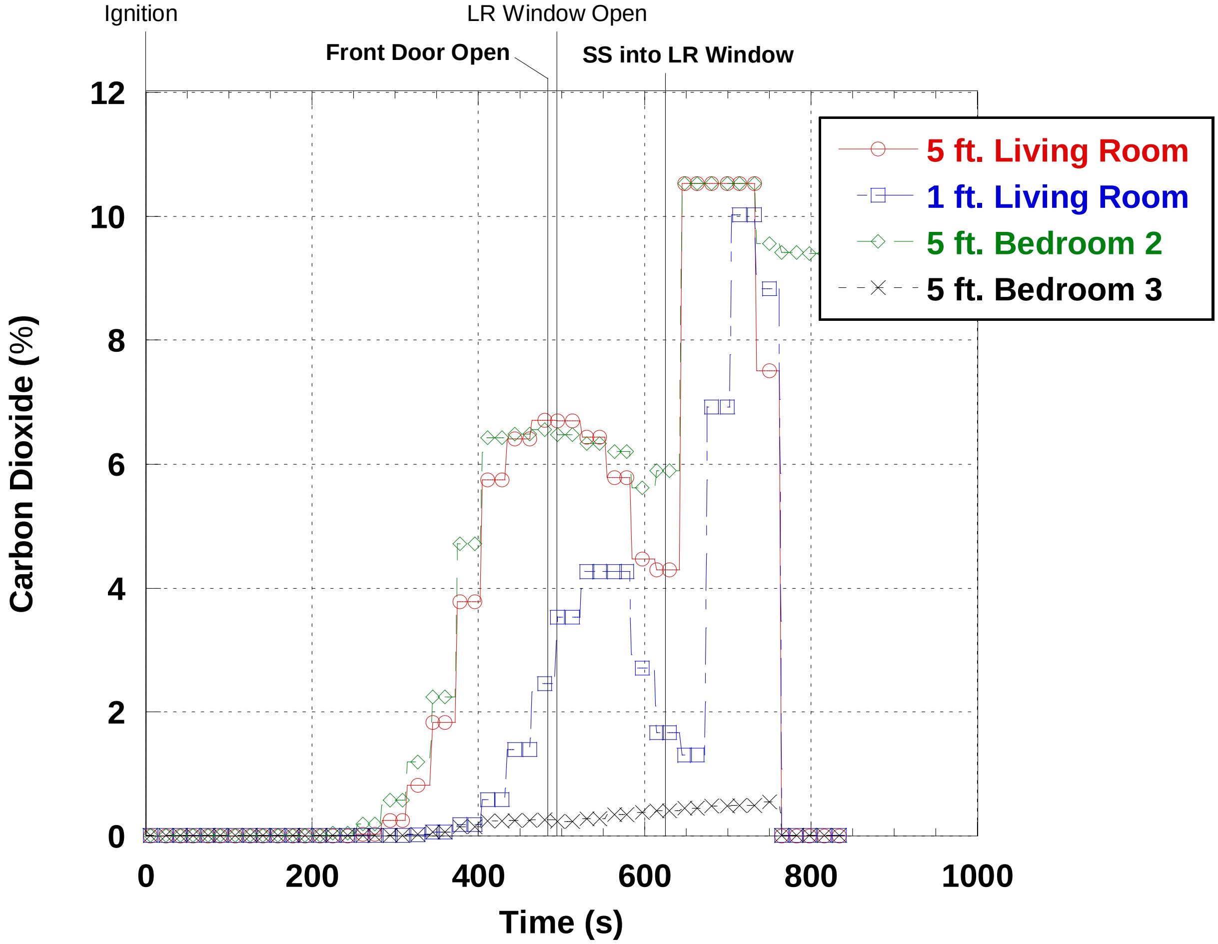


Figure 203. Experiment 3 - CO_2 Concentrations

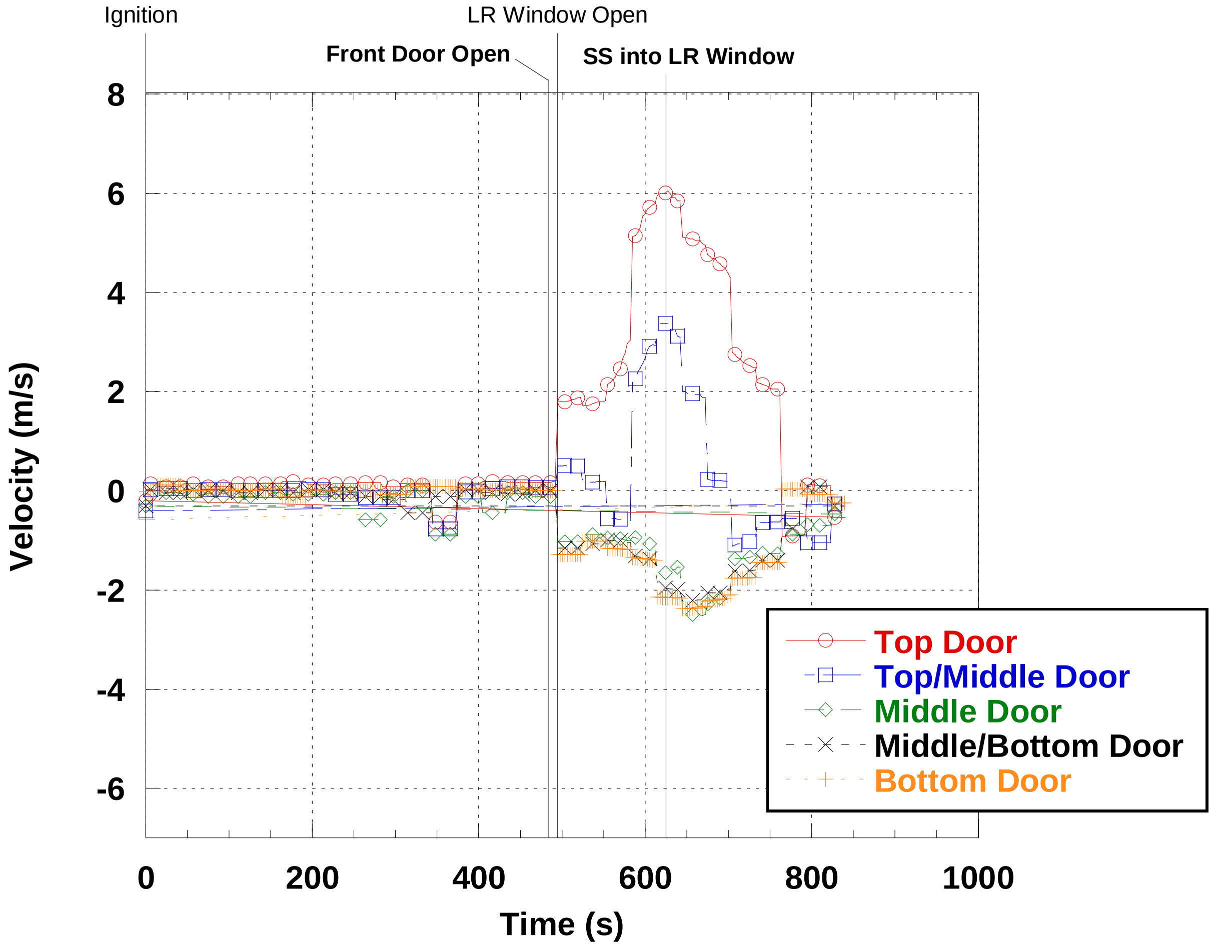


Figure 204. Experiment 3 - Front Door Velocity

8.6.3. Experiment 5

Experiment 5 was the third experiment conducted in the one-story house. This experiment was designed to simulate a crew making a ventilation opening near the seat of the fire prior to entry. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 8 minutes after ignition at which time the living room window was opened (Table 19). The fire again was allowed to grow until 11:32 when 10 seconds of water were flowed into the living room window with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 12:45 and was extinguished by the suppression crew. Figure 206 through Figure 213 show the front of the house during the experiment.

Table 19. Experiment 5 Timeline

Event	Time (mm:ss)
Ignition	0:00
Living Room Window Open	8:00
Straight Stream into Living Room Window	11:32-11:42
End of Experiment	12:45

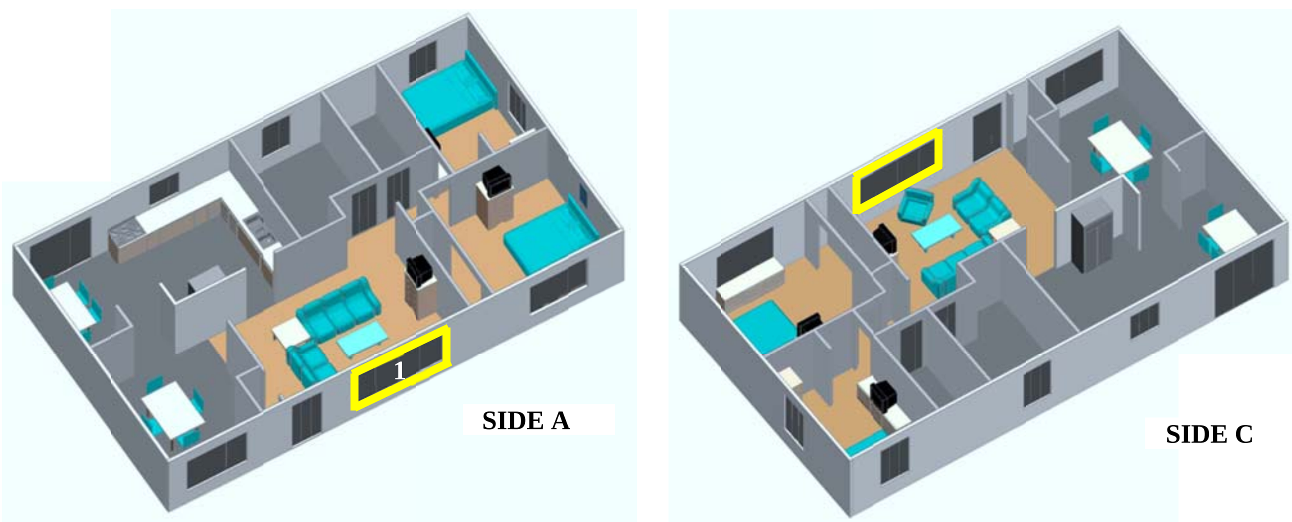


Figure 205. House graphic highlighting ventilation location

Figure 206. Experiment 5 - 0:00

Figure 207. Experiment 5 - 5:00

Figure 208. Experiment 5 - 8:05

Figure 209. Experiment 5 - 10:00

Figure 210. Experiment 5 - 10:30

Figure 211. Experiment 5 - 11:25

Figure 212. Experiment 5 - 11:40

Figure 213. Experiment 5 - 12:40

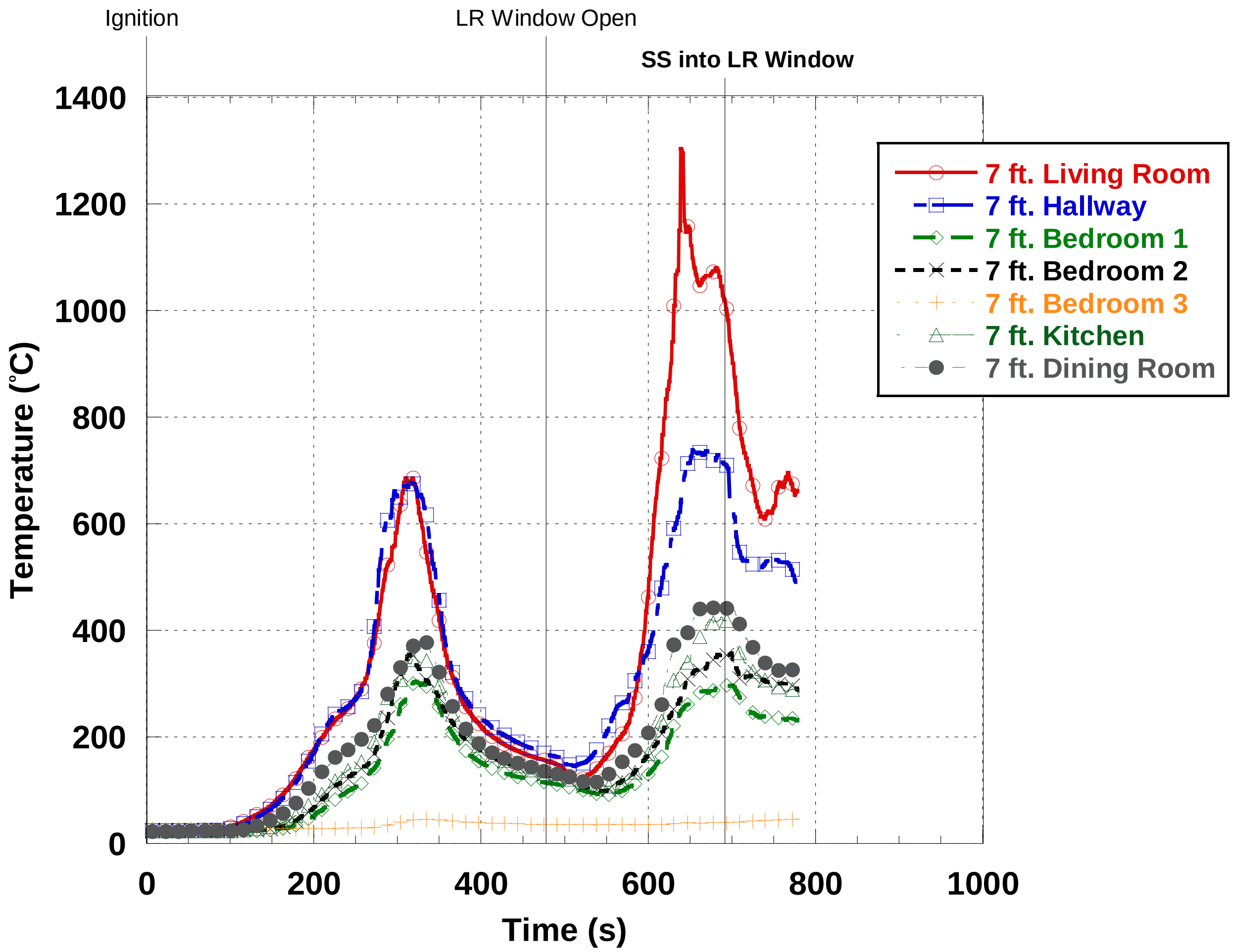


Figure 214. Experiment 5- 7ft. Temperatures

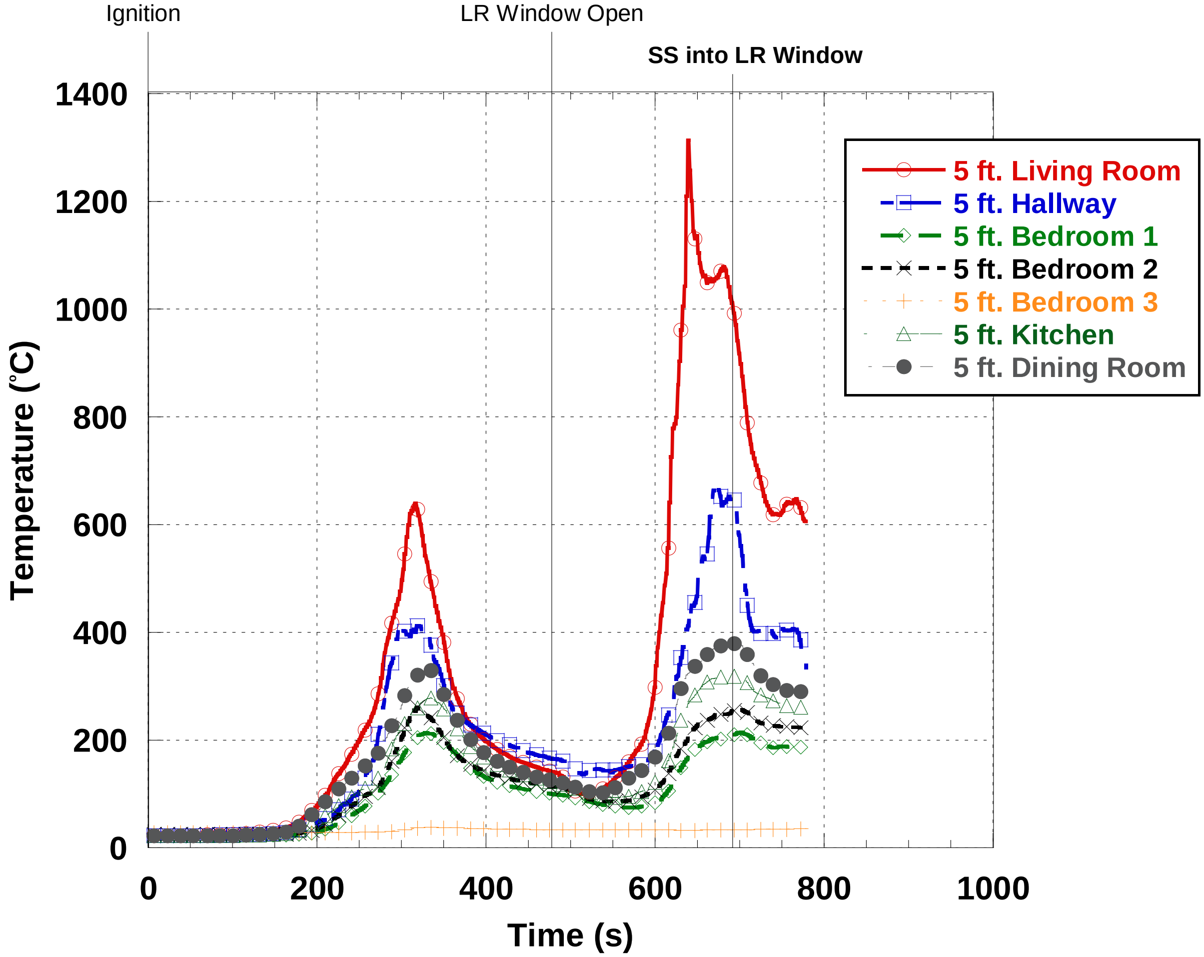


Figure 215. Experiment 5- 5ft. Temperatures

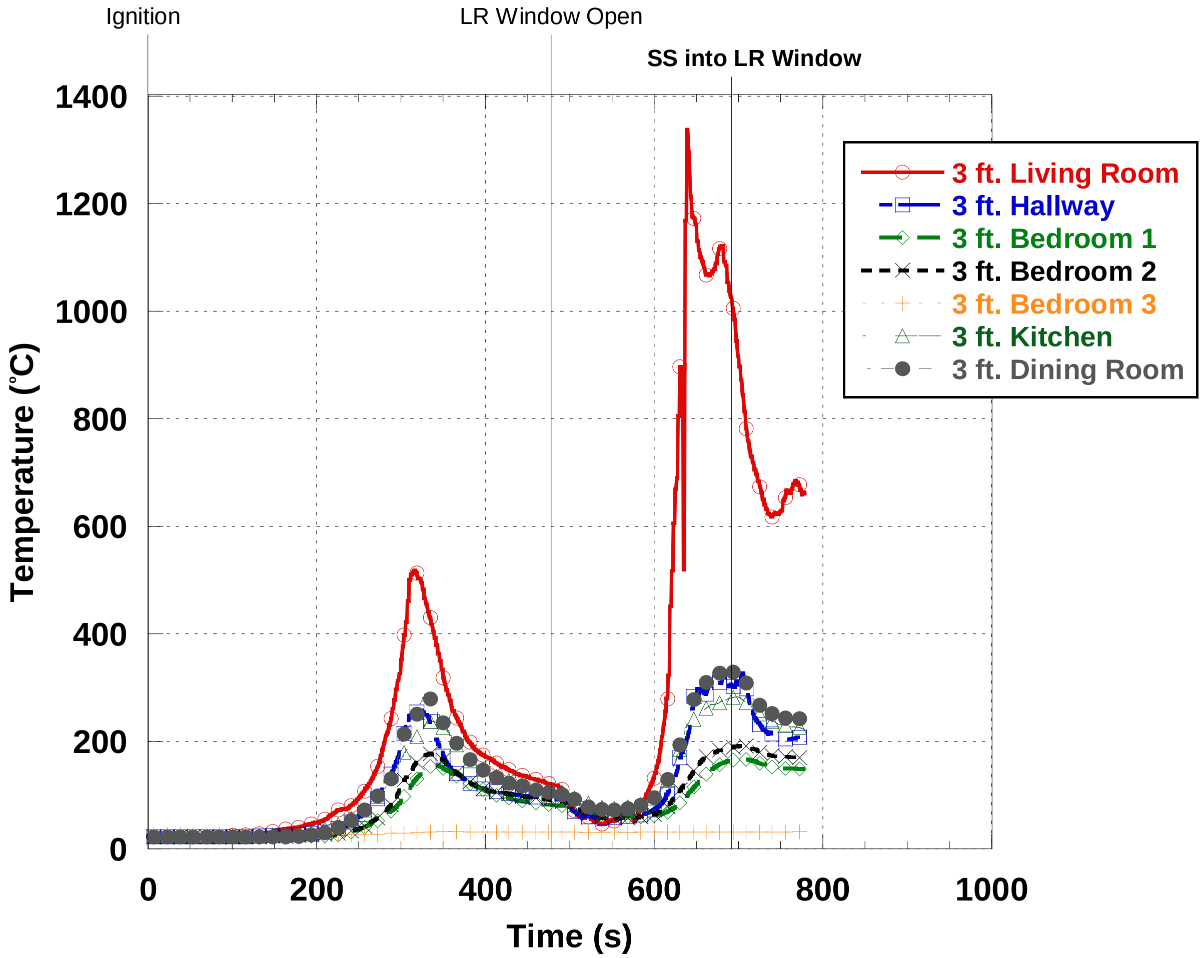


Figure 216. Experiment 5- 3ft. Temperatures

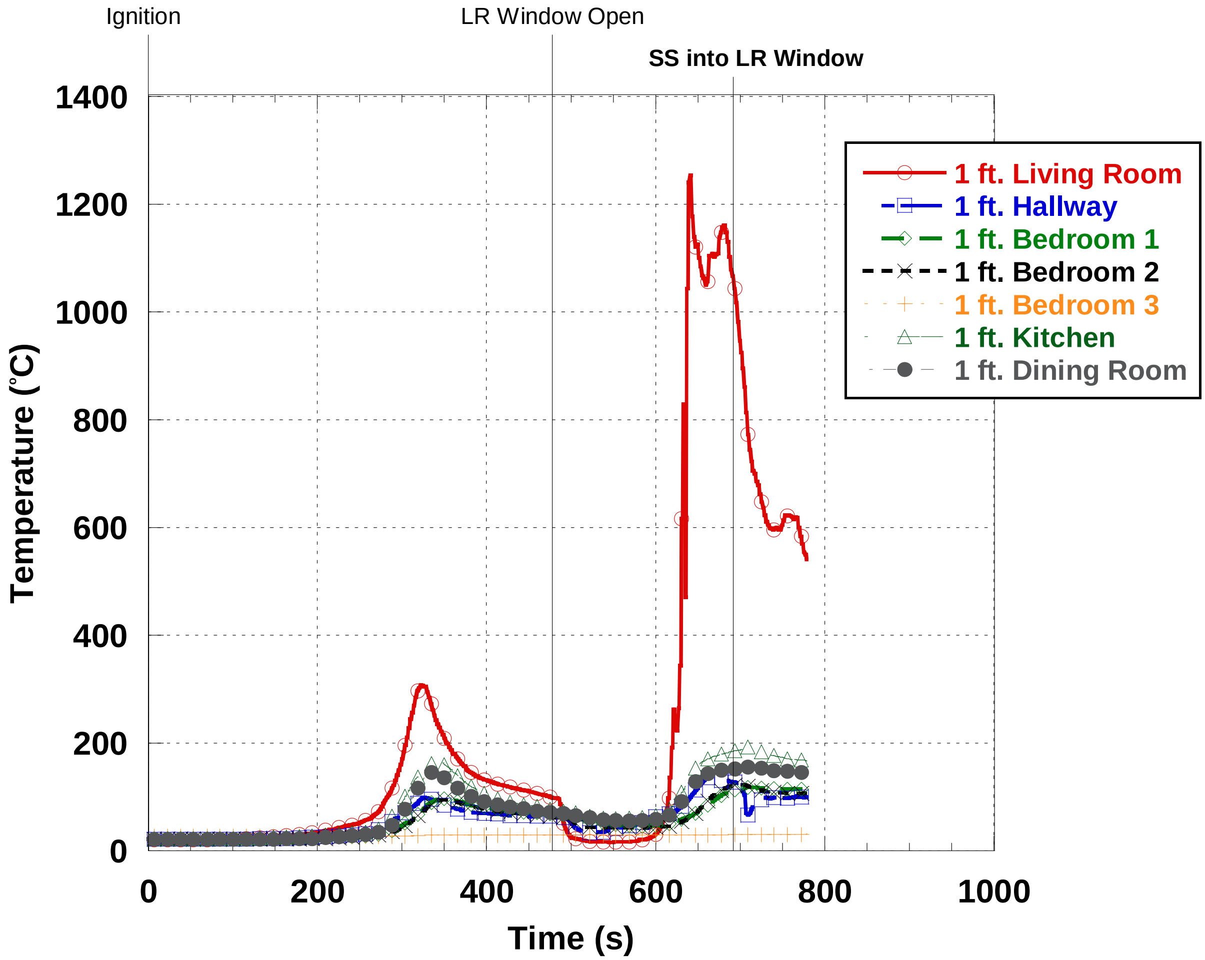


Figure 217. Experiment 5- 1ft. Temperatures

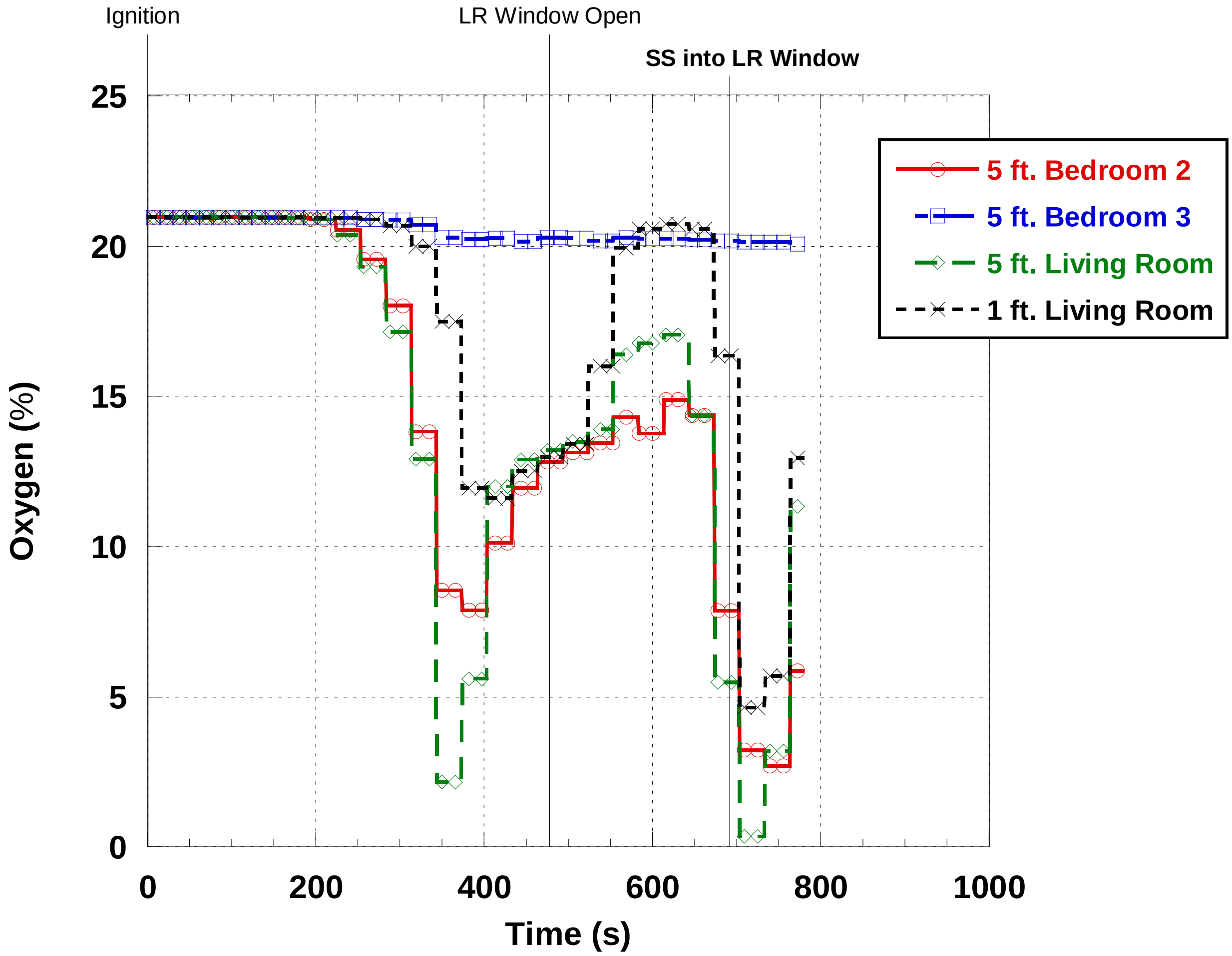


Figure 218. Experiment 5- Oxygen Concentrations

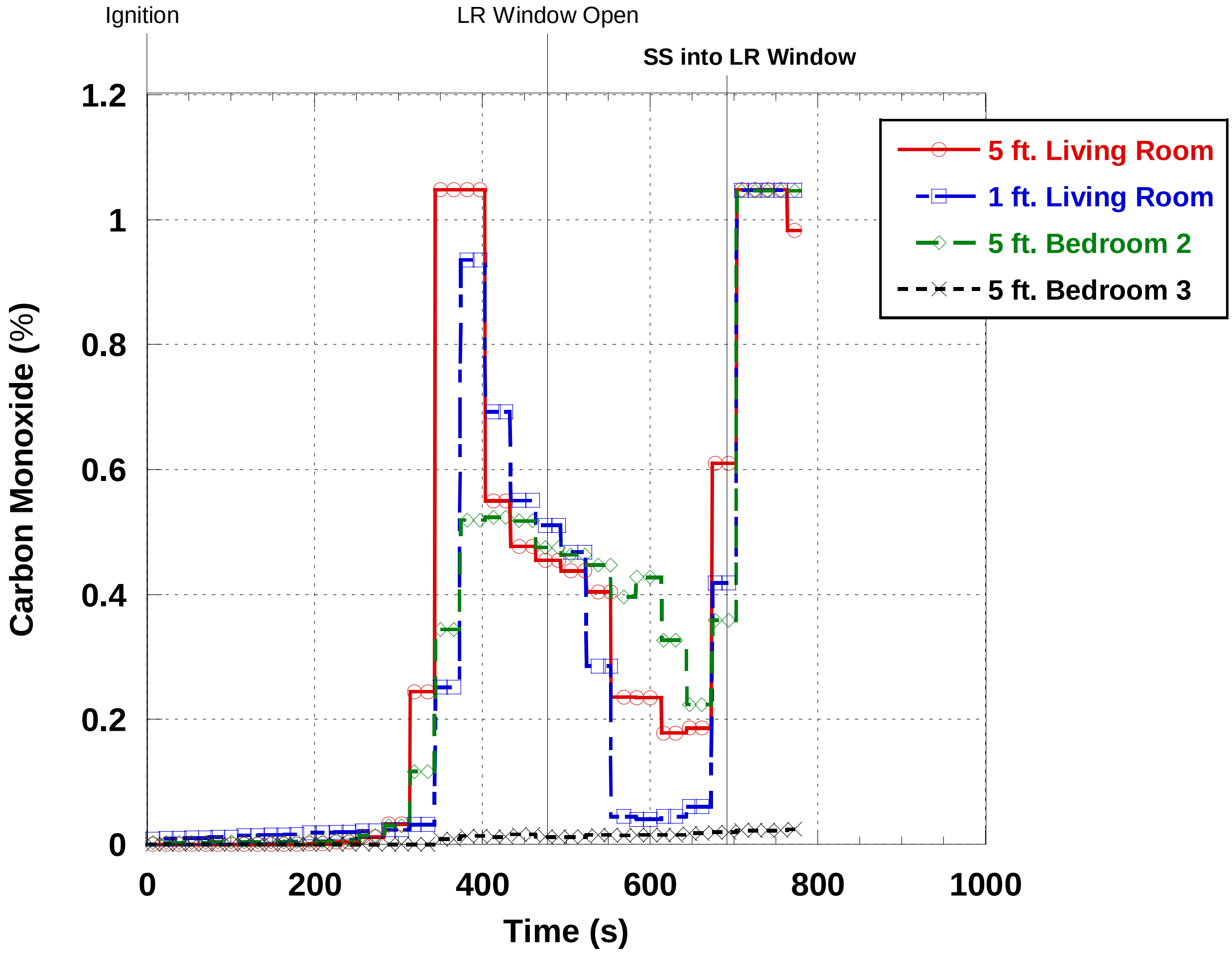


Figure 219. Experiment 5- CO Concentrations

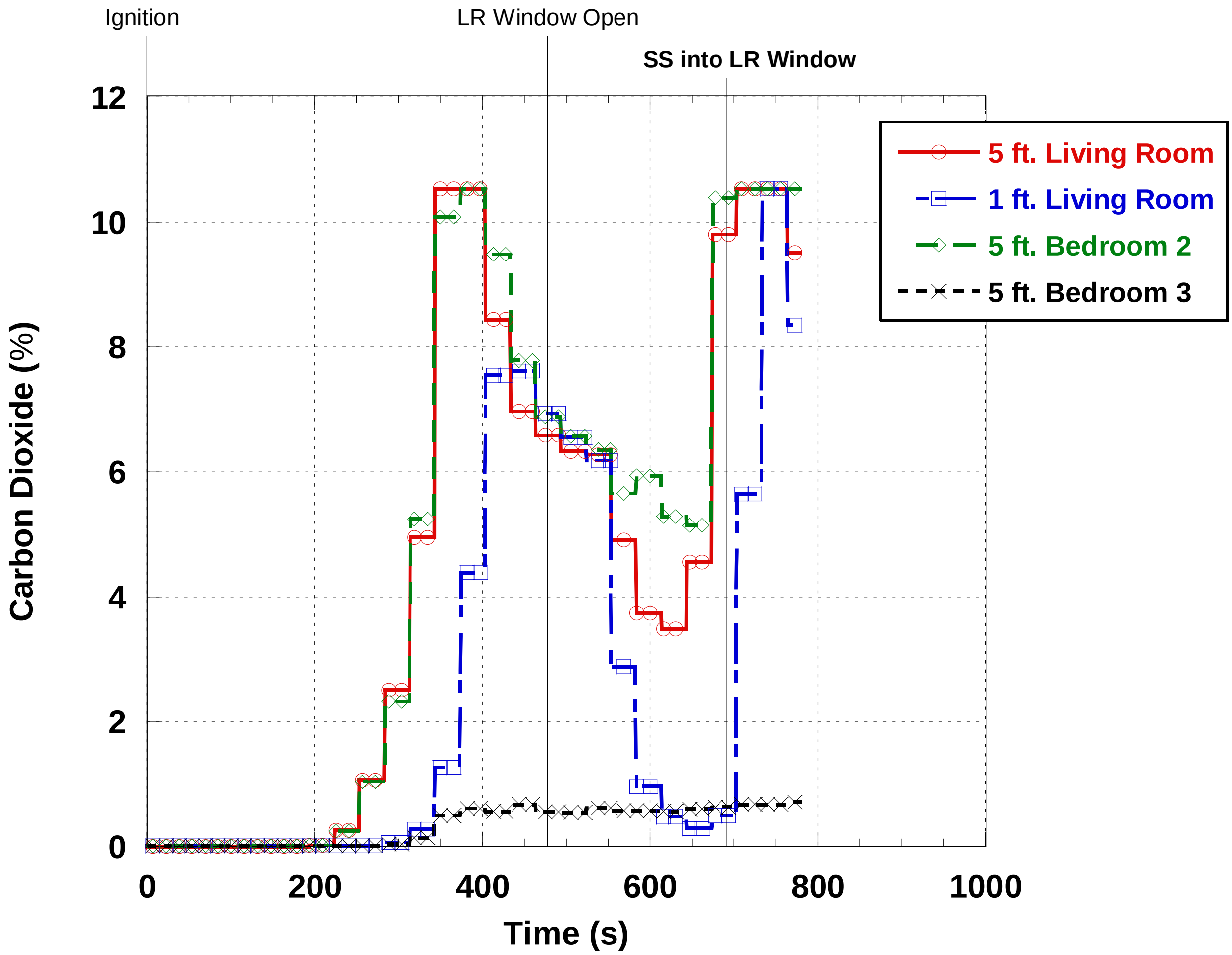


Figure 220. Experiment 5- CO_2 Concentrations

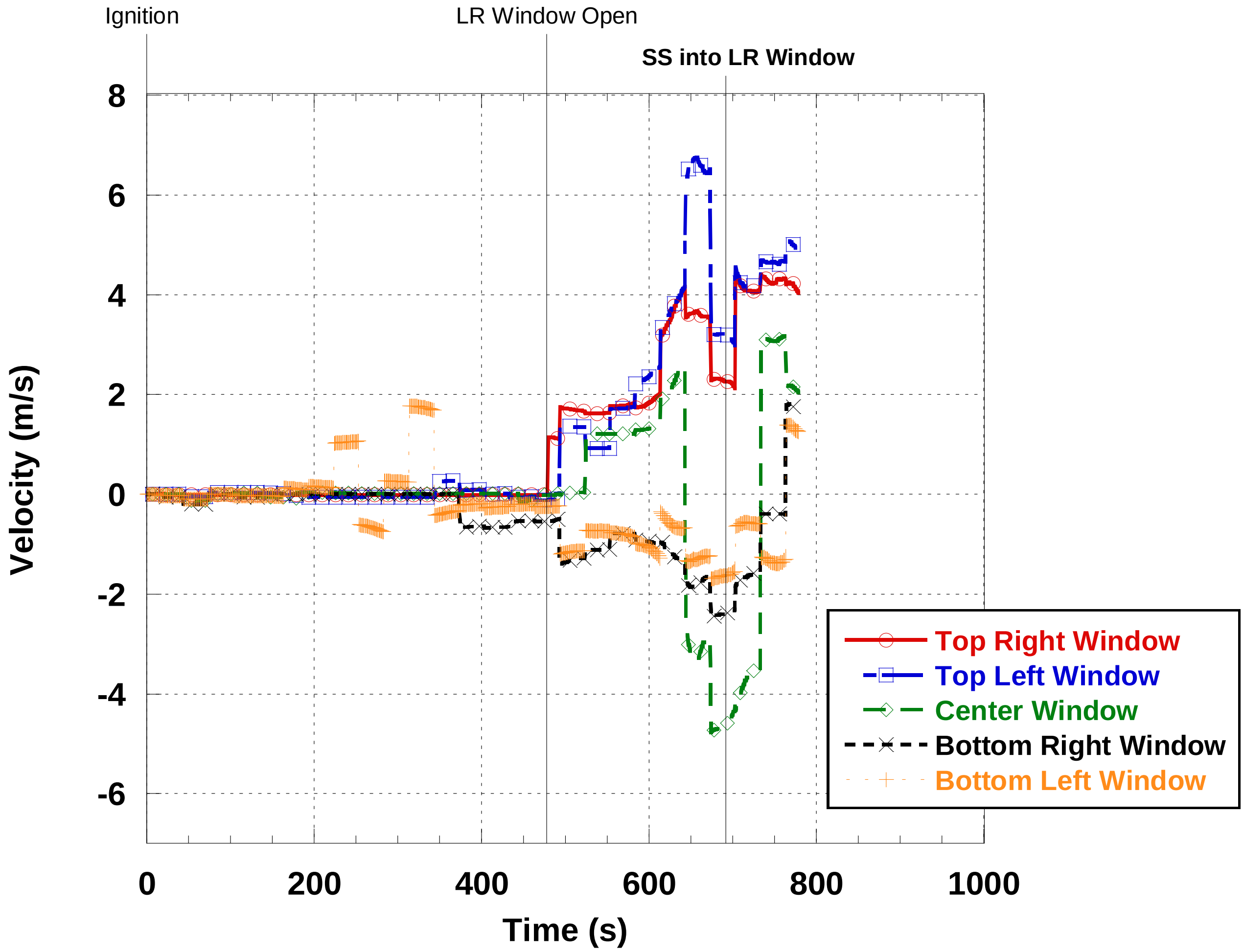


Figure 221. Experiment 5- Ventilation Window Velocities

8.6.4. Experiment 7

Experiment 7 was conducted in the one-story house as well. This experiment was designed to simulate a crew making entry through the front door and having a ventilation opening made shortly after remote from the seat of the fire. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 8 minutes after ignition at which time the front door was opened followed 15 s later by the opening of the rear bedroom window (Table 20). The fire again was allowed to grow until 15:46 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 16:40 and was extinguished by the suppression crew. Figure 223 through Figure 230 show the front and rear of the structure during the experiment.

Table 20. Experiment 7 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	8:00
Bedroom Window Open	8:16
Straight Stream into Front Door	15:46-15:56
End of Experiment	16:40

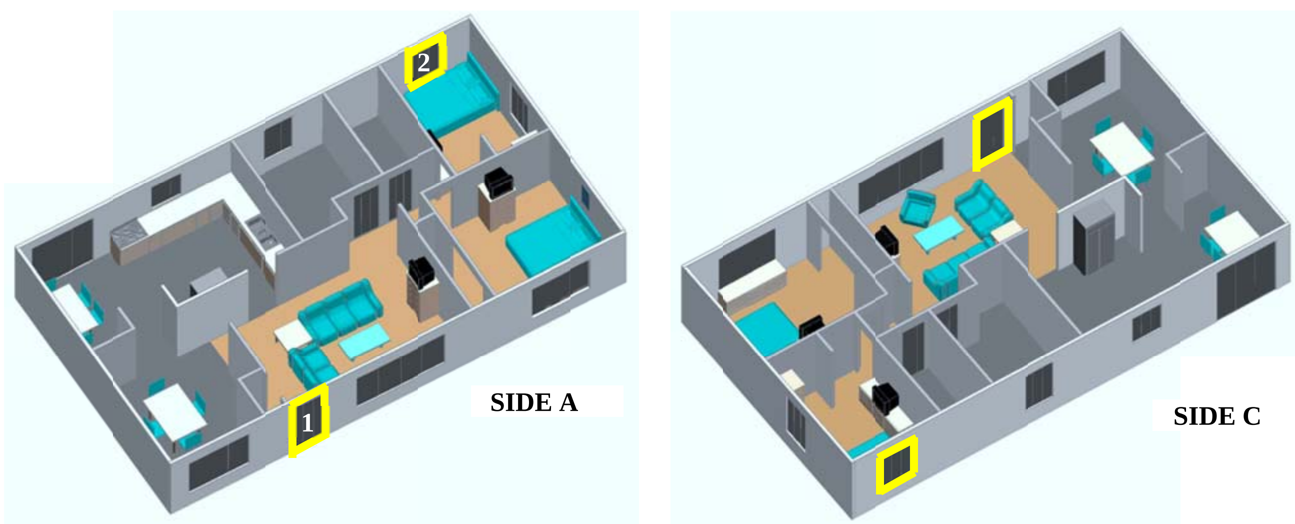


Figure 222. House graphic highlighting ventilation locations


Figure 223. Experiment 7 - 0:00


Figure 224. Experiment 7 - 0:00


Figure 225. Experiment 7 - 8:05


Figure 226. Experiment 7 - 8:17


Figure 227. Experiment 7 - 10:30


Figure 228. Experiment 7 - 11:30


Figure 229. Experiment 7 - 15:50


Figure 230. Experiment 7 - 15:50

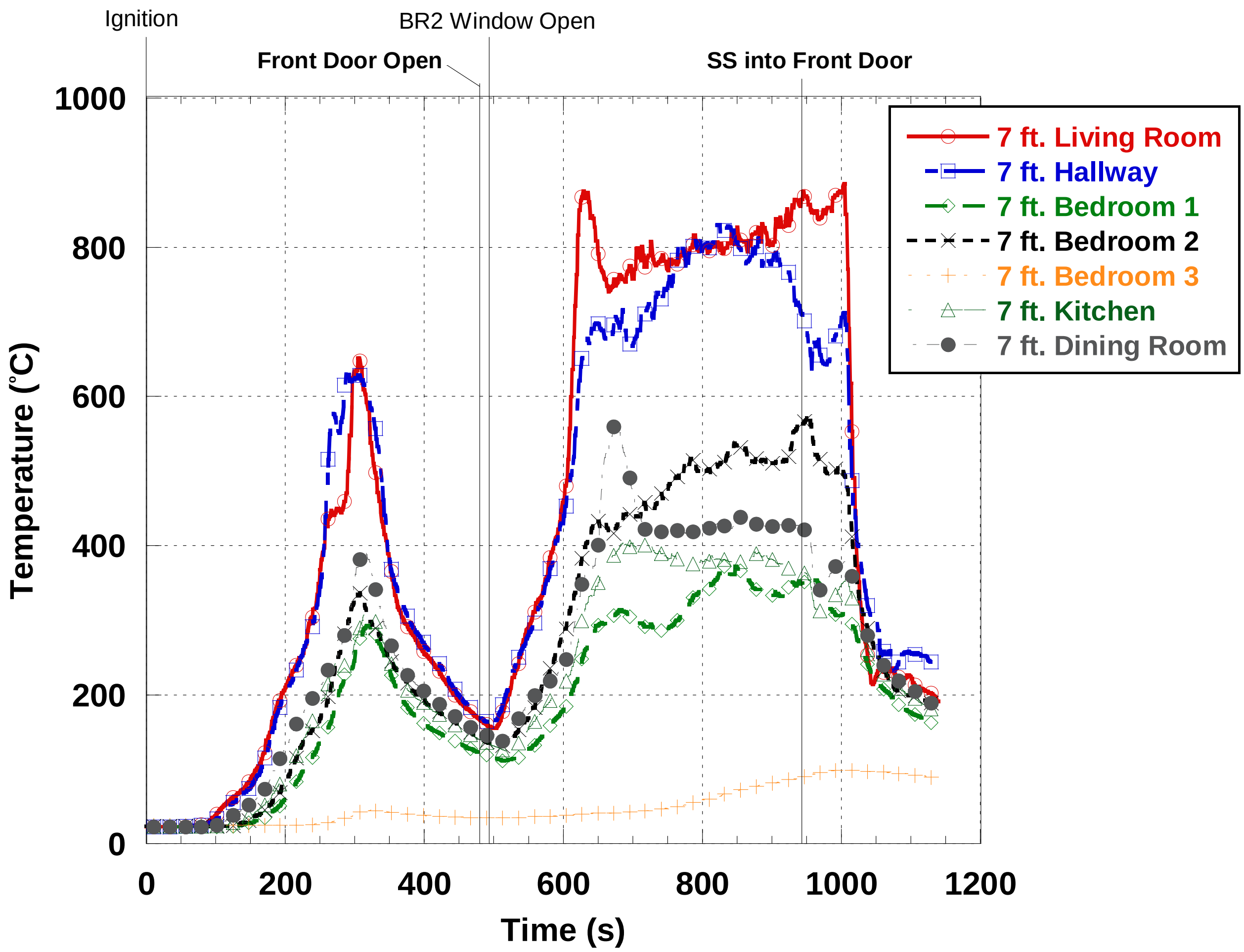


Figure 231. Experiment 7- 7ft. Temperatures

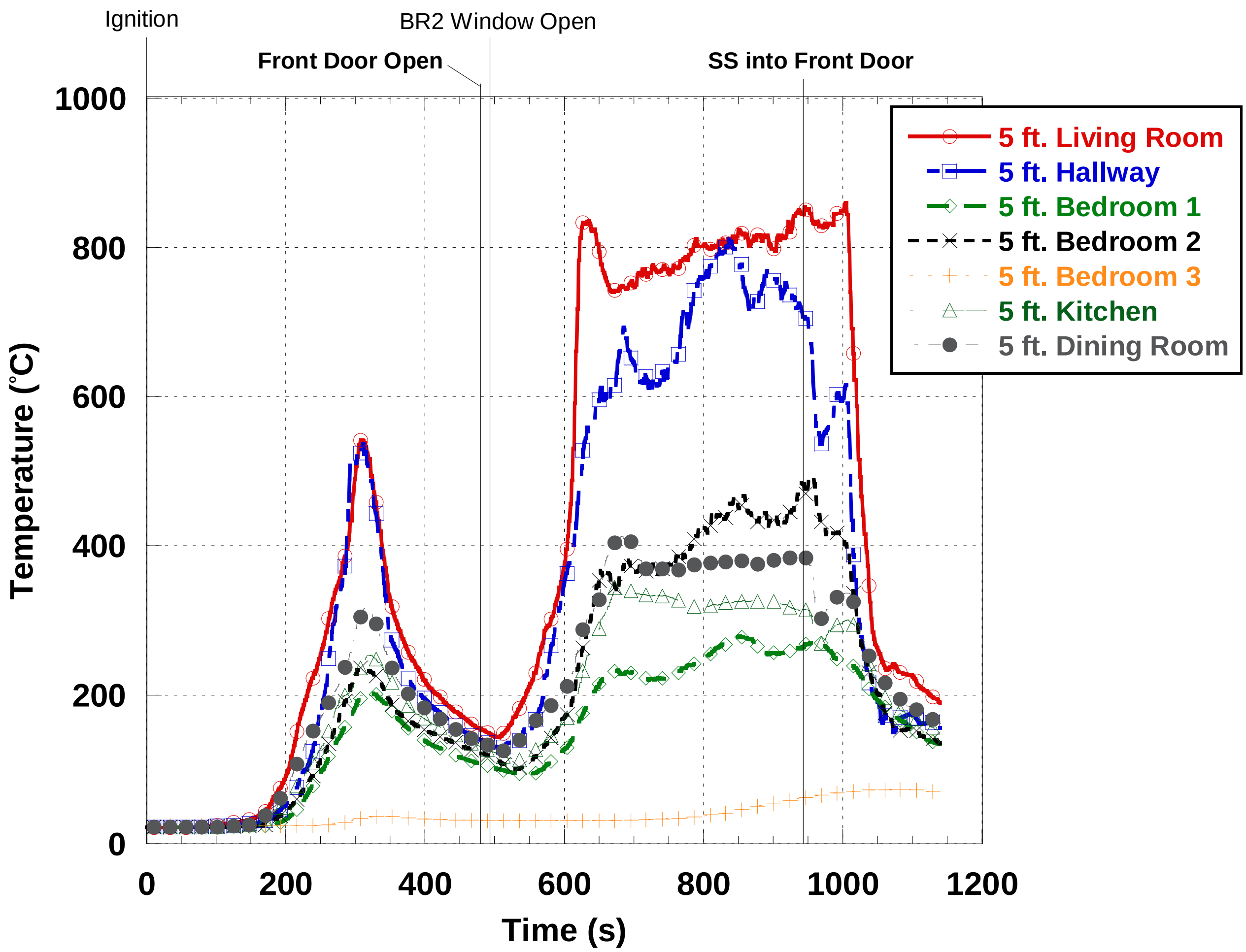


Figure 232. Experiment 7- 5ft. Temperatures

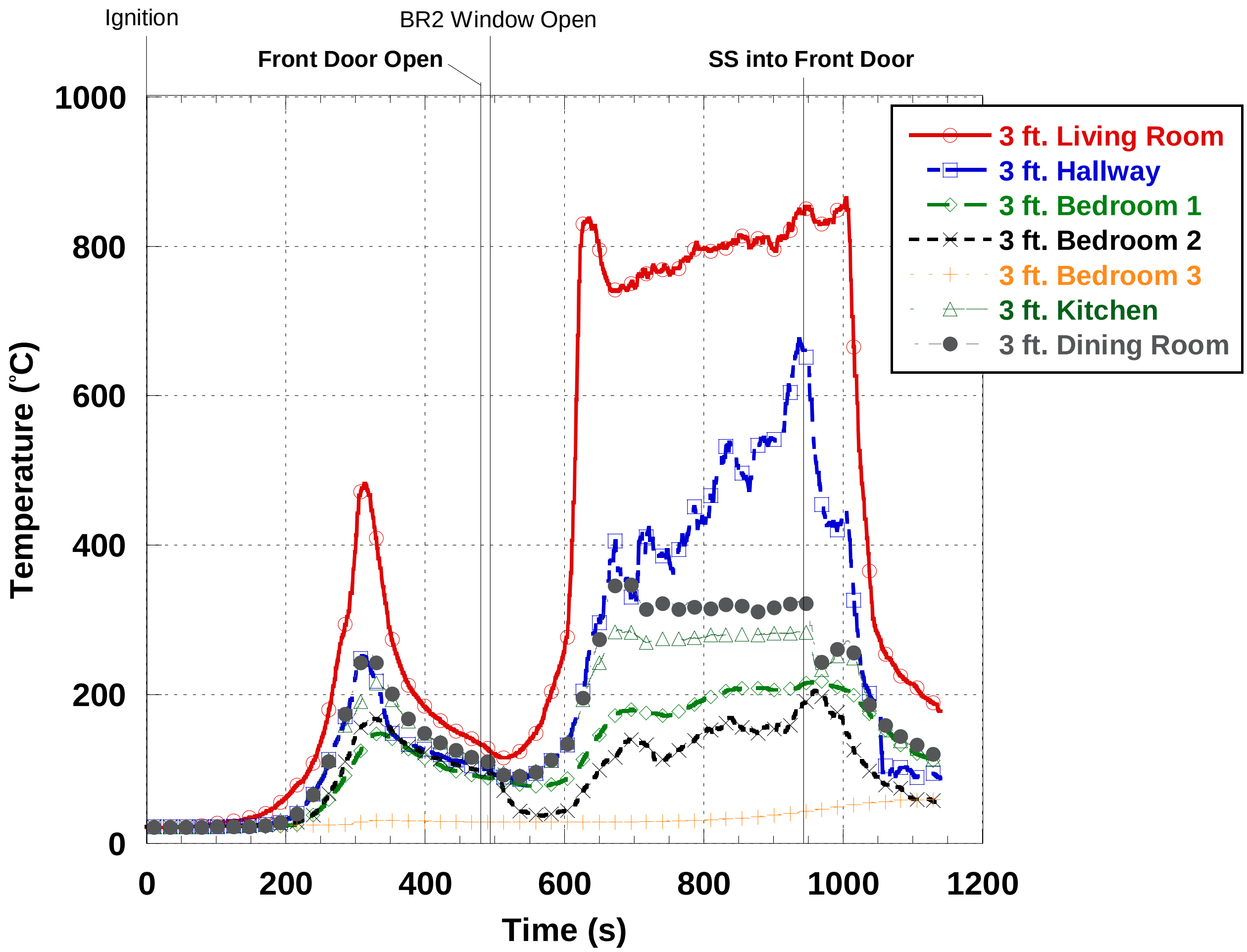


Figure 233. Experiment 7- 3ft. Temperatures

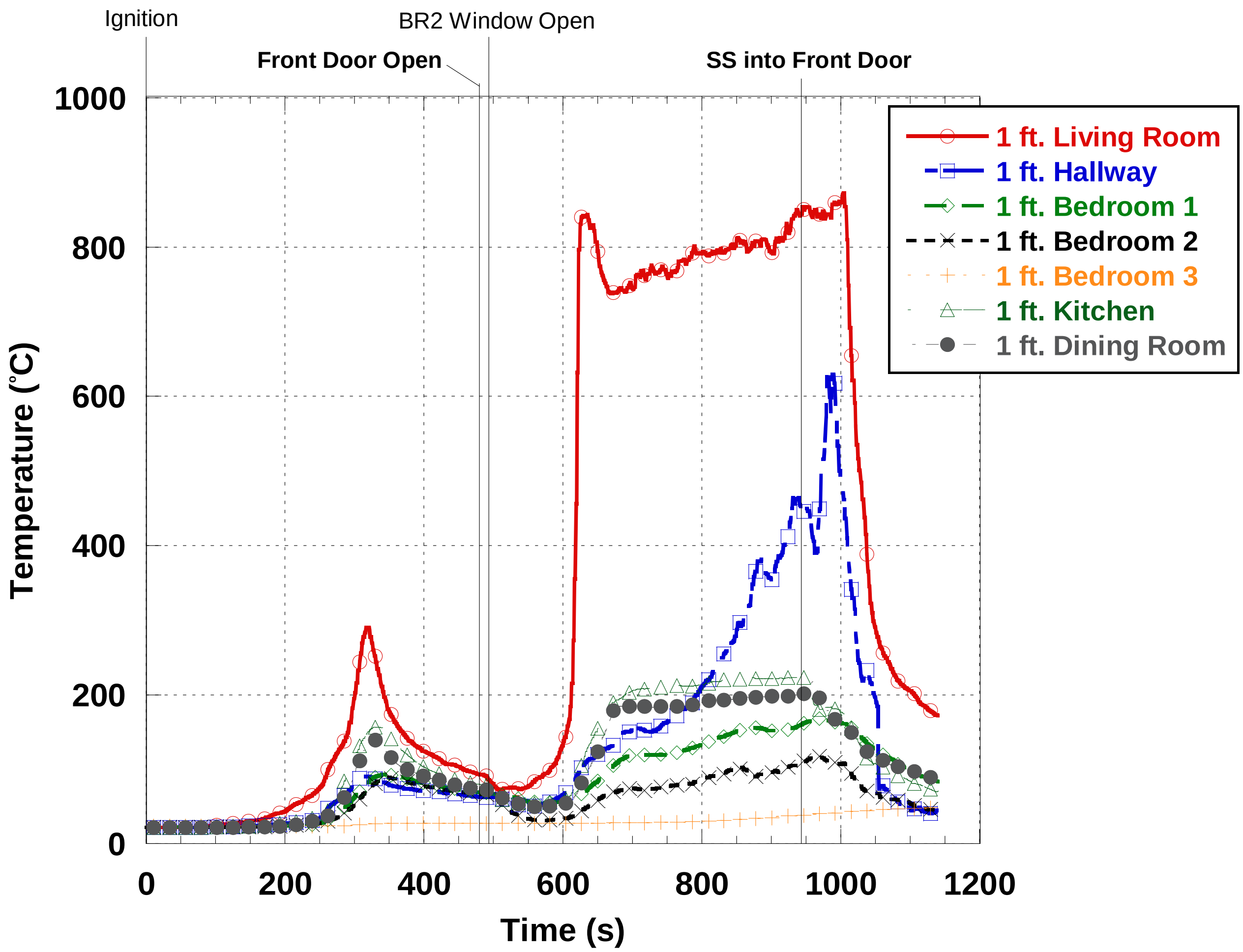


Figure 234. Experiment 7- 1ft. Temperatures

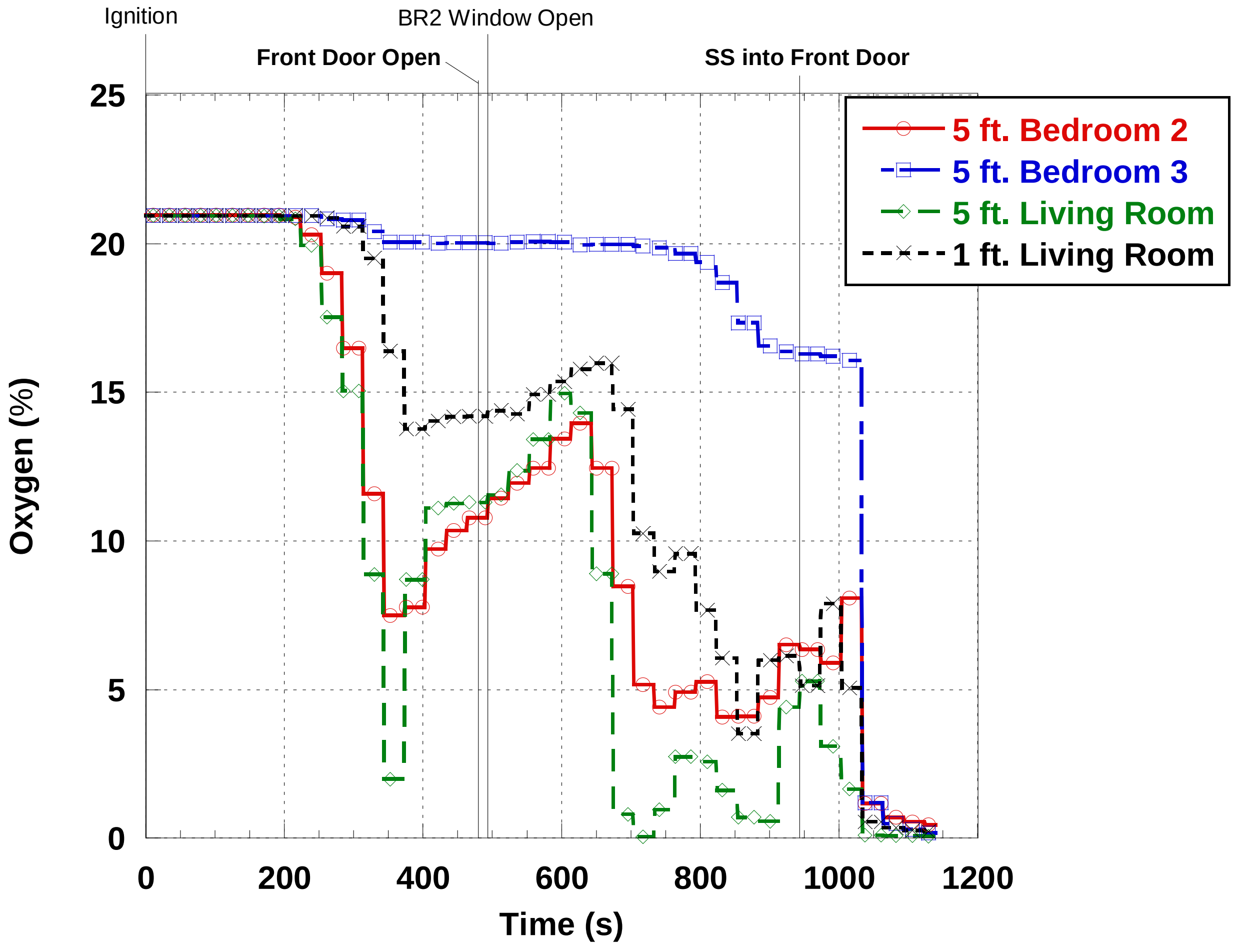


Figure 235. Experiment 7- Oxygen Concentrations

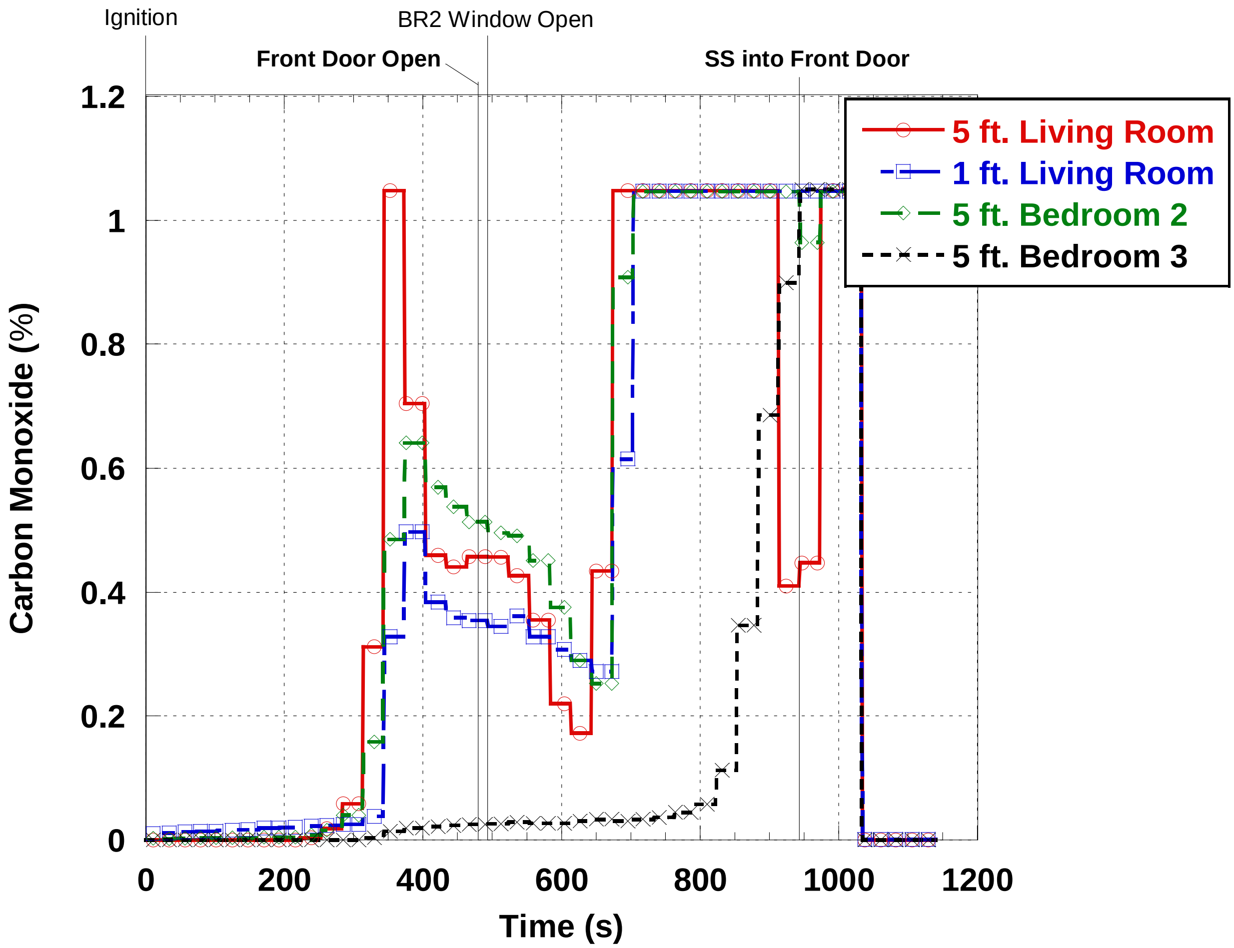


Figure 236. Experiment 7- CO Concentrations

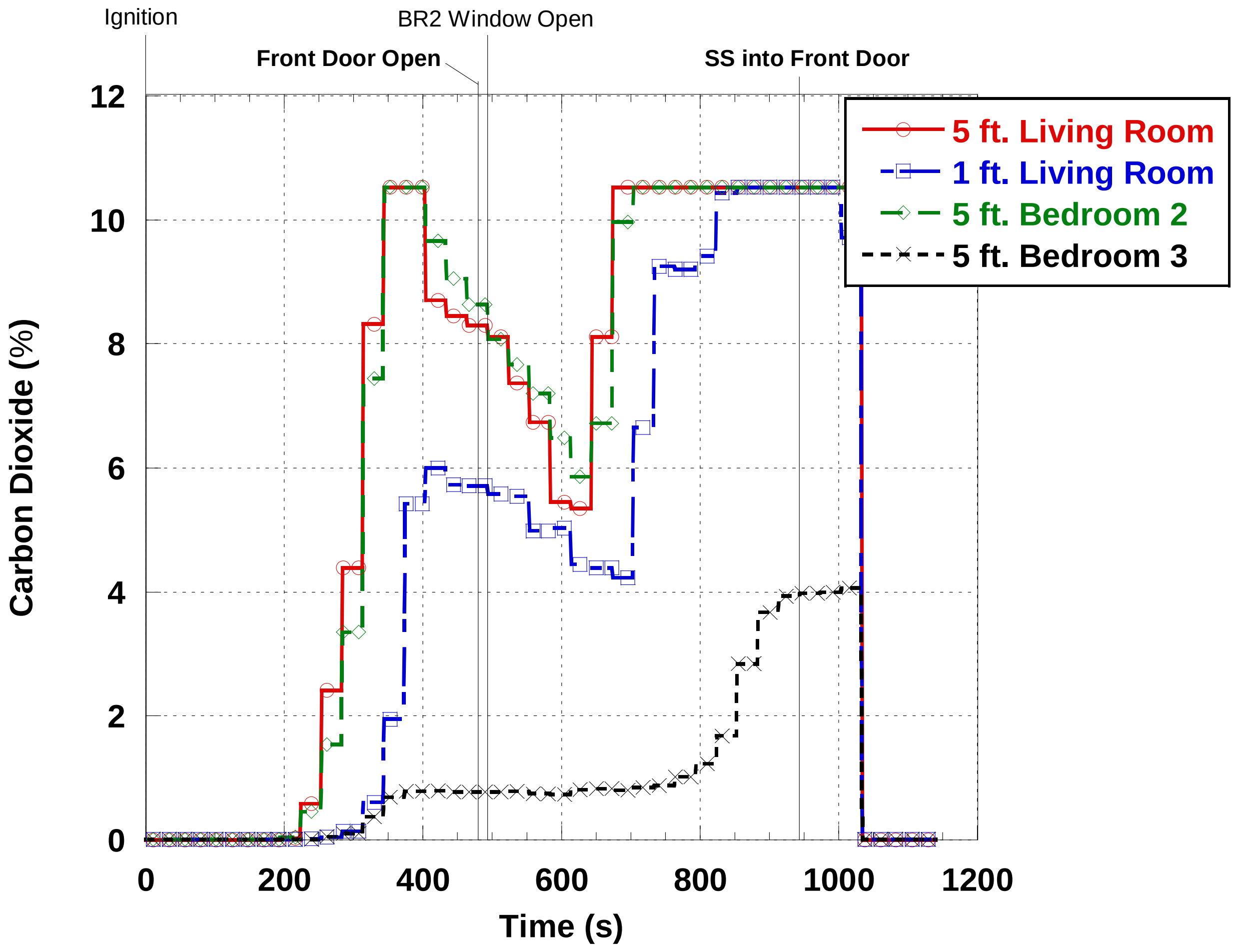


Figure 237. Experiment 7- CO_2 Concentrations

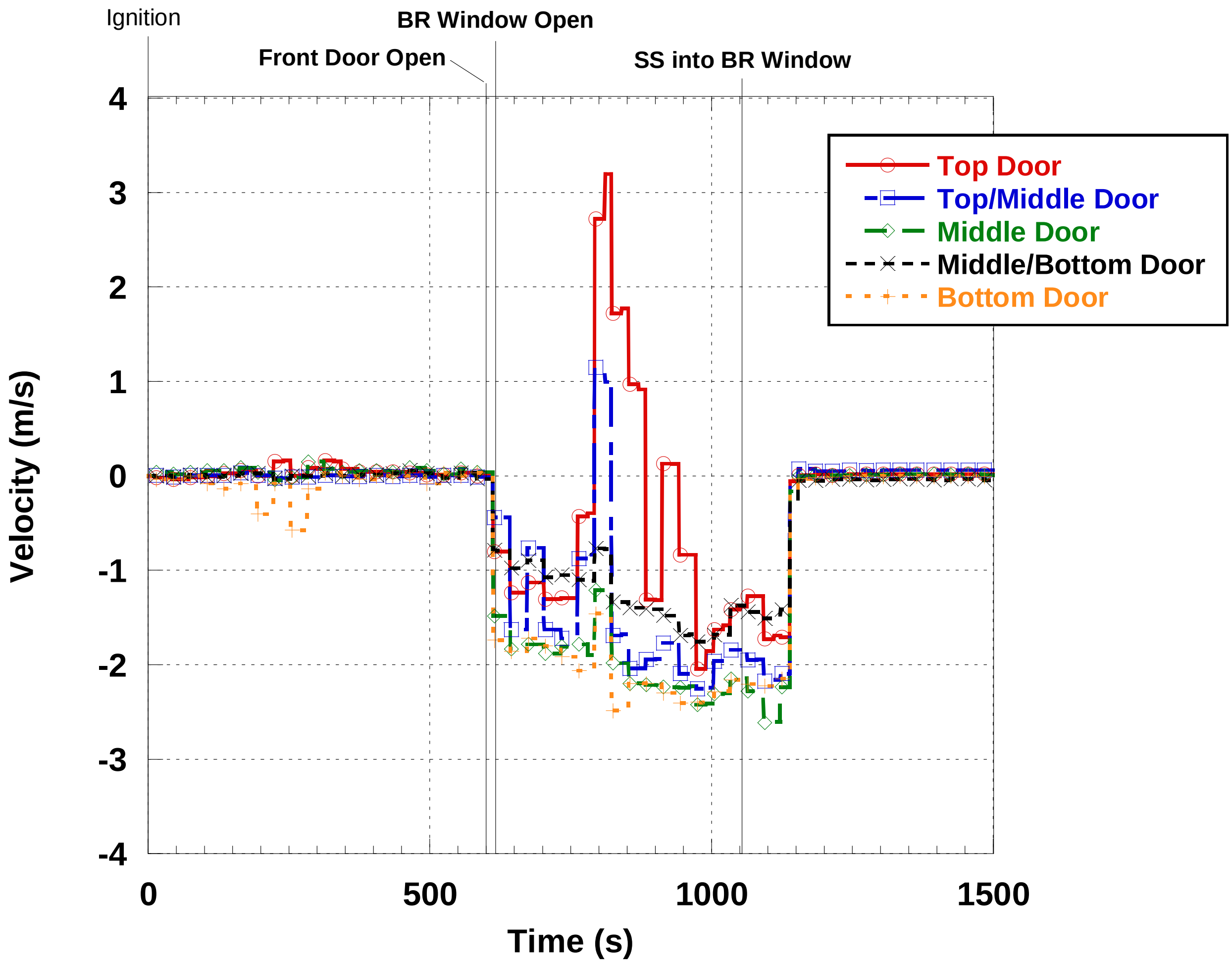


Figure 238. Experiment 7- Front Door Velocities

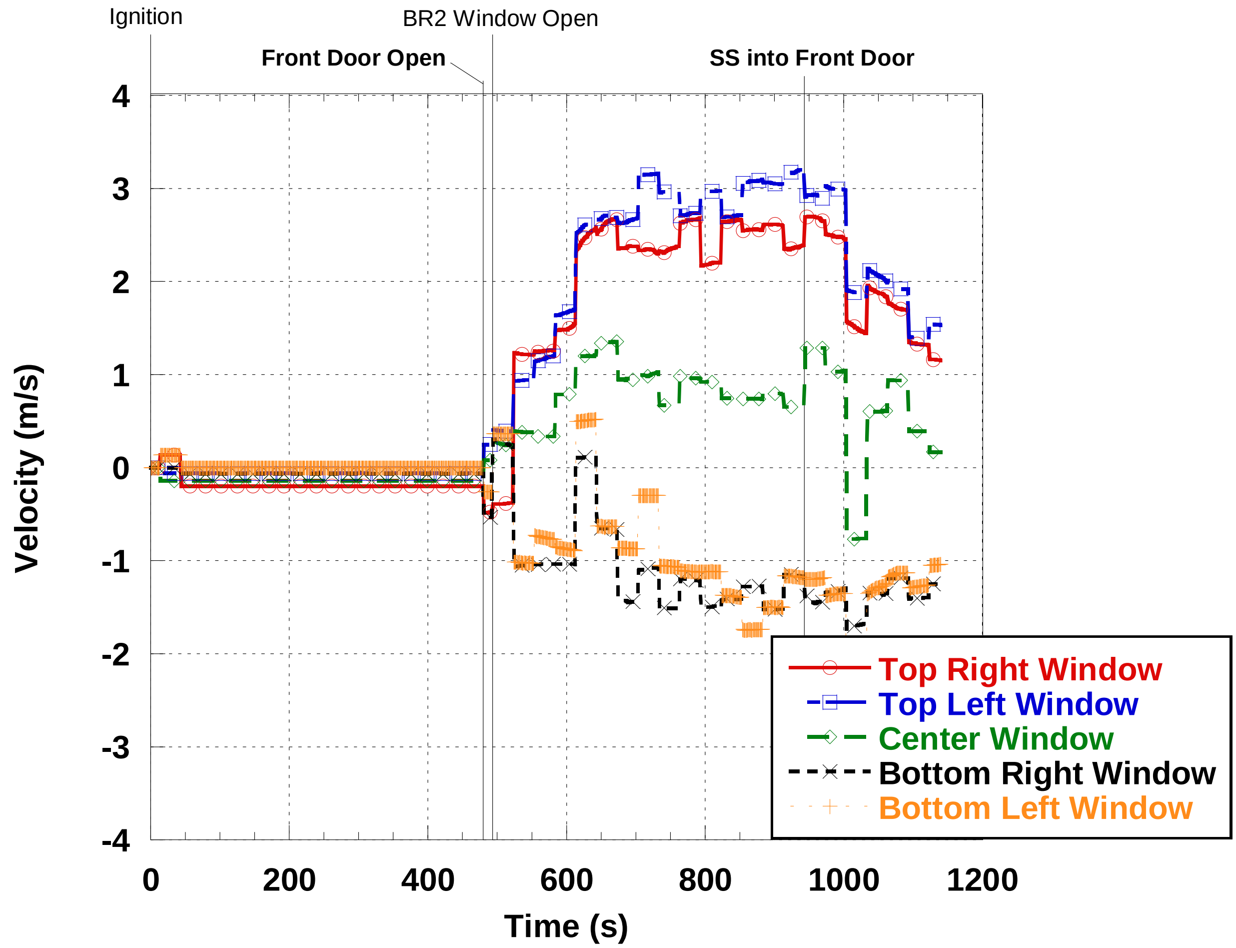


Figure 239. Experiment 7- Ventilation Window Velocities

8.6.5. Experiment 9

Experiment 9 was the fifth experiment conducted in the one-story house. This experiment was the second of three replicate experiments to examine repeatability. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 8 minutes after ignition at which time the front door was opened. Fifteen seconds after the front door was opened the living room window was opened (Table 21). The fire again was allowed to grow until 11:12 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 12:20 and was extinguished by the suppression crew. Figure 241 through Figure 247 show the front of the house during the experiment.

Table 21. Experiment 9 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	8:00
Living Room Window Open	8:15
Straight Stream into Living Room Window	11:12-11:22
End of Experiment	12:20

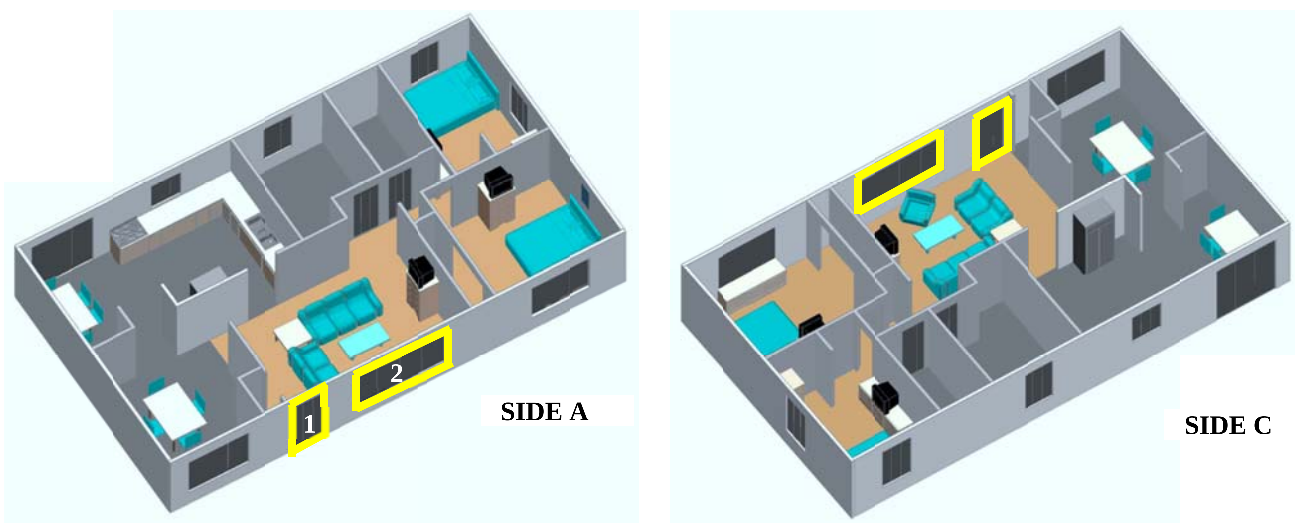


Figure 240. House graphics highlighting ventilation locations


Figure 241. Experiment 9 - 0:00


Figure 242. Experiment 9 - 5:00


Figure 243. Experiment 9 - 8:05


Figure 244. Experiment 9 - 8:20


Figure 245. Experiment 9 - 10:00


Figure 246. Experiment 9 - 11:15


Figure 247. Experiment 9 - 12:15

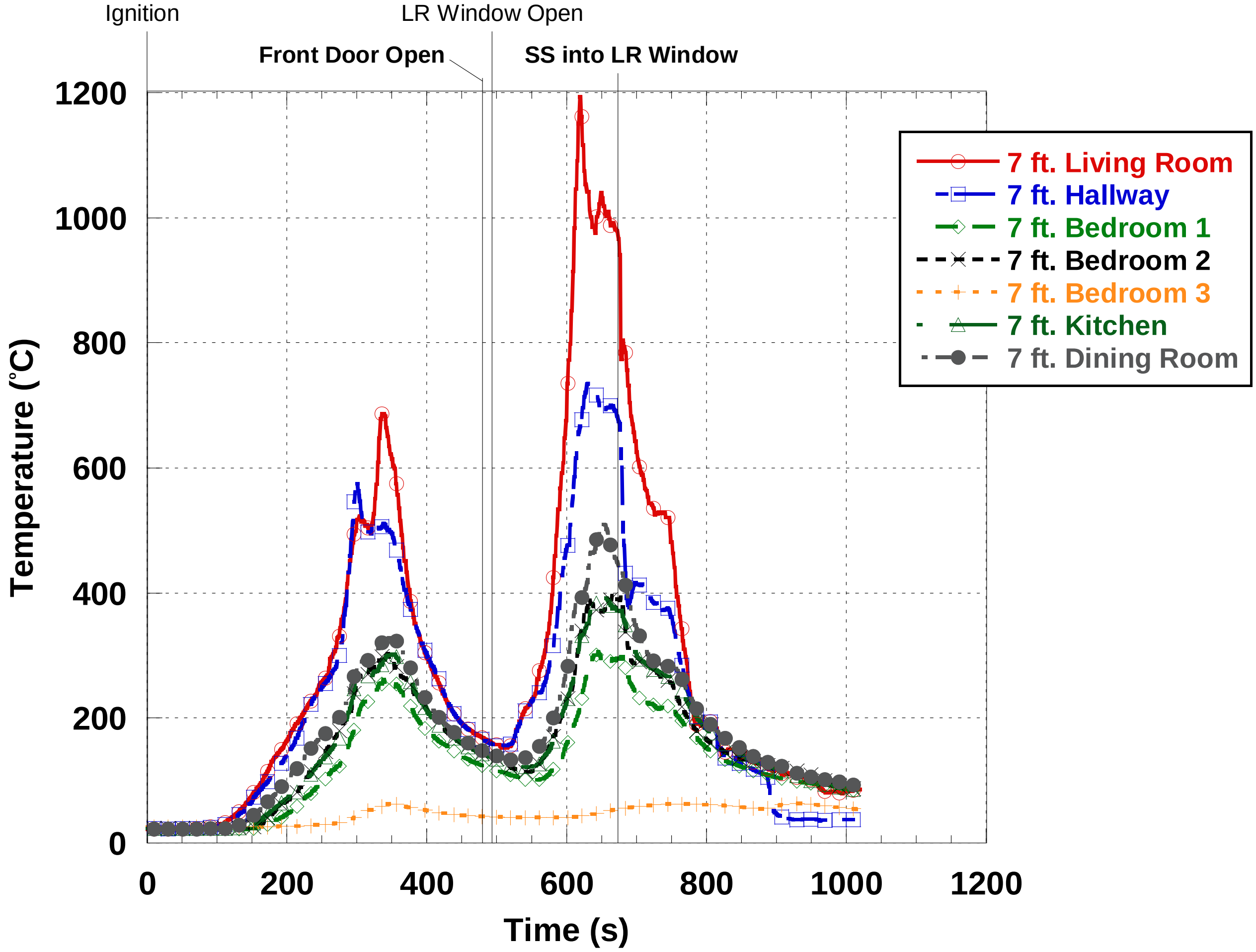


Figure 248. Experiment 9- 7ft. Temperatures

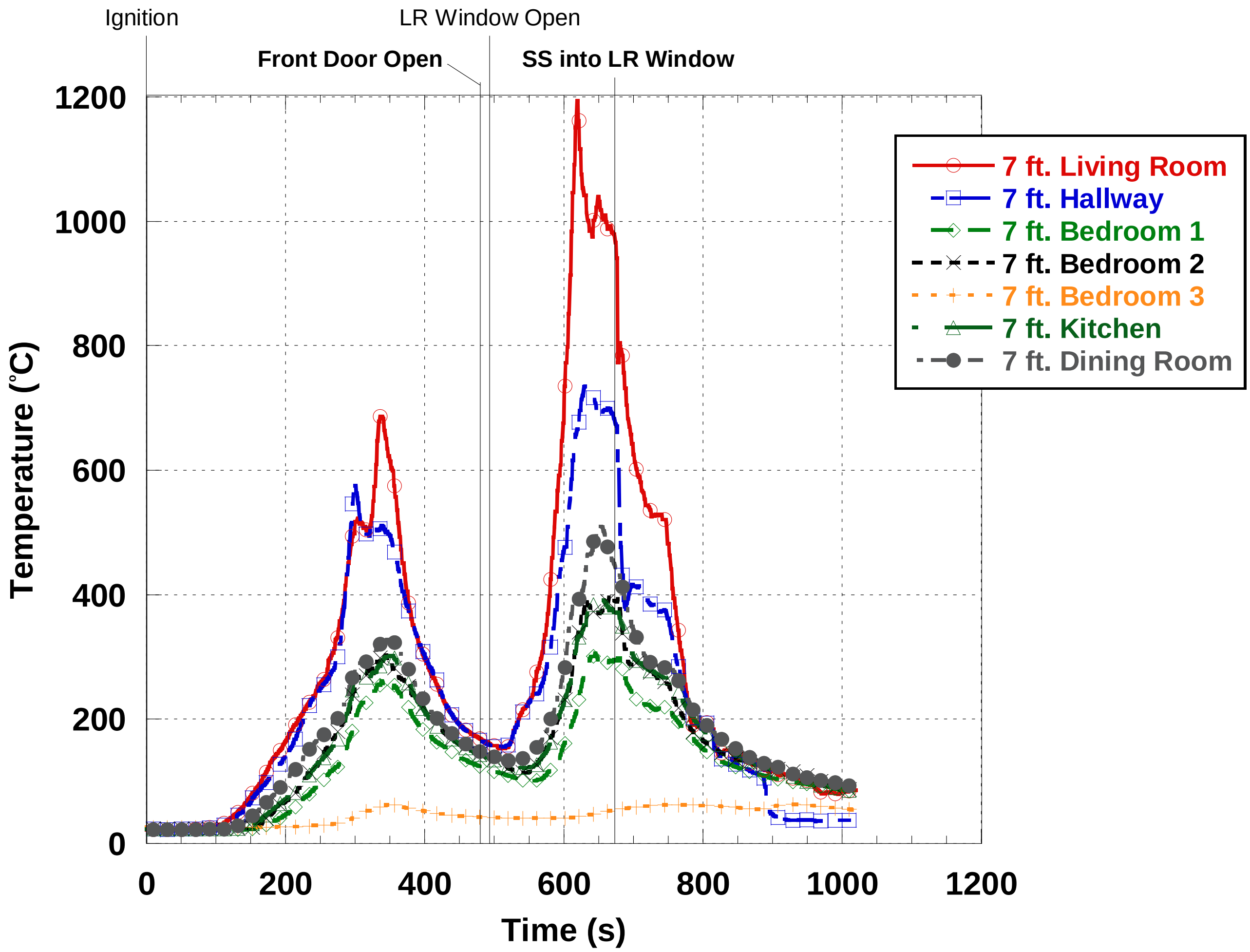


Figure 249. Experiment 9- 5ft. Temperatures

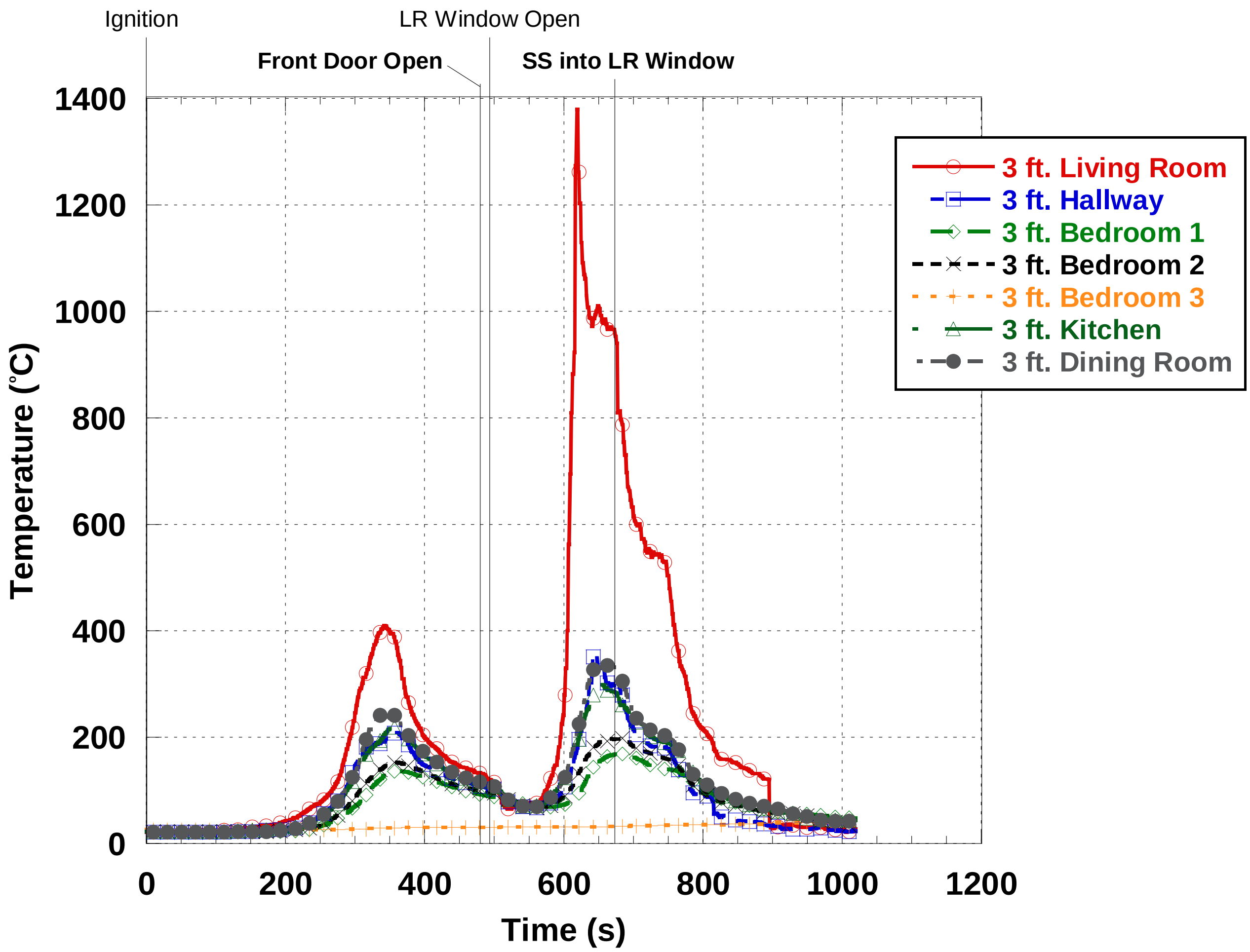


Figure 250. Experiment 9- 3ft. Temperatures

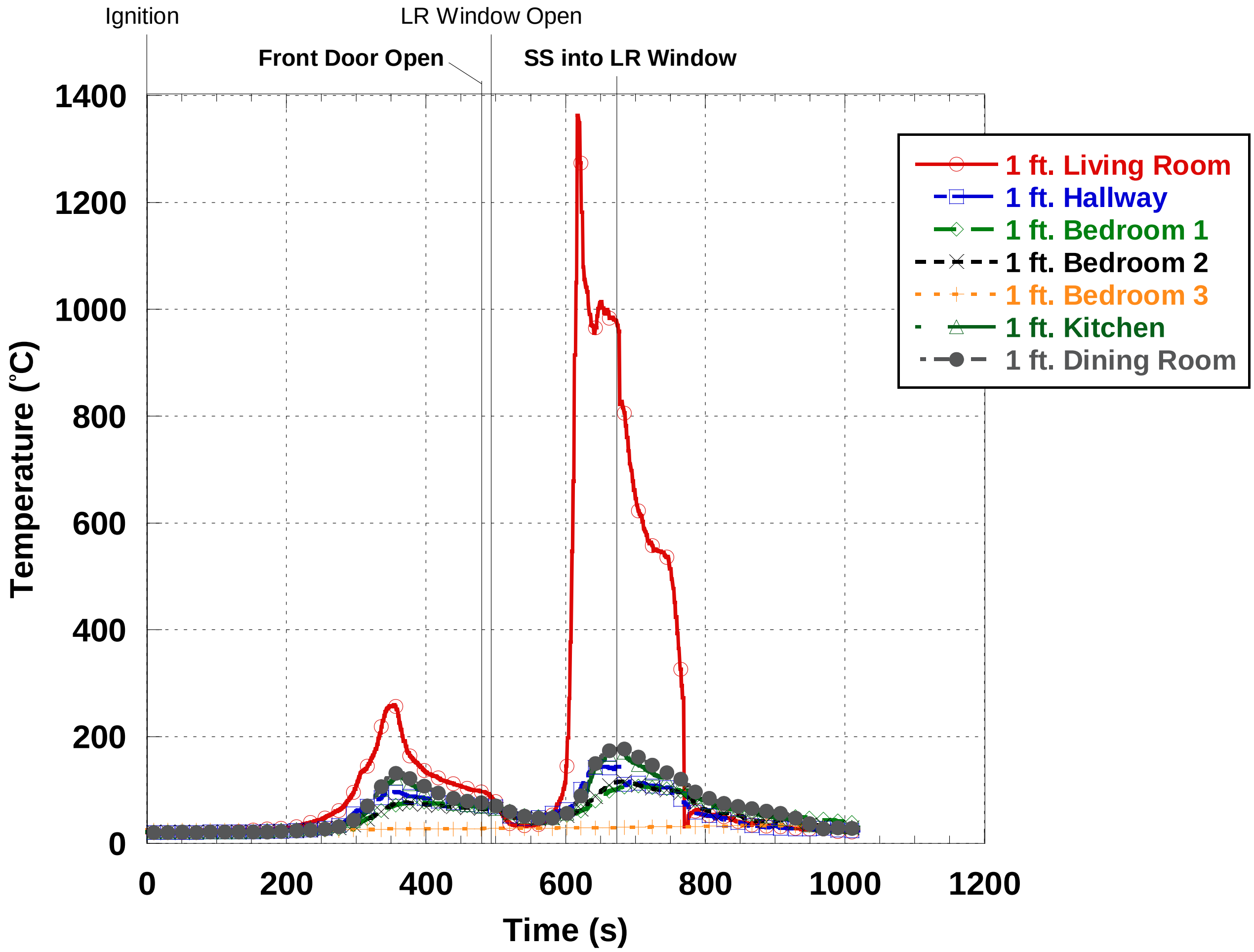


Figure 251. Experiment 9- 1ft. Temperatures

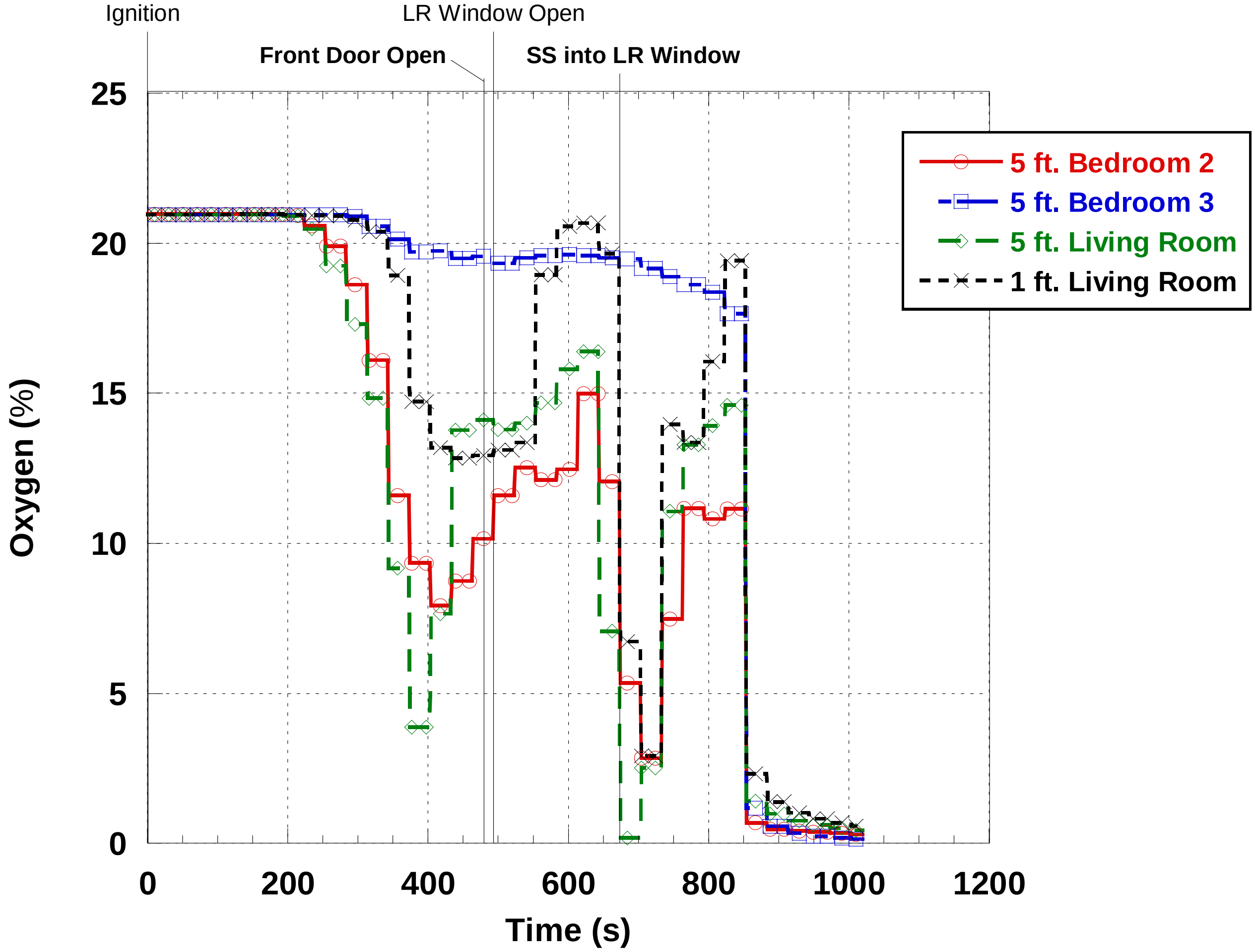


Figure 252. Experiment 9- Oxygen Concentrations

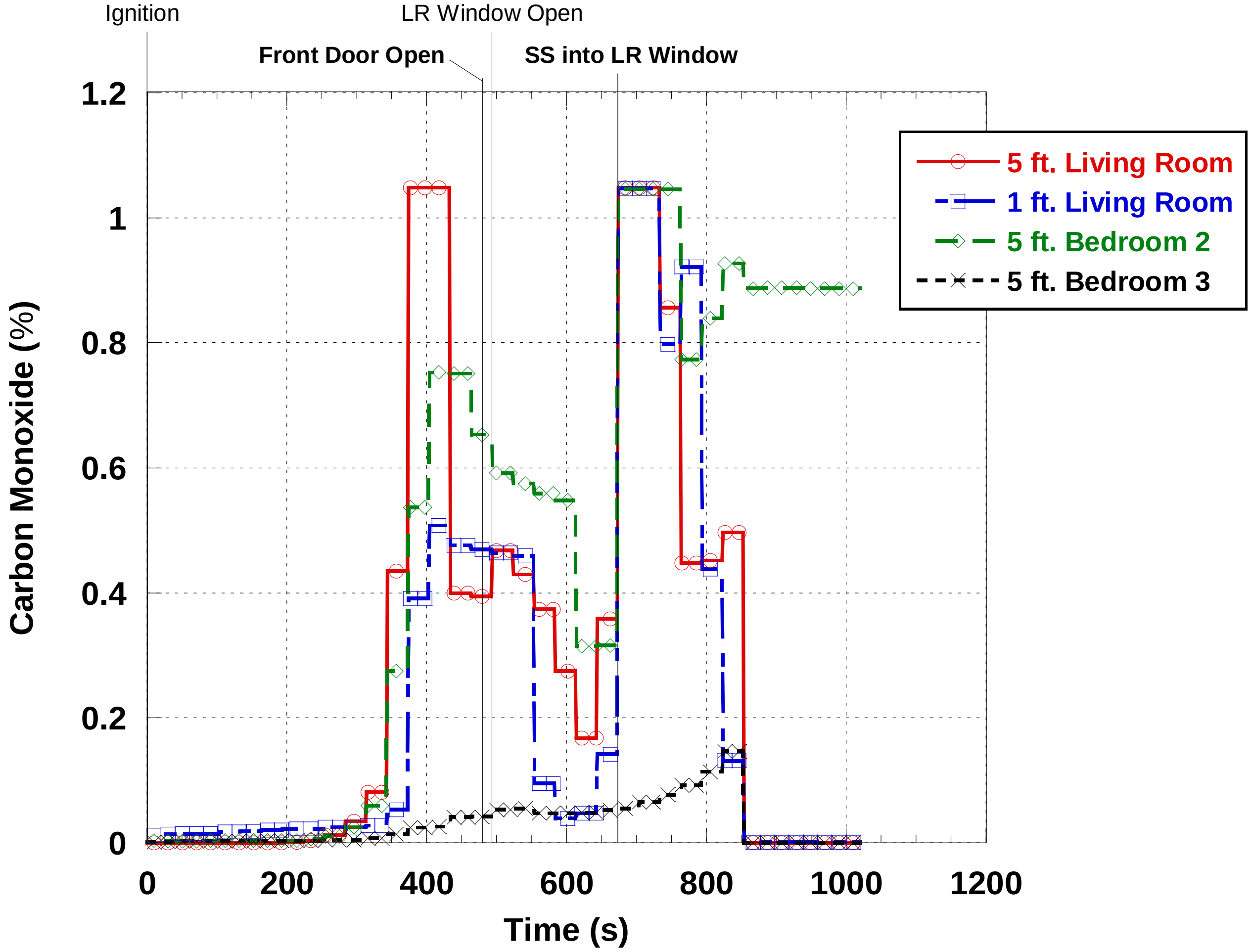


Figure 253. Experiment 9 - CO Concentrations

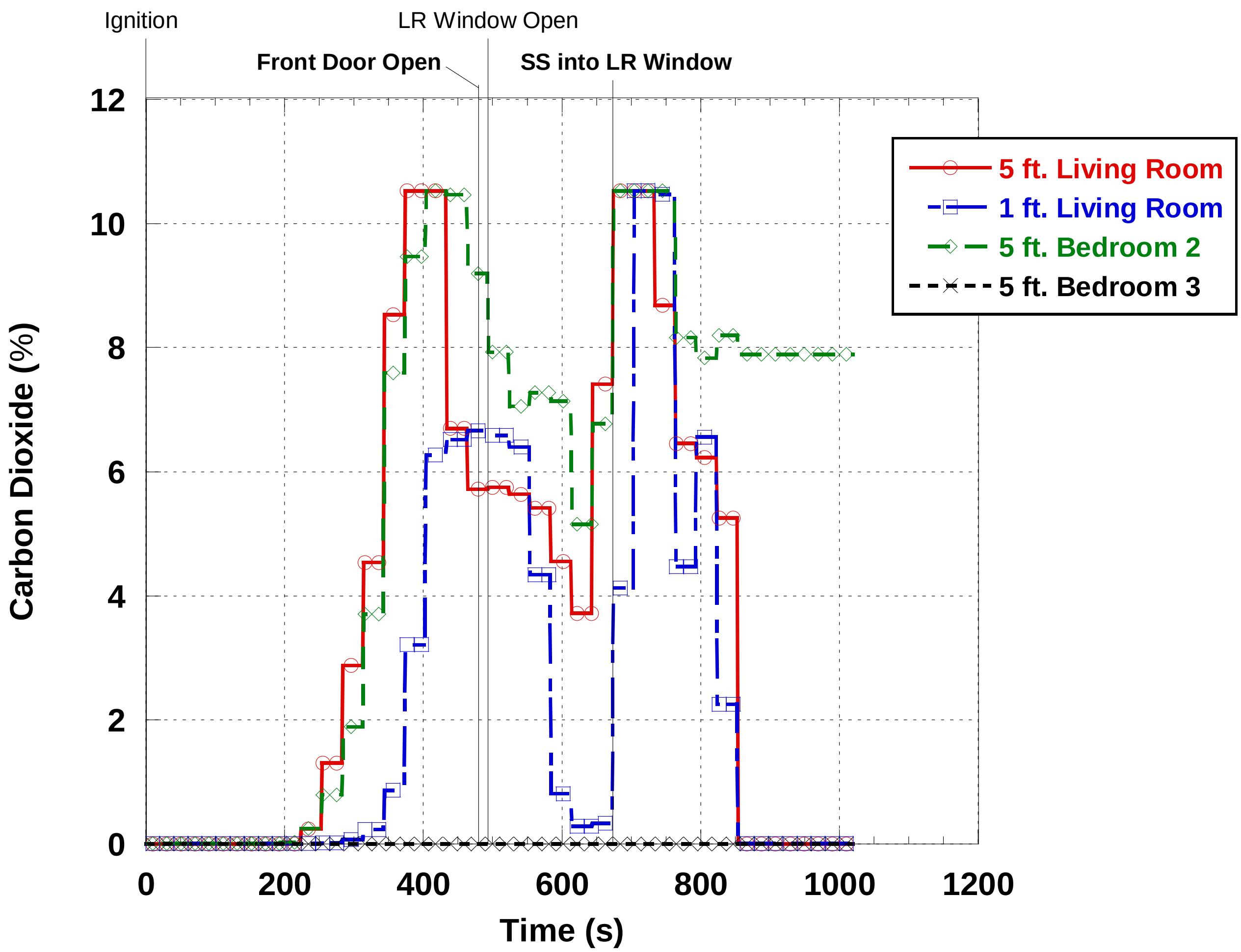


Figure 254. Experiment 9- CO_2 Concentrations

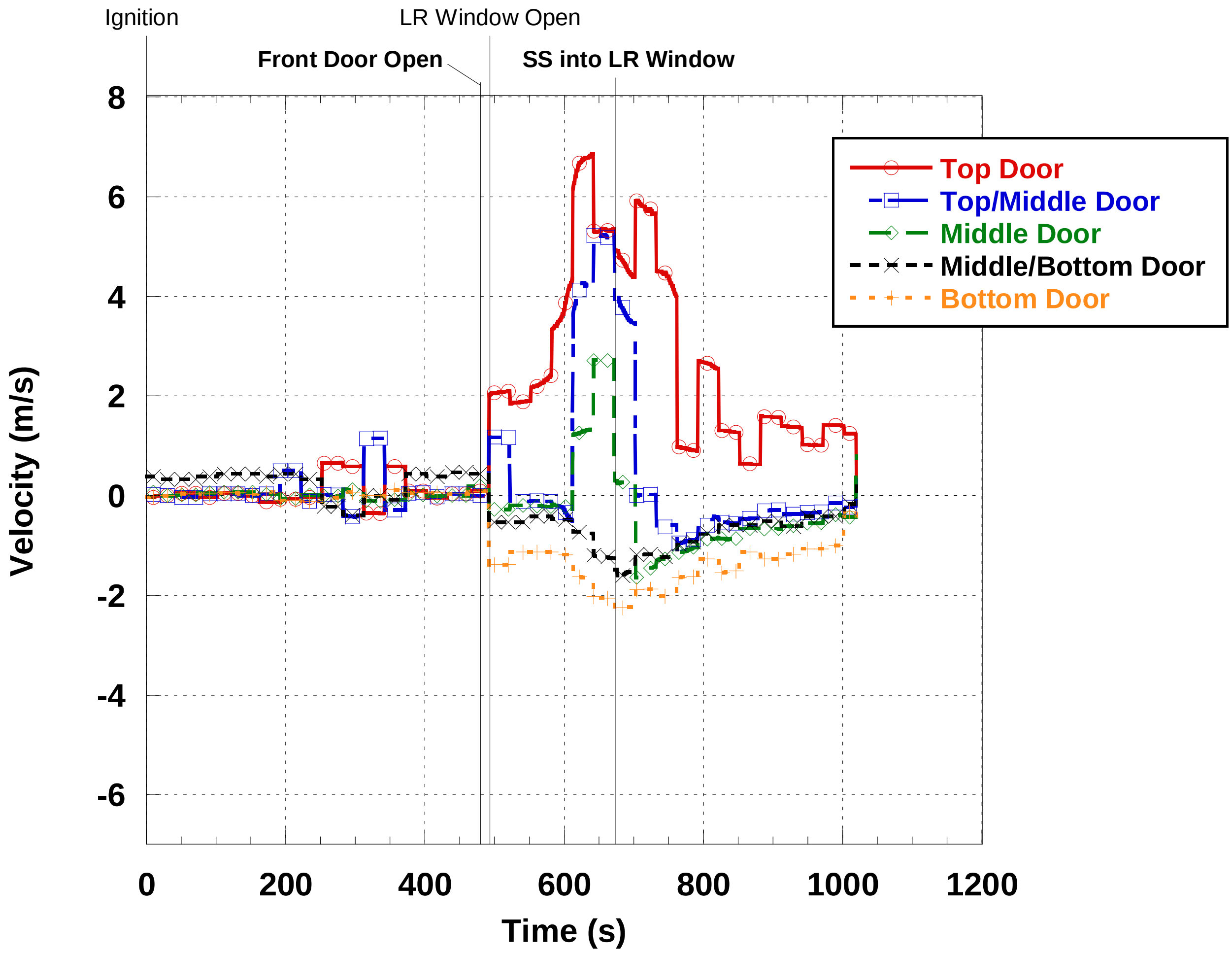


Figure 255. Experiment 9- Front Door Velocities

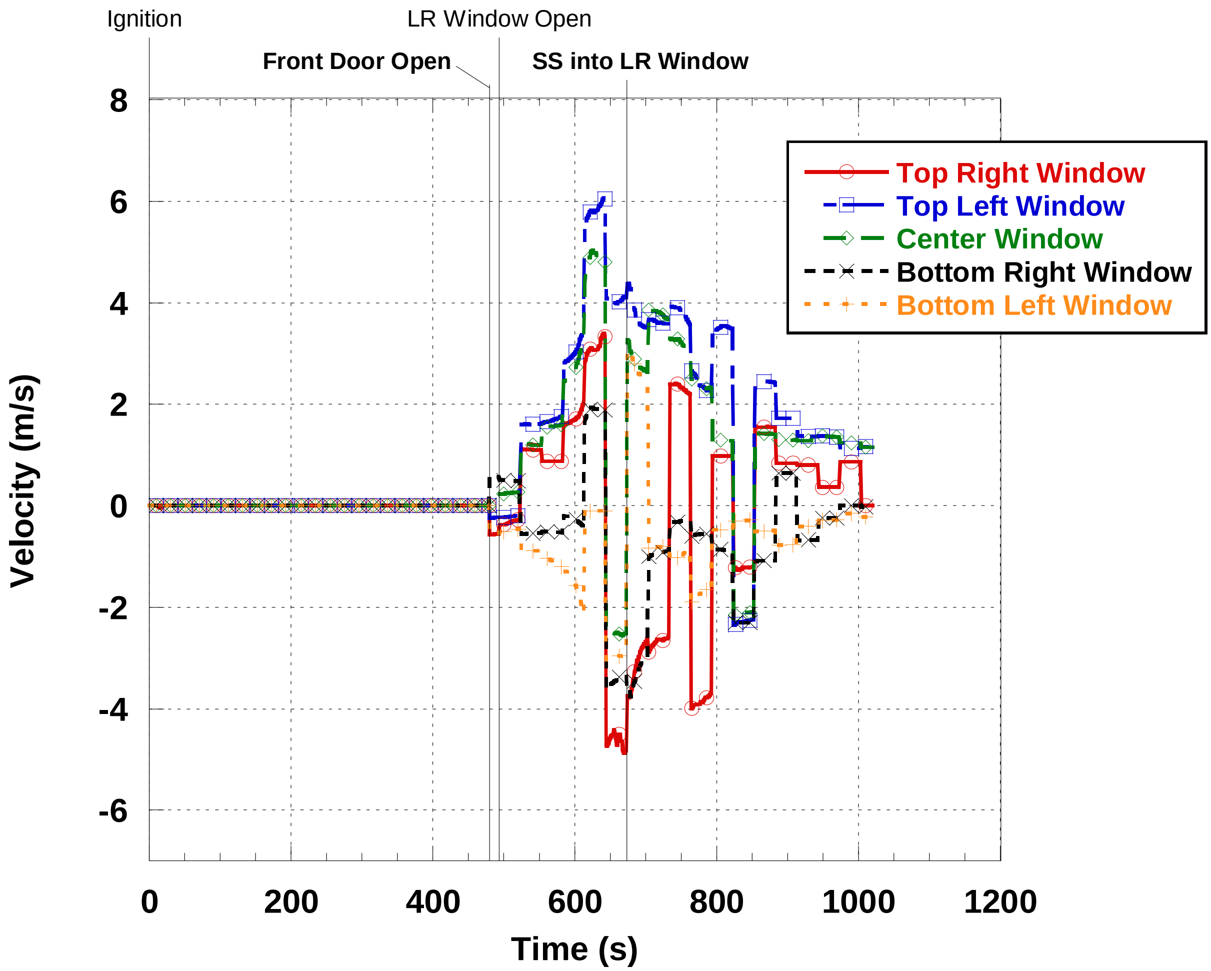


Figure 256. Experiment 9- Ventilation Window Velocities

8.6.6. Experiment 12

Experiment 12 was the sixth experiment conducted in the one-story house. This experiment was the third of three replicate experiments to examine repeatability. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 8 minutes after ignition at which time the front door was opened. Fifteen seconds after the front door was opened the living room window was opened (Table 22). The fire again was allowed to grow until 11:09 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 12:20 and was extinguished by the suppression crew. Figure 258 through Figure 264 show the front of the house during the experiments.

Table 22. Experiment 12 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	8:00
Living Room Window Open	8:15
Straight Stream into Living Room Window	11:09:11:19
End of Experiment	12:20

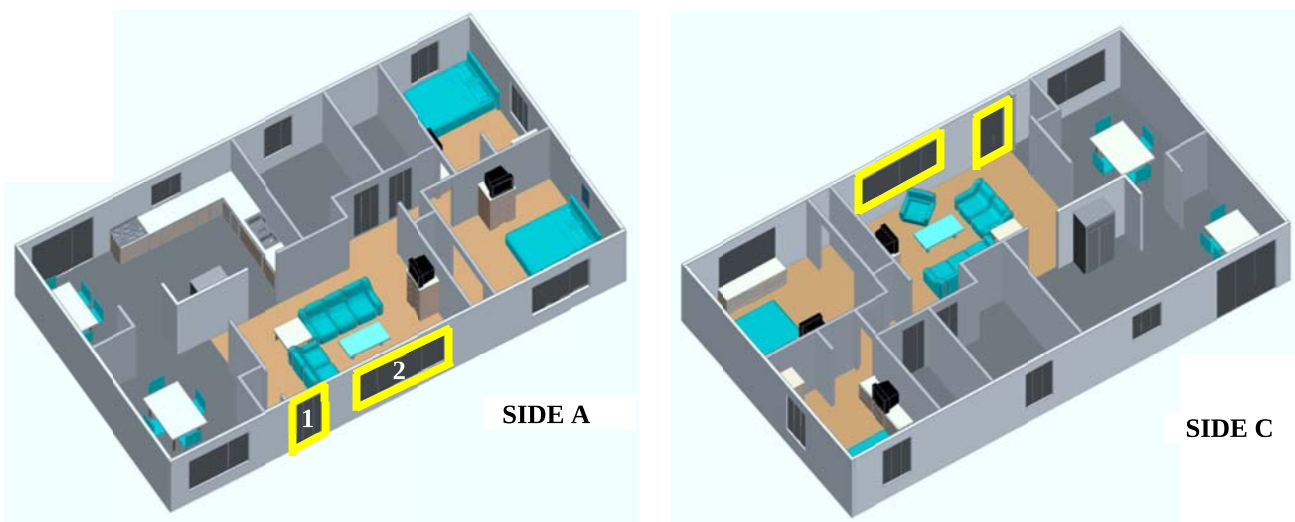


Figure 257. House graphic highlighting ventilation locations

Figure 258. Experiment 12 - 0:00

Figure 259. Experiment 12 - 5:00

Figure 260. Experiment 12 - 8:05

Figure 261. Experiment 12 - 8:20

Figure 262. Experiment 12 - 10:00

Figure 263. Experiment 12 - 11:20

Figure 264. Experiment 12 - 12:00

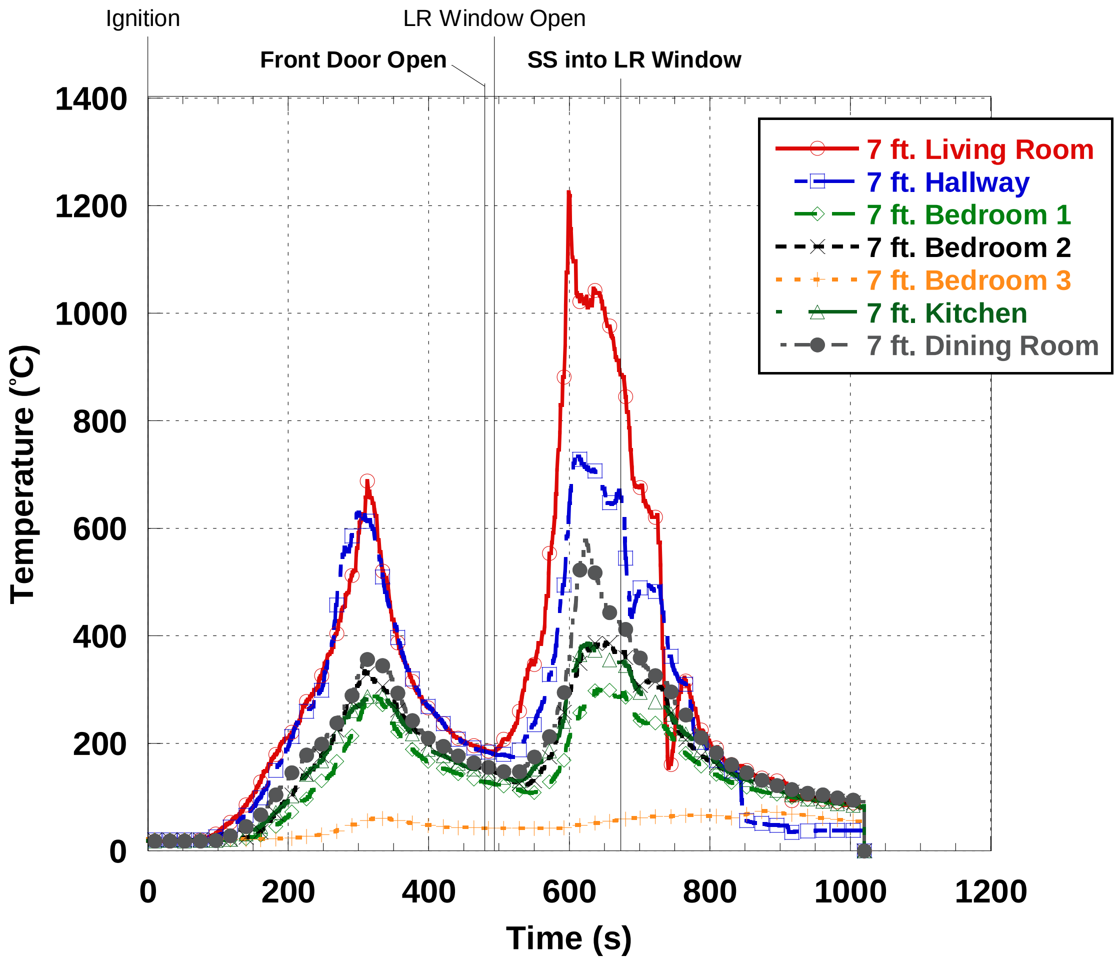


Figure 265. Experiment 12- 7ft. Temperatures

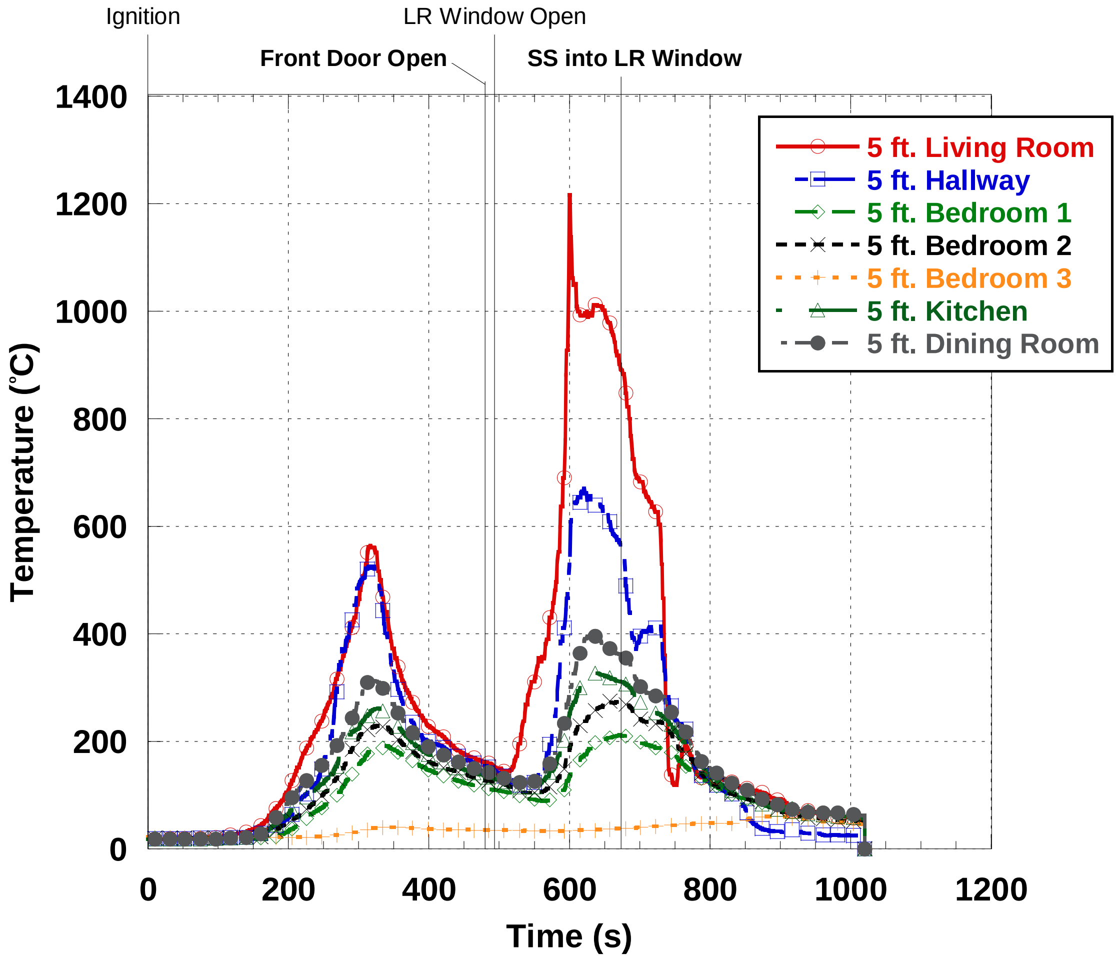


Figure 266. Experiment 12- 5ft. Temperatures

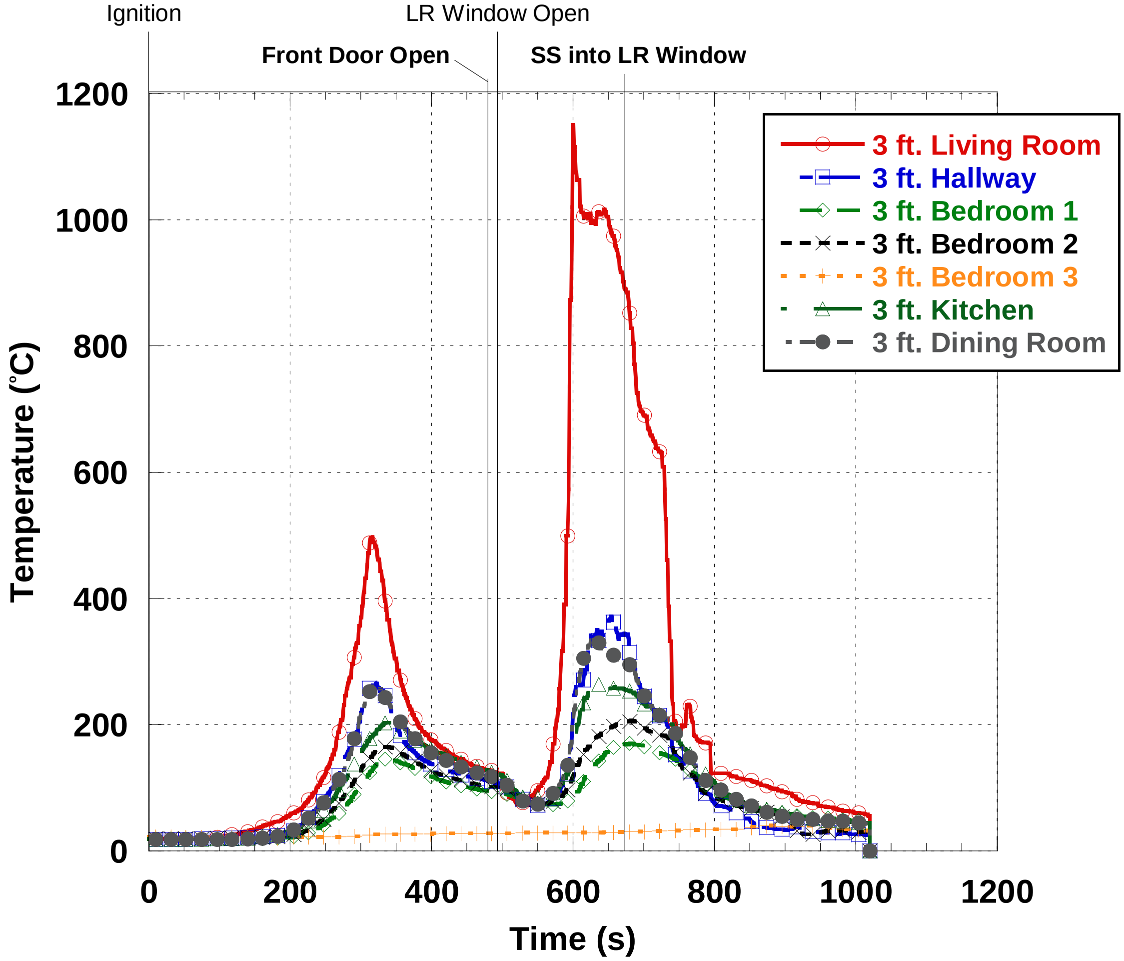


Figure 267. Experiment 12- 3ft. Temperatures

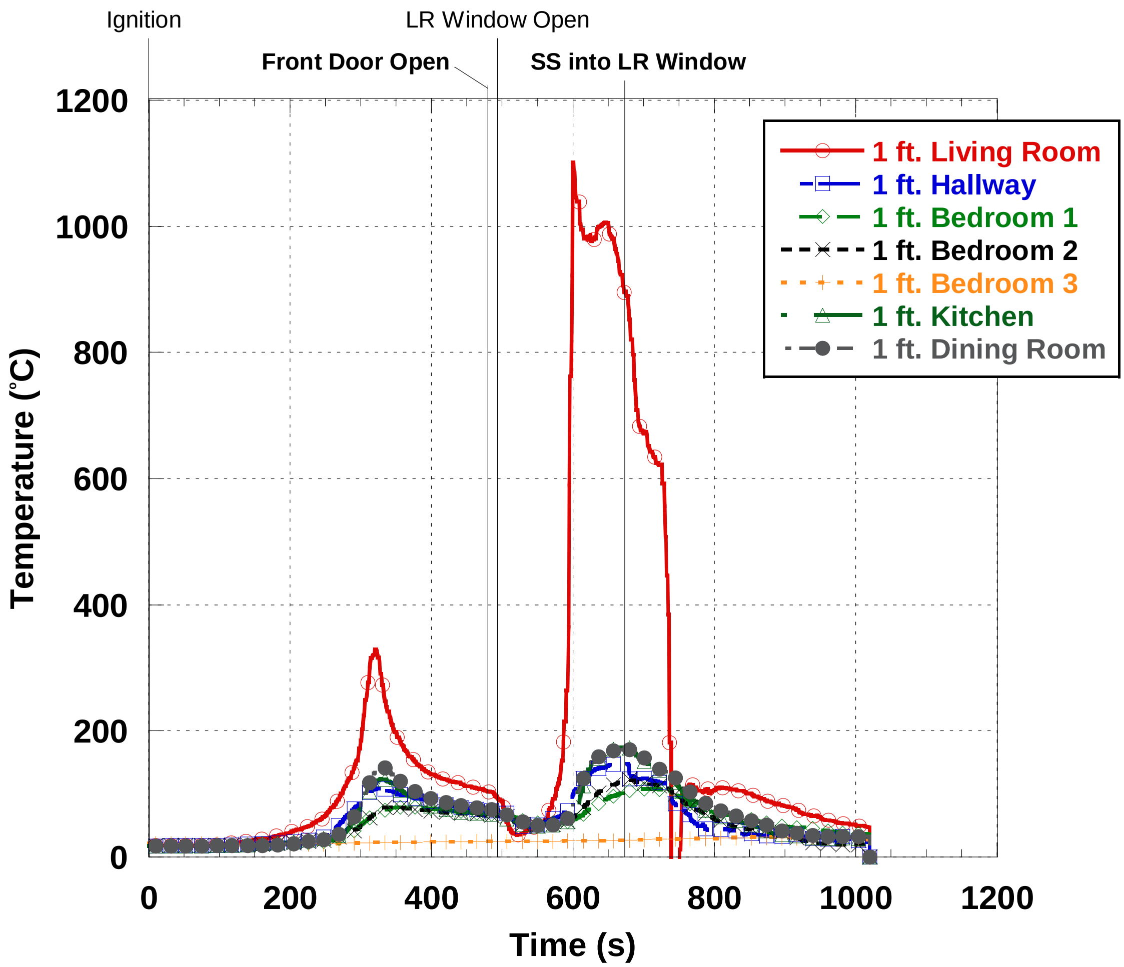


Figure 268. Experiment 12- 1ft. Temperatures

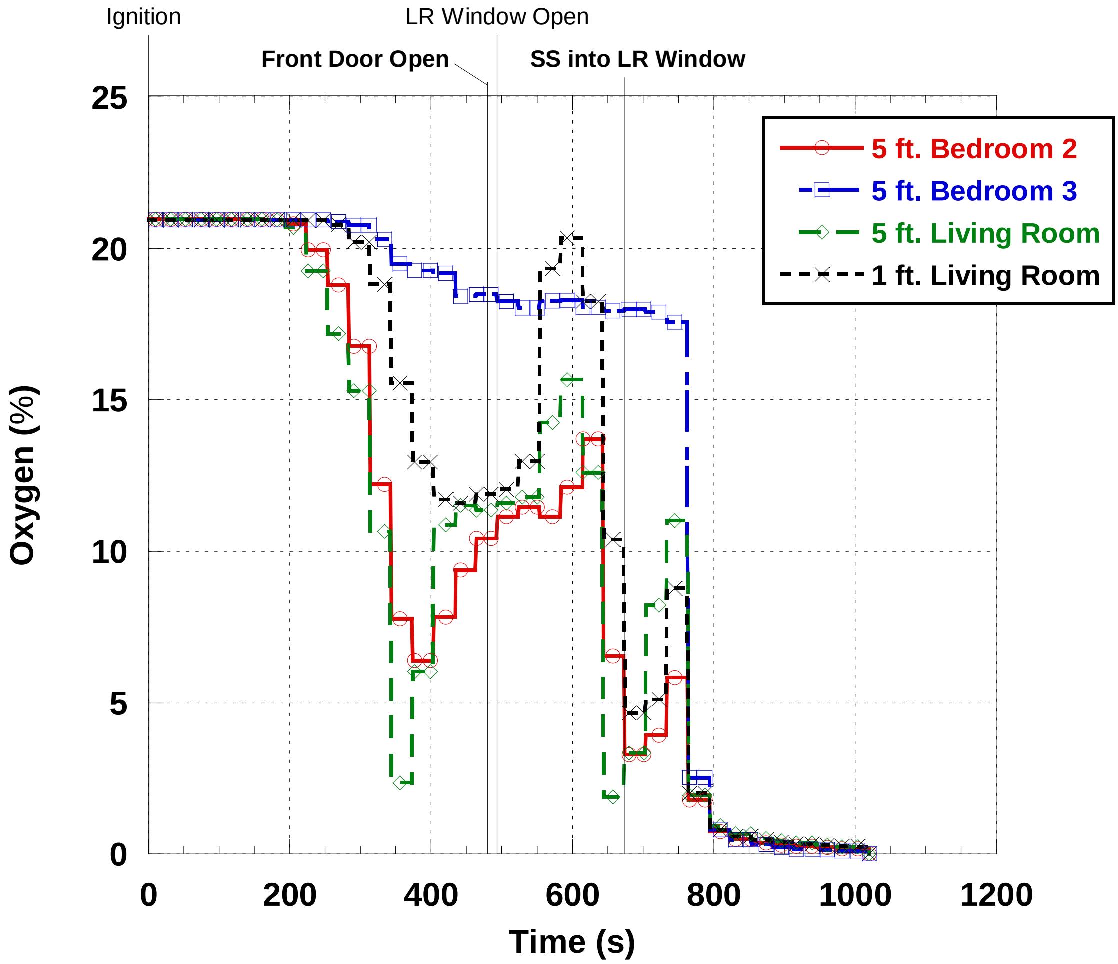


Figure 269. Experiment 12- Oxygen Concentration

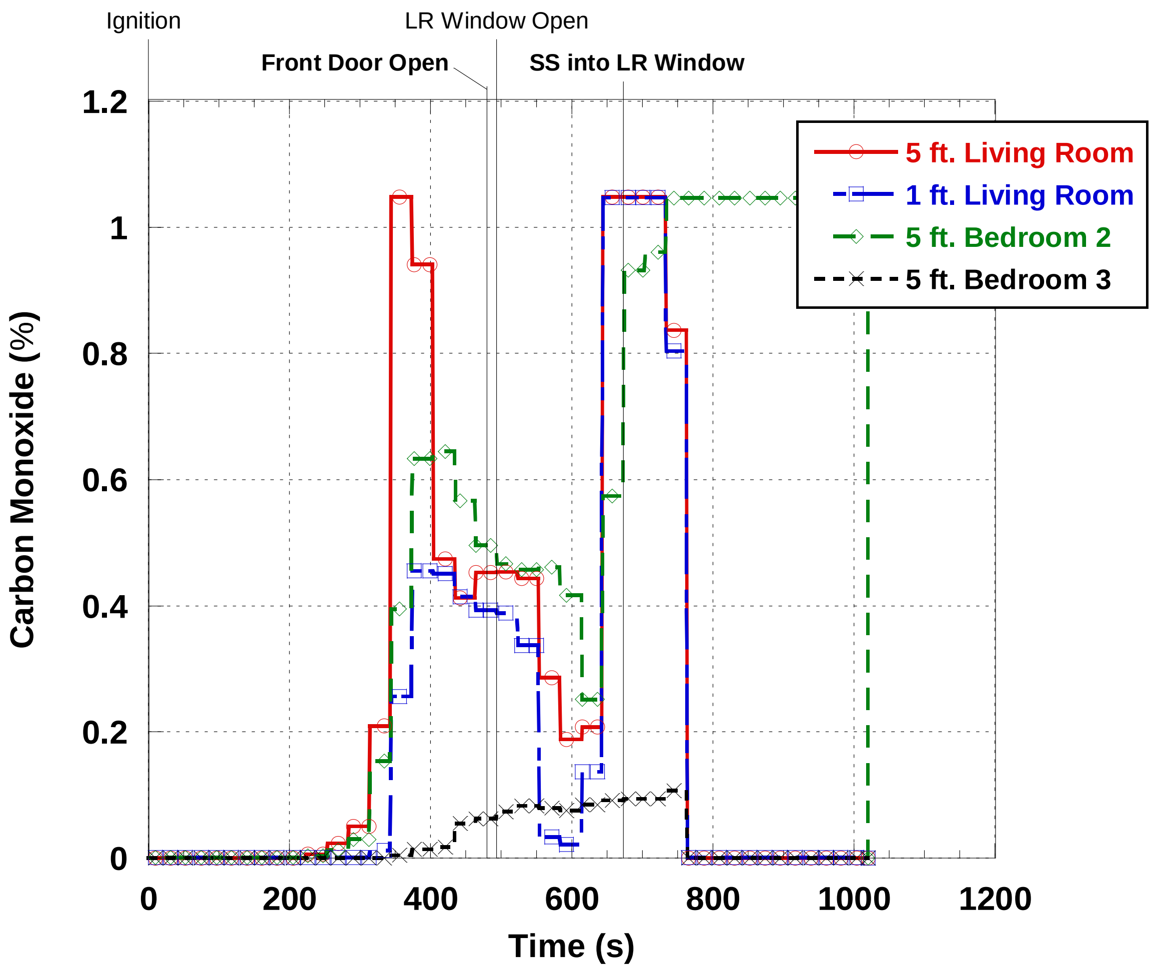


Figure 270. Experiment 12- CO Concentration

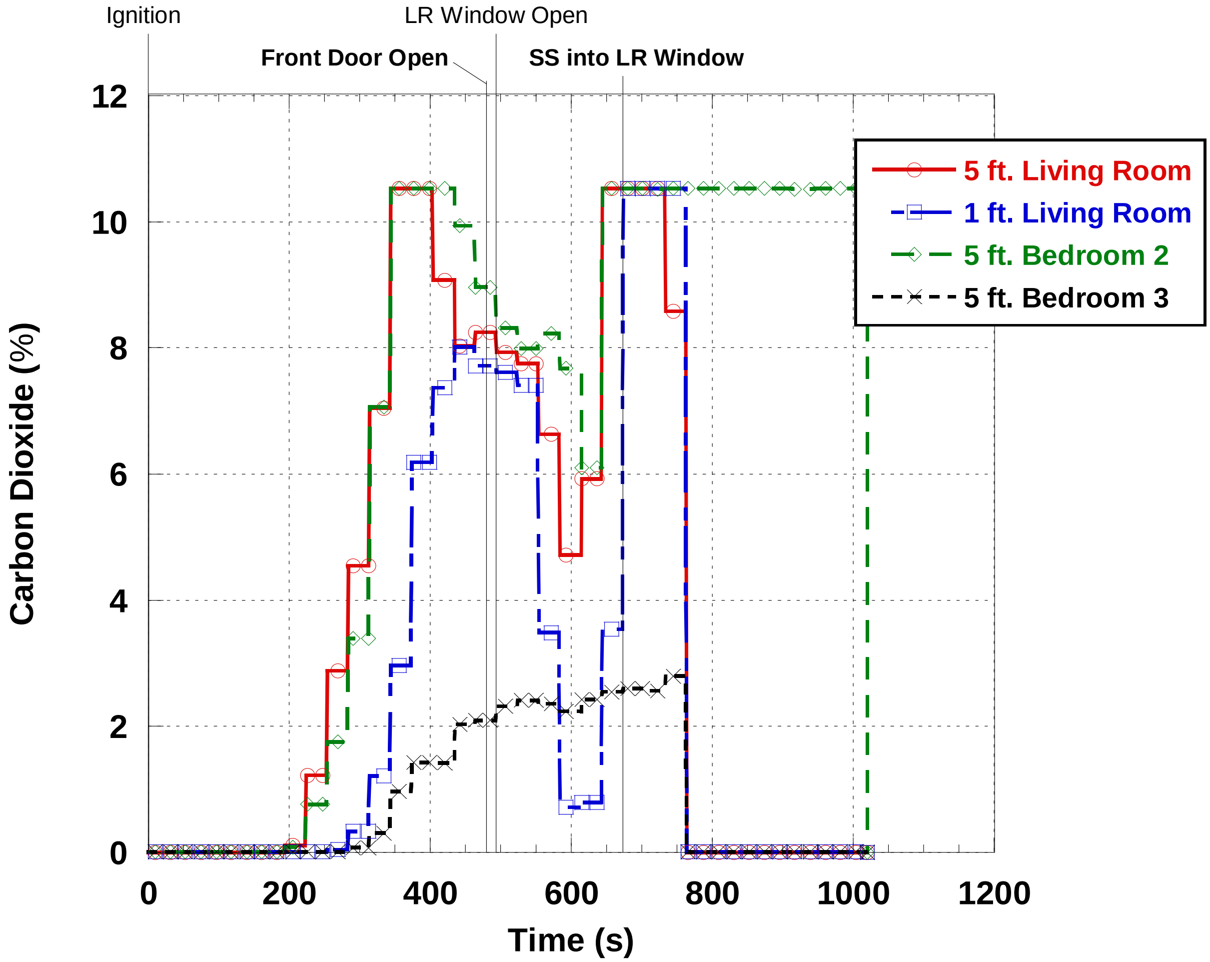


Figure 271. Experiment 12- CO_2 Concentration

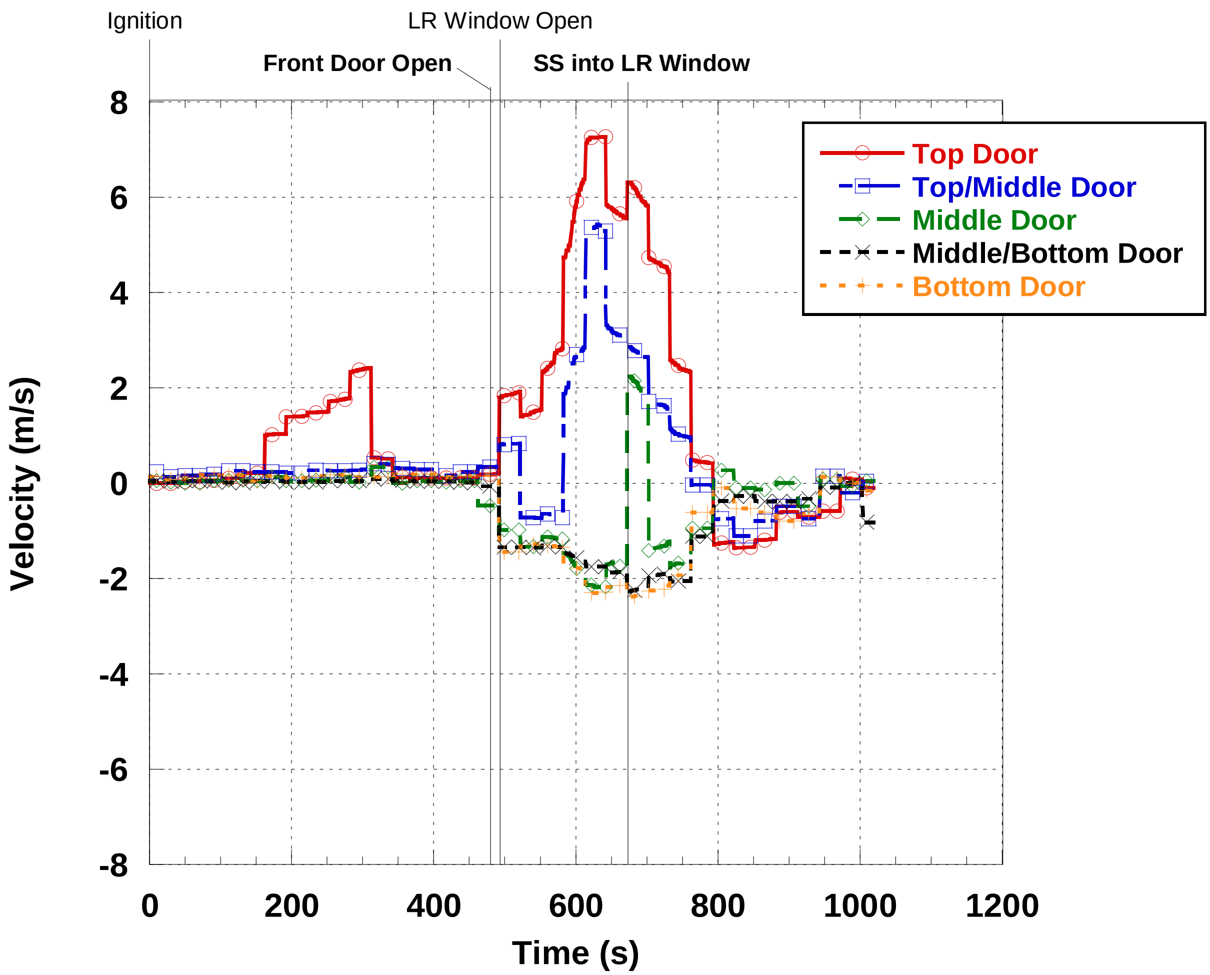


Figure 272. Experiment 12- Front Door Velocities

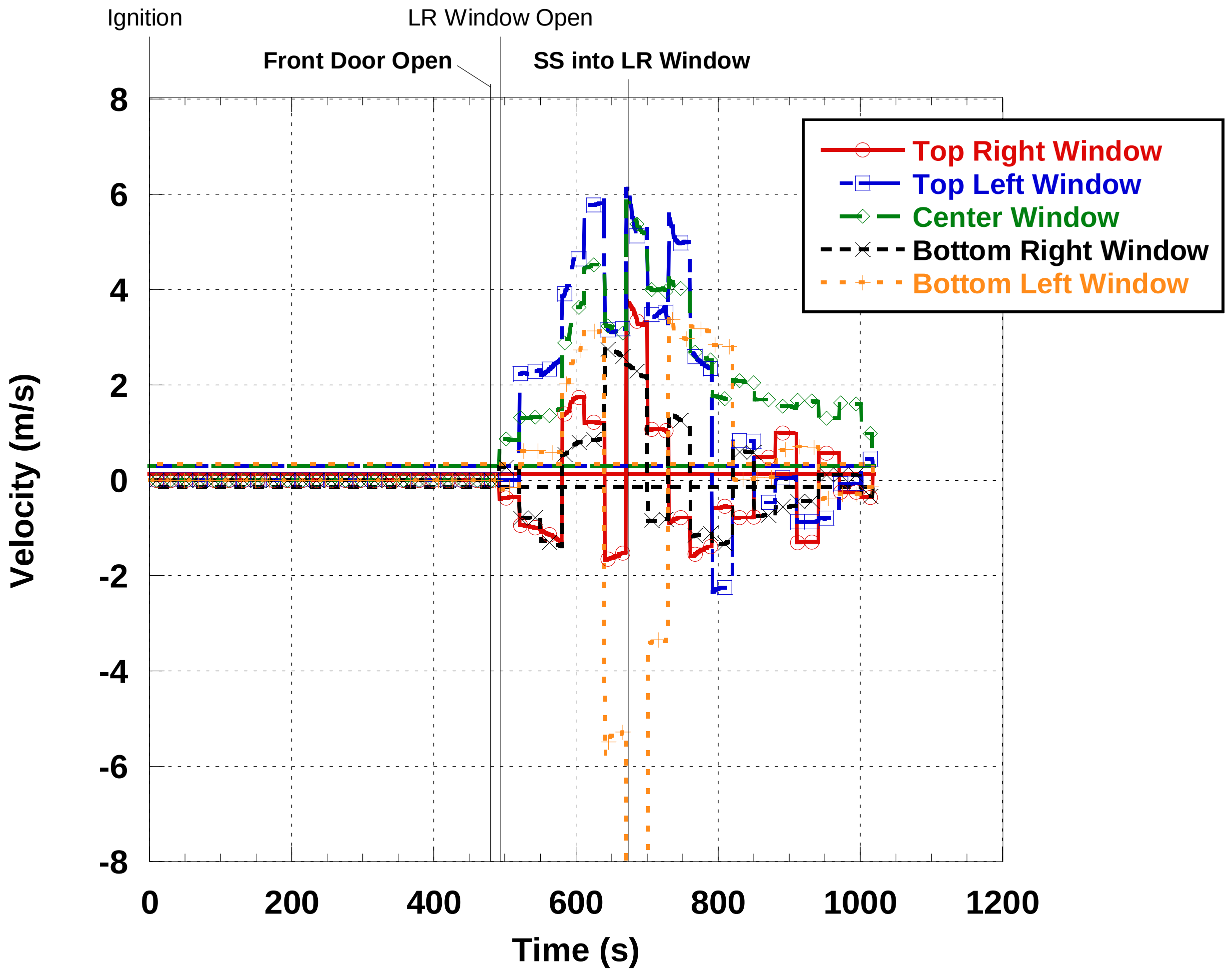


Figure 273. Experiment 12- Ventilation Window Velocities

8.6.7. Experiment 14

Experiment 14 was the final experiment conducted in the one-story house. This experiment was designed to examine the impact of ventilating with several openings. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 8 minutes after ignition at which time the front door was opened. Fifteen seconds after the front door was opened the living room window was opened. In fifteen second intervals the master bedroom window, bedroom 2 window and bedroom 3 window were opened (Table 23). The fire again was allowed to grow until 13:02 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a fog stream pattern. The experiment was terminated at 14:10 and was extinguished by the suppression crew. Figure 275 through Figure 282 show the front and rear of the house during the experiment.

Table 23. Experiment 14 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	8:00
Living Room Window Opened	8:15
Master Bedroom Window Opened	8:30
Bedroom 2 Window Opened	8:45
Bedroom 3 Window Opened	9:00
Fog Stream into Living Room Window	13:02-13:12
End of Experiment	14:10

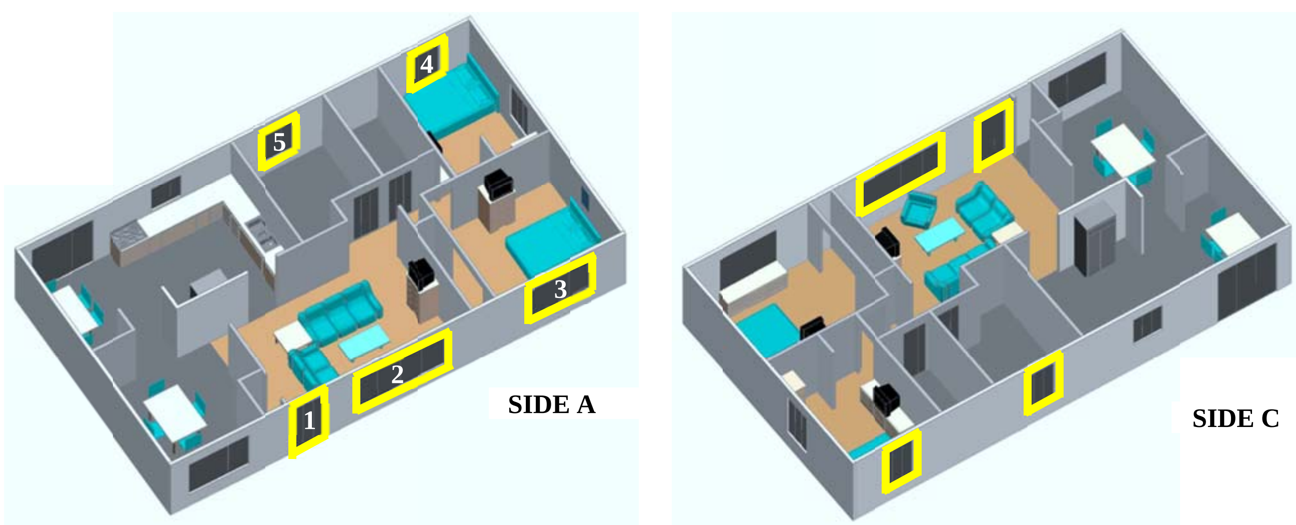


Figure 274. House graphic highlighting ventilation locations

Figure 275. Experiment 14 - 0:00

Figure 276. Experiment 14 - 0:00

Figure 277. Experiment 14 - 8:05

Figure 278. Experiment 14 - 8:20

Figure 279. Experiment 14 - 8:35

Figure 280. Experiment 14 - 10:00

Figure 281. Experiment 14 - 10:00

Figure 282. Experiment 14 – 13:05

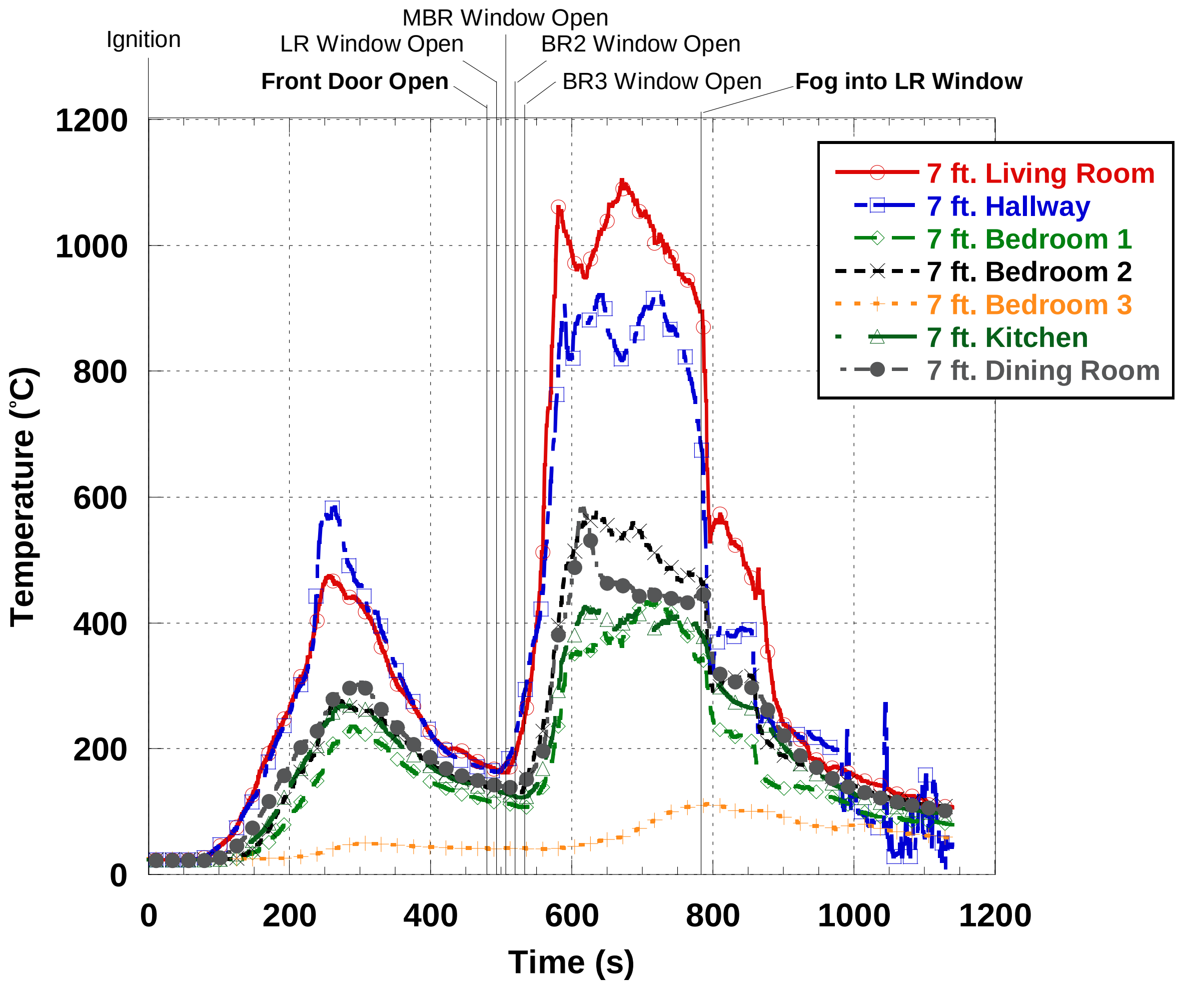


Figure 283. Experiment 14- 7ft. Temperatures

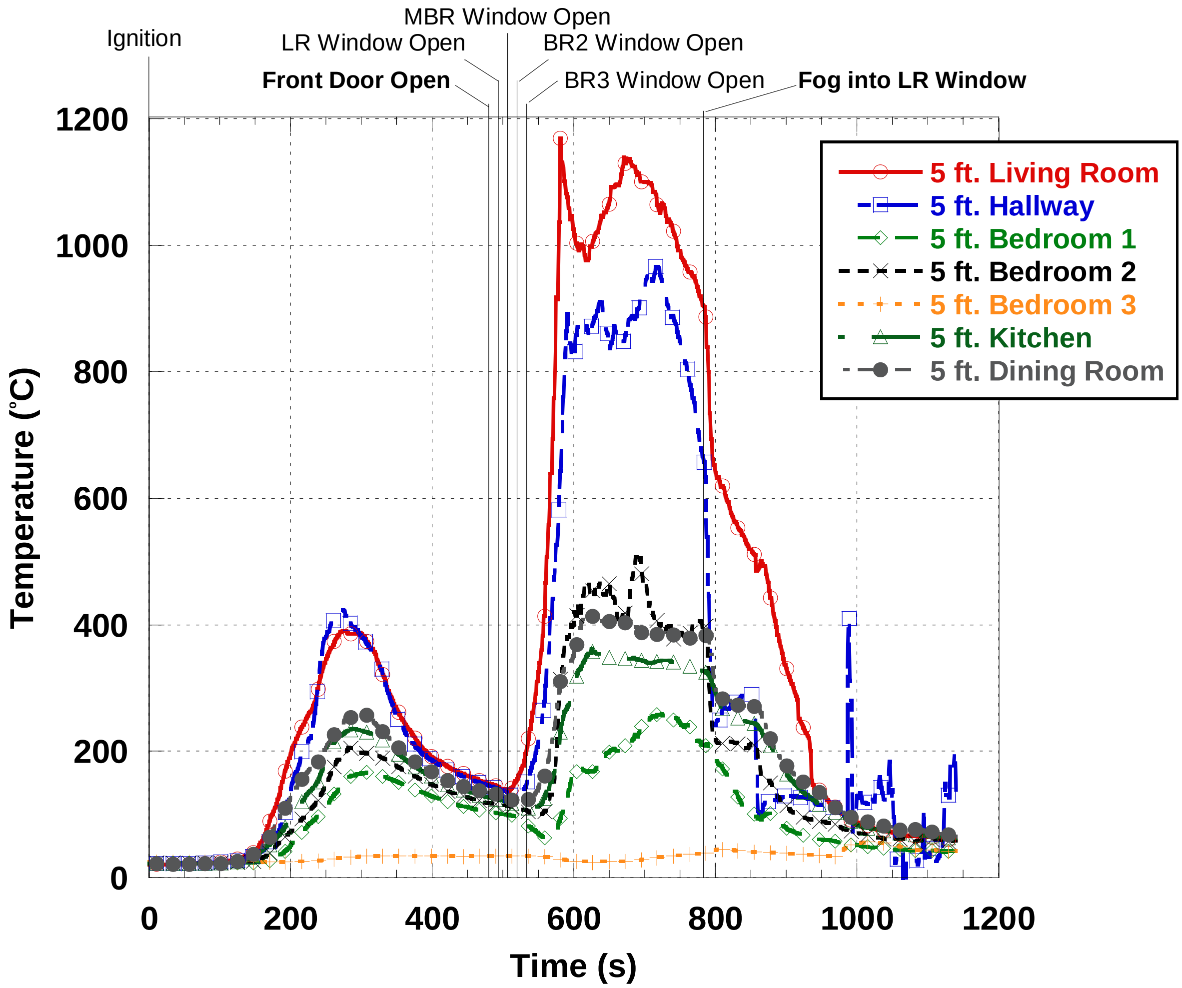


Figure 284. Experiment 14- 5ft. Temperatures

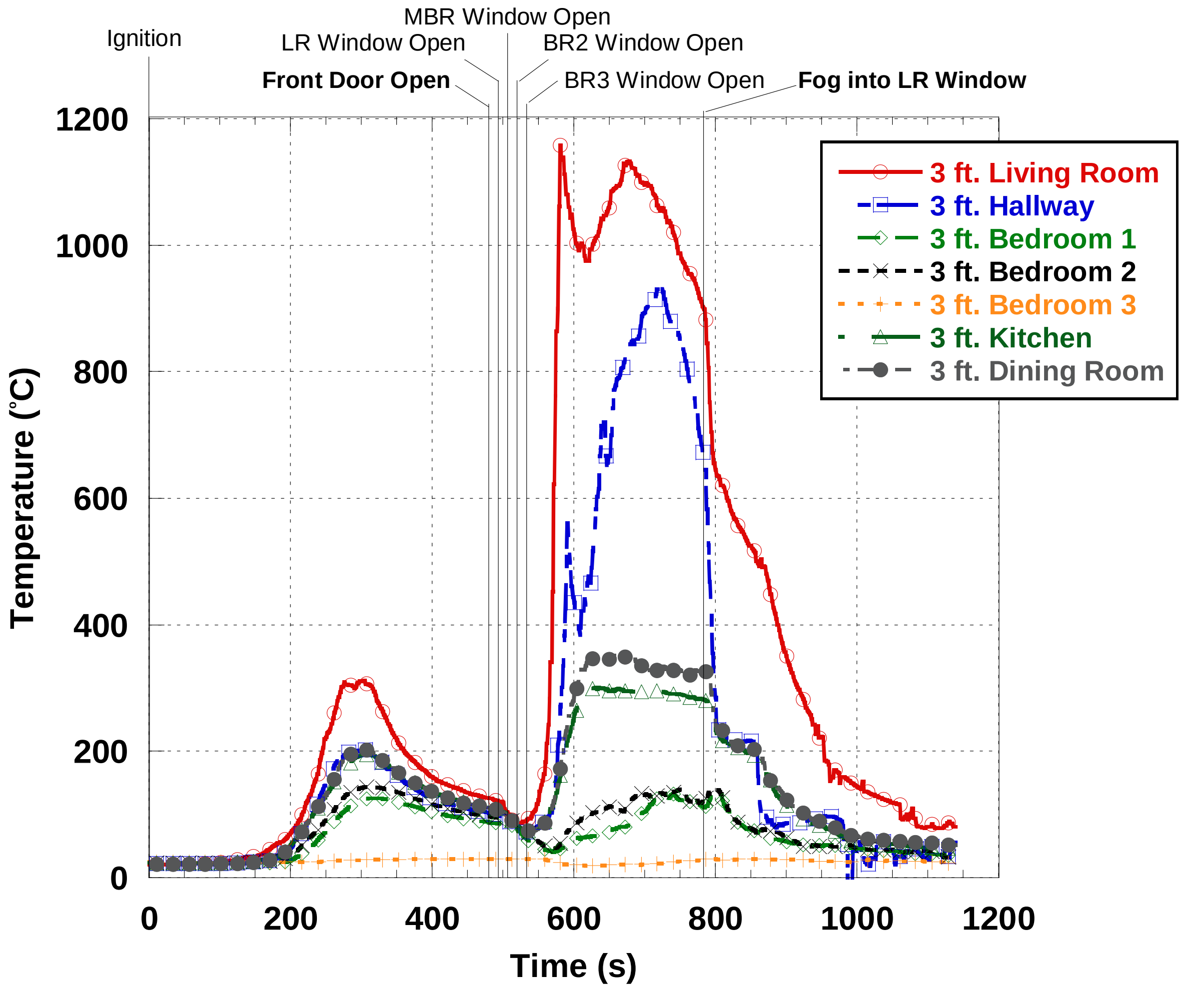


Figure 285. Experiment 14- 3ft. Temperatures

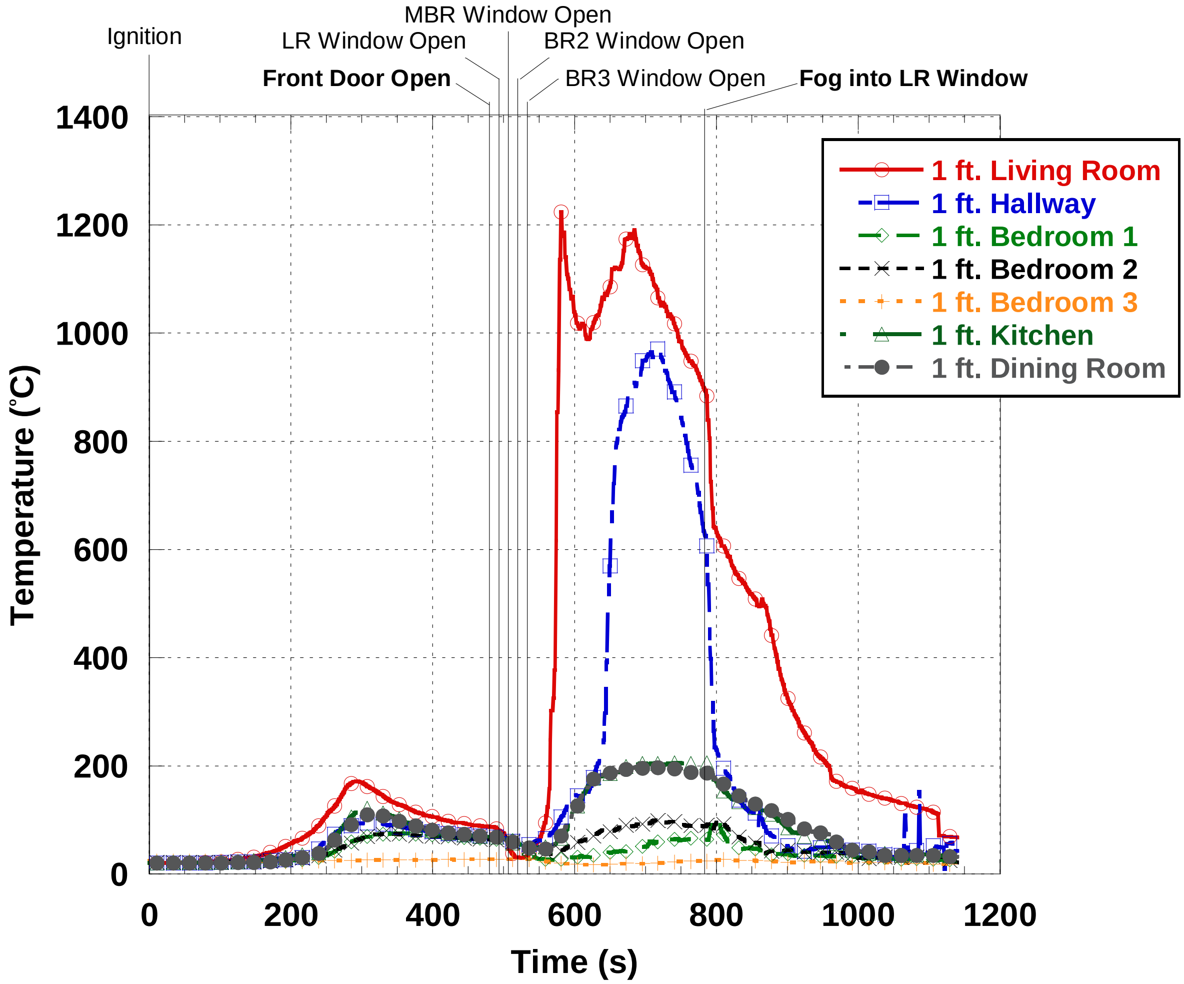


Figure 286. Experiment 14- 1ft. Temperatures

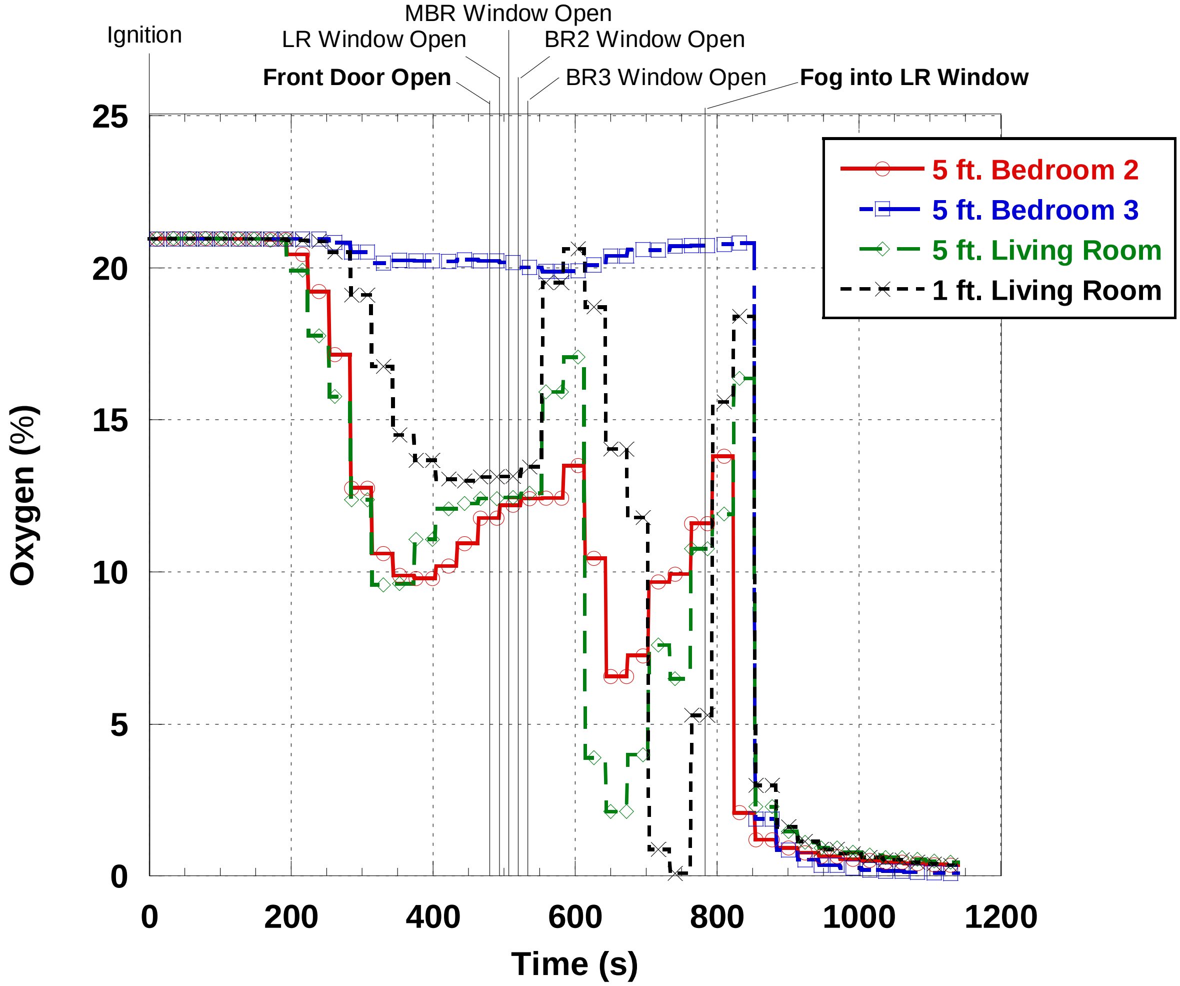


Figure 287. Experiment 14- Oxygen Concentration

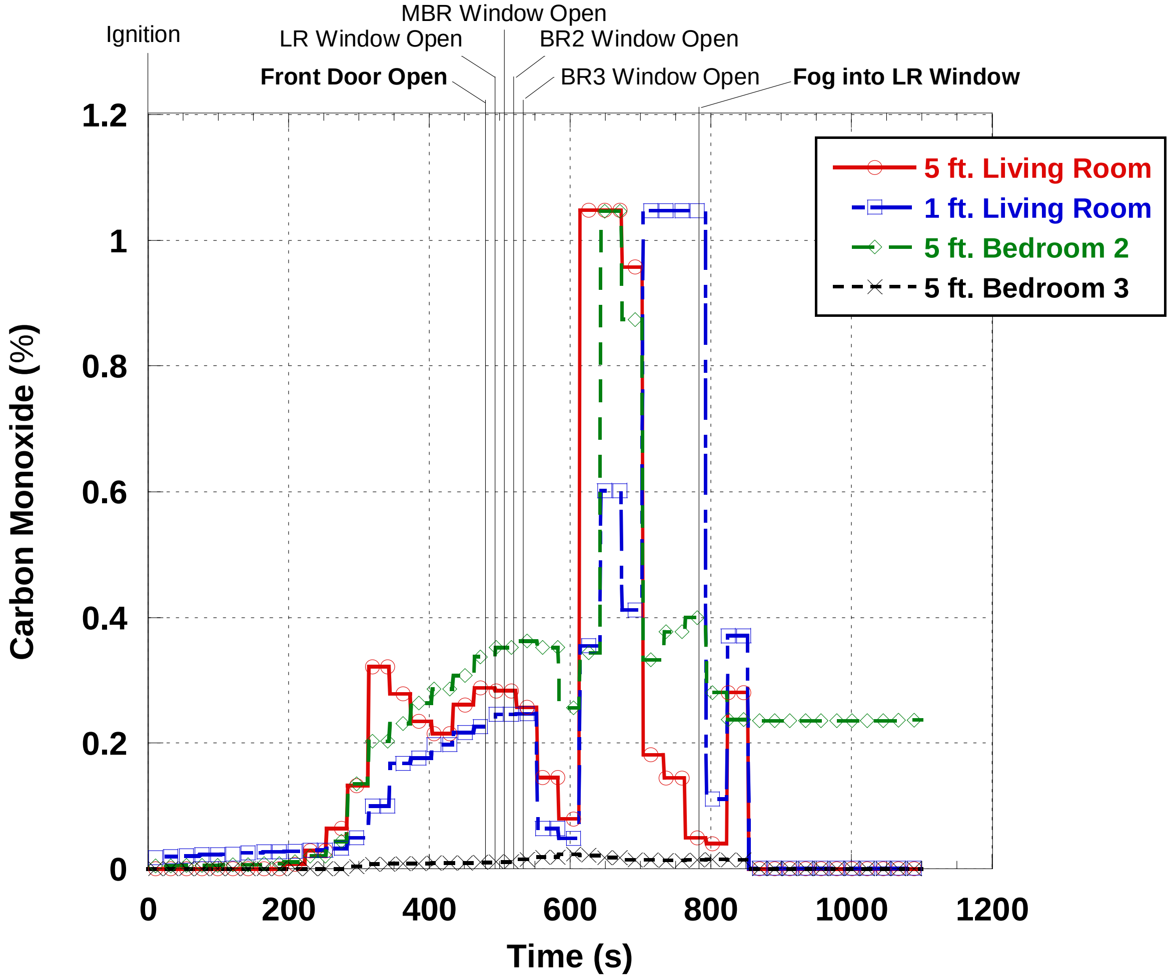


Figure 288. Experiment 14- CO Concentration

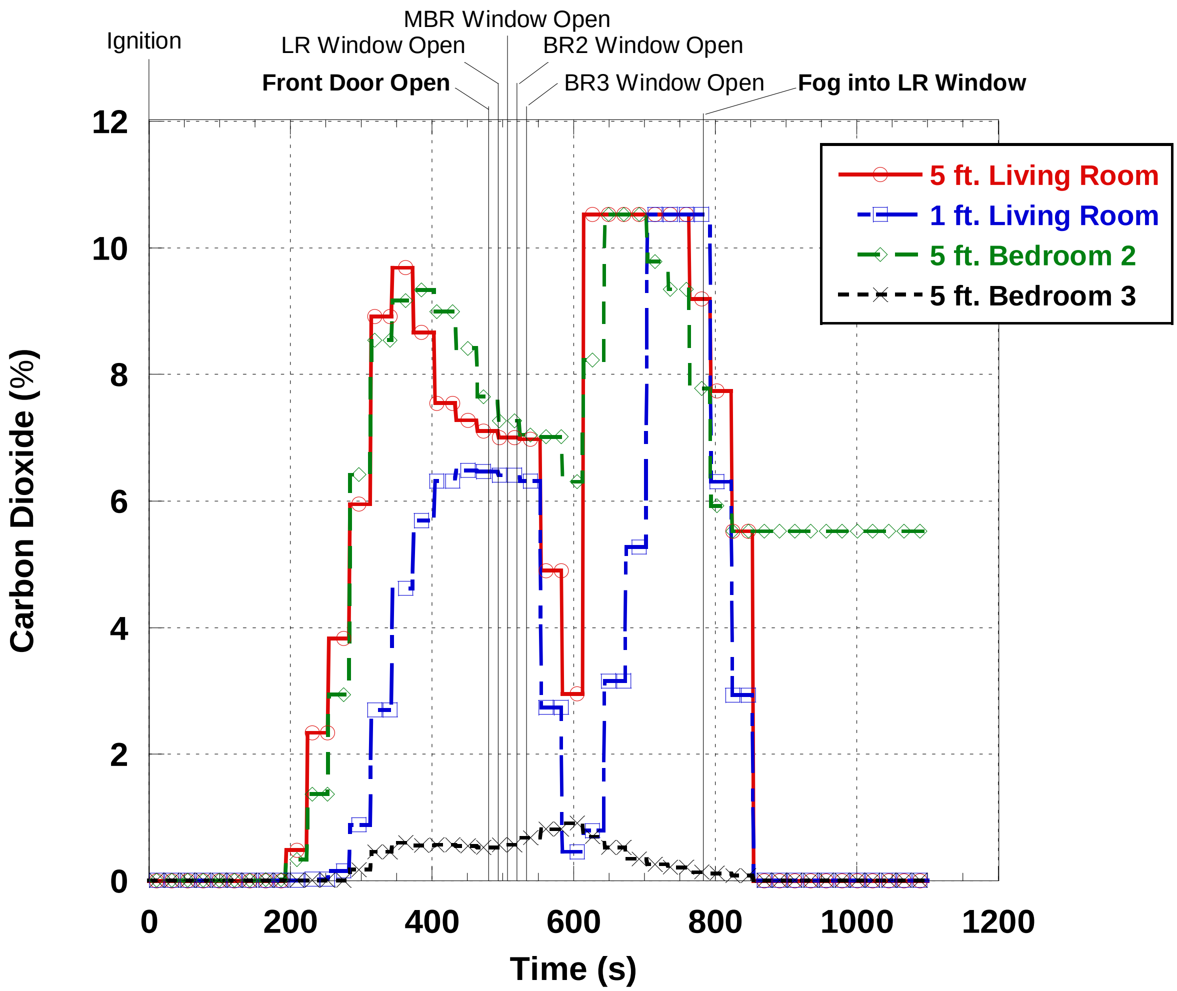


Figure 289. Experiment 14- CO_2 Concentration

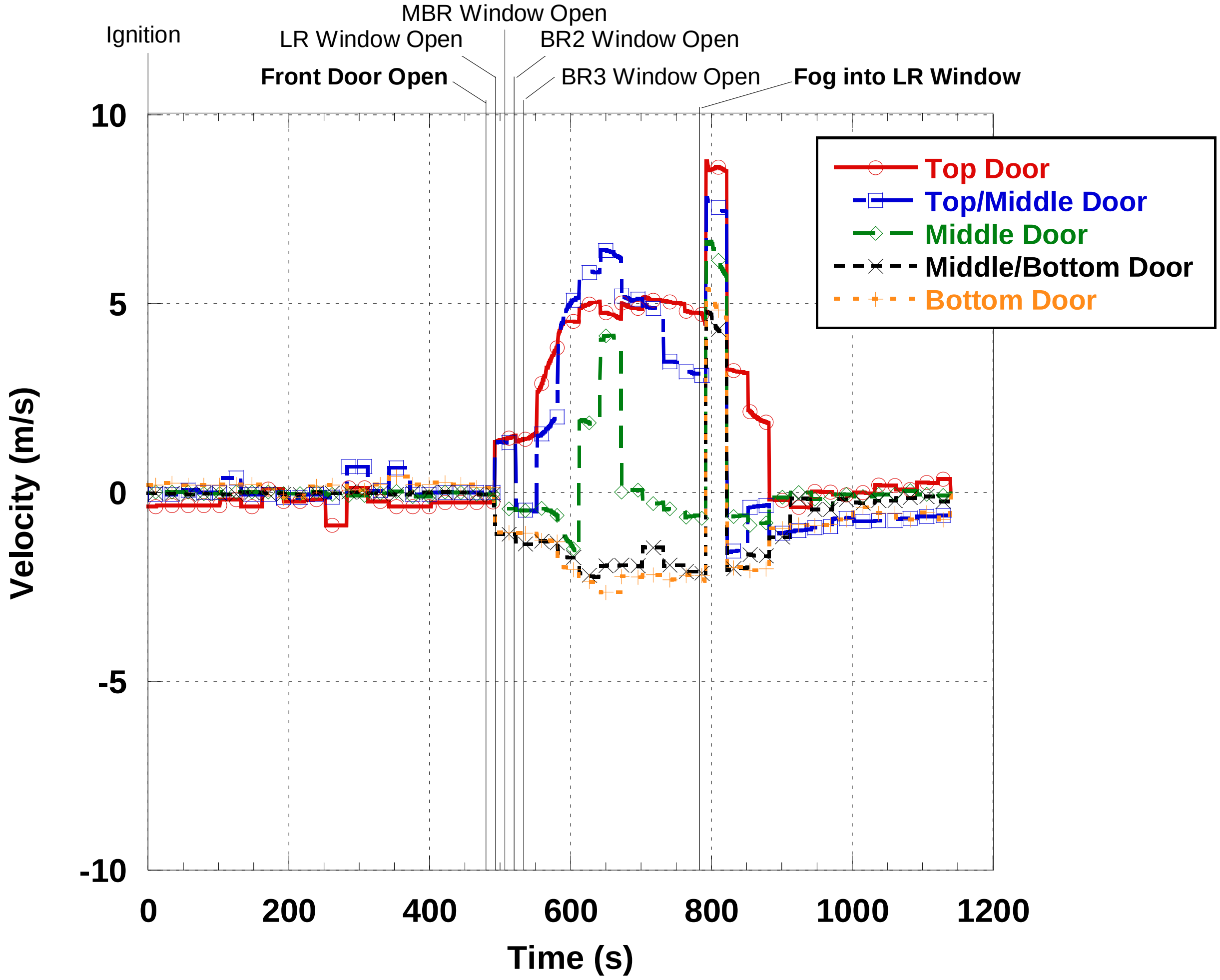


Figure 290. Experiment 14- Front Door Velocities

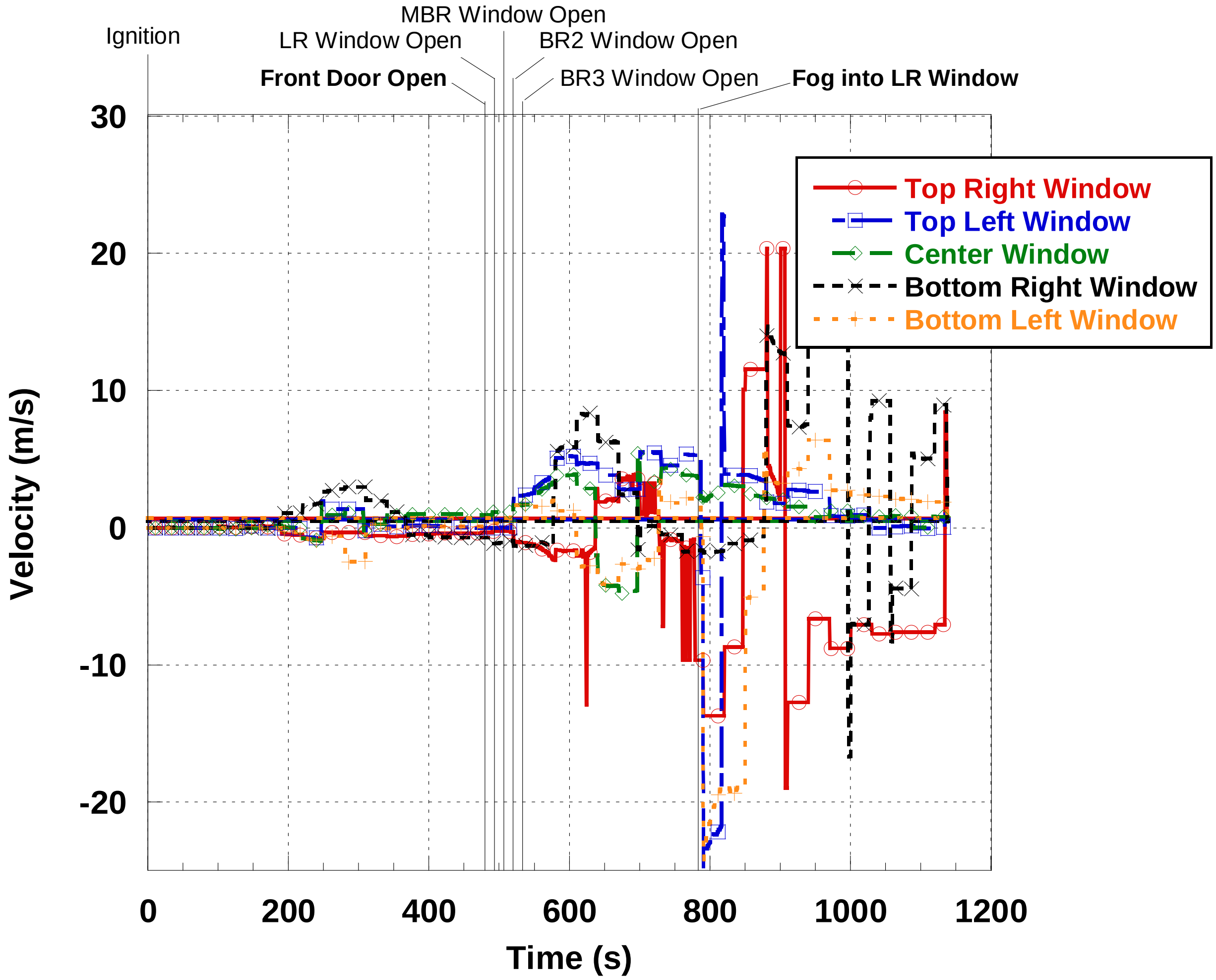


Figure 291. Experiment 14- Ventilation Window Velocities (Living Room Window)

8.7. Two-Story Experimental Results

Eight experiments were conducted in the two story structure (Table 24). Each experiments purpose will be described and a figure will show the fire and ventilation locations. The experimental timeline will show the time of ventilation and suppression changes. Data graphs are provided for temperatures throughout the structure at multiple elevations, gas concentrations at four locations and gas velocities at the opening(s) for each experiment. Each graph has the events labeled on the top with a vertical line indicating when they occurred.

Table 24. Two-Story Experimental Outline

Experiment #	Structure	Location of Ignition	Ventilation Parameters
2	2-Story	Family Room	Front Door
4	2-Story	Family Room	Front Door + Family Room Window (Window near seat of the fire)
6	2-Story	Family Room	Family Room Window Only
8	2-Story	Family Room	Front Door + Bedroom 3 Window (Window remote from fire)
10	2-Story	Family Room	Front Door + Family Room Window (Repeat Exp. 4)
11	2-Story	Family Room	Front Door + Family Room Window (Repeat Exp. 4)
13	2-Story	Family Room	Front Door + Upper Family Room Window
15	2-Story	Family Room	Front Door + 4 Windows (LR, Den, FR1, FR2)

8.7.1. Experiment 2

Experiment 2 was conducted in the two-story house. This experiment was designed to simulate a crew making entry by opening the front door. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the front door was opened (Table 25). The fire again was allowed to grow until 16:05 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 18:00 and was extinguished by the suppression crew. Figure 293 through Figure 298 shows the front of the house during the experiment.

Table 25. Experiment 2 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	10:00
Straight Stream into Front Door	16:05-16:15
End of Experiment	18:00

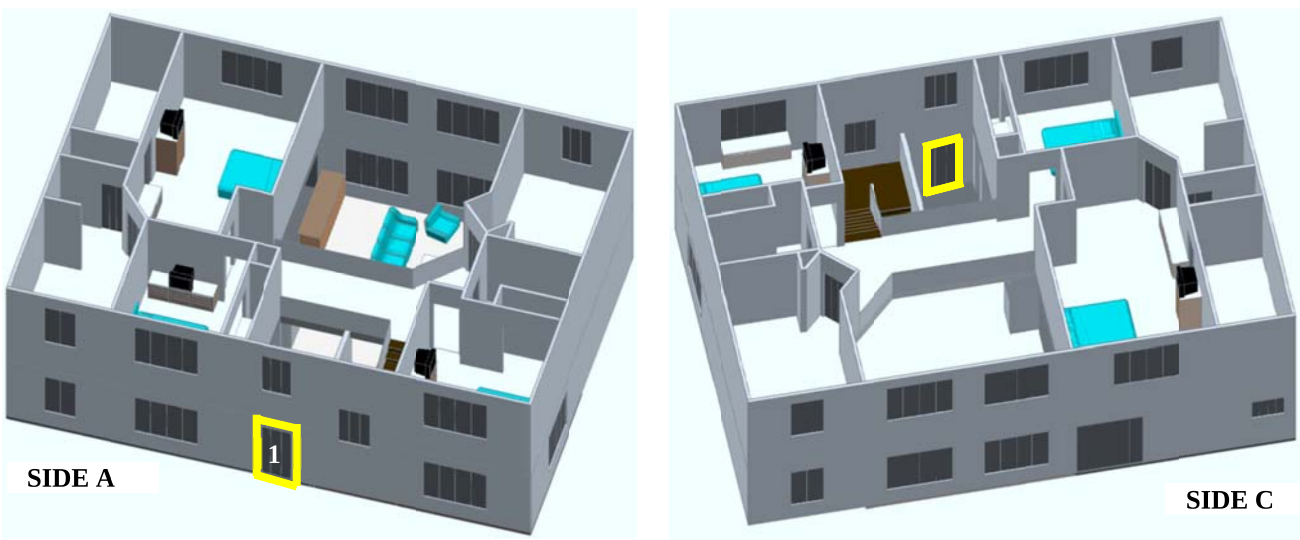


Figure 292. House graphic highlighting ventilation location


Figure 293. Experiment 2 - 0:00


Figure 294. Experiment 2 - 5:00


Figure 295. Experiment 2 - 10:05


Figure 296. Experiment 2 - 13:00


Figure 297. Experiment 2 - 16:10


Figure 298. Experiment 2 - 17:10

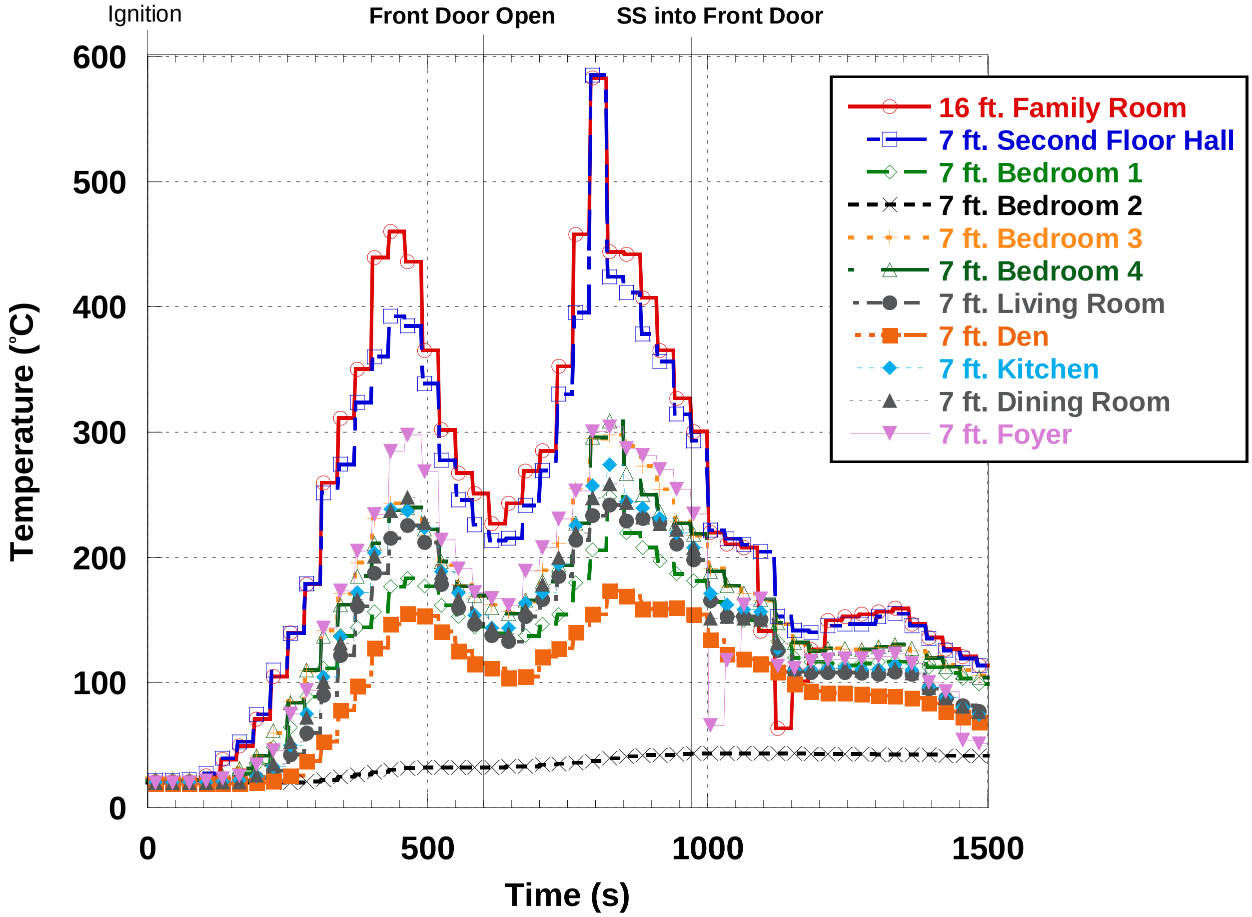


Figure 299. Experiment 2- 7ft. Temperatures

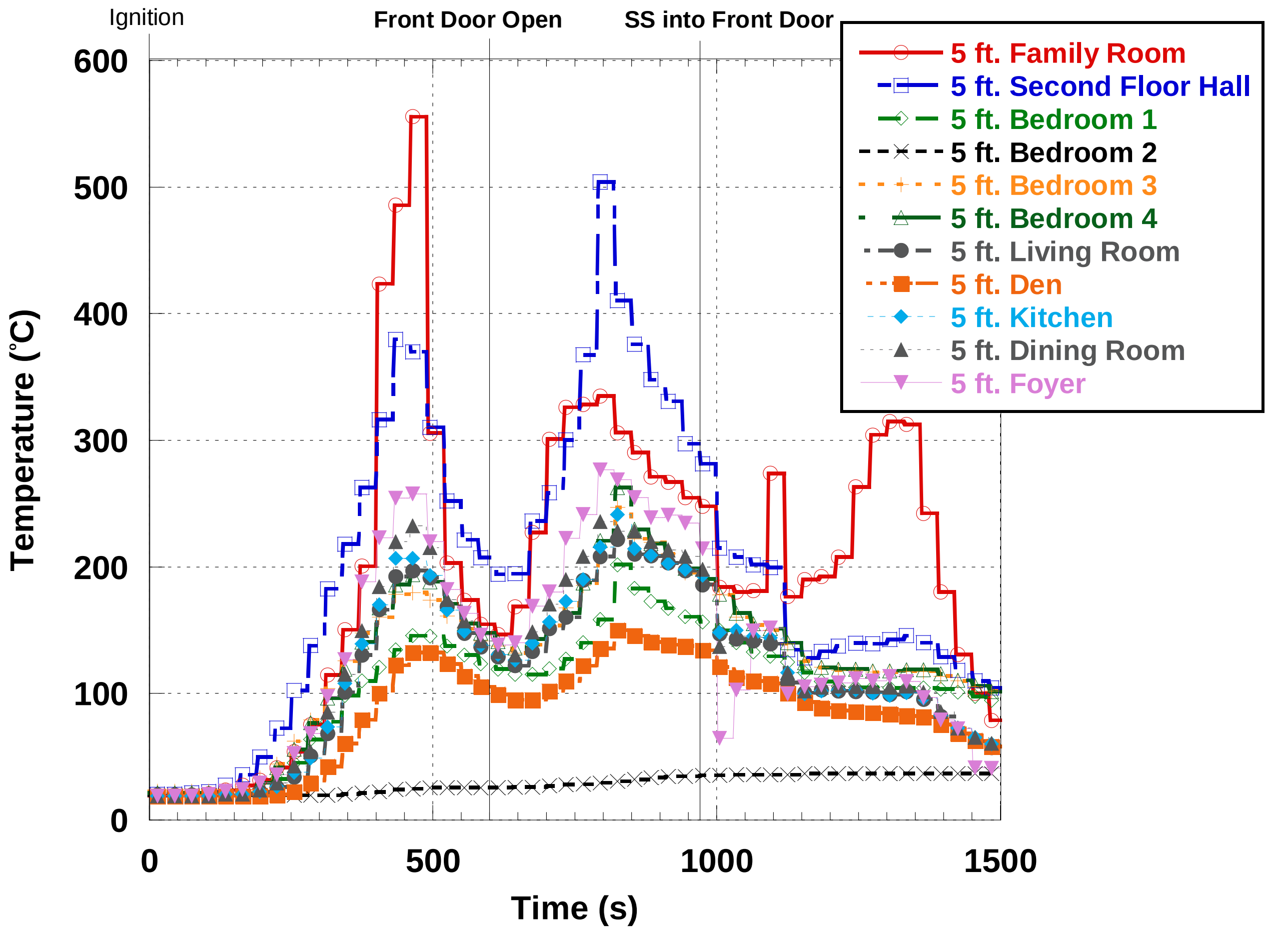


Figure 300. Experiment 2- 5ft. Temperatures

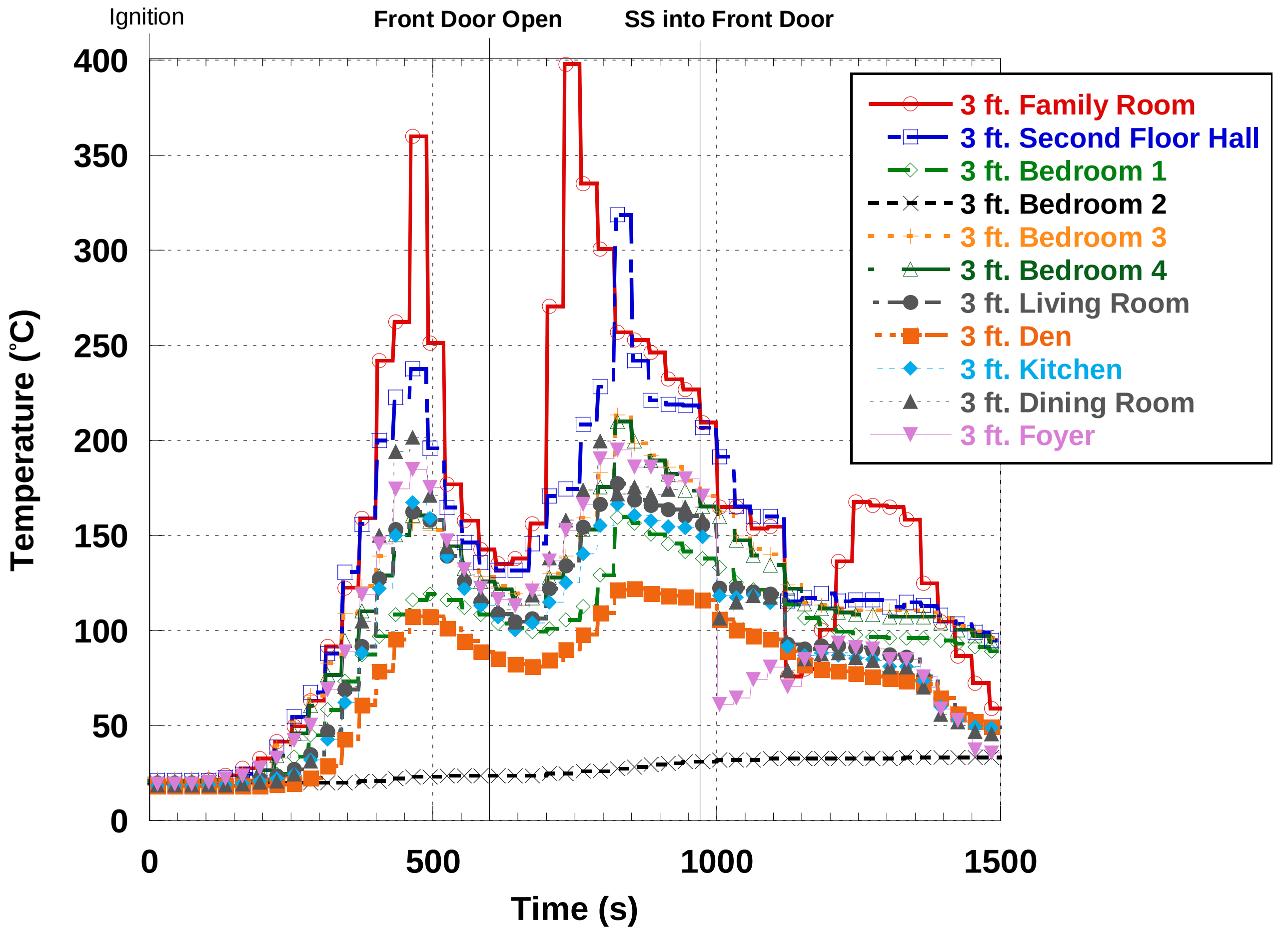


Figure 301. Experiment 2- 3ft. Temperatures

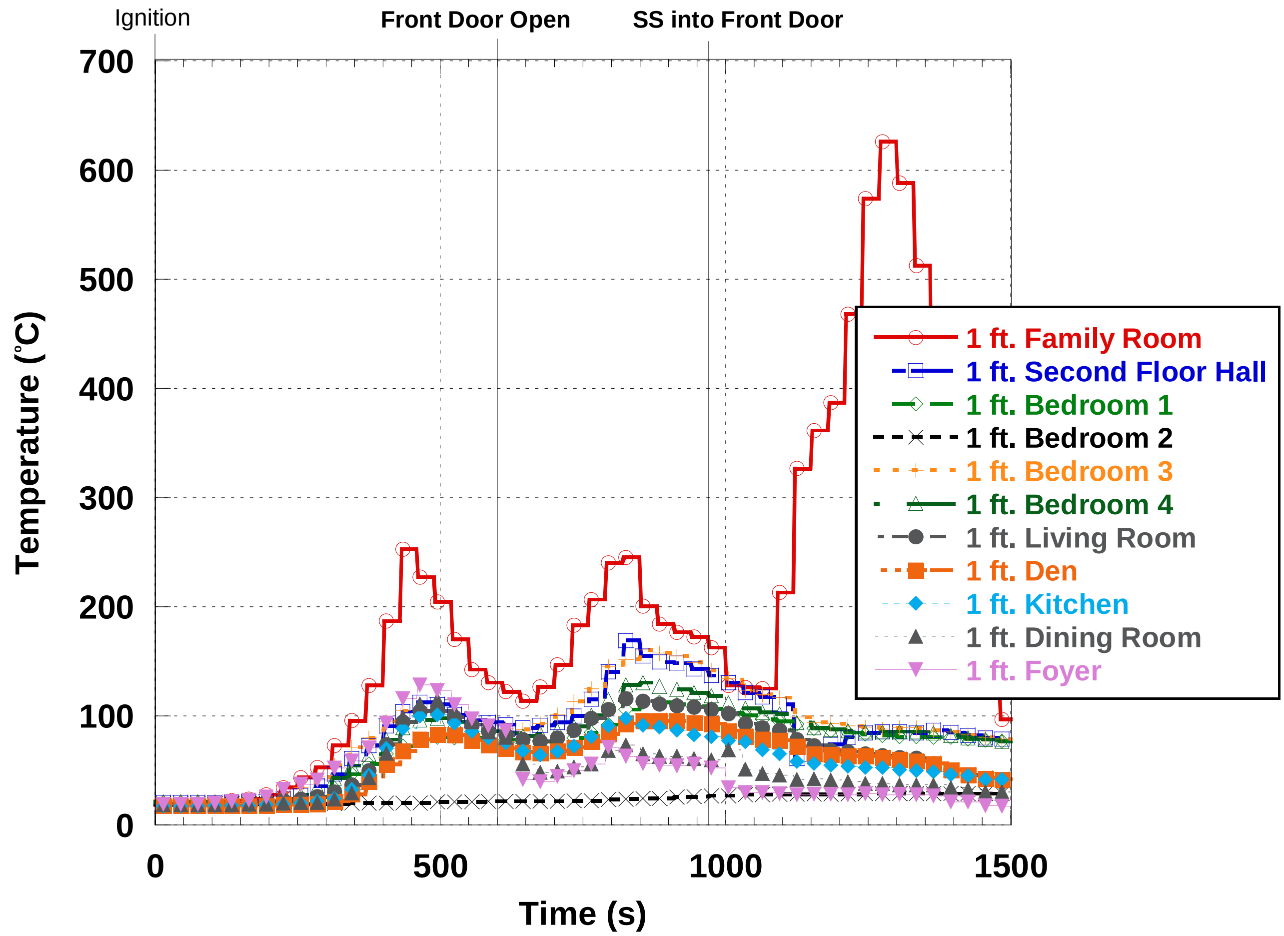


Figure 302. Experiment 2- 1ft. Temperatures

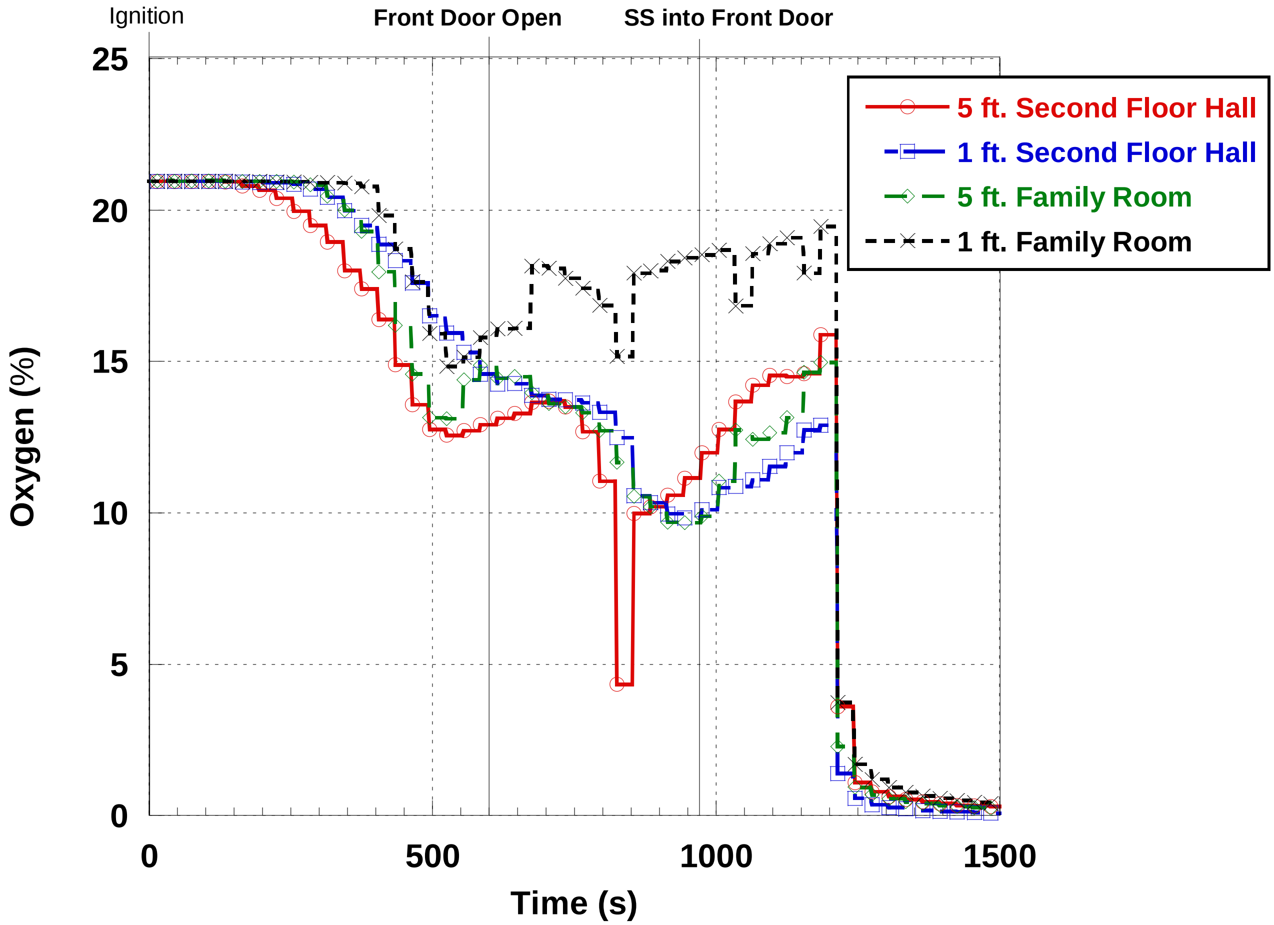


Figure 303. Experiment 2- Oxygen Concentration

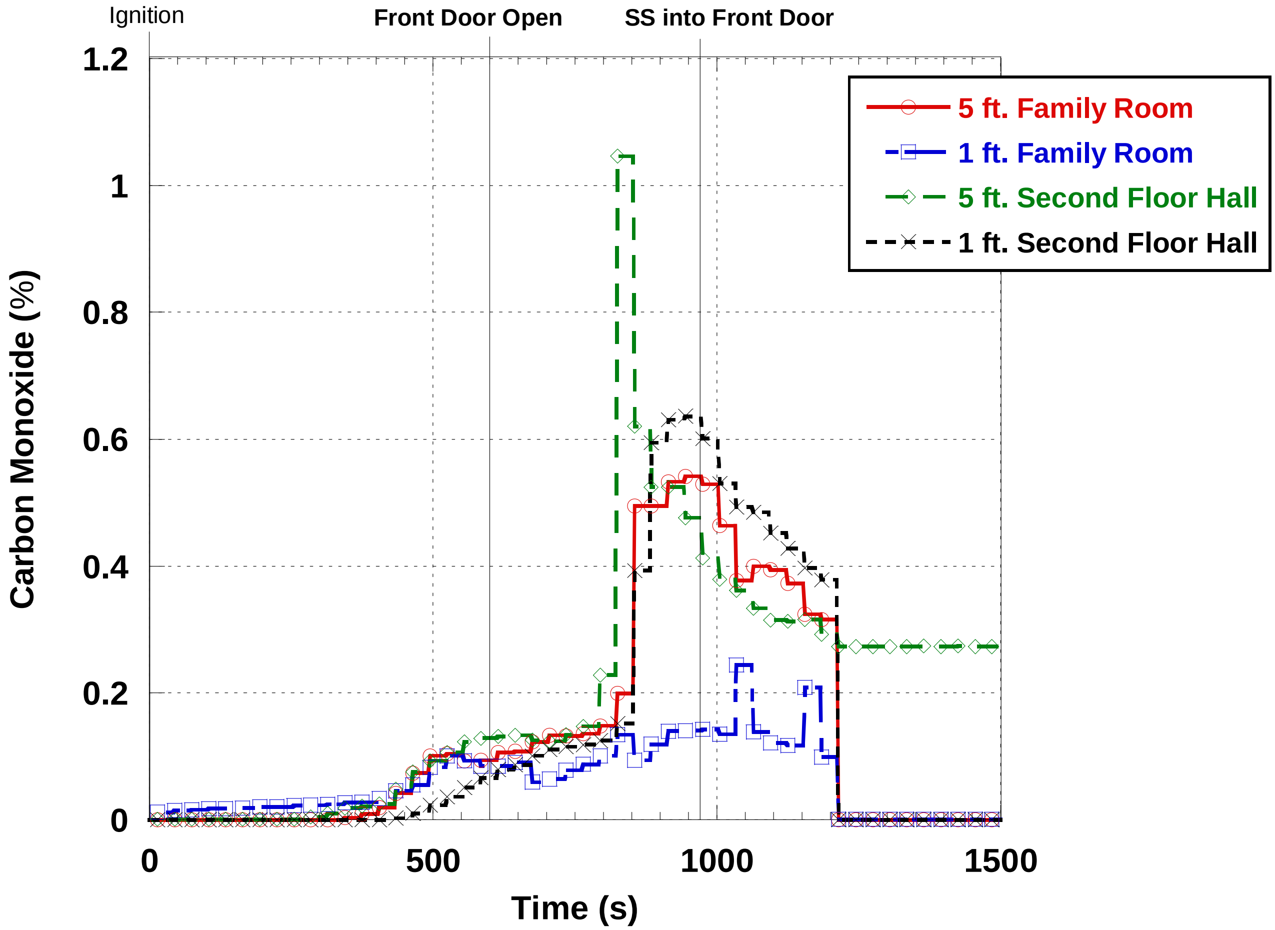


Figure 304. Experiment 2 - CO Concentration

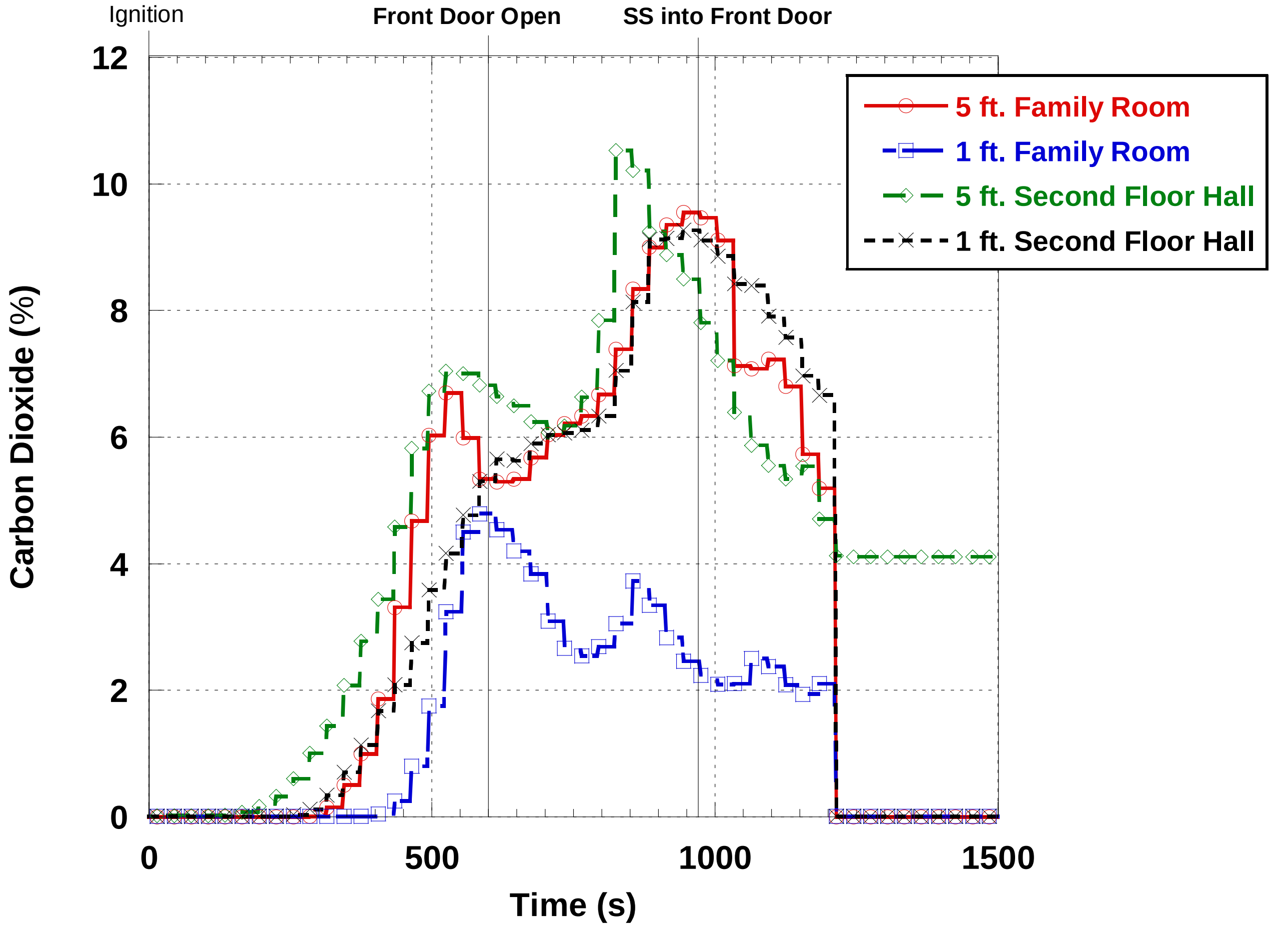


Figure 305. Experiment 2 - CO_2 Concentration

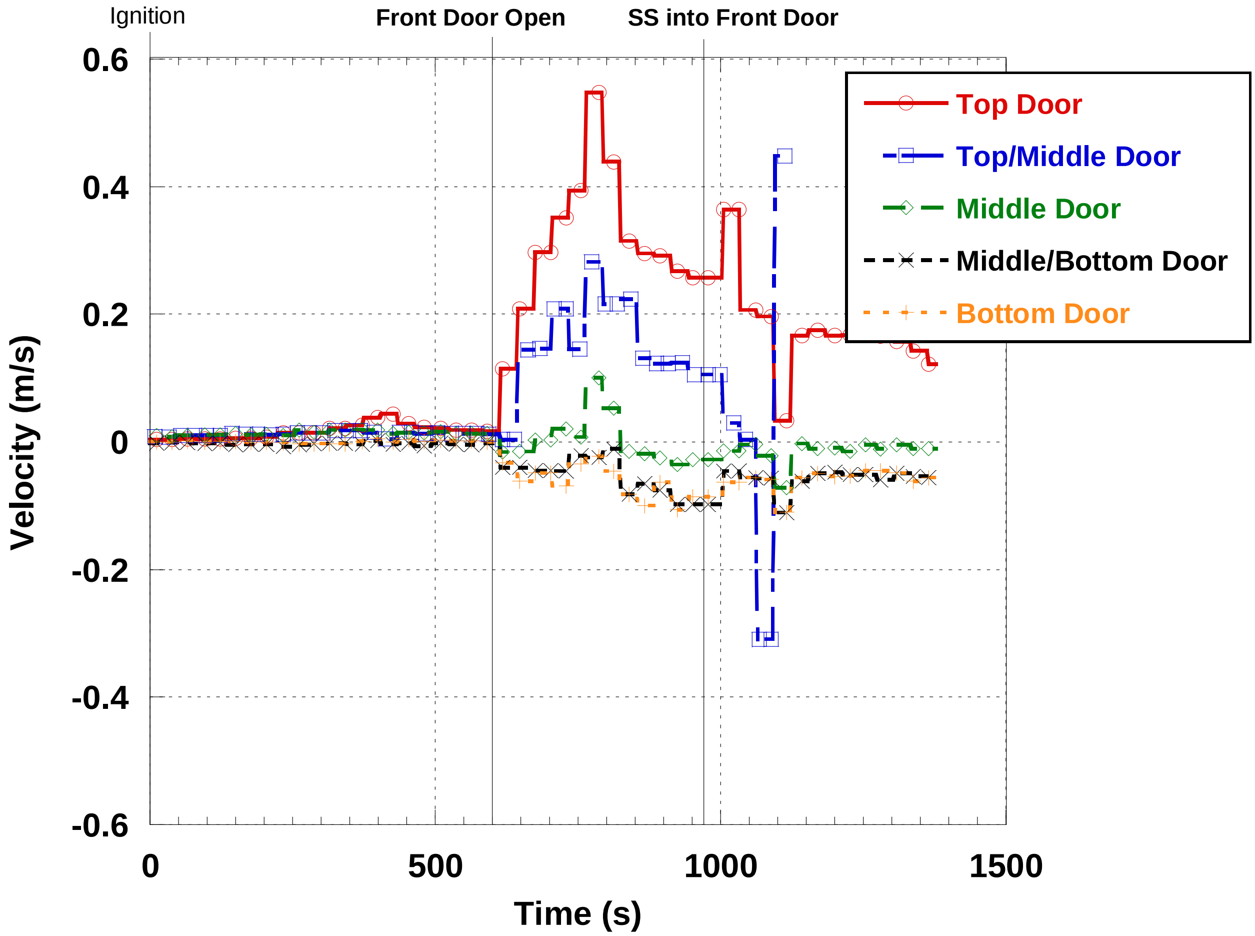


Figure 306. Experiment 2 - Front Door Velocites

8.7.2. Experiment 4

Experiment 4 was conducted in the two-story house. This experiment was designed to simulate a crew making entry through the front door and having a ventilation opening made shortly after near the seat of the fire. Ignition took place in the living room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the front door was opened. Fifteen seconds later the first floor family room window was opened (Table 26). The fire again was allowed to grow until 17:31 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 18:30 and was extinguished by the suppression crew. Figure 308 through Figure 315 show the front and rear of the house during the experiment.

Table 26. Experiment 4 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	10:00
Family Room Window Open	10:15
Straight Stream into Family Room Window	17:31-17:41
End of Experiment	18:30

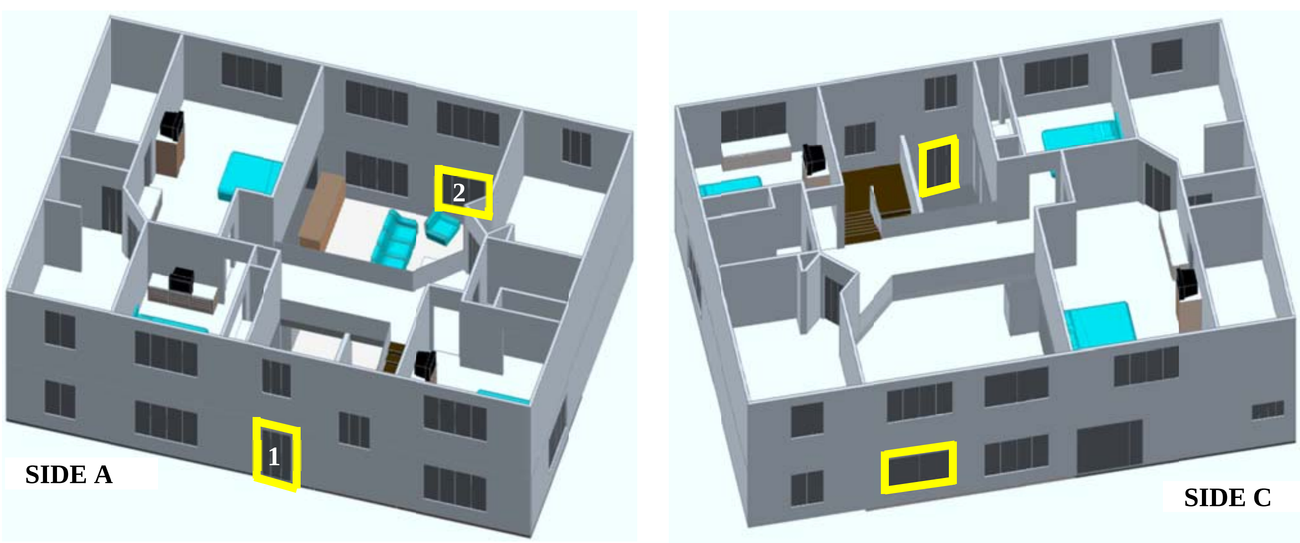


Figure 307. House graphic highlighting ventilation locations

Figure 308. Experiment 4 - 0:00

Figure 309. Experiment 4 - 0:00

Figure 310. Experiment 4 - 5:00

Figure 311. Experiment 4 - 10:05

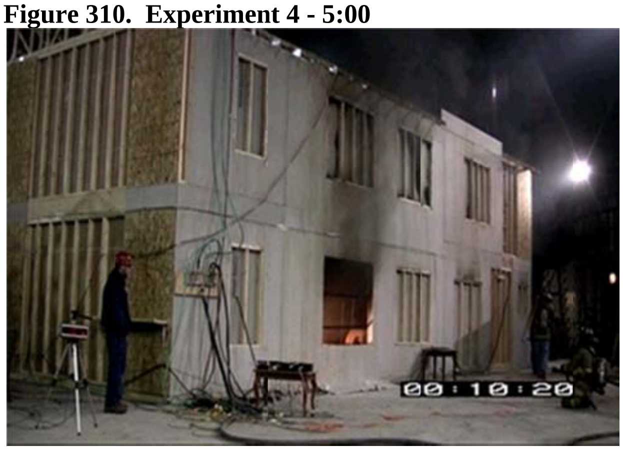


Figure 312. Experiment 4 - 10:20

Figure 313. Experiment 4 - 15:00

Figure 314. Experiment 4 - 17:05

Figure 315. Experiment 4 - 17:35

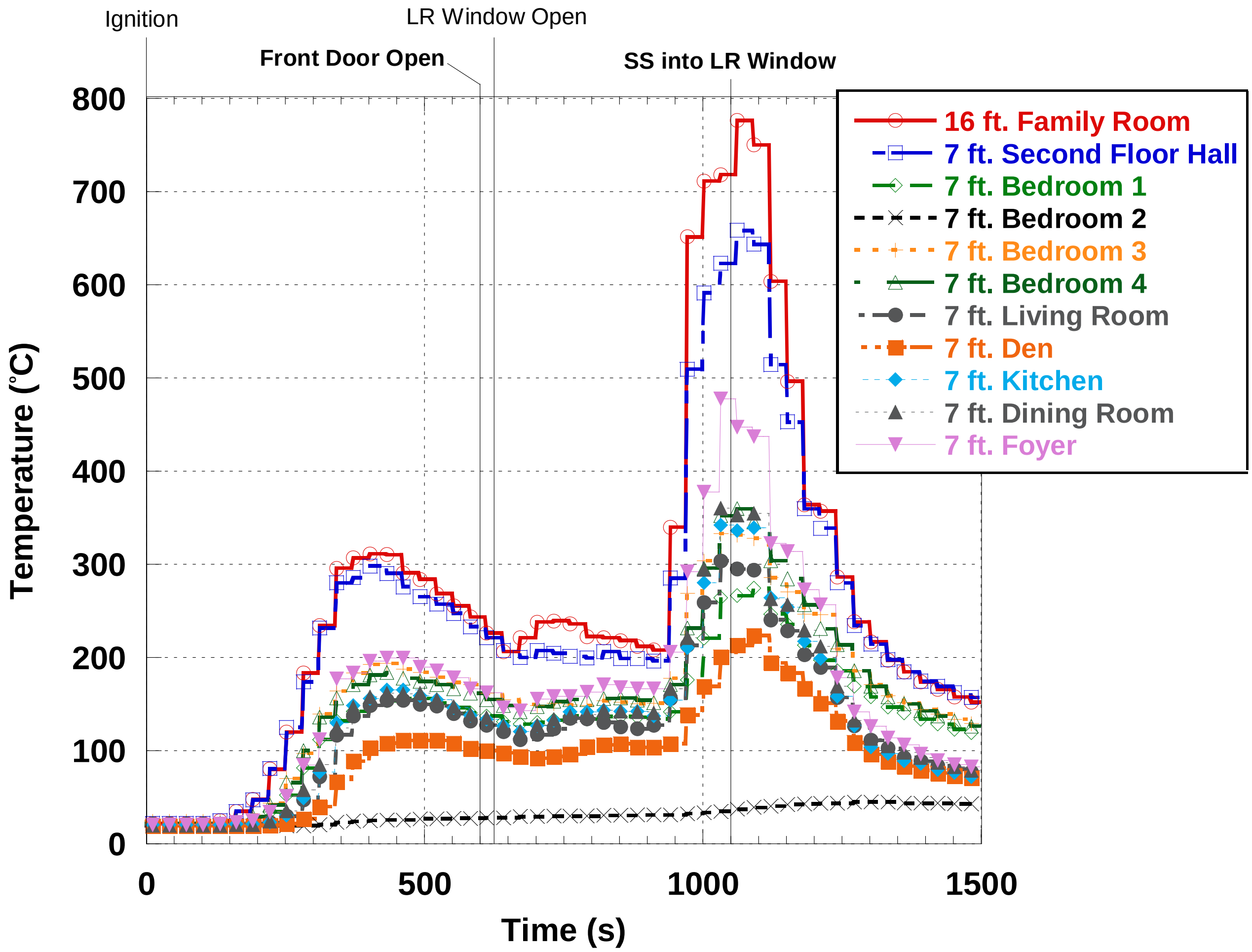


Figure 316. Experiment 4- 7ft. Temperatures

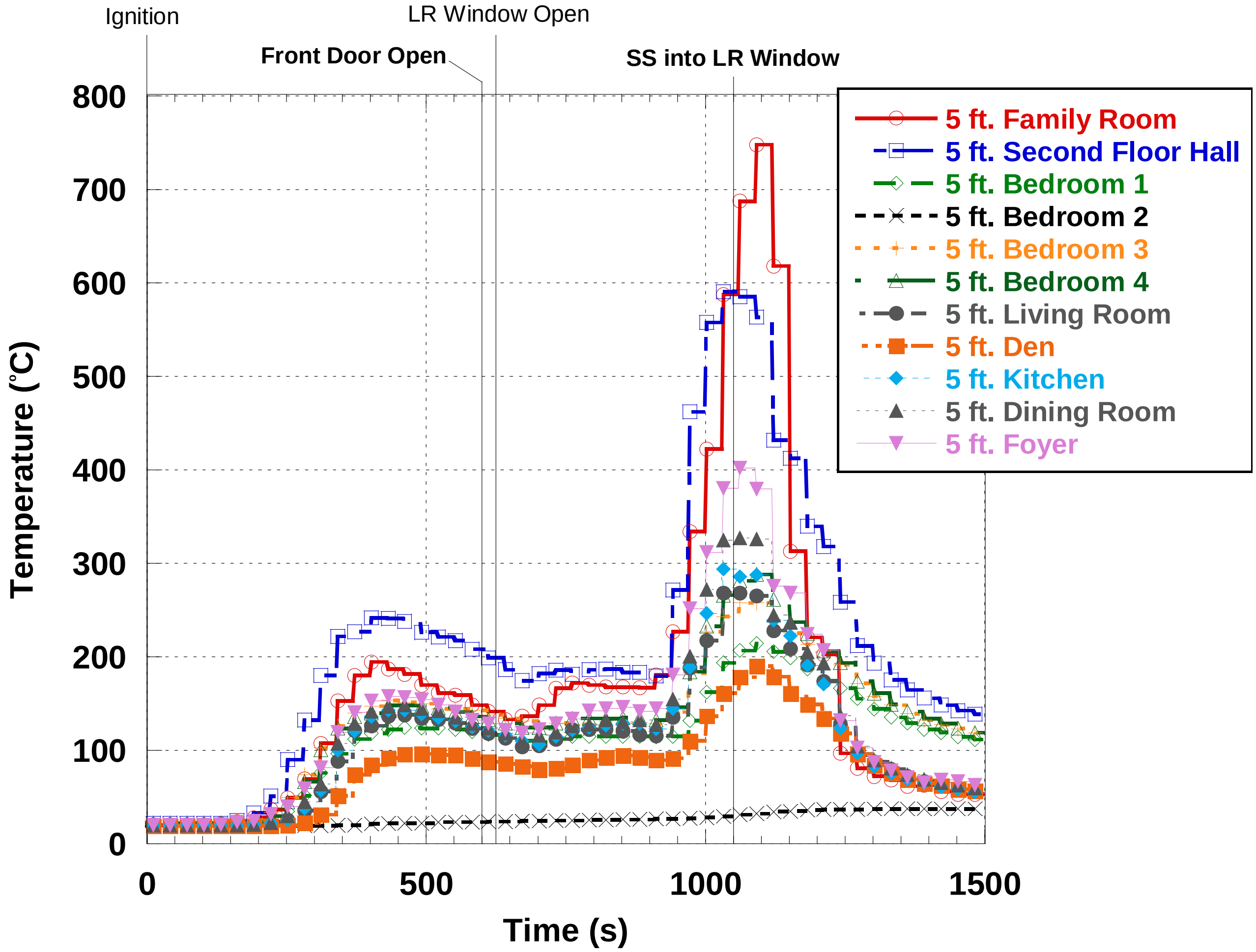


Figure 317. Experiment 4- 5ft. Temperatures

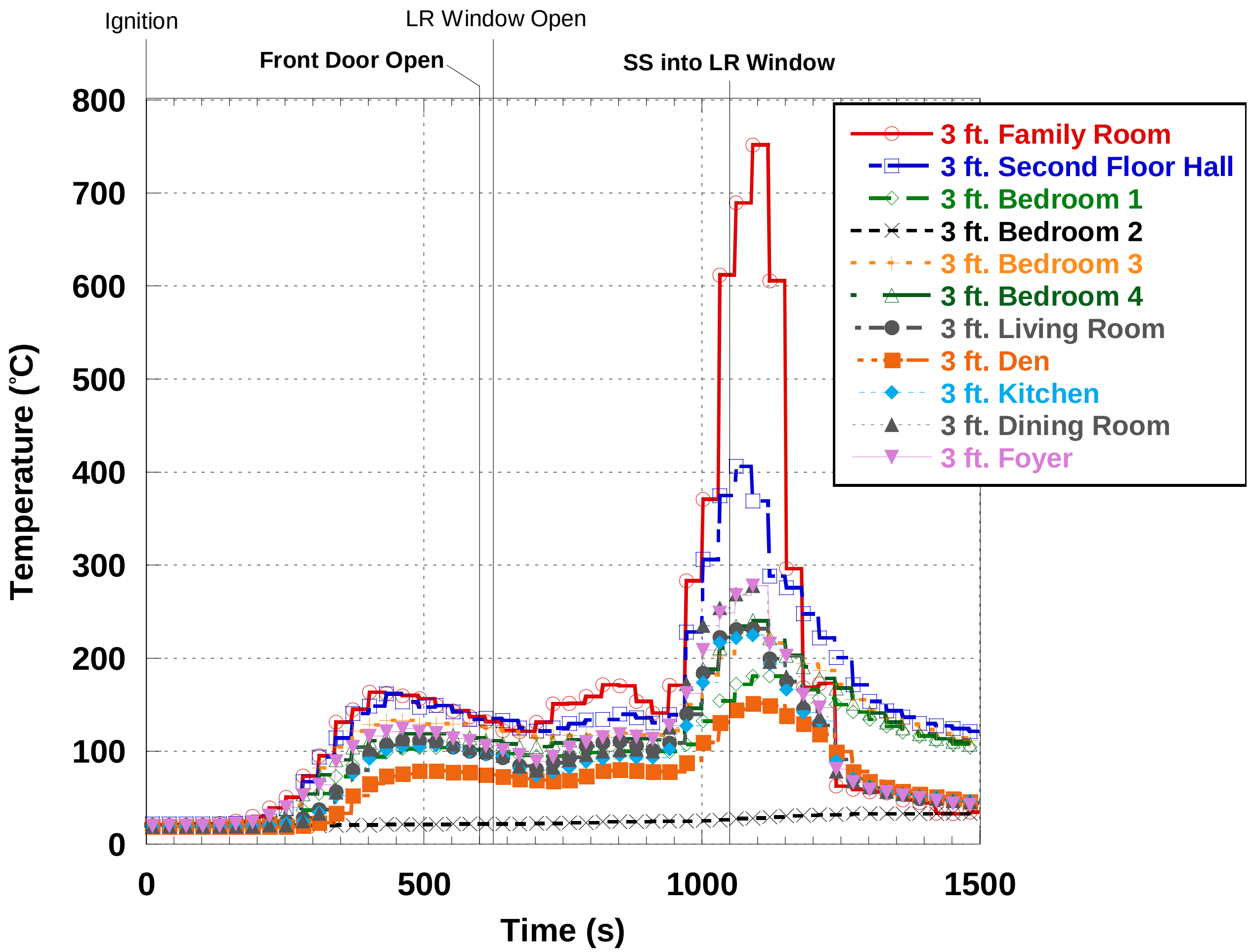


Figure 318. Experiment 4- 3ft. Temperatures

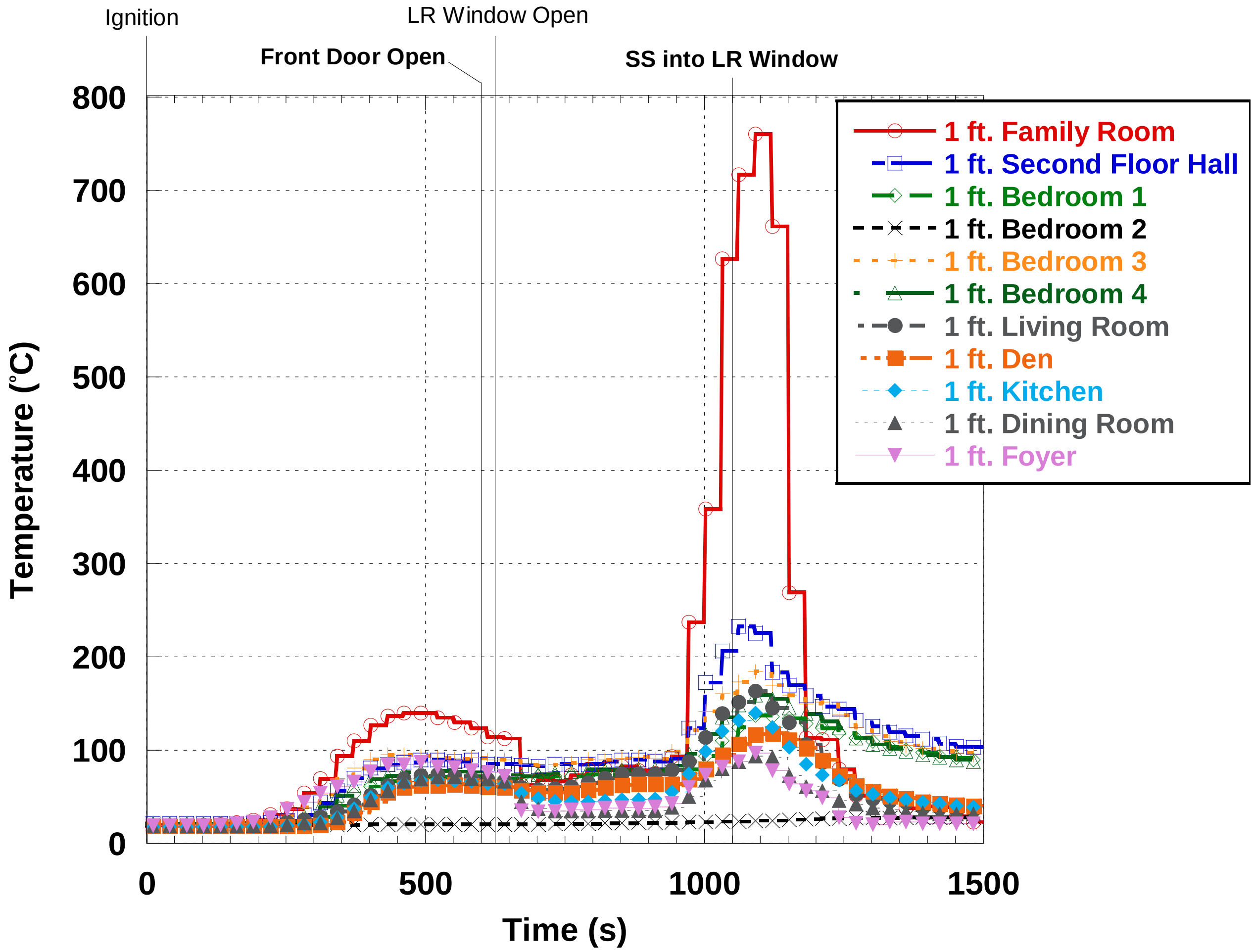


Figure 319. Experiment 4- 1ft. Temperatures

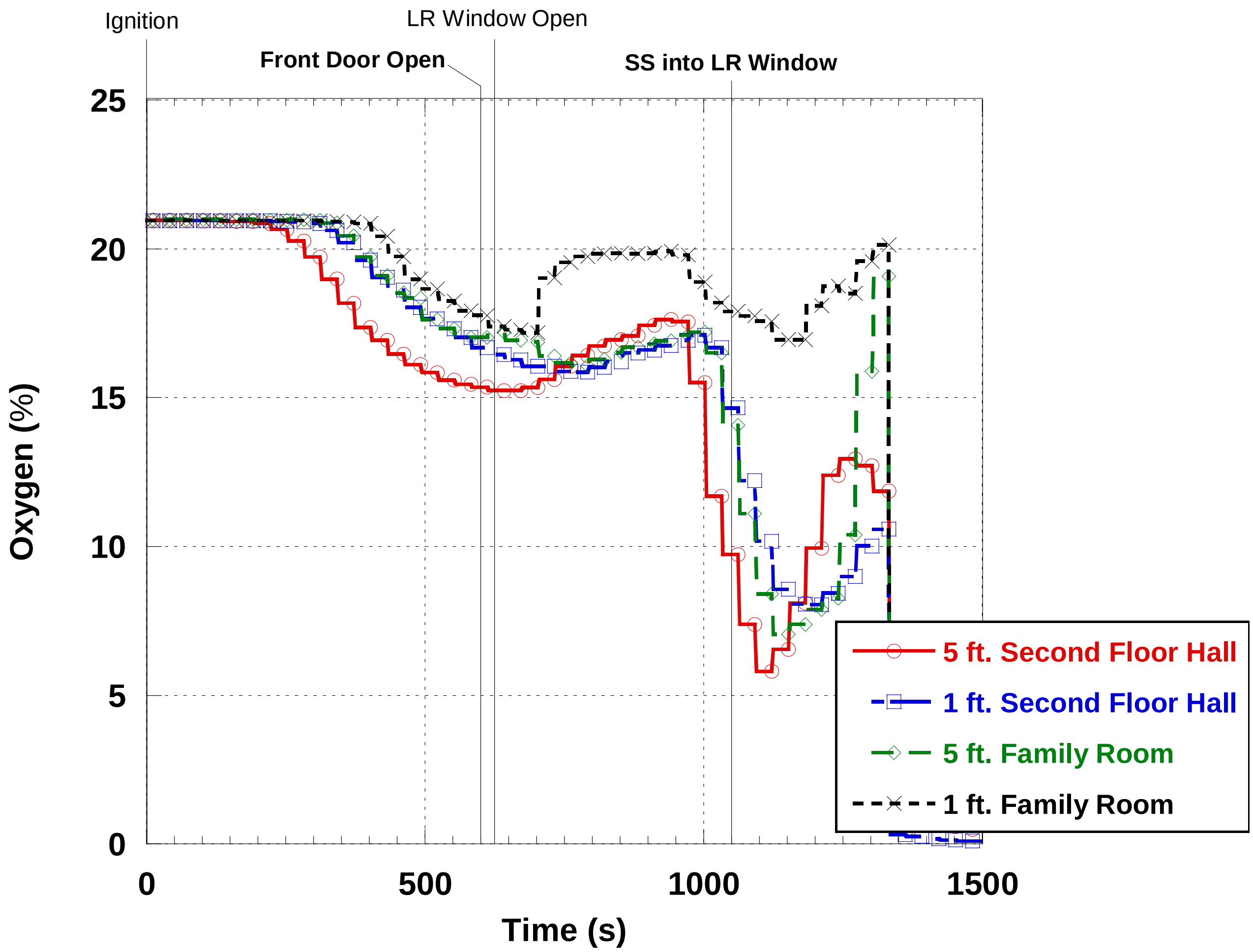


Figure 320. Experiment 4- Oxygen Concentration

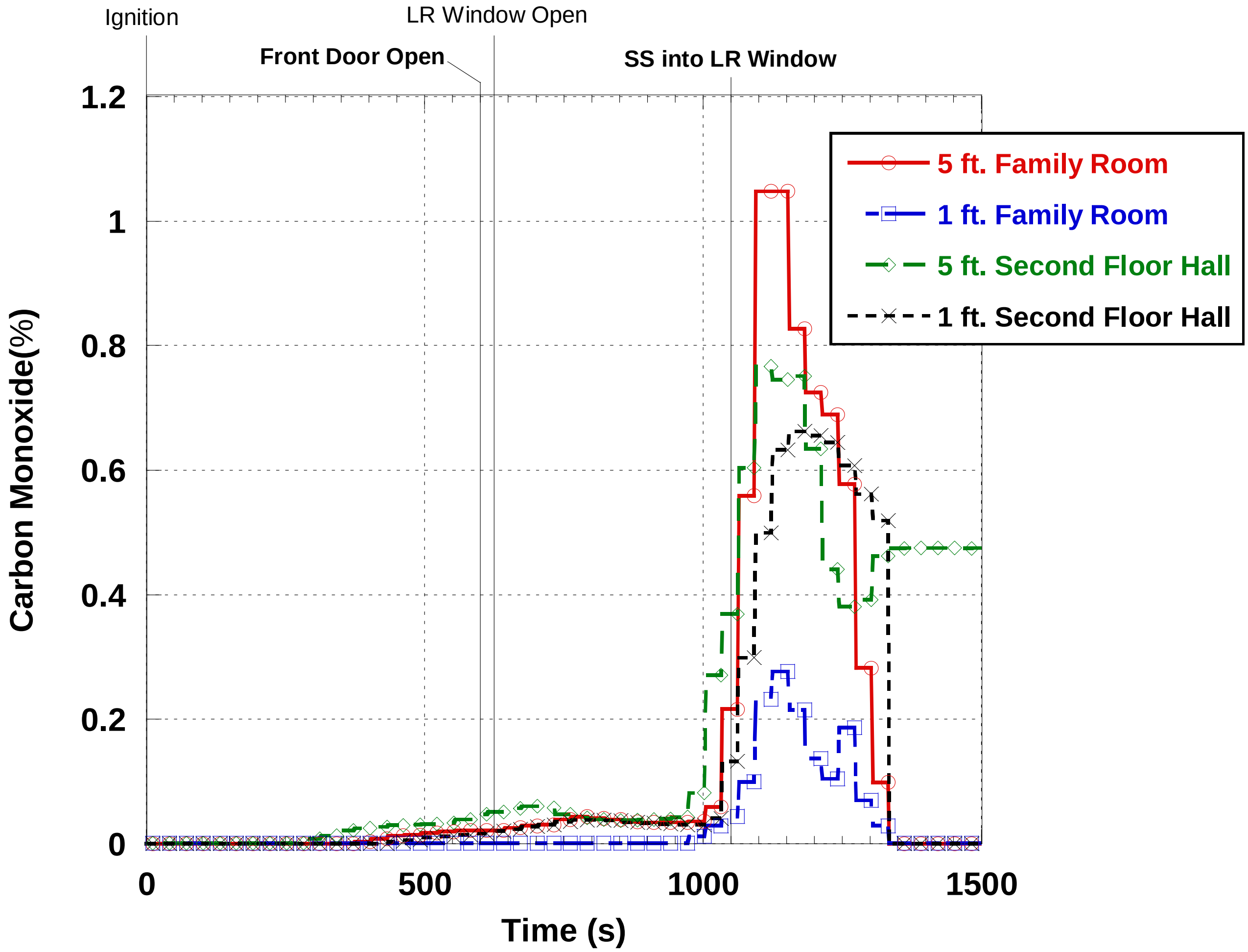


Figure 321. Experiment 4- CO Concentration

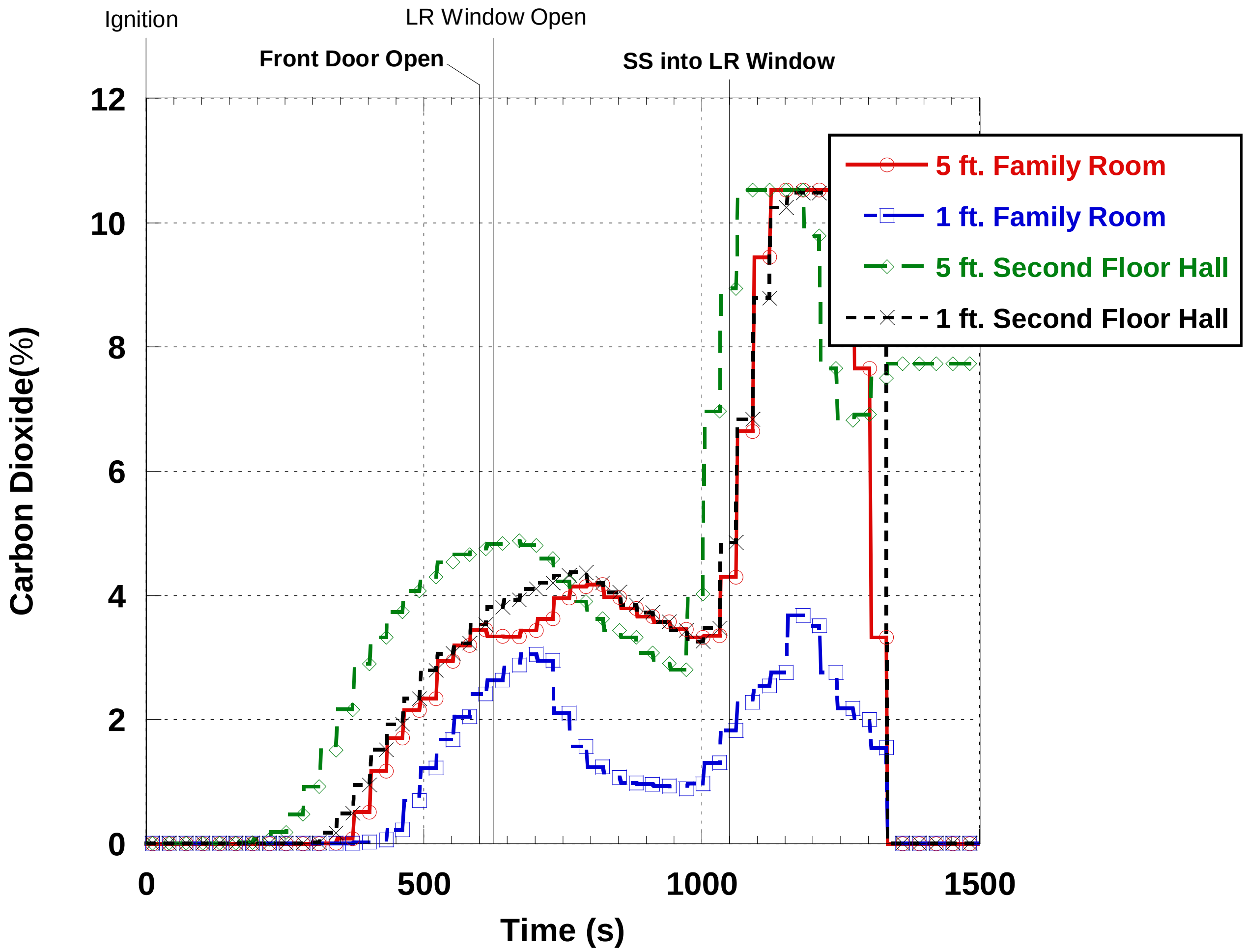


Figure 322. Experiment 4- CO_2 Concentration

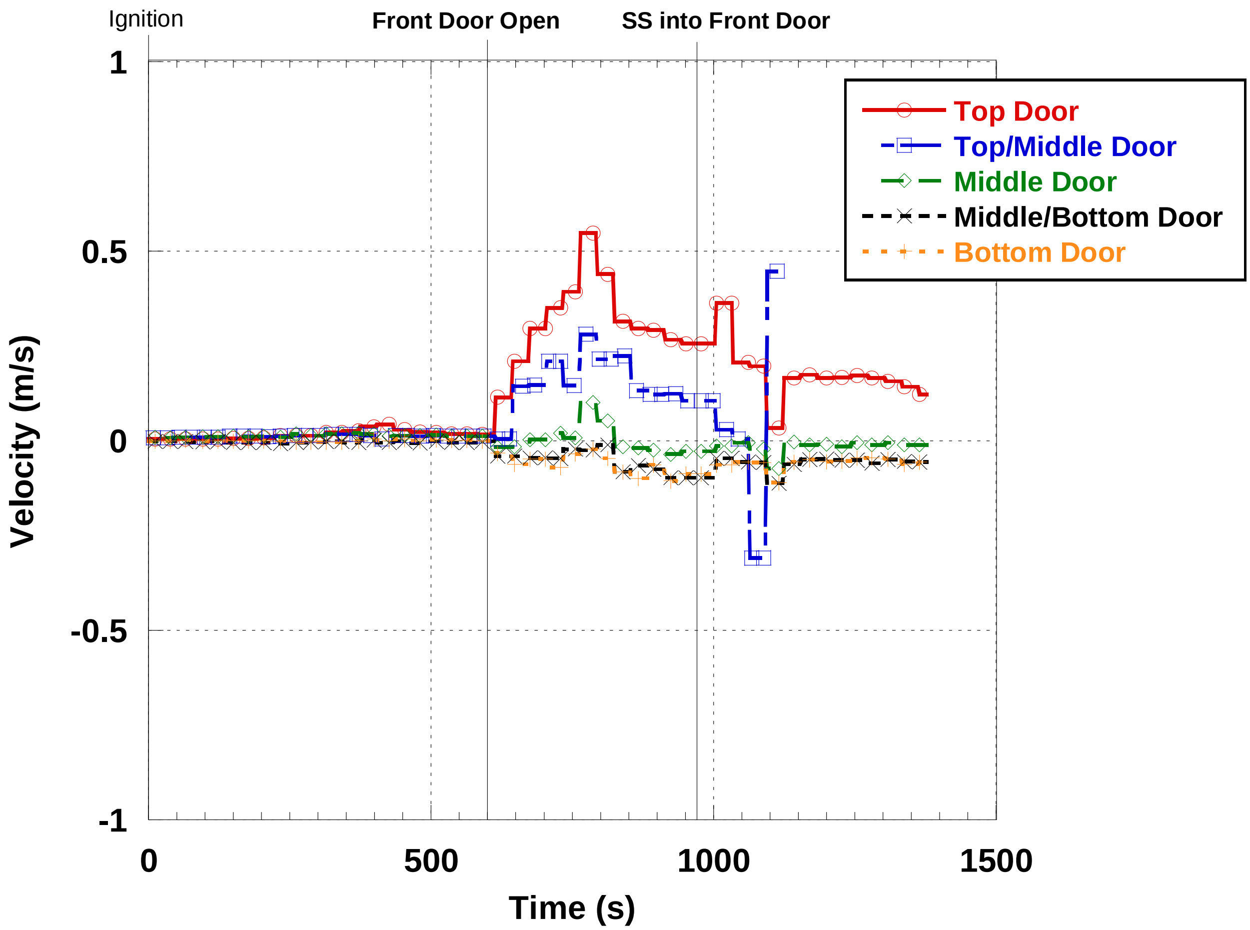


Figure 323. Experiment 4- Front Door Velocities

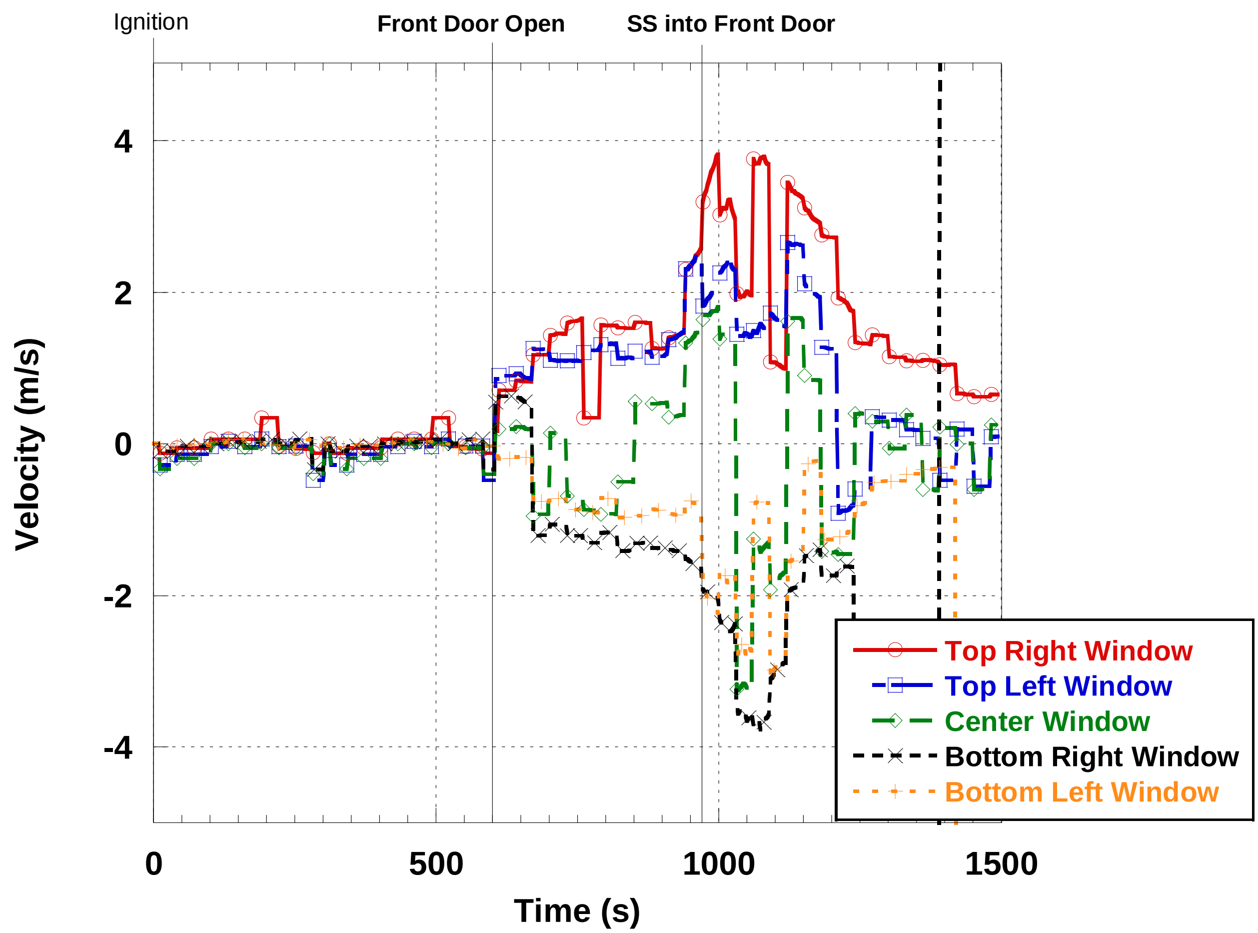


Figure 324. Experiment 4- Ventilation Window Velocities

8.7.3. Experiment 6

Experiment 6 was the third experiment conducted in the two-story house. This experiment was designed to simulate a crew making a ventilation opening near the seat of the fire prior to entry. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the first floor family room window was opened (Table 27). The fire again was allowed to grow until 16:32 when 10 seconds of water were flowed into the family room window with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 17:30 and was extinguished by the suppression crew. Figure 326 through Figure 331 show the front and rear of the house during the experiment.

Table 27. Experiment 6 Timeline

Event	Time (mm:ss)
Ignition	0:00
Family Room Window Open	10:02
Straight Stream into Family Room Window	16:32-16:42
End of Experiment	17:30

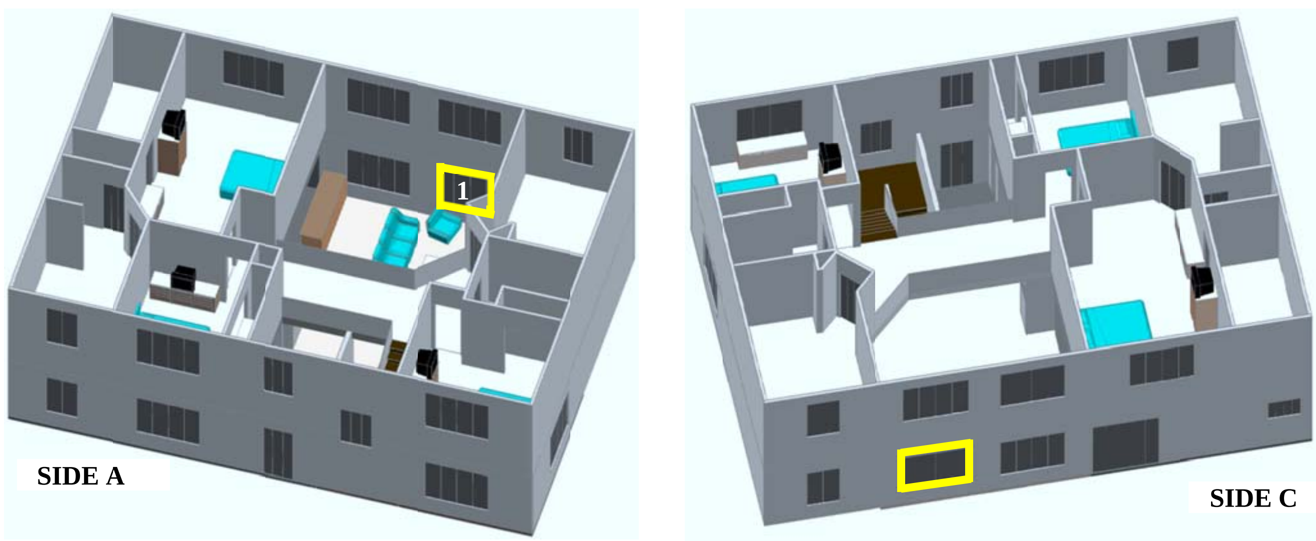


Figure 325. House graphic highlighting ventilation location

Figure 326. Experiment 6 - 0:00

Figure 327. Experiment 6 - 0:00

Figure 328. Experiment 6 - 5:00

Figure 329. Experiment 6 - 10:05

Figure 330. Experiment 6 - 14:45

Figure 331. Experiment 6 - 16:35

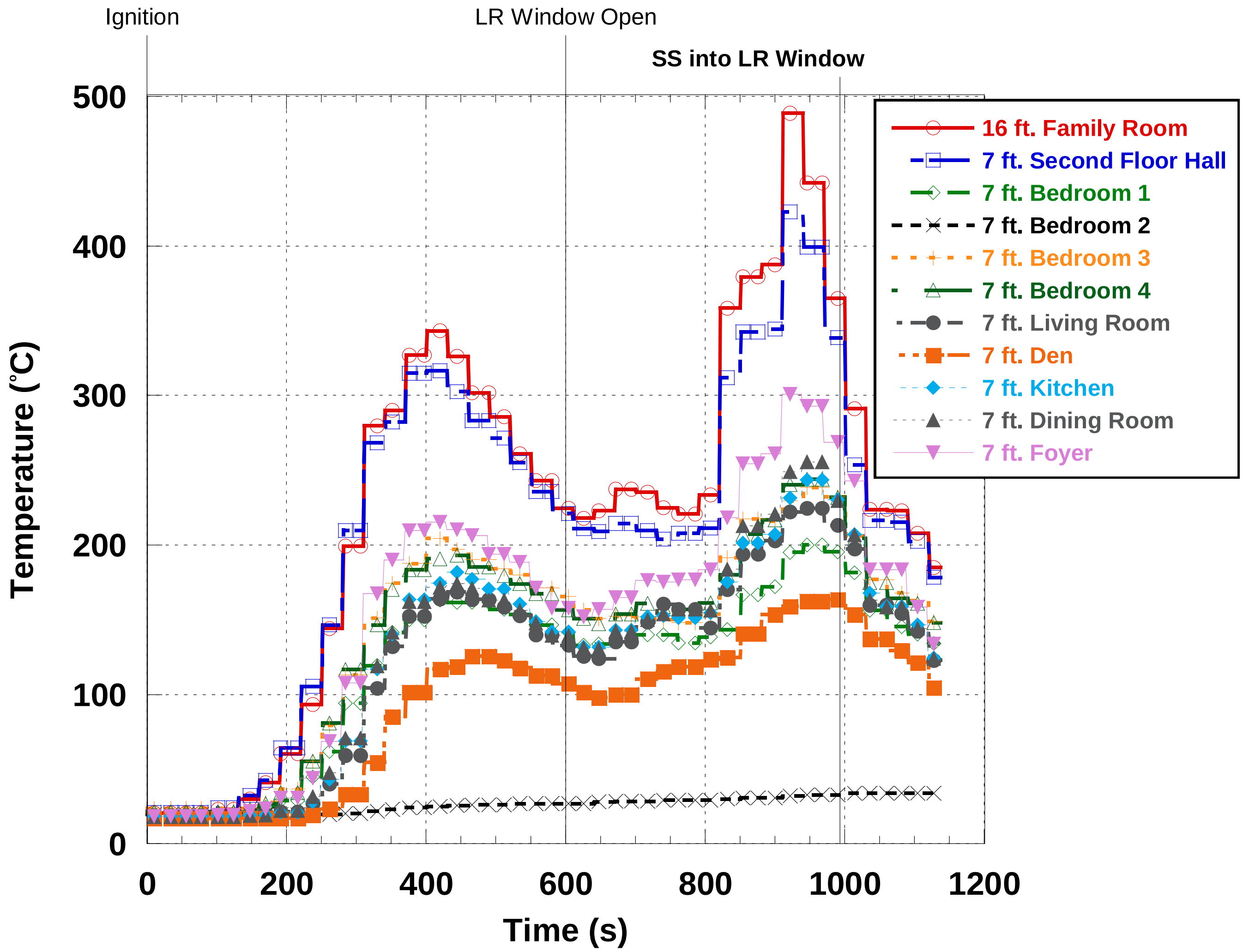


Figure 332. Experiment 6- 7ft. Temperatures

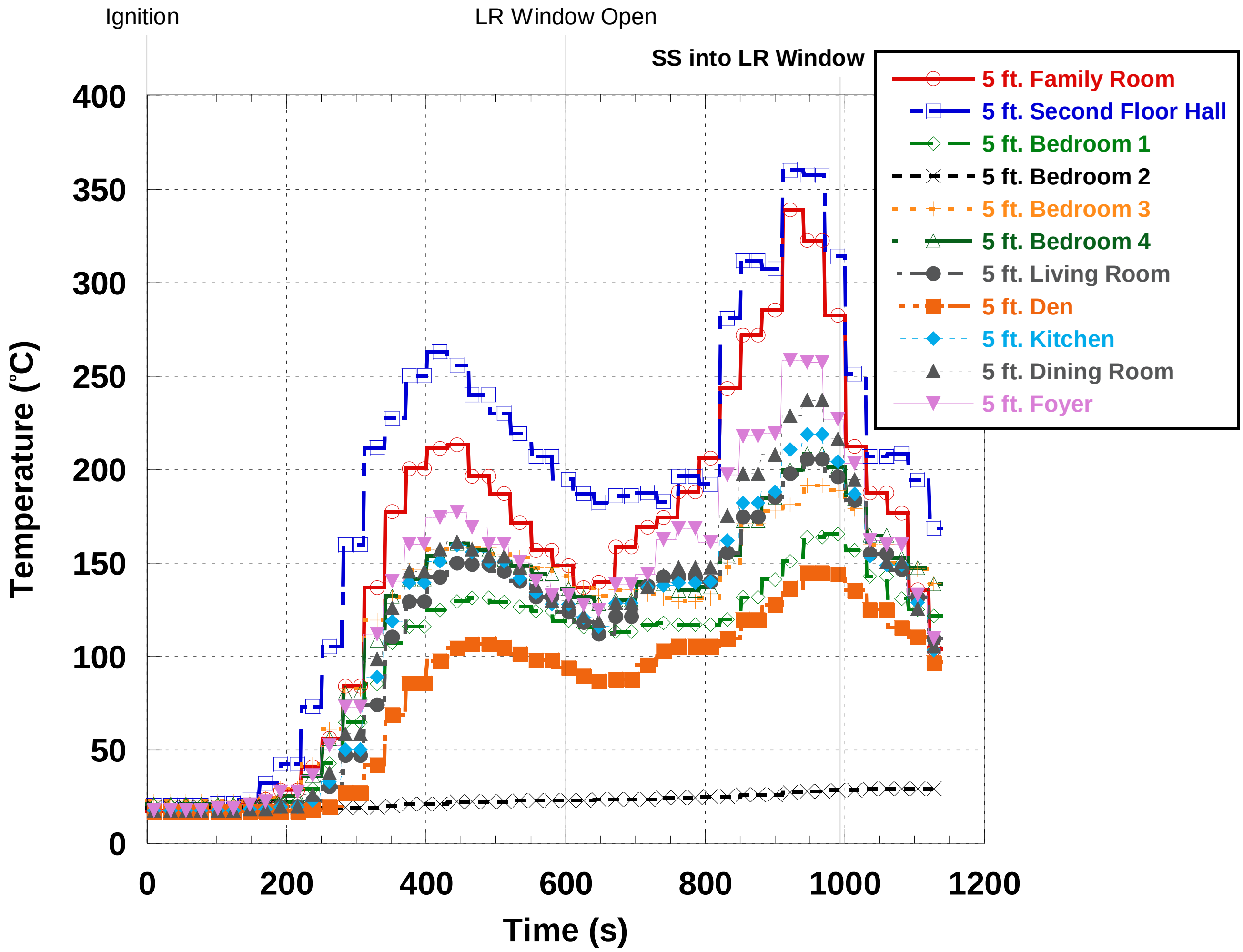


Figure 333. Experiment 6 - 5ft. Temperatures

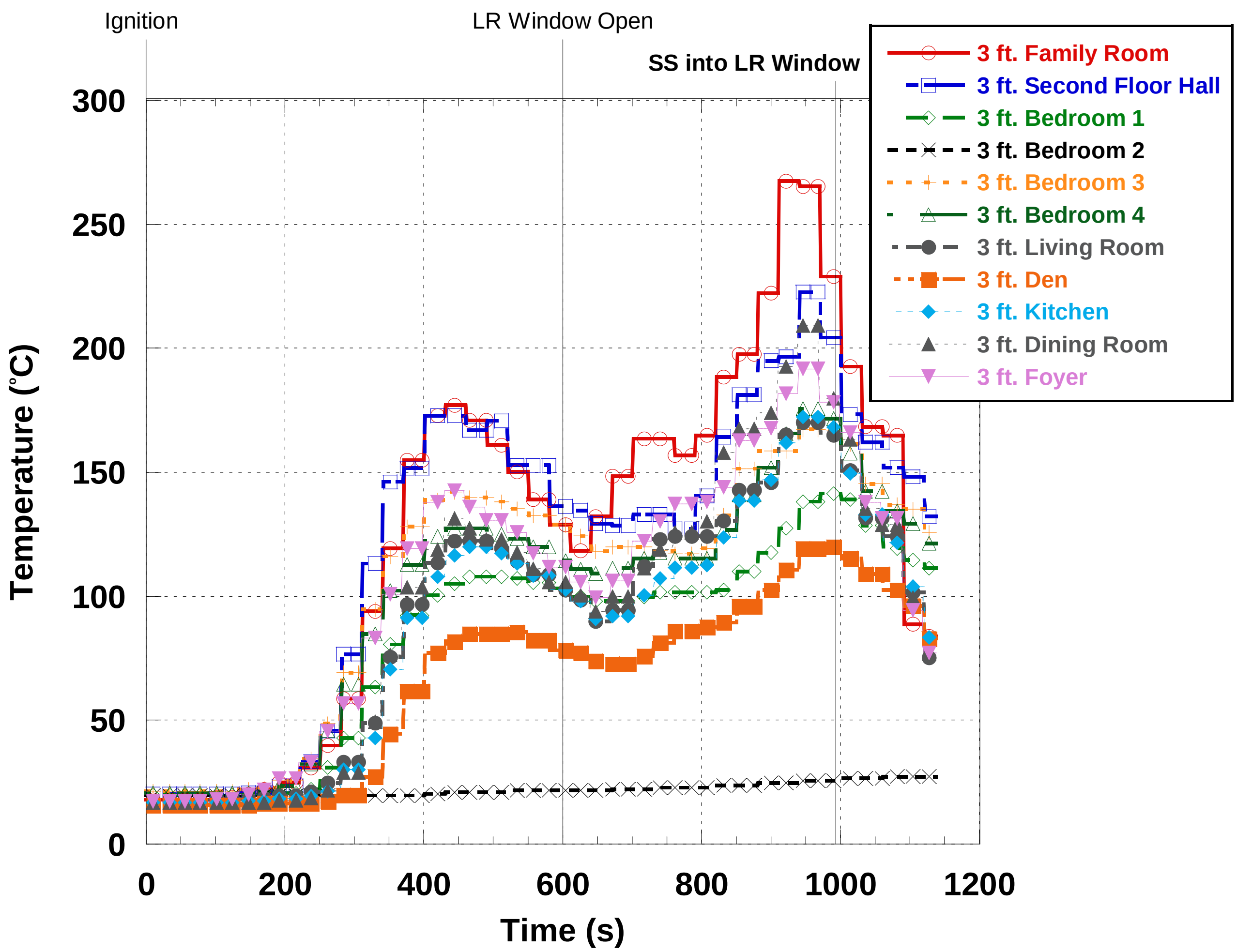


Figure 334. Experiment 6- 3ft. Temperatures

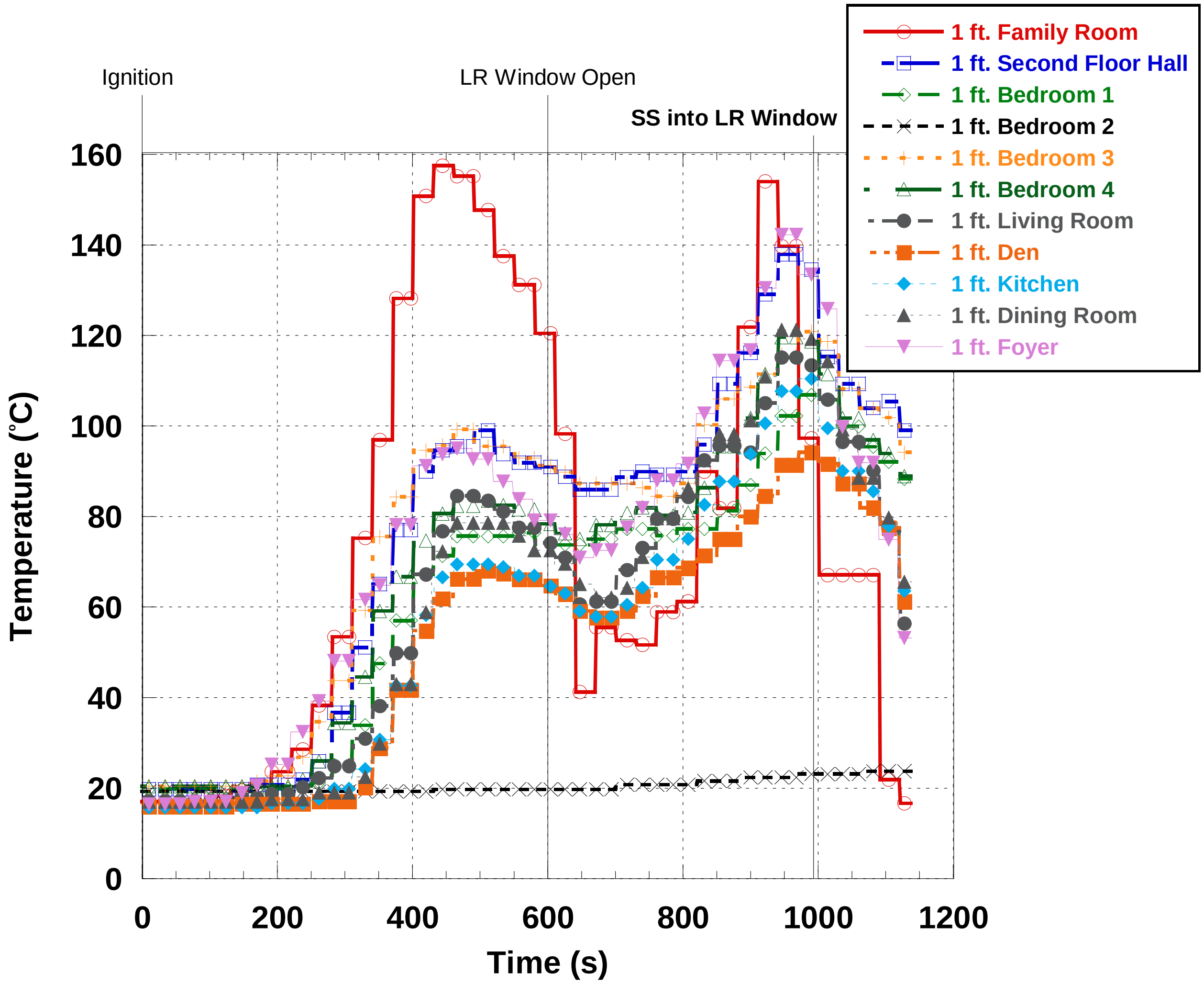


Figure 335. Experiment 6- 1ft. Temperatures

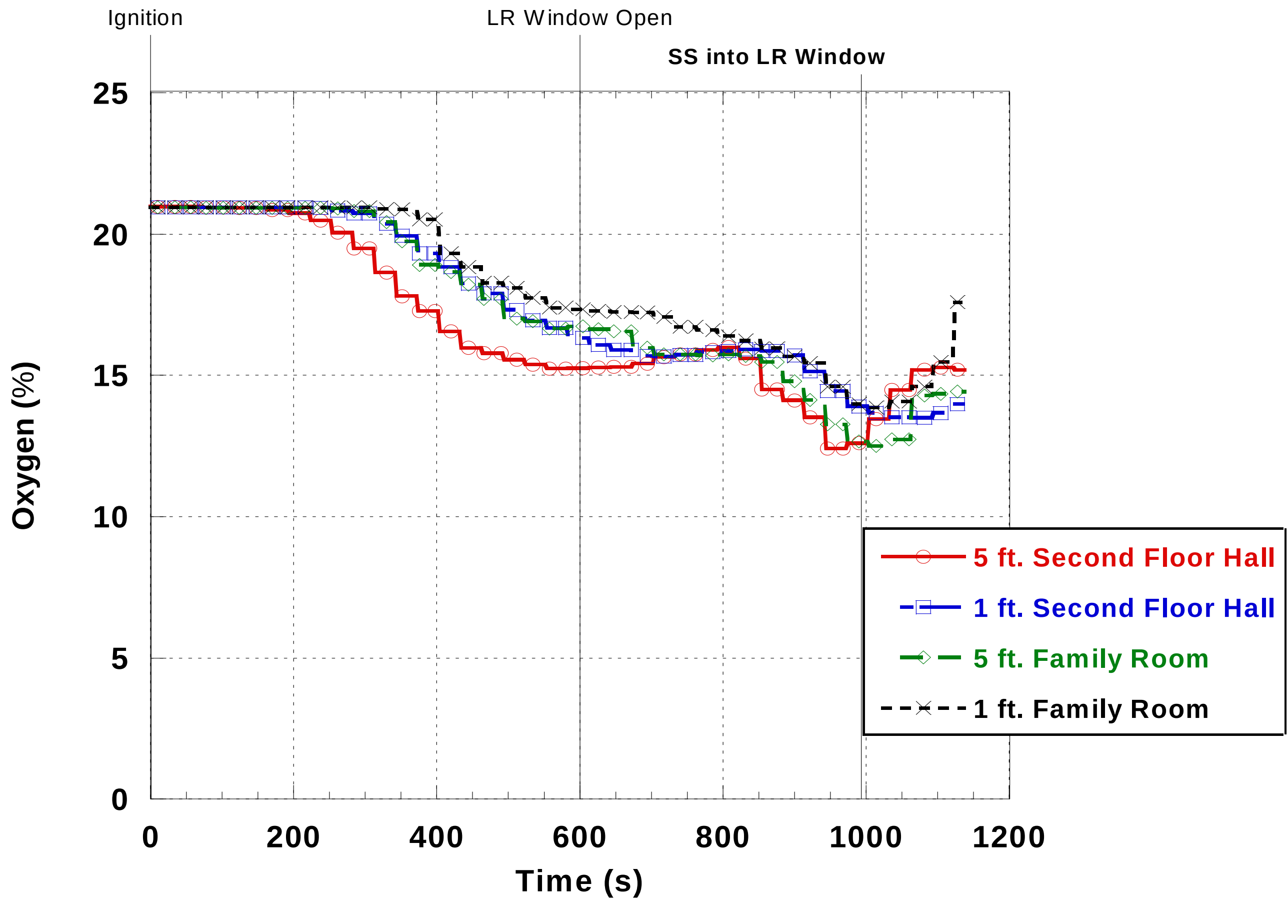


Figure 336. Experiment 6- Oxygen Concentration

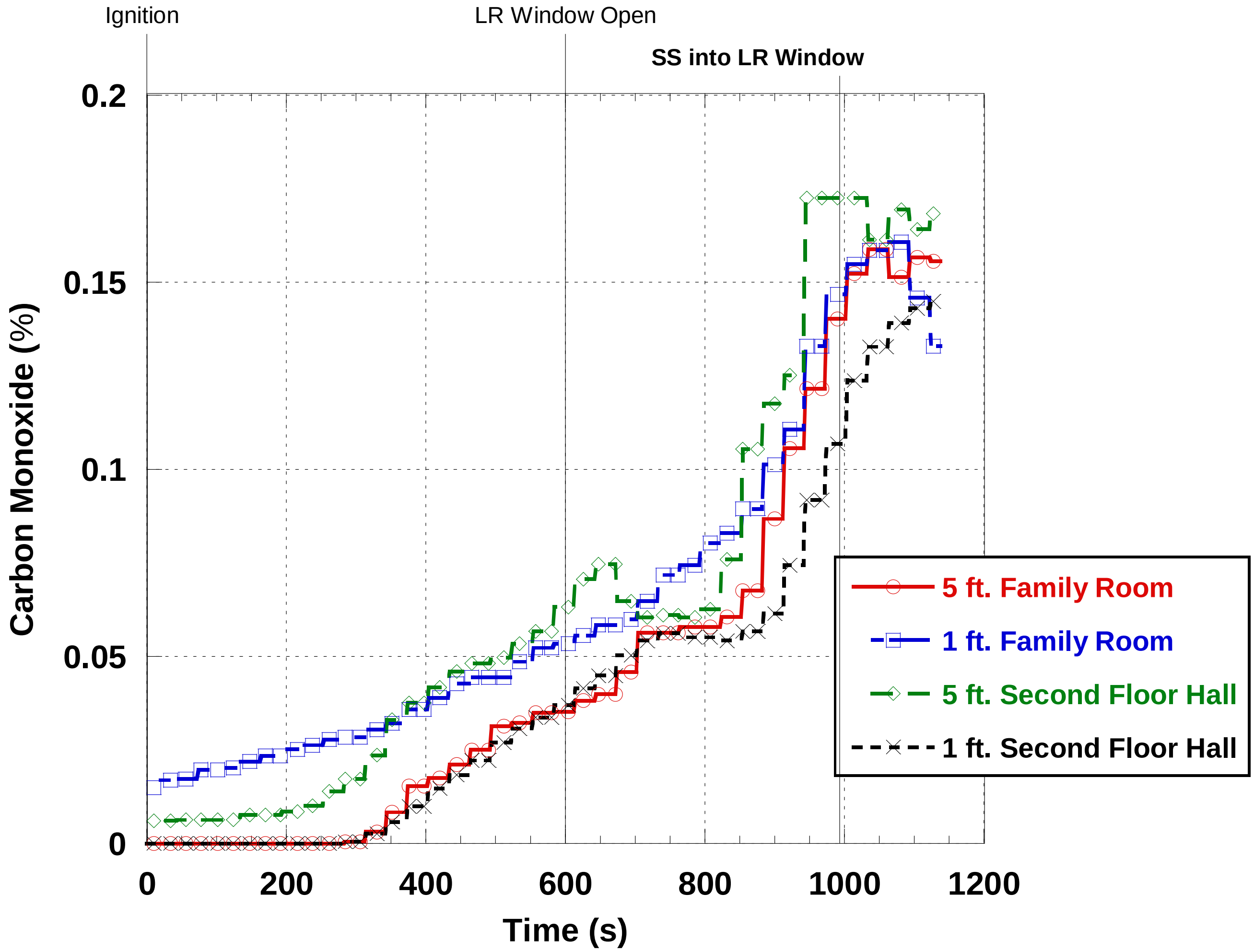


Figure 337. Experiment 6- CO Concentration

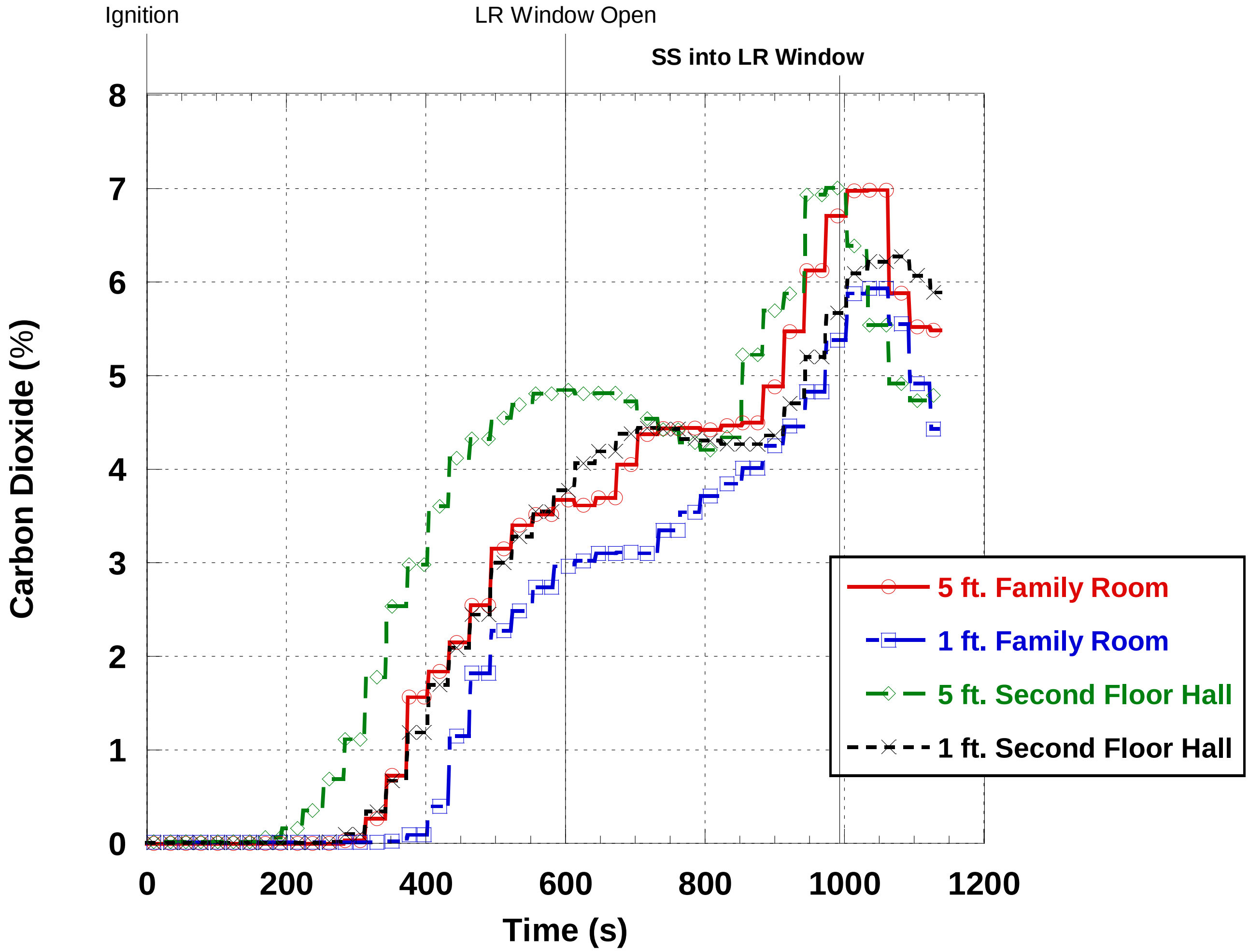


Figure 338. Experiment 6- CO_2 Concentration

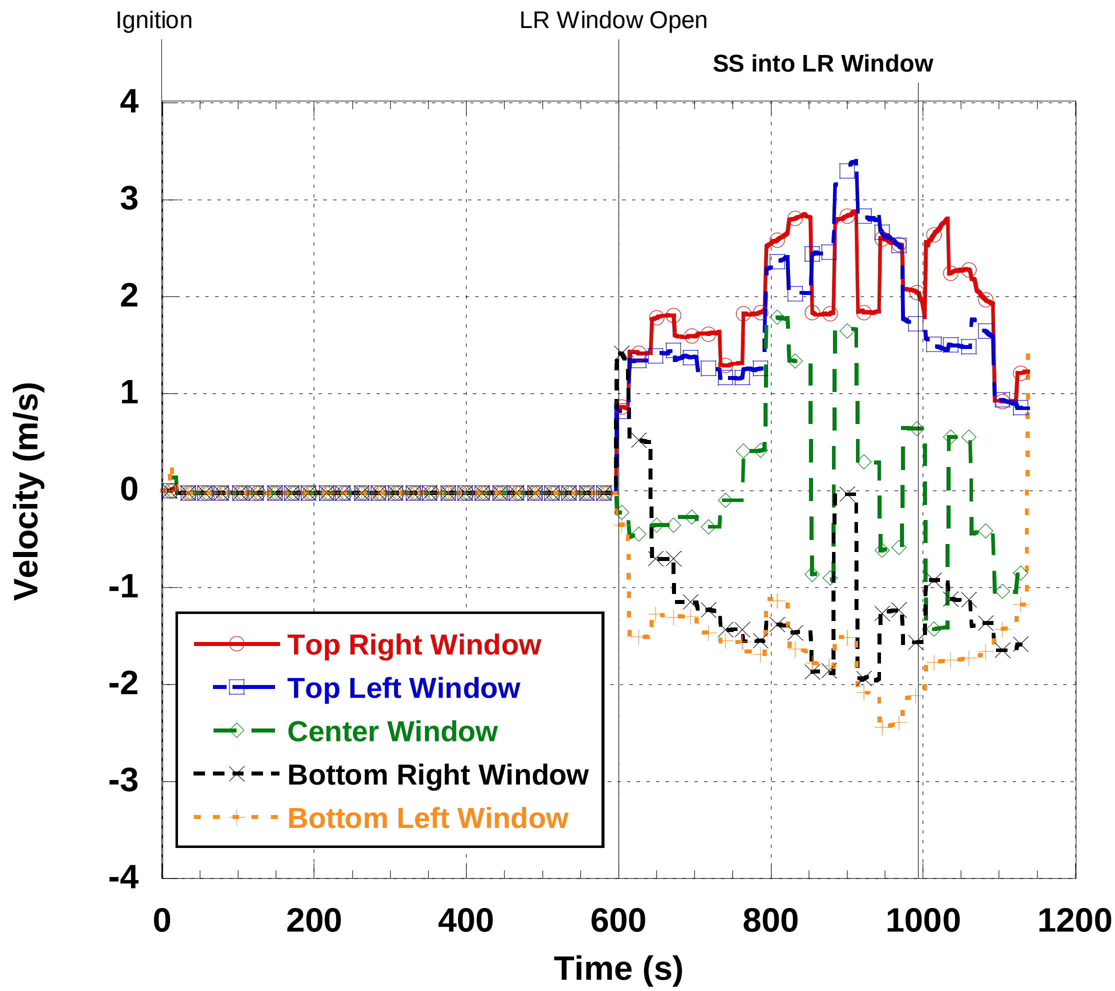


Figure 339. Experiment 6- Ventilation Window Velocities

8.7.4. Experiment 8

Experiment 8 was conducted in the two-story house as well. This experiment was designed to simulate a crew making entry through the front door and having a ventilation opening made shortly after remote from the seat of the fire. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the front door was opened followed 15 s later by the opening of the second floor front bedroom window (Table 28). The fire again was allowed to grow until 17:32 when 10 seconds of water were flowed into the bedroom window with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 18:30 and was extinguished by the suppression crew. Figure 341 through Figure 348 show the front of the house during the experiment.

Table 28. Experiment 8 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	10:00
Bedroom Window Open	10:15
Straight Stream into Bedroom Window	17:32-17:42
End of Experiment	18:30

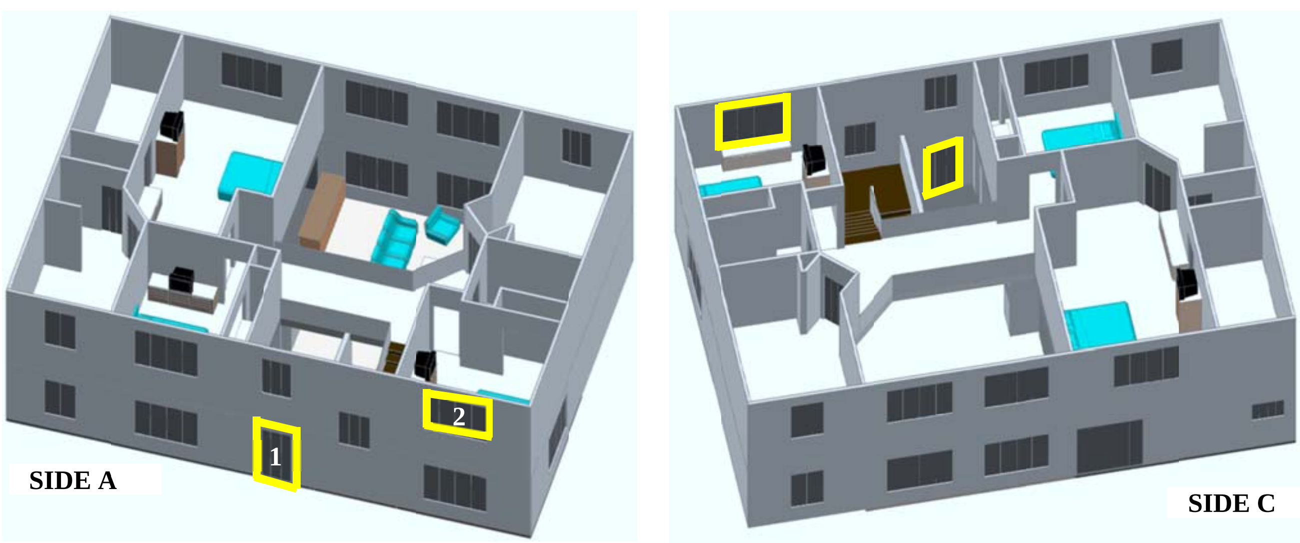


Figure 340. House graphic highlighting ventilation locations

Figure 341. Experiment 8 - 0:00

Figure 342. Experiment 8 - 5:00

Figure 343. Experiment 8 - 10:05

Figure 344. Experiment 8 - 10:20

Figure 345. Experiment 8 - 13:00

Figure 346. Experiment 8 - 17:00

Figure 347. Experiment 8 - 17:40

Figure 348. Experiment 8 - 18:40

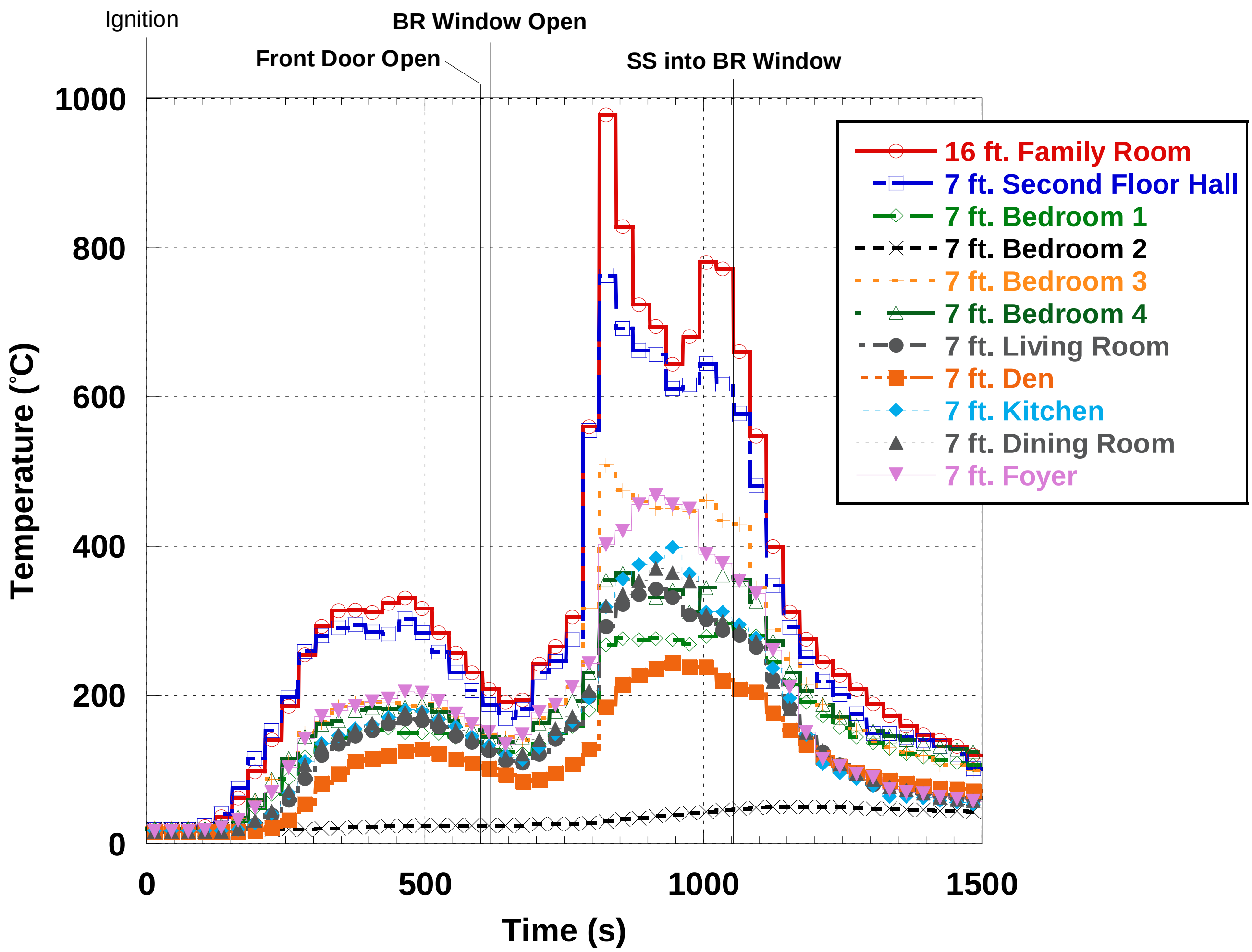


Figure 349. Experiment 8- 7ft. Temperatures

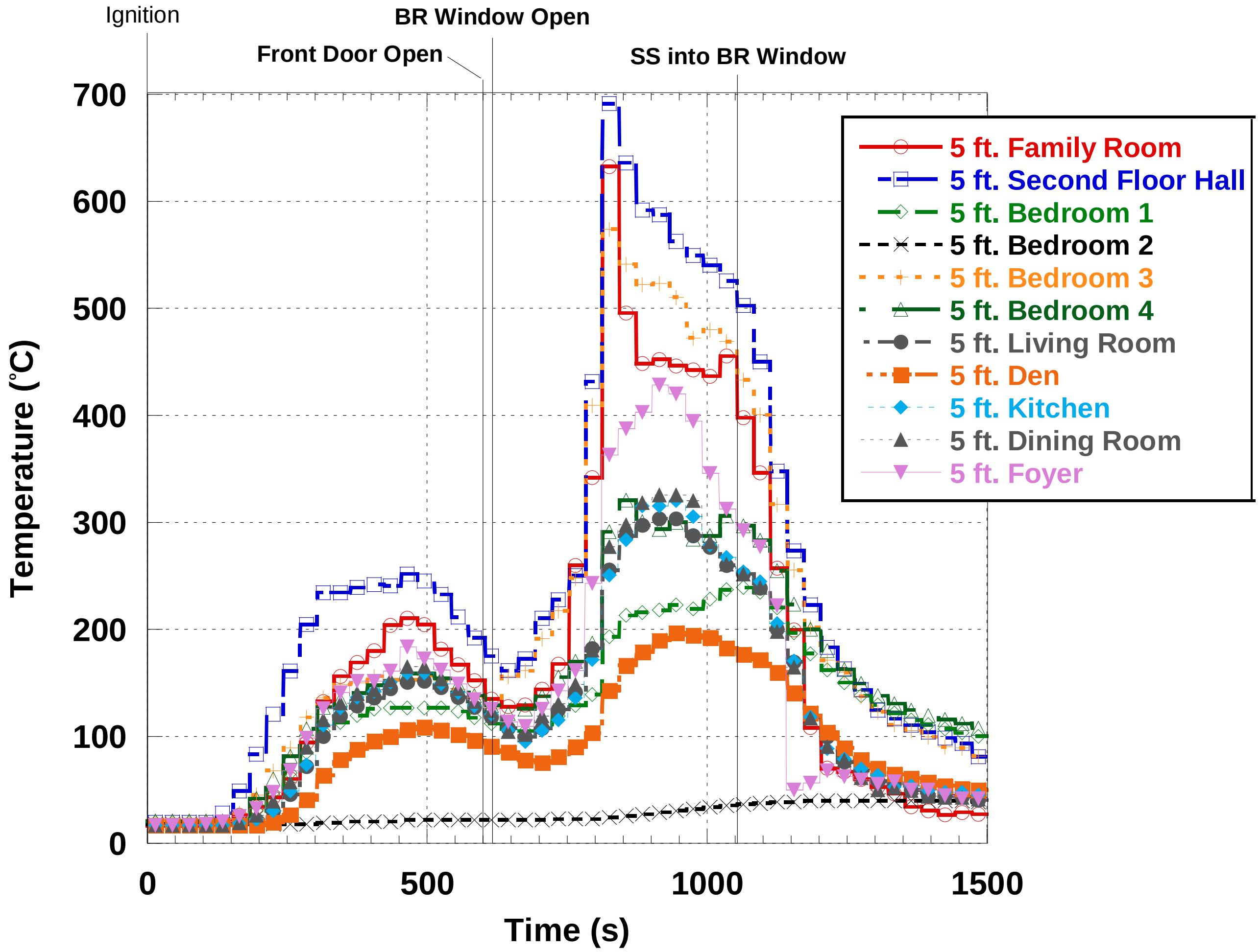


Figure 350. Experiment 8- 5ft. Temperatures

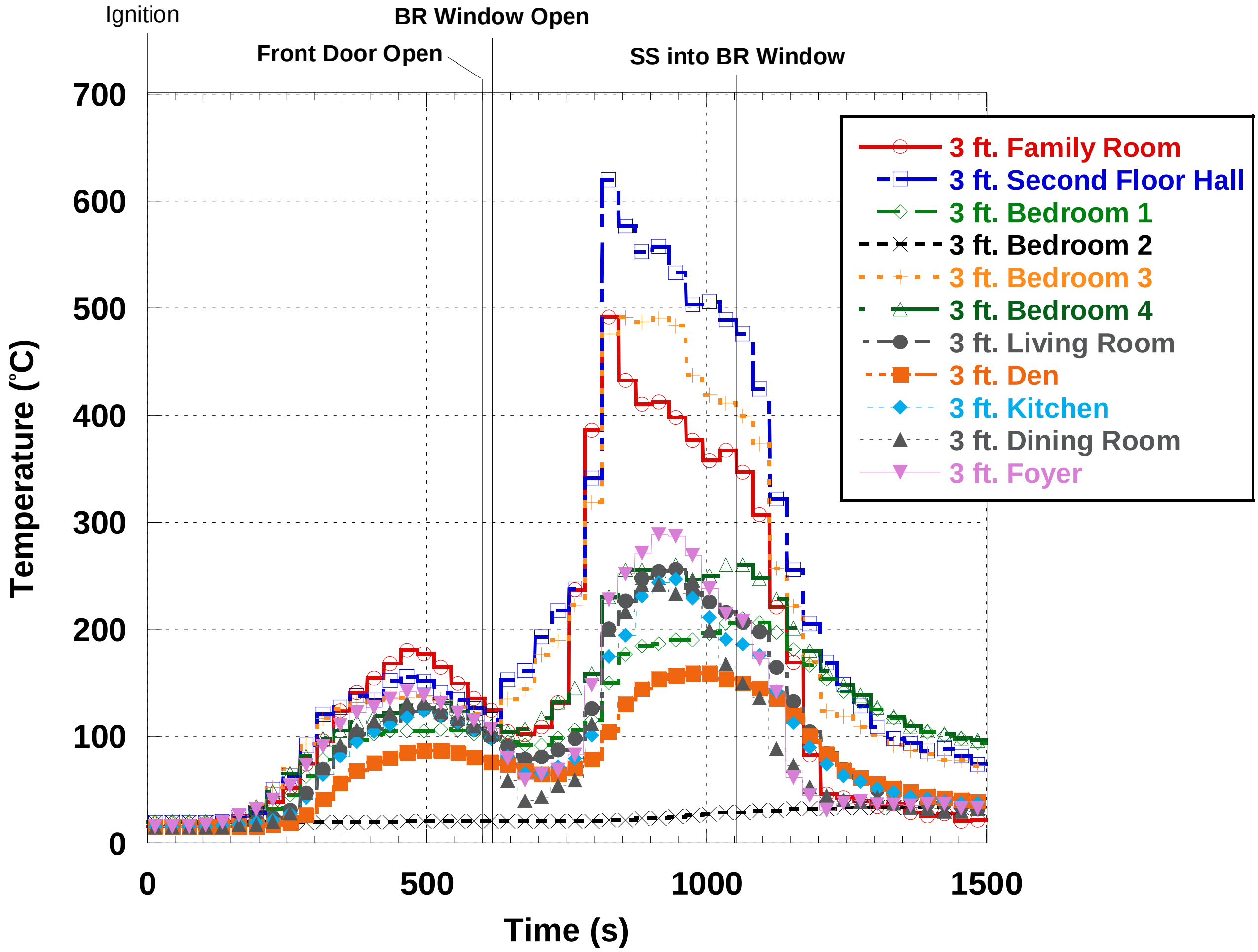


Figure 351. Experiment 8- 3ft. Temperatures

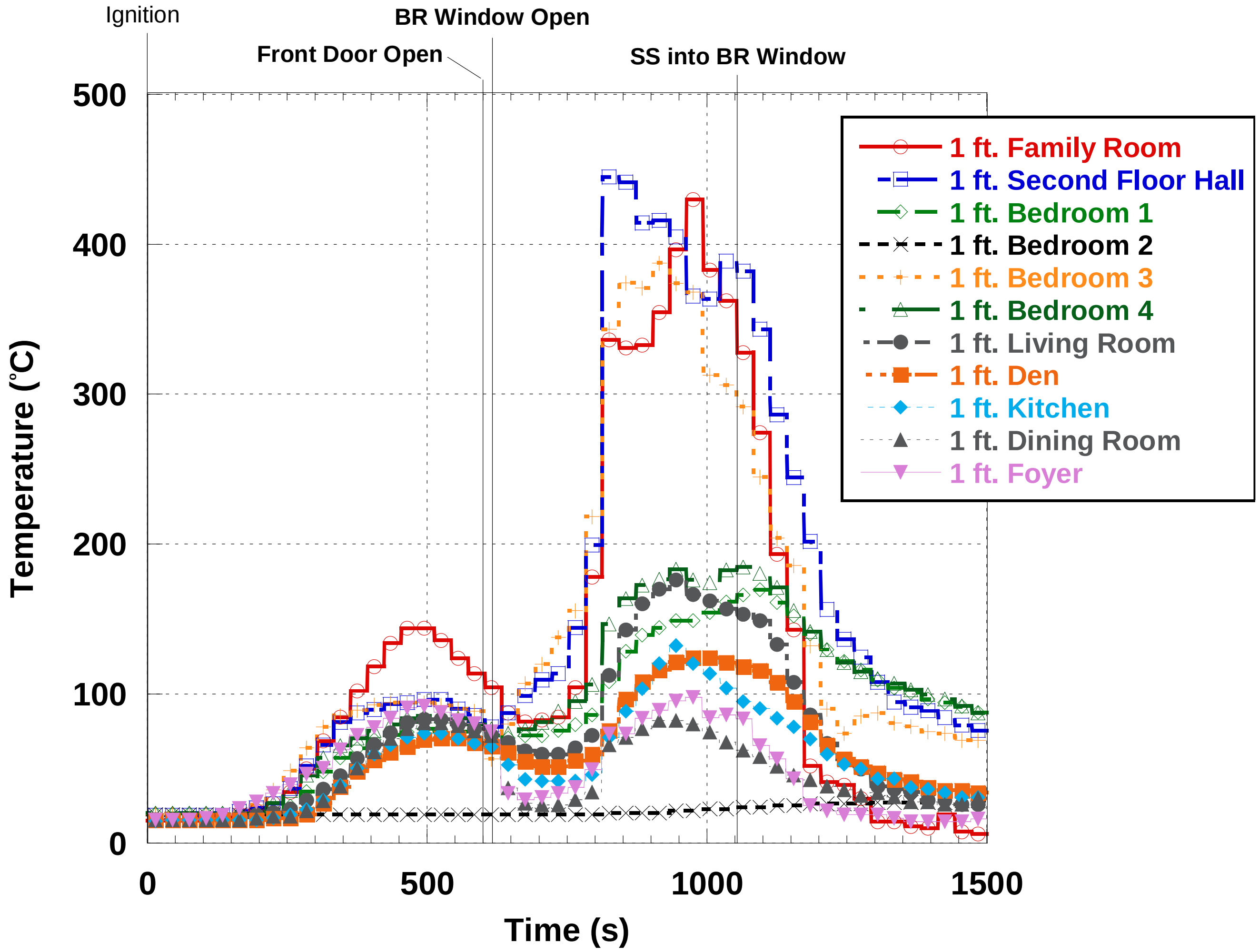


Figure 352. Experiment 8 - 1ft. Temperatures

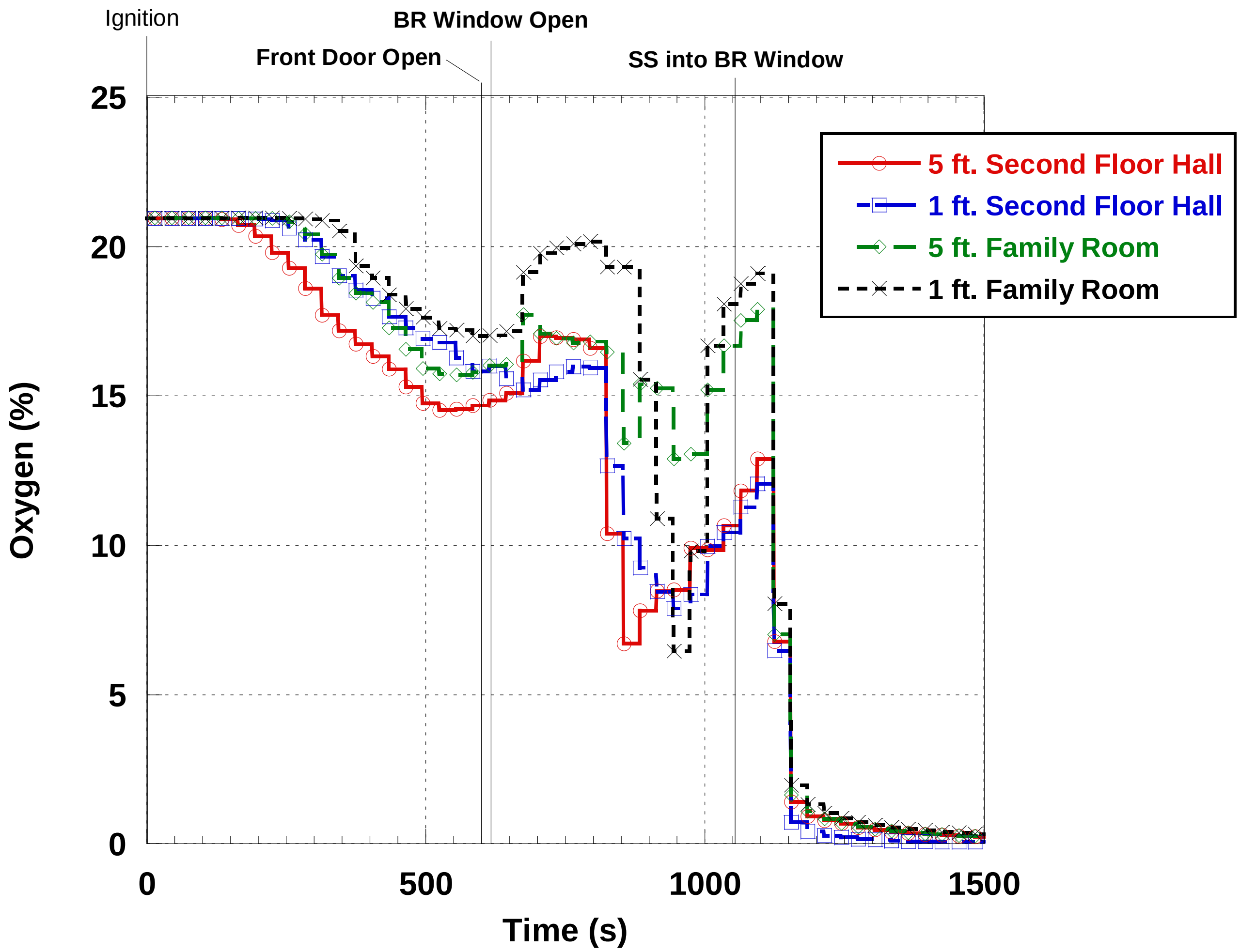


Figure 353. Experiment 8- Oxygen Concentration

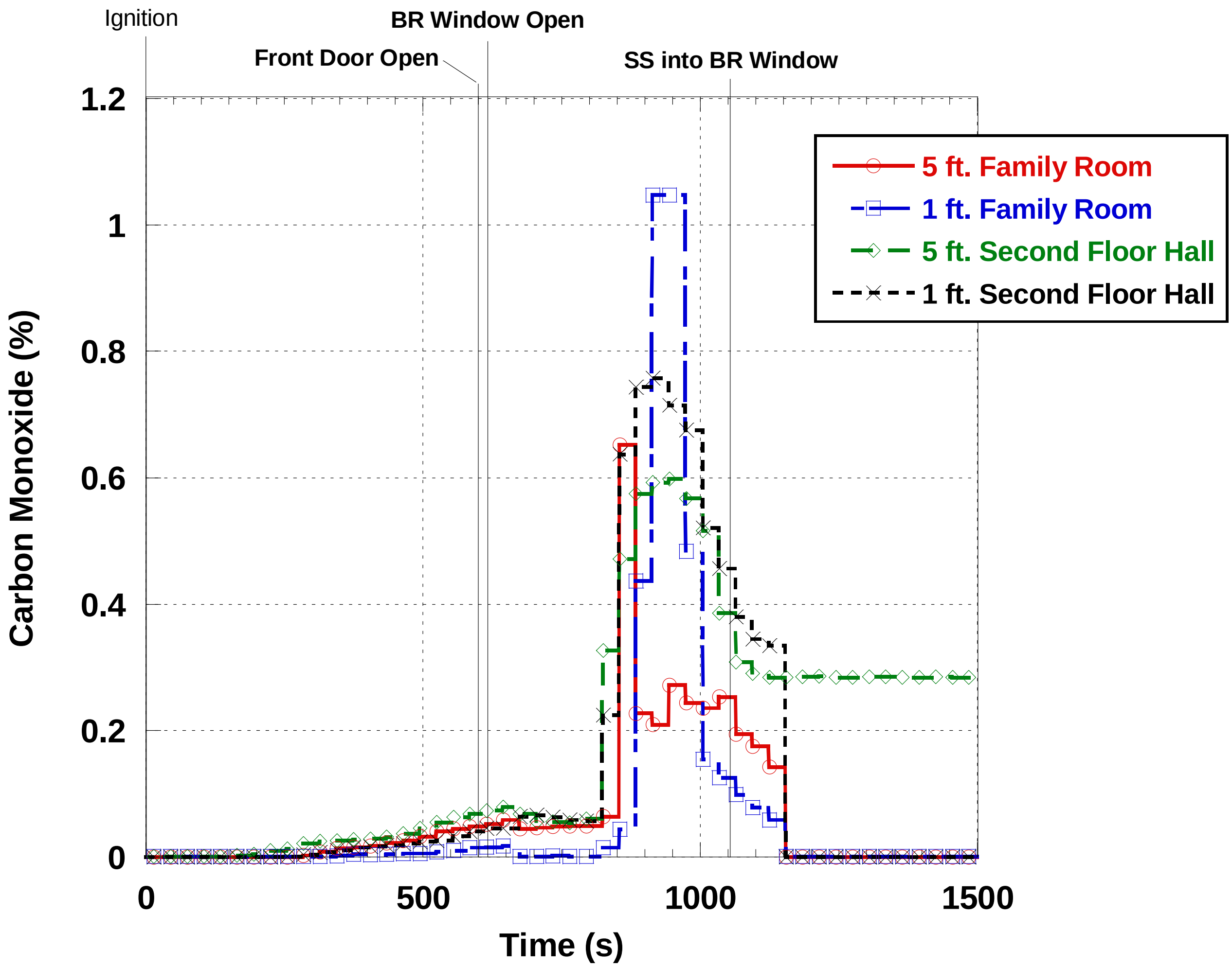


Figure 354. Experiment 8- CO Concentration

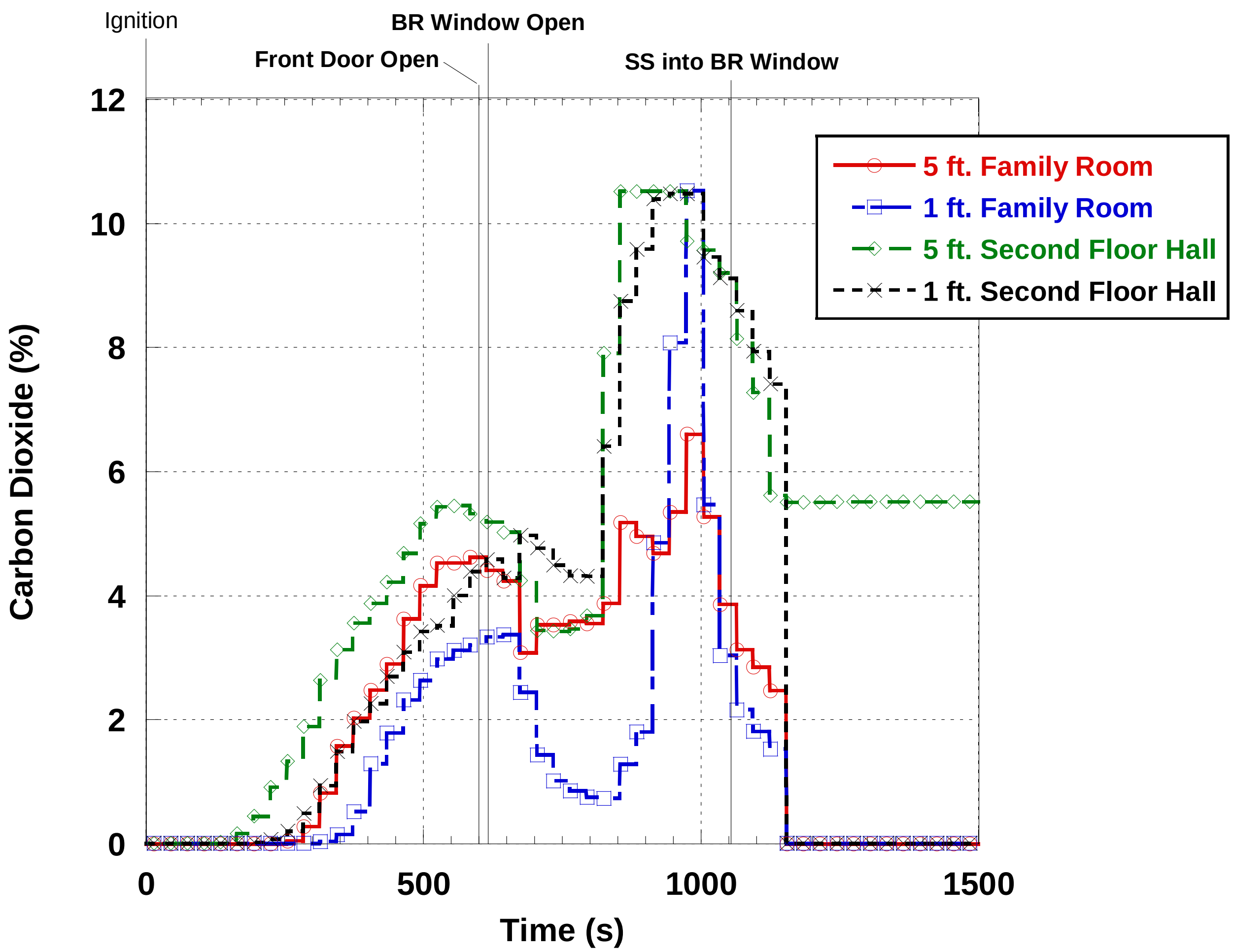


Figure 355. Experiment 8- CO_2 Concentration

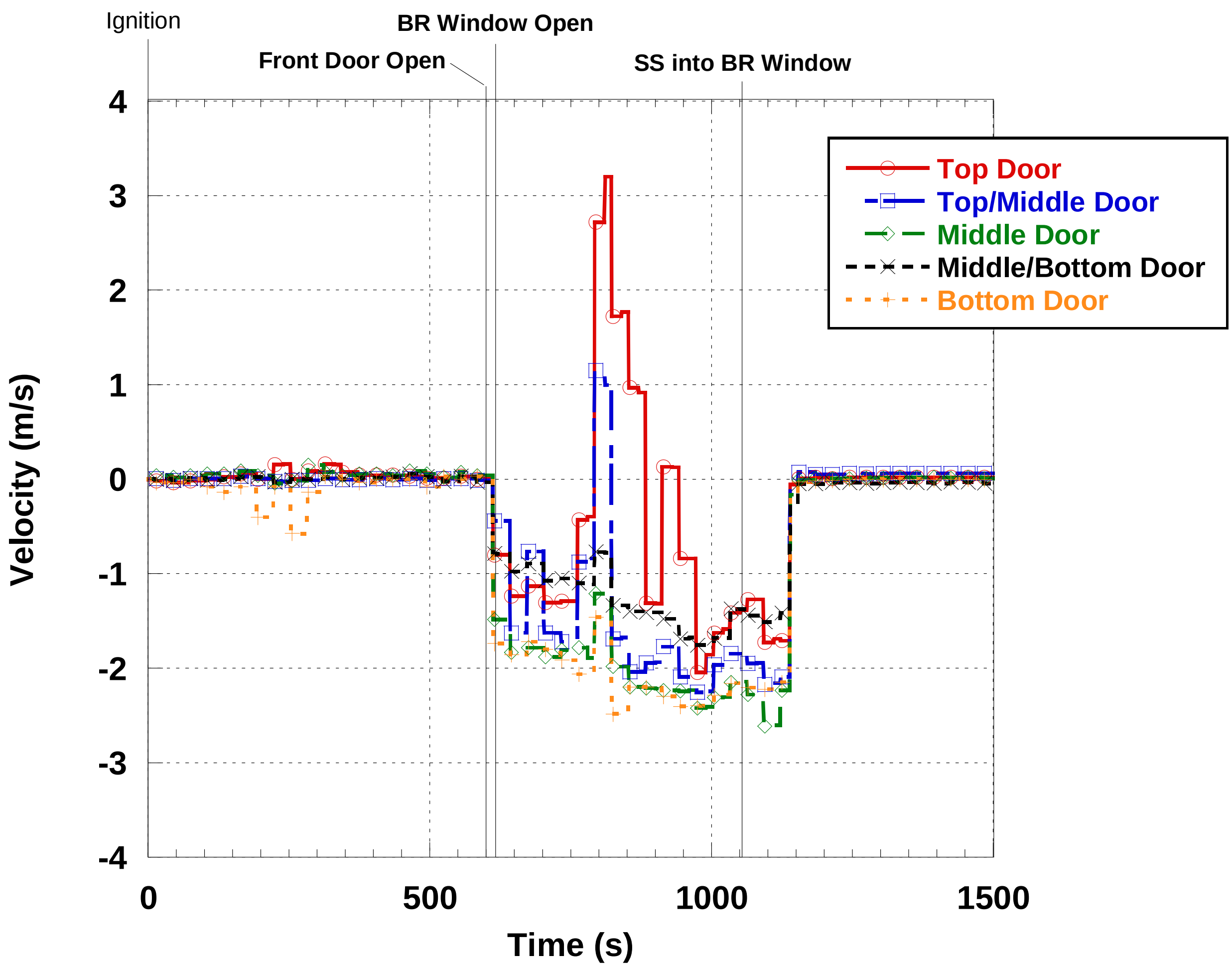


Figure 356. Experiment 8- Front Door Velocities

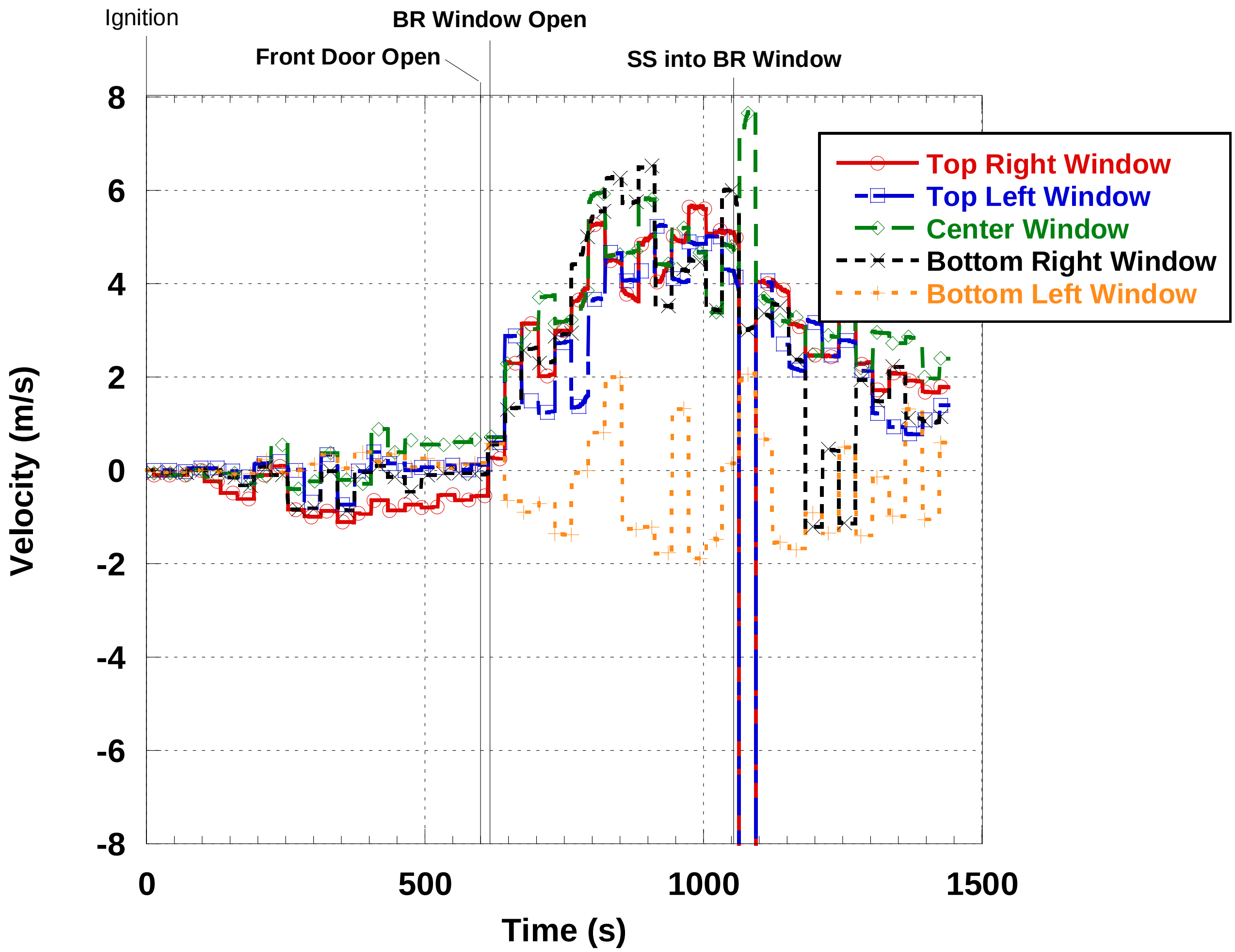


Figure 357. Experiment 8- Ventilation Window Velocities

8.7.5. Experiment 10

Experiment 10 was the fifth experiment conducted in the two-story house. This experiment was the second of three replicate experiments to examine repeatability. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the front door was opened. Fifteen seconds after the front door was opened the first floor family room window was opened (Table 29). The fire again was allowed to grow until 24:16 when 10 seconds of water were flowed into the family room window with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 25:30 and was extinguished by the suppression crew. Figure 359 through Figure 365 show the front and rear of the house during the experiment.

Table 29. Experiment 10 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	10:00
Living Room Window Open	10:15
Straight Stream into Living Room Window	24:16-24:26
End of Experiment	25:30

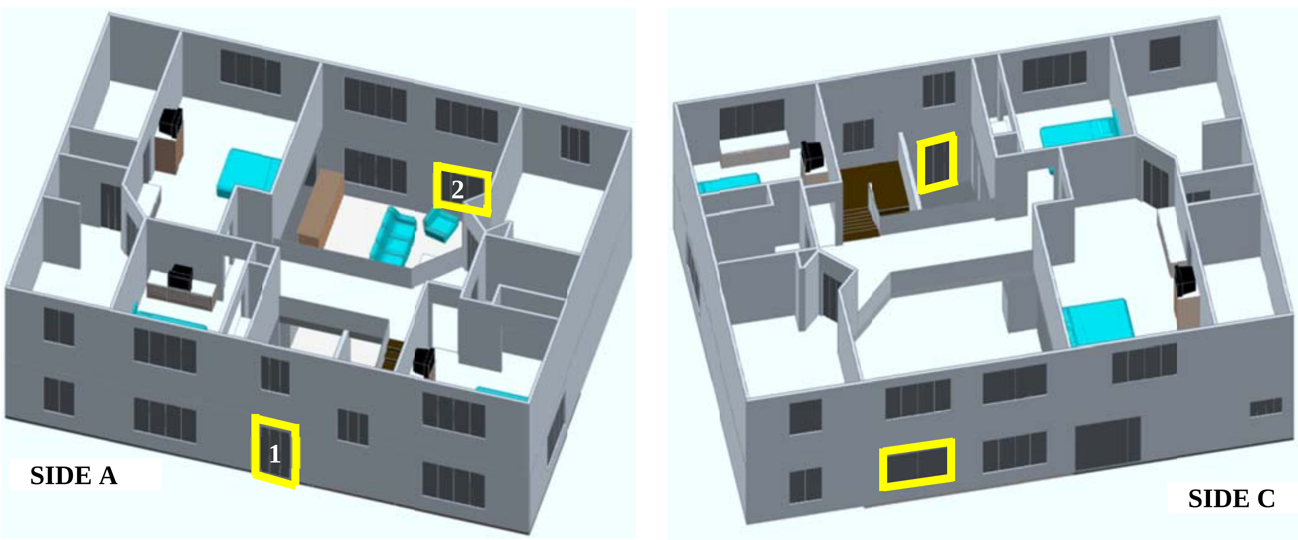


Figure 358. House graphic highlighting ventilation locations


Figure 359. Experiment 10 - 0:00

Figure 360. Experiment 10 - 0:00


Figure 361. Experiment 10 - 5:00


Figure 362. Experiment 10 - 10:05

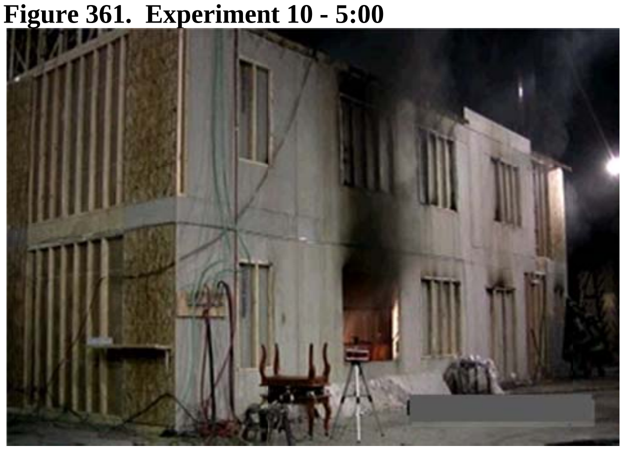


Figure 363. Experiment 10 - 10:20


Figure 364. Experiment 10 - 22:15


Figure 365. Experiment 10 - 24:50

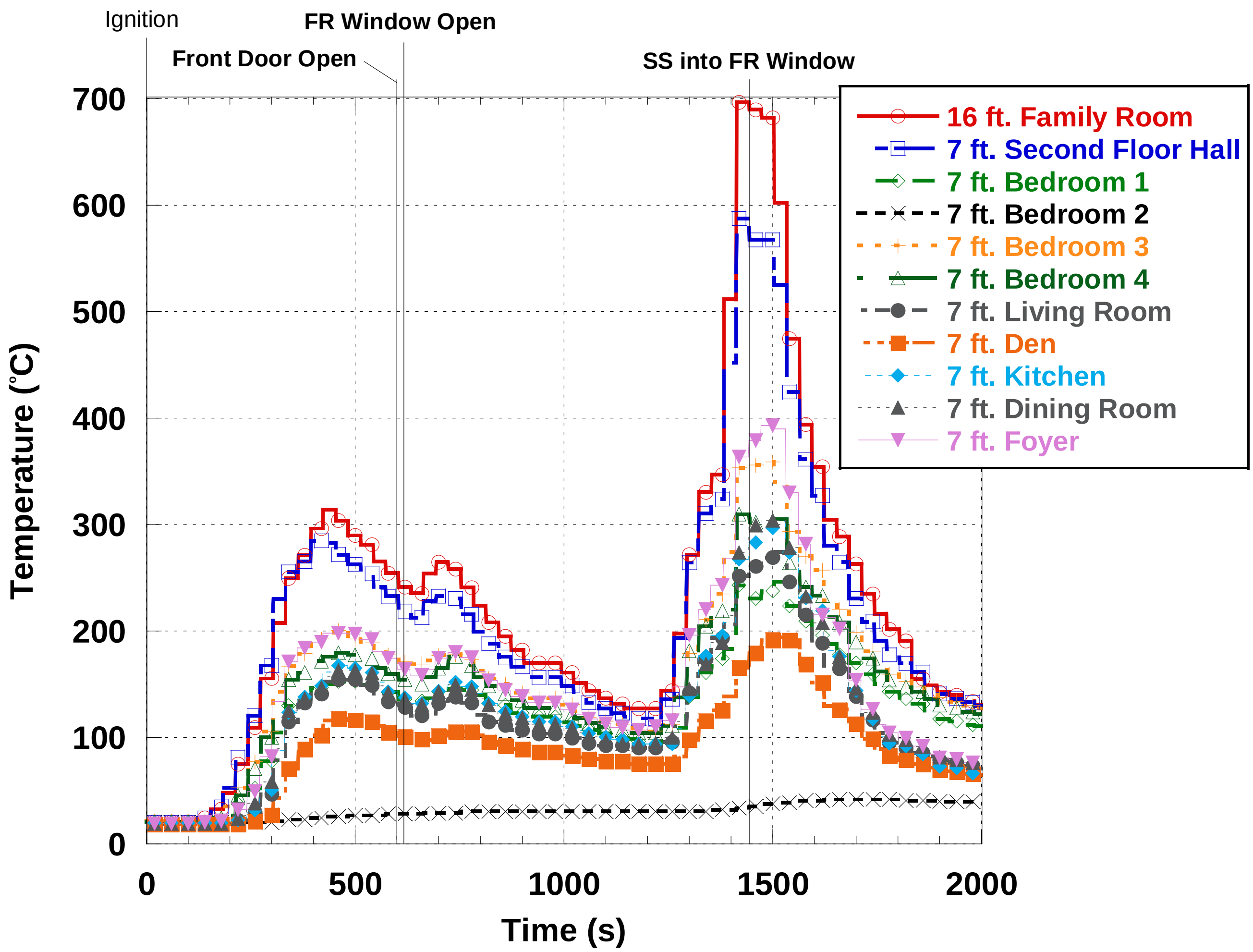


Figure 366. Experiment 10- 7ft. Temperatures

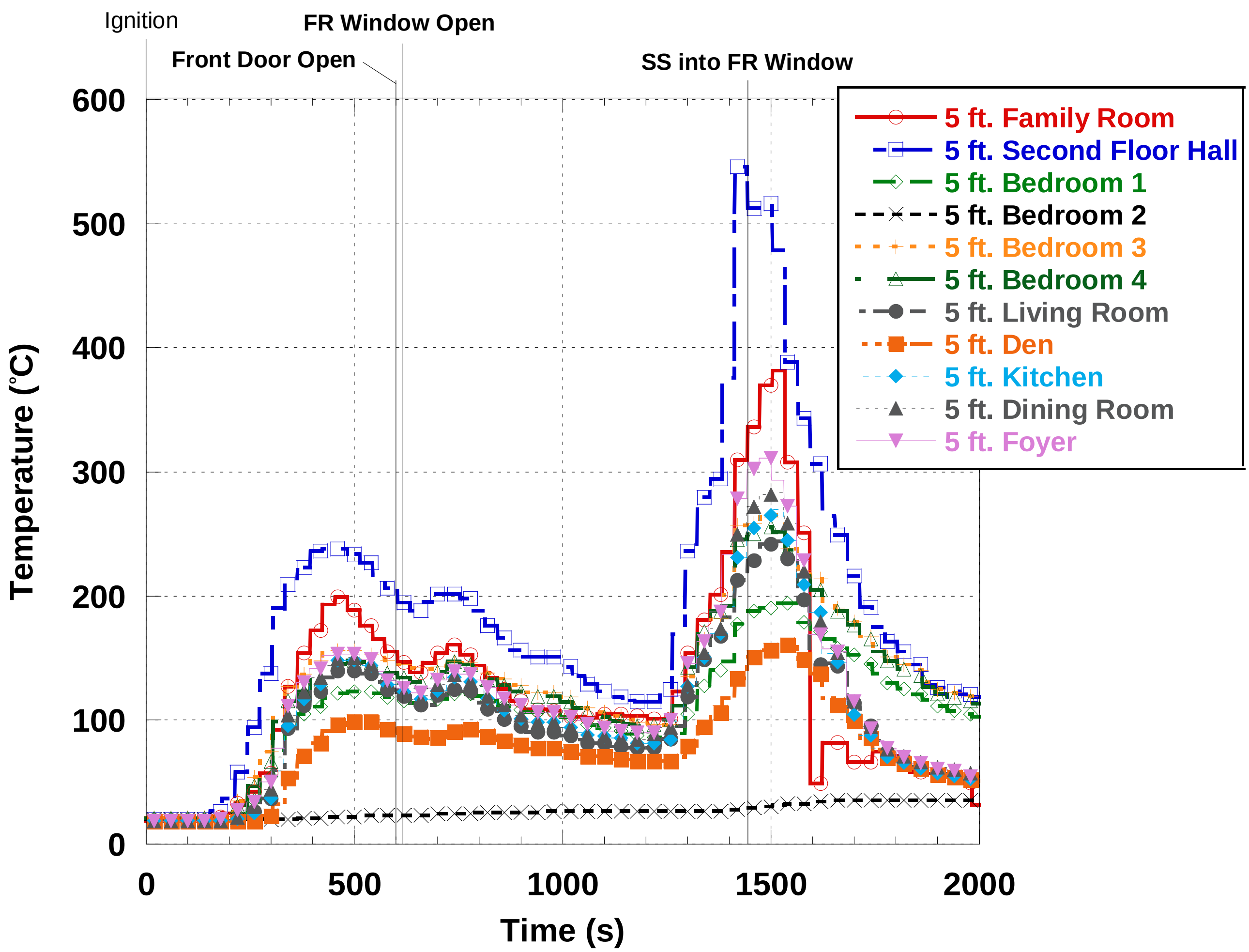


Figure 367. Experiment 10- 5ft. Temperatures

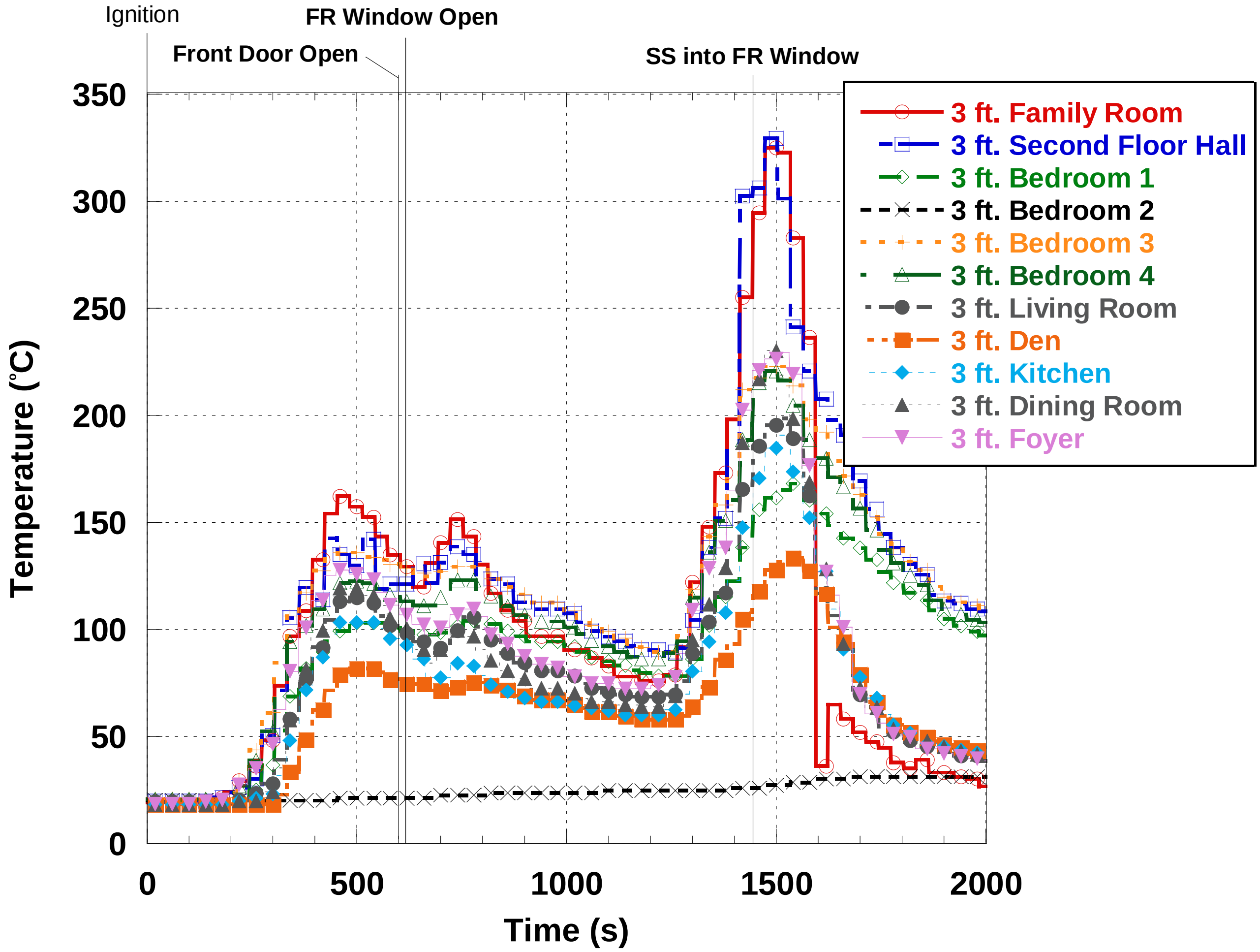


Figure 368. Experiment 10- 3ft. Temperatures

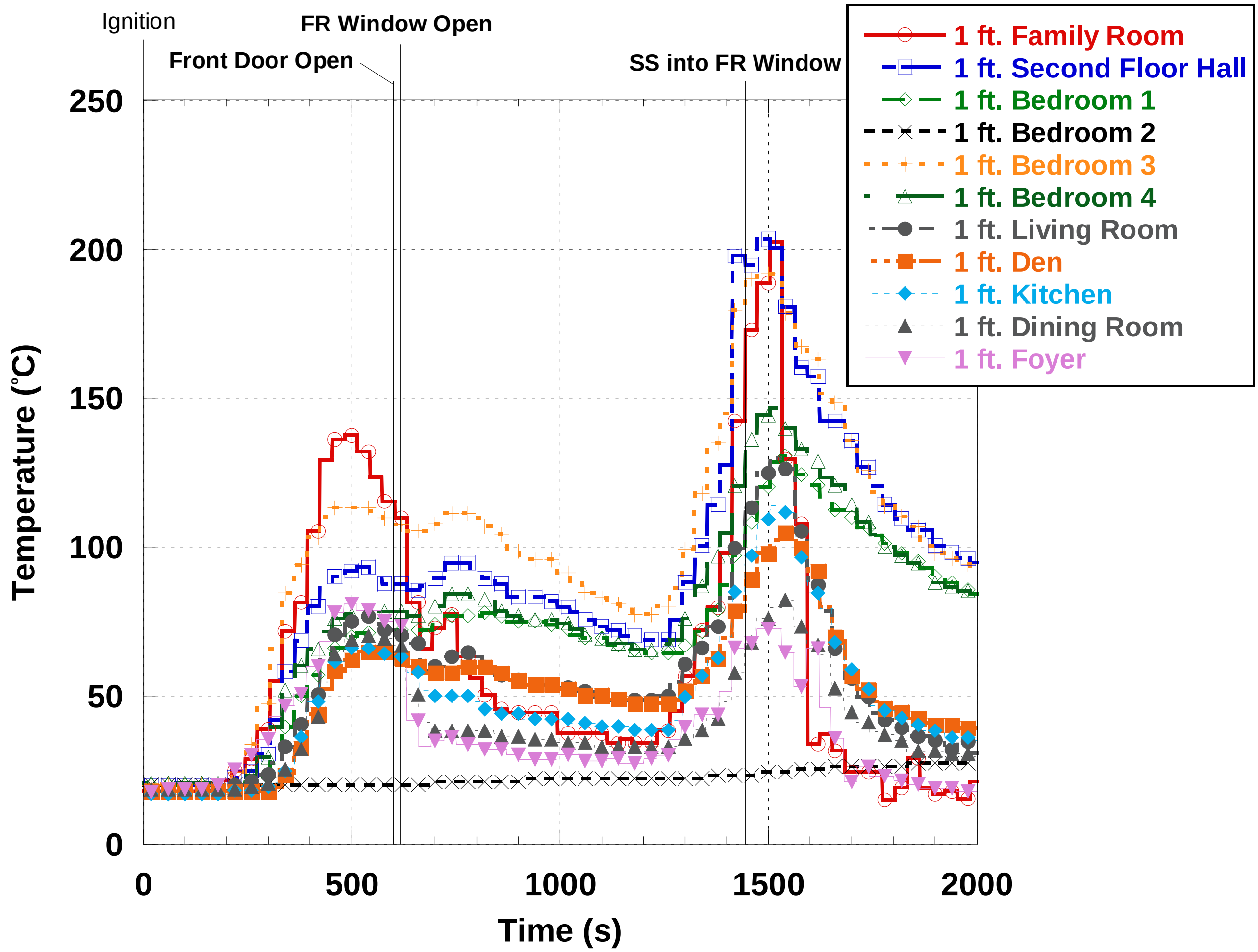


Figure 369. Experiment 10- 1ft. Temperatures

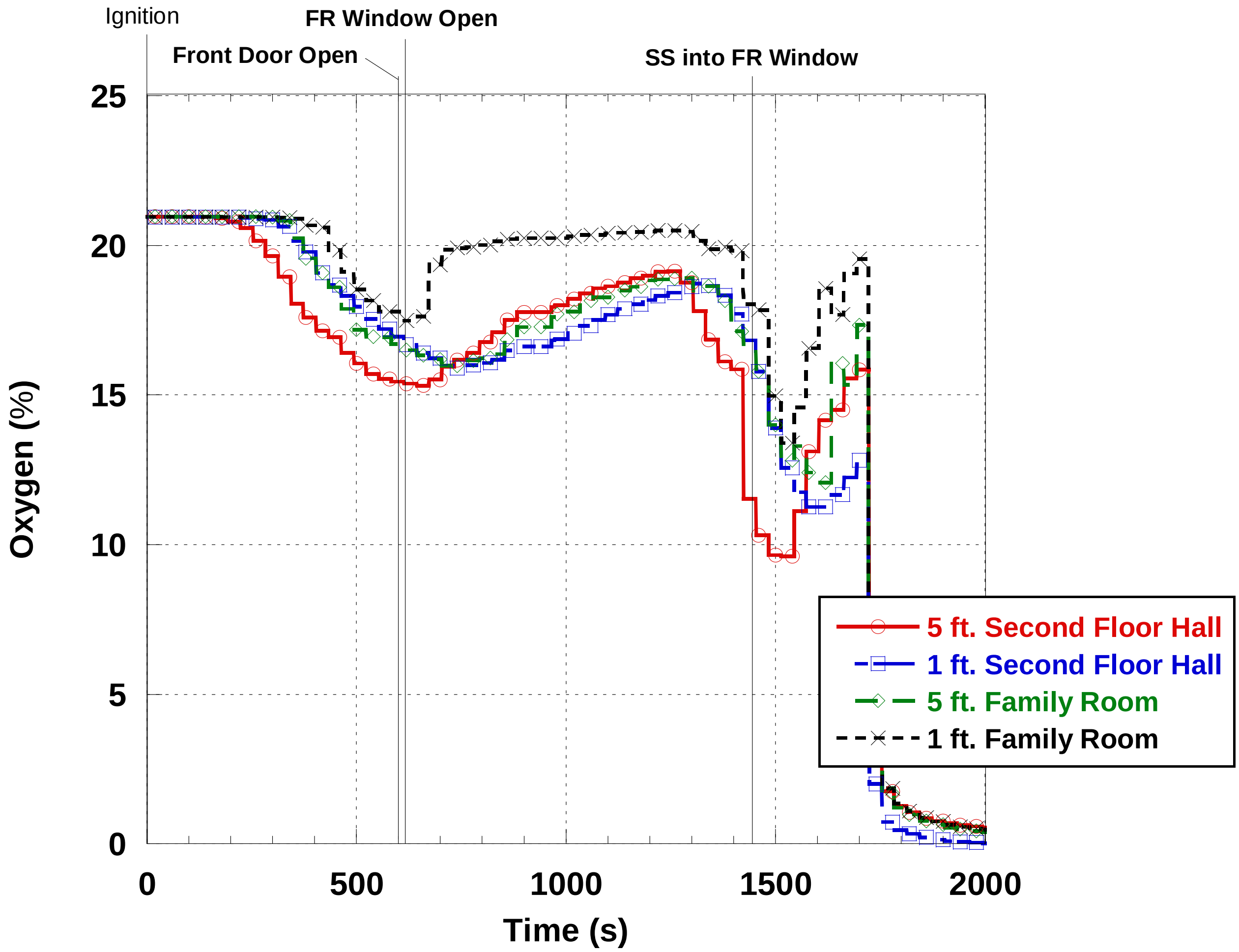


Figure 370. Experiment 10- Oxygen Concentration

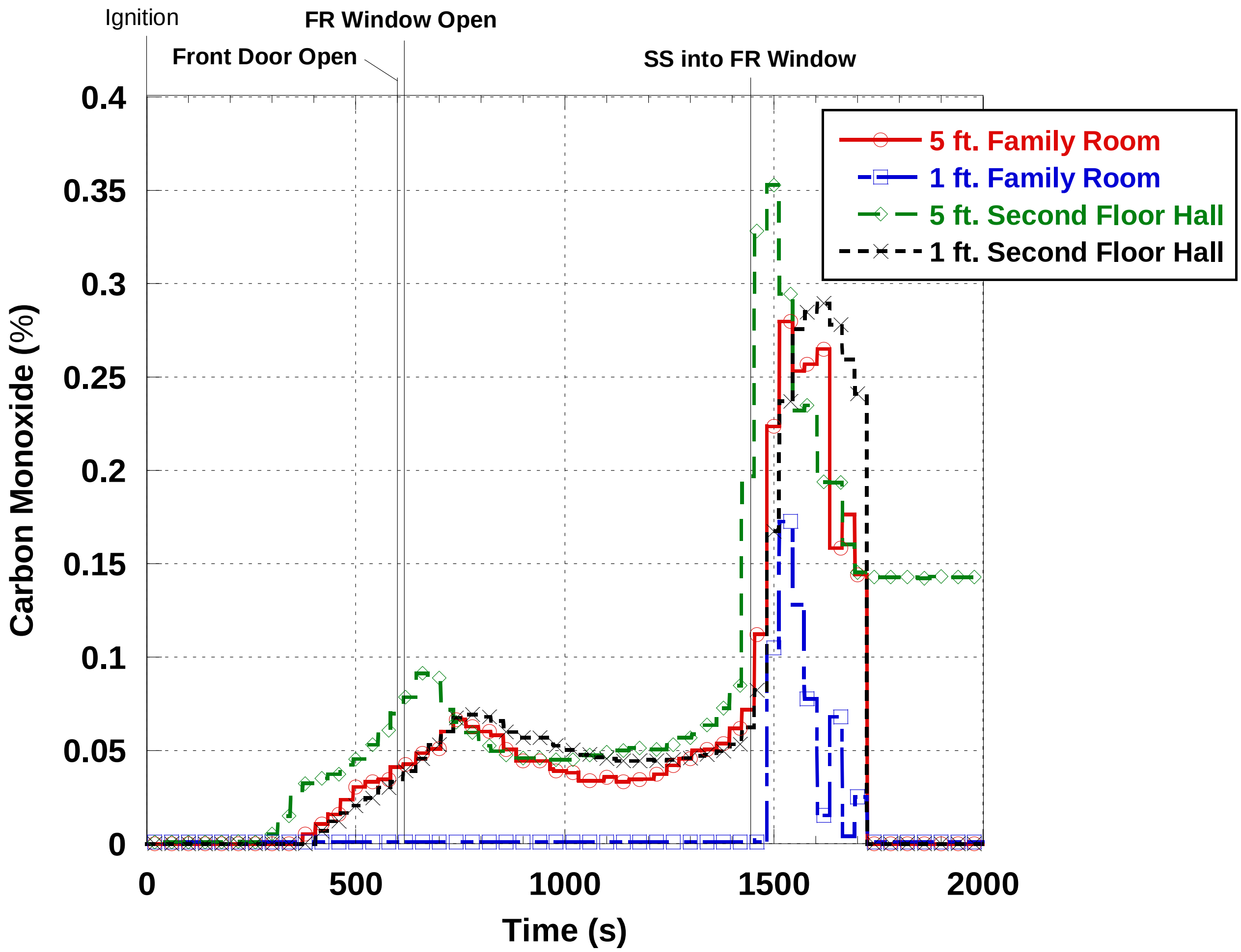


Figure 371. Experiment 10- CO Concentration

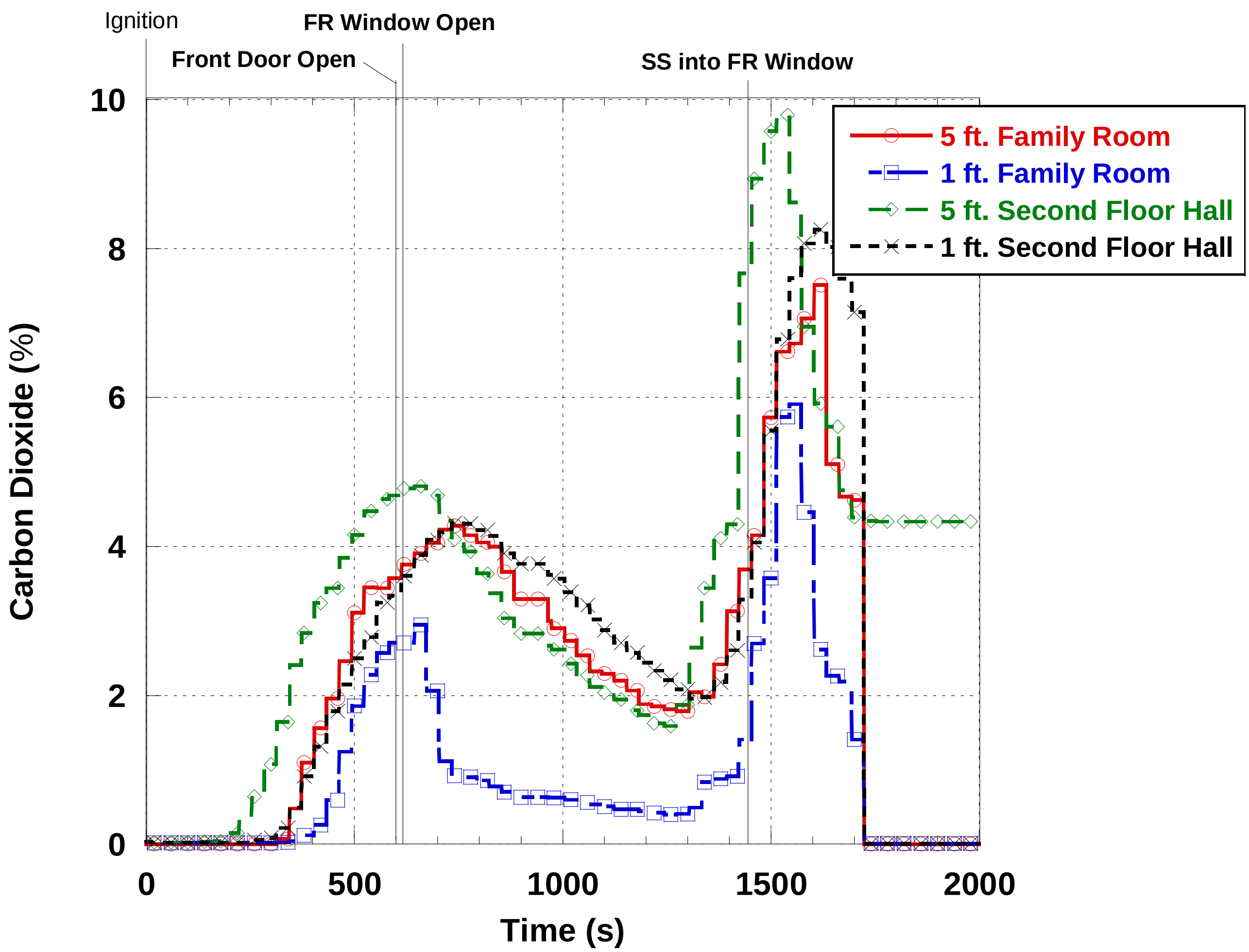


Figure 372. Experiment 10- CO_2 Concentration

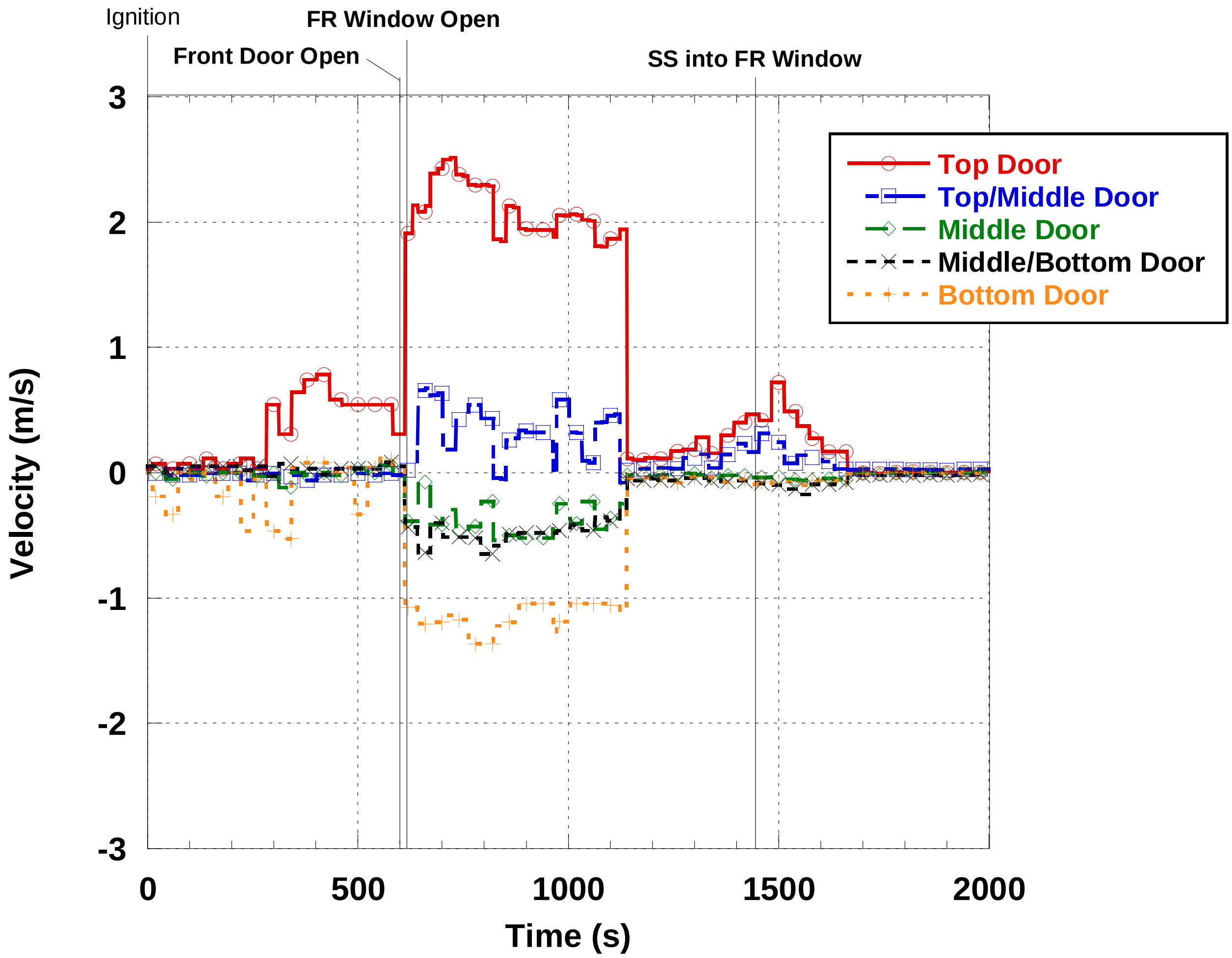


Figure 373. Experiment 10- Front Door Velocities

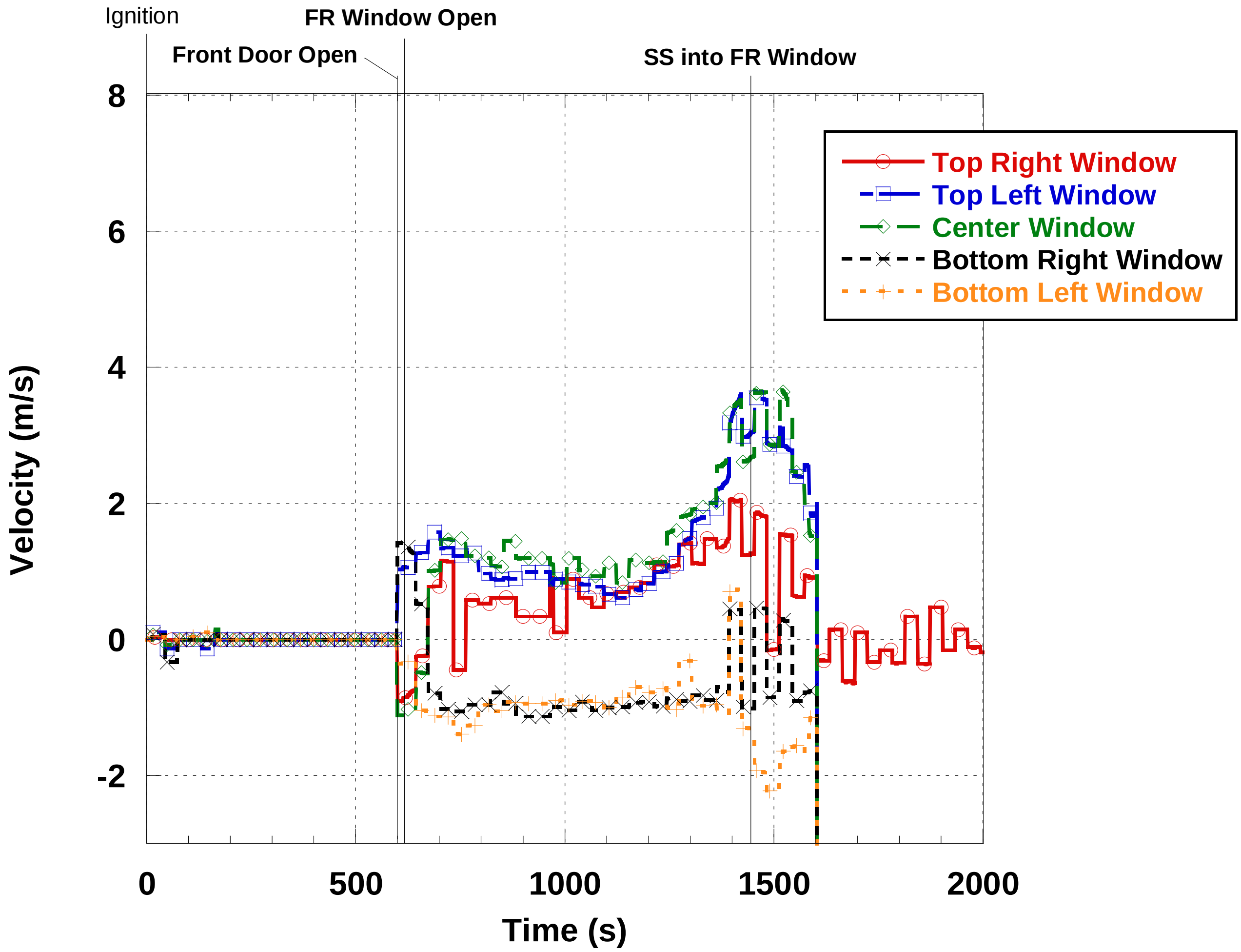


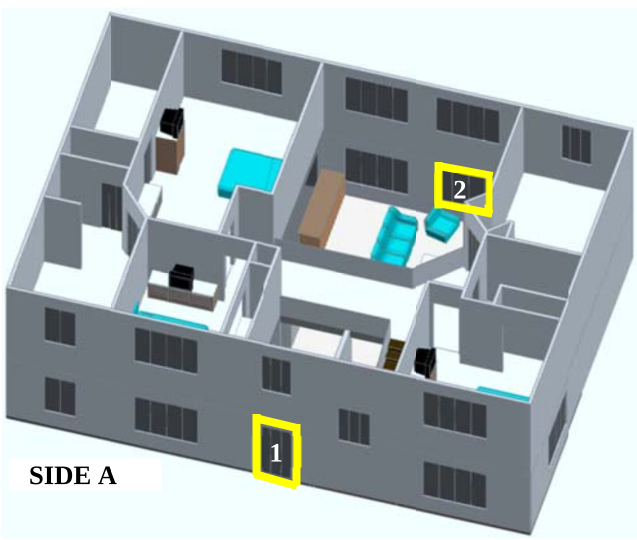
Figure 374. Experiment 10- Ventilation Window Velocities

8.7.6. Experiment 11

Experiment 11 was the sixth experiment conducted in the two-story house. This experiment was the third of three replicate experiments to examine repeatability. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the front door was opened. Fifteen seconds after the front door was opened the first floor family room window was opened (Table 30). The fire again was allowed to grow until 15:17 when 10 seconds of water were flowed into the front door with a combination nozzle positioned in a straight stream pattern. The experiment was terminated at 16:30 and was extinguished by the suppression crew. Figure 376 through Figure 383 show the front and rear of the house during the experiment.

Table 30. Experiment 11 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	10:00
Living Room Window Open	10:15
Straight Stream into Living Room Window	15:17-15:27
End of Experiment	16:30



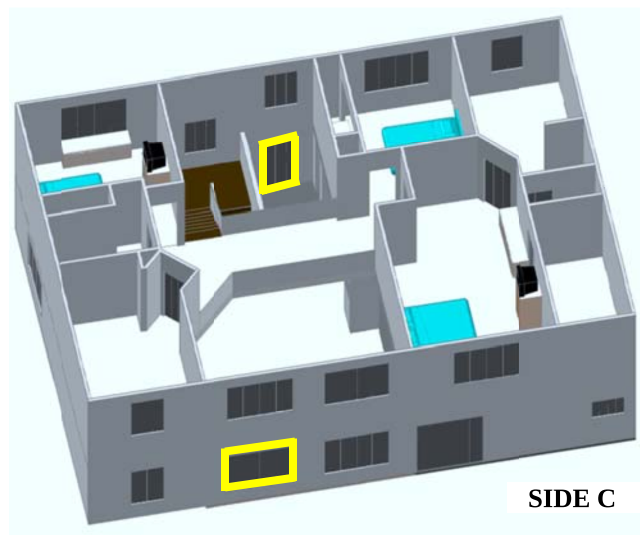


Figure 375. House graphic highlighting ventilation locations

Figure 376. Experiment 11 - 0:00

Figure 377. Experiment 11 - 0:00

Figure 378. Experiment 11 - 5:00

Figure 379. Experiment 11 - 10:05

Figure 380. Experiment 11 - 10:20

Figure 381. Experiment 11 - 14:25

Figure 382. Experiment 11 - 14:25

Figure 383. Experiment 11 - 15:20

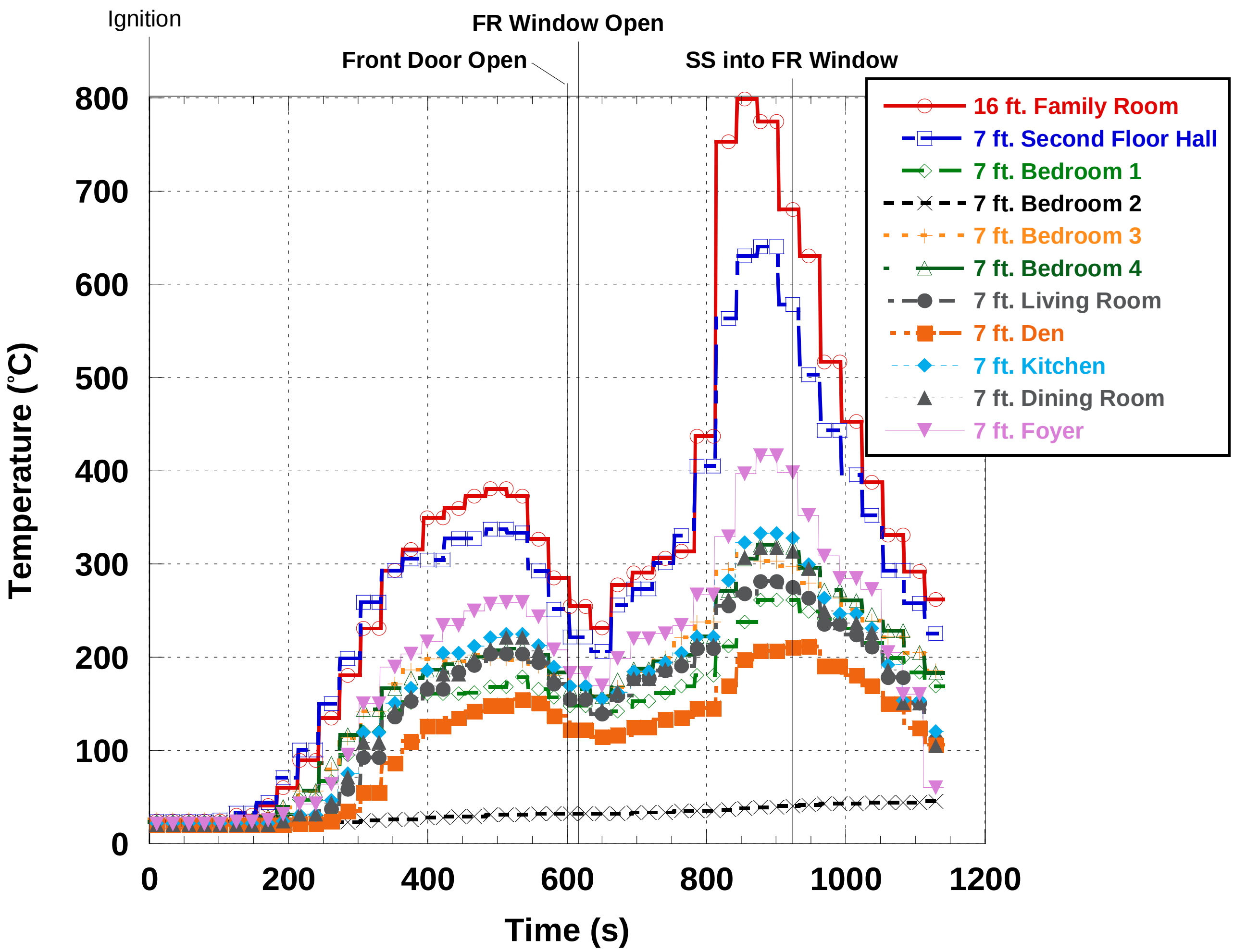


Figure 384. Experiment 11- 7ft. Temperatures

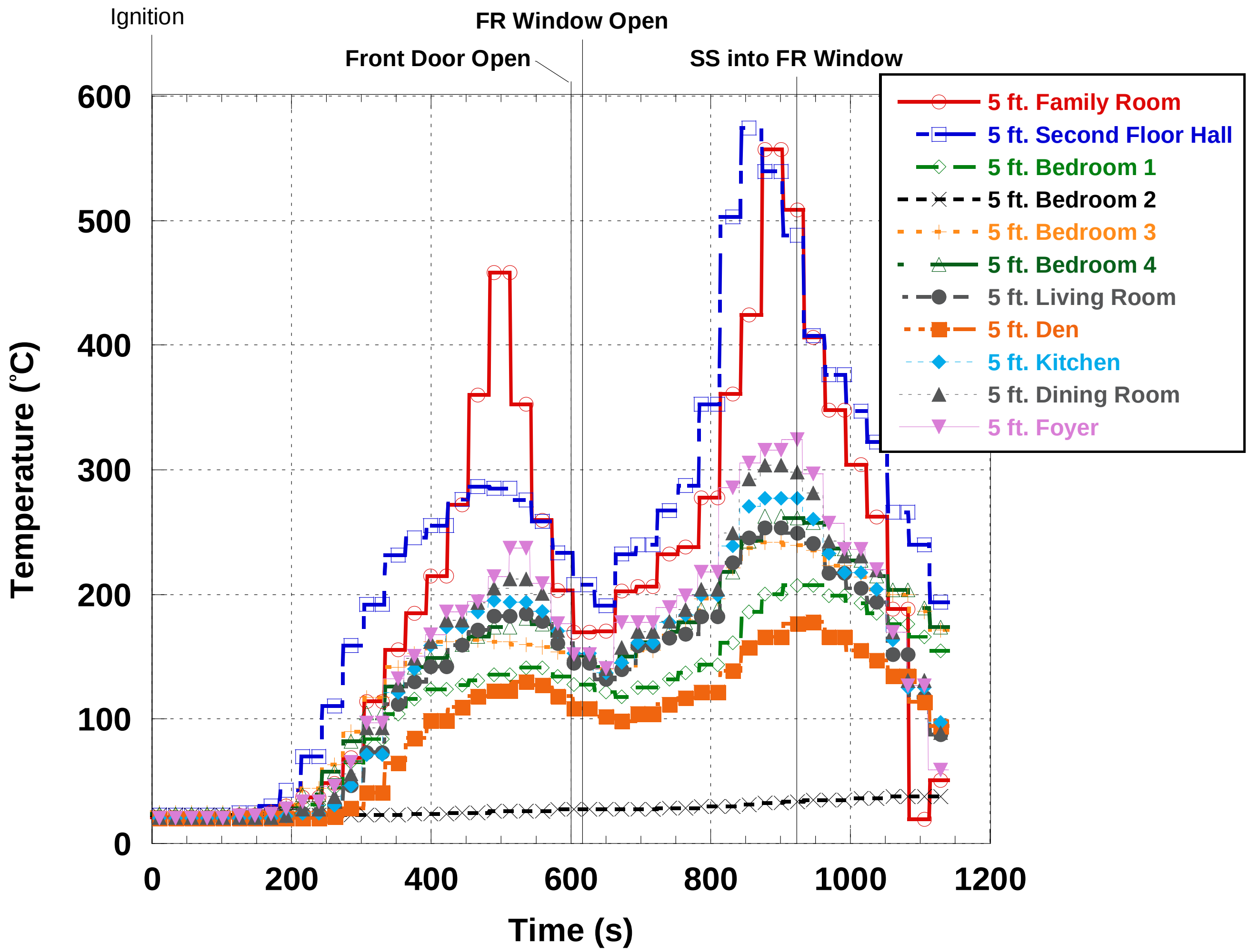


Figure 385. Experiment 11- 5ft. Temperatures

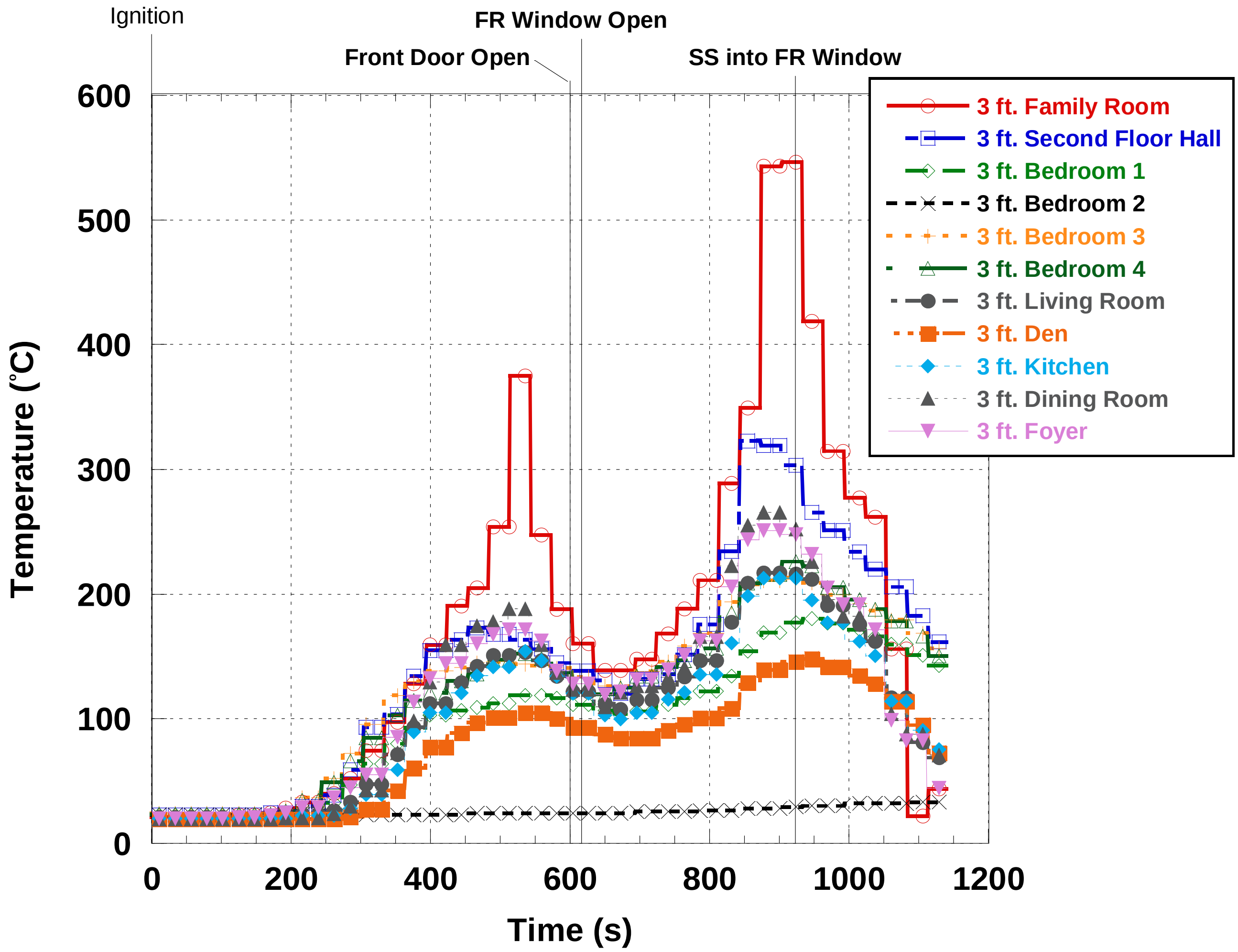


Figure 386. Experiment 11- 3ft. Temperatures

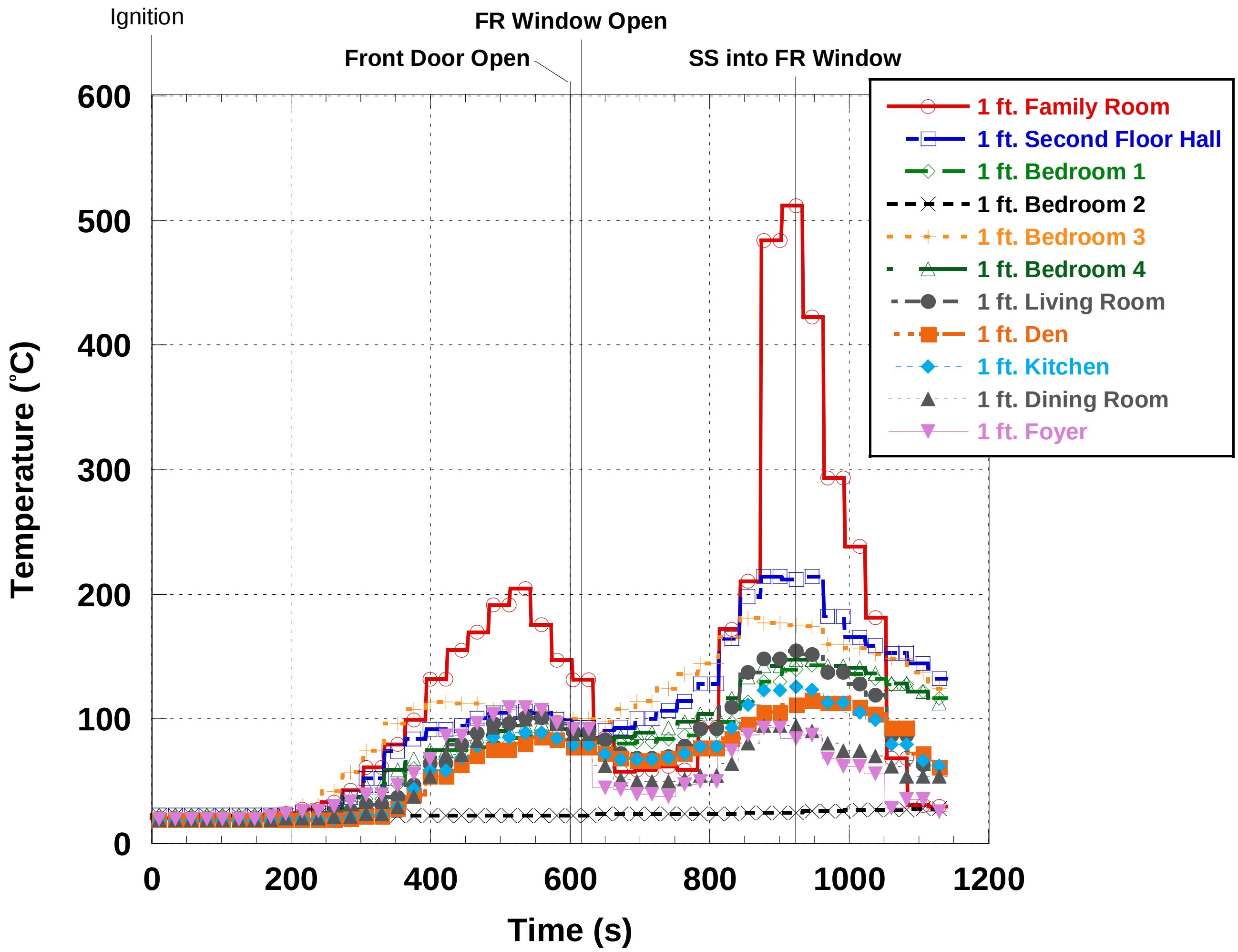


Figure 387. Experiment 11- 1ft. Temperatures

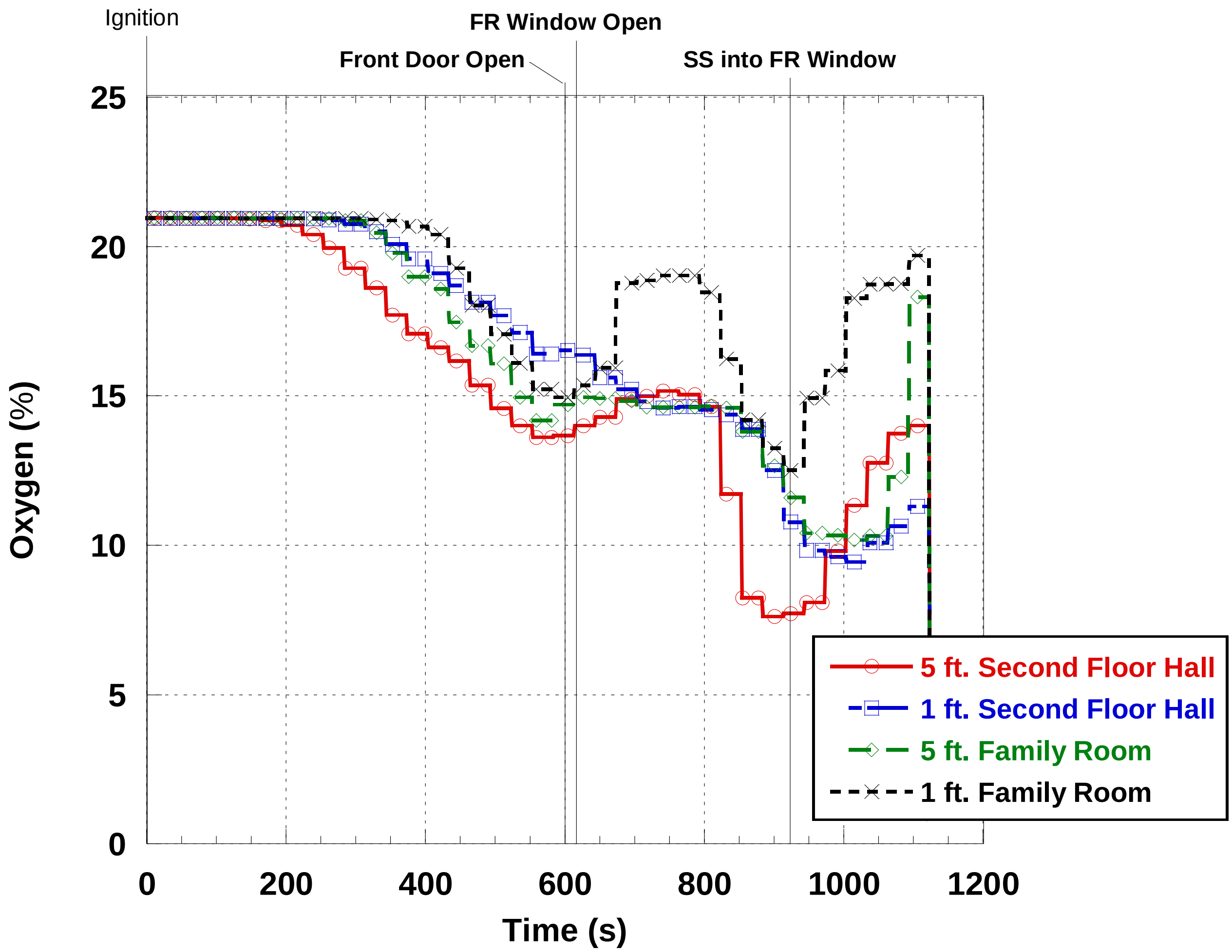


Figure 388. Experiment 11- Oxygen Concentration

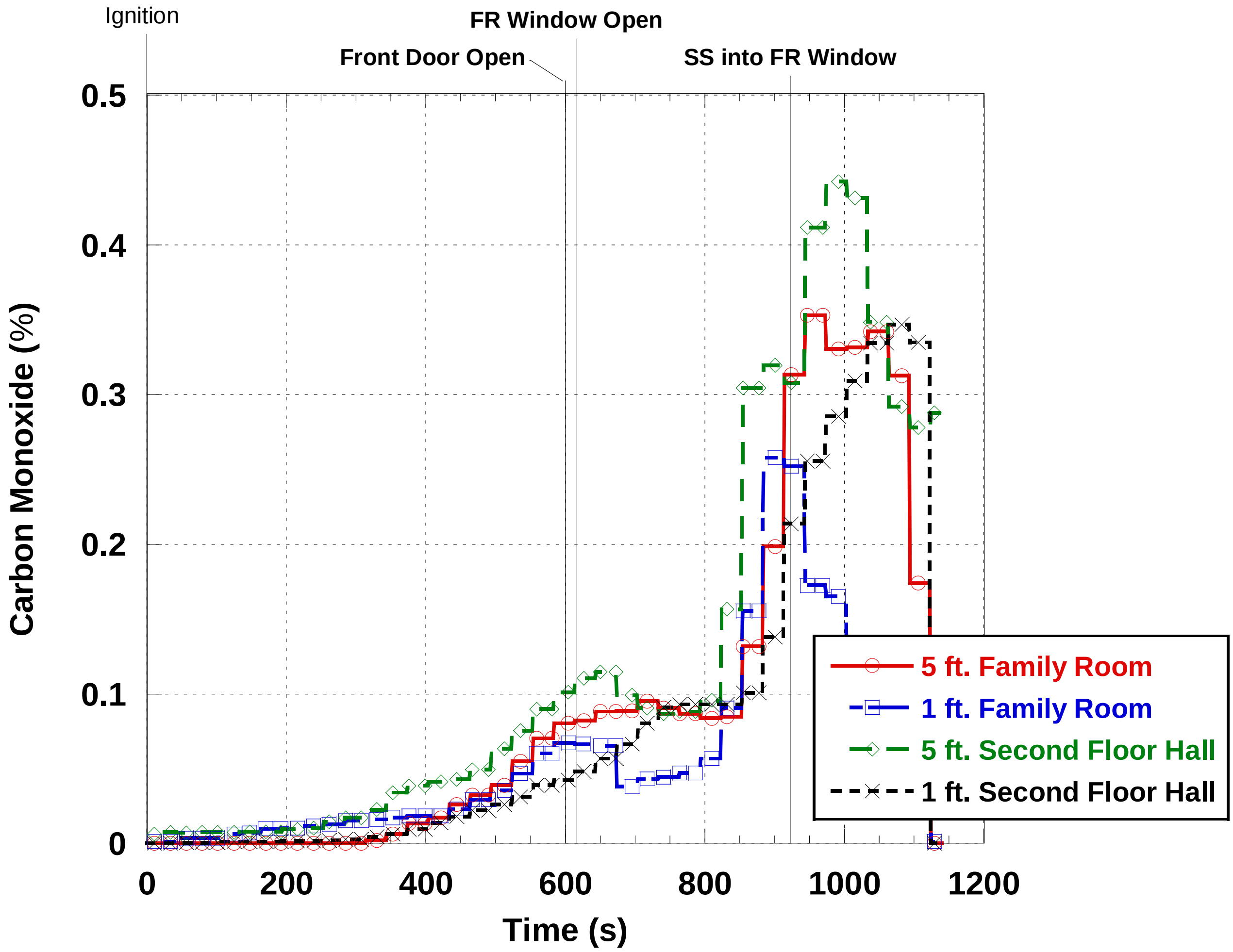


Figure 389. Experiment 11- CO Concentration

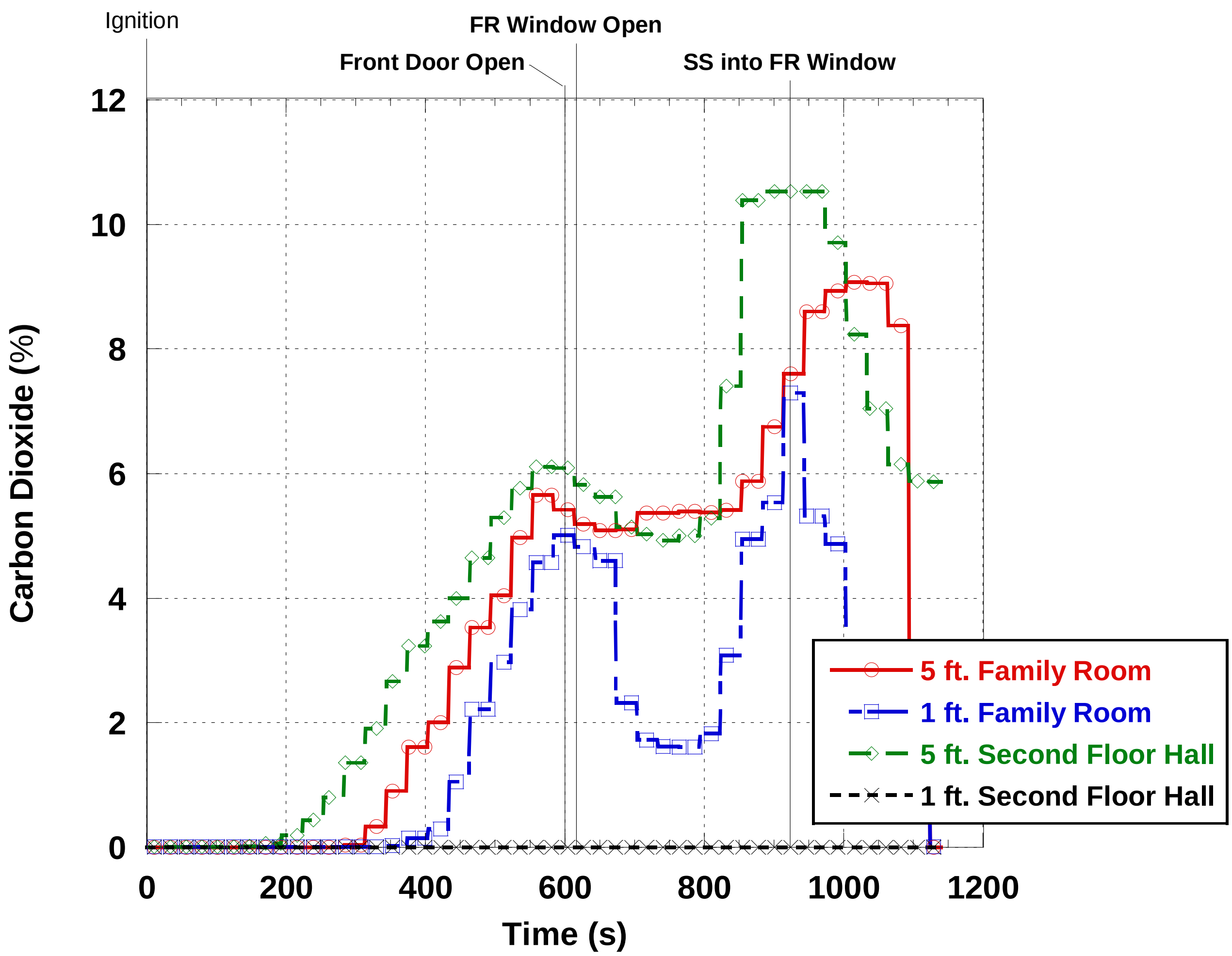


Figure 390. Experiment 11- CO_2 Concentration

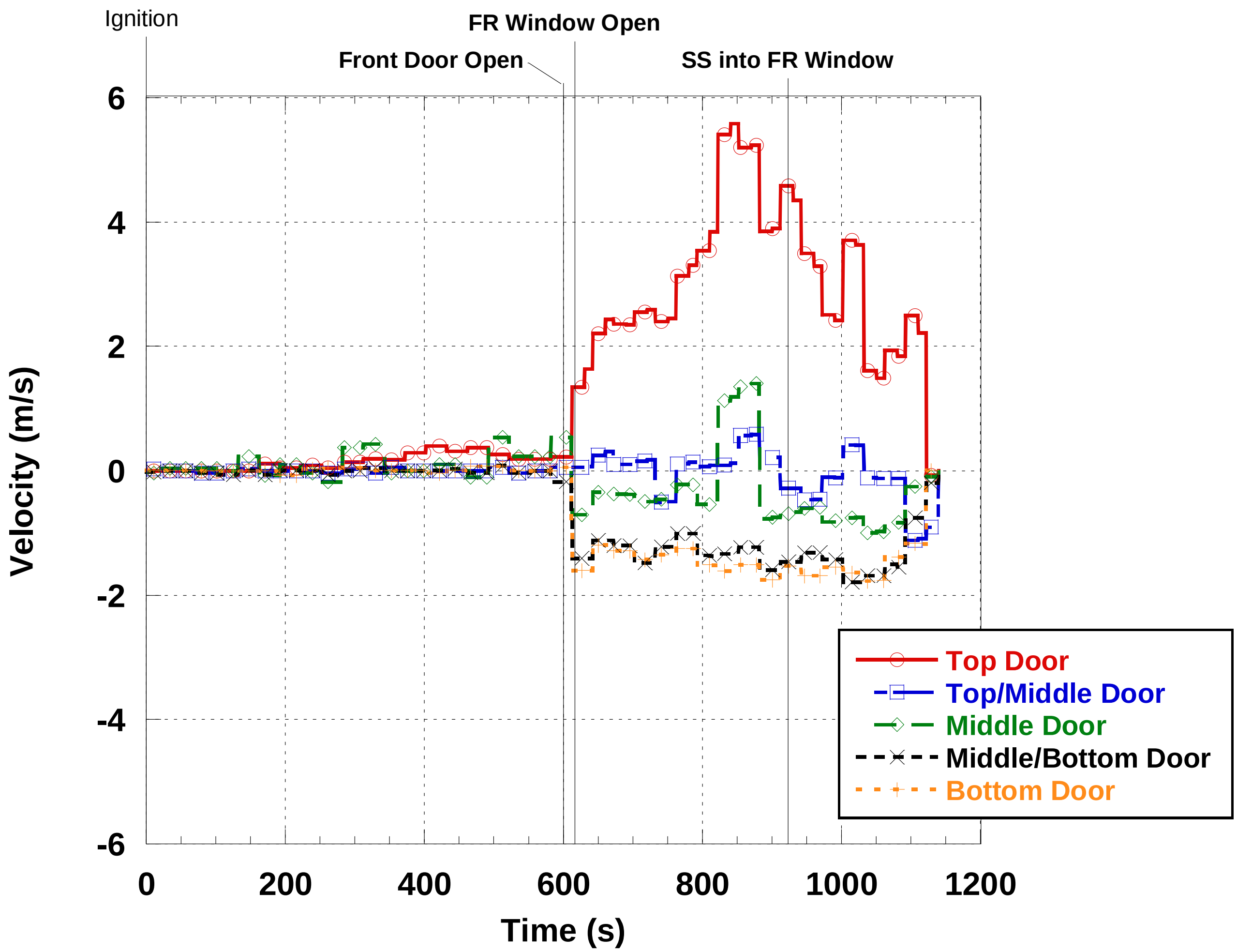


Figure 391. Experiment 11- Front Door Velocities

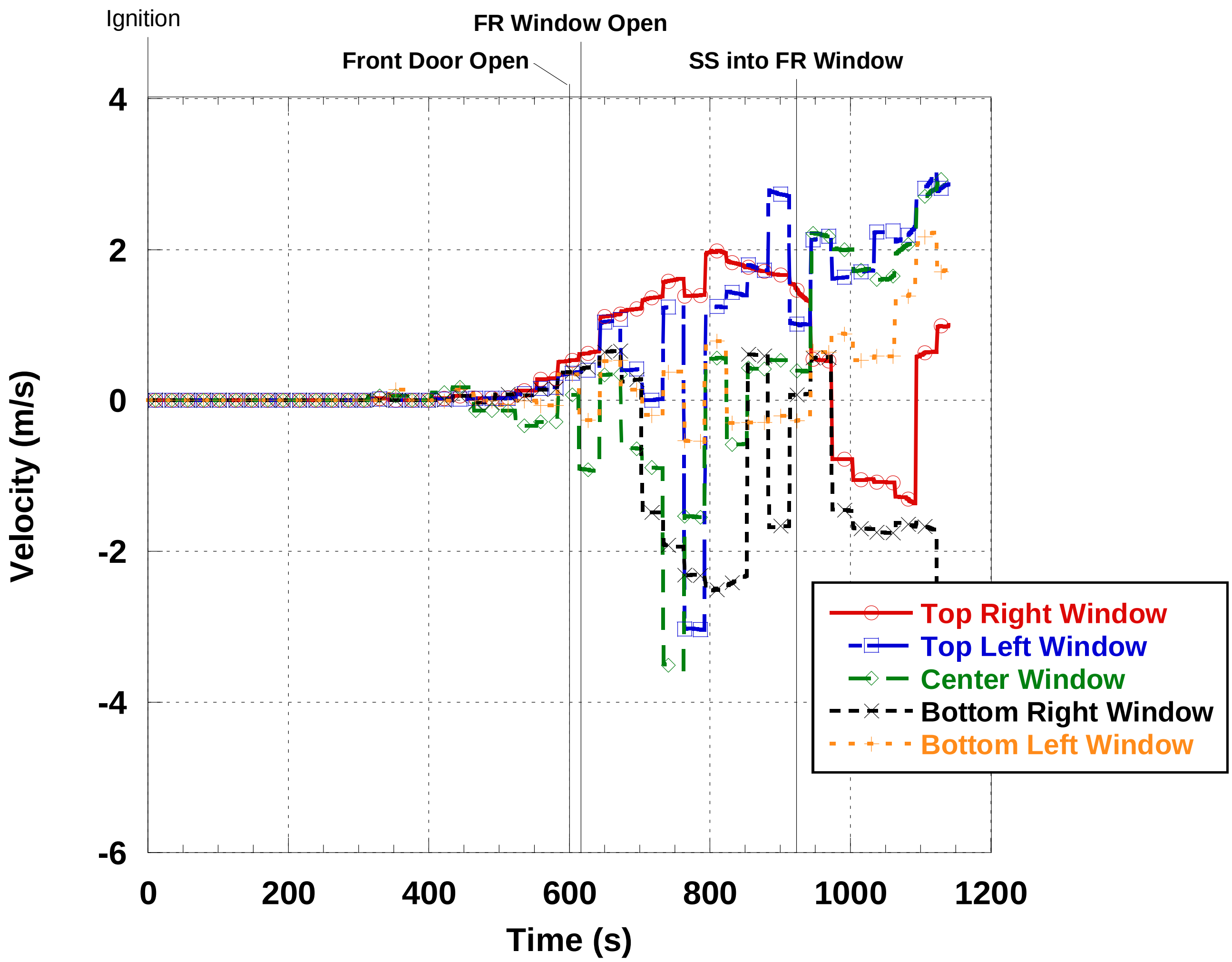


Figure 392. Experiment 11- Ventilation Window Velocities

8.7.7. Experiment 13

Experiment 13 was the seventh experiment conducted in the two-story house. This experiment was designed to examine the impact of ventilation horizontally as high as possible near the seat of the fire. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the front door was opened. Fifteen seconds after the front door was opened the second floor family room window was opened (Table 31). The fire again was allowed to grow until 12:28 when 10 seconds of water were flowed into the second floor family room window with a combination nozzle positioned in a straight stream pattern. A second 10 s burst of water was directed into the same window at 14:28 with the same nozzle positioned in a fog pattern. The experiment was terminated at 15:30 and was extinguished by the suppression crew. Figure 394 through Figure 401 show the front and rear of the house during the experiment.

Table 31. Experiment 13 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	10:00
Upper Living Room Window Open	10:15
Straight Stream into Living Room Window	12:28-12:38
Fog Stream into Living Room Window	14:28-14:38
End of Experiment	15:30

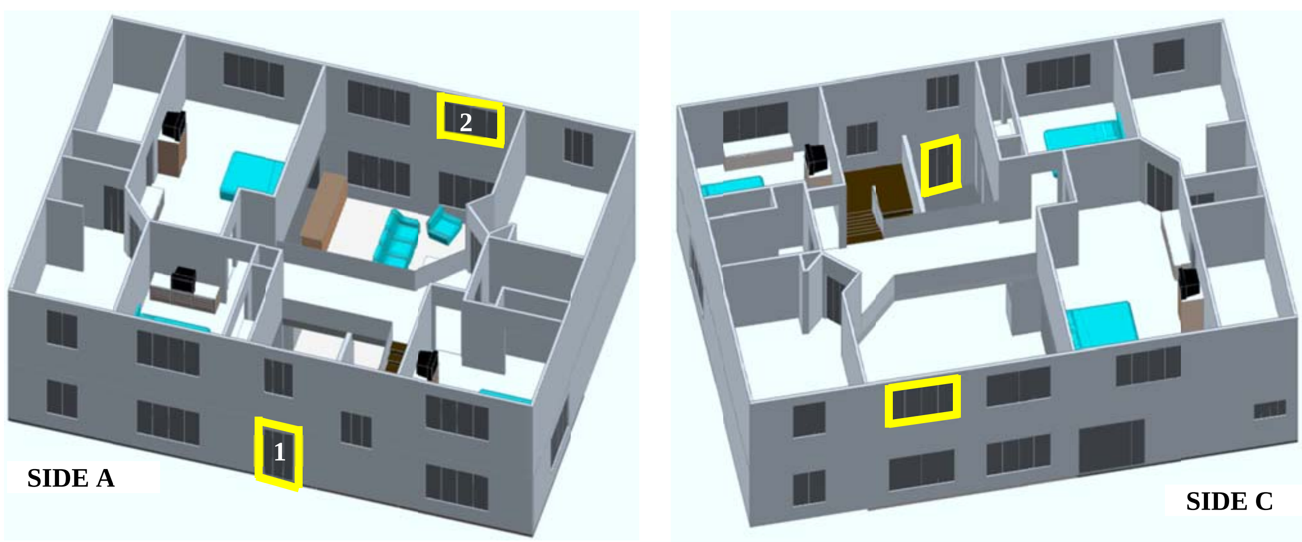


Figure 393. House graphic highlighting ventilation locations

Figure 394. Experiment 13 - 0:00

Figure 395. Experiment 13 - 0:00

Figure 396. Experiment 13 - 5:00

Figure 397. Experiment 13 - 10:05

Figure 398. Experiment 13 - 10:20

Figure 399. Experiment 13 - 11:45

Figure 400. Experiment 13 - 12:35

Figure 401. Experiment 13 - 14:35

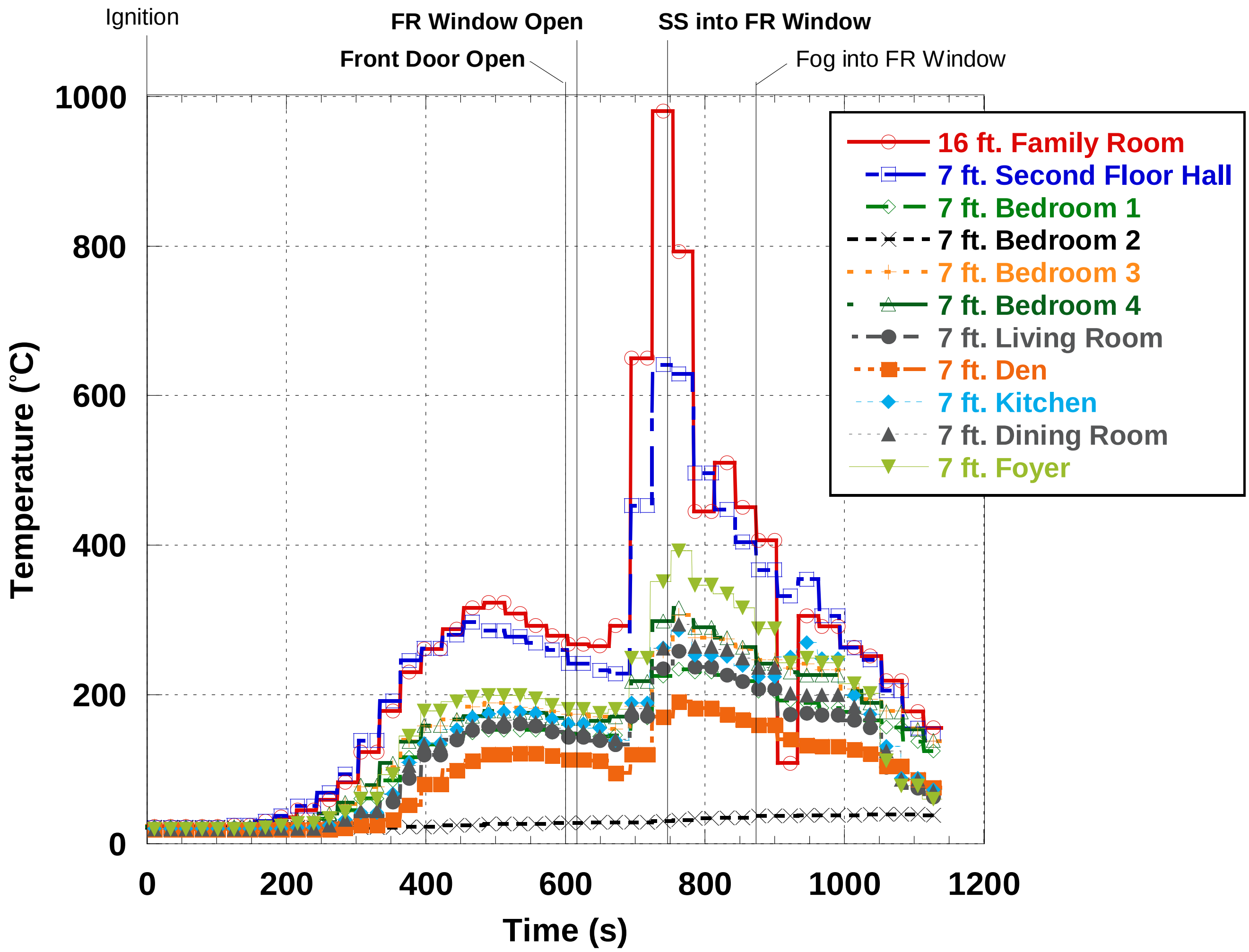


Figure 402. Experiment 13- 7ft. Temperatures

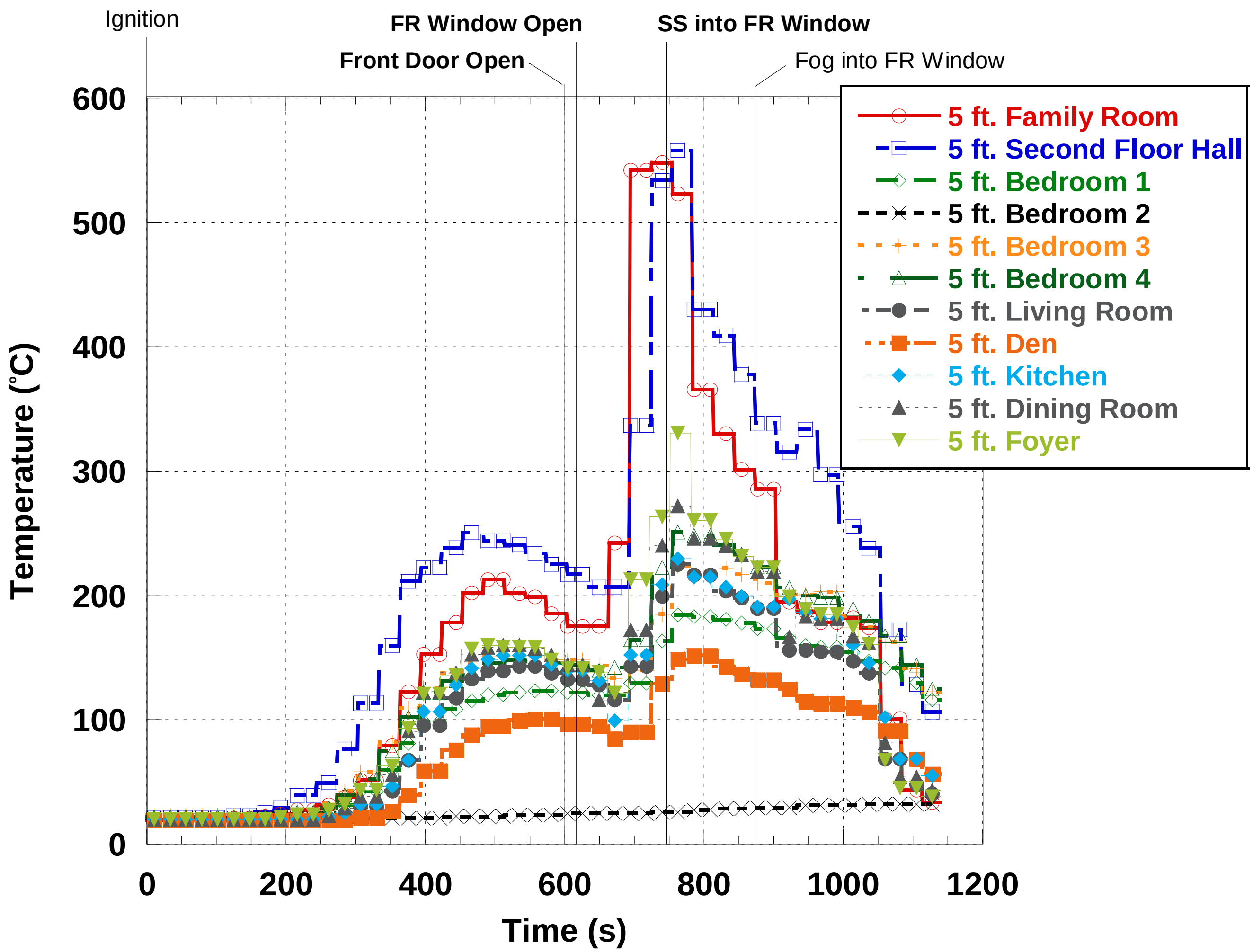


Figure 403. Experiment 13- 5ft. Temperatures

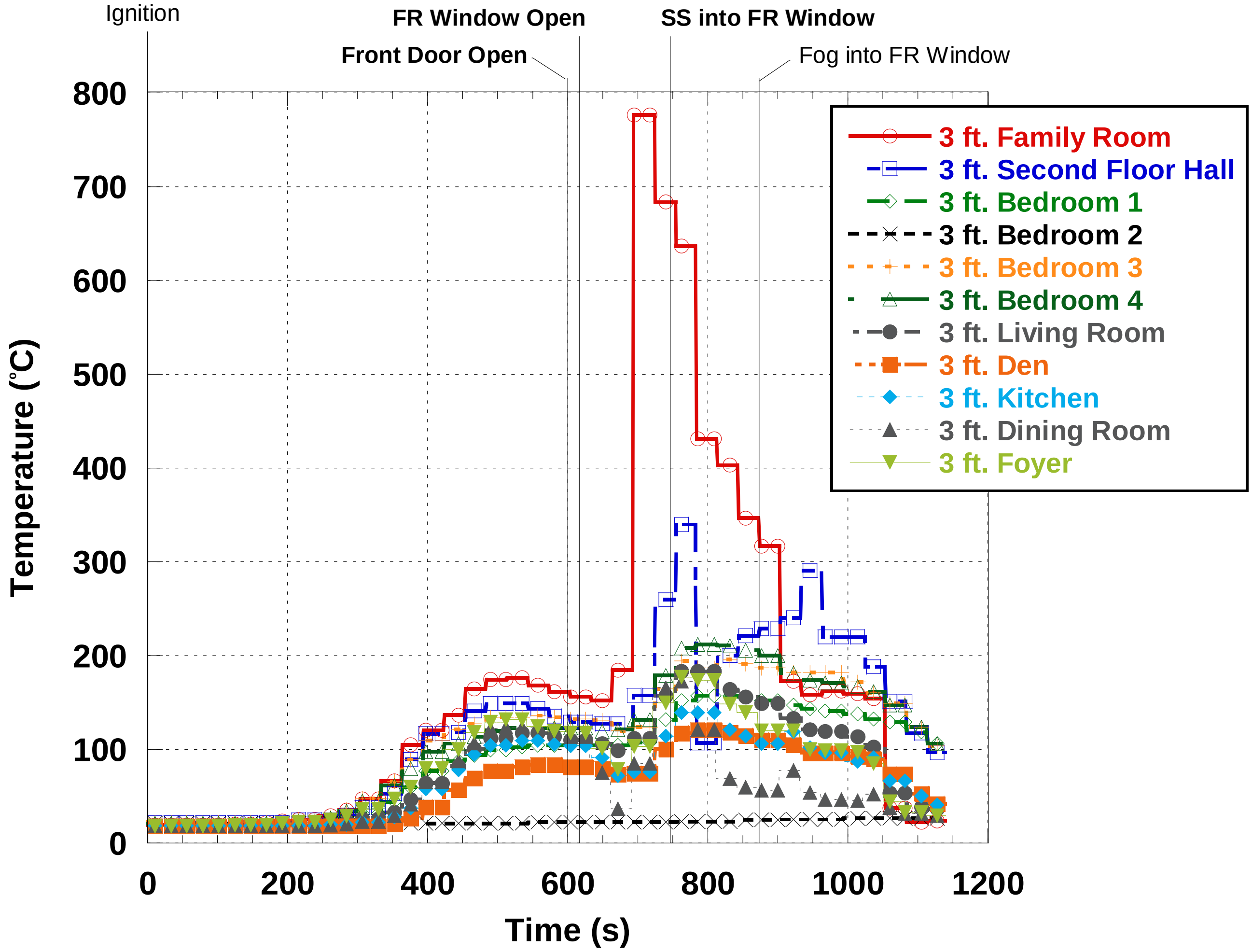


Figure 404. Experiment 13- 3ft. Temperatures

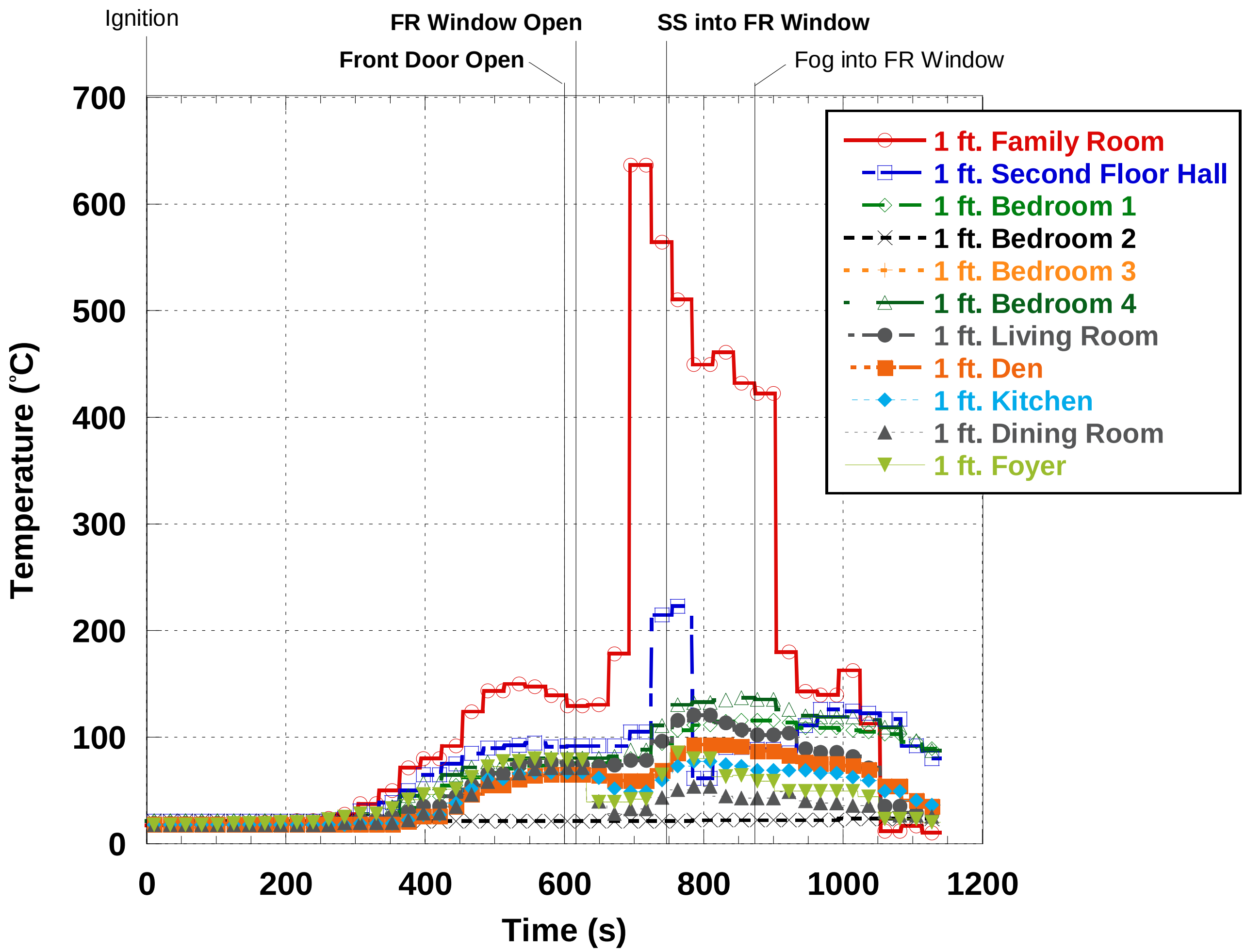


Figure 405. Experiment 13- 1ft. Temperatures

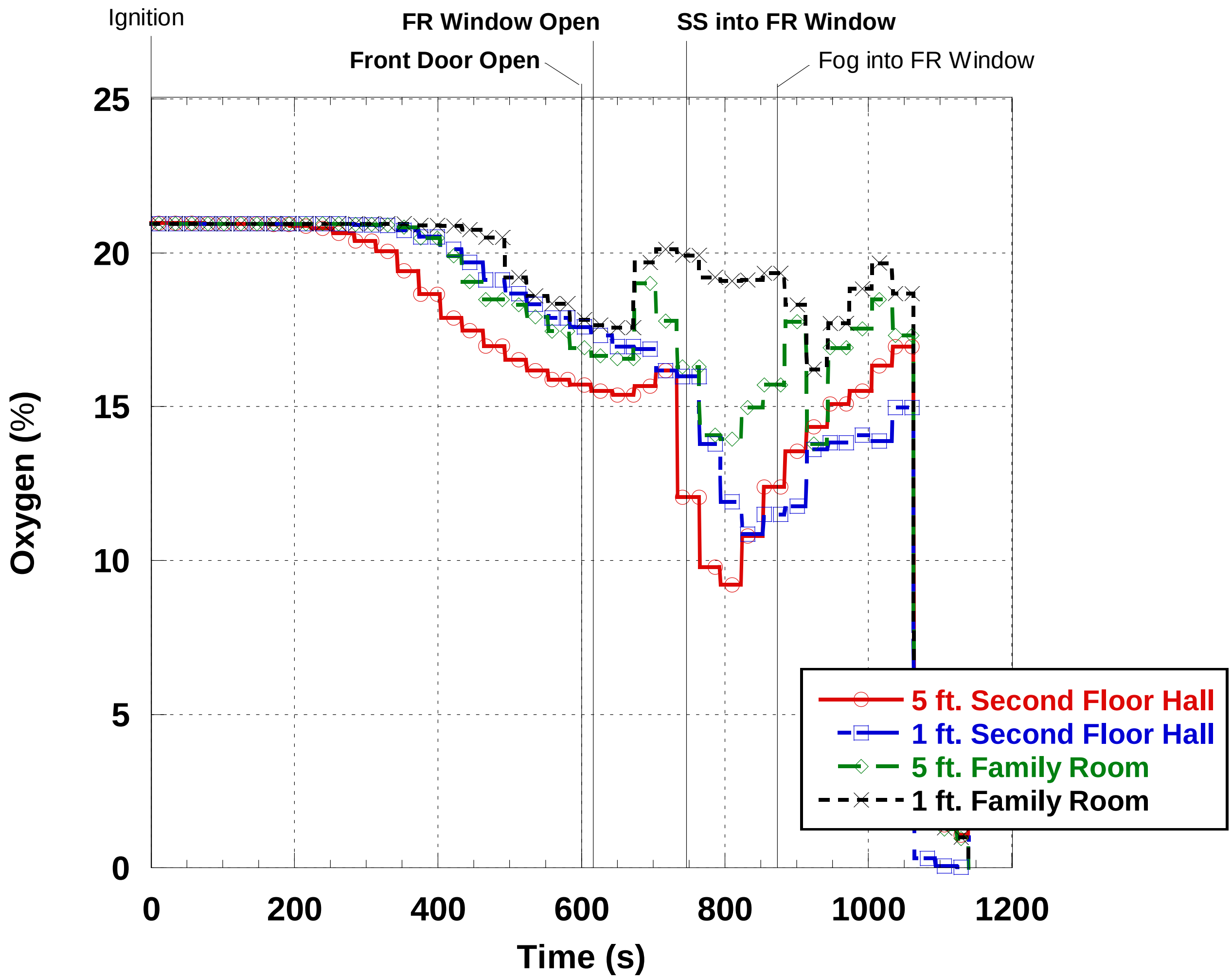


Figure 406. Experiment 13- Oxygen Concentration

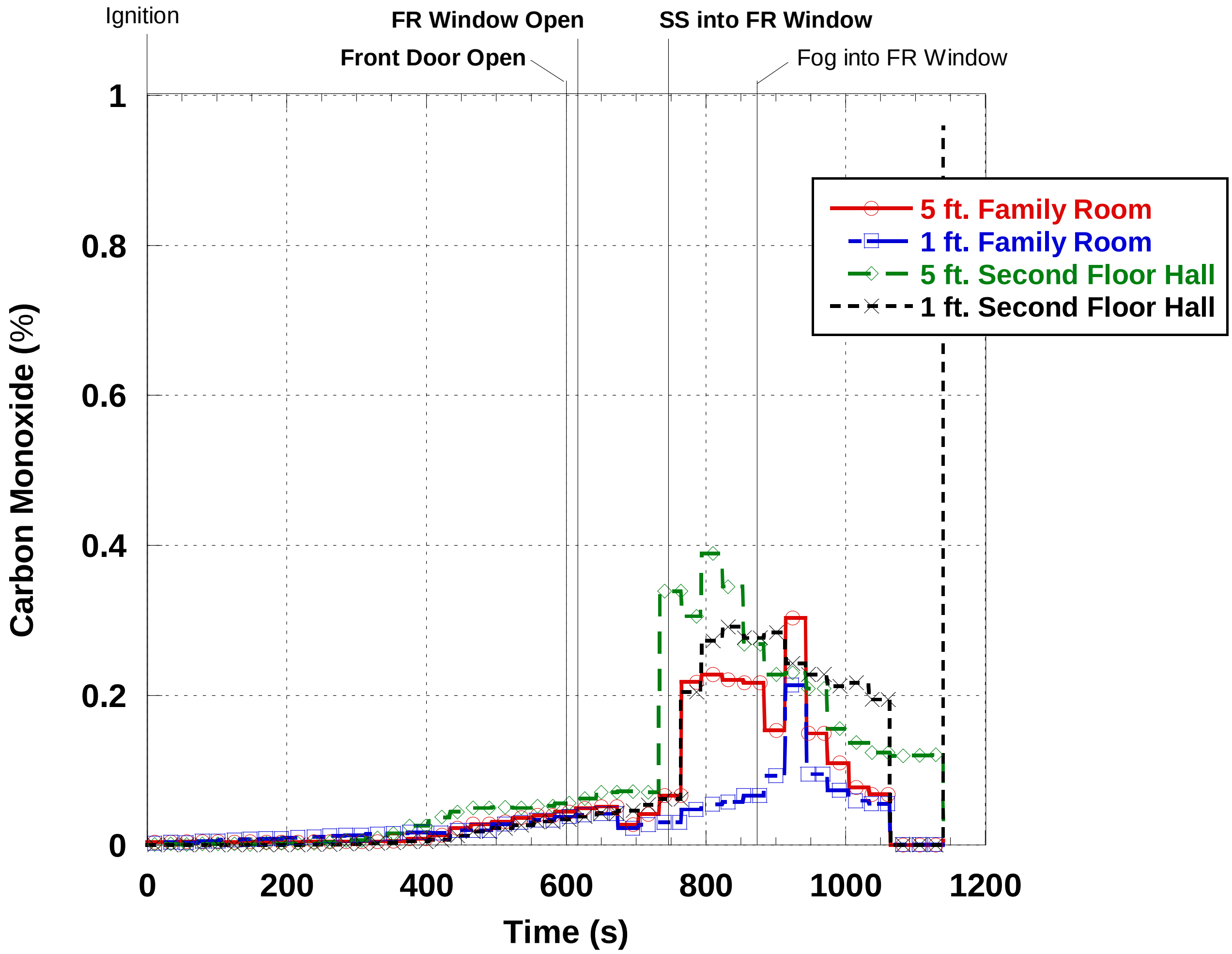


Figure 407. Experiment 13- CO Concentration

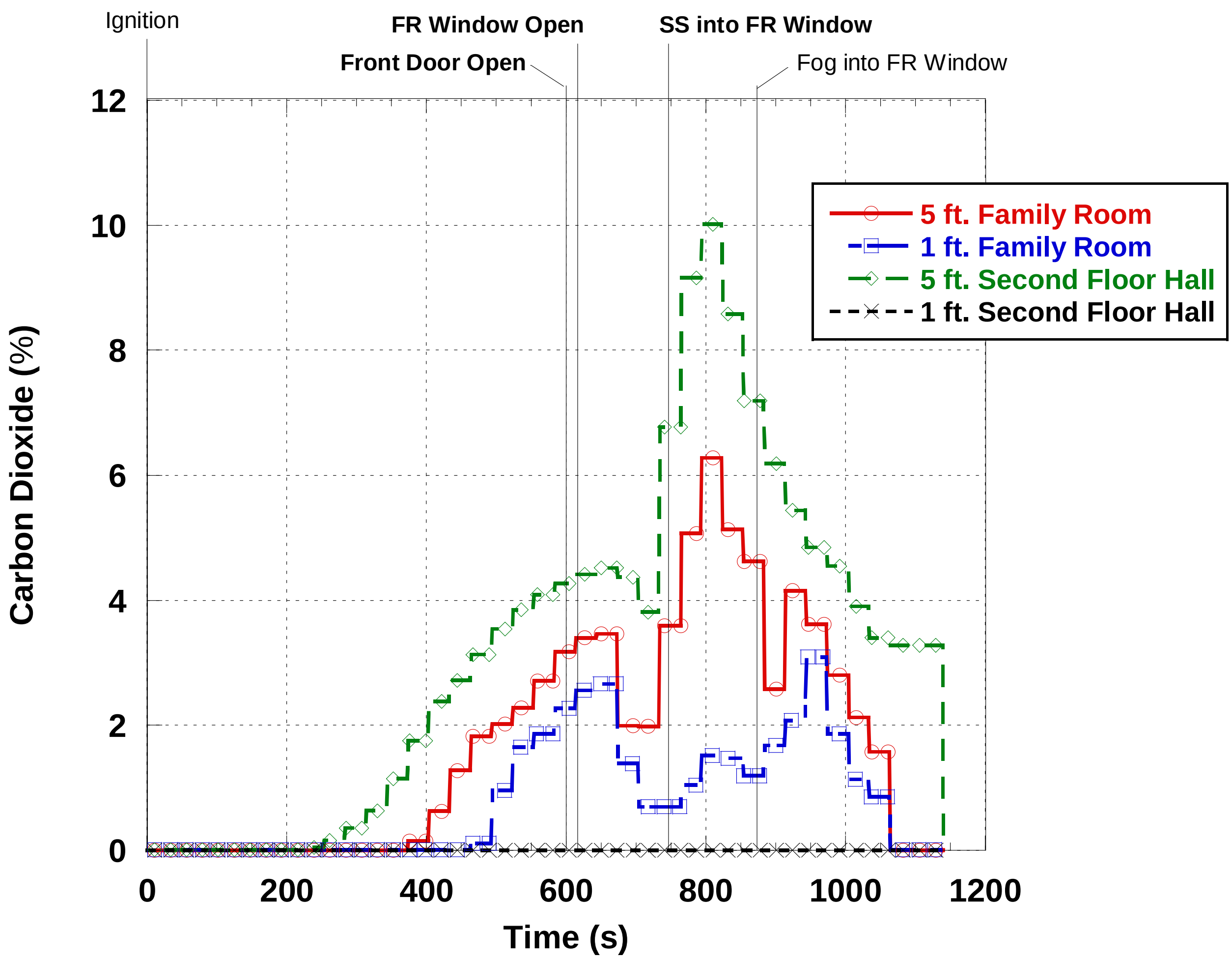


Figure 408. Experiment 13- CO_2 Concentration

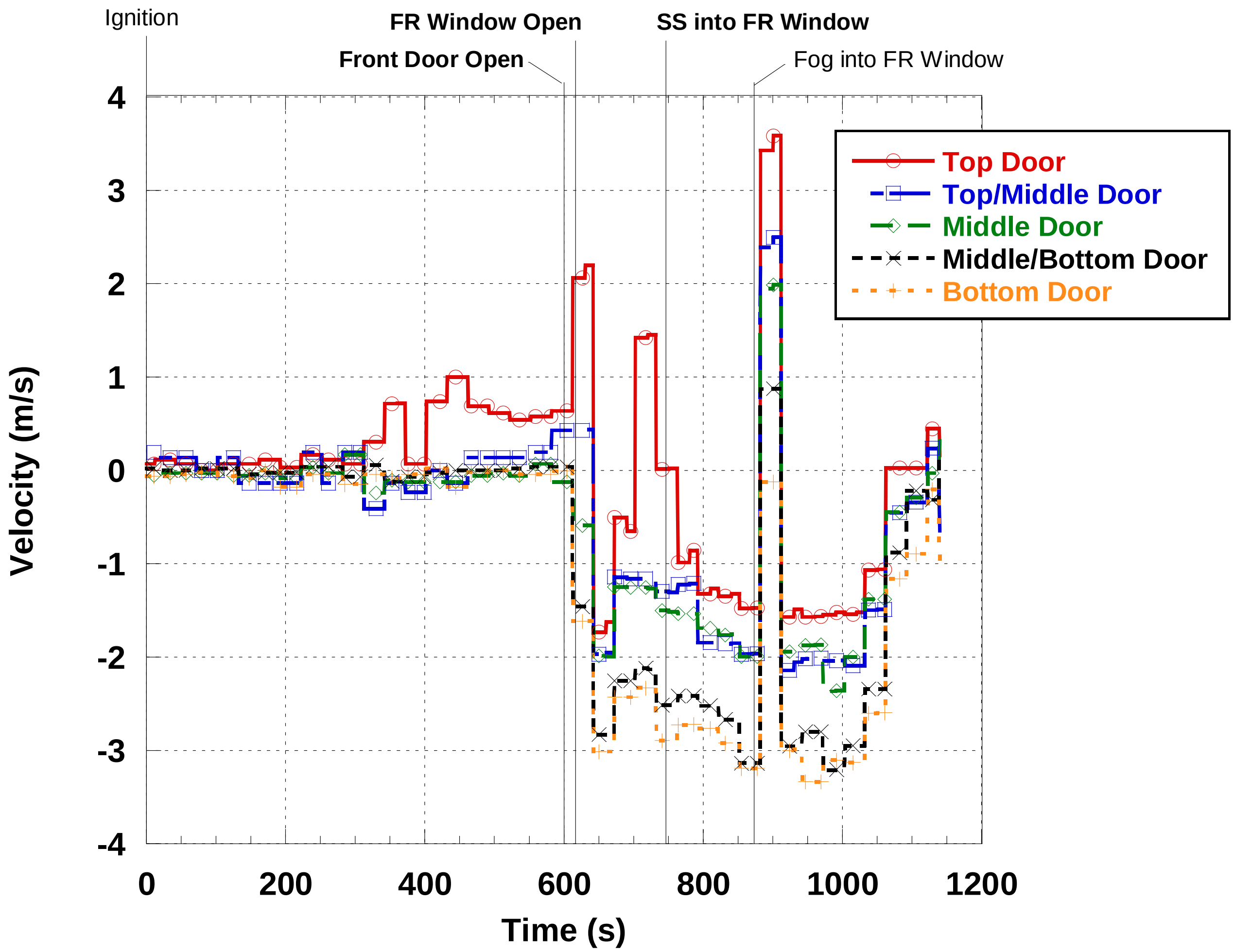


Figure 409. Experiment 13 - Front Door Velocities

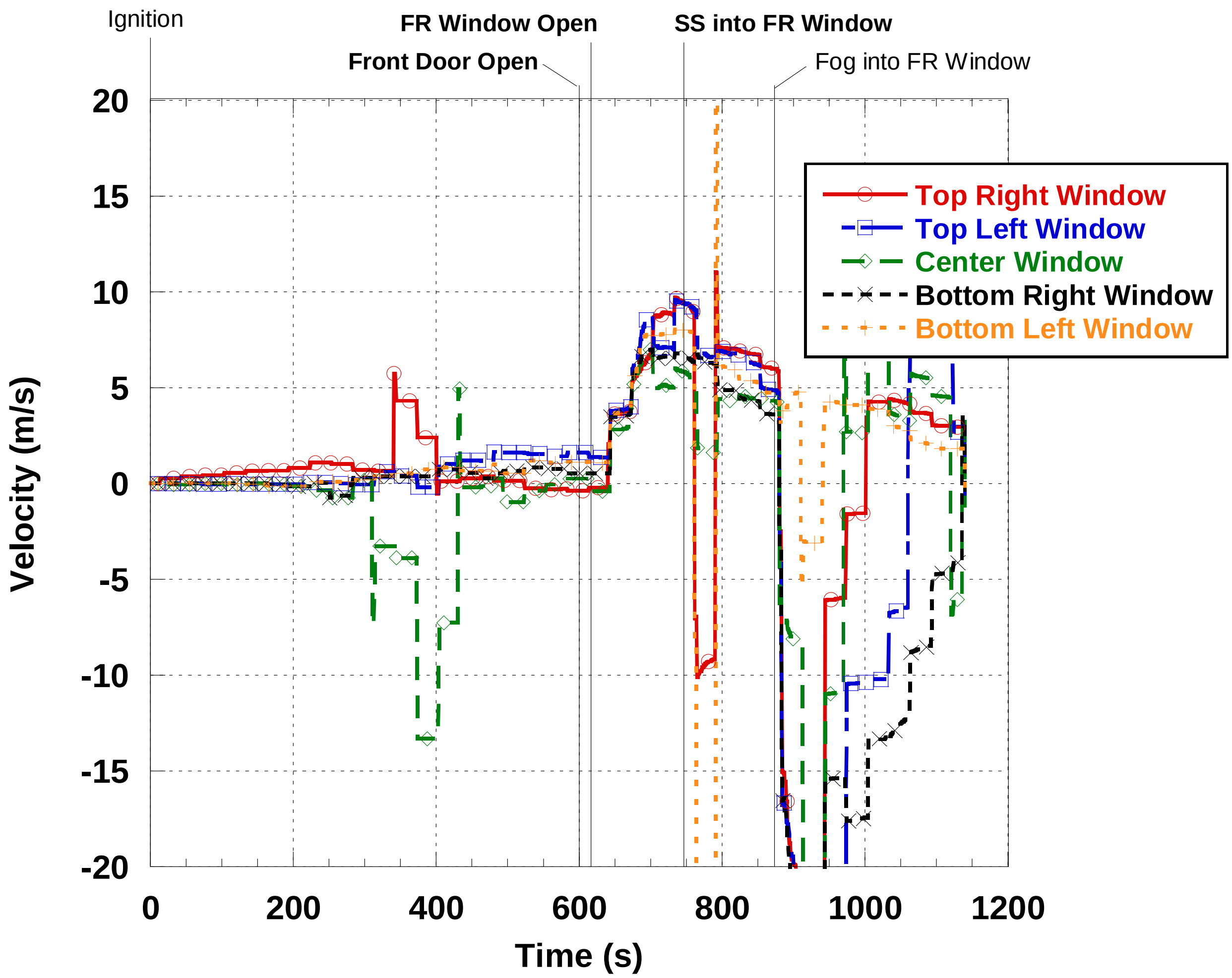


Figure 410. Experiment 13 - Ventilation Window Velocities

8.7.8. Experiment 15

Experiment 15 was the final experiment conducted in the two-story house. This experiment was designed to examine the impact of ventilating with several openings. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 minutes after ignition at which time the front door was opened. Fifteen seconds after the front door was opened the living room window was opened. In fifteen second intervals the den window, first floor right family room window and first floor left family room window were opened (Table 32). The fire again was allowed to grow until 14:33 when 10 seconds of water were flowed into the first floor right family room window with a combination nozzle positioned in a fog stream pattern. The experiment was terminated at 16:00 and was extinguished by the suppression crew. Figure 412 through Figure 419 show the front and rear of the house during the experiment.

Table 32. Experiment 15 Timeline

Event	Time (mm:ss)
Ignition	0:00
Front Door Open	10:00
Living Room Window Open	10:15
Den Window Open	10:30
Family Room Window Open	10:45
Second Family Room Window Open	11:00
Fog Stream into Family Room Window	14:33-14:43
End of Experiment	16:00

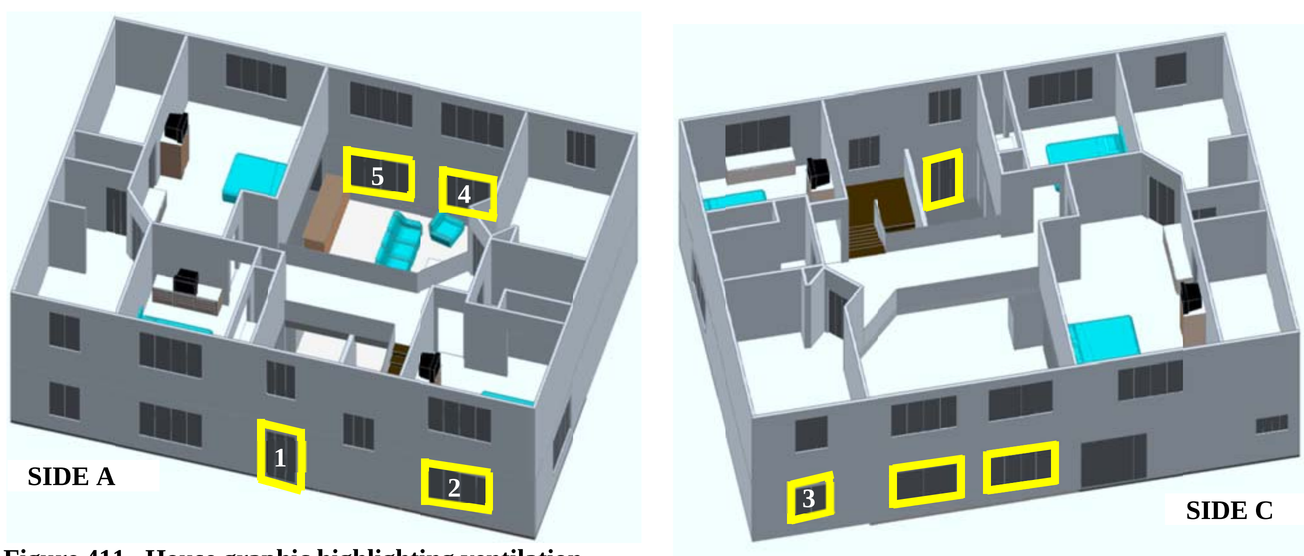


Figure 411. House graphic highlighting ventilation locations

Figure 412. Experiment 15 - 0:00

Figure 413. Experiment 15 - 0:00

Figure 414. Experiment 15 - 10:05

Figure 415. Experiment 15 - 10:20

Figure 416. Experiment 15 - 10:35

Figure 417. Experiment 15 - 11:05

Figure 418. Experiment 15 - 14:00

Figure 419. Experiment 15 - 14:40

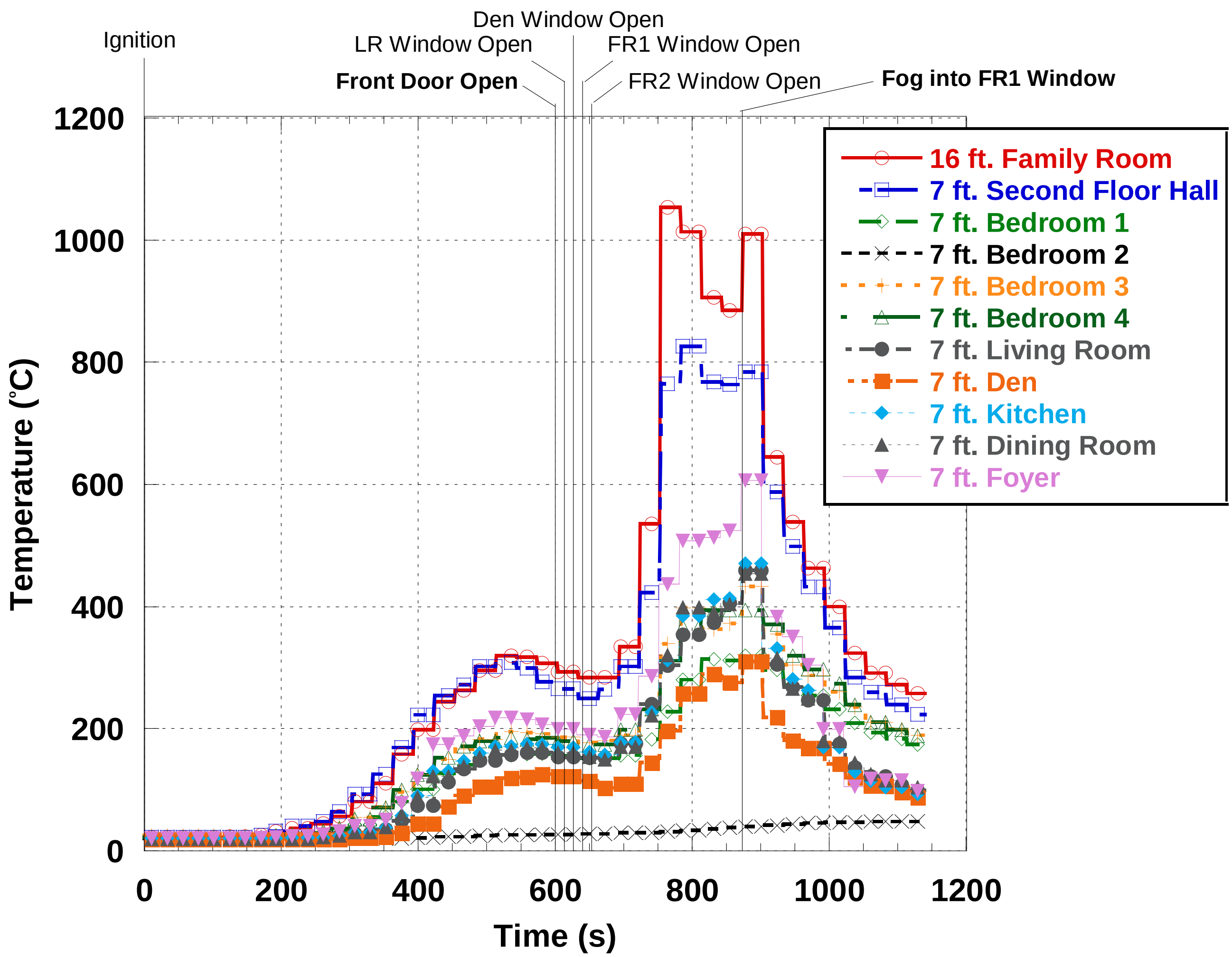


Figure 420. Experiment 15- 7ft. Temperatures

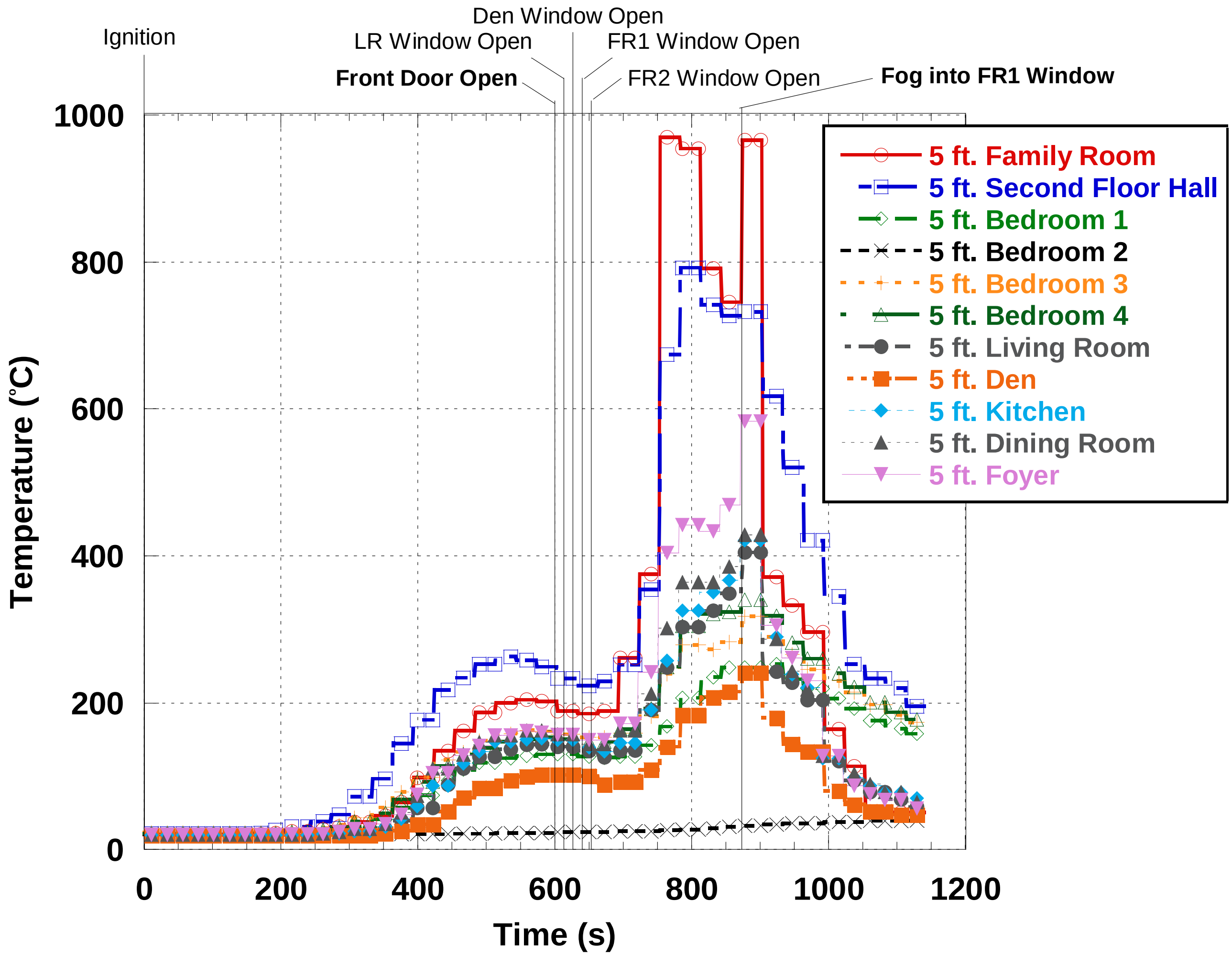


Figure 421. Experiment 15- 5ft. Temperatures

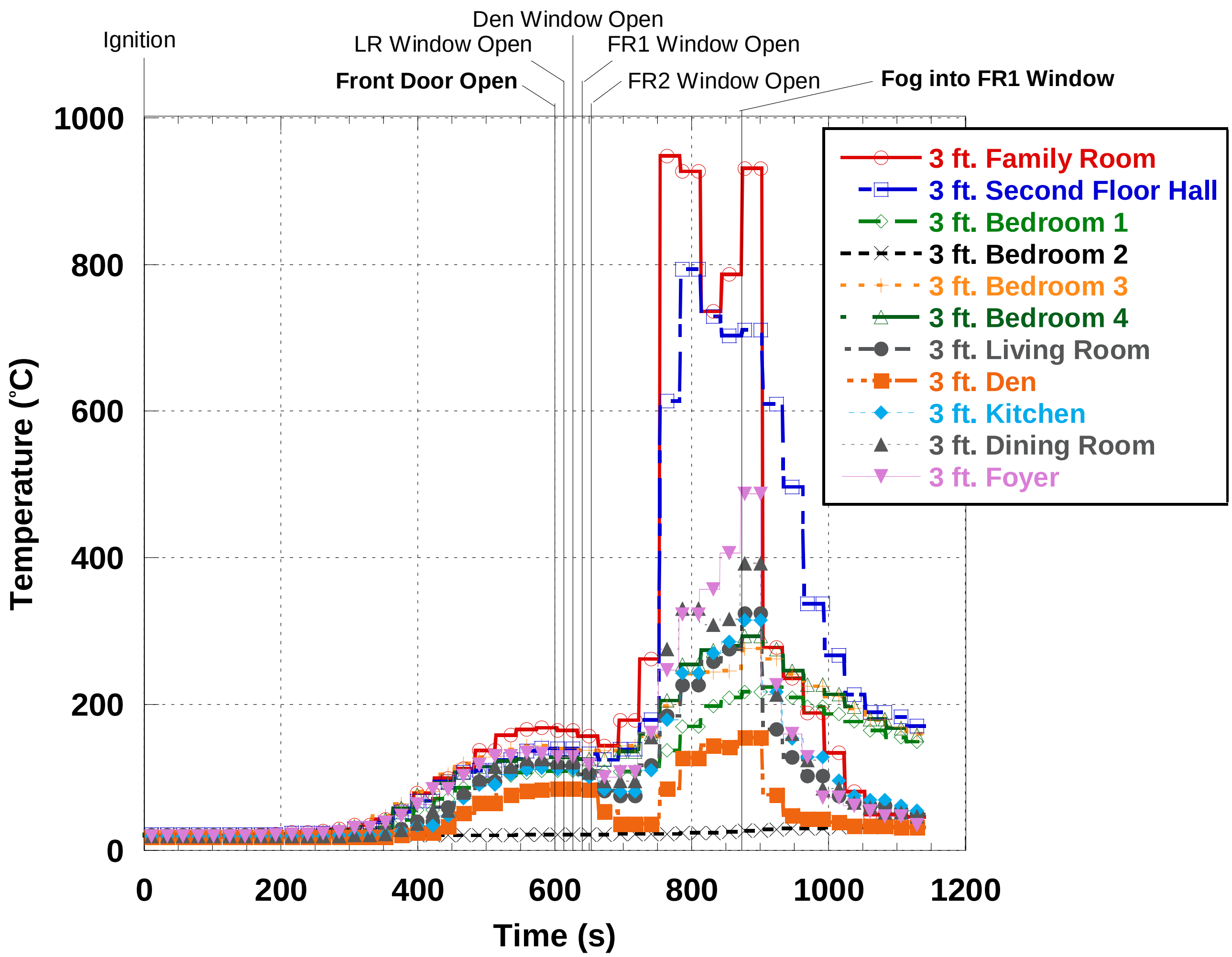


Figure 422. Experiment 15- 3ft. Temperatures

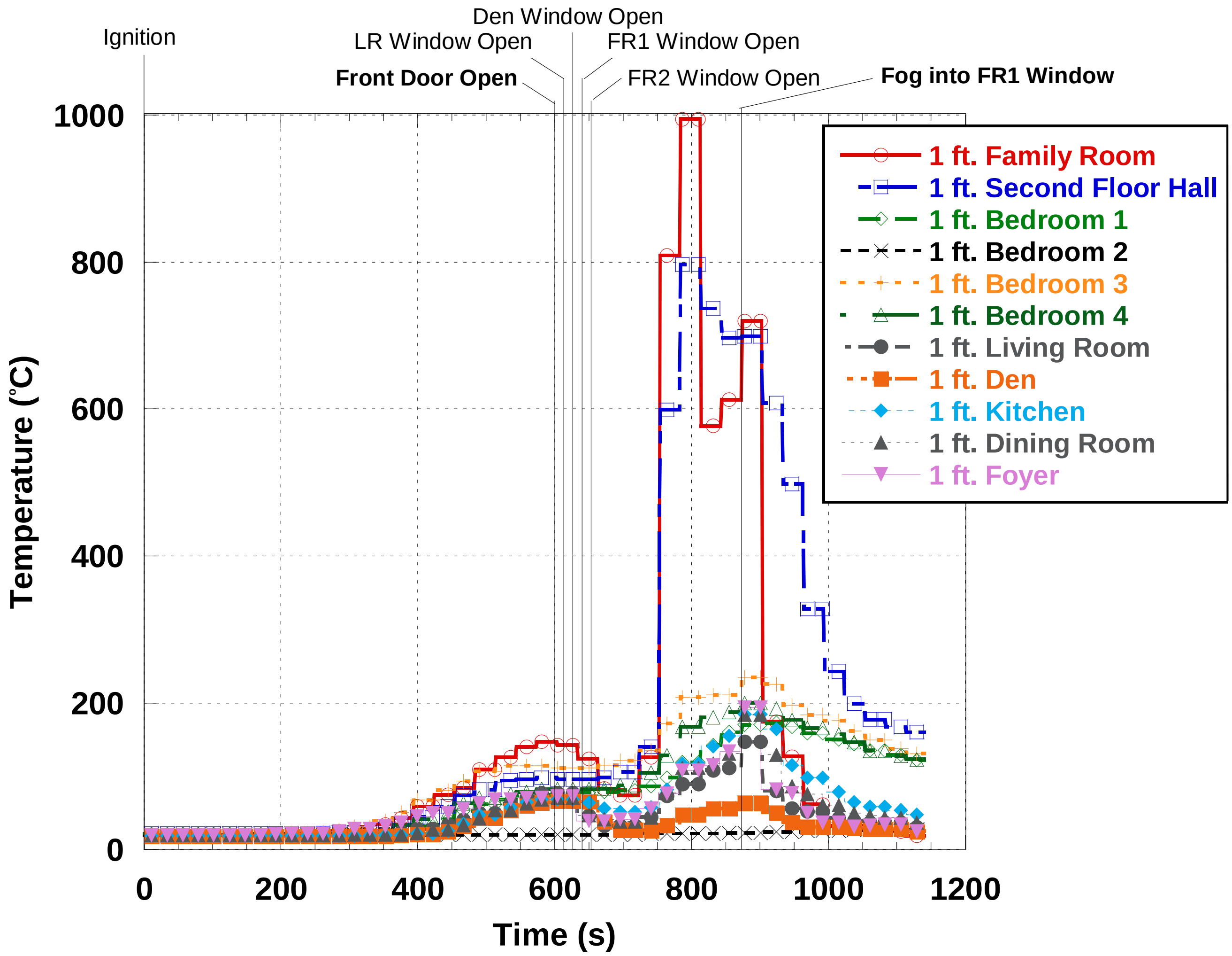


Figure 423. Experiment 15- 1ft. Temperatures

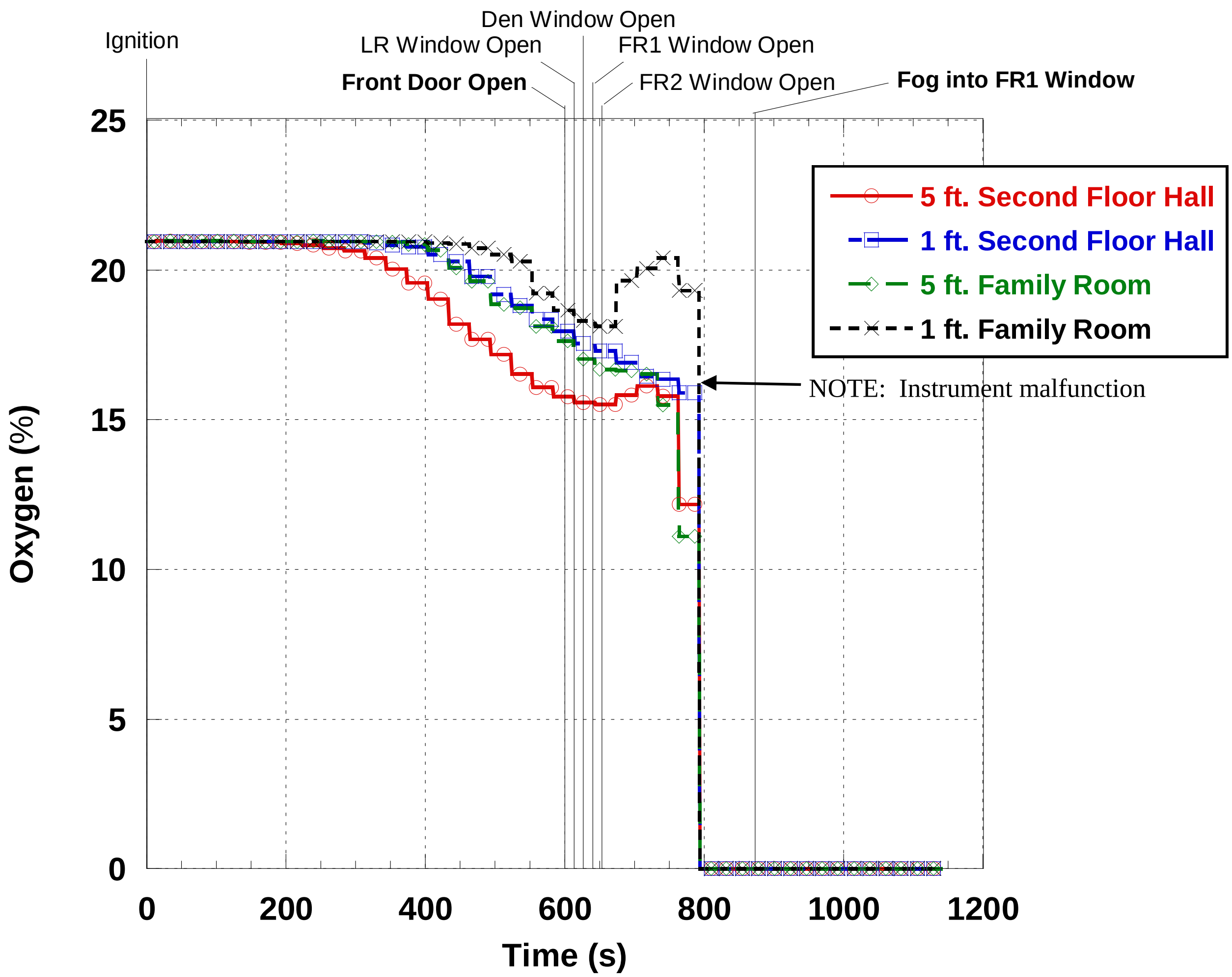


Figure 424. Experiment 15- Oxygen Concentration

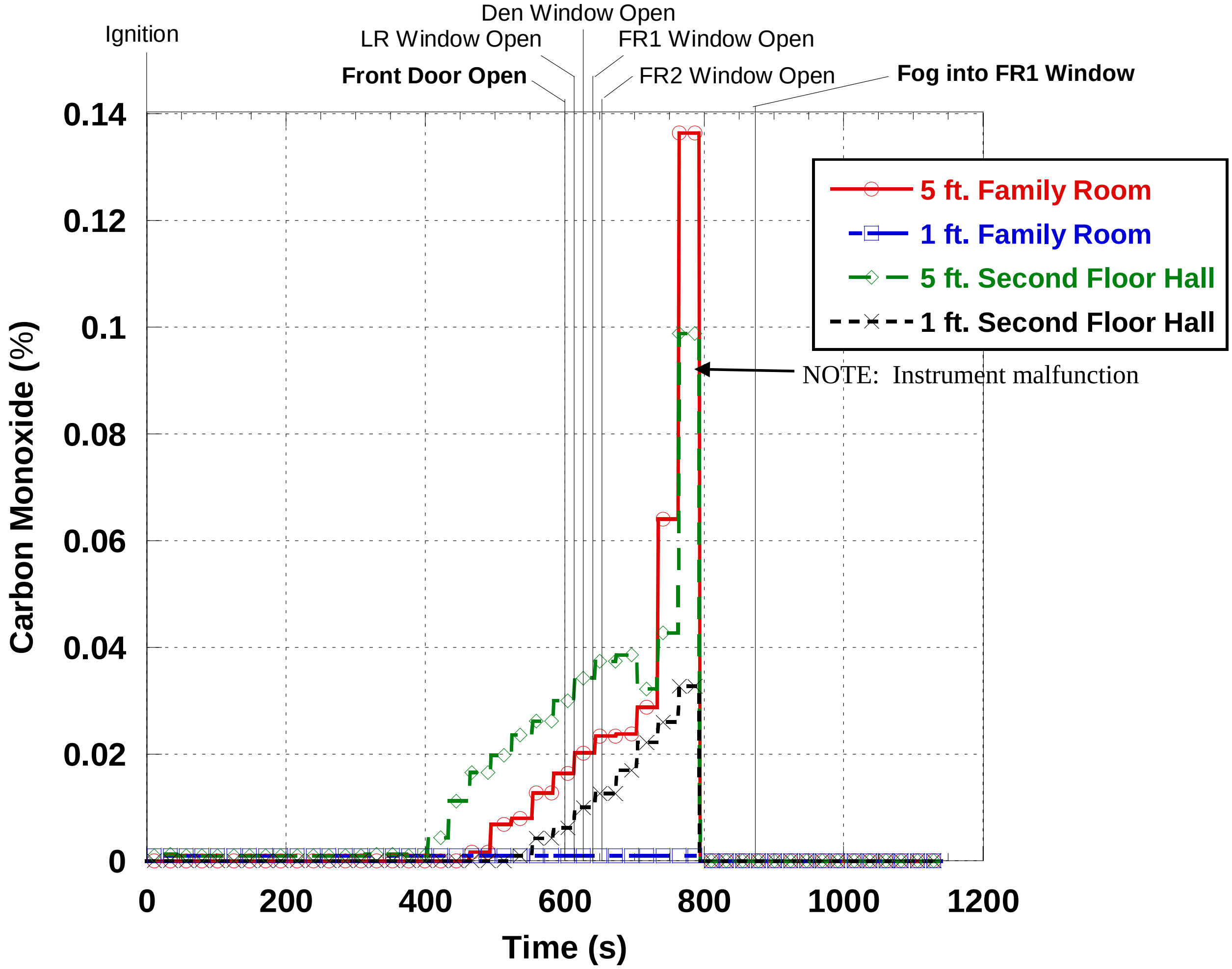


Figure 425. Experiment 15- CO Concentration

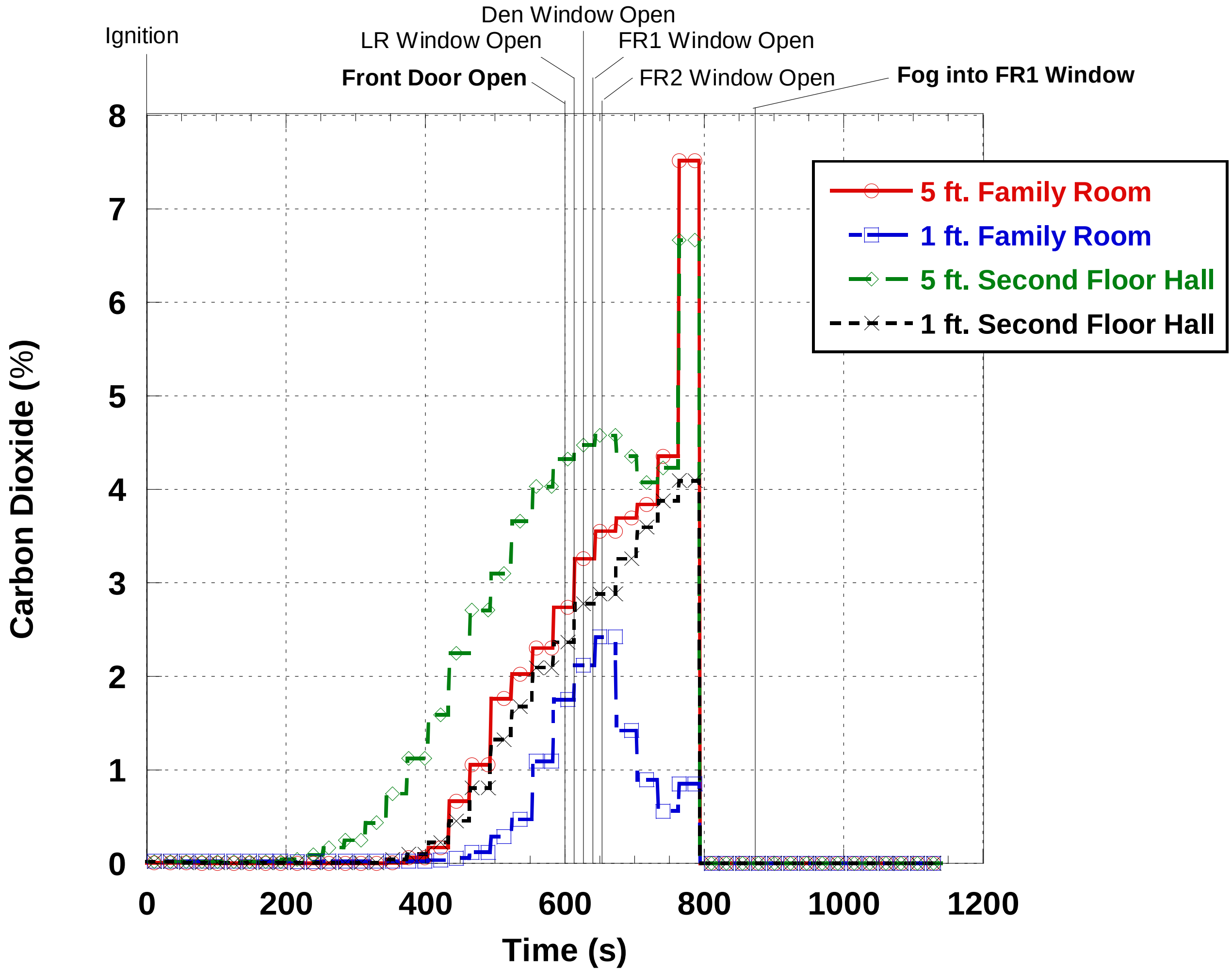


Figure 426. Experiment 15- CO_2 Concentration

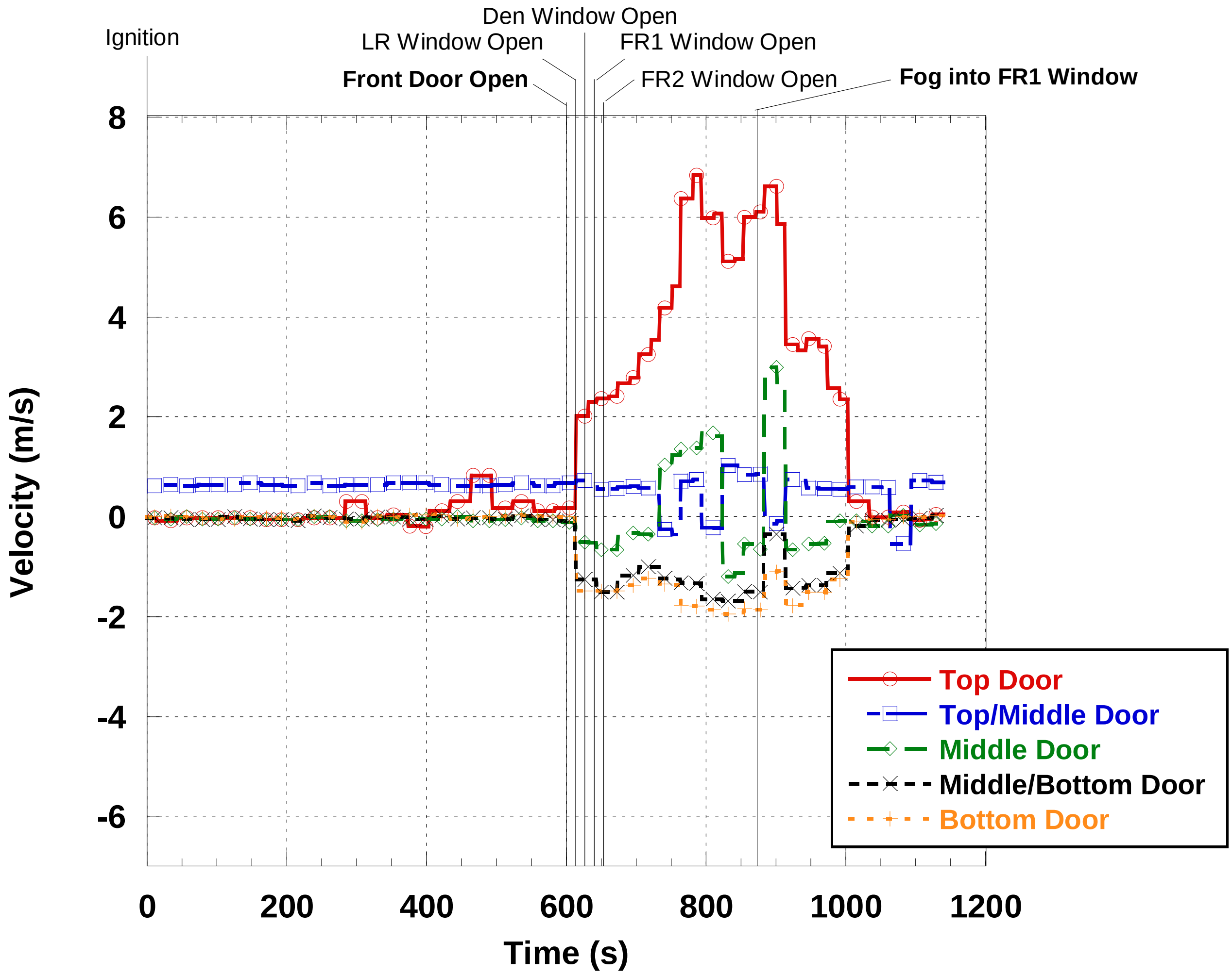


Figure 427. Experiment 15- Front Door Velocities

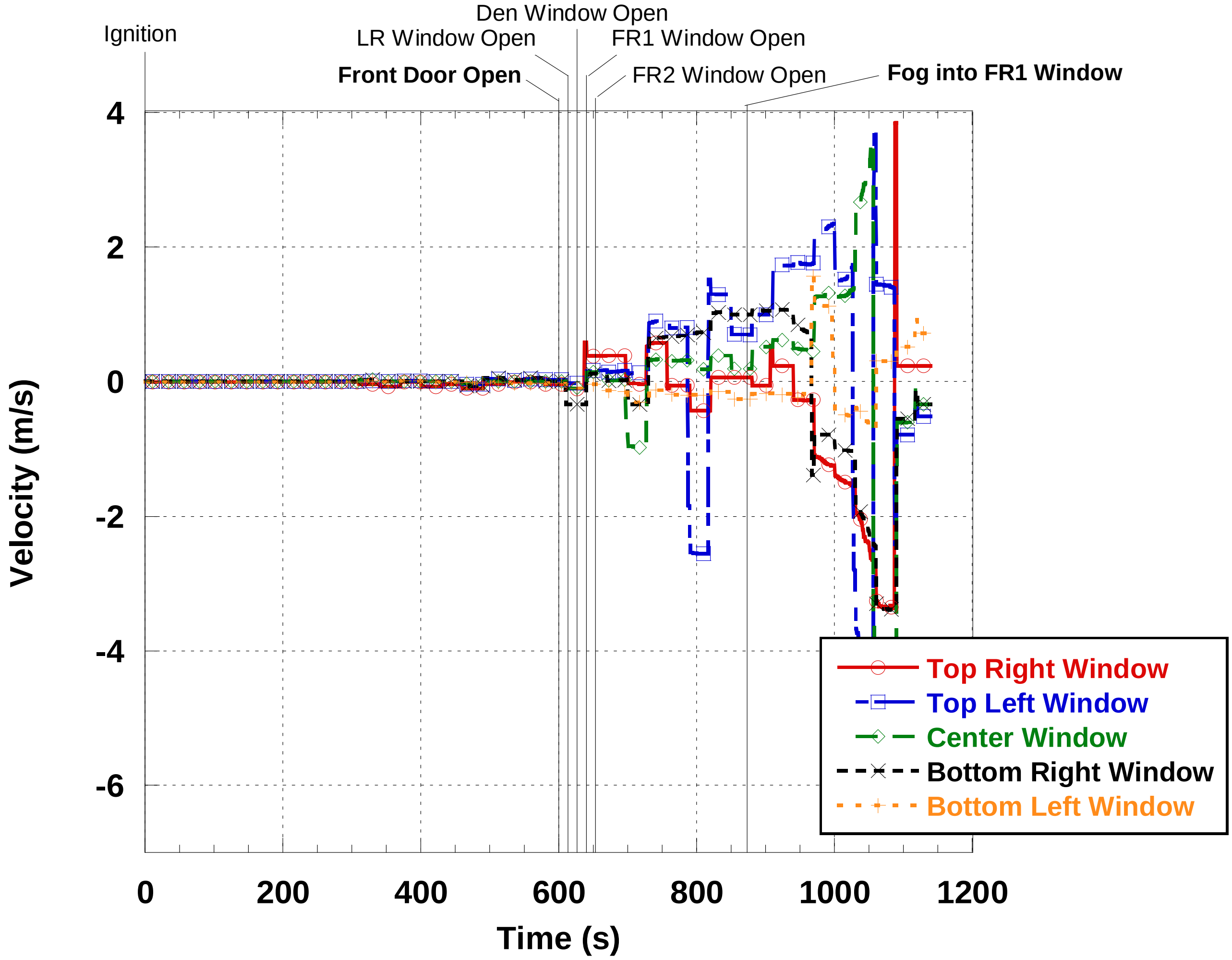


Figure 428. Experiment 15- Ventilation Window Velocities (Family Room Window)

8.8. Discussion

The overall objective of this study was to examine the effectiveness of horizontal ventilation performed by initial arriving companies at two common types of structures, a one story, 1200 ft^2 house with compartmentation and a two story, 3200 ft^2 house with an open floor plan and high ceilings. All of the fires started in the same location and were allowed to grow for the same amount of time prior to ventilation. The repeatability of these experiments was examined by comparing the first 8 minutes of the one story experiments and the first 10 minutes of the two story experiments. Additionally two scenarios were run in triplicate for each structure in order to compare repeatability of the entire experimental series. Another important factor in these experiments is tenability of potential occupants in the structures prior to fire department intervention as well as after fire department intervention. Tenability will also be examined for the firefighters that could be operating in the structure during ventilation operations. A significant factor in this tenability is the rate of change of hazardous conditions and how this varies with different ventilation practices.

8.8.1. One Story Repeatability

In order to compare the ventilation practices a large amount of attention was placed into making sure pre-ignition conditions were as close to identical as possible. All of the furniture was purchased to be the same and the positioning of the furniture was the same between experiments. Ignition was initiated in the same location and the amount of air leakage area was controlled by filling cracks around the doors and windows with fiberglass insulation. Figure 429 through Figure 435 compare temperatures and oxygen concentrations across all of the experiments in the one story house. Of the seven experiments, Experiment 3 had a slower growing fire and Experiment 14 had a faster growing fire. The other 5 experiments grew similarly for the first 8 minutes before ventilation.

Temperatures near the ceiling in the living room of the 5 similar experiments reached approximately 700 °C (1290 °F) at around 320 s and quickly decreased to 175 °C (350 °F) at 480 s as the oxygen was consumed in the house (Figure 429). The temperatures at the same elevation in Bedroom 2 (most remote from the living room) reached 350 °C (660 °F) before decreasing to an average of 150 °C (300 °F) as the fire became ventilation limited (Figure 430). As a further comparison the temperatures at 1 ft above the floor in both the living room and rear bedroom were plotted together. Living room temperatures reached 325 °C (620 °F) and the Bedroom 2 temperatures reached an average of 80 °C (180 °F) before declining to 100 °C (210 °F) and 60 °C (140 °F) respectively (Figure 431 and Figure 432).

Oxygen levels in the living room and the bedroom at 5 ft above the floor were between 10% and 14% at the time of ventilation. However, they did drop as low as 2 to 5% at 6 minutes after ignition (Figure 433 and Figure 435). At the 1 ft level in the living room the oxygen level declined to 11 to 14% at 360 s and remained there until ventilation (Figure 434). The oxygen probes in the living room for Experiment 3 were not functioning properly so that data can be ignored.

As a whole, the set of experiments in the one-story structure showed good repeatability prior to ventilation. The two experiments which showed different growth rates from the others, 3 and 14, still had similar temperatures and oxygen concentrations at the time of ventilation. Every experiment was within 50 °C (120 °F) at the time of ventilation at the 4 measurement locations chosen, which were remote from each other. Oxygen concentrations were also similar, within 4% of each other, at the time of ventilation.

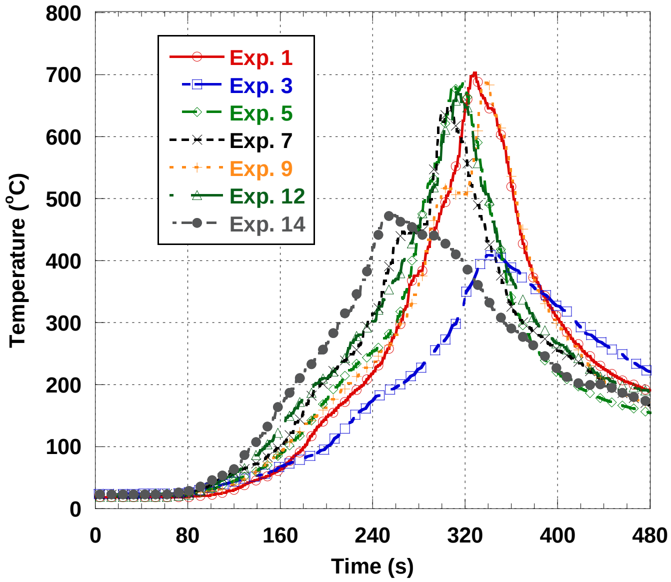


Figure 429. 7 ft. Living Room Temperatures

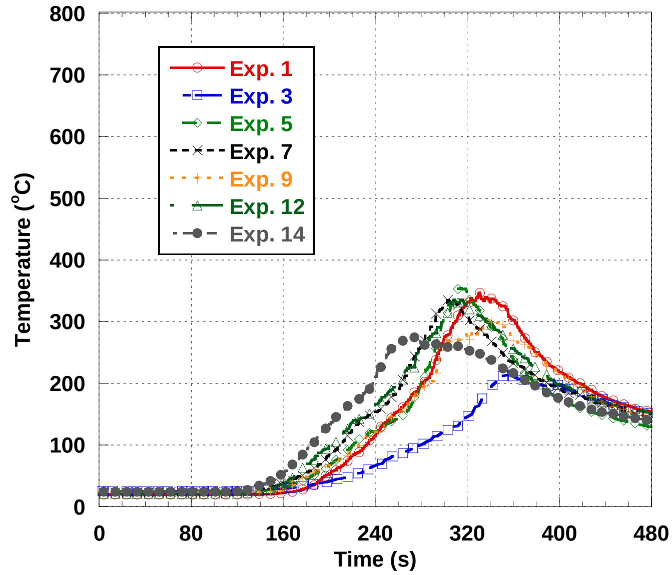


Figure 430. 7 ft. Bedroom 2 Temperatures

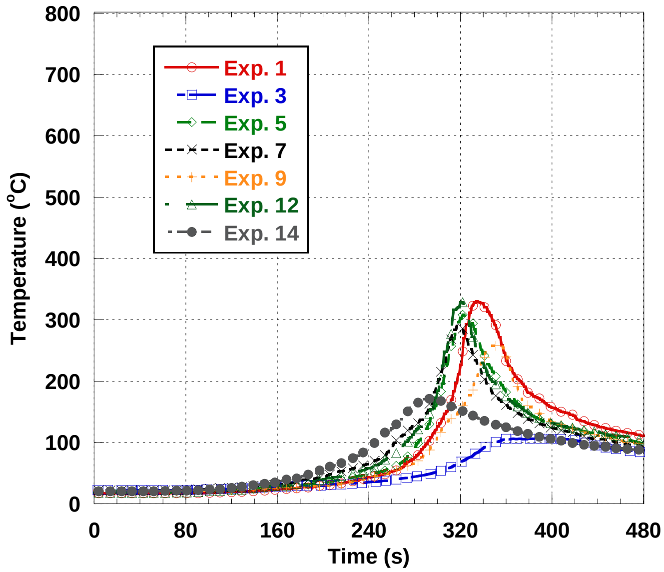


Figure 431. 1 ft. Living Room Temperatures

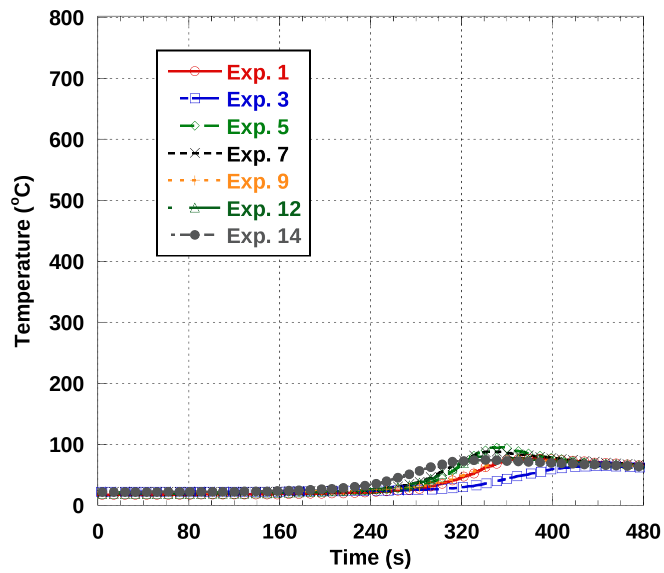


Figure 432. 1 ft. Bedroom 2 Temperatures

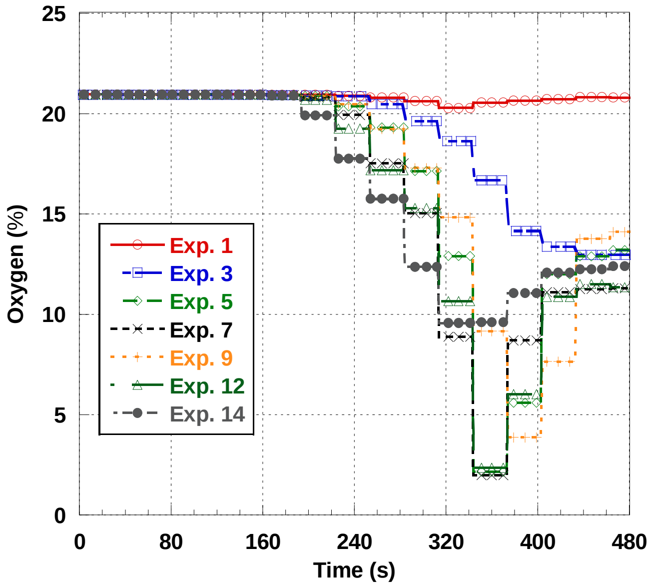


Figure 433. 5 ft. Living Room Oxygen Concentrations

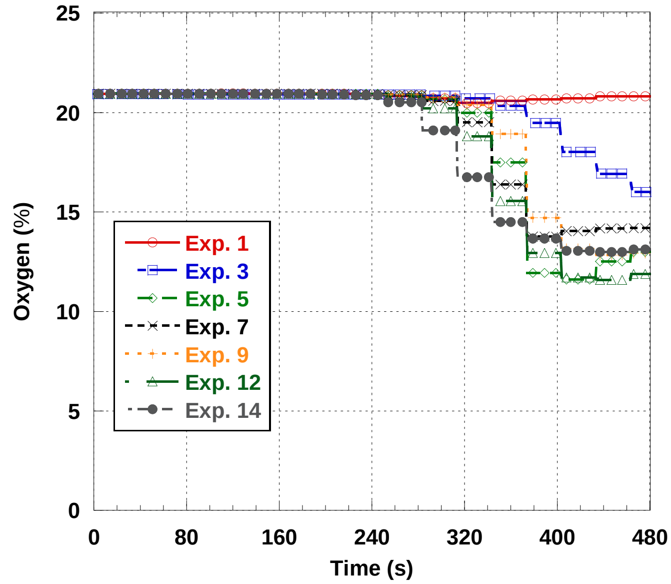


Figure 434. 1 ft. Living Room Oxygen Concentrations

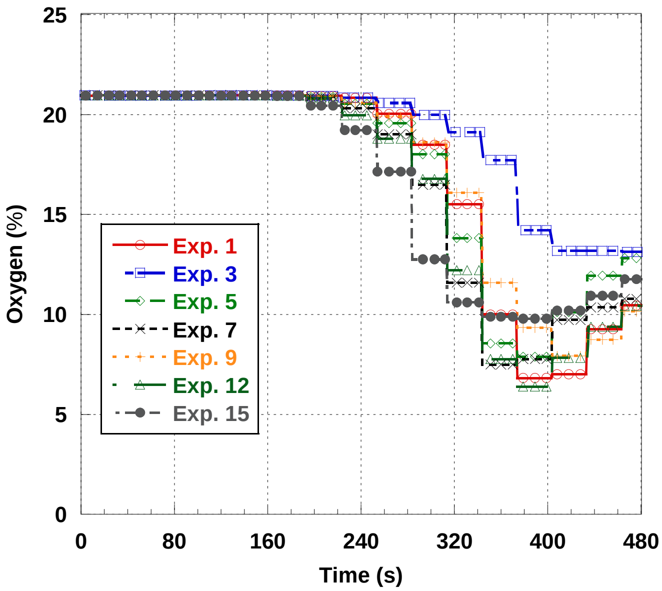


Figure 435. 5 ft. Bedroom 2 Oxygen Concentrations

Experiments 3, 9 and 12 followed the same timeline to examine repeatability through the entire experiment. In all three experiments the front door was opened at 8 minutes and the living room window was opened 15 seconds later. The fire was allowed to burn until a post flashover condition was reached. Figure 436 and Figure 437 show the temperature versus time at 7 ft. and 1 ft. above the floor in the living room and bedroom 2. Experiments 9 and 12 were very similar throughout the entire timeline. Experiment 3 develops slower prior to ventilation but responds faster to the window being ventilated. After ventilation all of the experiments have similar temperature rates of change as well as peaks.

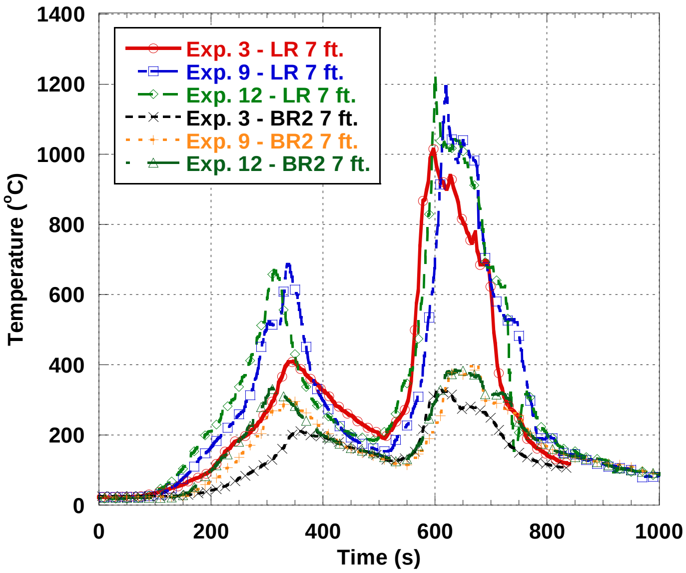


Figure 436. Exp. 3, 9, 12 Repeatability -7 ft. Temperatures

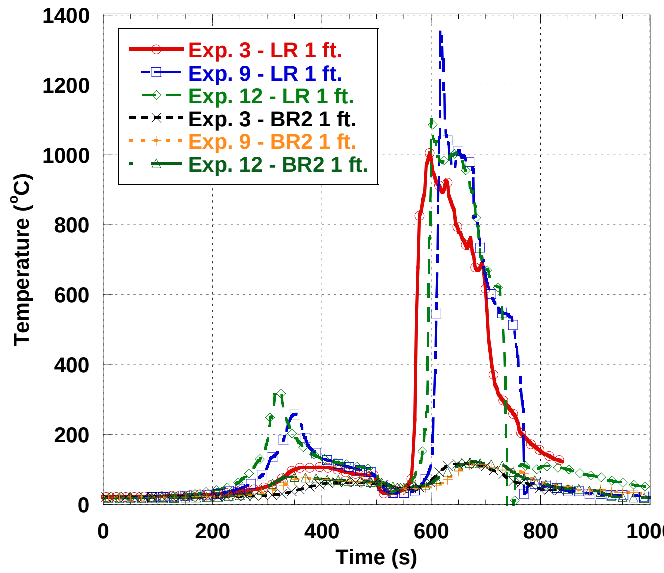


Figure 437. Exp. 3, 9, 12 Repeatability -1 ft. Temperatures

8.8.2. Two Story Repeatability

The two story house had the same furniture layout and ignition location as the one story house. The only difference in the family room was the geometry of the room. To examine repeatability in all 8 two story house experiments the first 10 minutes of each experiment was compared. Ventilation took place at 10 minutes after ventilation in every experiment. Figure 438 through Figure 444 compare temperatures at various elevations in two locations remote from each other. Oxygen concentrations were also compared at two different locations in the house.

Three different elevations were examined in the 17 ft tall family room. The first was 16 ft from the floor. Temperatures at this elevation peak between 325 °C (620 °F) and 450 °C (840 °F) at between 450 s and 550 s. Just before ventilation the temperatures at this elevation are all between 240 °C (460 °F) and 310 °C (590 °F) (Figure 438). Experiments 13 and 15 grew slower than the other 6 experiments, but every experiment peaked and declined in temperature prior to ventilation which is consistent with a ventilation limited fire. The second elevation was 7 ft above the floor. These temperatures were a little more varied as the fire grew but converged at between 180 °C (360 °F) and 230 °C (450 °F) just prior to ventilation (Figure 439). The temperatures at 1 ft above the floor behave similarly to the two other elevations and converge at between 110 °C (230 °F) and 150 °C (300 °F) just prior to ventilation (Figure 440).

Temperatures in Bedroom 3 were also compared between the 8 experiments. Bedroom 3 was remote from the family room and is a good indication of heat flow to the second floor of the house. At 7 ft. above the floor in Bedroom 3 all of the temperatures peaked around 200 °C (390 °F) and leveled off or slightly decreased up to the ventilation time. At 1 ft above the floor in Bedroom 3 the temperature followed the same trend but peaked at approximately 100 °C (210 °F).

Oxygen concentrations were compared at 5 ft in the family room and at 5 ft in the hallway on the second floor. In the family room oxygen concentrations steadily decrease from ignition to ventilation. Just prior to ventilation concentrations range from 13 to 16 % for the 8 experiments.

On the second floor hallway the oxygen concentrations decrease to 14 % to 18% just prior to ventilation. Experiment 2 was the only experiment that decreased to a minimum of 13% and increased slightly to 14% prior to ventilation, all others steadily declined from ignition.

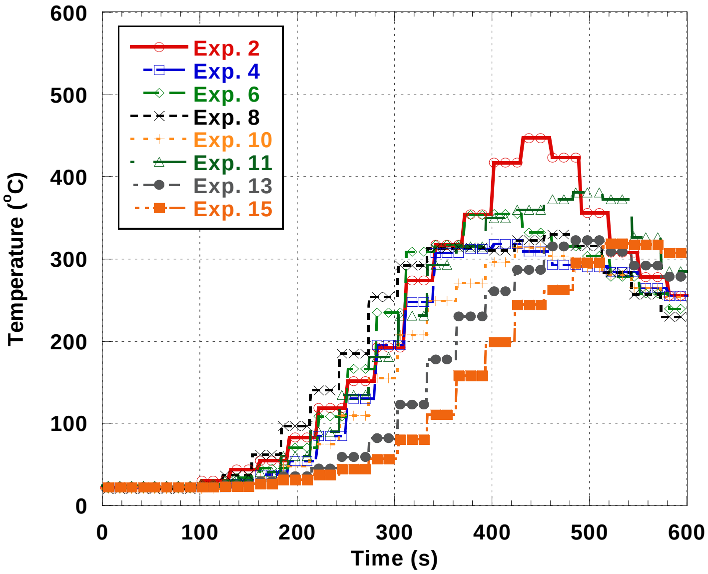


Figure 438. 16 ft. Family Room Temperatures

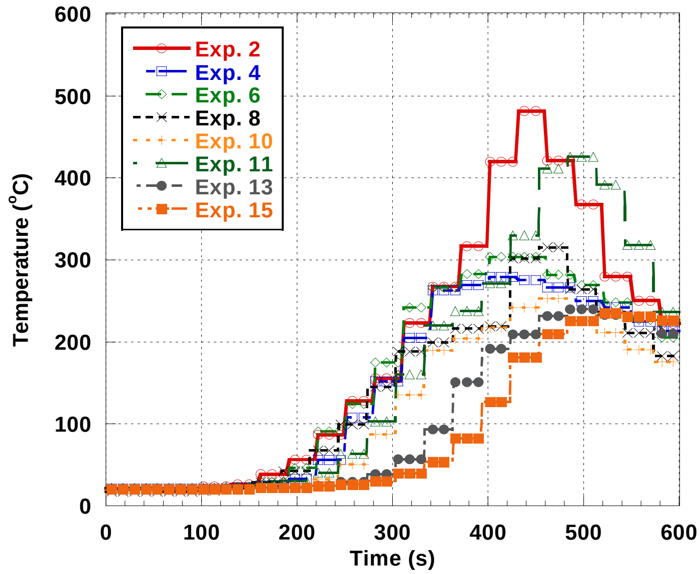


Figure 439. 7 ft. Family Room Temperatures

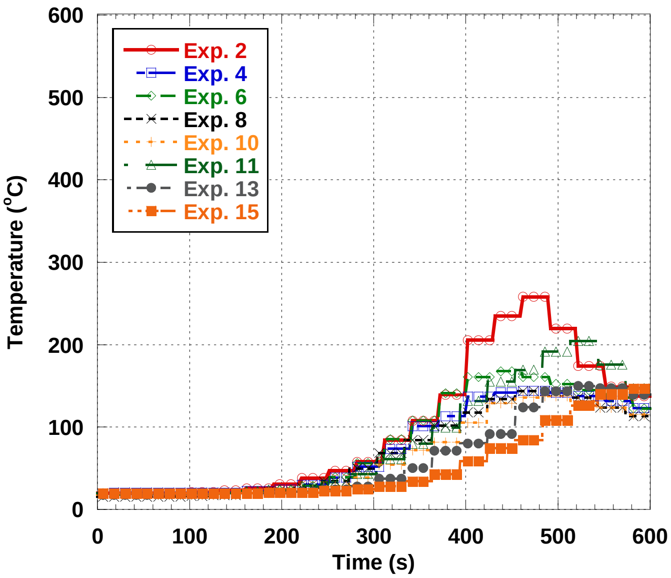


Figure 440. 1 ft. Family Room Temperatures

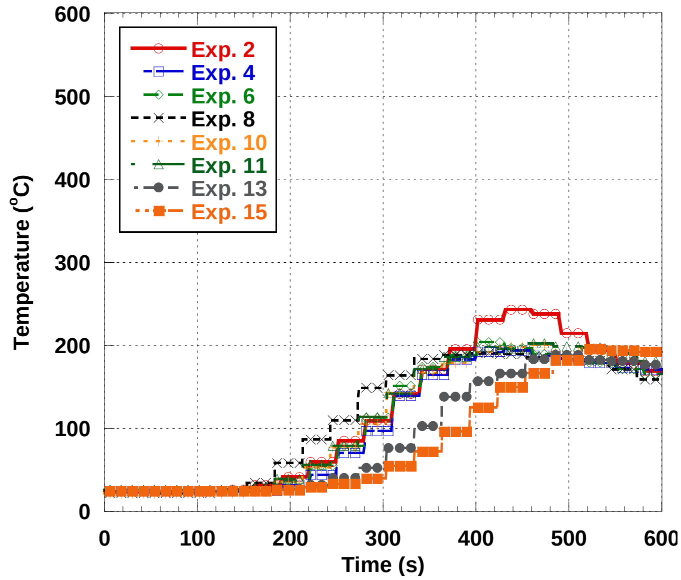


Figure 441. 7 ft. Bedroom 3 Temperatures

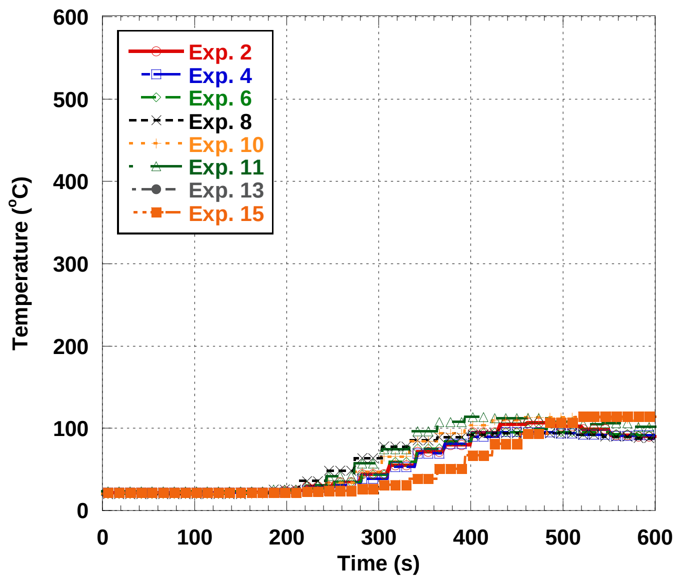


Figure 442. 1 ft. Bedroom 3 Temperatures

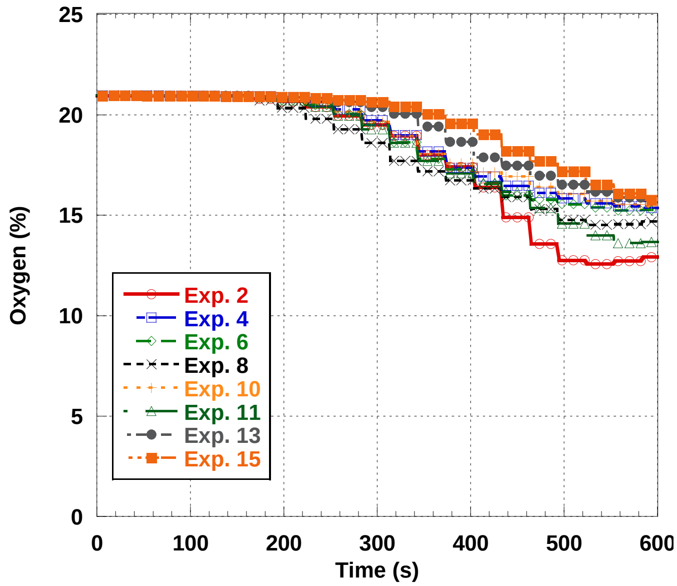


Figure 443. 5 ft. Family Room Oxygen Concentrations

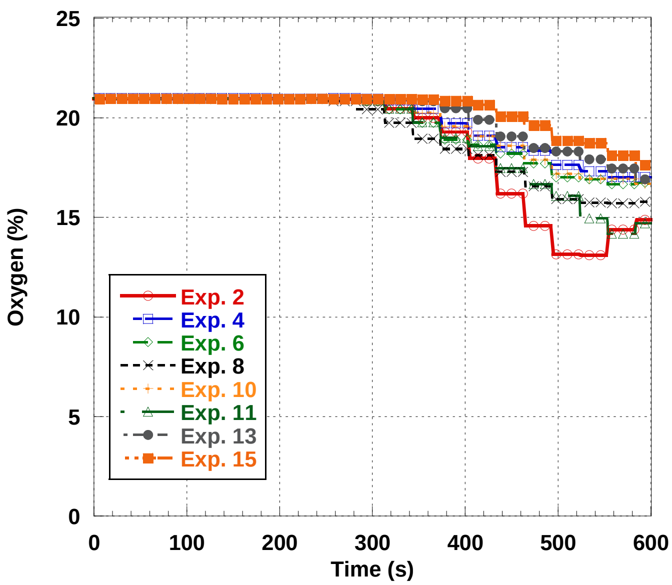


Figure 444. 5 ft. Upper Hallway Oxygen Concentrations

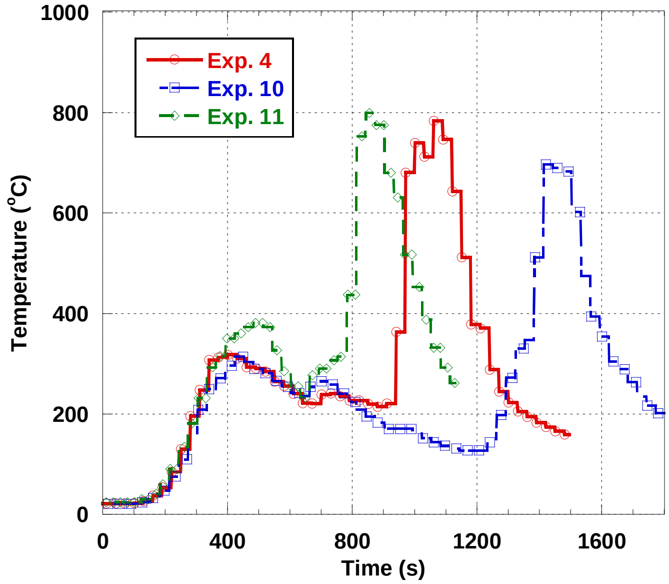


Figure 445. Exp. 4, 10, 11 Repeatability -16 ft. LR Temps.

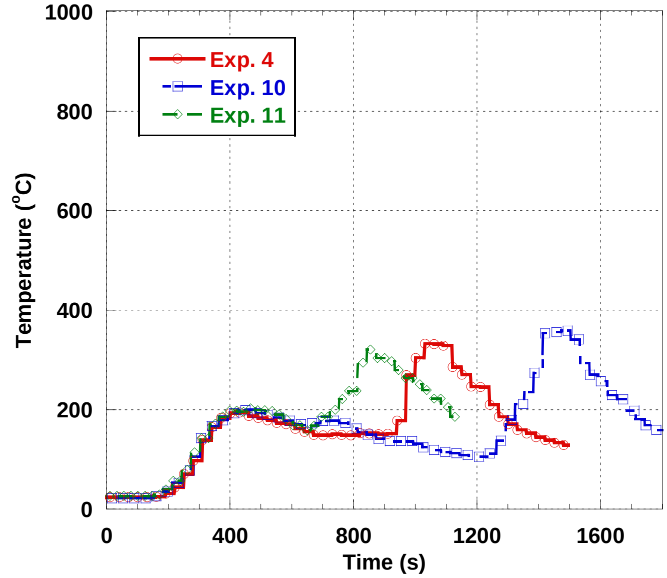


Figure 446. Exp. 4, 10, 11 Repeatability -7 ft. BR Temps.

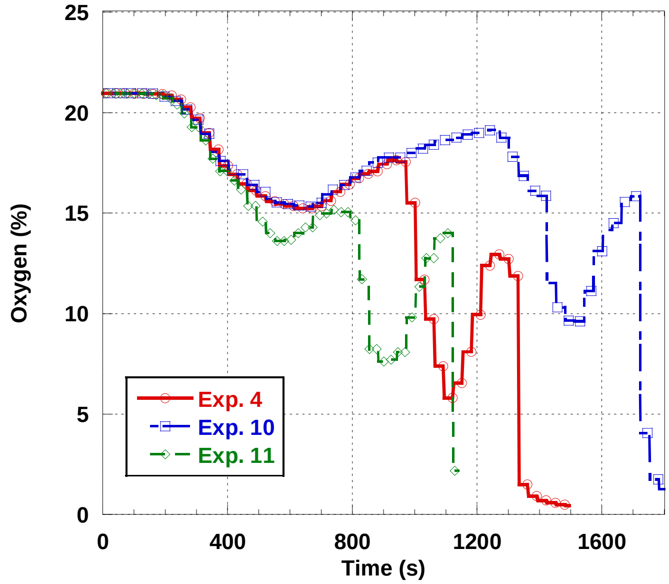


Figure 447. Exp. 4, 10, 11 Repeatability - 5 ft. FR Oxygen

8.8.3. Tenability

A core mission of the fire service is life safety, both their own and that of occupants. These experiments allow for the assessment of tenability prior to fire department intervention and after fire department intervention. Ventilation is viewed as a tactic that if use properly increases tenability for the fire service and occupants. However when not used properly can decrease tenability. Two measures of tenability were used during these experiments, temperature and gas concentration.

Temperature measurements taken throughout the houses allowed for the analysis of occupant tenability. Research by Montgomery[47] in 1975 indicated that in humid air, rapid skin burns would occur at 100 °C (210 °F), and 150 °C (300 °F) was the exposure temperature at which escape was not likely. In 1947, Moritz[48] conducted experiments on large animals and found that 100 °C (210 °F) represented the threshold for local burning and hyperemia (general burning). For this analysis, a temperature value of 150 °C (300 °F) was considered the temperature at which victims would be incapacitated. The measurements at 1 ft above the floor were used, assuming that the victim was lying on the floor where the lowest temperatures are typically found. Temperatures and oxygen concentrations at 5 ft above the floor were also used to examine a walking person.

Firefighters operating in structures are also susceptible to harm from exposure to elevated temperatures. Firefighter protective clothing standards such as NFPA 1971 require that protective clothing withstand exposure to 260 °C (500 °F) for five minutes without substantial damage[49]. Other data indicate that a fire fighter can survive flashover conditions of 816 °C (1500 °F) for up to 15 seconds depending on the conditions. For this analysis, a temperature value of 260 °C (500 °F) was considered the upper limit for a fire fighter to remain in the environment for a short period of time. The temperatures were evaluated at 3 ft above the floor assuming that fire fighters would be crawling in an attempt to operate in the lowest temperature region of the room.

This analysis is based on temperature alone and does not factor in heat flux which would further reduce the firefighters ability to operate in a location. Another important factor not accounted for is the time the firefighter is in an elevated temperature environment. Turnout gear protects the firefighter inside by absorbing energy and keeping it from reaching the firefighter inside. A firefighter could be operating in lower temperatures than the 260 °C (500 °F) threshold for a period of time and their gear could become saturated with energy. The energy would then be passed onto the firefighter inside causing burn injuries.

According to Purser a room becomes untenable for people when the oxygen volume fraction drops below 12%[50]. This level is generally accepted by the fire protection engineering profession as leading to incapacitation, but may be tolerated for a short (unspecified) time. A lethal concentration of carbon monoxide in humans has been reported to be as low as 0.5% for 5 minutes[51].

The temperatures, oxygen concentrations and carbon monoxide concentrations were examined in the Living Room (LR) and Bedroom 2 (BR2) of the one-story house to determine the time at which the tenability thresholds were exceeded. Table 33 shows the results for the one-story experiments. Temperature was the tenability criteria exceeded first in every experiment. In every experiment tenability was exceeded in at least one location prior to ventilation taking place (before the simulated fire department arrival). The average time to untenability in the living room, 1 ft above the floor was 336 seconds, and 292 seconds 5 ft above the floor in the bedroom. The elevation of the measurement in the living room assumes someone lying on the floor, while the elevation in the bedroom assumes someone sitting up out of bed or walking to escape.

Figure 448 through Figure 454 show the peak temperatures throughout the house prior to simulated fire department arrival (480 seconds). Temperatures in red are above the tenability threshold and temperatures in blue are below that threshold. These figures show the potentially survivable locations within the house. These locations are very close to the floor (1 ft in most locations but 3 ft in some locations) and not near the fire and in the bedroom behind a closed door (Bedroom 3). With the door closed to the bedroom the temperatures remained at less than 63 °C (150 °F) in every experiment.

Table 33. Time to occupant untenability in one-story house

Experiment	Temp Untenability		Oxygen Untenability		CO Untenability	
	LR @ 1 ft	BR2 @ 5 ft	LR @ 1ft	BR2 @ 5ft	LR @ 1ft	BR2 @ 5ft
1	308	296	NA*	350	NA*	380
3	570	357	640	610	NA	NA
5	296	286	380	340	380	380
7	292	270	700	310	380	380
9	320	302	680	350	400	380
12	294	278	400	340	650	350
14	274	252	700	320	650	650

NOTE: NA = Not Achieved

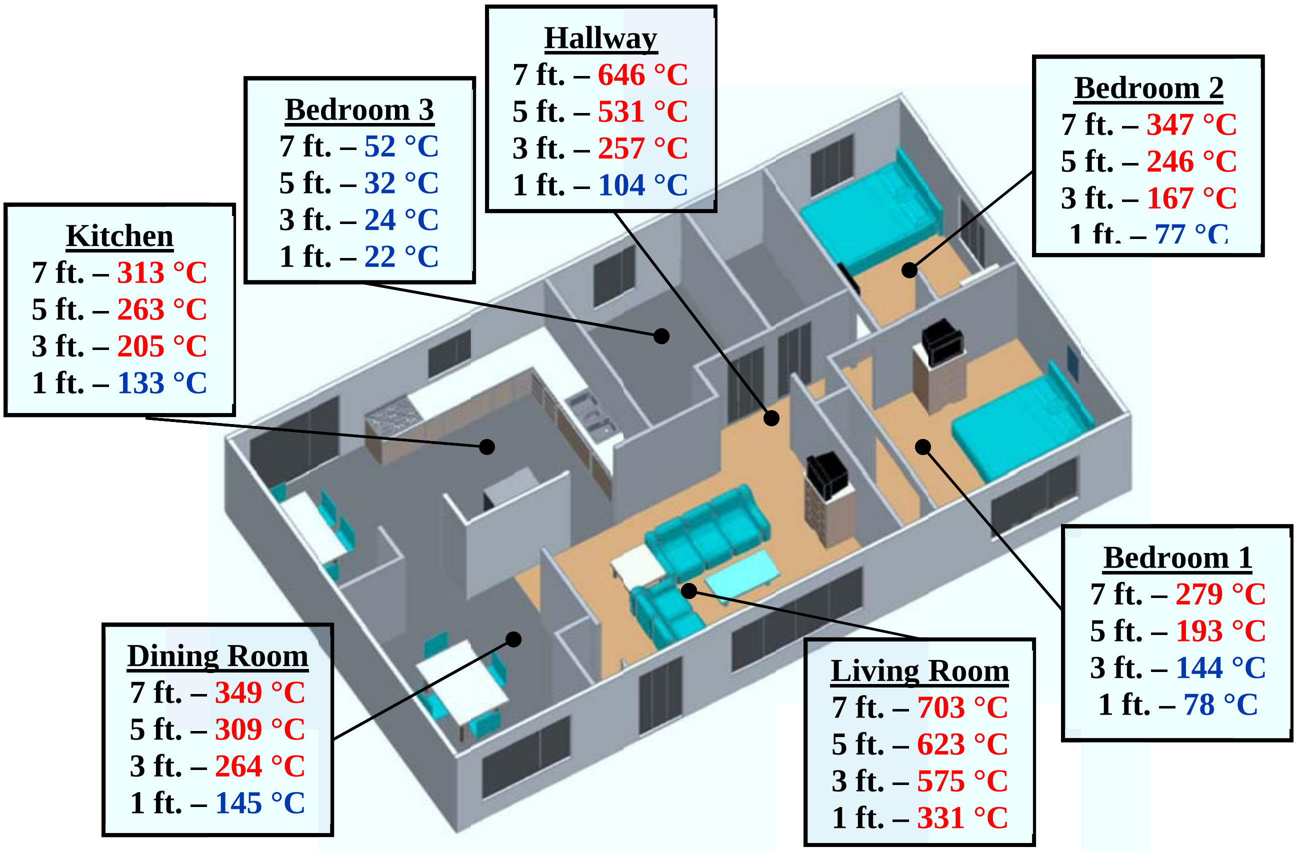


Figure 448. Experiment 1 - Peak temperatures before ventilation (Red = untenable for occupants)

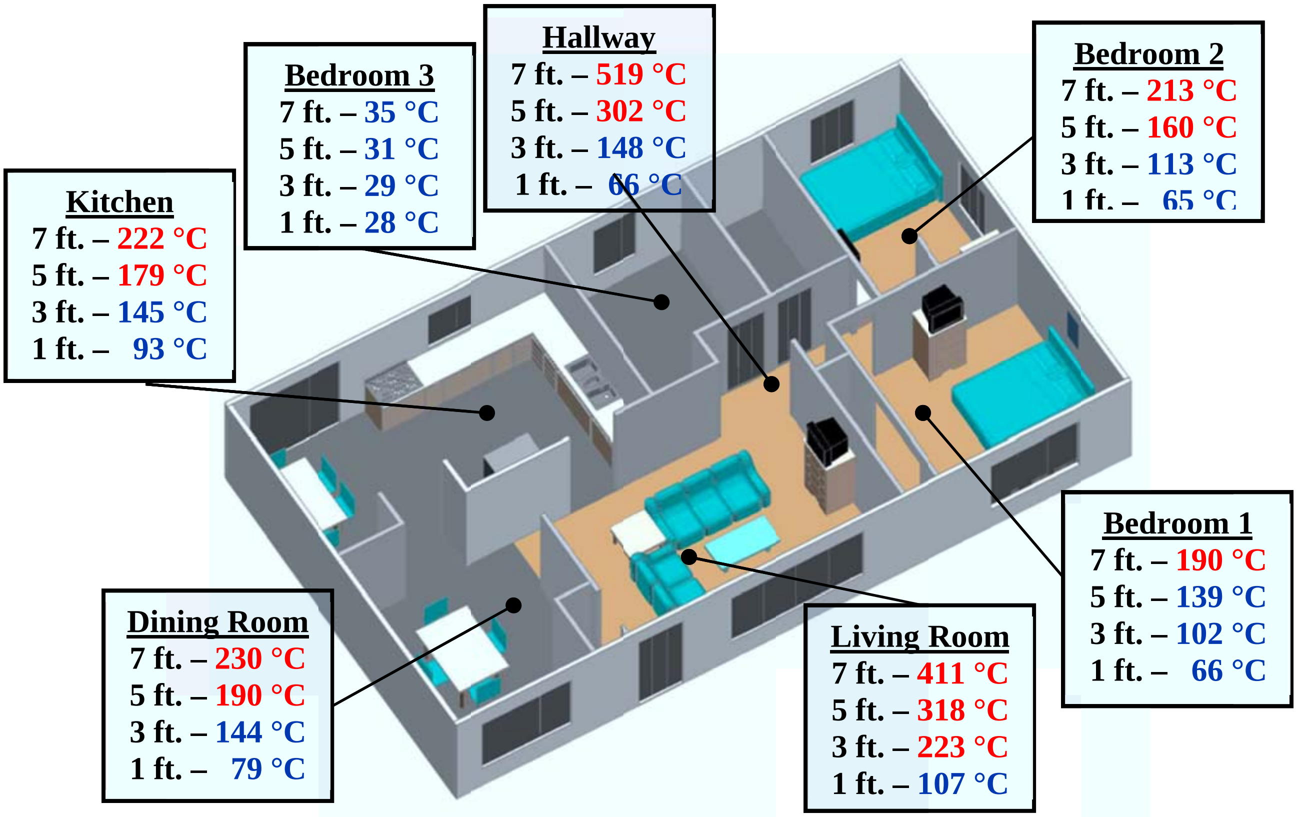


Figure 449. Experiment 3 - Peak temperatures before ventilation (Red = untenable for occupants)

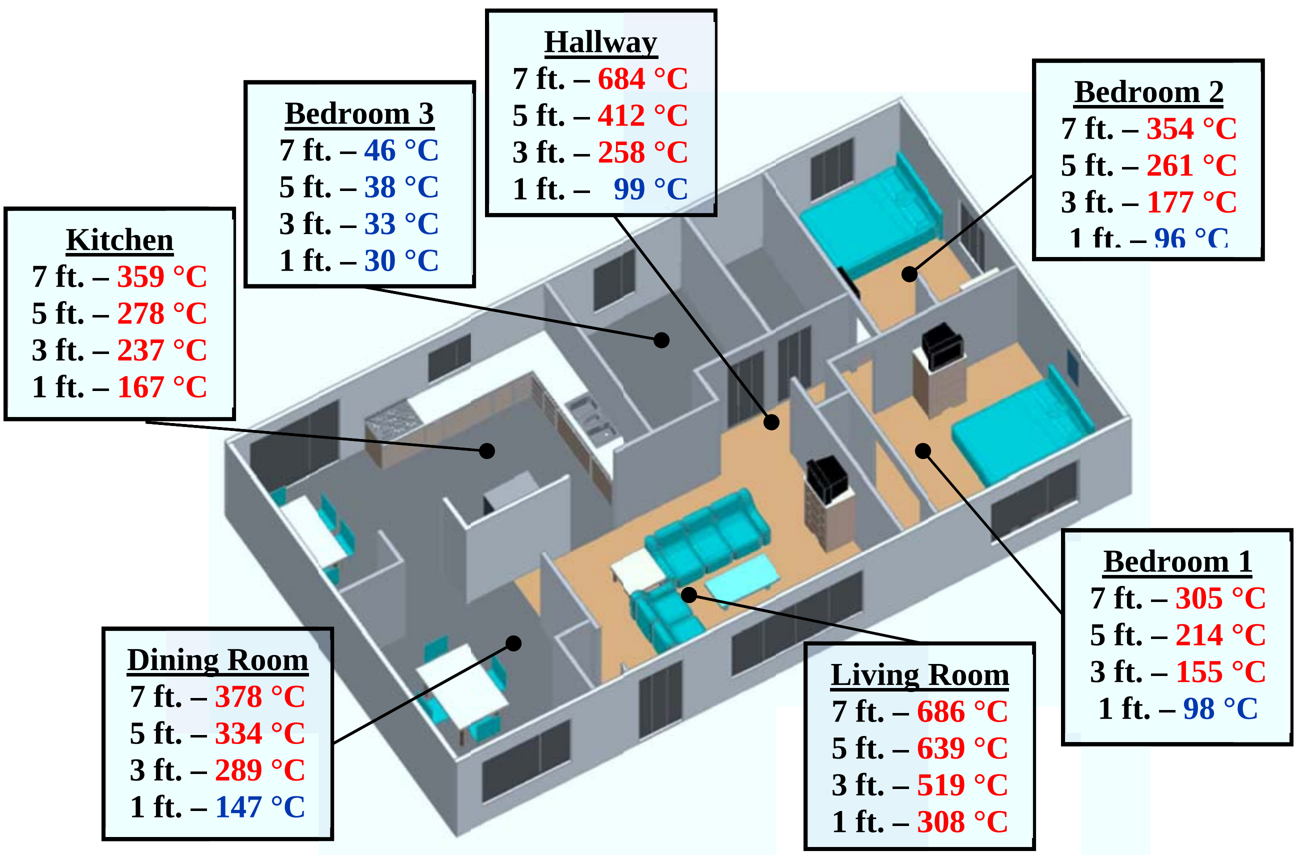


Figure 450. Experiment 5 - Peak temperatures before ventilation (Red = untenable for occupants)

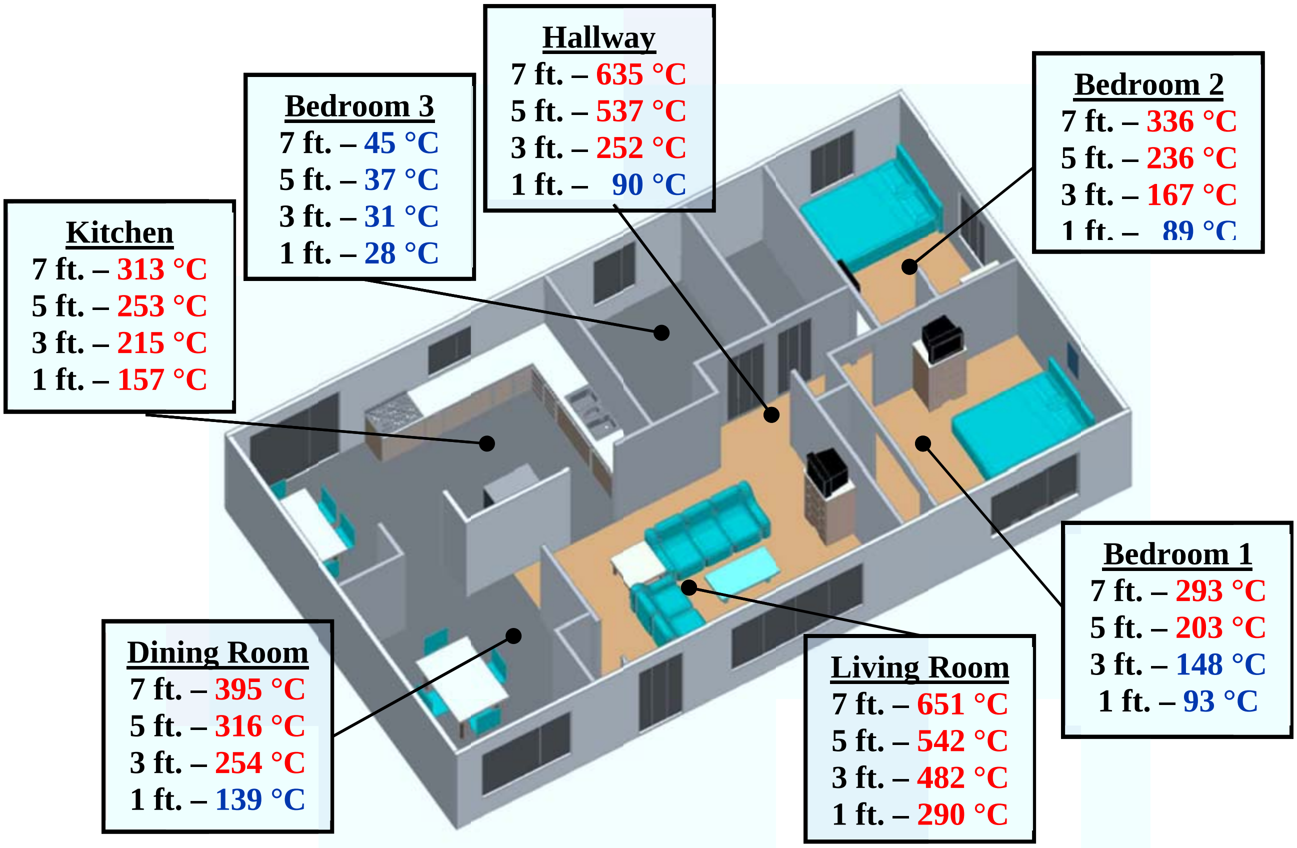


Figure 451. Experiment 7 - Peak temperatures before ventilation (Red = untenable for occupants)

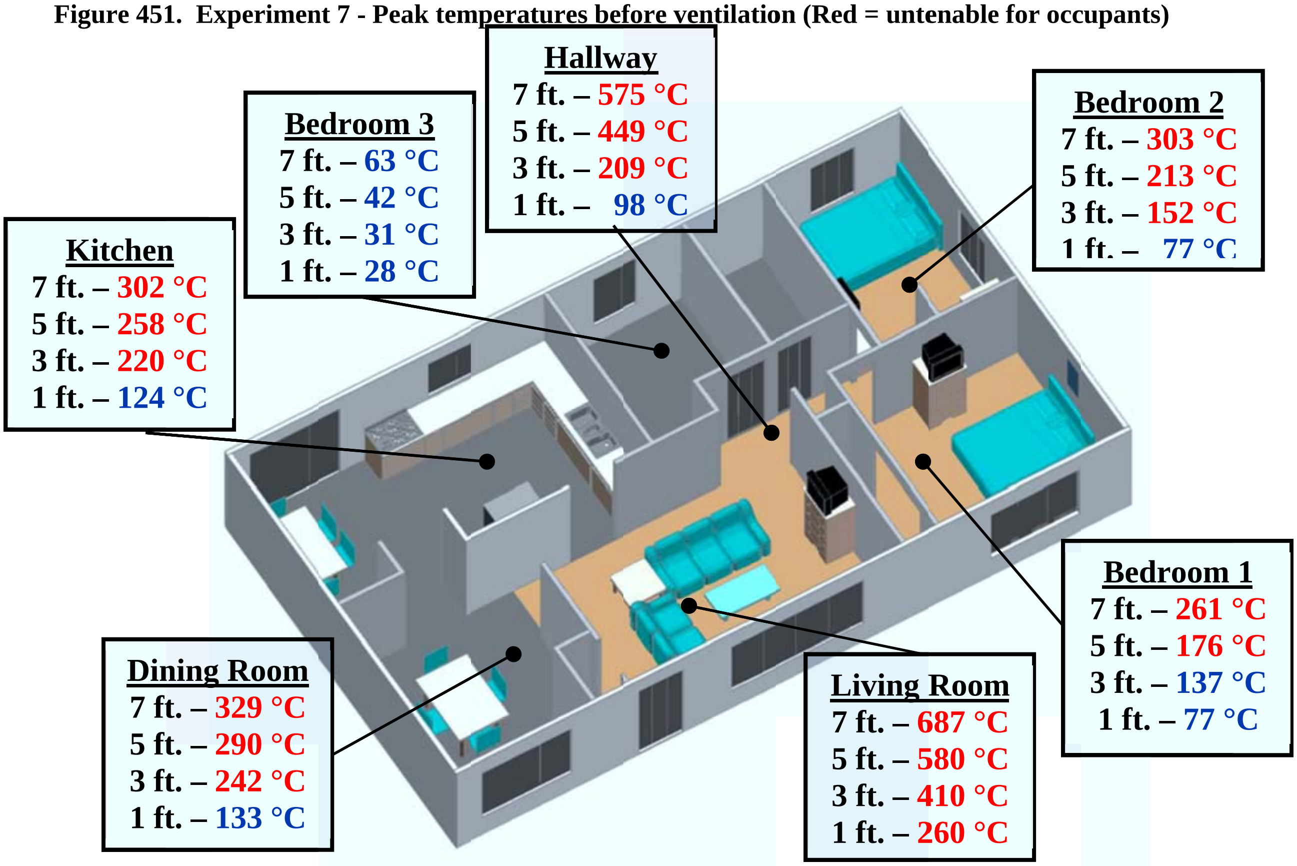


Figure 452. Experiment 9 - Peak temperatures before ventilation (Red = untenable for occupants)

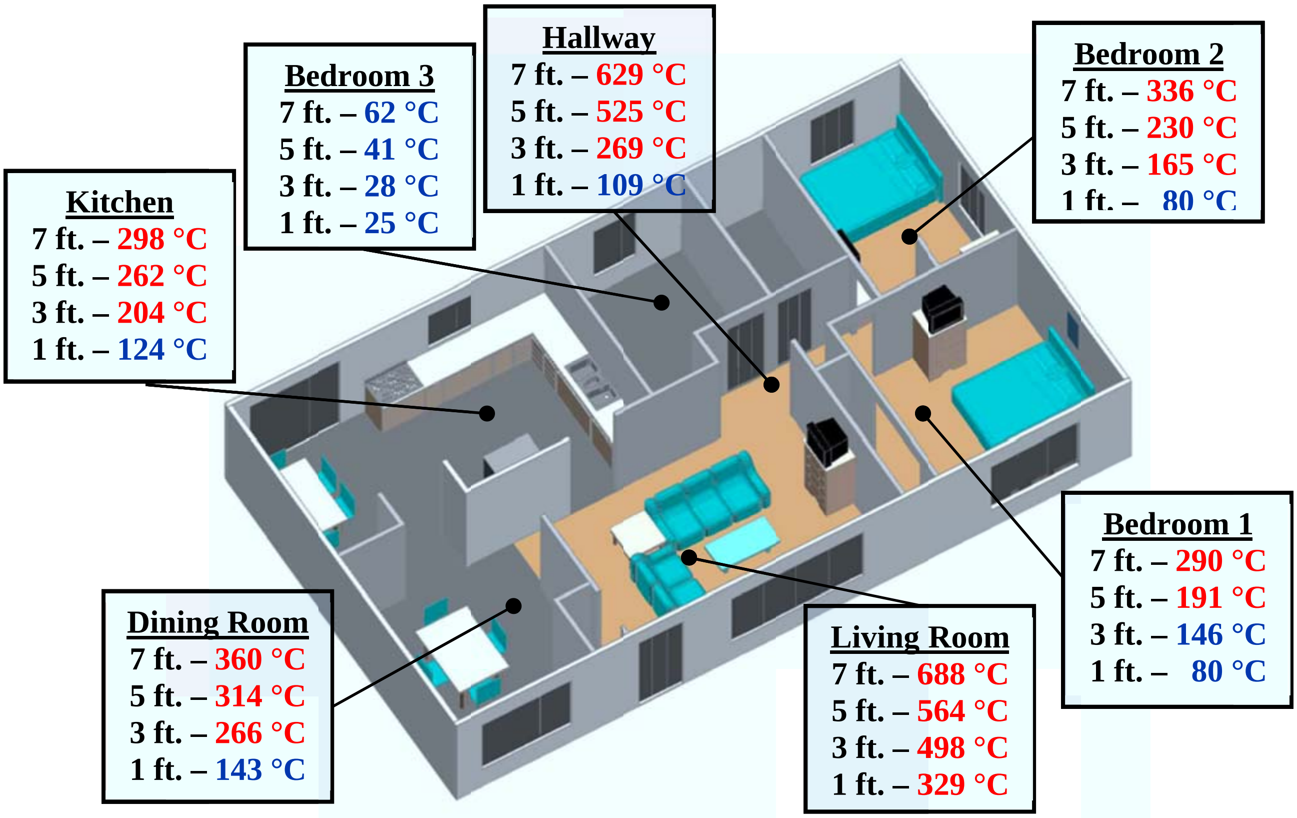


Figure 453. Experiment 12 - Peak temperatures before ventilation (Red = untenable for occupants)

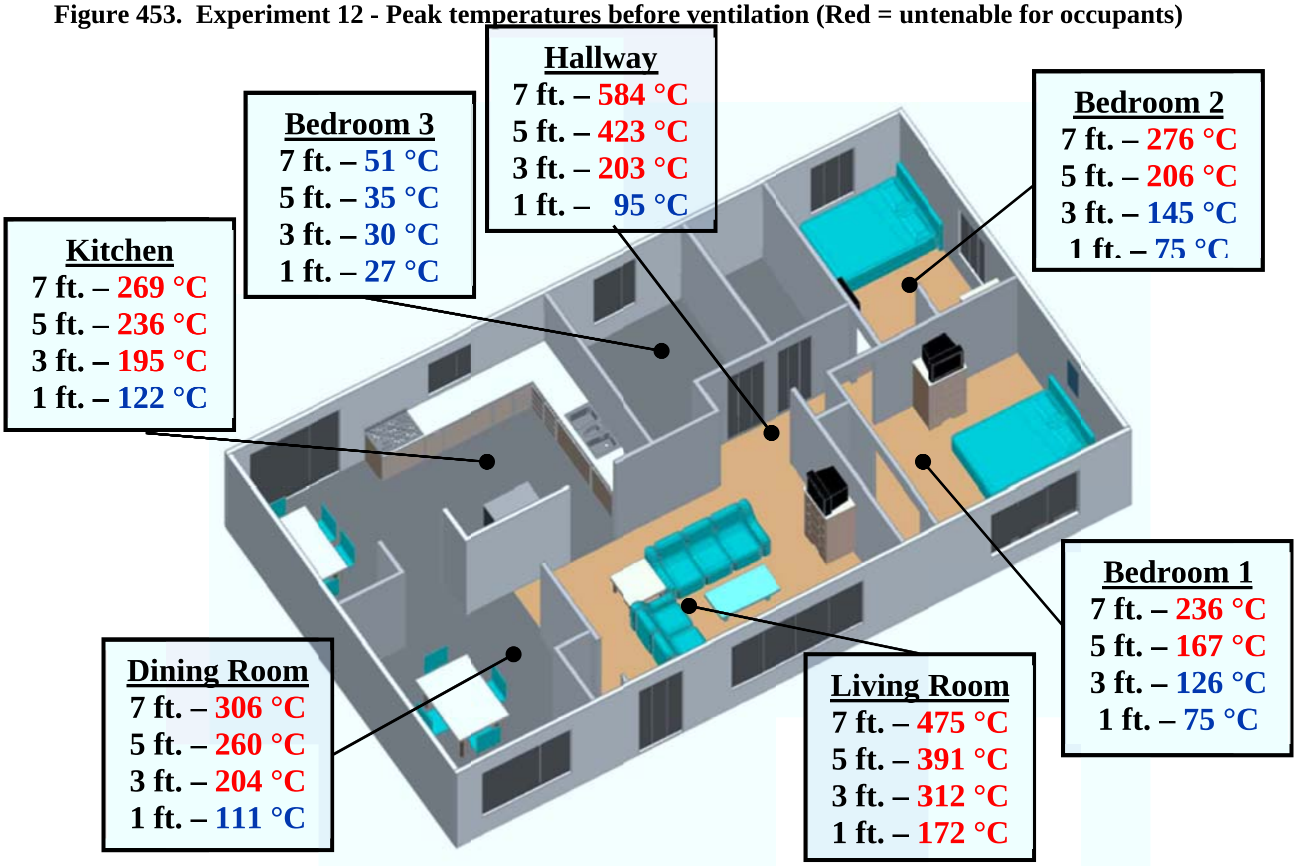


Figure 454. Experiment 14 - Peak temperatures before ventilation (Red = untenable for occupants)

The temperatures, oxygen concentrations and carbon monoxide concentrations were also examined in the Family Room (FR) and Second Floor Hallway (Hall) of the two-story house to determine the time at which the tenability thresholds were exceeded. Table 34 shows the results for the two-story experiments. Temperature was the tenability criteria exceeded first in every experiment in this house as well. In every experiment tenability was exceeded in at least one location prior to ventilation taking place (before the simulated fire department arrival). The average time to untenability in the family room, 1 ft above the floor was 558 seconds, and 423 seconds 5 ft above the floor in the second floor hallway. The elevation of the measurement in the family room assumes someone lying on the floor, while the elevation in the second floor hallway assumes someone walking to escape the bedrooms.

Figure 455 through Figure 462 show the peak temperatures throughout the house prior to simulated fire department arrival (600 seconds). Temperatures in red are above the tenability threshold and temperatures in blue are below that threshold. These figures show the potentially survivable locations within the house. Remote from the fire, below 3 ft throughout the house was usually tenable. The Den and Bedroom 2 were the most tenable rooms. The den door was open and the door to Bedroom 2 was closed. With the door closed to the bedroom the temperatures remained at less than 32 °C (100 °F) in every experiment. The two-story house had more tenable locations due to the larger volume at the same fuel package.

Table 34. Time to occupant untenability in two-story house

Experiment	Temp Untenability (s)		Oxygen Untenability		CO Untenability	
	FR @ 1 ft	Hall @ 5ft	FR @ 1ft	Hall @ 5ft	FR @ 1 ft	Hall @ 5ft
2	252	402	NA	850	NA	820
4	282	432	NA	1000	NA	NA
6	252	402	NA	NA	NA	NA
8	784	364	900	820	900	850
10	1444	424	NA	1400	NA	NA
11	424	364	NA	850	NA	NA
13	514	484	NA	740	NA	NA
15	754	514	NA*	NA*	NA*	NA*

*- Instrumentation Malfunction, NOTE: NA = Not Achieved

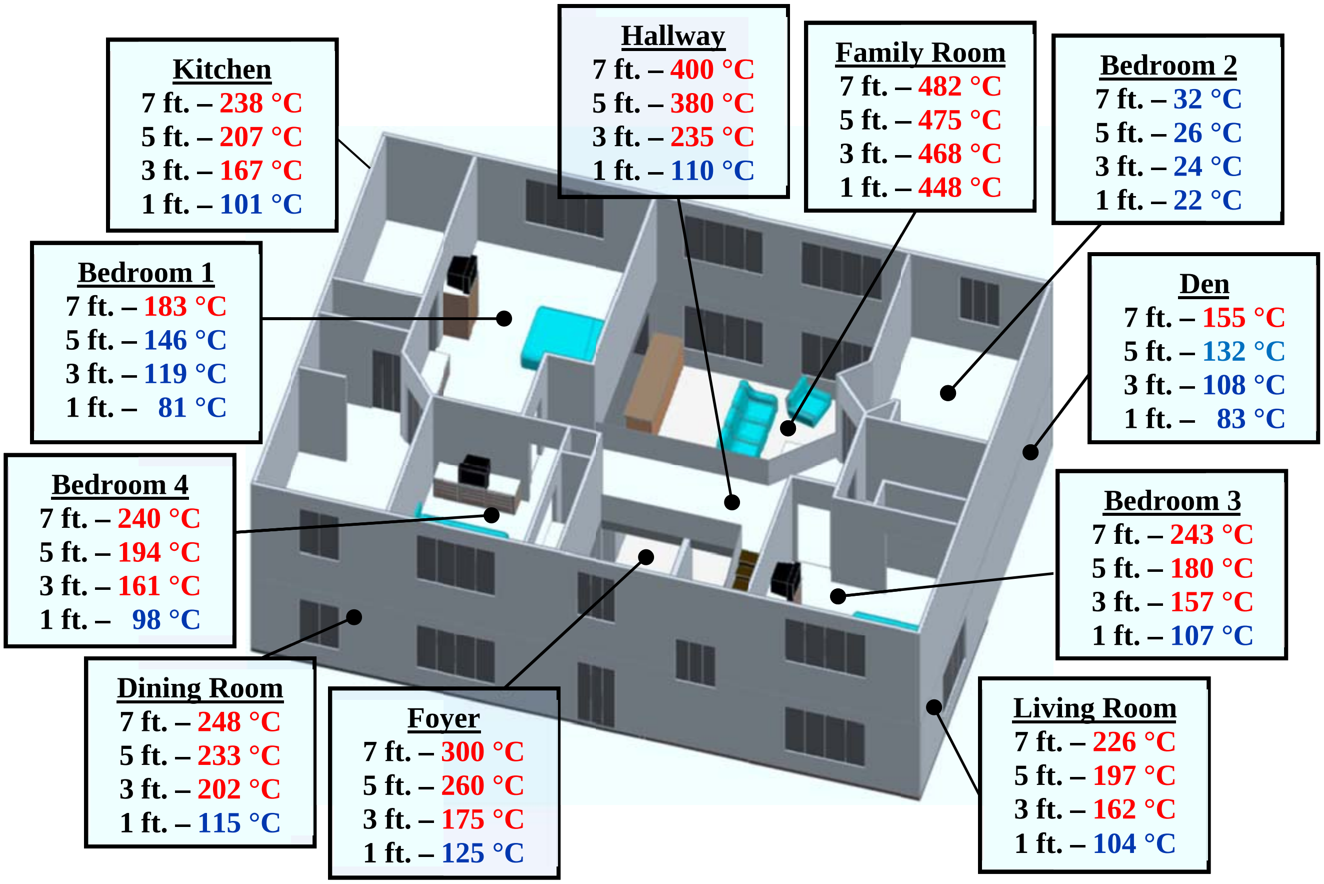


Figure 455. Experiment 2 - Peak temperatures before ventilation (Red = untenable for occupants)

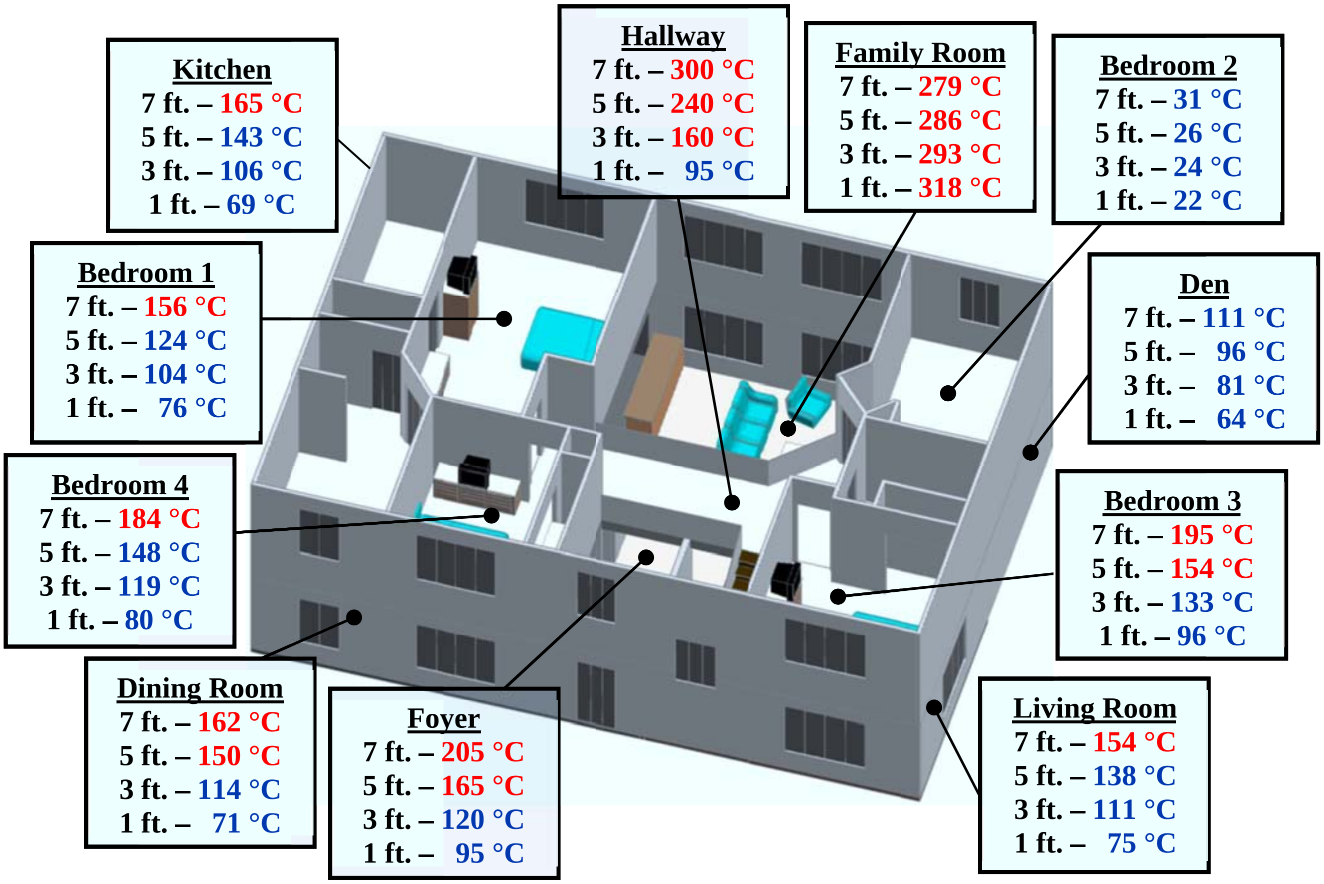


Figure 456. Experiment 4 - Peak temperatures before ventilation (Red = untenable for occupants)

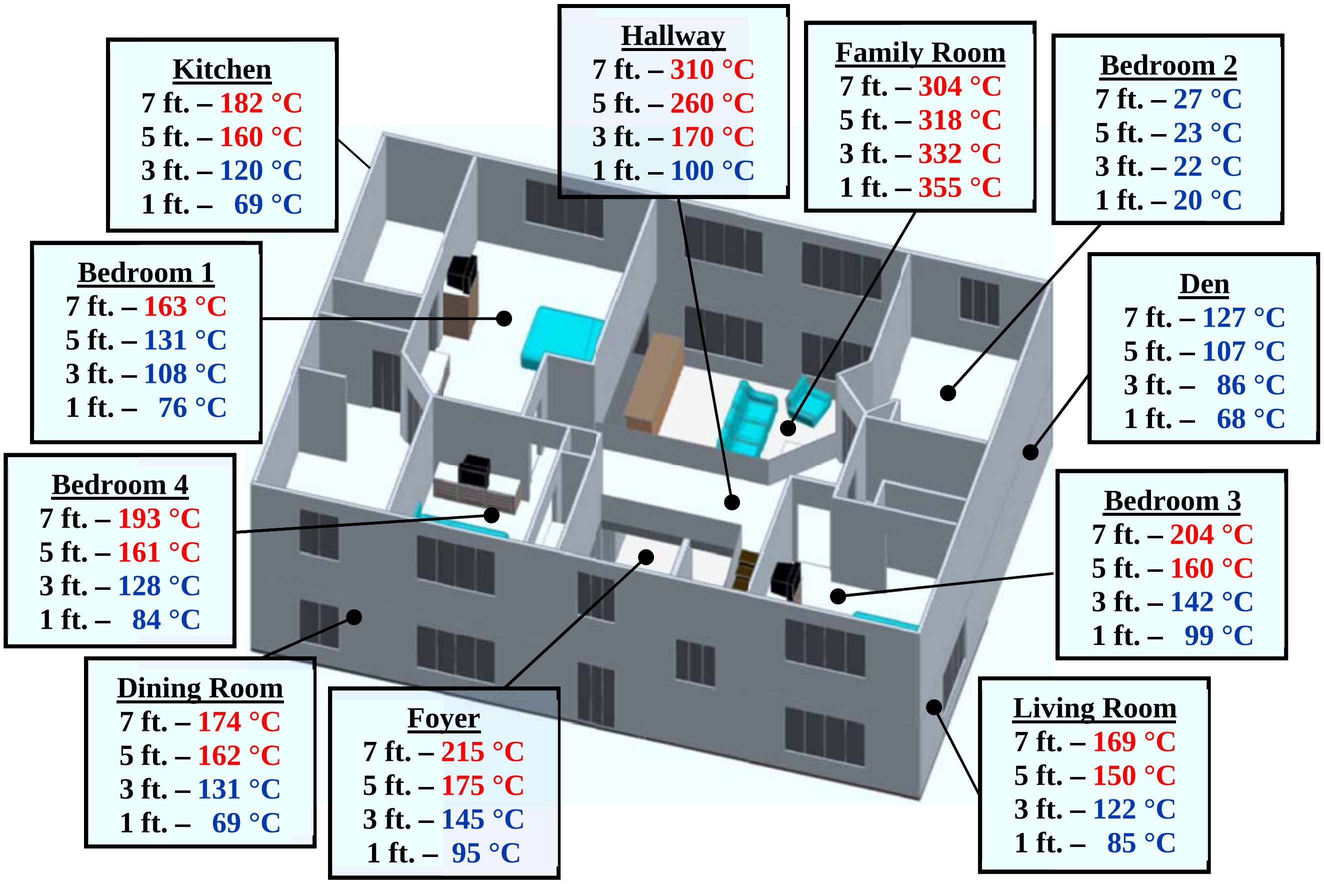


Figure 457. Experiment 6 - Peak temperatures before ventilation (Red = untenable for occupants)

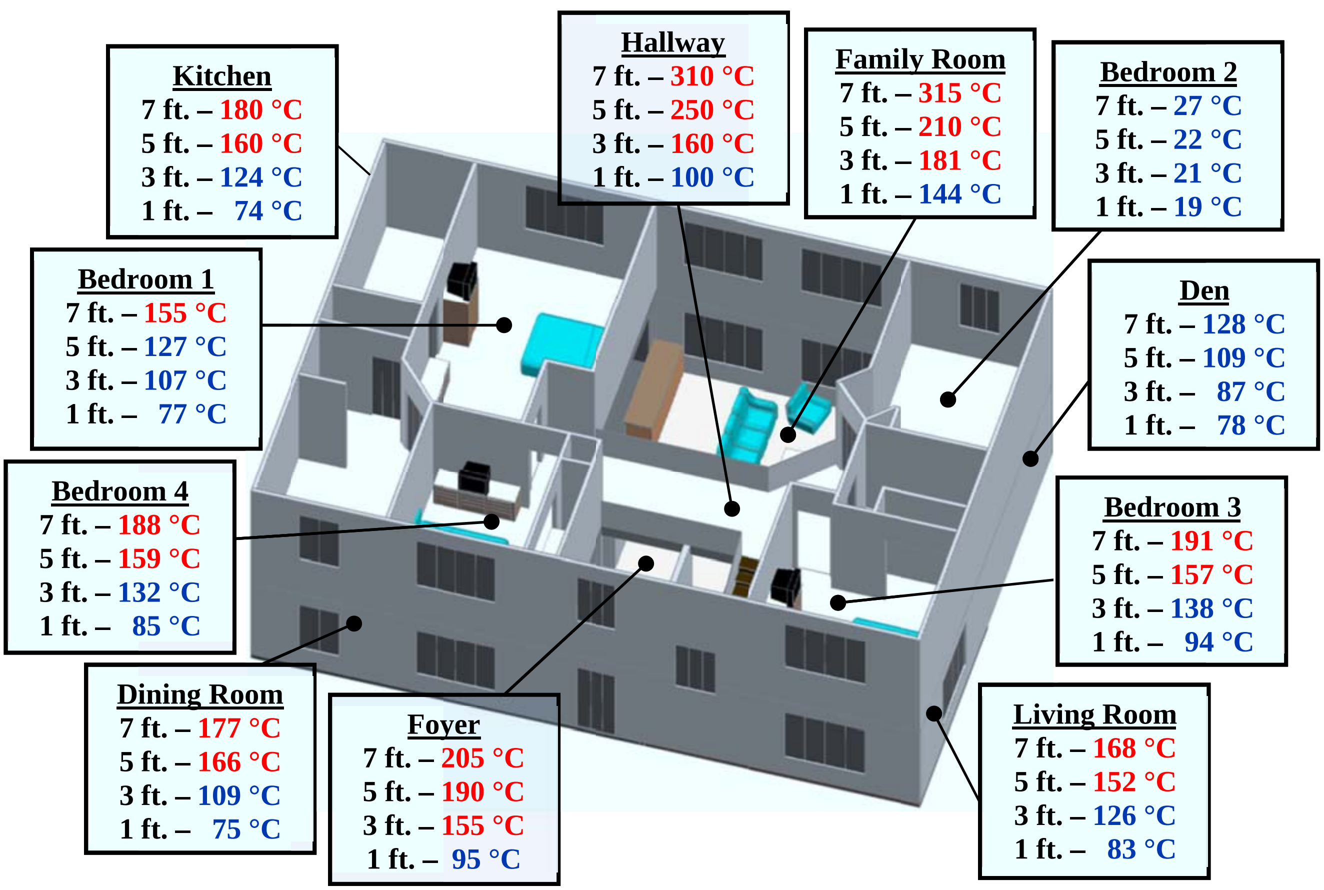


Figure 458. Experiment 8 - Peak temperatures before ventilation (Red = untenable for occupants)

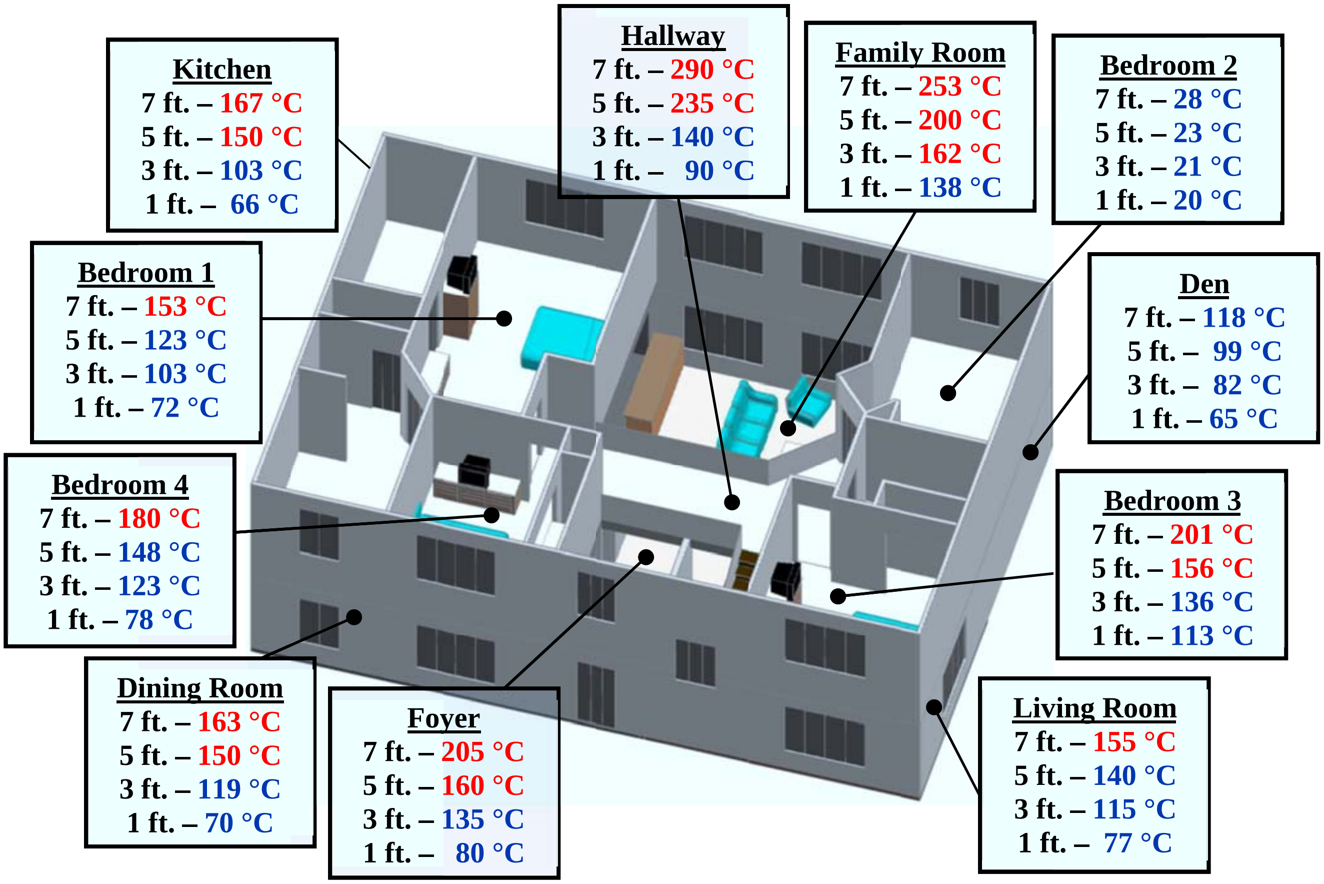


Figure 459. Experiment 10 - Peak temperatures before ventilation (Red = untenable for occupants)

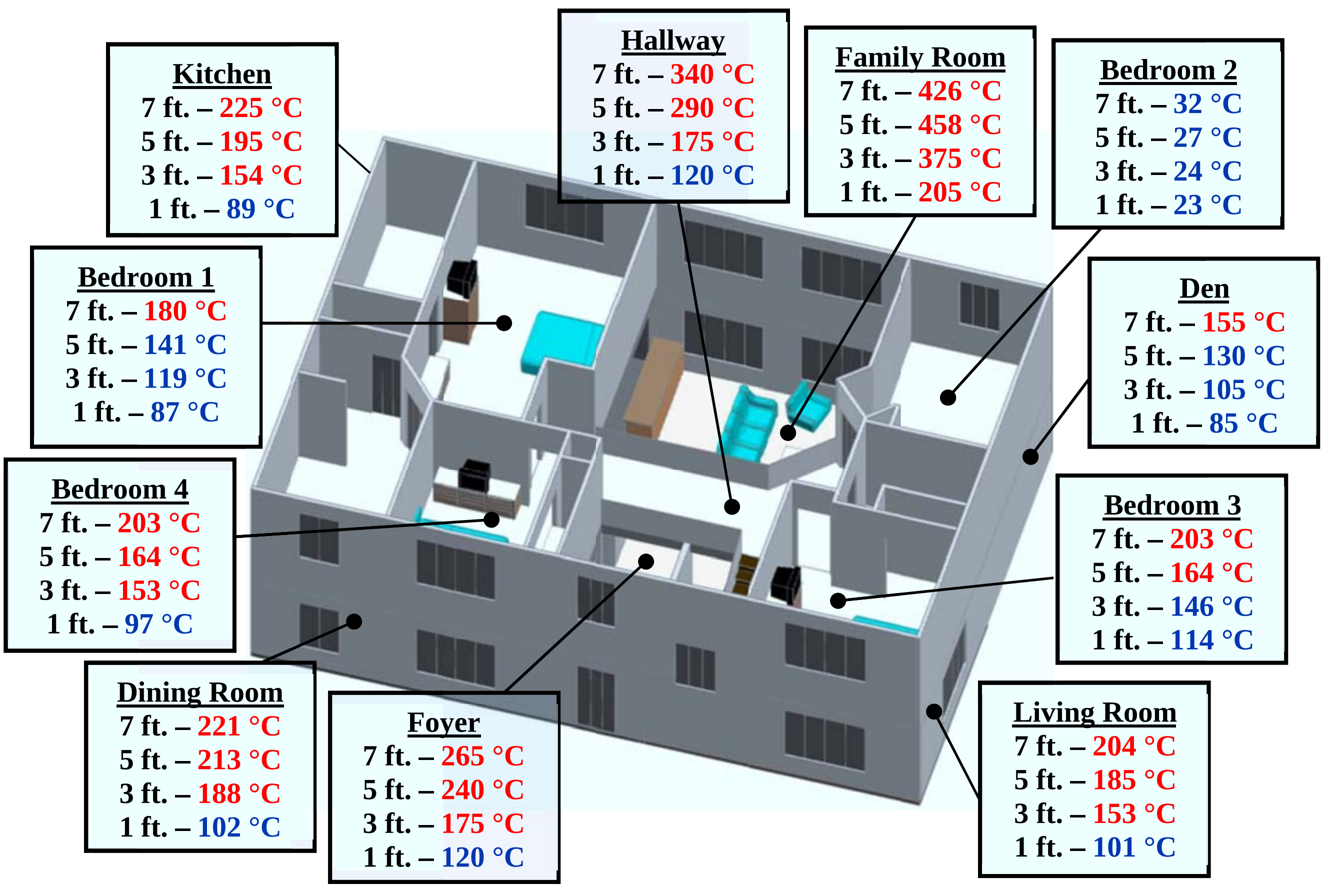


Figure 460. Experiment 11 - Peak temperatures before ventilation (Red = untenable for occupants)

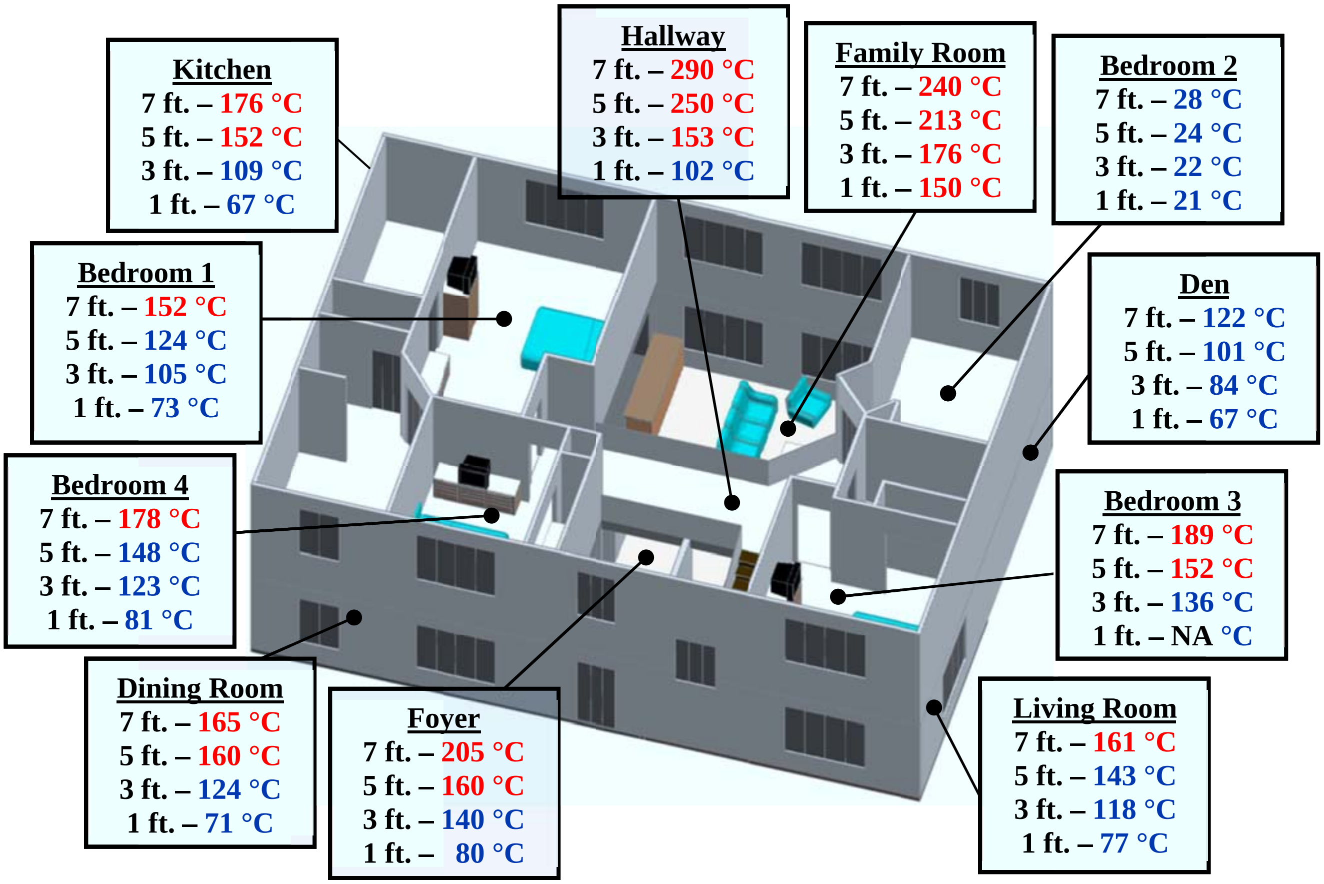


Figure 461. Experiment 13 - Peak temperatures before ventilation (Red = untenable for occupants)

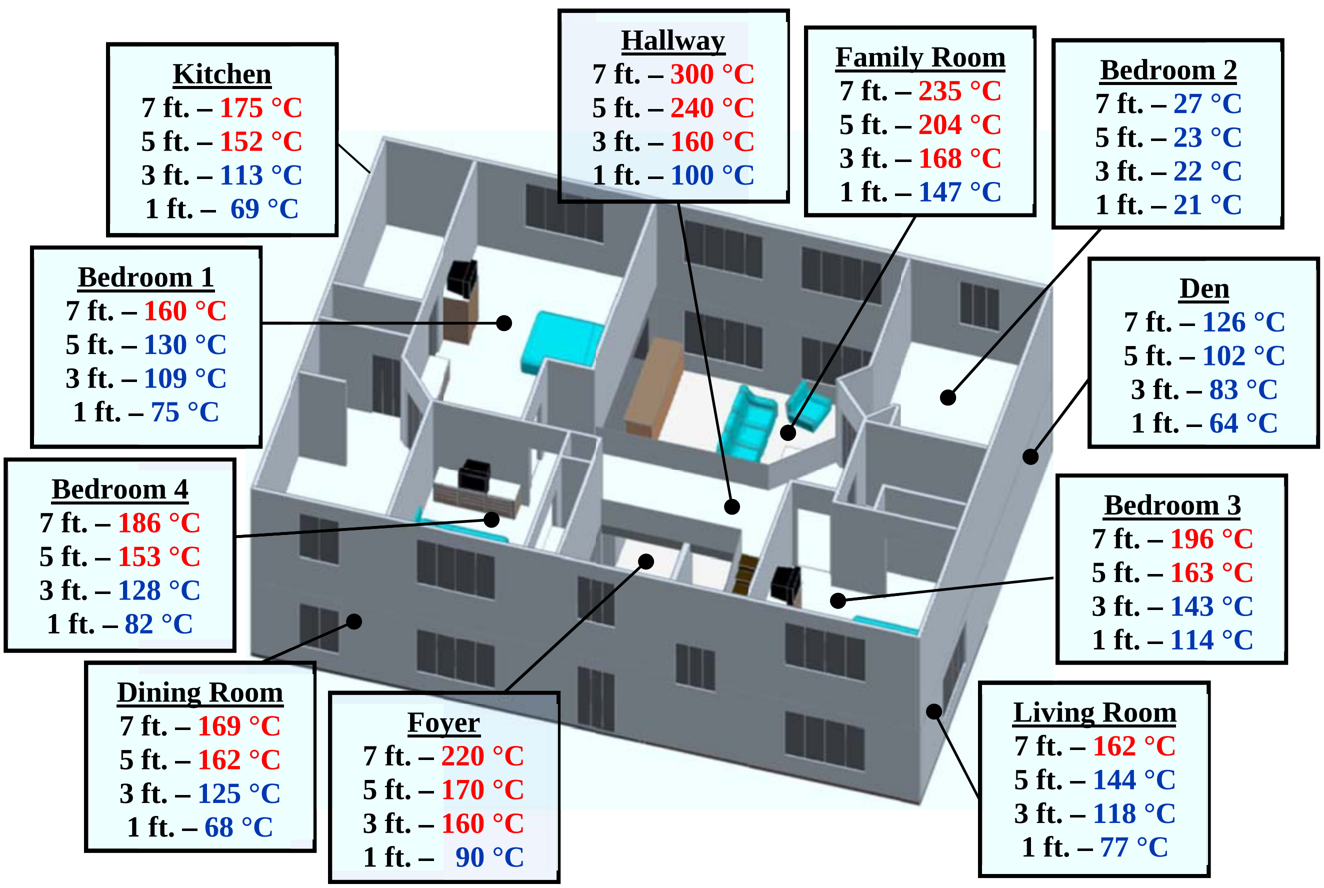


Figure 462. Experiment 15 - Peak temperatures before ventilation (Red = untenable for occupants)

The previous section identified a high hazard for occupants during a fire in either of the two houses. While most of the houses would be untenable there were locations in which occupants could need to be rescued from. Firefighters are going to need to make ventilation openings in order to gain access to search for occupants. This section examines the time that the firefighters have before the fire responds to the additional oxygen and conditions become untenable for them.

Table 35 and Table 36 show the time from ignition to untenability for potential firefighters that may be inside during the time following ventilation for the one-story and two-story houses respectively. Temperatures are reported at the elevation of 3 ft above the floor. This represents a firefighter crawling close to the ground in an attempt to stay as cool as possible. This analysis also assumes that no water is being applied to the fire. Practical examples of this could be searching ahead of a hoseline or searching and something goes wrong with the hoseline.

In the one-story house, during Experiment 1, only the front door was opened which limited the amount of oxygen made available to the fire so only the living room and dining room became untenable. During all of the other experiments the entire house became untenable with the exception of the bedrooms. The two experiments that included the ventilation of the bedrooms had upper layer temperatures greatly increase but the lower layer, below 3 ft remained below 260 °C (500 °F) because the outside air was being pulled in through the windows to grow the fire in the living room and hallway. Minimum time from ventilation to firefighter untenability in the one-story house averaged 100 seconds (87 seconds minimum and 113 seconds maximum). During this time the firefighters would have to suppress the fire or evacuate to remain safe.

Table 35. Time and location of firefighter untenability (One-story)

Experiment	Time of Firefighter Temperature Untenability @ 3 ft (s)						
	LR	DR	Kit	Hall	BR1	BR2	BR3
1	595	651	NA	NA	NA	NA	NA
3	567	606	618	597	NA	NA	NA
5	613	641	651	645	NA	NA	NA
7	599	645	655	635	NA	NA	NA
9	601	625	634	633	NA	NA	NA
12	581	606	622	604	NA	NA	NA
14	566	593	601	581	NA	NA	NA

NOTE: NA = Not Achieved

In the two-story house there were few locations that were untenable for firefighters. In every experiment but Experiment 6 both the family room and second floor hallway became untenable after ventilation. Depending upon the ventilation location(s) additional room became untenable for firefighters. In Experiment 2, only the front door was opened, which limited the air to the fire and no other rooms became untenable. Experiment 6 was similar in that only the window was opened, therefore only the family room became untenable. Experiments 4, 10 and 11 all opened the front door and window in the family room. This additional air created additional heat generation and the dining room and foyer also became untenable. Experiment 4 and 11 were similar and Experiment 10 behaved differently because the second sofa did not ignite until after the first sofa was completely consumed by fire. This caused slow fire growth and is not similar to the other 7 experiments. Experiment 13 was similar to Experiments 4 and 11 except the upper family room window was ventilated. This caused untenability faster but localized the untenability to just the family room and second floor hallway. Ventilating the front door and a window remote from the fire (upstairs bedroom) caused the living room, foyer and two upstairs bedrooms to become untenable. Ventilating the from door and 4 additional first floor window allowed the most air into the fire and created untenability for firefighters in most of the house.

Due to the very different fire growth in Experiment 10 a median time to untenability is more appropriate than the average. The median time from ventilation to firefighter untenability in the two-story house was 200 seconds. During this time the firefighters would have to suppress the fire or evacuate to remain safe.

Table 36. Time and location of firefighter untenability (Two-story)

Experiment	Time of Firefighter Temperature Untenability @ 3 ft (s)										
	FR	Den	LR	DR	Kit	Foyer	Hall	BR1	BR2	BR3	BR4
2	672	NA	NA	NA	NA	NA	825	NA	NA	NA	NA
4	942	NA	NA	1032	NA	1050	1000	NA	NA	NA	NA
6	822	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
8	784	NA	904	NA	NA	844	784	NA	NA	784	844
10	1414	NA	NA	NA	NA	NA	1414	NA	NA	NA	NA
11	814	NA	NA	842	NA	874	844	NA	NA	NA	NA
13	694	NA	NA	NA	NA	NA	775	NA	NA	NA	NA
15	724	NA	814	752	814	752	752	NA	NA	874	784

NOTE: NA = Not Achieved

There are a number of variables beyond the two measurements described above that could lead to incapacitation or death in a fire scenario. Some of them are the exposure time, the rate of change of the exposure, the susceptibility of a particular individual, or any preexisting antagonistic conditions. It has also been well studied that these measures have additive effects. For example an oxygen deficient environment could cause an individual to breath faster which would increase the intake of CO and hot gases.

8.8.4. Rate of Change

An important factor when analyzing ventilation is how long it takes for the fire to respond to the air provided by the ventilation event and when the environment becomes untenable for firefighters operating in the structure. To examine this for each experiment the time of ventilation was subtracted from the time of untenability. Looking closer at this time window you can see when the temperature begins to rise and at what rate. This could be the time firefighters notice there is a problem and how long they have to evacuate.

Figure 463 shows the temperatures at 1 ft above the floor in the living room of the one-story house from time of ventilation until post flashover. This shows the exponential growth of the fire once it responds to the air provided by the ventilation. From the time the temperatures begin to increase until firefighter untenability and further to flashover is a very short period of time (Table 37). Experiments 3, 9 and 14 have temperatures that increase from 260 °C (500 °F) to over 600 °C (1110 °F) in less than 10 seconds. This requires the firefighter to make it to an exit very quickly when conditions begin to deteriorate.

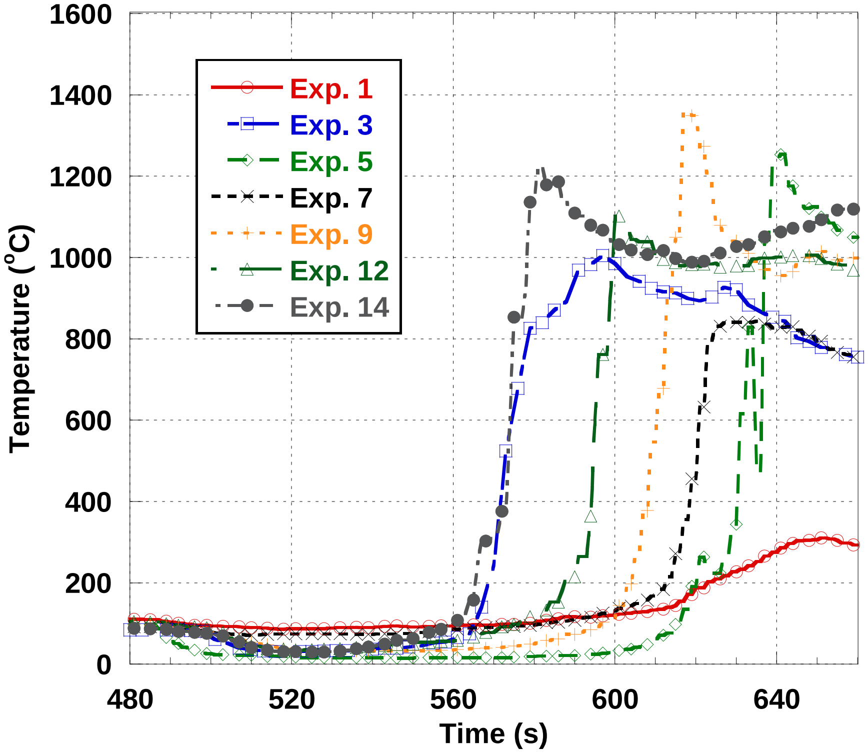


Figure 463. One-story LR 1 ft. Rate of Change

Figure 464 shows the temperatures at 1 ft above the floor in the family room of the two-story house from time of ventilation until post flashover. There were fewer experiments that transitioned to flashover in the two story house but the three experiments that did were Experiments 4, 13 and 15. Due to the larger volume they took a little longer than the one-story house to have dramatic temperature increases but they still occurred. Experiments 13 and 15 had temperatures that went from 260 °C (500 °F) to 600 °C (1110 °F) in less than 20 seconds and 36 seconds respectively. This is also very little time for firefighters to react to the changing conditions.

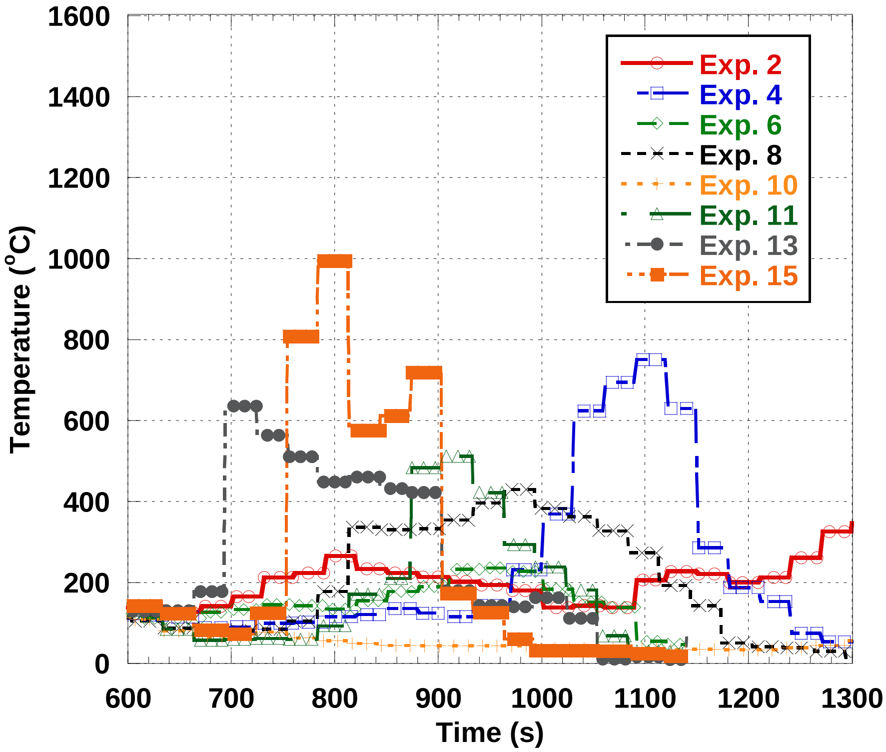


Figure 464. Two-story FR 1 ft. Rate of Change

Table 37. Time to untenability and flashover after ventilation

Experiment	Time from Ventilation Until FF Untenability (seconds)	Time from FF Untenability Until Flashover (600 °C) (seconds)
1	115	NA
2	72	NA
3	85	8
4	342	86
5	133	17
6	220	NA
7	119	21
8	184	NA
9	119	9
10	814	NA
11	214	NA
12	101	14
13	94	20
14	86	7
15	124	36

NOTE: NA = Not Achieved

8.8.5. Comparison of Tactical Ventilation Methods

Fifteen experiments were conducted varying the ventilation locations and the number of ventilation openings. Ventilation scenarios included ventilating the front door only, opening the front door and a window near and remote from the seat of the fire, opening a window only and ventilating a higher opening in the two-story house. The temperature data will be compared to examine the conditions in the houses dependent upon which ventilation openings are made. Firefighters are taught to ventilate based on the location of the fire and in coordination with the operation that is being implemented. These comparisons provide a way to examine why they are taught those ideas and what those ideas mean for the tenability and fire dynamics within the houses.

8.8.5.1. Influence of Creating Additional Ventilation Openings

The amount of air and the location that the air supplied to an oxygen limited fire changes how much energy a fire generates and how fast it generates it. Figure 465 shows the living room temperatures 5 ft above the floor in each of the one-story ventilation scenarios. This figure shows how fast the temperatures in the living room increase and to what magnitude. When only the door was opened (RED), the fire was not getting all the air it needed to burn to its potential so it reached a peak temperature of approximately 700 °C (1290 °F) and did so the slowest of the 5 scenarios. Opening the bedroom window (ORANGE) in addition to the door allowed the fire to peak at 825 °C (1520 °F) about 30 seconds faster. Opening the living room window only (BLUE) allowed the fire to reach a peak of over 1200 °C (2190 °F) and it reached the temperature of the previous two scenarios faster. When the door and the living room window (GREEN) were opened the fire also reached in excess of 1200 °C (2190 °F), but did it even faster. The final scenario of opening the door and 4 windows (GREY) including the living room window and bedroom windows the fire reached close to 1200 °C (2190 °F) and did so 20 seconds faster than the next closest scenario and 75 seconds faster than just opening the door.

Figure 466 shows the family room temperatures 5 ft above the floor in four of the two-story ventilation scenarios. When only the door was opened (RED) the fire approached flashover but did not have enough air to achieve it. Opening only the window (BLUE) did not allow for flashover and the maximum temperature remained below approximately 450 °C (840 °F) and was the slowest developing of the scenarios. When the door and window were opened (GREEN) the fire grew faster and peaked at 550 °C (1020 °F). The final scenario where the front door and 4 windows (ORANGE) were opened the fire transitioned to flashover the fastest of any of the scenarios and peaked at 950 °C (1740 °F).

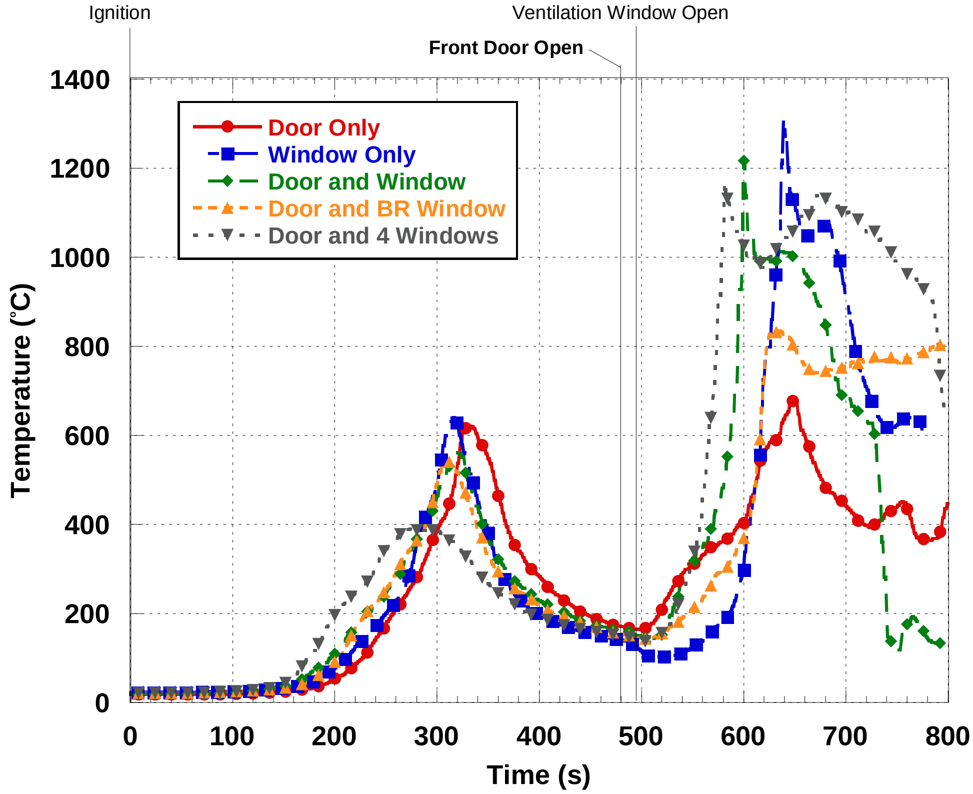


Figure 465. One-Story House Living Room Temperatures 5 ft above the floor

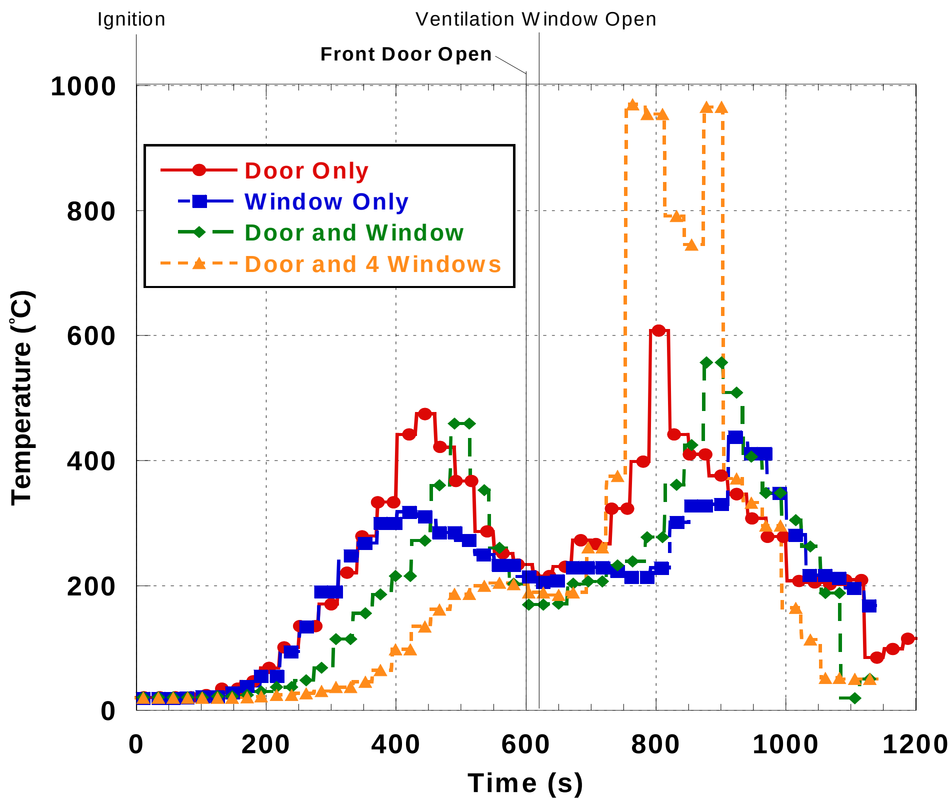


Figure 466. Two-Story House Family Room Temperatures 5 ft above the floor

8.8.5.2. Near the Seat of Fire and Remote From the Seat of Fire

The main guidance firefighters are given in their basic ventilation training is to ventilate as close to the seat of the fire as possible. This is meant to localize the growth of the fire to the area of origin. Ventilating remote from the seat of the fire creates the potential to spread the fire to uninvolved parts of the house by creating a flow path and source of oxygen from that uninvolved area.

Experiment 12 (Figure 467) and Experiment 7 (Figure 468) in the one-story house are compared in Figure 469. The RED lines represent the temperatures 5 ft above the floor during the experiment when the front door was opened, followed by opening the living room window. This scenario represents ventilating near the seat of the fire which is consistent with a correct ventilation action based on firefighter training. The BLUE lines are measurements in the same locations but from the experiment where the front door was opened followed by the opening of the window in Bedroom 2. The graph shows a slightly faster growing fire when ventilated near the seat of the fire. This can be expected because the source of oxygen is in the fire room and the fire can react to this and increase its heat release rate. The bedrooms also increase in temperature but Bedroom 2 only peaks at approximately 250 °C (480 °F) and Bedroom 1 peaks at 210 °C (410 °F). Then they begin to decrease in temperature because of the lack of oxygen available to burn at that side of the house. When ventilated remote from the seat of the fire the living room temperature does not peak as high because it has less oxygen supplied to it. The difference is in the bedrooms. An area that was previously limited in temperature because it was out of the flow path has now become part of the flow path. This increases the temperatures to close to 500 °C (930 °F) in Bedroom 2 and up to 300 °C (570 °F) in Bedroom 1. If the fire had not been suppressed in order to save the structure for subsequent experiments both bedrooms would have become involved in fire creating an undesired situation from a ventilation choice. Bedroom 3 was unaffected by either ventilation scenario because the door was closed.

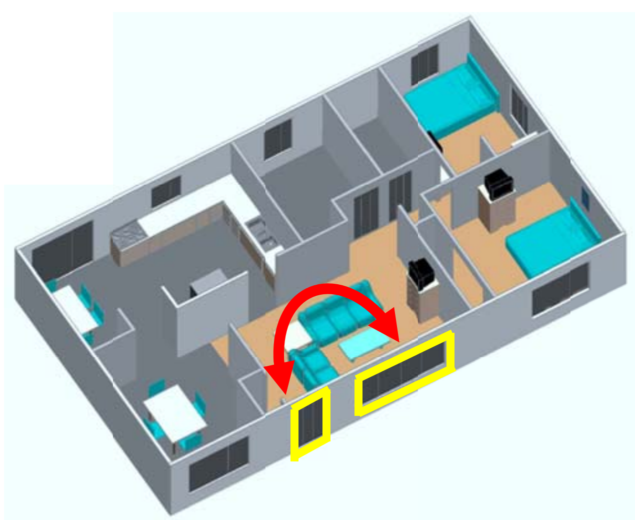


Figure 467. Near Seat of the Fire Flow Path

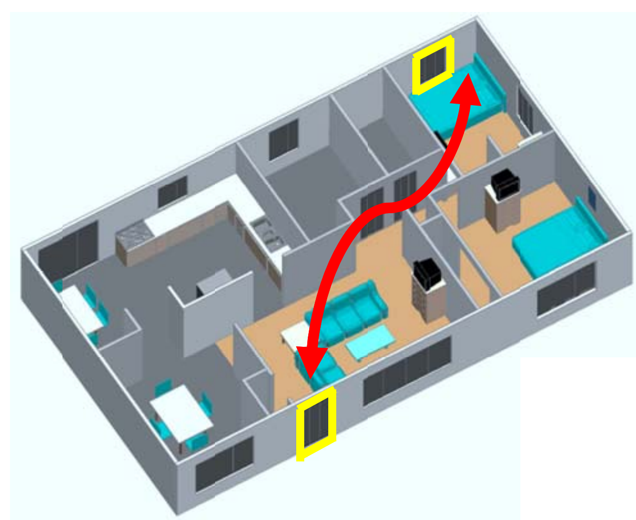


Figure 468. Remote from Seat of the Fire Flow Path

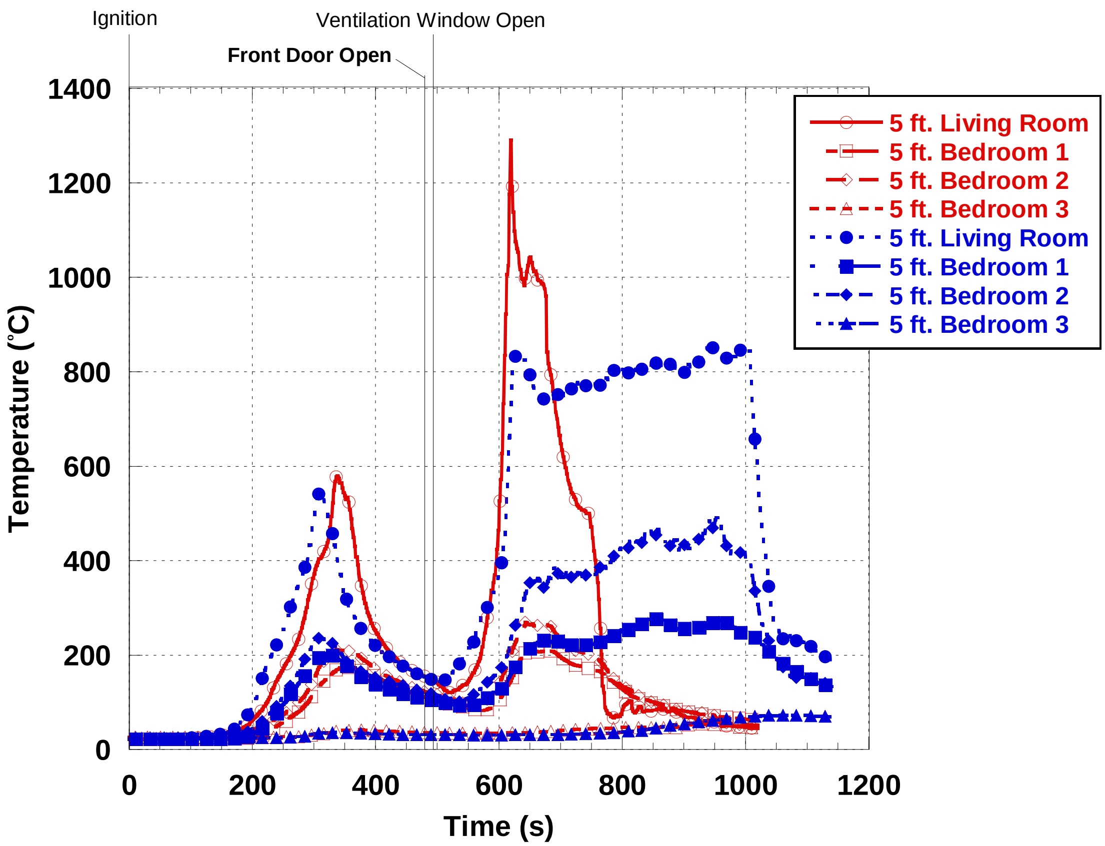


Figure 469. Comparison of Living Room and Bedroom Temperatures at 5 ft above the floor

Experiment 4 (Figure 470) and Experiment 8 (Figure 471) in the two-story house are compared in Figure 472. The RED lines represent the temperatures 5 ft above the floor during the experiment where the front door was opened, followed by opening the family room window. This scenario represents ventilating near the seat of the fire which is consistent with a correct ventilation action based on firefighter training. The BLUE lines are measurements in the same locations but from the experiment where the front door was opened followed by the opening of the window in Bedroom 3. Ventilating near the seat of the fire localizes the temperatures and the combustion. This also creates the highest peak temperature (775 °C [1430 °F]) in the family room because all of the available oxygen is coming right into the family room. Unlike the ranch house ventilating near the seat of the fire peaked later than ventilating remote from the seat of the fire because the remote vent location was on the second floor which allowed more air to enter from the front door and grow the fire. This air was limited which did not allow for temperatures to peak as high as the two ventilation points of the near the seat of the fire experiment. Comparing the bedroom temperatures highlights the impact of creating a flow path through the bedroom. When Bedroom 3 was not in the flow path, its peak temperature was 250 °C (480 °F). However, when it was in the flow path, temperatures increased to 575 °C (1070 °F).

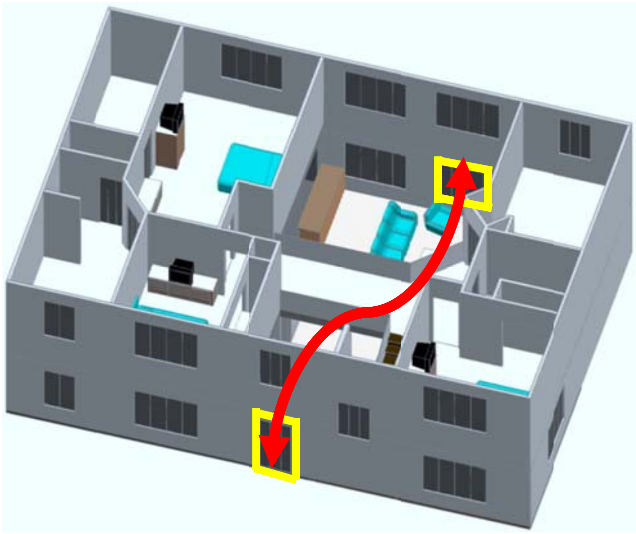


Figure 470. Two-story Near Seat of the Fire Flow Path

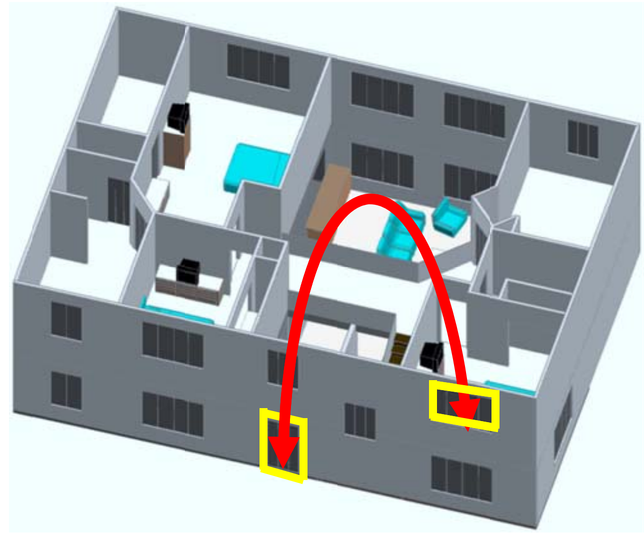


Figure 471. Two-story Remote from the Seat of the Fire Flow Path

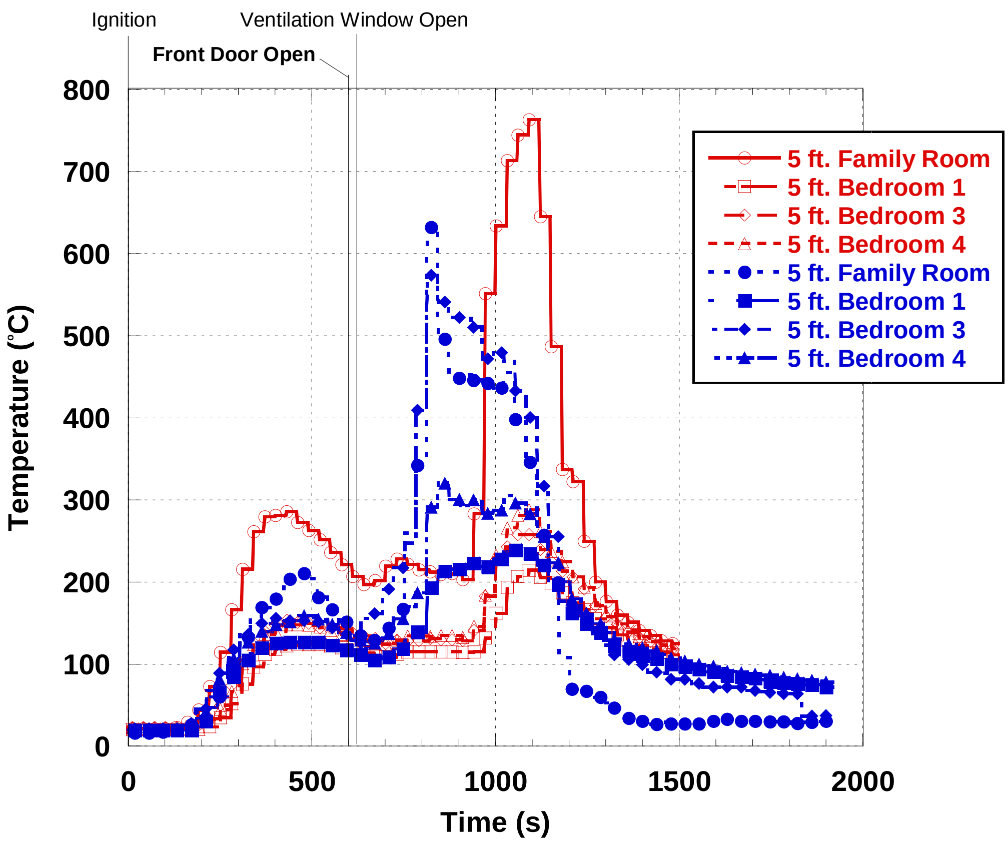


Figure 472. Comparison of Family Room and Bedroom Temperatures at 5 ft above the floor

8.8.5.3. Ventilating High and Ventilating Low

When determining how to most effectively ventilate a room it would be intuitive to ventilate near the top of the room since that is where the hot gases from a fire develop a layer. One must also consider how the cool air enters the room as the hot gases are leaving the room. If the cool air entering the room is needed by the available fuel, then the room will transition to flashover and the burning will take place at the ventilation locations, leaving the room fully involved in flames. Clearly, in this scenario ventilating the top of the room did not provide the relief that was intended.

Figure 473 and Figure 474 show renderings of the windows that were opened to ventilate low and high in the family room. The temperatures at 1 ft above the floor and 16 ft above the floor are plotted in Figure 475. In both experiments, the fire grew, became ventilation limited and then the temperatures decreased. Once the door and window were opened, the high ventilation window caused temperatures to increase much faster than the low ventilation window. The high window experiment reached 950 °C (1740 °F) at the ceiling and 650 °C (1200 °F) at the floor at approximately 720 seconds. A floor temperature above 600 °C (1110 °F) indicates that the family room transitioned to flashover. The low window experiment reached 800 °C (1470 °F) at the ceiling and 500 °C (930 °F) at the floor at approximately 870 seconds.

This is a dramatic difference in fire growth. A comparison can be made to a wood burning stove when fresh air is allowed to flow in low and the hot combustion products are allowed to flow out high. Allowing air into a ventilation limited fire low and letting the hot gases out high can create prime conditions for a flashover, even in a large volume like the two story family room. Another point illustrated by this graph is that the family room did not cool much, if at all, when the high window was ventilated. The temperature 1 ft above the floor did not decrease from 125 °C (260 °F) before it increased exponentially to 650 °C (1200 °F). This is counterintuitive to the reason a ventilation opening would be made in the first place. In this case the ventilation limited fire responded so quickly to the additional/needed air that it did not cool the family room.

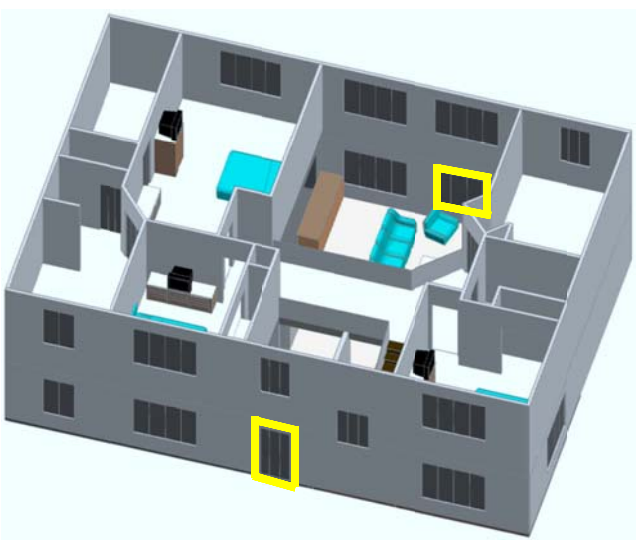


Figure 473. Ventilating the Family Room Low

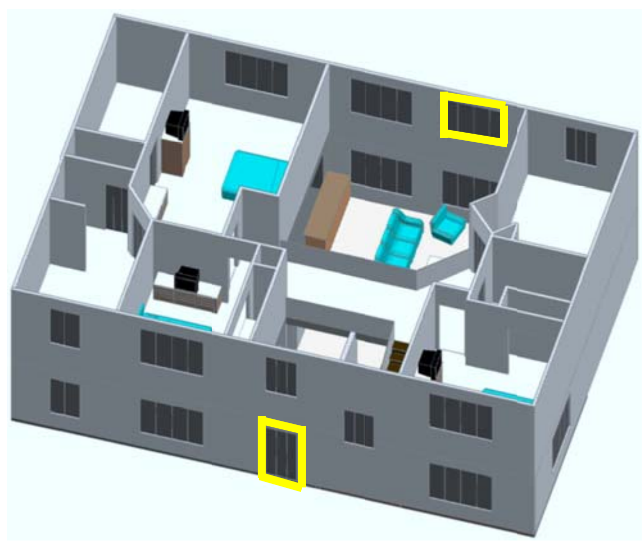


Figure 474. Ventilating the Family Room High

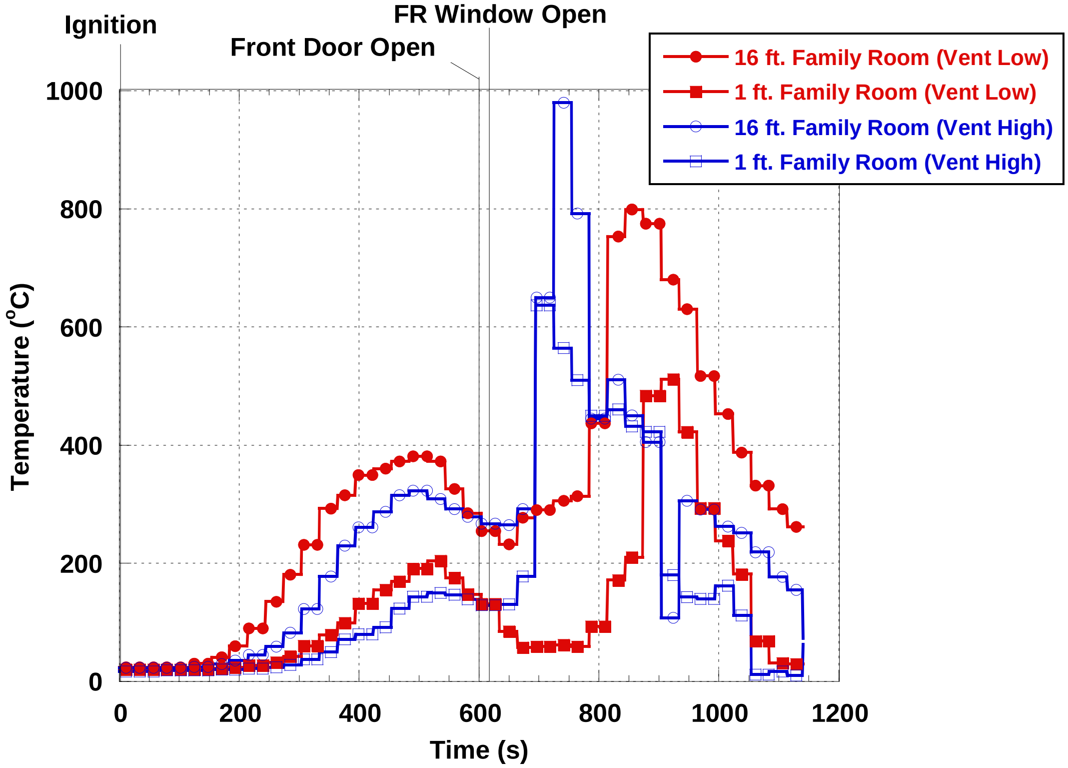


Figure 475. Comparison of ventilating high and low

9. Tactical Considerations

Bringing together the results of these experiments or all experiments for the fire service, to understand how they may impact tactics on the fire ground is crucial to the safety of the fire service. All of the changes to the fire environment that have occurred over the past few decades make it essential for the fire service to reevaluate their tactics on a regular basis. This section will attempt to bring the science to the street. Many of the topics examined in this section can be attributed to the projects technical panel which consisted of fire service leaders from around the world.

Before you read this section it is very important to understand this information and these considerations as they pertain to the types of structures used in these experiments. Another important factor to keep in your mind is the capabilities and resources available to your particular department. If your department has 3 person staffing on an engine and your mutual aid is 20 minutes away you should look at these considerations differently that if your department has 6 person staffing and you expect 4 engines and 2 trucks on the scene in 10 minutes. There are no two fires that are the same and not every scenario has one answer that is correct every time, most of the time it depends on a number of variables. Even in these controlled experiments with the same house and fuel load there are differences in how the fire develops. These tactical considerations are not meant to be rules but to be concepts to think about, and if they pertain to you by all means adapt them to your operations.

9.1. Stages of fire development

A key element to fire behavior training is the fire growth curve that is used to demonstrate where the different stages occur in relation to each other. The basic fire growth curve shows fire ignition followed by the growth stage, flashover, fully developed stage and finally the decay stage (Figure 476). This curve can be misleading. If an item like a sofa was placed in a large room or outside, where plenty of oxygen is available, then the growth curve will look like Figure 476. A more realistic explanation of the modern fire environment where there is usually not enough oxygen available would be ignition followed by a growth stage, decay stage, ventilation (either by the fire service or by an opening created by the fire like window failure), a second growth stage, flashover, fully developed stage and finally the decay stage. Figure 477 depicts what this would look like. Taking an average of all of the fire room ceiling temperatures for both houses shows the shape of the time-temperature curve for all of the ventilation scenarios (Figure 478).

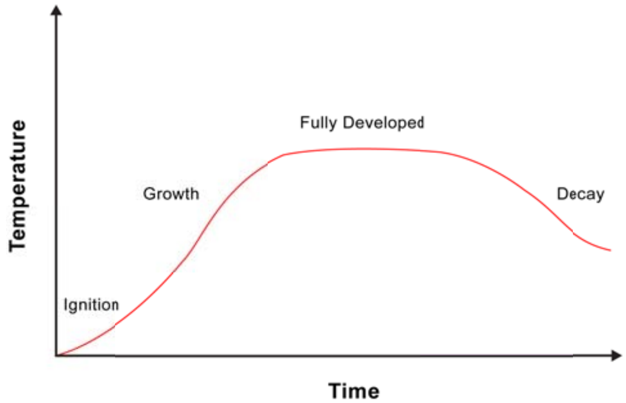


Figure 476. Basic fire growth curve

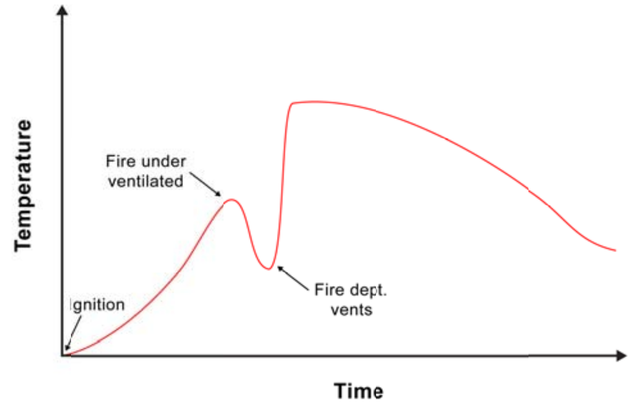


Figure 477. Compartment fire growth curve

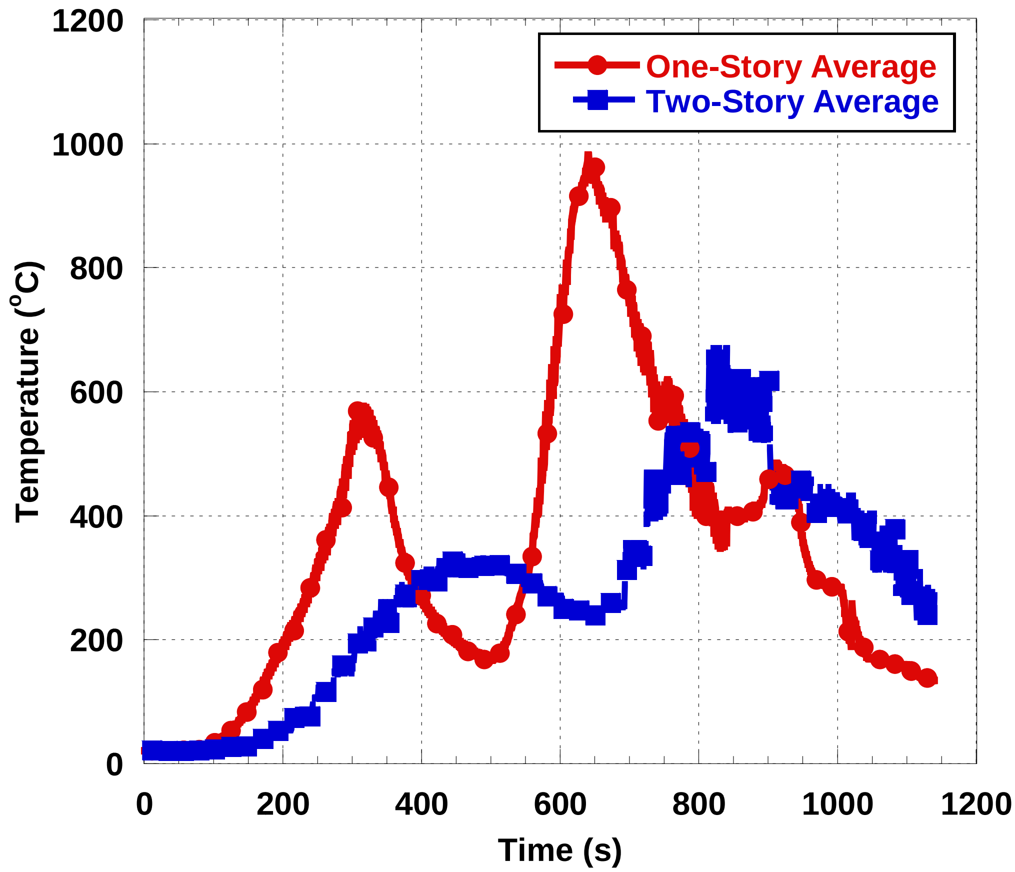


Figure 478. Average fire room ceiling temperature for each house

9.2. Forcing the front door is ventilation

In most cases, when ventilation is taught to new firefighters it is defined by the removal of heat and smoke from a structure. International Fire Service Training Association (IFSTA) defines ventilation as, "Systematic removal of heated air, smoke, and airborne contaminants from a structure and replacing them with fresh air."[52] The problem is that proper respect is not given to the fact that as an opening is made, air is able to enter the structure and provide the missing piece of the fire triangle to a ventilation limited fire. Many firefighters do not think of opening the front door as ventilation, but rather as forced entry for access to search and attack the fire. While entry is necessary, one must also realize that air is being feeding the fire and there is little time before either the fire gets extinguished or it grows until a untenable condition exists, jeopardizing the safety of everyone in the structure.

Examining fire room temperatures at 5 ft above the floor in both houses during the experiments where only the front door was opened shows the increase in temperature following ventilation (Figure 479). In the one story experiment (Experiment 1) the temperature was 180 °C (360 °F) at ventilation (480 s), exceeded the firefighter tenability threshold of 260 °C (500 °F) at 550 s and reached 600 °C (1110 °F) at 650 s. In the two story experiment (Experiment 2) the temperature was 220 °C (430 °F) at ventilation (600 s), exceeded the firefighter tenability threshold of 260 °C (500 °F) at 680 s and reached 600 °C (1110 °F) at 780 s. Both of these experiments show that opening the front door needs to be thought of as ventilation as well as an access point. This necessary tactic also needs to be coordinated with the rest of the operations on the fireground. A simple action of pulling the front door closed after forcing entry until access is ready to be made as part of the coordinated attack will limit the air to the fire and slow the potential rapid fire progression.

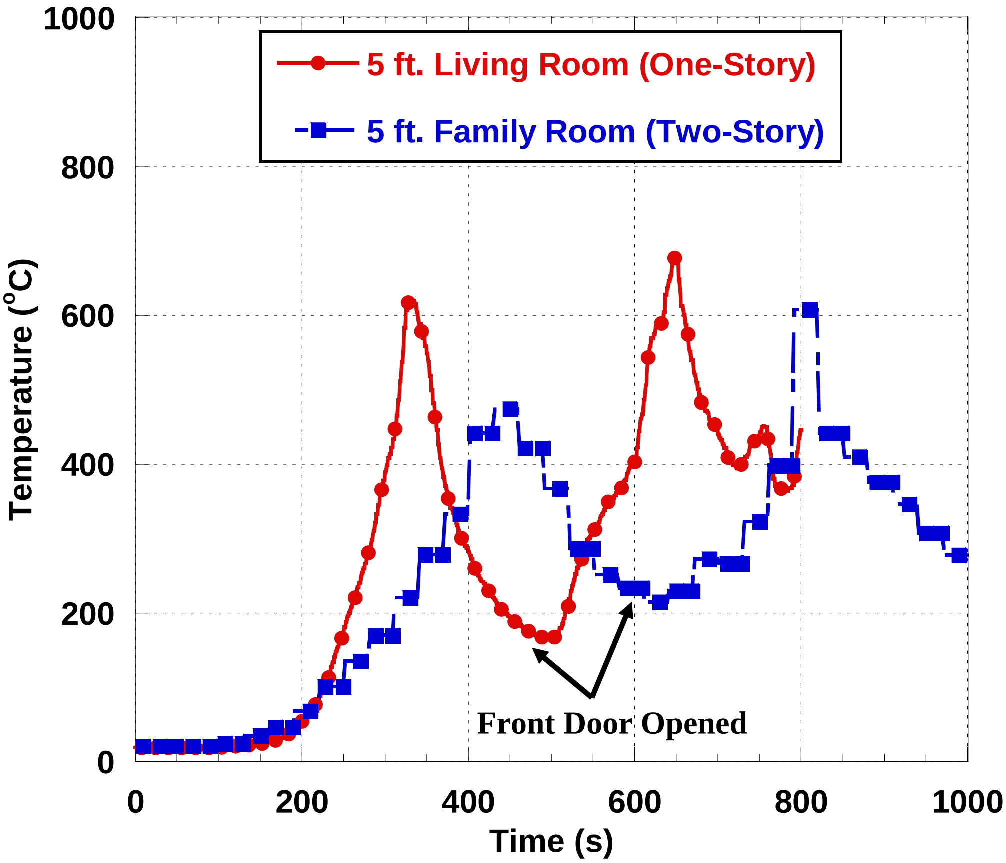


Figure 479. Living/Family room temperatures during front door only ventilation experiments

9.3. No smoke showing

During the experiments it was observed that prior to ventilation smoke stopped coming out of the gaps in the structures. As the fire became ventilation limited the temperatures decreased rapidly and significantly. While this drop was occurring the pressure in the structure would also be decreasing as temperature and pressure created by the fire are dependent on each other. While the pressure was decreasing, smoke would completely stop coming out of the cracks in the structure. Figure 480 shows the temperature in the living room prior to ventilation. As the fire grows, smoke is visible coming from around the windows and the door. As the temperature peaks and then declines, there is no longer smoke visible from the front of the one-story house. The same phenomenon was seen in the two-story house. Figure 481 shows the temperature in the family room and images of the rear of the two-story house during the growth of the fire until it became ventilation limited and decayed. Smoke is visible coming from the windows at 390 seconds but no smoke is visible at 510 seconds.

Tactically, this could be very important for the initial crews sizing up a fire. With no smoke showing from the structure complacency could easily set in. It is important to consider that little or no smoke showing does not mean that conditions are safer than having fire showing. Smoke conditions need to be used to try to determine the conditions inside the structure but this should be done with extreme caution because smoke is not always an indicator of what is happening in the structure. With the modern fire environment and response times being what they are, consider that the fire is most likely in the initial decay stage of the fire growth curve and not the incipient stage.

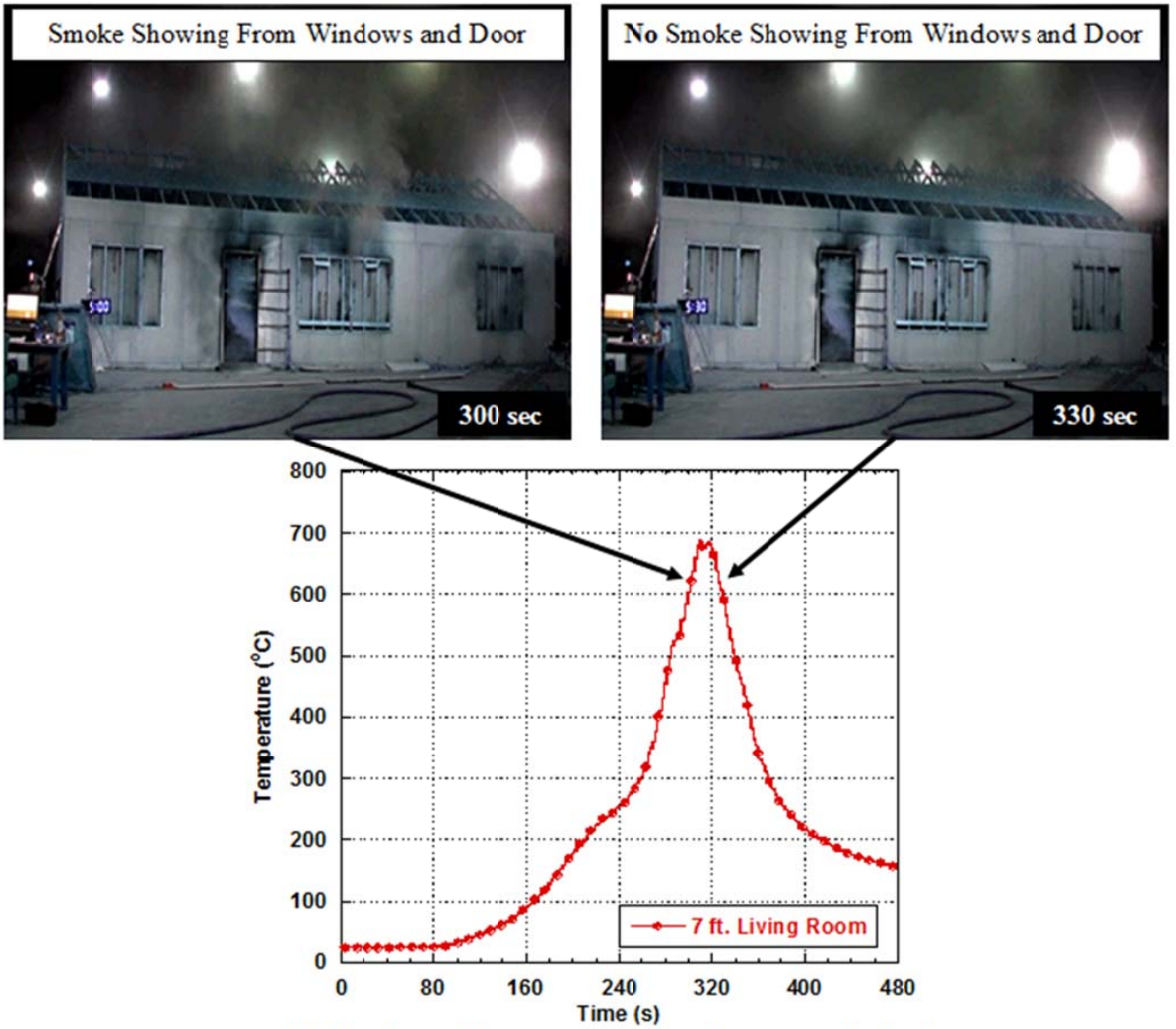


Figure 480. Experiment 5 size-up comparison, smoke vs. no smoke showing

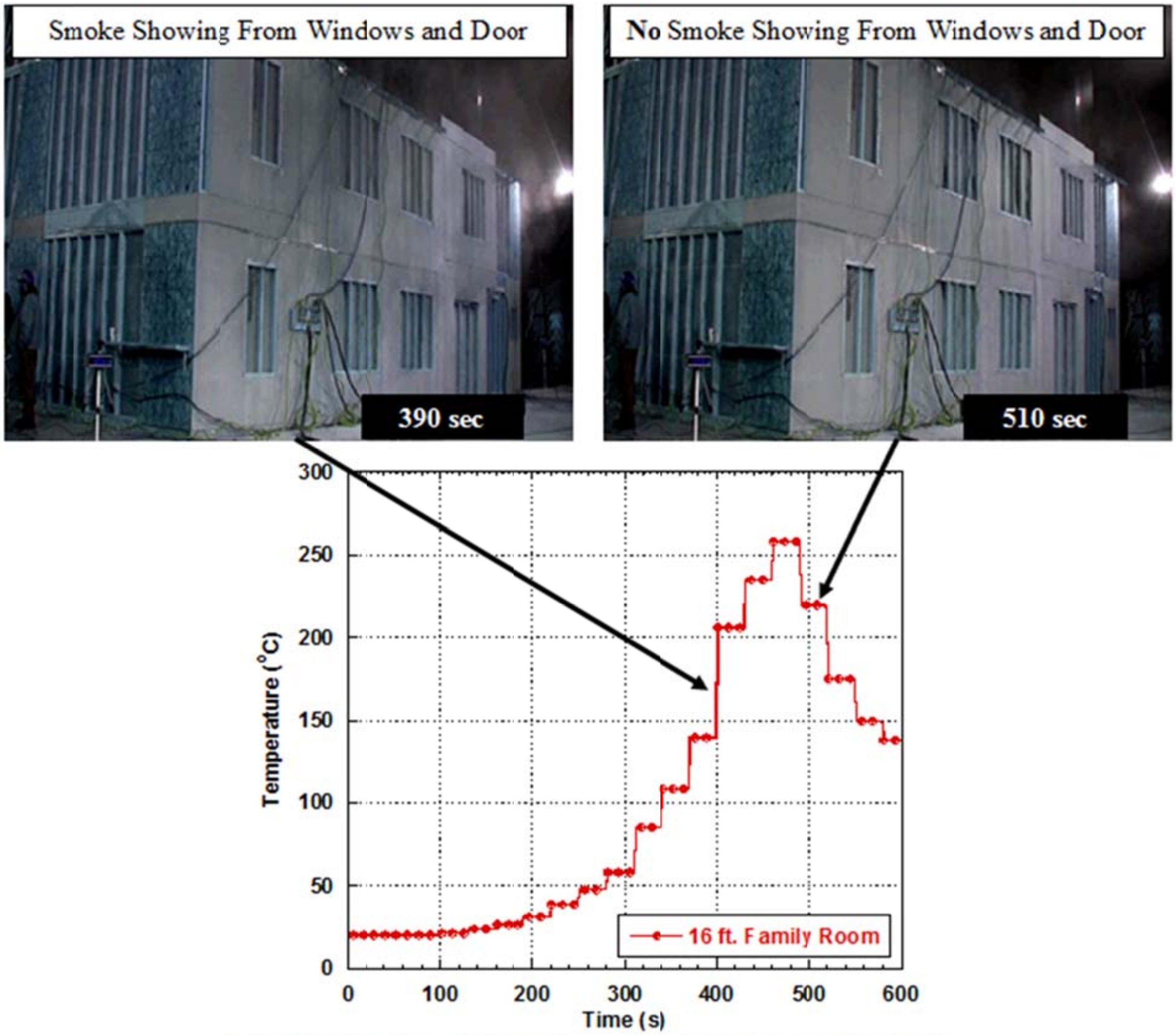


Figure 481. Experiment 2 size-up comparison, smoke vs. no smoke showing

9.4. Coordination

There are many fire service publications that say that fire attack should be coordinated and there is a very good reason for that. As shown in previous sections, if air is added to the fire and water is not applied in the appropriate time frame the fire gets larger and the hazard to firefighters increases. Examining the times to untenability provides the best case scenario of how coordinated the attack needs to be. Taking the average time for every experiment from the time of ventilation to the time of the onset of firefighter untenability conditions yields 100 seconds for the one-story house and 200 seconds for the two-story house. In many of the experiments from the onset of firefighter untenability until flashover was less than 10 seconds. These times should be treated as being very conservative. If a vent location already exists because the homeowner left a window or door open then the fire is going to respond faster to additional ventilation openings because the temperatures in the house are going to be higher at the time of the additional openings.

When to make the ventilation opening is another consideration for a coordinated fire attack. This question will be answered independently on every fire because no two fires are the same. Respect needs to be given to the time it is going to take the hoseline to get to the seat of the fire. If it is a ranch house like the one used in these experiments then it probably won't take long to get to the seat of the fire. This means you may want to ventilate once the attack line is charged at the front door. In larger structures like the 2-story house or a commercial structure it may be safer to delay ventilation until the engine advises they are prepared to put water on the fire. Making ventilation openings before water can be applied to the seat of the fire could lead to rapid fire progression and life threatening situations.

Figure 482 through Figure 489 describe a hypothetical search operation during a fire in the one-story house. The red line in Figure 482 shows their search pattern and timeline of the search. The search team forces open the front door at 8:00 (See Figure 483 and Figure 484 for conditions). They see the amount of smoke coming out of the doorway and they put on their SCBA face pieces. While they are doing this the ventilation team vents the front window at 8:15. The search team then makes entry and begins to search the living room. They see fire on the sofas in the middle of the room but conditions are still tenable for them. They skip the bedrooms and decide to search the left side of the house. They enter the kitchen at 9:00 (See Figure 485 and Figure 486 for conditions) and search it quickly and move into the dining room at 9:30. They make their way around the dining room and make it back to the entrance to the living room at 10:00 (See Figure 487 and Figure 488 for conditions). This shows that 2 minutes is not a lot of time to operate inside a structure and those conditions can go from tenable for a search to untenable very quickly. Figure 489 shows the temperatures at crawling height (3 ft above the floor) for the rooms being searched. This depicts that the rooms were tenable while they were being searched but once the firefighters circle back toward the living room it is untenable and they must find another way out, which at that point the dining room and kitchen become untenable so the only option is to bail out of a window.

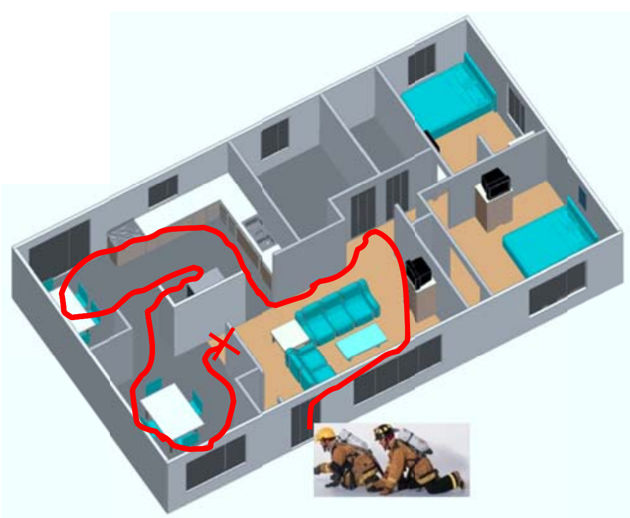


Figure 482. Search team path

<u>Hypothetical Search Team Operation</u>
8:00 – Team forces front door
8:00 – 8:20 - Team puts on SCBA masks
8:15 – Ventilation team vents the front window
8:20 – 8:30 - Team enters to start search
8:30 – 9:00 – Team searches living room
9:00 – 9:30 – Team searches kitchen
9:30 – 10:00 – Team searches dining room

Figure 483. Front of house at 8:00

Figure 484. Inside view of house at 8:00

Figure 485. Front of house at 9:00

Figure 486. Inside view of house at 9:00

Figure 487. Fornt of house at 10:00

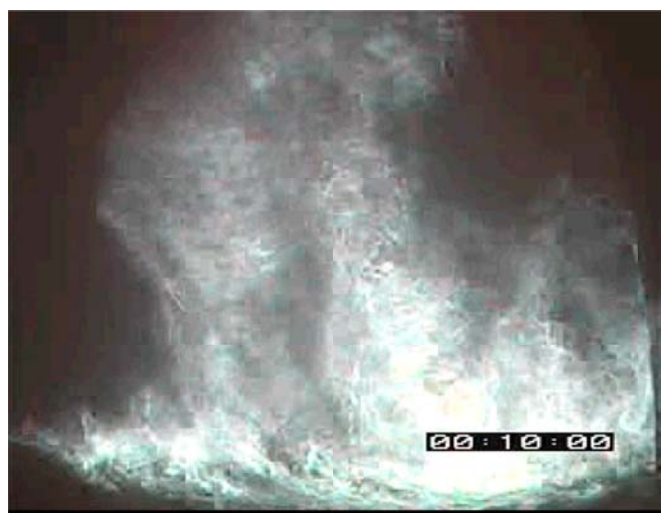


Figure 488. Inside view of house at 10:00

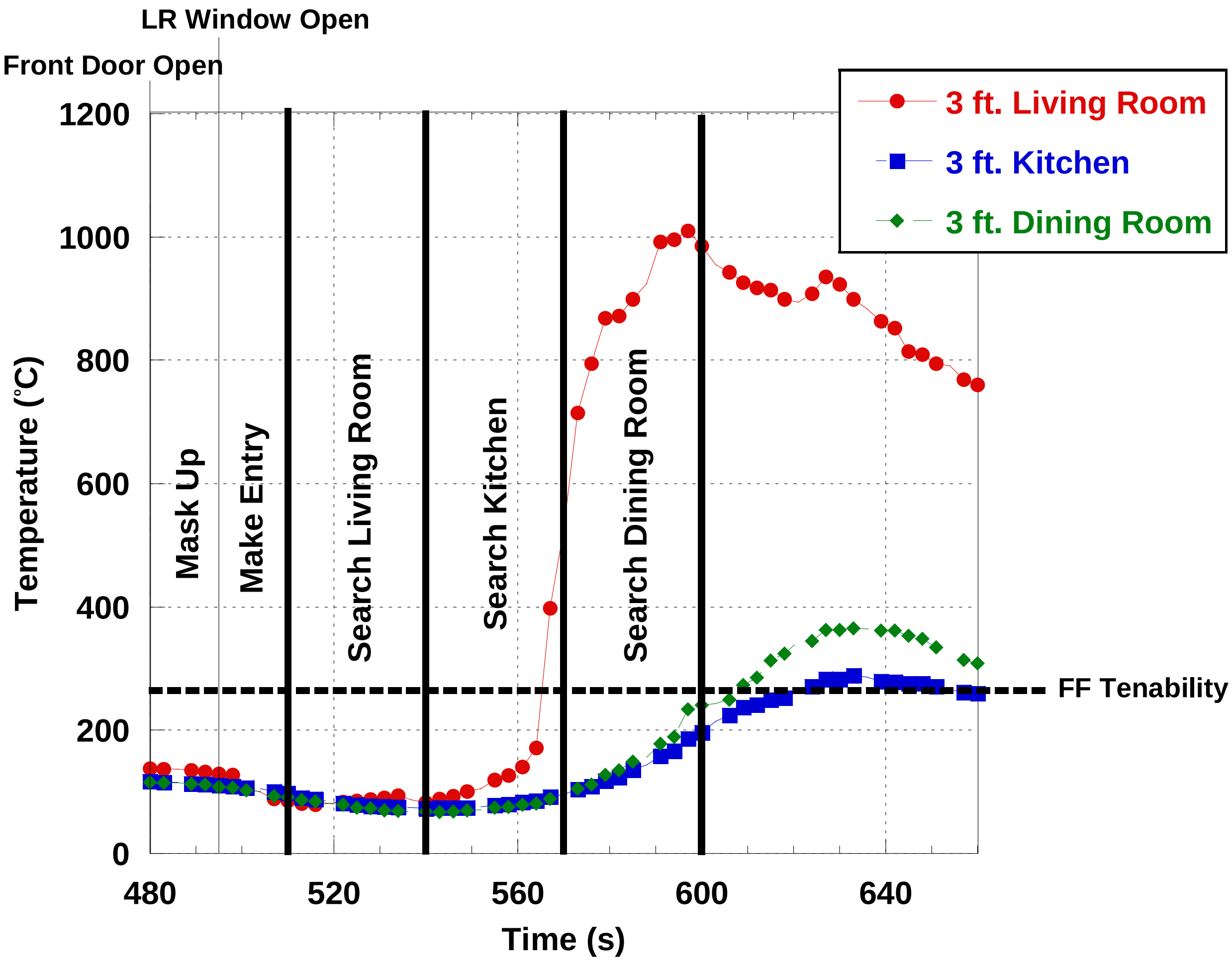


Figure 489. Search Room Temperatures at 3 ft.

9.5. Smoke tunneling and rapid air movement in through front door

In today's fire environment there is more smoke generated due to the increased usage of synthetic materials[53]. In all of these experiments the smoke layer reached the floor prior to ventilation leaving zero visibility in the houses. After ventilation this smoke layer did not repeatedly lift above the floor throughout the house. A better way of describing the impact of ventilation on the smoke was a temporary tunnel as air rushed in through the ventilation opening. Higher smoke release rates and heat release rates have decreased the desired smoke lifting that is traditionally the intent of ventilation. If visibility is increased then search and fire attack are easier to accomplish. It appeared that as the fire received air it produced more smoke than was being ventilated out of the house and therefore not lifting the smoke layer.

It is possible to get an idea of what may be happening inside the structure by observing the flows at the front door after it is opened. In these experiments there was an obvious flow in through the front door toward the fire location. The average velocity through the bottom of the front door for all of the experiments where the door was opened was 1.5 m/s (3.4 mph). There was also a tunneling effect that resulted from the in rush of air through the front door. Figure 490 and Figure 491 show this effect during Experiment 10. An image was captured from the video camera inside the front door 5 seconds before ventilation and 5 seconds after ventilation. Another similar example was captured during Experiment 13 in Figure 492 and Figure 493.

Without the impact of wind this could indicate there is a ventilation limited fire inside and precautions should be taken. Slowing down and ensuring a charged hoseline with the crew is a good primary precaution. In some cases the smoke lifted above the floor in adjacent rooms to the fire but rarely in remote rooms such as the bedrooms. The lifting usually went away once the fire room transitioned to flashover.

Figure 490. Front Door Image from Experiment 10, 5 seconds before Ventilation

Figure 491. Front Door Image from Experiment 10, 5 seconds after Ventilation

Figure 492. Front Door Image from Experiment 13, 5 seconds before Ventilation

Figure 493. Front Door Image from Experiment 13, 5 seconds after Ventilation

9.6. Vent Enter Search (VES)

VES is a tactic used by many fire departments. It can be described as ventilating a window, entering the window, searching that room and exiting out of the same window entered. These experiments show the ability of a closed door to protect a room from fire conditions even with an open window. They also show how conditions can worsen as a window is ventilated remote from the fire, creating a flow path from the window to the fire. A primary objective of VES is to close the door of the room ventilated to isolate the flow path to the fire and not allow the air from the open window to make it to the underventilated fire. This can be thought of as Vent Enter Isolate Search. While one may be able to search the room quickly and exit, the new flow path created by this tactic if not isolated could cause an unintended interior condition crews are not expecting.

During Experiment 8 the second floor bedroom (Bedroom 3) was ventilated. This tactic could represent a firefighter conducting a VES operation of the bedroom without closing the door to the bedroom. Figure 494 shows the bedroom temperatures versus time with arrows indicating tenability thresholds. If a VES operation were conducted in this bedroom temperatures would increase significantly. The temperature 1 ft above the floor was approximately 60 °C (140 °F) at ventilation and increased to the occupant tenability limit in 2 minutes and to the firefighter tenability threshold in 3 minutes. If the door had been closed the temperatures would not have increased much above 60 °C (140 °F) based on the peak temperature of Bedroom2 (the adjacent bedroom) that had the door closed.

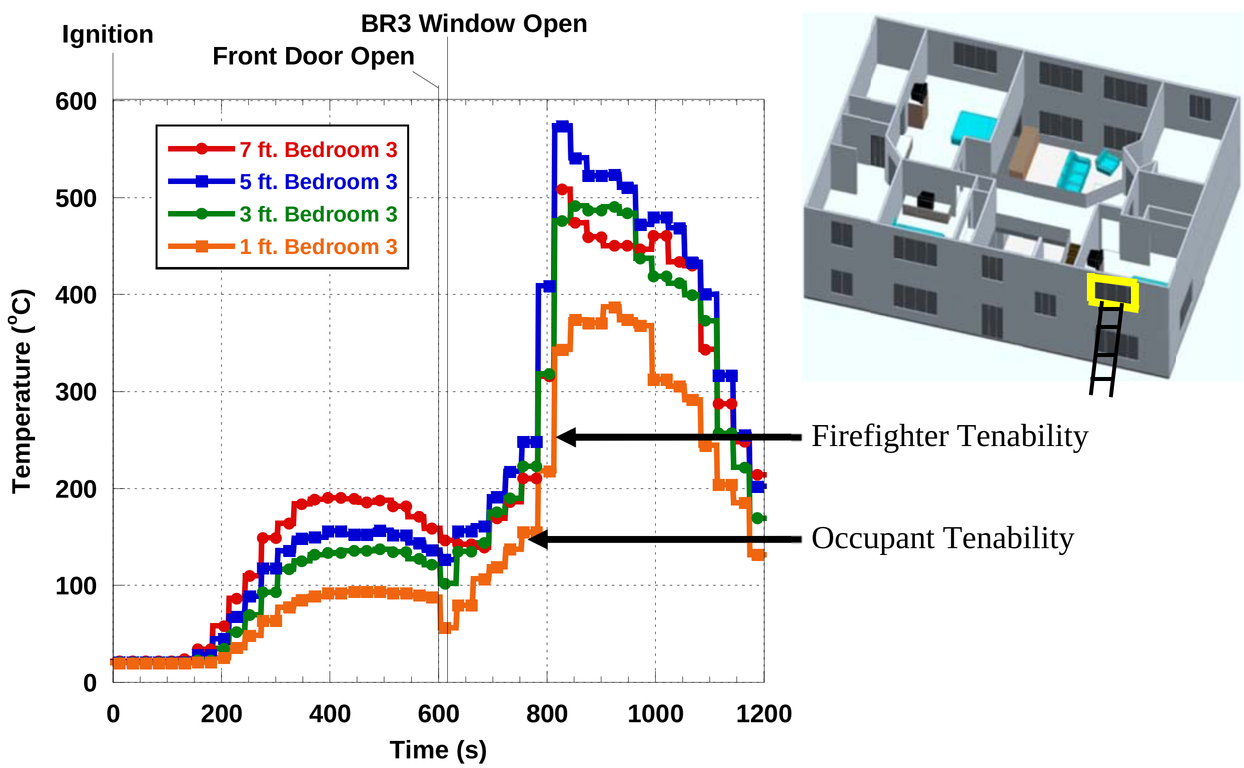


Figure 494. VES bedroom temperatures

In Experiment 14 the window to the closed bedroom, Bedroom 3, was opened at 8:42 (Figure 495). This could simulate conducting a VES with a closed bedroom or what would happen when the door was closed. Figure 496 and Figure 497 show the same view one minute and two minutes after ventilation respectively. During each of these pictures there is a fully developed fire right outside the door to the bedroom and the smoke layer is lifted and conditions improved in the bedroom for the duration of the experiment. This further highlights the importance of closing the door during VES operations. The image of the rear of the house also shows thick black smoke ventilating out of Bedroom 2 which has an open bedroom door. Closing a door between a firefighter and a fire during emergency conditions is also a good way to buy more time to be rescued.

Figure 495. Experiment 14 view of rear of house and Bedroom 3 at 8:42

Figure 496. Experiment 14 view of rear of house and Bedroom 3 at 9:42

Figure 497. Experiment 14 view of rear of house and Bedroom 3 at 10:42

9.7. Flow paths

Many fire departments teach their search crews to "ventilate as they go." The reasoning is that the procedure may create cooler and clearer conditions throughout the structure. Experiments 14 and 15 show this is not the case if water is not applied to the fire. Figure 498 shows the flow paths created between the seat of the fire and the 4 open windows. The living room temperature from ventilating the door and 4 windows is compared to ventilating the front door and only 1 window near the seat of the fire (Figure 499). Opening more windows created faster fire growth and flashover approximately 40 seconds faster. Figure 500 shows the flow path from the same ventilation scenario in the two-story house. In this experiment, opening multiple windows also created faster fire growth and flashover conditions approximately 80 seconds faster (Figure 501). Every new ventilation opening provides a new flow path to the fire and vice versa. This could create very dangerous conditions when there is a ventilation limited fire. Adding many openings does not confuse the fire or create cooler temperatures for a longer period of time.

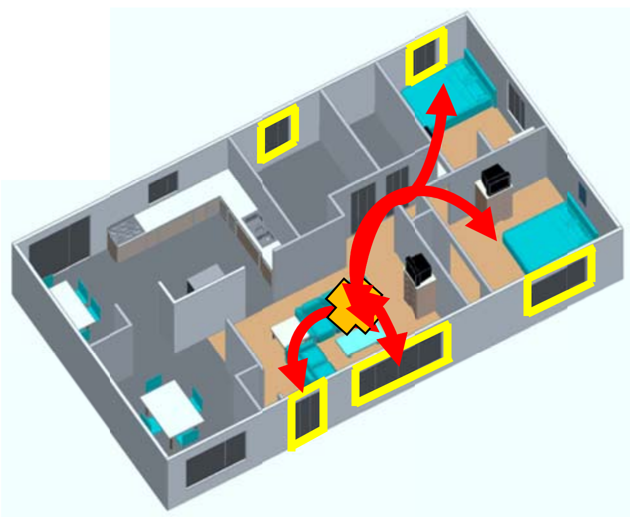


Figure 498. Experiment 14 flow paths

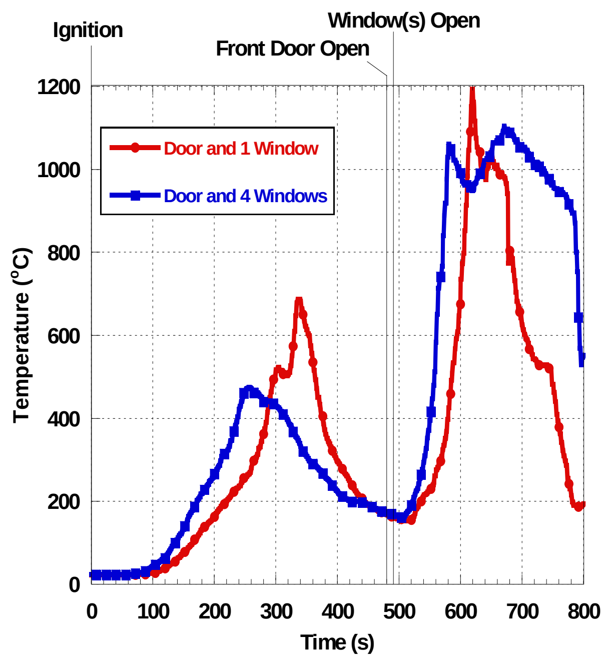


Figure 499. One-Story 1 window versus 4 windows

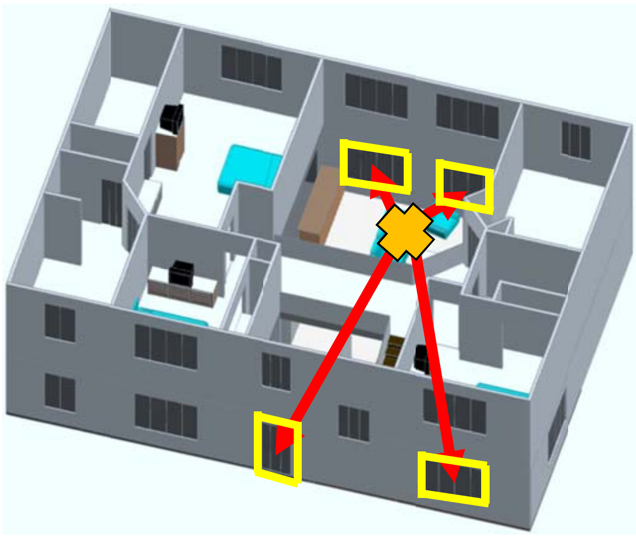


Figure 500. Experiment 15 flow paths

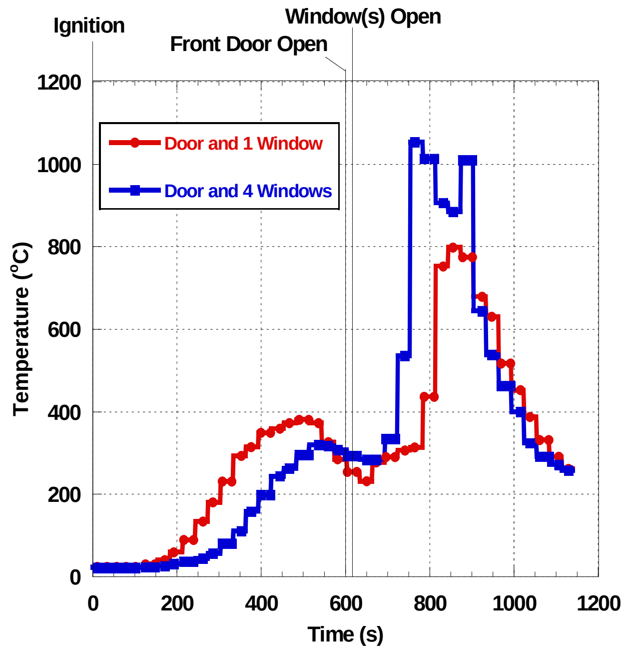


Figure 501. Two-Story 1 window versus 4 windows

9.8. Can you vent enough?

Another firefighter hypothesis is that opening enough ventilation locations will transform a ventilation limited fire to a fuel limited fire. Figure 502 shows the temperatures 1 ft above the floor in the living room for each of the different ventilation scenarios. In all four scenarios the living room transitions to flashover. The orange curve represents the scenario where the door and 4 windows were opened and this is also the scenario where flashover occurred the fastest. During this experiment there was 102 square feet of ventilation openings (Table 38). All four scenarios also remained ventilation limited throughout the experiment, until suppression took place. The two-story house behaved very similar to the one-story house in that the scenario with the front door and 4 additional windows transitioned to flashover the fastest (Figure 503). During this experiment there was 159 square feet of ventilation openings. In the heat release rate experiment in Section 7 there was 70 square feet open on the front of the room and the fire was ventilation limited. In both of the house experiments, with significantly more ventilation area, the fire still burned at the openings indication a ventilation limited fire and not a fuel limited fire.

Table 38. Experimental Ventilation Area

Experiment #	Structure	Ventilation Parameters	Ventilation Area (ft^2)
1	1-Story	Front Door	19.1
2	2-Story	Front Door	19.1
3	1-Story	Front Door + Living Room Window (Window near seat of the fire)	61.2
4	2-Story	Front Door + Family Room Window (Window near seat of the fire)	61.2
5	1-Story	Living Room Window Only	42.1
6	2-Story	Family Room Window Only	42.1
7	1-Story	Front Door + Bedroom 2 Window (Window remote from fire)	32.5
8	2-Story	Front Door + Bedroom 3 Window (Window remote from fire)	61.2
9	1-Story	Front Door + Living Room Window (Repeat Exp. 3)	61.2
10	2-Story	Front Door + Family Room Window (Repeat Exp. 4)	61.2
11	2-Story	Front Door + Family Room Window (Repeat Exp. 4)	61.2
12	1-Story	Front Door + Living Room Window (Repeat Exp. 3)	61.2
13	2-Story	Front Door + Upper Family Room Window	61.2
14	1-Story	Front Door + 4 Windows (LR, BR1, BR2, BR3)	102.4
15	2-Story	Front Door + 4 Windows (LR, Den, FR1, FR2)	158.8

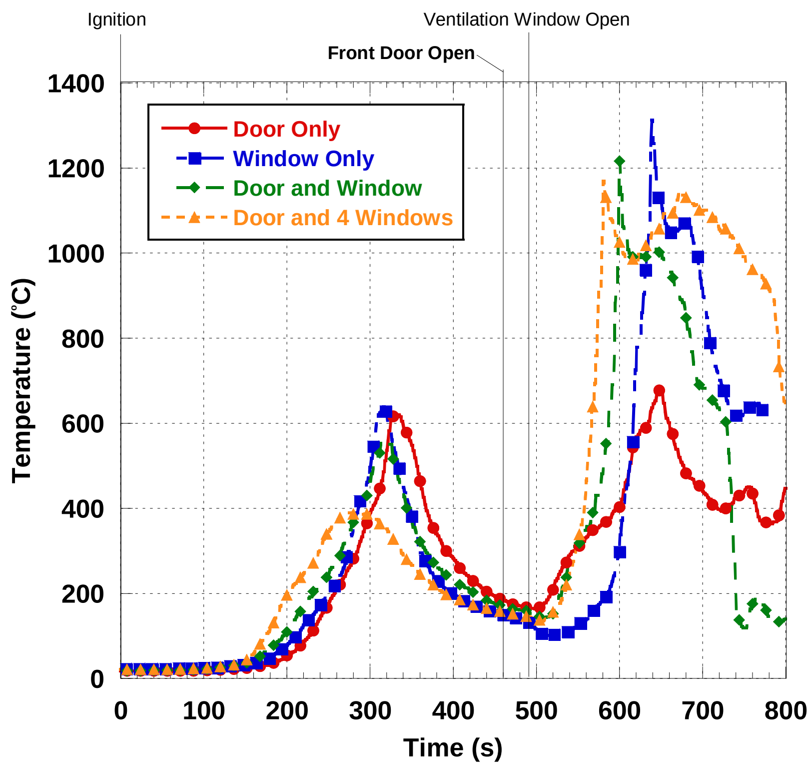


Figure 502. One-story comparison of different ventilation areas

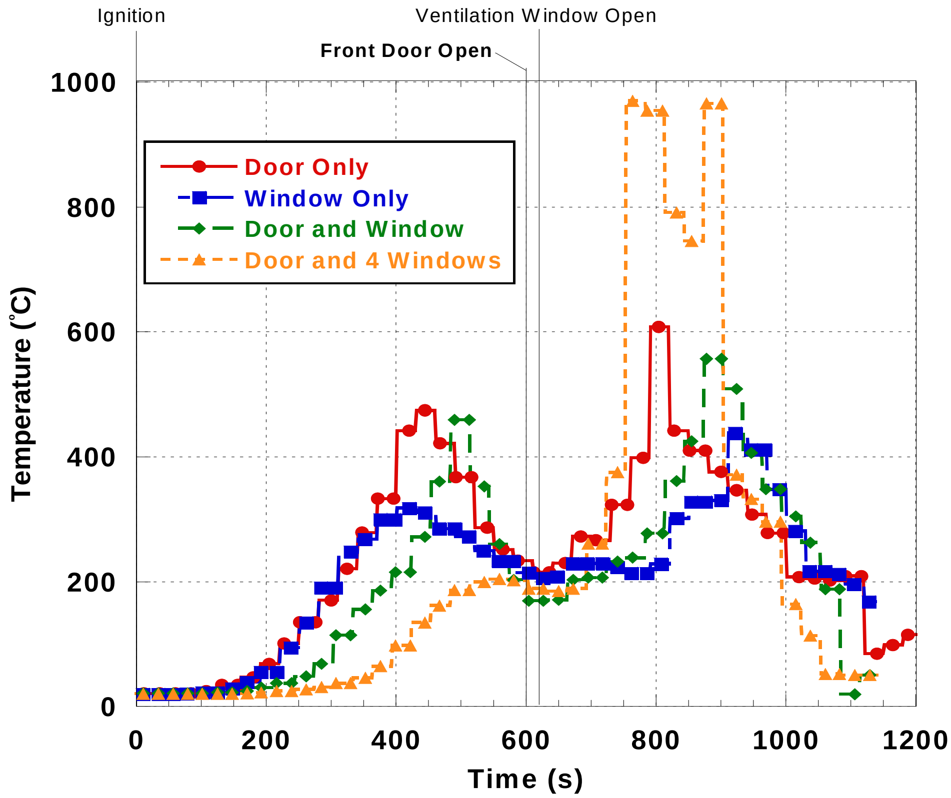


Figure 503. Two-story comparison of different ventilation areas

9.9. Impact of shut door on victim tenability and firefighter tenability

When it comes to rescuing occupants, the fire service makes risk based decisions on the tenability of occupants. They assume personal risk if it may save someone in the house. During the experimental design it was decided to have one closed bedroom in each house for every experiment. This allowed for the comparison of tenability of two side by side bedrooms, one with an open door and another with the door closed assuming the occupant already had a closed door or the closed it when they discovered there was a fire in the house.

In the one-story house there was a thermocouple tree in the closed bedroom (Bedroom 3) and one in the hallway right outside the closed bedroom. Figure 504 shows the ceiling (worst case scenario) temperatures during Experiment 14 in both of these locations for comparison. In the hallway the temperature reached 900 °C (1650 °F) while the Bedroom remained below 125 °C (260 °F). Large variances in temperature were observed in every experiment. The oxygen concentrations were also compared from inside the closed bedroom at 5 ft. above the floor, in the adjacent open bedroom and outside the room in the living room at 5 ft. above the floor (Figure 505). The living room and open bedroom had oxygen concentrations decline to 10% while the closed bedroom did not decline below 19.5%. The closed bedroom conditions were tenable while the open bedroom was not.

A comparison can also be made in the two-story house. Bedroom 2 had a closed door and the adjacent Bedroom 3 was open. There is also a thermocouple tree on the second floor hallway landing right outside the two bedrooms. Figure 506 compares the temperatures at these 3 locations. The second floor hallway temperature reaches 825 °C (1520 °F) and the open bedroom reaches 430 °C (810 °F) while the closed bedroom remains below 100 °C (210 °F).

Conditions in every experiment for the closed bedroom remained tenable for temperature and oxygen concentration thresholds. This means that the act of closing a door between the occupant and the fire or a firefighter and the fire can increase the chance of survival. During firefighter operations if a firefighter is searching ahead of a hoseline or becomes separated from their crew, and conditions deteriorate then an option would be to get in a room with a closed door until the fire is knocked down or escape out of the room's window with more time provided by the closed door.

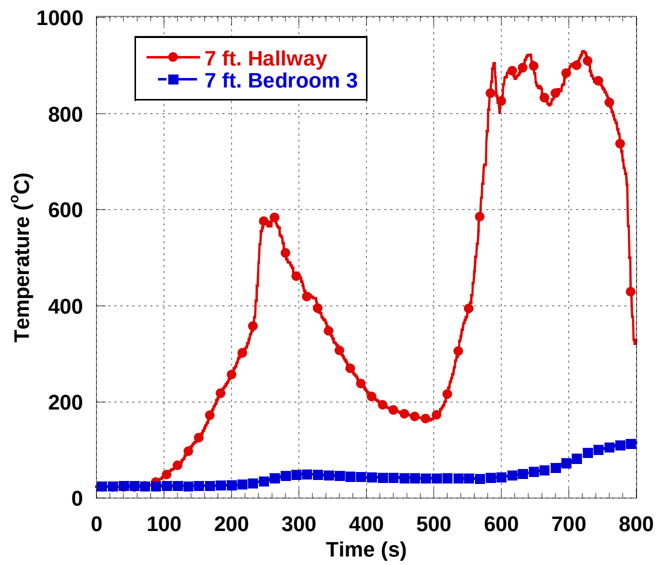


Figure 504. Experiment 14 Hallway and Bedroom 3 Temperatures with Door Closed

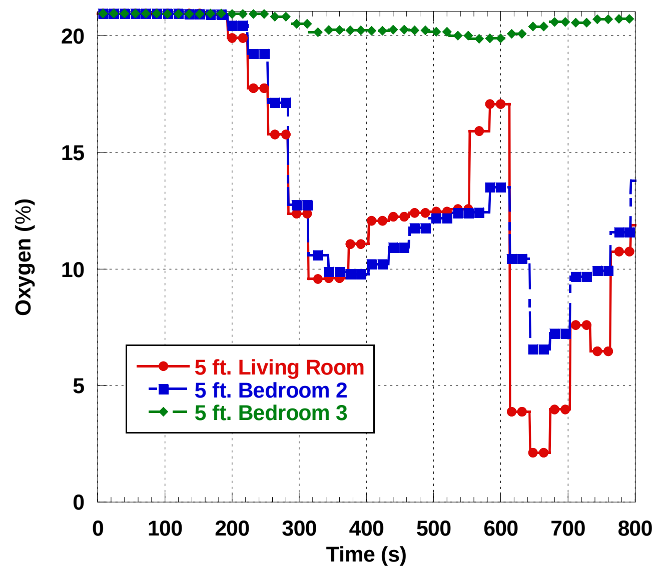


Figure 505. Experiment 14 Hallway, Bedroom 3 and Bedroom 2 Oxygen Concentration with Door Closed

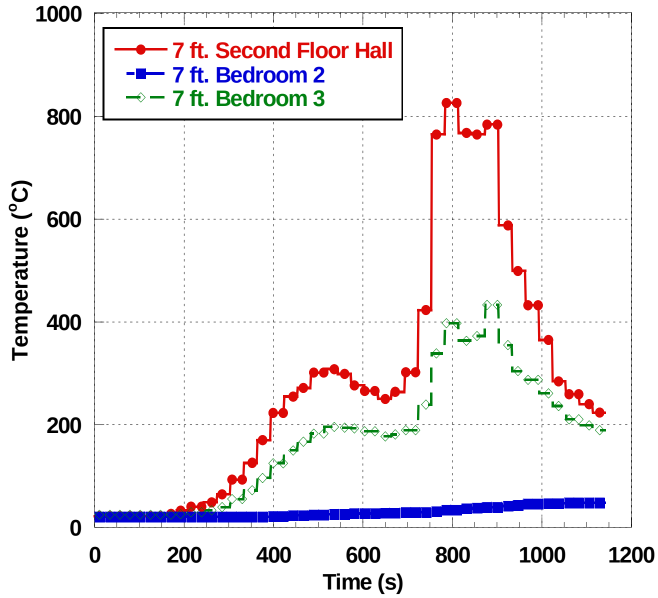


Figure 506. Experiment 15 Temperatures on the 2nd Floor Hallway and in Bedroom 2 with the door closed

9.10. Potential impact of open window already on flashover time

All of these experiments were designed to examine the first ventilation actions by an arriving crew when there are no ventilation openings. It is possible that the fire will break a window prior to fire department arrival or that a door or window was left open by the occupant while exiting. It is important to understand that an already open ventilation location provides air to the fire, allowing it to sustain or grow. In the experiments where multiple ventilation locations were made it was not possible to create fuel limited fires. The fire responded to the additional air provided. That means that even with a ventilation location open the fire is still ventilation limited and will respond just as fast or faster to any additional air. It is more likely that the fire will respond faster because the already open ventilation location is allowing the fire to maintain a higher temperature than if everything was closed. In these cases rapid fire progression is highly probable and coordination of fire attack with ventilation becomes even more important.

The closest experiment to demonstrate this phenomenon was Experiment 1. The fire was ventilated at 480 seconds by opening the front door. The fire produced its peak temperatures of 725 °C (1340 °F) at approximately 660 seconds (Figure 507). The fire was allowed to grow and then two 10 second bursts of water were flowed into the front door. At 857 seconds one half of the living room window was opened (Figure 508). This caused the living room to transition to flashover in approximately 30 seconds and peak above 1300 °C (2370 °F) (Figure 509 and Figure 510).

Figure 507. Peak fire conditions with front door open

Figure 508. Conditions at time of window opening (14:15)

Figure 509. Conditions after ventilation of window (14:50)

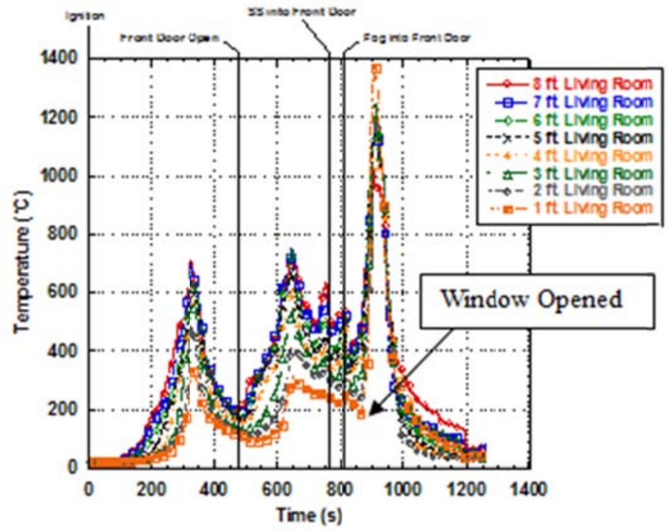


Figure 510. Living room temperatures for Experiment 1

9.11. Pushing Fire

With the changes that have occurred in the fire environment and the speed at which fires grow there have been questions posed about the validity to the belief that fire can be "pushed" with a hose stream. Pushing fire could occur as a result of three potential mechanisms. Once a hose stream is directed into an opening with fire or hot gases exiting, the pressure from the stream, airflow created by the stream or steam expansion could create conditions in the house that are worse downstream. It was not the focus of this research to examine this problem but since these fires were knocked down by external water application, the data can be analyzed to look at the possibility of pushing fire.

In each experiment, the fire was allowed to grow to approximately peak burning rate before water was introduced through the opening. In order to examine the impact of the water, temperatures were examined in each room, 30 seconds before water application, during the 10 seconds of water application and 30 seconds after water application. Figure 511 through Figure 527 show the temperature versus time for every water application, for every experiment, and for every room. The water application duration is identified by the time interval between the two black vertical lines. In Experiment 1 and Experiment 13 both types of streams were used. The stream was directed toward the ceiling to cool the ceiling and was not directed directly onto any burning fuel which is why there is no dramatic cooling seen in the graphs. Examining the graphs from the 15 experiments, there is no evidence of "pushing fire". Temperatures tend to decrease and any temperature increase after water application was minimal. There were also no temperature spikes in any of the rooms, especially the rooms adjacent to the fire room. It appears that in most cases the fire was slowed down by the water application and that external water application had no negative impacts to occupant survivability.

While room temperatures were not influenced by the use of the fog stream, there was an impact on visibility or the disruption of the thermal layer in Experiment 14 and 15. Two key factors for this were the air entrainment on the stream and the presence of a flow path. The flow from the nozzle caused steam formation and that steam flowed through the flow path created by the open door and windows. Figure 528 and Figure 529 show an example of this thermal layer disruption in the two-story house. The first quad view shows the front, rear, front door and living room views from the video just before the fog nozzle was operated. The second quad view was captured 10 seconds after the first and the visibility has greatly decreased because of the flow of gases out of the front door and living room windows. Figure 530 and Figure 531 show this same phenomenon in the one-story house during Experiment 14. The first two pictures show the front of the house and the master bedroom just prior to fog stream application. The second two pictures were captured 10 seconds later and the gases from the water application are forced into the bedroom in the flow path with the open window. This did not occur with the use of the straight stream water application but the fog stream was more effective at cooling during these experiments. While steam was "pushed" along the flow path there was no fire "pushed".

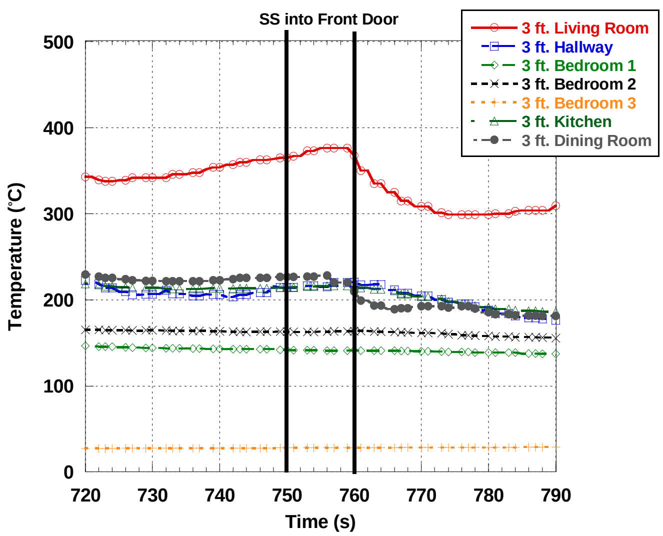


Figure 511. Experiment 1 Straight Stream

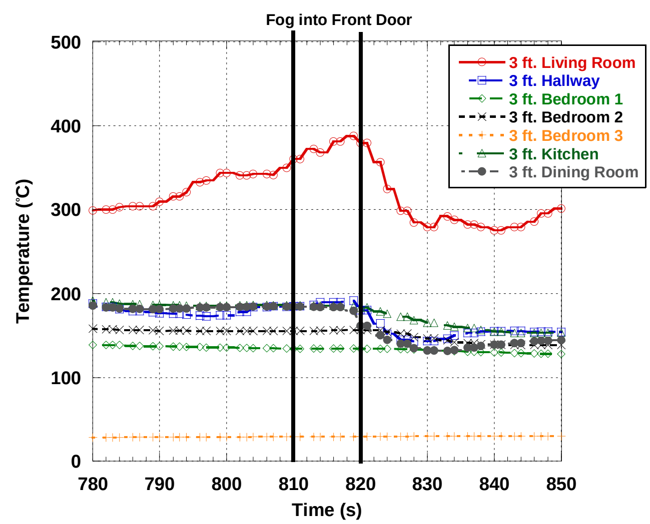


Figure 512. Experiment 1 Fog Stream

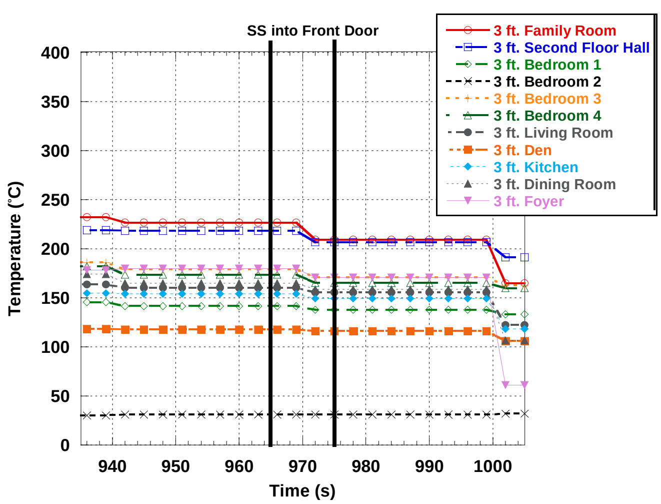


Figure 513. Experiment 2 Straight Stream

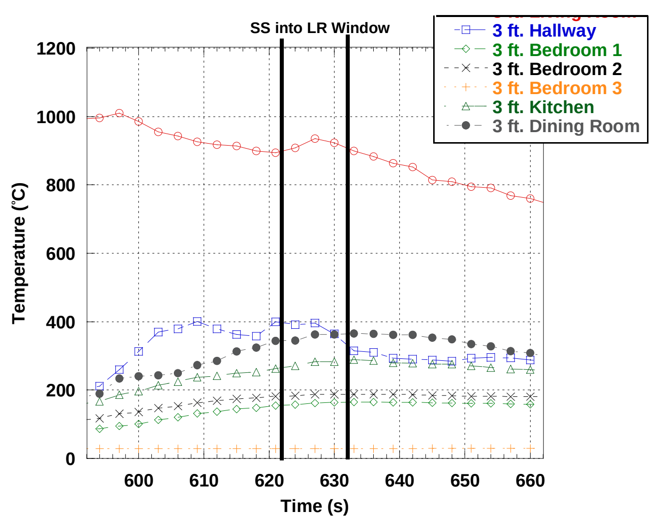


Figure 514. Experiment 3 Straight Stream

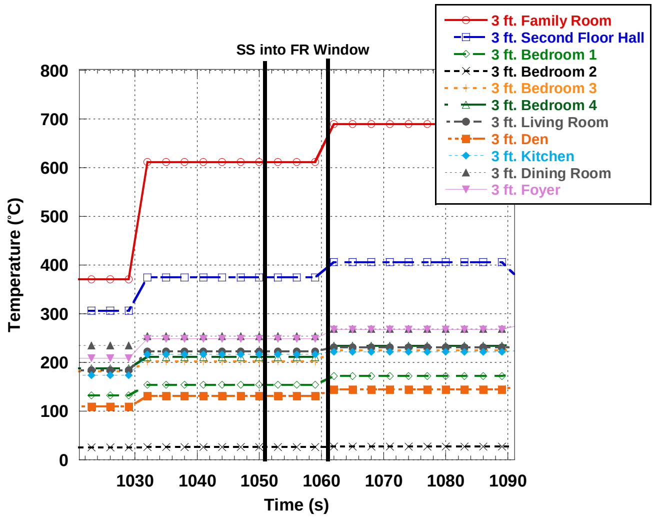


Figure 515. Experiment 4 Straight Stream

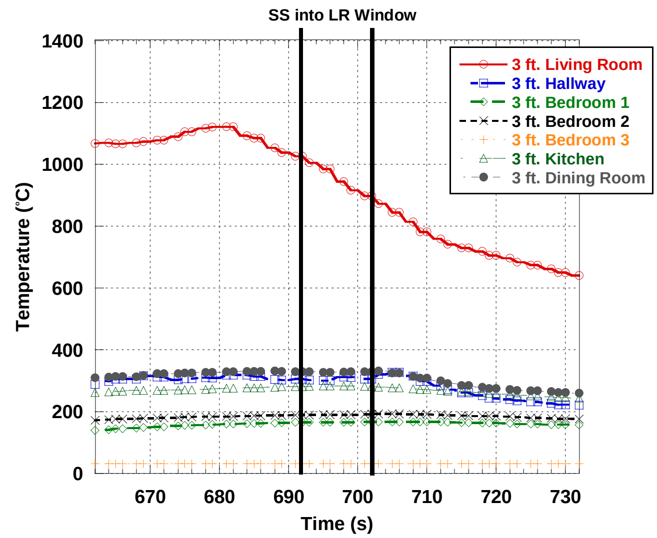


Figure 516. Experiment 5 Straight Stream

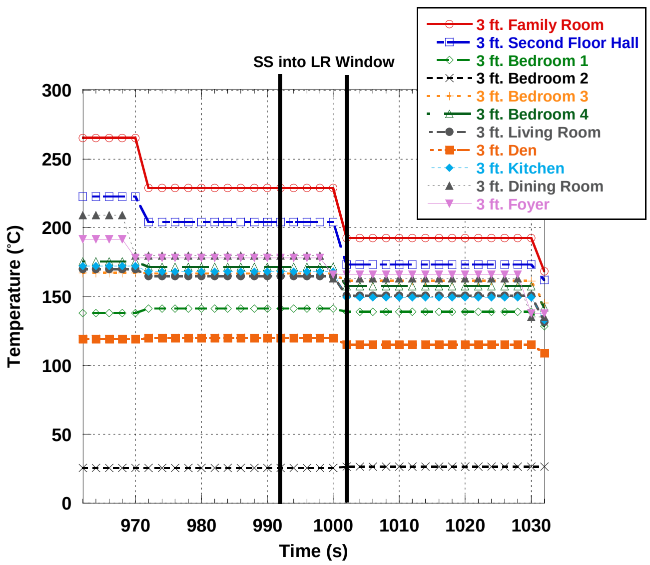


Figure 517. Experiment 6 Straight Stream

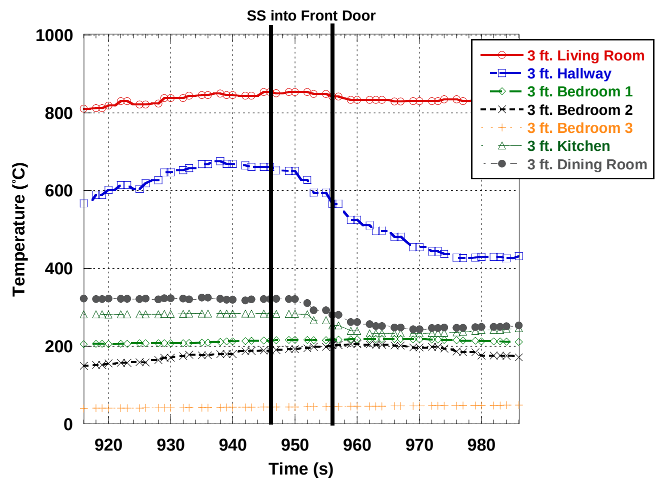


Figure 518. Experiment 7 Straight Stream

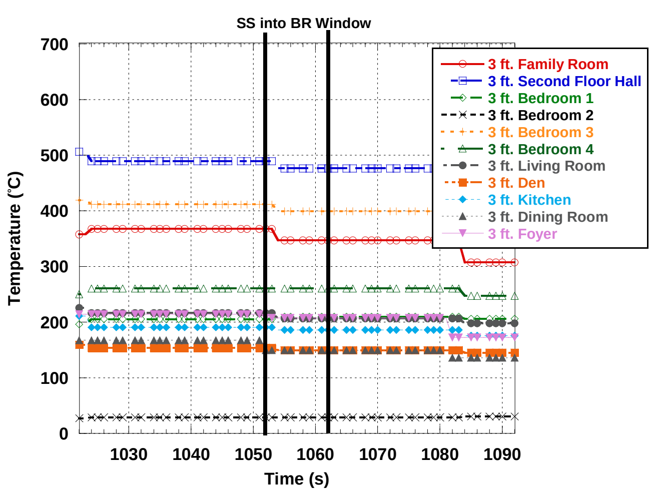


Figure 519. Experiment 8 Straight Stream

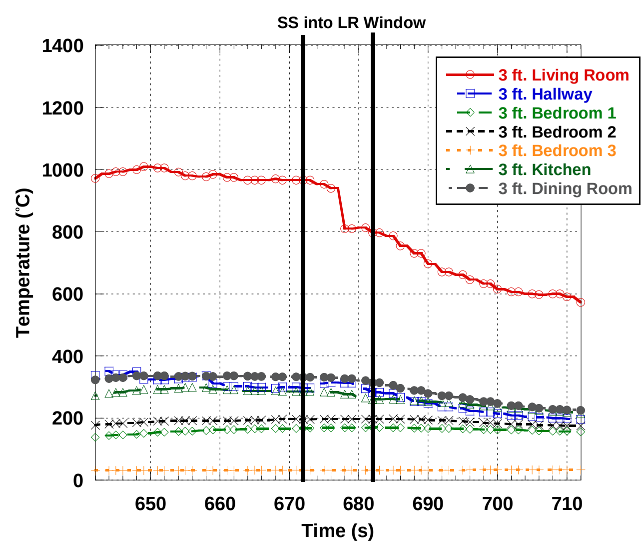


Figure 520. Experiment 9 Straight Stream

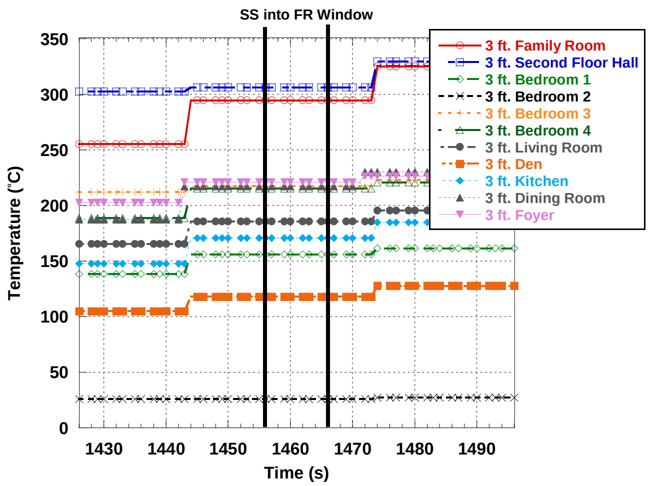


Figure 521. Experiment 10 Straight Stream

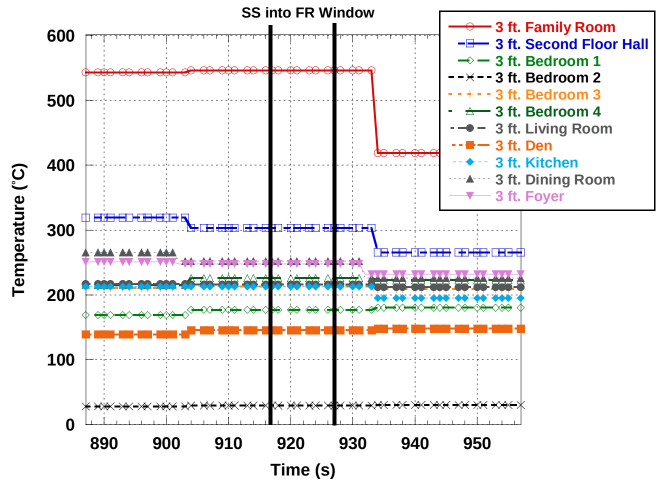


Figure 522. Experiment 11 Straight Stream

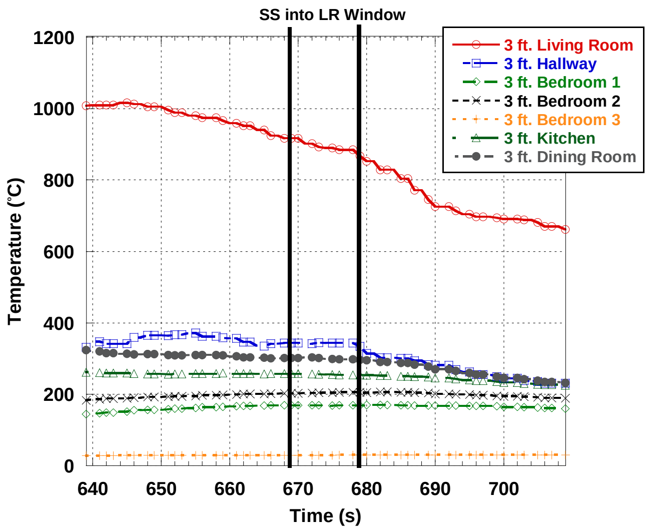


Figure 523. Experiment 12 Straight Stream

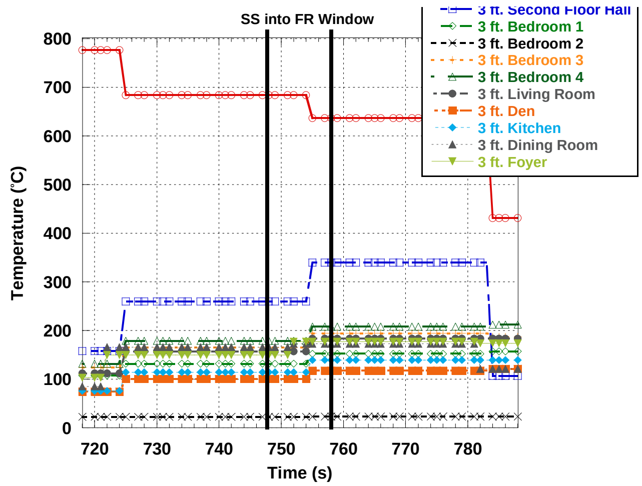


Figure 524. Experiment 13 Straight Stream

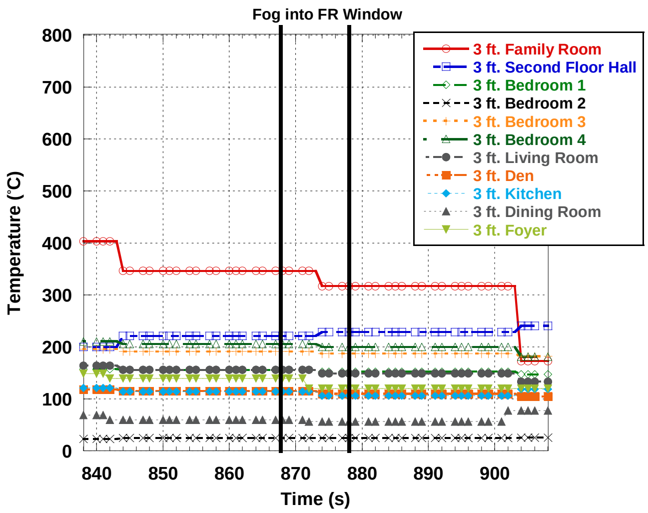


Figure 525. Experiment 13 Fog Stream

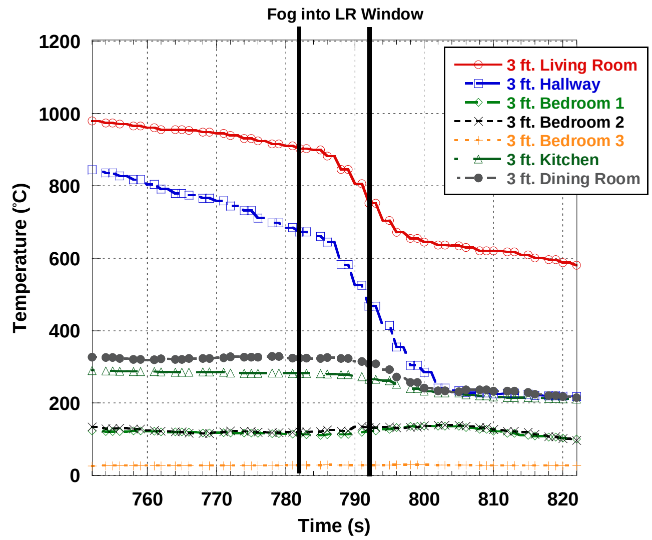


Figure 526. Experiment 14 Fog Stream

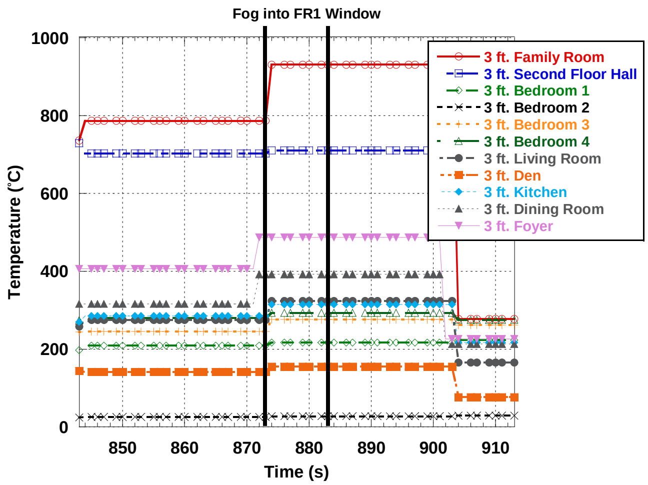


Figure 527. Experiment 15 Fog Stream

Figure 528. Two-story house before fog stream application (Experiment 15)

Figure 529. Two-story house 10 seconds after start of fog stream application (Experiment 15)


Figure 530. One-story house before fog stream application, Front, left and Bedroom 1, right (Experiment 15)


Figure 531. One-story house 10 seconds after fog stream application (Experiment 14)

9.12. No damage to surrounding rooms

Just as the fire triangle depicts, fire needs oxygen to burn. A condition that existed in every experiment was that the fire (living room or family room) grew until oxygen was reduced below levels to sustain it. This means that it decreased the oxygen in the entire house by lowering the oxygen in surrounding rooms and the more remote bedrooms until combustion was not possible. In most cases surrounding rooms such as the dining room and kitchen had no fire in them even when the fire room was fully involved in flames and was ventilating out of the structure. There was not enough oxygen in the structure to burn so there was some pyrolysis or melting because of high temperatures, but there was no burning in the adjacent rooms. The only time this did not hold was when remote windows were ventilated. Doing this created a flow path for oxygen to come from another part of the house and ignite rooms in the flow path but not outside the flow path. This is a good demonstration as to why ventilating near the seat of the fire is ideal. The fully developed fire conditions were localized by ventilating near the seat of the fire.

Examining the video of the interior conditions in the houses as compared to the exterior conditions highlighted the flame locations and extent of fire extension within the houses. Figure 532 shows the video views from Experiment 3. At 10 minutes after ignition, flames were extending out of the entire front door and living room window. The view in the bottom right is the view from the kitchen into the living room, and the flames are filling the entire doorway and intermittently flowing in through the top of the door but are not filling the kitchen due to lack of oxygen. During all of the experiments the appliances, cabinets, kitchen table and chairs melted a little bit but never became involved in the fire. If the kitchen door or windows were ventilated this would change and the flow path would allow for burning of the combustibles in the kitchen.

Figure 532. Experiment 3 at 10:00 showing flame extension.

10. Summary of Findings:

There has been a steady change in the residential fire environment over the past several decades. These changes include larger homes, more open floor plans and volumes and increased synthetic fuel loads. UL conducted a series of 15 full-scale residential structure fires to examine this change in fire behavior and the impact of firefighter ventilation tactics. This fire research project developed the empirical data that is needed to quantify the fire behavior associated with these scenarios and result in immediately developing the necessary firefighting ventilation practices to reduce firefighter death and injury.

The increased use of synthetic materials in the home has created faster flashover times. The two experiments demonstrated flashover times of less than 4 minutes with modern furnishings as compared to more than 29 minutes with legacy furnishings. This difference has a substantial impact on occupant and firefighter safety.

Tenability in these two homes was limited for occupants but the possibility of savable lives, especially behind closed doors should be considered by the fire service in their risk analysis. Also, emphasis should be placed on closing doors when the fire service is educating the public. Tenability for firefighters can also be quantified for these experiments. Firefighters had 100 seconds in the one-story house and 200 seconds in the two-story house after ventilation before water would have to be applied to remove the hazard or the firefighter would have to exit the house. These numbers should be considered conservative as the fire were allowed to become ventilation limited and decrease to a low temperature without becoming extinguished.

A significant portion of the 100 second and 200 second time to firefighter untenability is fresh air being entrained into the ventilation limited fire. In many of the experiments the time from the beginning of temperature escalation until untenability was less than 10 seconds. This provides little warning that the fire is going to flashover and highlights the need to understand that ventilation opening are not only allowing hot gases to escape but fresh air to enter.

Several ventilation comparisons could be made from the experimental series. First, the more ventilation openings that were made the faster the fire room transitioned to flashover. This shows that even in these modestly furnished homes fuel is not the limiting factor and that more air will create more burning and less tenability. Ventilating near the seat of the fire localized the combustion and temperatures within the house. Ventilating remote from the seat of the fire created a flow path which expanded the area available to burn and further decreased tenability within the homes. Allowing air into a ventilation limited fire low and letting the hot gases out high can create prime conditions for a flashover, even in a large volume like the two-story family room. More efficient ventilation can mean more efficient air entrainment which can lead to faster flashover times if water is not applied in the shorter tenability window.

Several tactical considerations were able to be developed with the assistance of the technical panel of fire service leaders. In summary, the stages of fire development change when a fire becomes ventilation limited. It is common with today’s fire environment to have a decay period prior to flashover which emphasizes the importance of ventilation. Forcing entry has to be thought of as ventilation as well. While forcing entry is necessary to fight the fire it must also trigger the thought that air is being fed to the fire and the clock is ticking before either the fire gets extinguished or it grows until an untenable condition exists jeopardizing the safety of everyone in the structure. A common event during the experiments was that once the fire became ventilation limited the smoke being forced out of the gaps of the houses greatly diminished or stopped all together. No smoke showing during size-up should increase awareness of the potential conditions inside. Once the front door is opened attention should be given to the flow through the front door. A rapid in rush of air or a tunneling effect could indicate a ventilation limited fire.

During a VES operation primary importance should be given to closing the door to the room. This eliminates the impact of the open vent and increases tenability for potential occupants and firefighters while the smoke ventilates from the now isolated room. Every new ventilation opening provides a new flow path to the fire and vice versa. This could create very dangerous conditions when there is a ventilation limited fire. Conditions in every experiment for the closed bedroom remained tenable for temperature and oxygen concentration thresholds. This means that the act of closing a door between the occupant and the fire or a firefighter and the fire can increase the chance of survivability. During firefighter operations if a firefighter is searching ahead of a hoseline or becomes separated from his crew and conditions deteriorate then a good choice of actions would be to get in a room with a closed door until the fire is knocked down or escape out of the room's window with more time provided by the closed door.

All of these experiments were designed to examine the first ventilation actions by an arriving crew when there are no ventilation openings. It is possible that the fire will fail a window prior to fire department arrival or that a door or window was left open by the occupant while exiting. It is important to understand that an already open ventilation location is providing air to the fire, allowing it to sustain or grow. In the experiments where multiple ventilation locations were made it was not possible to create fuel limited fires. The fire responded to all the additional air provided. That means that even with a ventilation location open the fire is still ventilation limited and will respond just as fast or faster to any additional air. It is more likely that the fire will respond faster because the already open ventilation location is allowing the fire to maintain a higher temperature than if everything was closed. In these cases rapid fire progression if highly probable and coordination of fire attack with ventilation is paramount.

If you add air to the fire and don't apply water in the appropriate time frame the fire gets larger and safety decreases. Examining the times to untenability gives the best case scenario of how coordinated the attack needs to be. Taking the average time for every experiment from the time of ventilation to the time of the onset of firefighter untenability conditions yields 100 seconds for the one-story house and 200 seconds for the two-story house. In many of the experiments from the onset of firefighter untenability until flashover was less than 10 seconds. These times should be treated as being very conservative. If a vent location already exists because the homeowner left a window or door open then the fire is going to respond faster to additional ventilation opening because the temperatures in the house are going to be higher. Coordination of fire attack crew is essential for a positive outcome in today's fire environment.

This research study developed empirical fire experiment data to demonstrate fire behavior resulting from varied ignition locations and ventilation opening locations in legacy residential structures compared to modern residential structures. The data will be used to provide education and guidance to the fire service in proper use of ventilation as a firefighting tactic that will result in mitigation of the firefighter injury and death risk associated with improper use of ventilation.

11. Future Research Needs:

These experiments were the first of their kind and there are countless experiments that could be done in two full-scale houses, especially the 2-story house. Other full-scale house experiments were done in an acquired structure and did not allow for repeatability or examination of multiple variables. There are several variable changes that could be done to further validate the conclusions from this series of experiments.

The first variable that could be altered is the fire location. These experiments focused on living room or family room fires. Additional experiments with fires in the kitchen or bedrooms would allow for analysis of fire spread from these locations. Additionally, changing fuel loading could provide some further insight. These experiments were realistically loaded but more experiments could examine the upper bound of fuel loading which may further emphasize the impact of ventilation.

Future experiments should also consider creating a ventilation point after one already exists from the fire creating one of its own by failing a window or a door being left open by an escaping occupant or a window left open on a warm day. This will also show the importance of ventilation. With an opening the fire will still be ventilation limited but will not be as starved for oxygen. This will allow the fire to respond to the ventilation faster demonstrating a very dangerous yet common situation.

There are also two more types of ventilation in addition to horizontal ventilation that are frequently used by the fire service that did not fit into the scope of this project but should be analyzed in a similar manner. These are vertical ventilation and positive pressure ventilation. Very little research has been conducted on these tactics used in a house.

12. Acknowledgements:

Without the financial support of the Department of Homeland Security's Assistance to Firefighters Grant Program's Fire Prevention and Safety Grants this research would not be possible, in particular the staff members Dave Evans, Kathy Patterson, Ellen Sogolow and Maggie Wilson.

13. References:

1. Ahrens, Marty. "Home Structure Fires", National Fire Protection Association, March 2010.
2. Karter, Michael J. "Patterns of Firefighter Fireground Injuries" National Fire Protection Association, February 2007.
3. Fahy, Rita F. "U.S. Fire Service Fatalities in Structure Fires, 1977-2009", National Fire Protection Research Foundation, June 2010.
4. "Commercial Structure Fire Claims the Life of One Fire Fighter—California", NIOSH report 98-F07.
5. "Volunteer Fire Fighter Dies Fighting a Structure Fire at a Local Residence – Texas", NIOSH report F2000-09.
6. "Volunteer Fire Fighter and Trapped Resident Die and a Volunteer Lieutenant is Injured following a Duplex Fire – Pennsylvania" NIOSH report F2008-06.
7. Press release from Prince Georges County Fire/EMS Department Chief Spokesman Mark Brady (http://pgfdpio.blogspot.com/), November 21, 2008.
8. "Nine Career Fire Fighter De in Rapid Fire Progression at Commercial Funiture Showroom – South Carolina," A summary of a NIOSH fire fighter fatality investigation, February 11, 2009.
9. "One Career Fire Fighter/Paramedic Dies and a Part-time Fire Fighter/Paramedic is Injured When Caught in a Residential Structure Flashover – Illinois" NIOSH report No. 2010-10, published September 13, 2010.
10. www.firefighternearmiss.com, Nearmiss report 09-0000300, accessed October 1, 2010.
11. www.firefighternearmiss.com, Nearmiss report 09-0000112, accessed October 1, 2010.
12. www.firefighternearmiss.com, Nearmiss report 05-0000420, accessed October 1, 2010.
13. www.firefighternearmiss.com, Nearmiss report 06-0000131, accessed October 1, 2010.
14. www.firefighternearmiss.com, Nearmiss report 06-0000496, accessed October 1, 2010.
15. www.census.gov, accessed January 12, 2009
16. Babrauskas, V, "Glass Breakage in Fires," Unpublished Author's document of 2009.
17. Hassani, S. K., Shields, T. J., and Silcock, G. W., An Experimental Investigation into the Behaviour of Glazing in Enclosure Fire, J. Applied Fire Science 4, 303-323 (1994/5).
18. Shields, T. J., Silcock, G. W. H., and Flood, M. F., Performance of Single Glazing Elements Exposed to Enclosure Corner Fires of Increasing Severity, Fire and Materials 25, 123-152 (2001).
19. Shields, J., Silcock, G. W. H., and Flood, F., Behaviour of Double Glazing in Corner Fires, Fire Technology 41, 37-65 (2005).
20. Fire Spread in Multi-Storey Buildings with Glazed Curtain Wall Facades (LPR 11: 1999), Loss Prevention Council, Borehamwood, England (1999).
21. Moulen, A. W., and Grubits, W. J., Water-Curtains to Shield Glass from Radiant Heat from Building Fires (Technical Record TR 44/153/422), Experimental Building Station, Dept. of Housing and Construction, North Ryde, Australia (1975).

22. Cohen, J. D., and Wilson, P., Current Results from Structure Ignition Assessment Model (SIAM) Research, presented in Fire Management in the Wildland/Urban Interface: Sharing Solutions, Kananaskis, Alberta, Canada (2-5 October 1994).
23. Harada, K., Enomoto, A., Uede, K., and Wakamatsu, T., An Experimental Study on Glass Cracking and Fallout by Radiant Heat Exposure, pp. 1063-1074 in Fire Safety Science--Proc. 6th Intl. Symp., Intl. Assn. for Fire Safety Science (2000).
24. Mowrer, F. W., Window Breakage Induced by Exterior Fires, pp. 404-415 in Proc. 2nd Intl. Conf. on Fire Research and Engineering, Society of Fire Protection Engineers, Bethesda, MD (1998). Also: Mowrer, F. W., Window Breakage Induced by Exterior Fires (NIST-GCR-98-751), Natl. Inst. Stand. and Technol., Gaithersburg MD (1998).
25. McArthur, N. A., The Performance of Aluminum Building Products in Bushfires, Fire and Materials 15, 117-125 (1991).
26. Tanaka, T., et al., Performance-Based Fire Safety Design of a High-rise Office Building, to be published (1998).
27. Kang, Kai, "Assessment of a model development for window glass breakage due to fire exposure in a field model," Fire Safety Journal, Vol. 44, Issue 3, April 2009, pgs. 415-424.
28. Obermayer, Robert, "Energy Efficient Windows," Firehouse; Nov. 1992; pgs. 41-42
29. Smith, Michael, "High-Energy Windows Can Be Deadly." Firehouse: Feb, 2008: pg. 46.
30. Svensson, Stefan, "Experimental Study of Fire Ventilation During Fire Fighting Operations," Fire Technology 2001; 37, pgs. 69-85.
31. Fleischmann, C.M., Bolliger, J.B., Millar, D.J., "Exploratory Experiments on Backdraft in a Full Residential Scale Compartment"
32. Saber, H.H., Kashef, A., "CFD simulation for fully-developed fires in a room under different ventilation conditions," 16th Annual Conference of the CFD Society of Canada, June 9-11, 2008, pp. 1-9
33. Kerber, Stephen, Walton, William D., "Effect of Positive Pressure Ventilation on a Room Fire," National Institute of Standards and Technology; NISTIR 7213, pgs. 1-55
34. Kerber, Stephen, Walton, William D., "Full-Scale Evaluation of Positive Pressure Ventilation In a Fire Fighter Training Building," National Institute of Standards and Technology; NISTIR 7342, pgs. 1-92
35. NFPA 1001. Standard for Fire Fighter Professional Qualifications. 2008 Edition.
36. Vincent, "The Dangers of Outside Venting," Fire Engineering, Strategy & Tactics; October 1989; pgs. 43-50
37. Jr., David C., Maxwell, Scott, "Firefighters 10 Deadly Sins of the Fireground," Fire Engineering January 2004; pgs. 105- 110
38. Murphy Denis, Molle Hank, "First Due Without a Clue: Don't let it happen to you," Fire Engineering: September 2005; pgs 16, 18-20
39. Hartin, Ed, "Flashover Fundamentals," Fire Research Magazine August 2008; pgs 63-66
40. Wolfe, Vincent, "Getting the Most From Horizontal Ventilation," Fire Engineering March 2009; pgs123-125
41. Peltier, Jack, "Gone with the wind," National Fire and Rescue September/October 2001; pgs 22-26

42. Donnelly, Tom "Primary Ventilation: A Review," Fire Engineering; Training Notebook, June 2007; pgs 24, 26
43. Brennan, T., "Still Talkin' in the Kitchen….," Fire Engineering, Random Thoughts; January 2006; pg. 234
44. Kertzie, Peter F., "Ventilation in Wood-Frame Structures," Fire Engineering; April 2005
45. Carlin, John T., "When to Break the Windows," Fire Engineering; September 2001; pgs. 12-17
46. Huggett, C., "Estimation of the rate of heat release by means of oxygen consumption," Journal of Fire and Materials, 12, pp. 61-65 (1980).
47. Krasny, J., Rockett, J. A.,and Huang, D. "Protecting Fire Fighters Exposed in Room Fires: Comparison of Results of Bench Scale Test for Thermal Protection and Conditions During Room Flashover." Fire Technology, p. 5-19, (1988).
48. Krasny, J., Rockett, J. A.,and Huang, D. "Protecting Fire Fighters Exposed in Room Fires: Comparison of Results of Bench Scale Test for Thermal Protection and Conditions During Room Flashover." Fire Technology, p. 5-19, (1988).
49. NFPA 1971. Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting, 2007 Edition.
50. Purser, D.A., "Toxicity Assessment of Combustion Products." Society of Fire Protection Engineers' Handbook of Fire Protection Engineering, Third Edition, DiNenno,P.J., Editor-in-Chief, Society of Fire Protection Engineers, Bethesda, MD, 2002.
51. Lewis, R.J., Sax's Dangerous Properties of Industrial Materials, Ninth Edition, Van Nostrand Reinhold, New York, NY, 1995.
52. IFSTA [2008]. Essentials of fire fighting. 5th ed. Stillwater, OK: Fire Protection Publications,International Fire Service Training Association.
53. Firefighter Exposure to Smoke Particulates. Underwriters Laboratories Inc. April 2010.

Appendix A: Firefighter Reference Scales for the Results Sections

This section includes tables with reference values that firefighters can use to assist with putting the results in the following sections into perspective. Table 39 provides a set of temperatures commonly experienced during firefighting operations and information on the human and equipment response. Table 40 provides common symptoms from carbon monoxide exposures of a given duration to a particular concentration. There are number of variables that could cause an individual to respond differently.

Table 39. Firefighter Temperature Reference Table

Temperature	Response
37 °C (98.6 °F)	Normal human oral/body temperature [1]
44 °C (111 °F)	Human skin begins to feel pain [2]
48 °C (118 °F)	Human skin receives a first degree burn injury [2]
55 °C (131 °F)	Human skin receives a second degree burn injury [2]
62 °C (140 °F)	A phase where burned human tissue becomes numb [2]
72 °C (162 °F)	Human skin is instantly destroyed [2]
100 °C (212 °F)	Water boils and produces steam [3]
140 °C (284 °F)	Glass transition temperature of polycarbonate [4]
230 °C (446 °F)	Melting temperature of polycarbonate [5]
250 °C (482 °F)	Charring of natural cotton begins [6]
>300 °C (>572 °F)	Charring of modern protective clothing fabrics begins [6]
>600 °C (1112 °F)	Temperatures inside a post-flashover room fire[7, 8]

References:

1. Klinghoffer, Max, M.D., “Triage Emergency Care Handbook,” Technomic Publishing Company, Inc., Lancaster, PA, 1985.
2. American Society for Testing and Materials, ASTM C1055, Standard Guide for Heated Systems Surface Conditions That Produce Contact Burn Injuries, 4:6, ASTM West Conshohocken, PA, 1997.
3. Shugar, G.J., Shugar, R.A., Lawrence, B., “Chemical Technicians’ Ready Reference Handbook,” McGraw-Hill Book Company, New York, 1973.
4. Quintiere, J., “Radiative and Convective Heating of a Clear Plastic Fireman’s Face Shield”, National Bureau of Standards (currently NIST), Gaithersburg, MD, NBS Report 10-855, March 1972.
5. Askeland, Donald R., “The Science and Engineering of Materials”, Wadsworth, Inc., Belmont, CA., 1984.
6. Krasny, John F., Sello, Stephen B., “Fibers and Textiles, Fire Protection Handbook,” 16th Edition, 1986. NFPA, pp.5-27.
7. Fang, J.B., and Breese, J.N., “Fire Development in Residential Basement Rooms,” National Bureau of Standards (currently NIST), Gaithersburg, MD, NBSIR 80-2120, 1980.

8 Drysdale, D., “An Introduction to Fire Dynamics”, 2nd Edition, John Wiley & Sons, New York, 1999.

Table 40. Carbon Monoxide Firefighter Reference Table [1, 2, 3]

Concentration	Common Symptoms	Duration of Exposure
35 ppm (0.0035 %)	None	<= 8 hours
150 ppm (0.0150 %)	Mild headache	2 – 3 hours
400 ppm (0.04 %)	Headache/nausea	1 – 2 hours
800 ppm (0.08 %)	Headache/nausea/dizziness Progressing to unconsciousness	45 minutes 2 hours
6400 ppm (0.64 %)	Headache/nausea/dizziness	1 – 2 minutes
12800 ppm (1.28%)	Immediately dangerous to life and health (IDLH)	1 – 2 minutes

References:

1. Delagi, Robert, “A CO Emergency: Whose Call Is It, Anyway?”, *Fire Engineering Magazine*, October 2007.
2. Henry CR, Satran D, Lindgren B, Adkinson C, Nicholson CI, Henry TD, MD (2006). "Myocardial Injury and Long-term Mortality Following Moderate to Severe Carbon Monoxide Poisoning". *JAMA* **295**: 398-402.
3. Raub JA, Mathieu-Nolf M, Hampson NB, Thom SR. (2000). "Carbon monoxide poisoning-a public health perspective". *Toxicology* **145** (1): 1-14.

Appendix B: Detailed One-Story House Drawings and Pictures

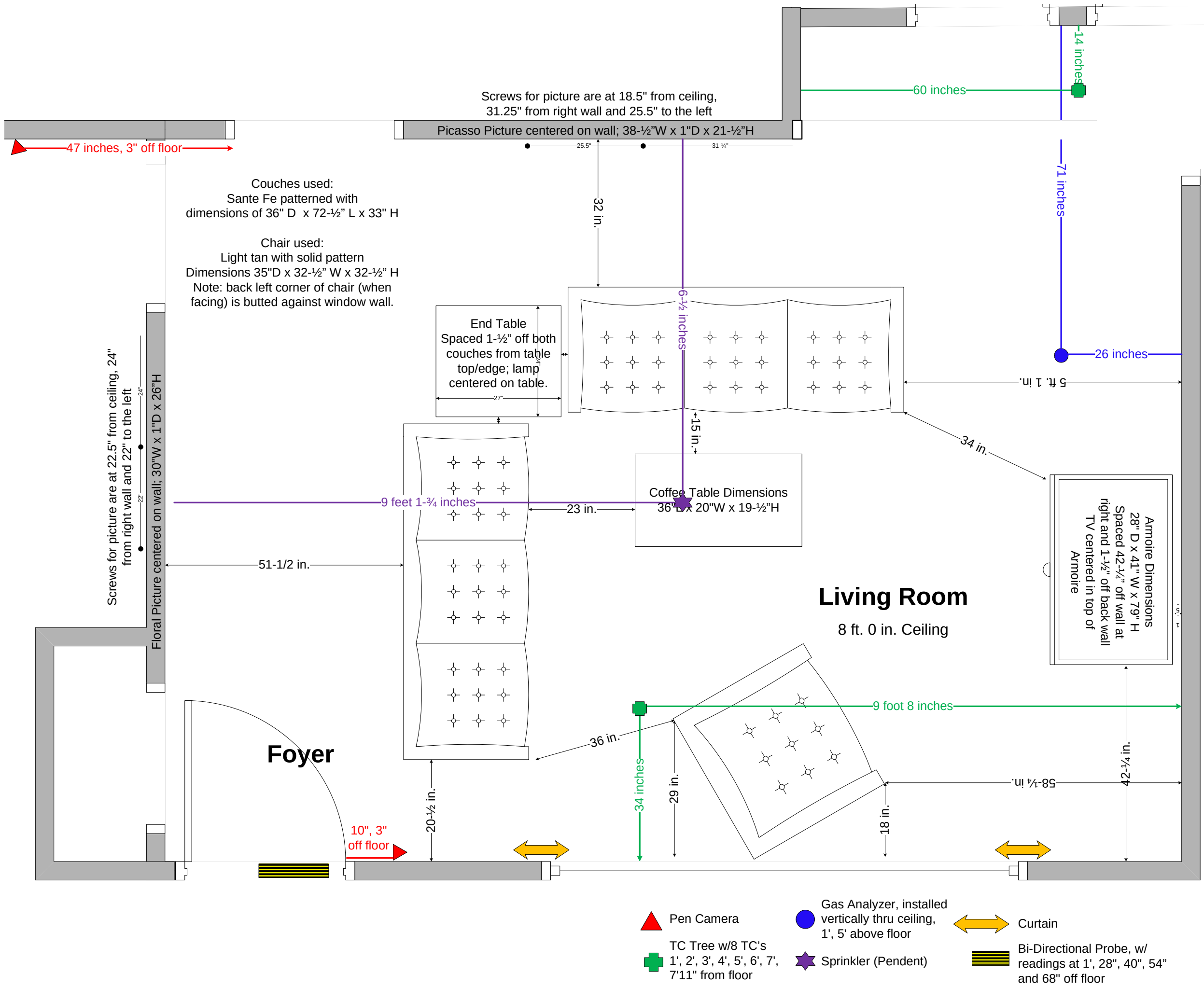


Figure 533. One-Story Living Room Detail

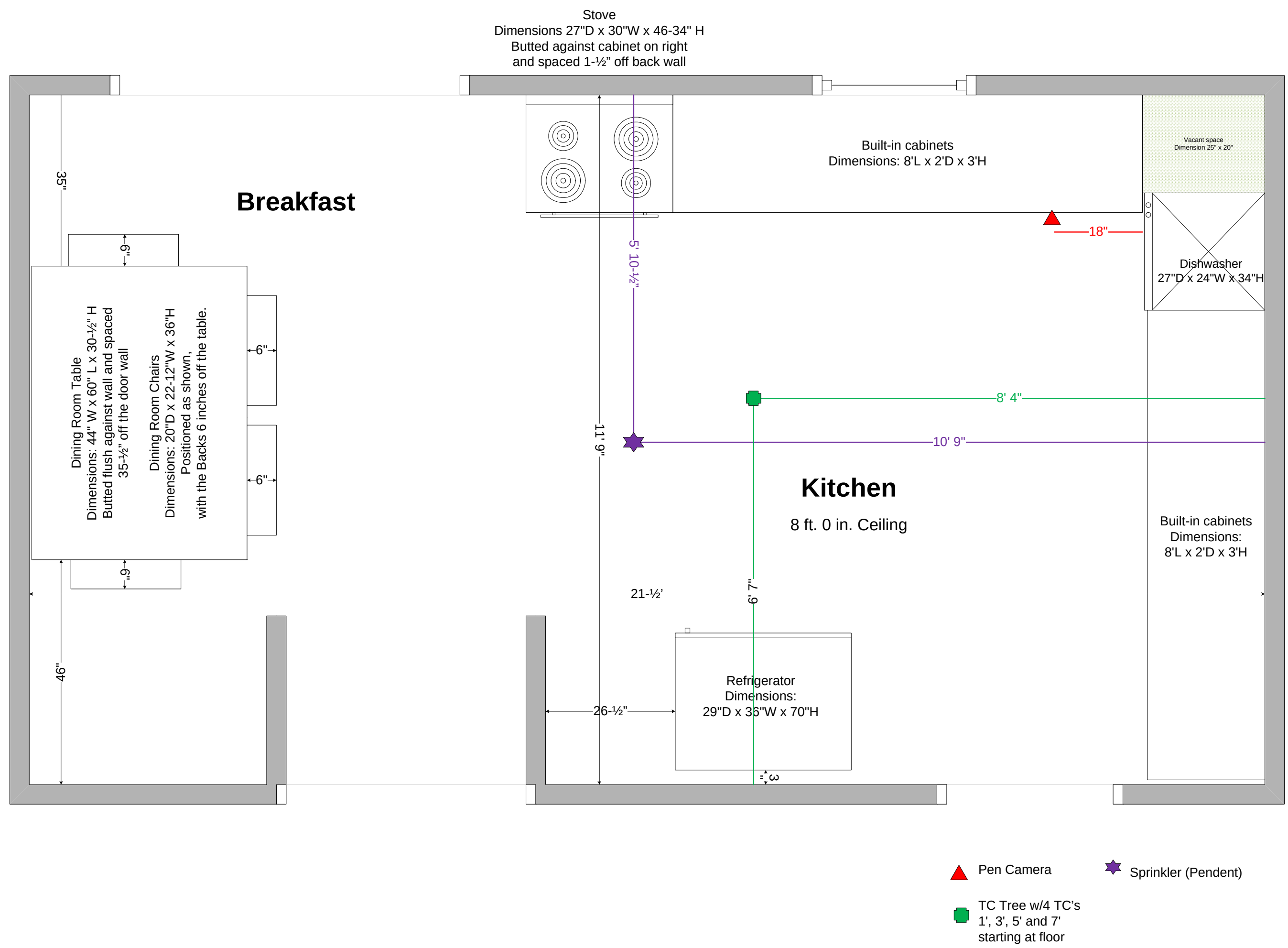


Figure 534. One-Story Kitchen Detail

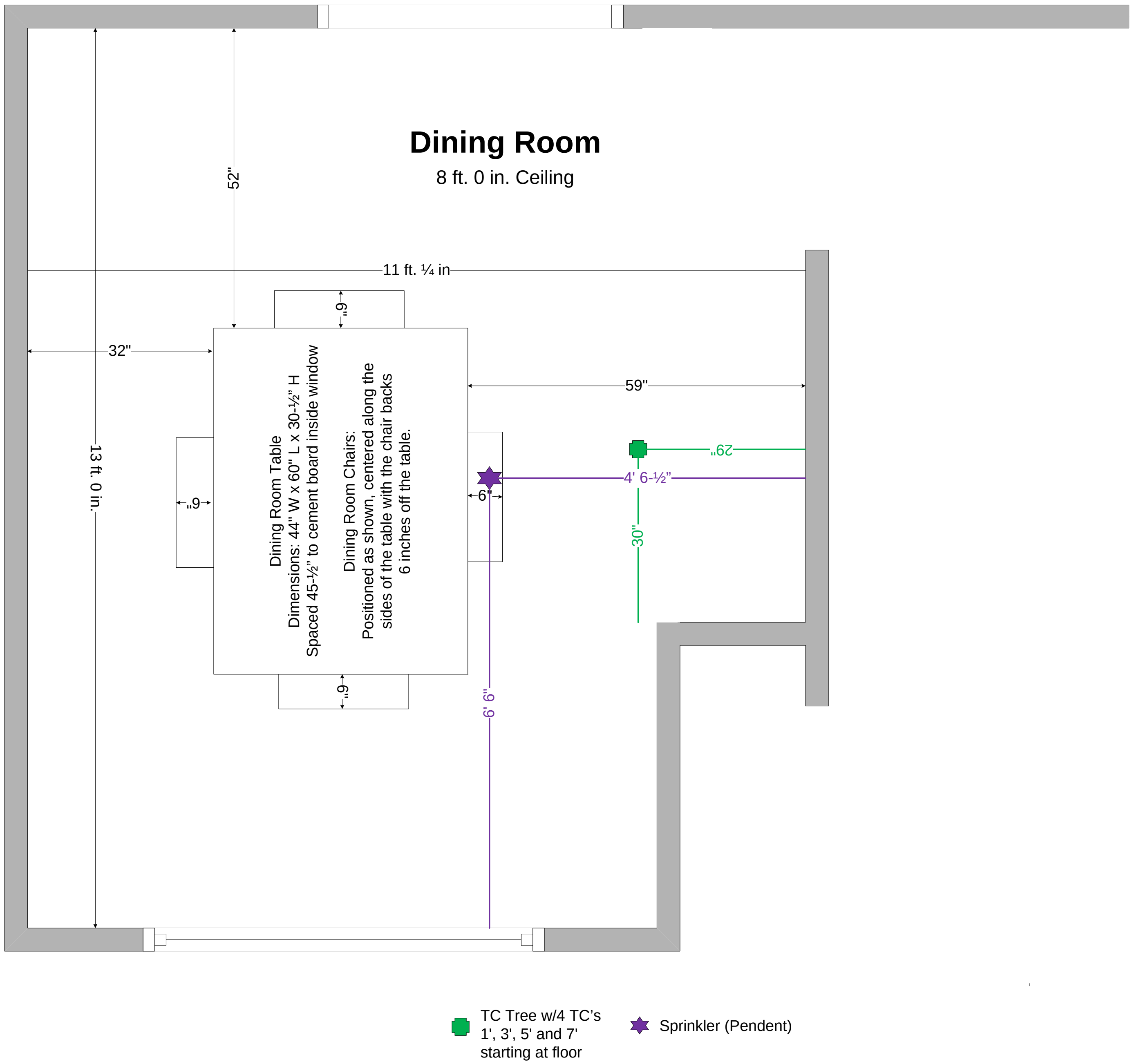


Figure 535. One-Story Dining Room Detail

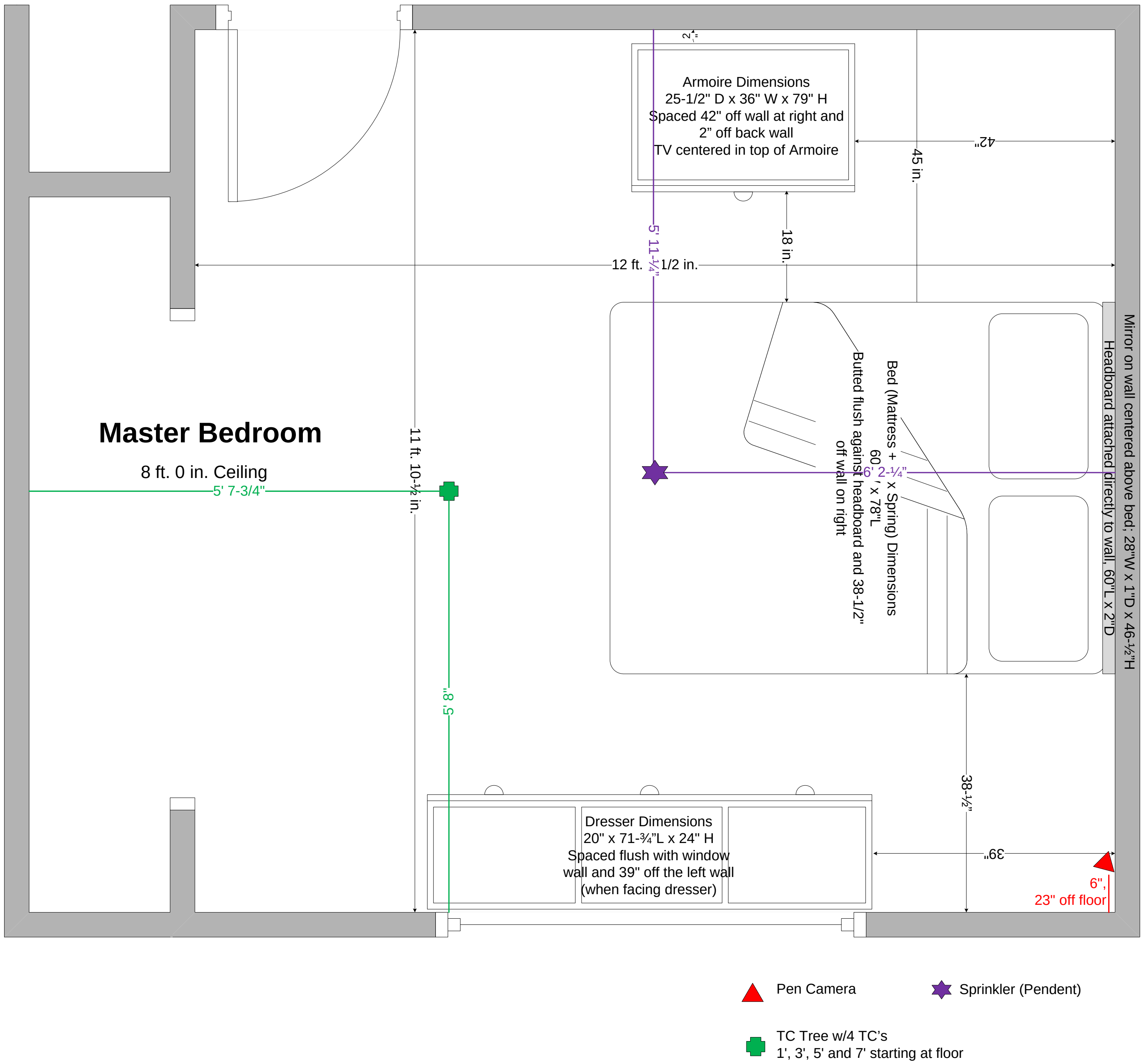


Figure 536. One-Story Master Bedroom (Bedroom 1) Detail

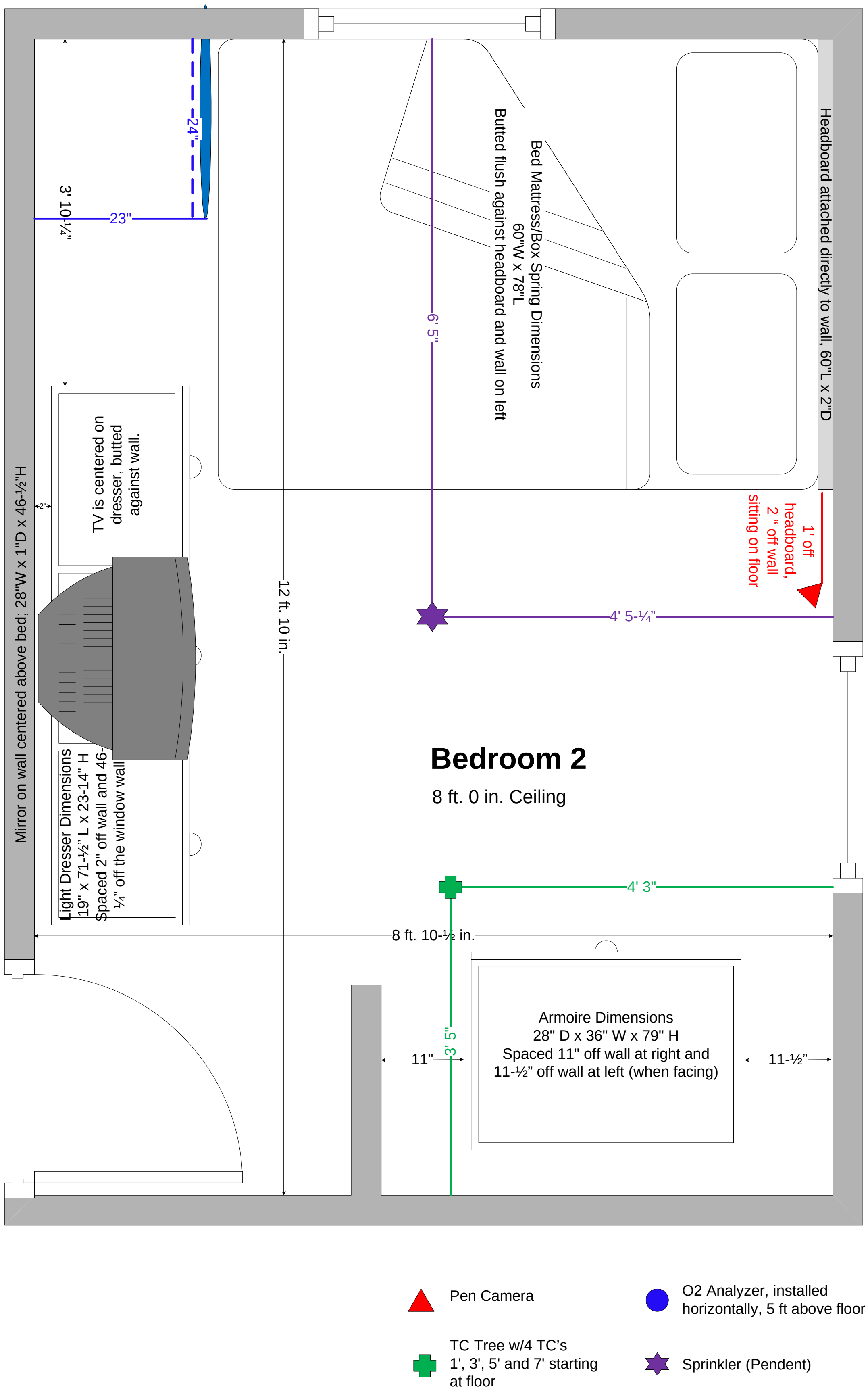


Figure 537. One-Story Bedroom 2 Detail

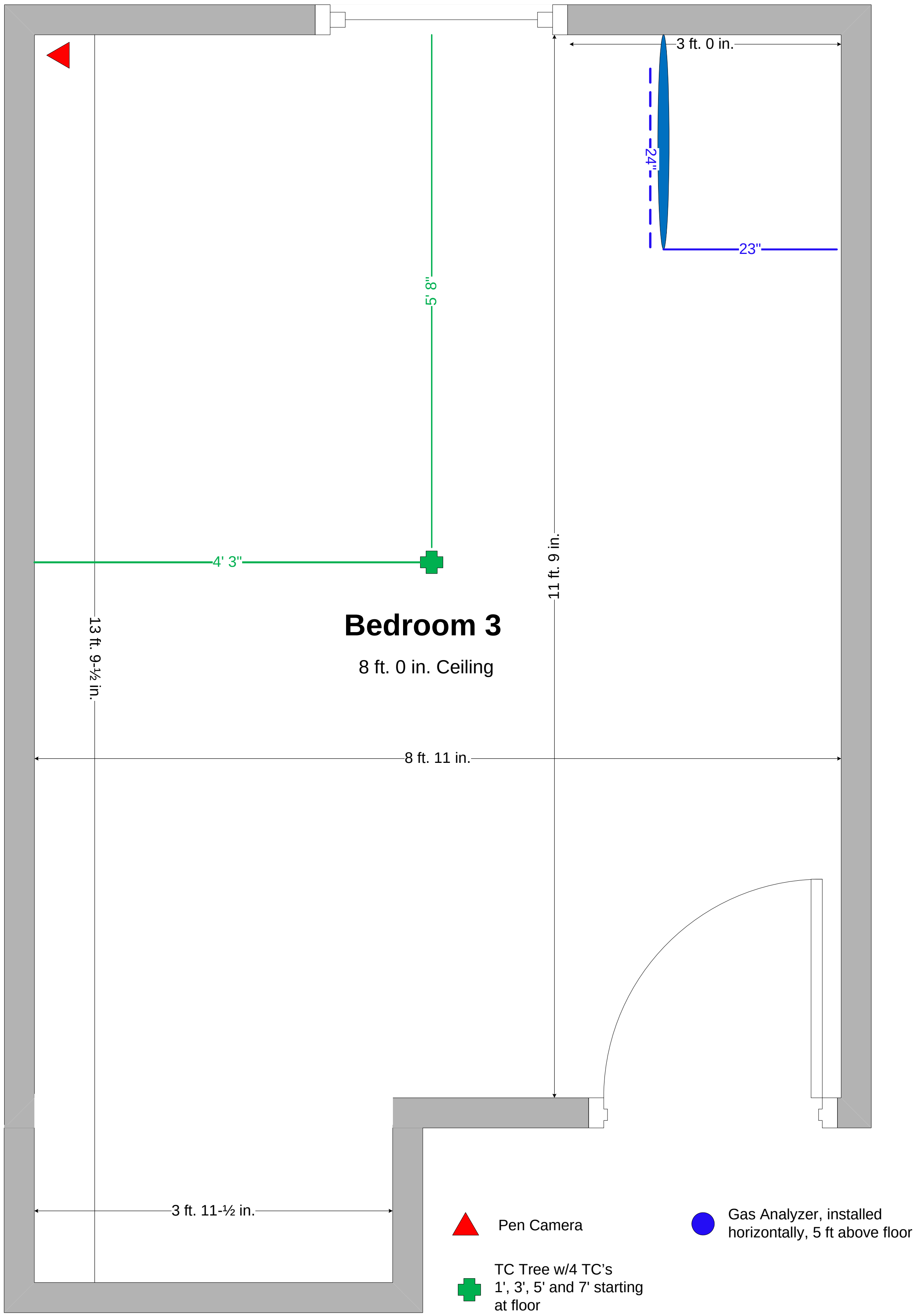


Figure 538. One-Story Bedroom 3 Detail

Appendix C: Detailed Two-Story House Drawings and Pictures

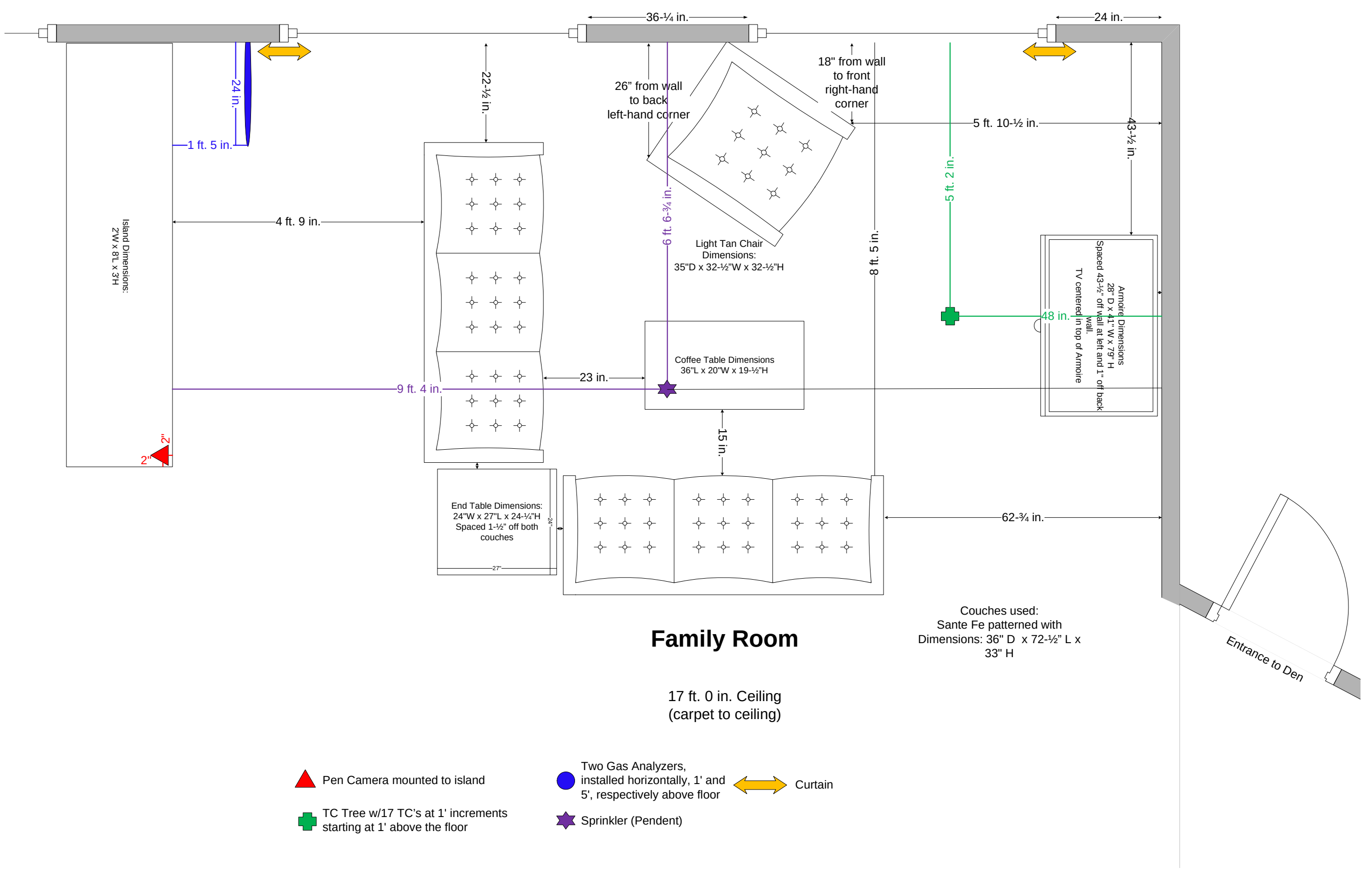


Figure 539. Two-Story Family Room Detail

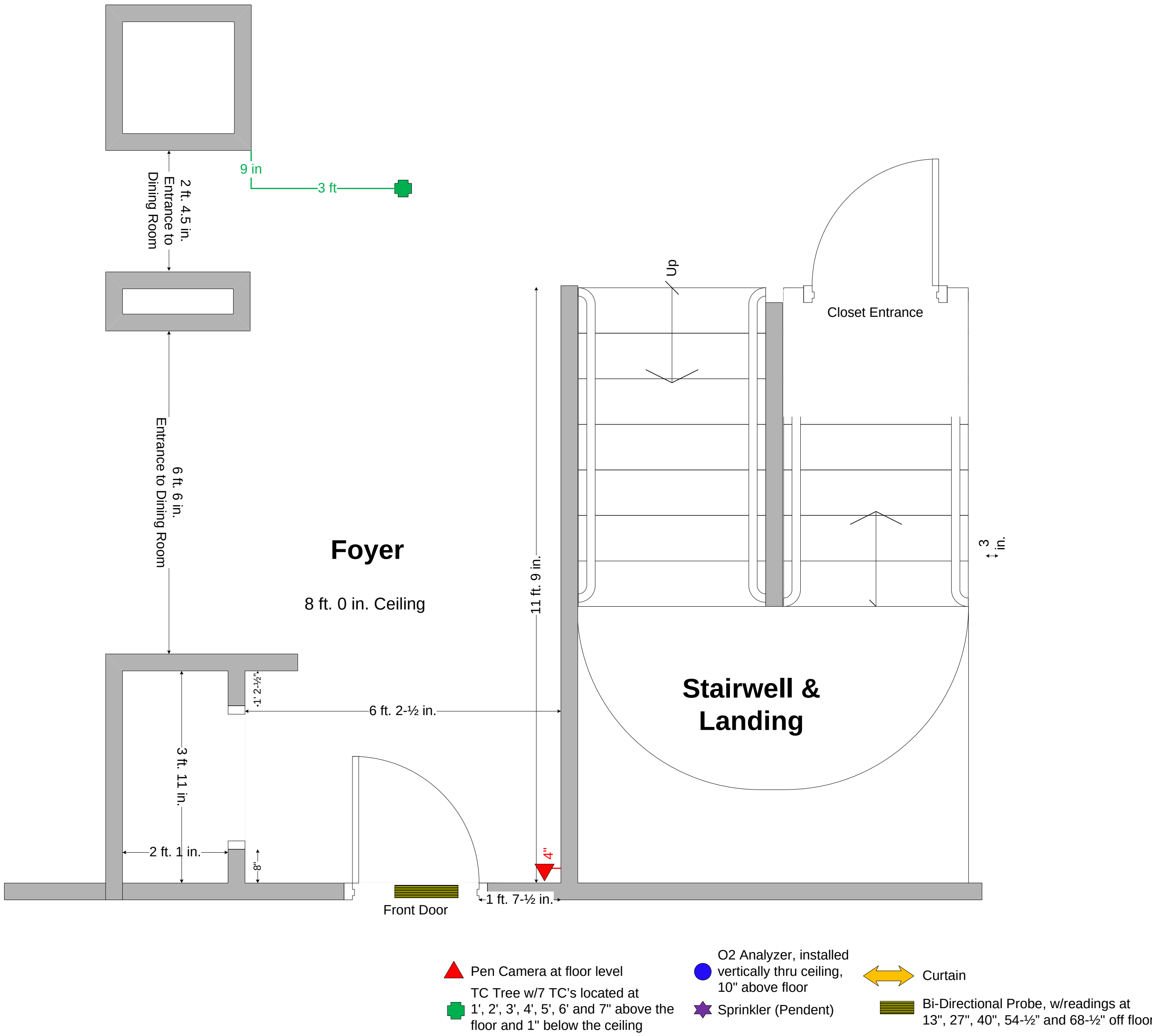


Figure 540. Two-Story Foyer Detail

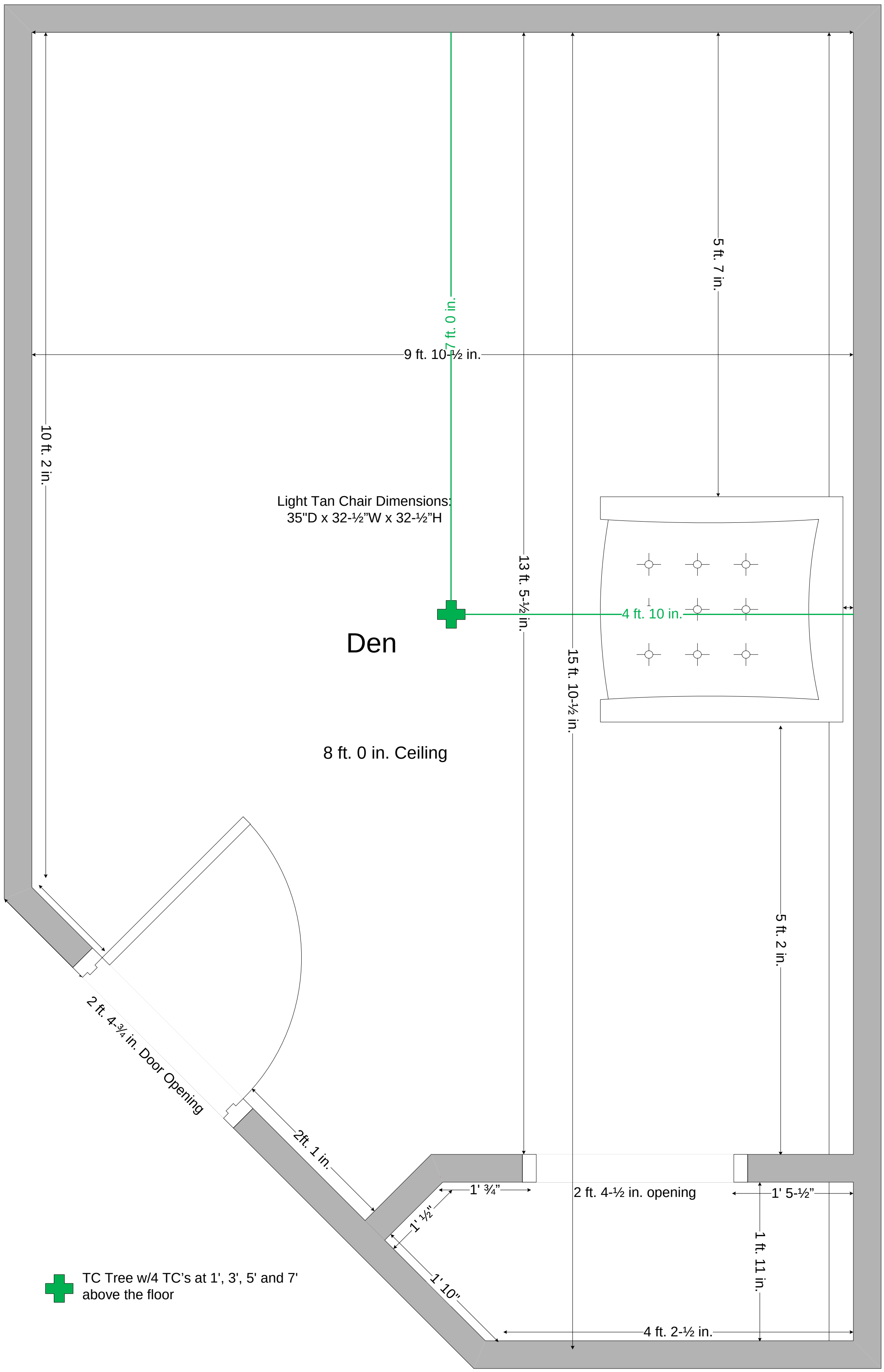


Figure 541. Two-Story Den Detail

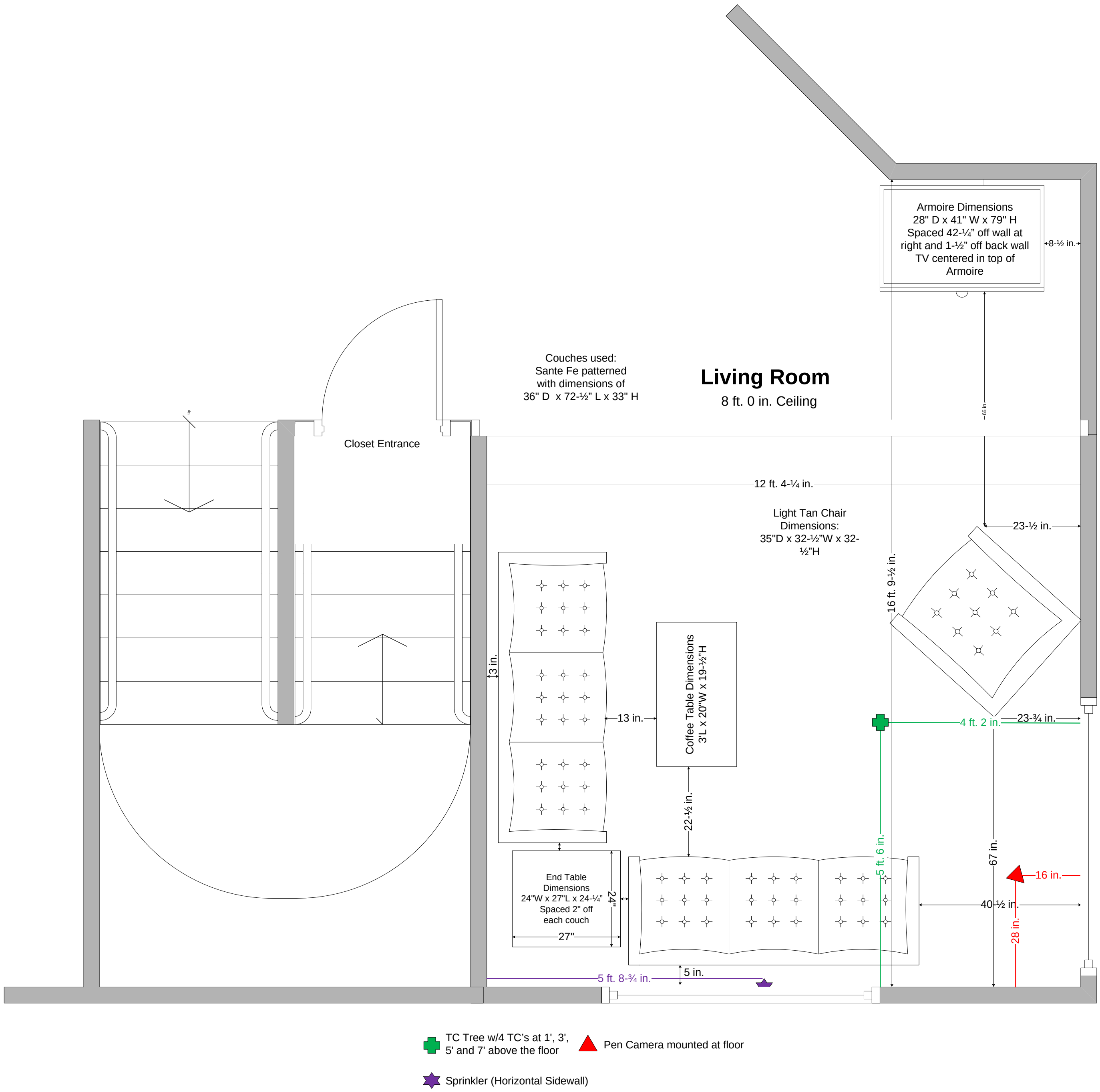


Figure 542. Two-Story Living Room Detail

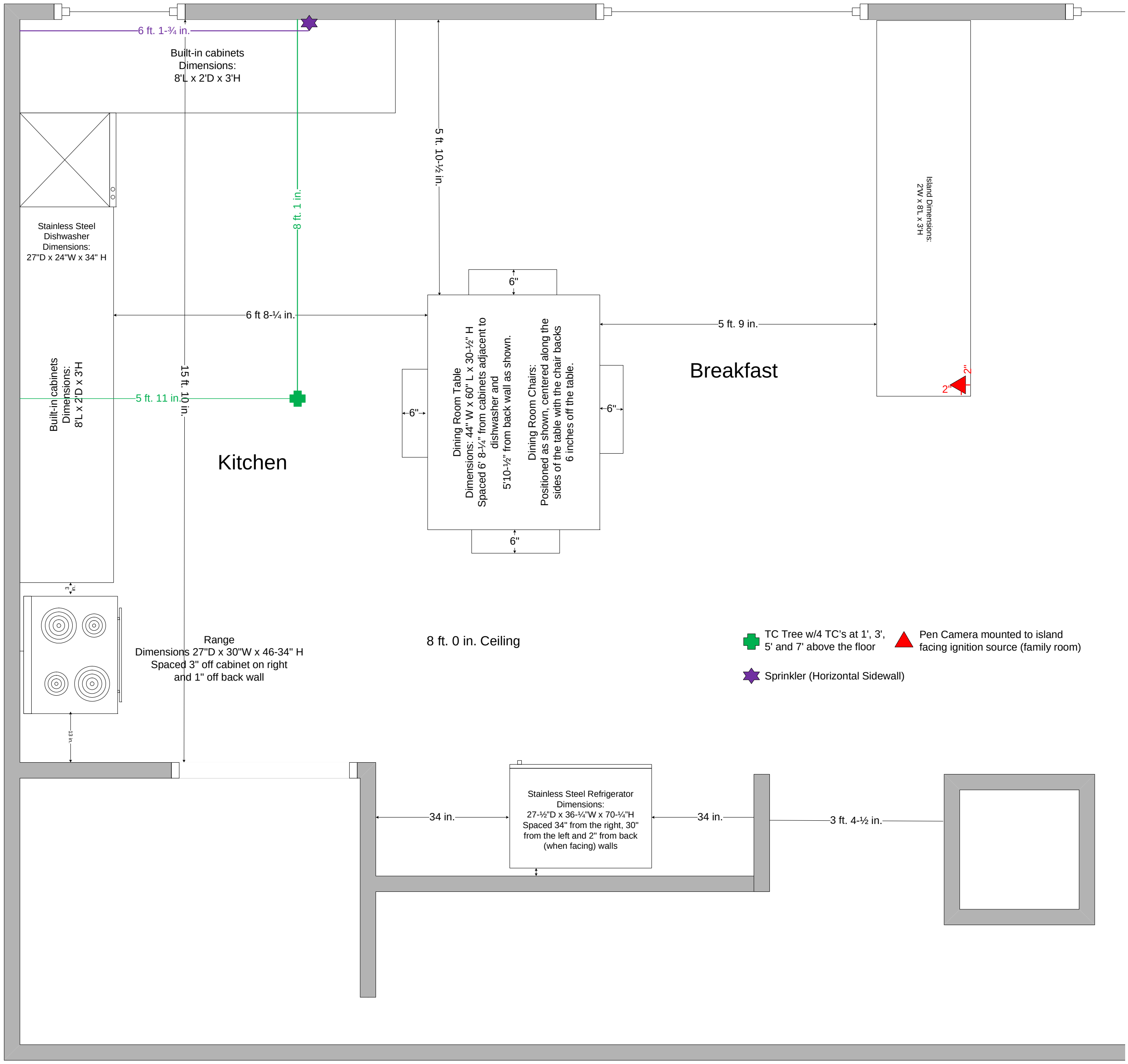


Figure 543. Two-Story Kitchen Detail

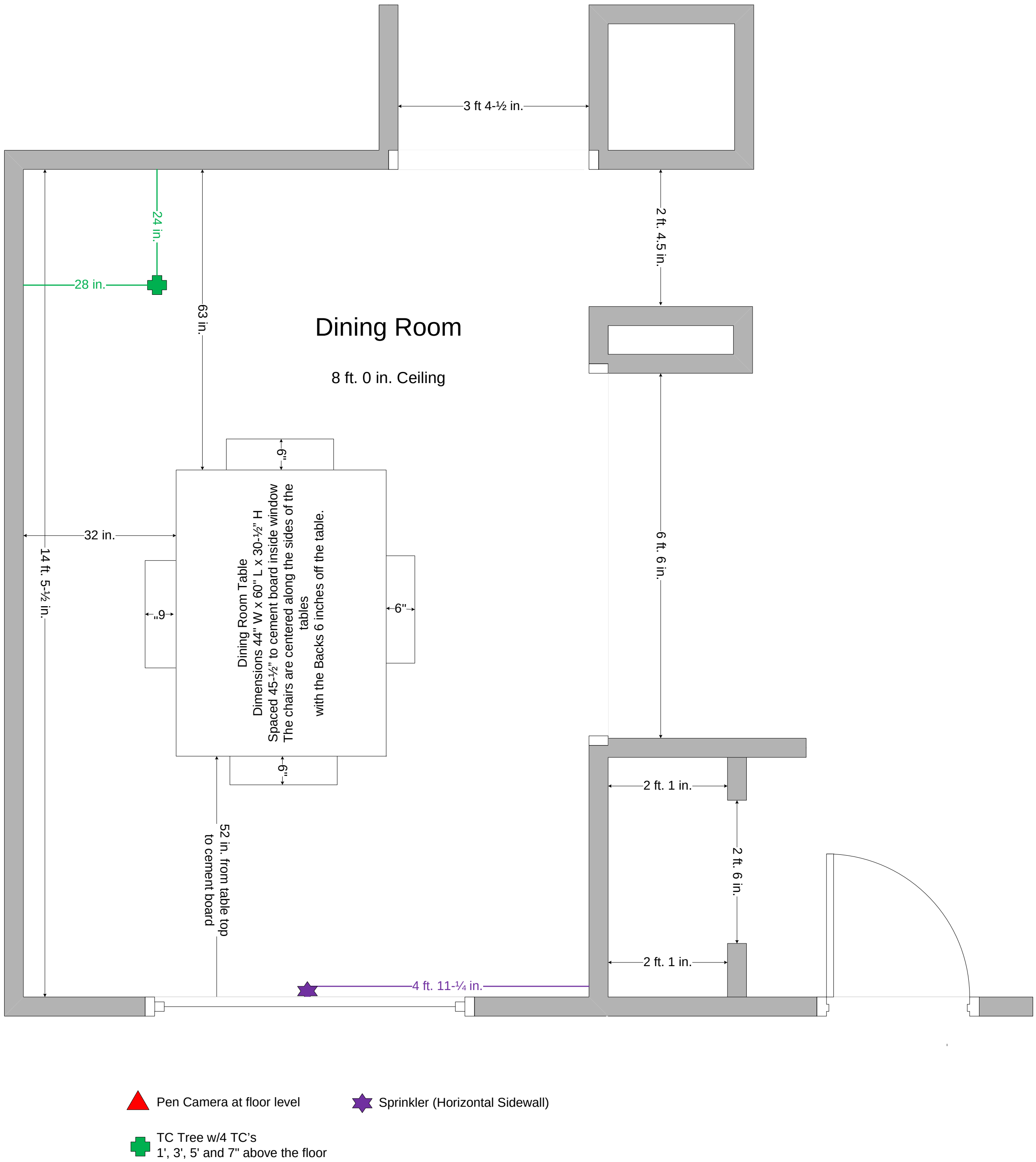


Figure 544. Two-Story Dining Room Detail

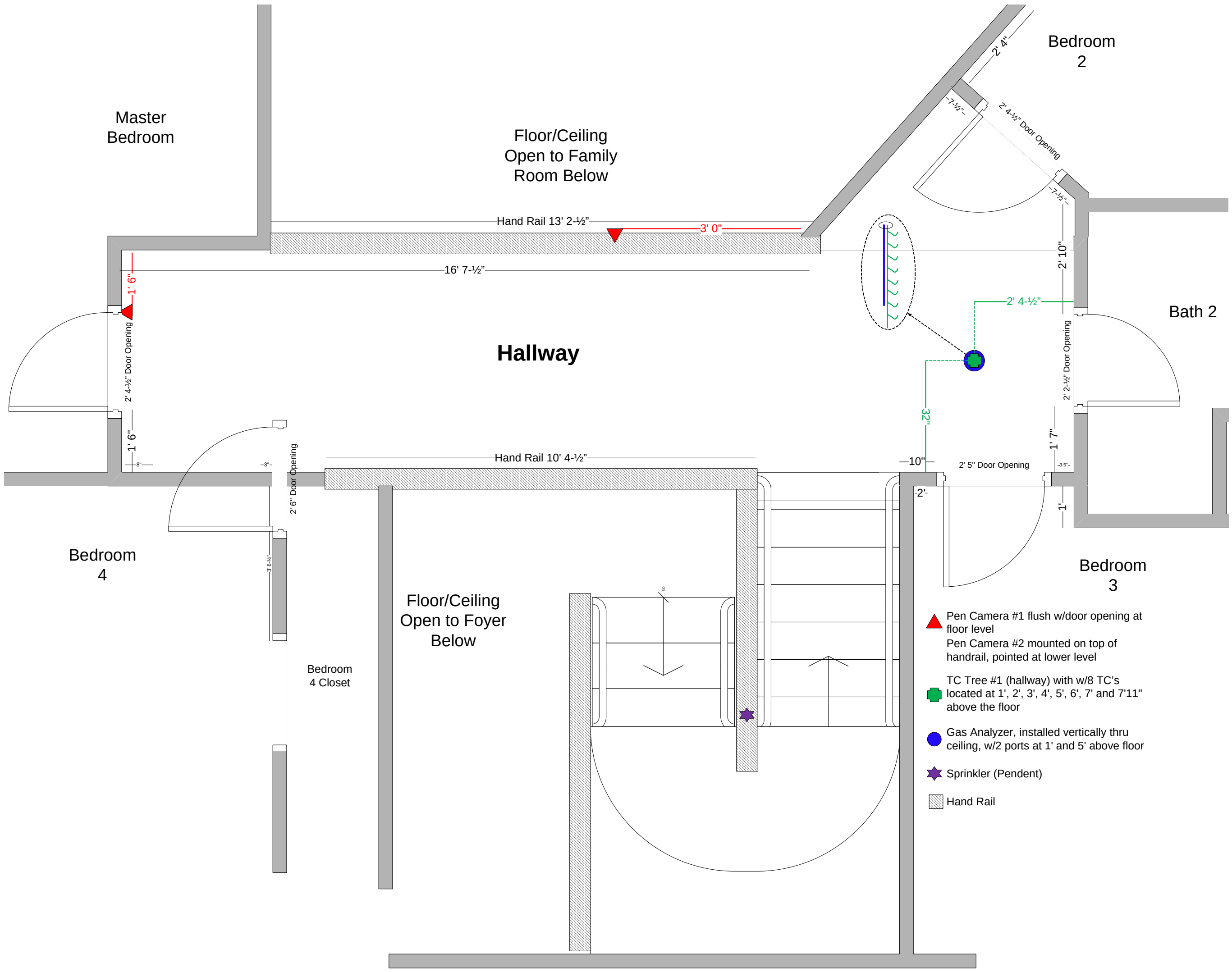


Figure 545. Two-Story Second Floor Hall Detail

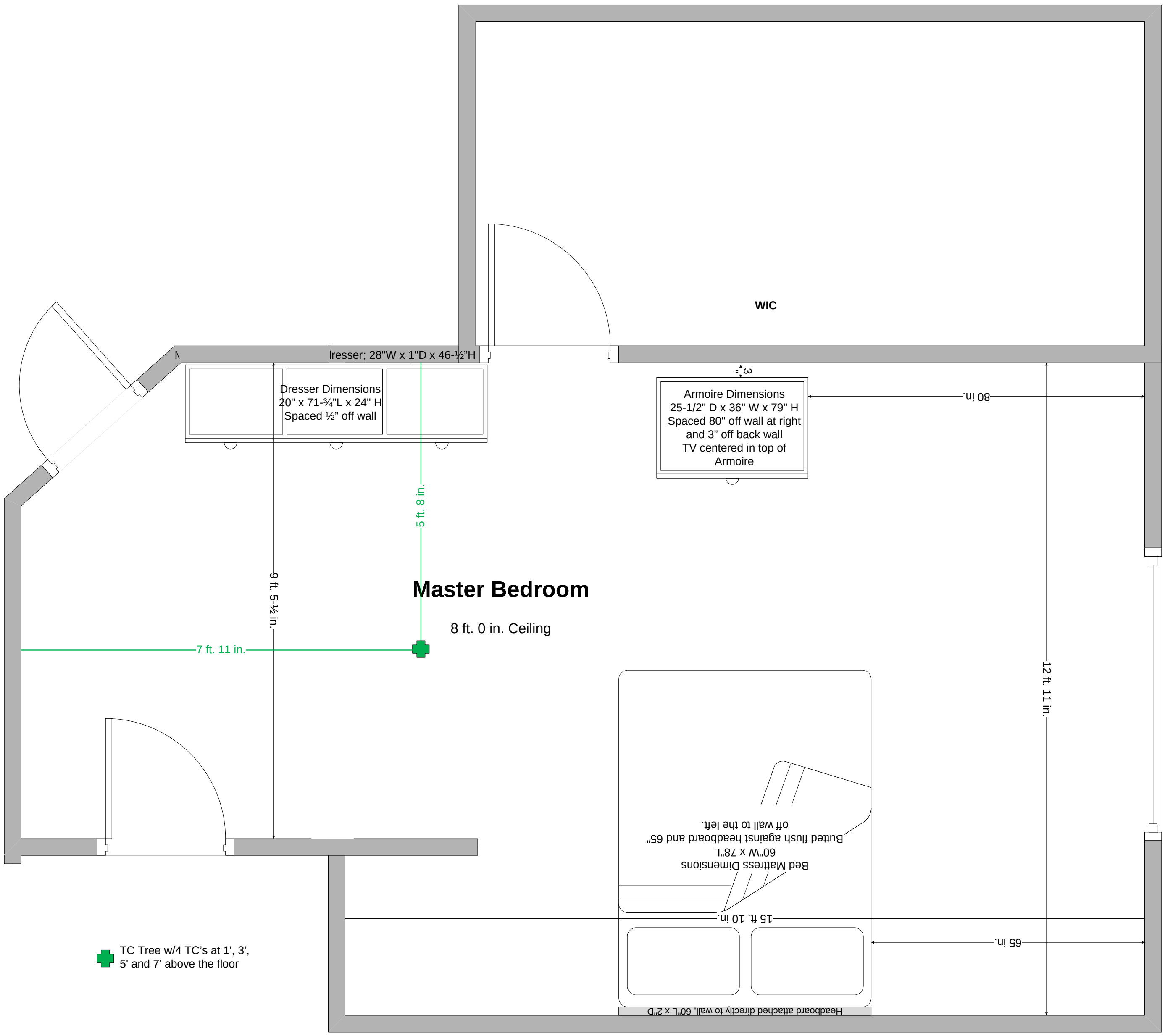


Figure 546. Two-Story Master Bedroom (Bedroom 1) Detail

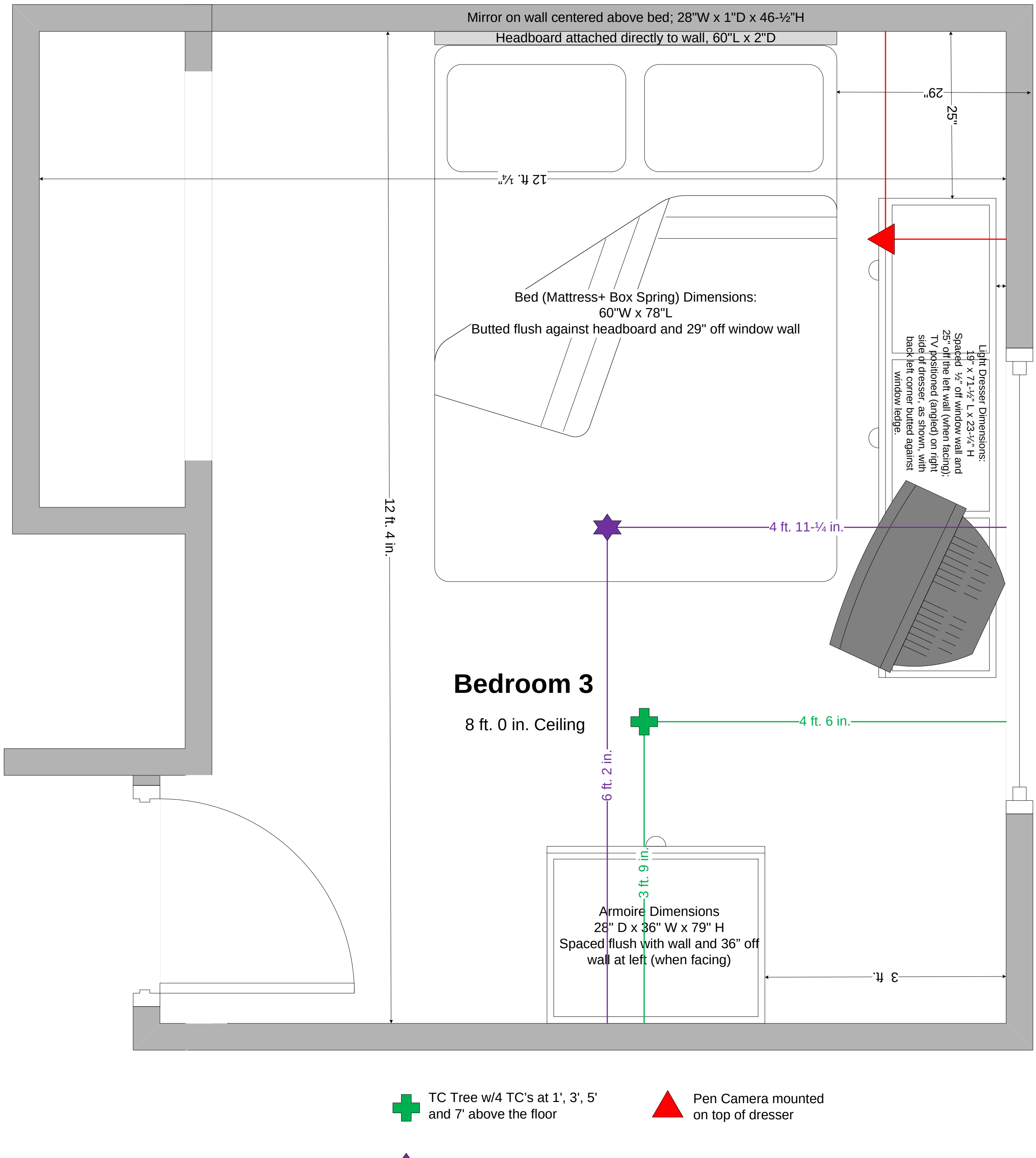


Figure 547. Two-Story Bedroom 3 Detail

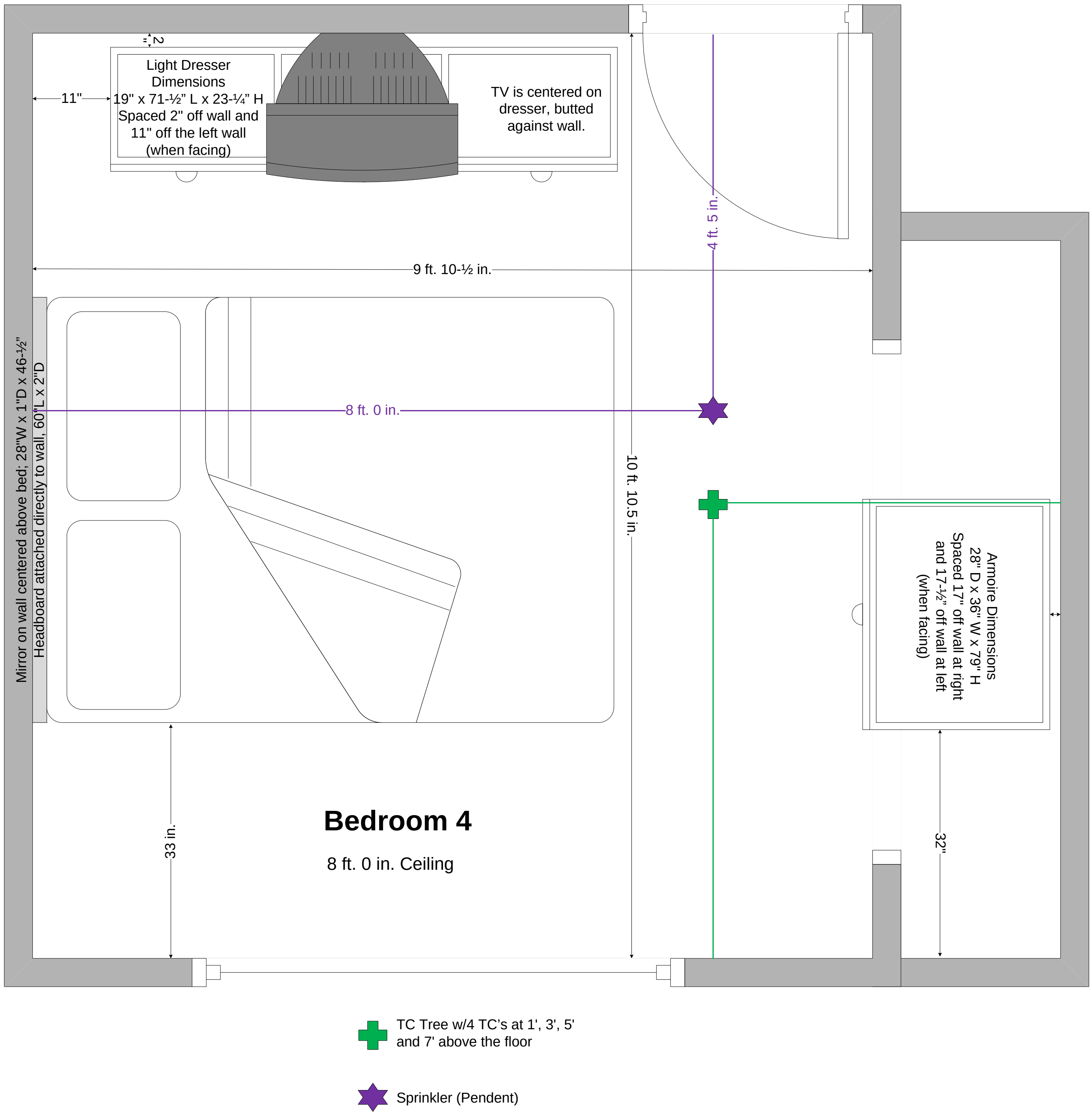


Figure 548. Two-Story Bedroom 4 Detail

Appendix D: Furniture Pictures

Figure 549. Sofa

Figure 550. Chair

Figure 551. Armoire and TV

Figure 552. Dining Room and Kitchen Table

Figure 553. End Table

Figure 554.   Television

Figure 555. Dark Brown Dresser

Figure 556. Light Brown Dresser

Figure 557. Kitchen

Figure 558. Den Chair

Figure 559. Brass Frame Picture

Figure 560. Blue Frame Picture

Figure 561. Bedroom Mirror

Figure 562. Bed

Figure 563. Kitchen Base Cabinet

Appendix E: Detailed House Experiment Room Temperature Graphs

Experiment 1

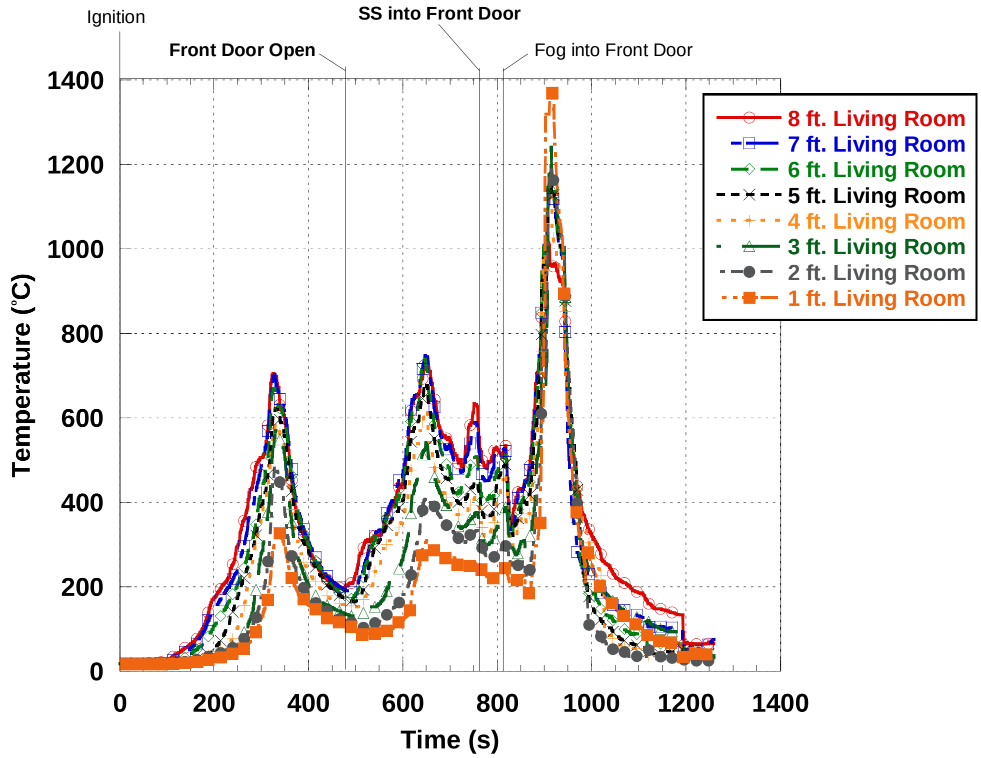


Figure 564. Experiment 1 - Living Room

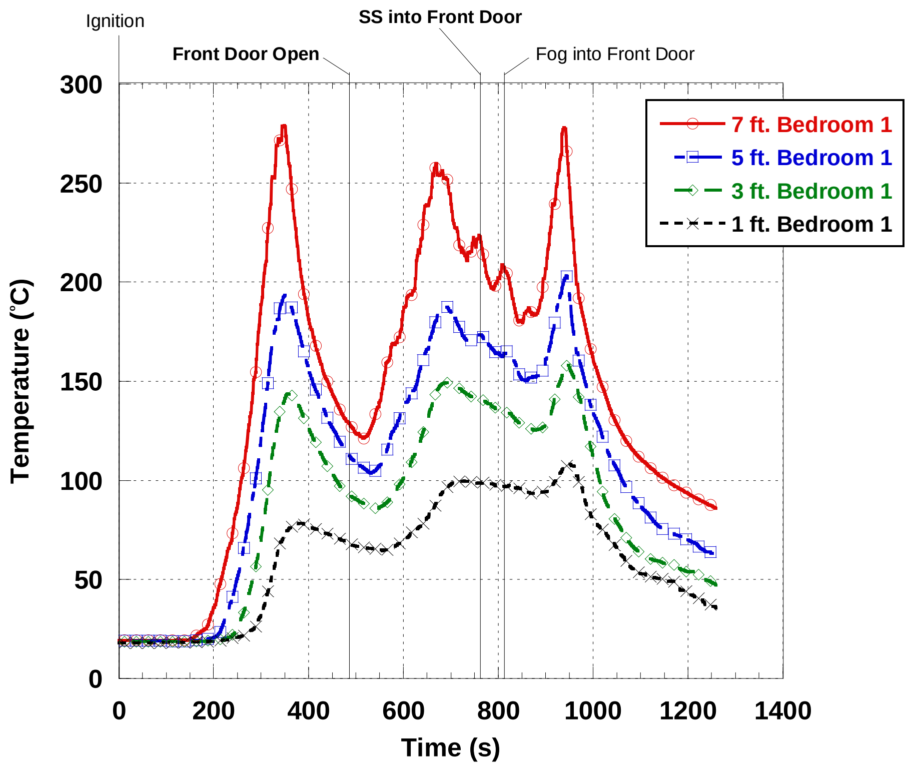


Figure 565. Experiment 1 - Bedroom 1

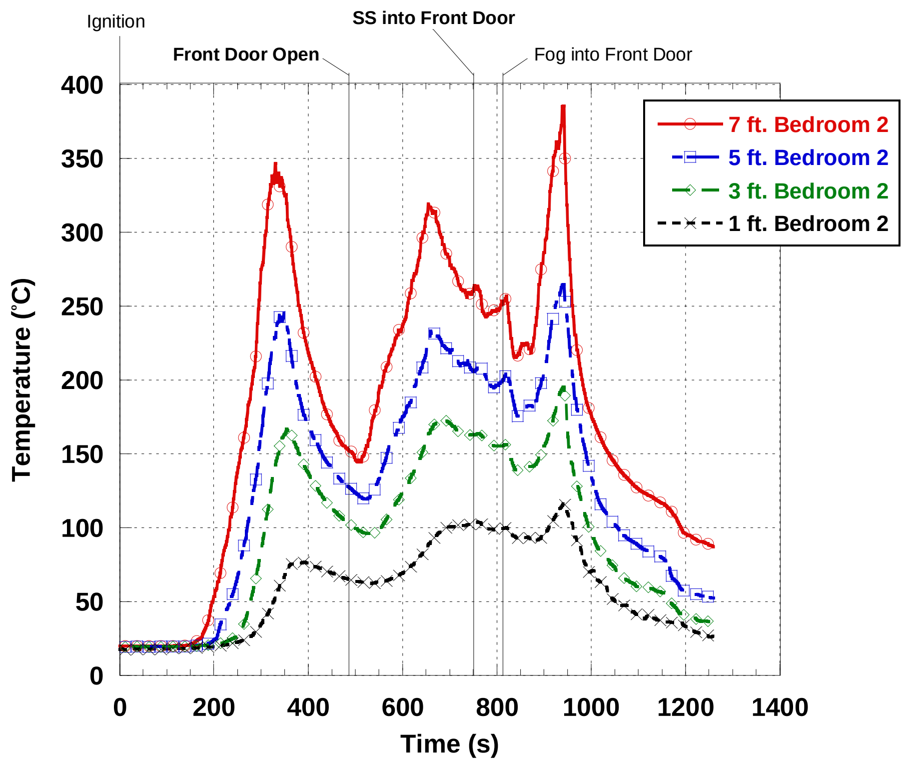


Figure 566. Experiment 1 - Bedroom 2

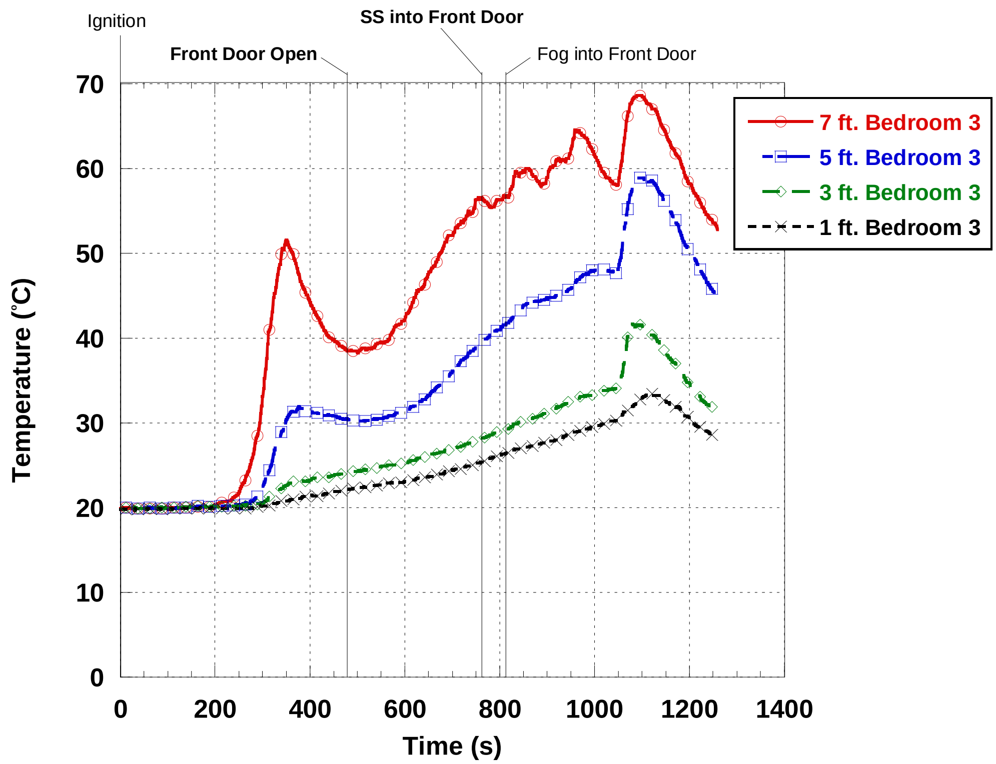


Figure 567. Experiment 1 - Bedroom 3

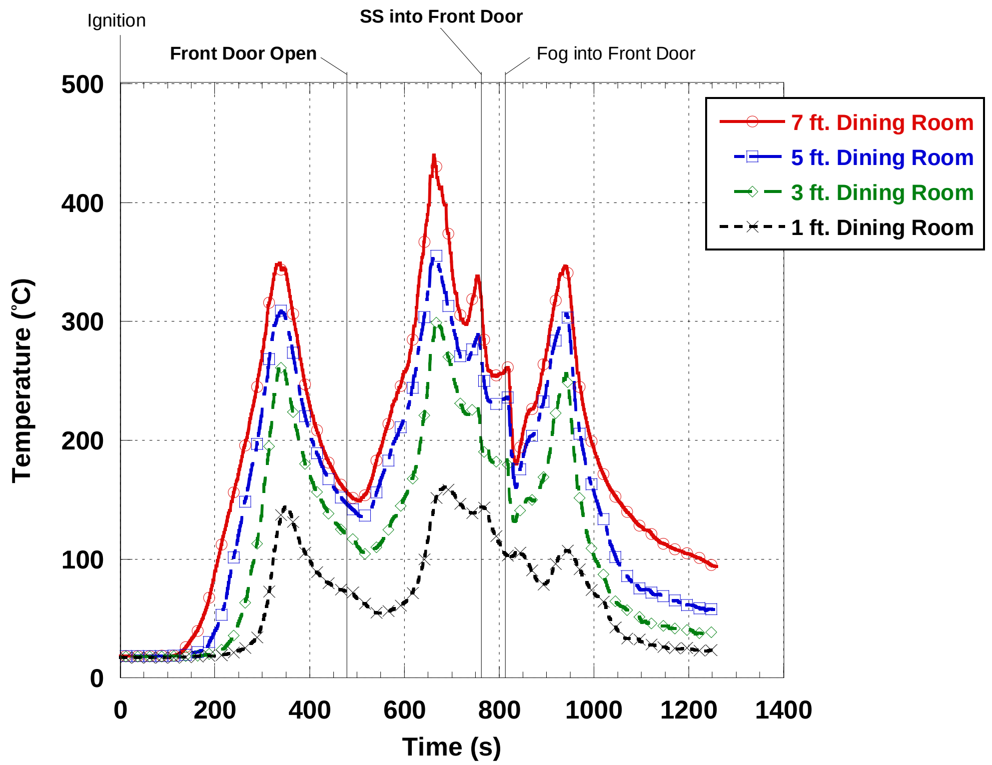


Figure 568. Experiment 1 - Dining Room

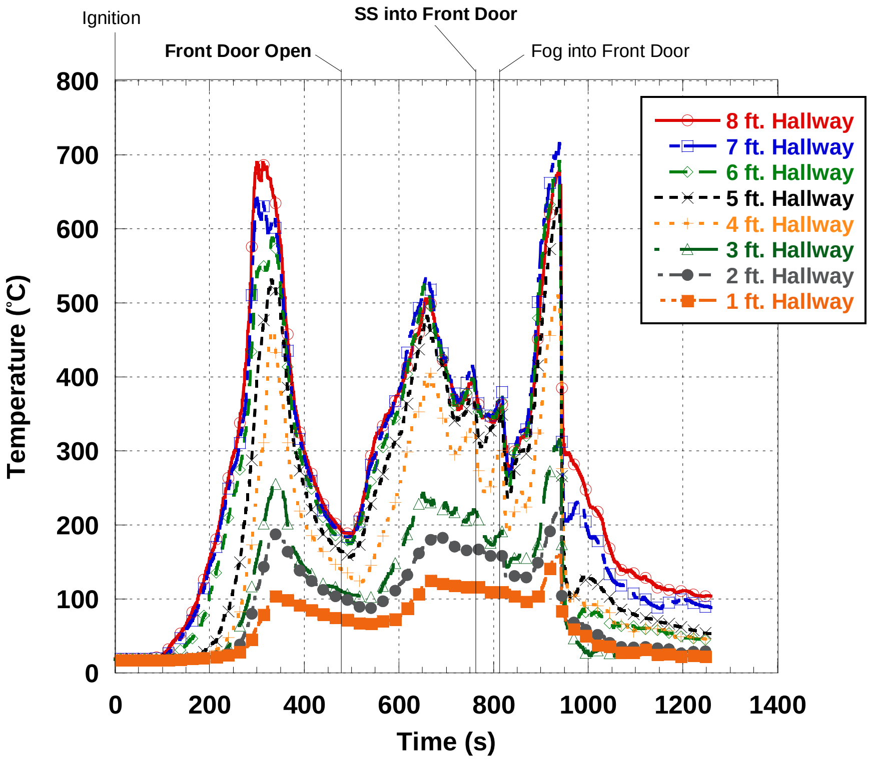


Figure 569. Experiment 1 - Hallway

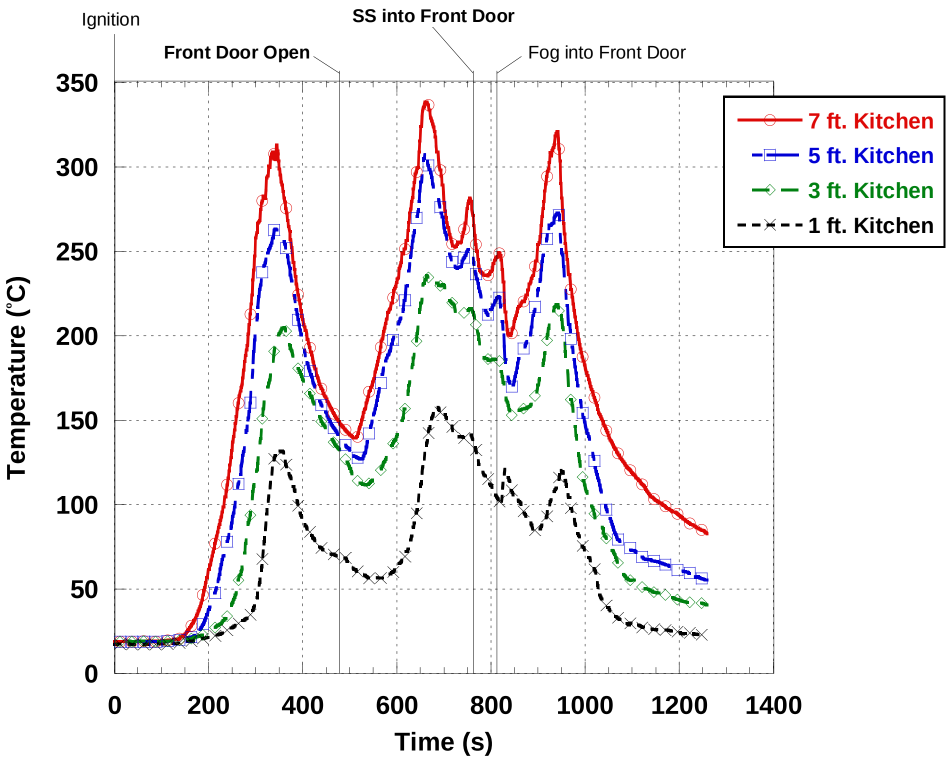


Figure 570. Experiment 1 - Kitchen

Experiment 2

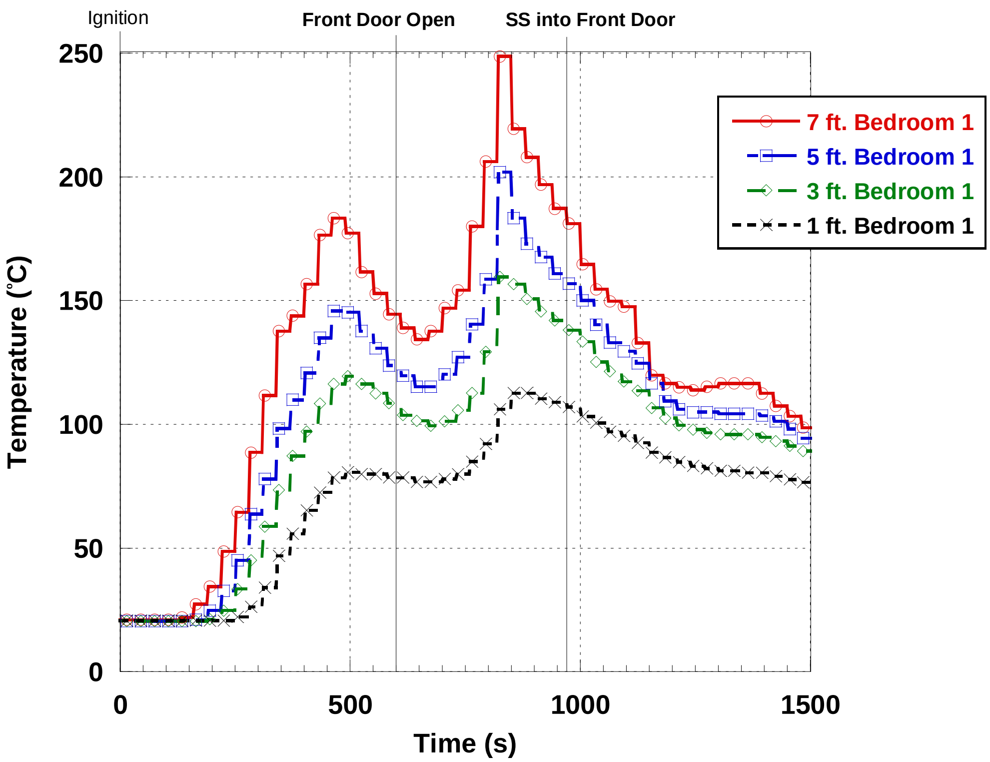


Figure 571. Experiment 2 - Bedroom 1

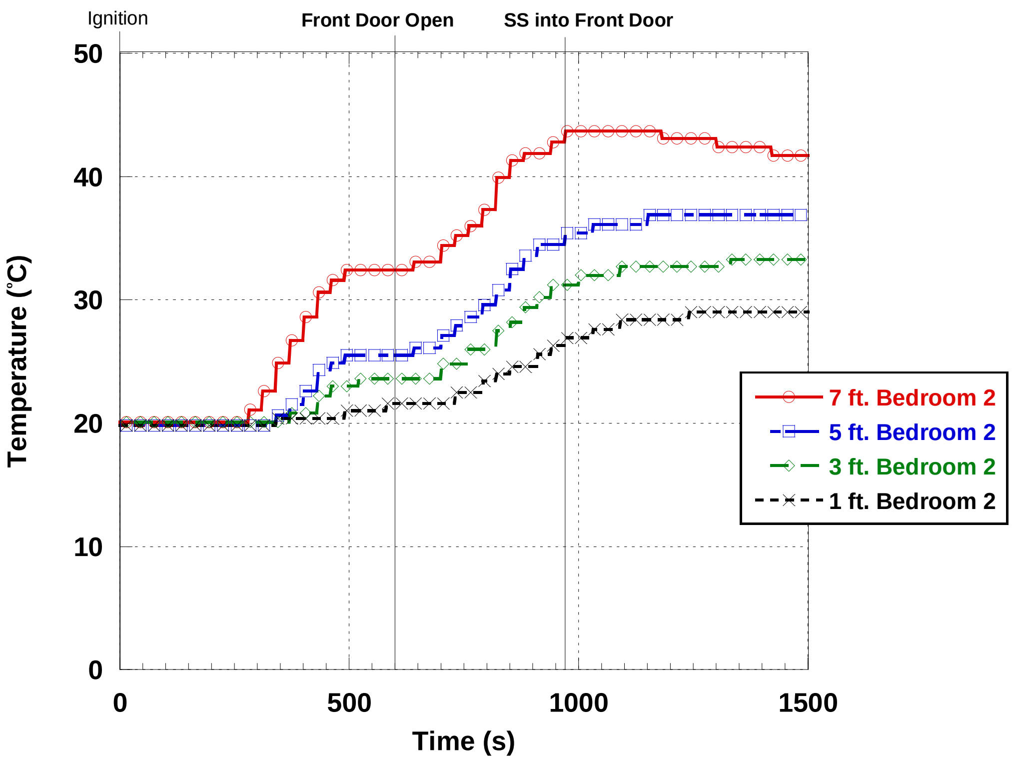


Figure 572. Experiment 2 - Bedroom 2

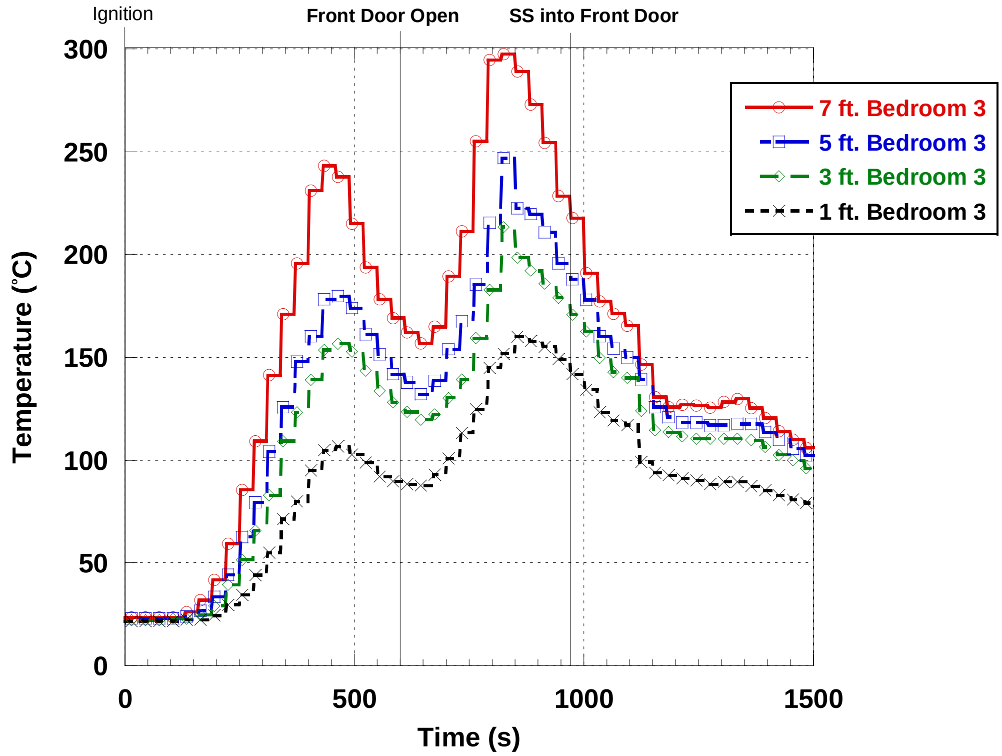


Figure 573. Experiment 2 - Bedroom 3

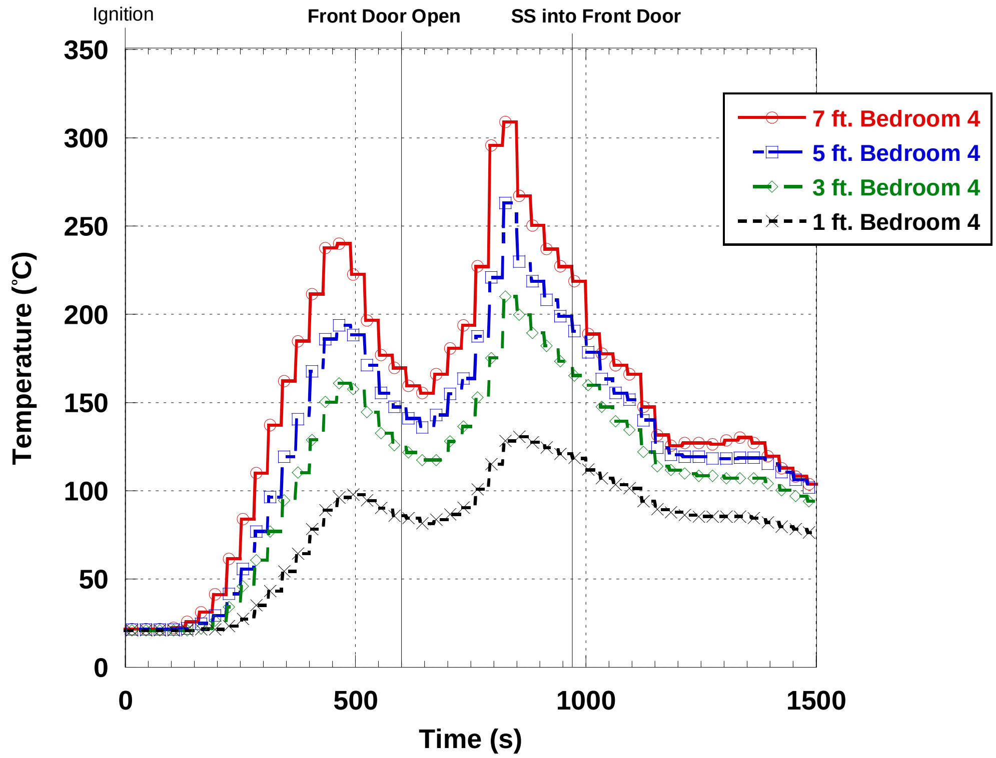


Figure 574. Experiment 2 - Bedroom 4

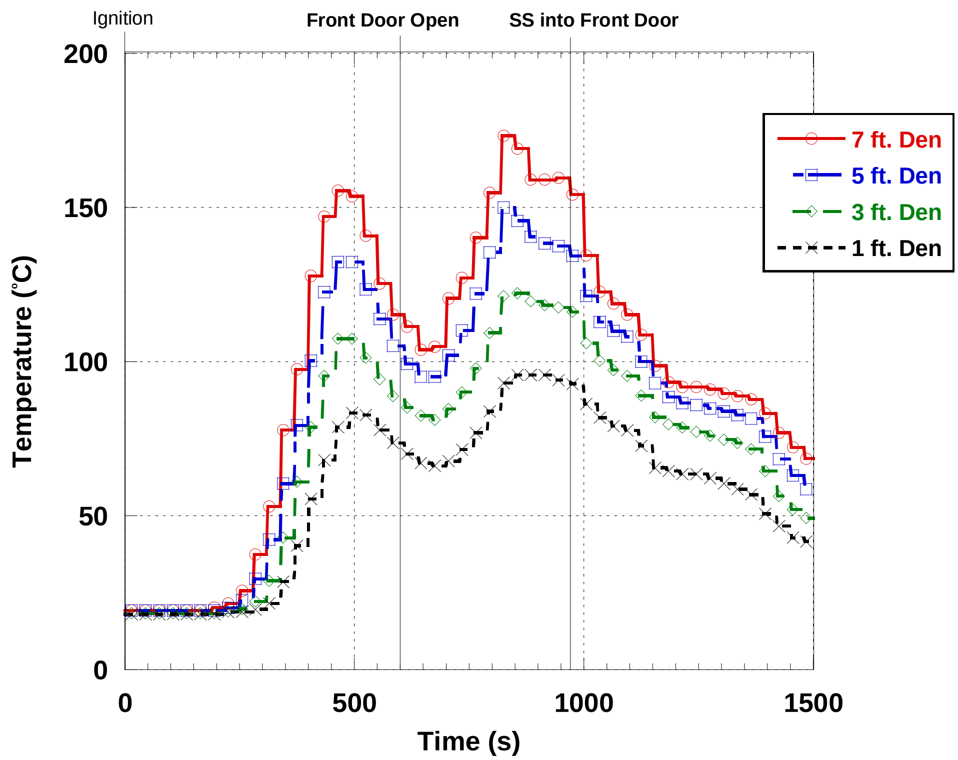


Figure 575. Experiment 2 - Den

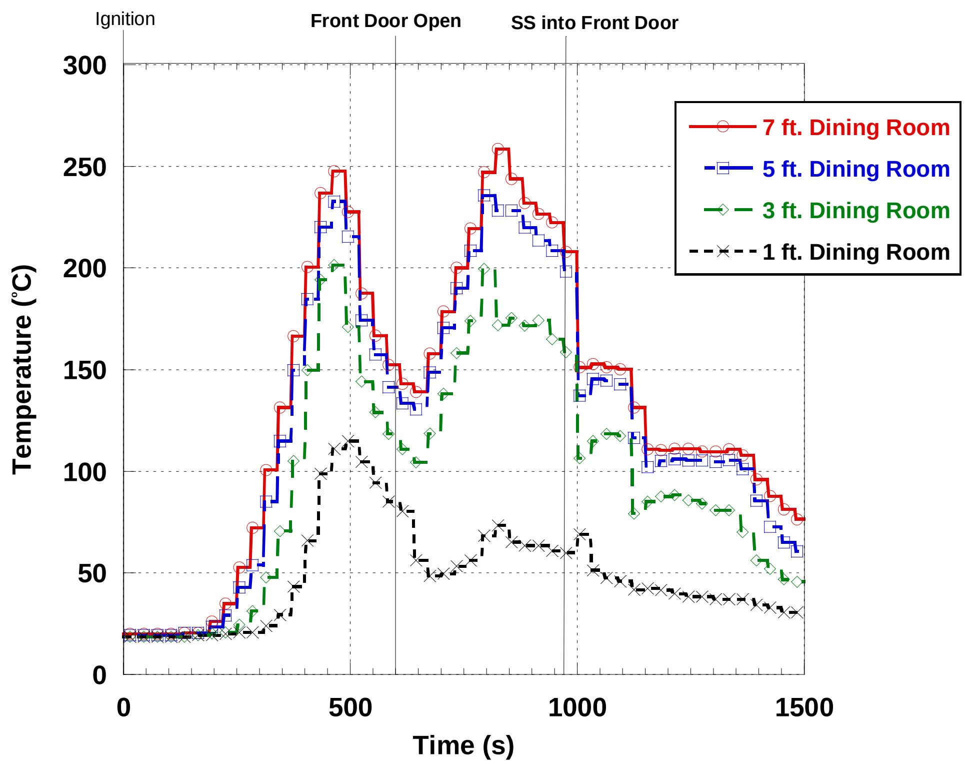


Figure 576. Experiment 2 - Dining Room

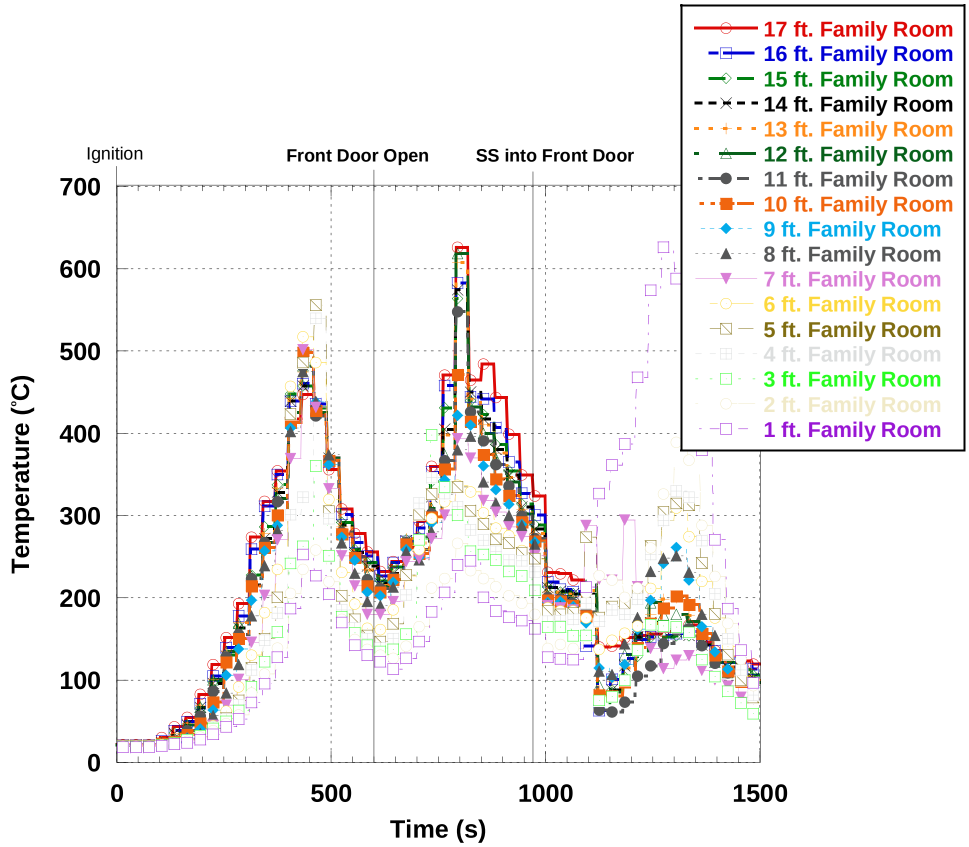


Figure 577. Experiment 2 - Family Room

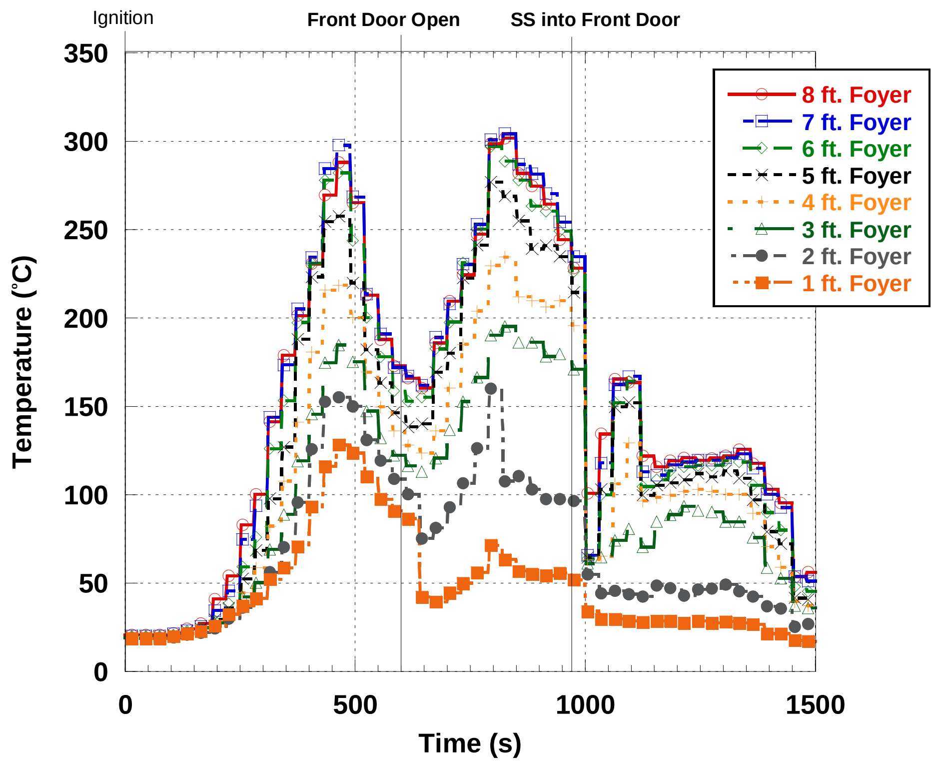


Figure 578. Experiment 2 - Foyer

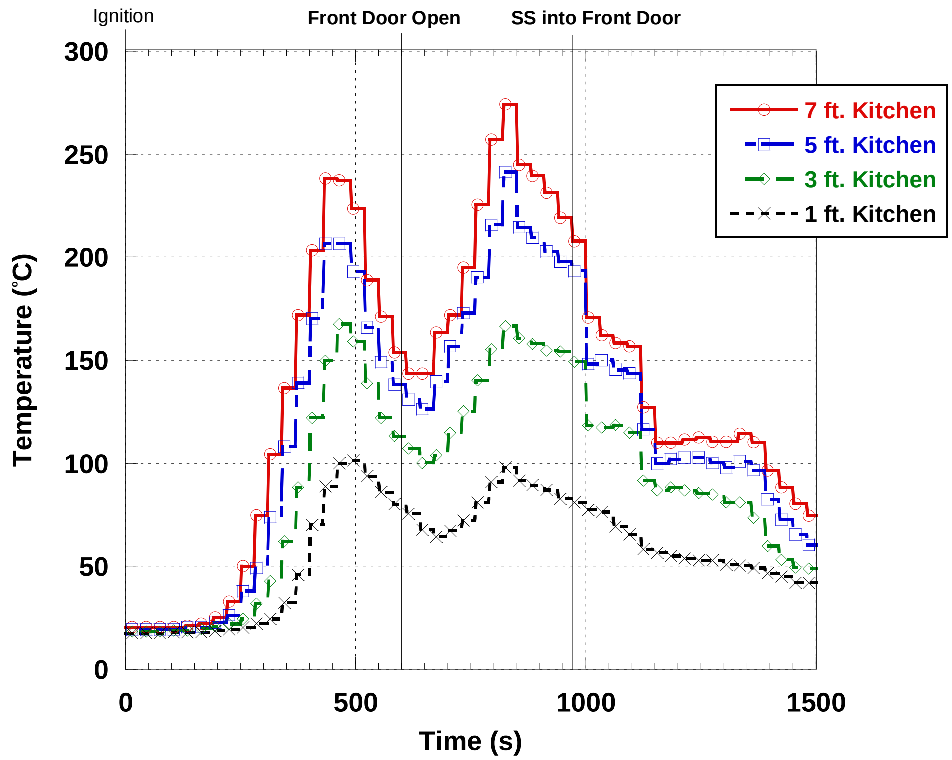


Figure 579. Experiment 2 - Kitchen

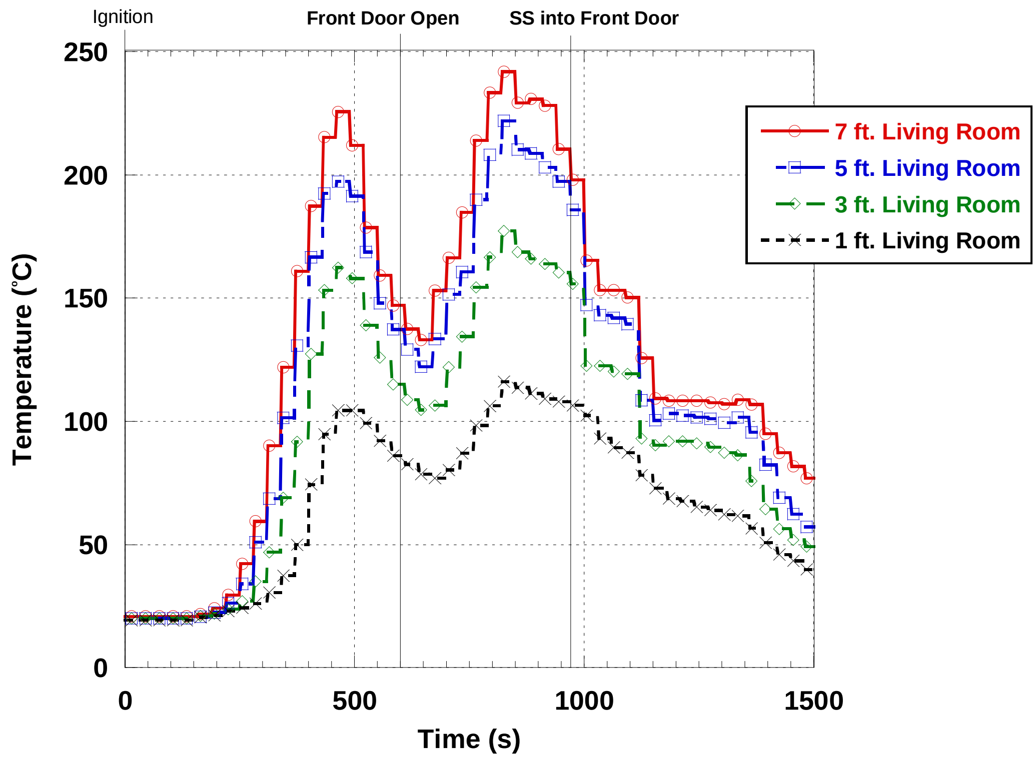


Figure 580. Experiment 2 - Living Room

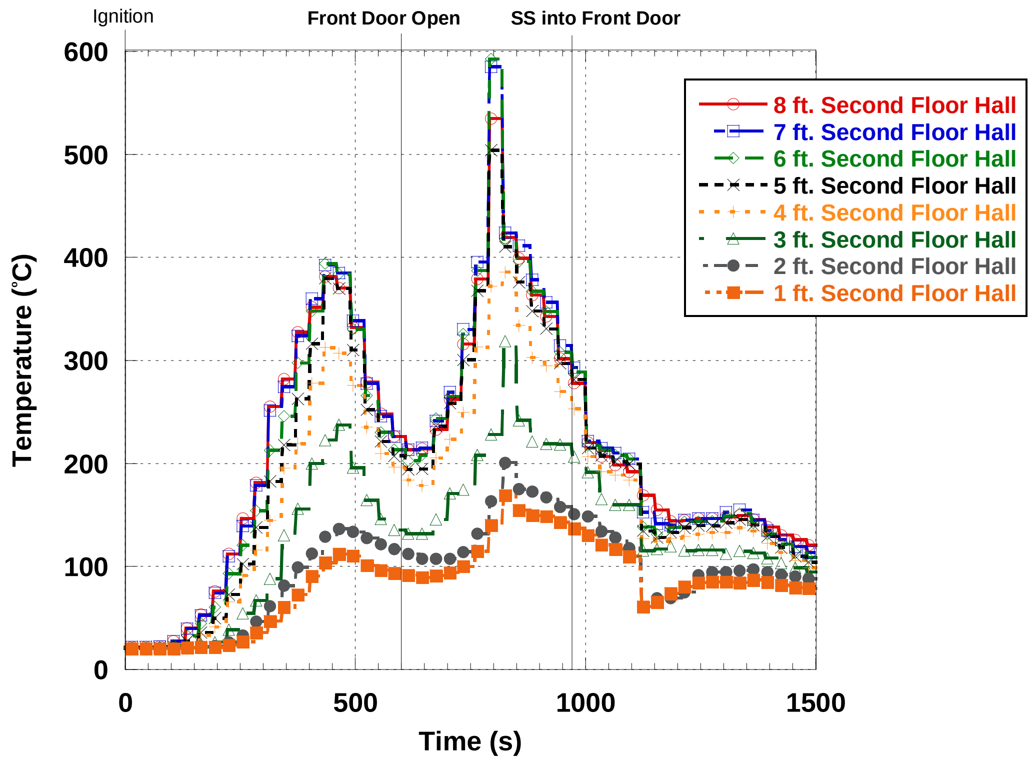


Figure 581. Experiment 2 - Second Floor Hall

Experiment 3

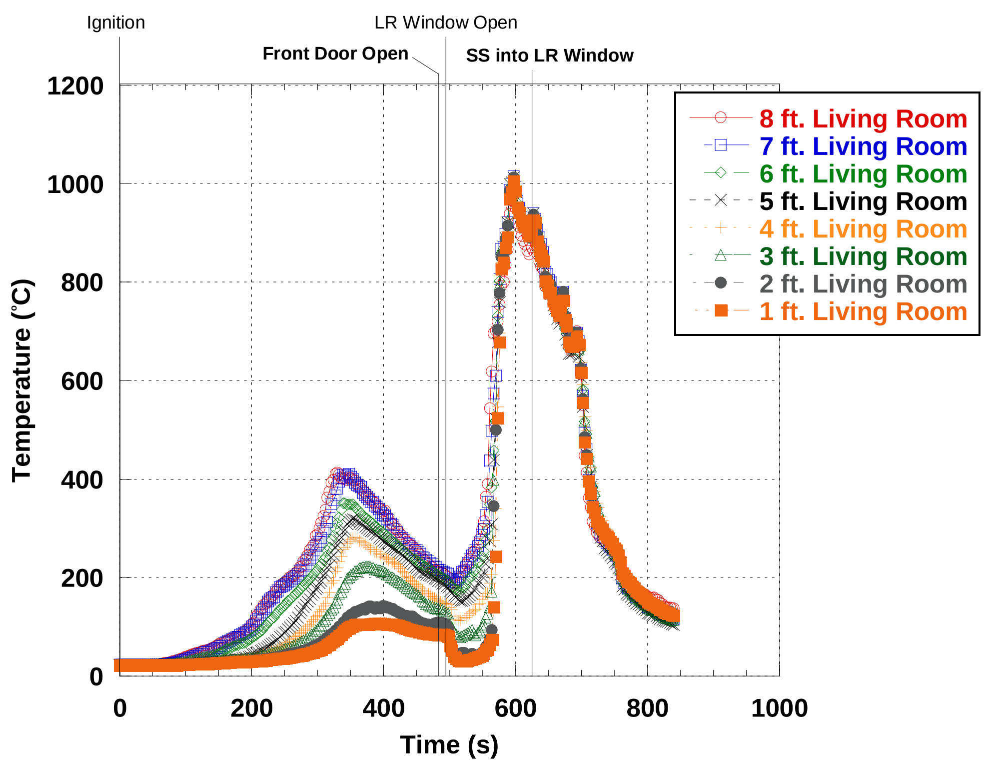


Figure 582. Experiment 3 - Living Room

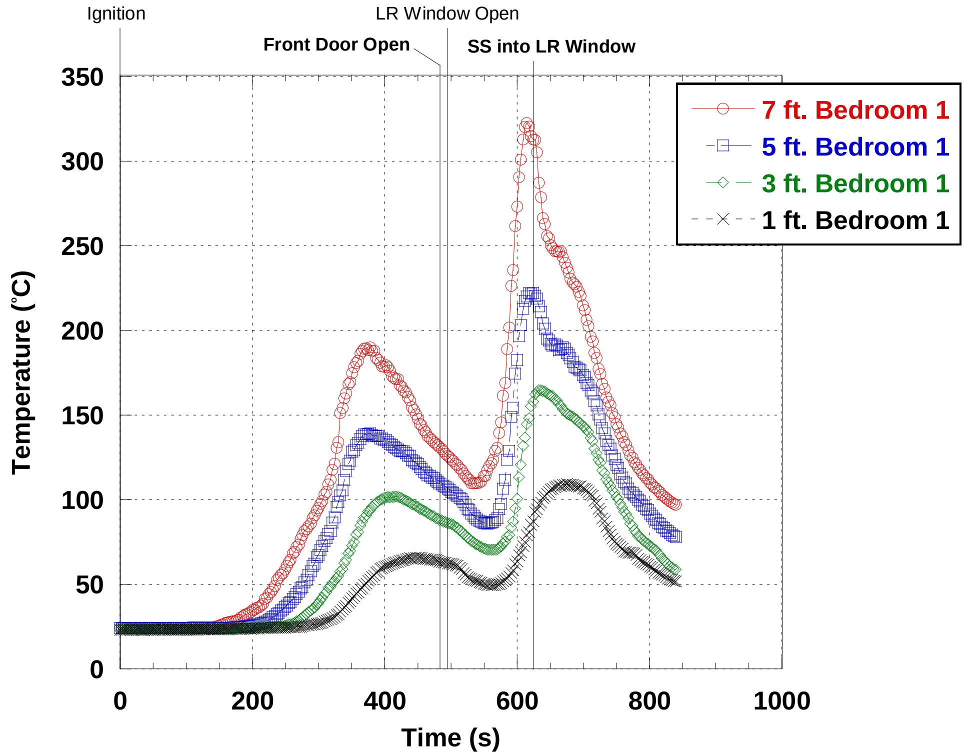


Figure 583. Experiment 3 - Bedroom 1

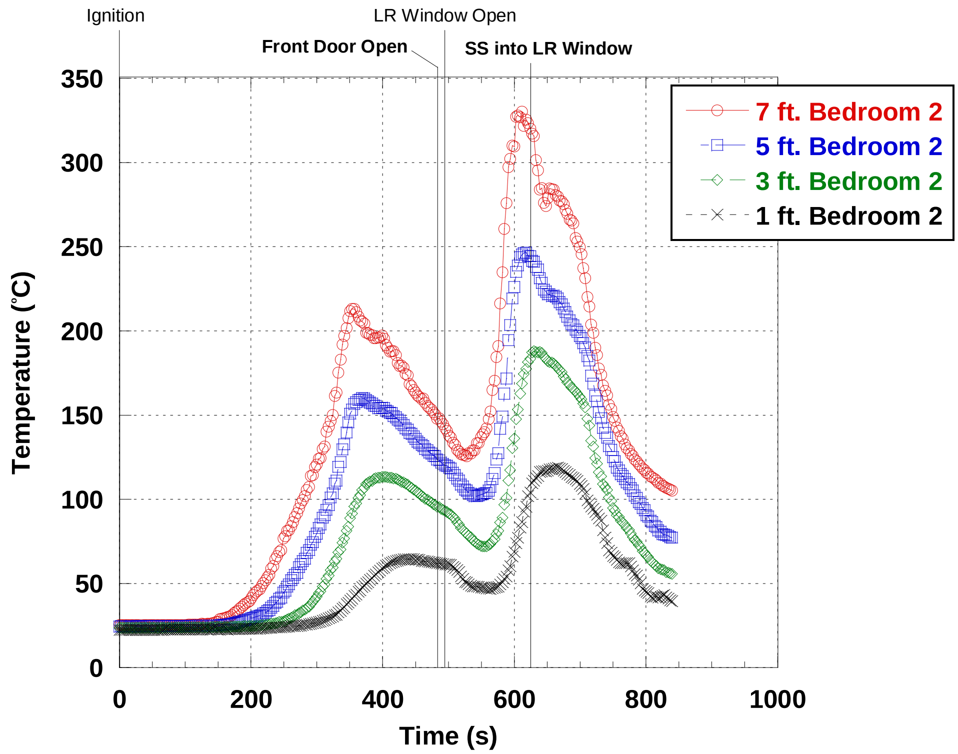


Figure 584. Experiment 3 - Bedoom 2

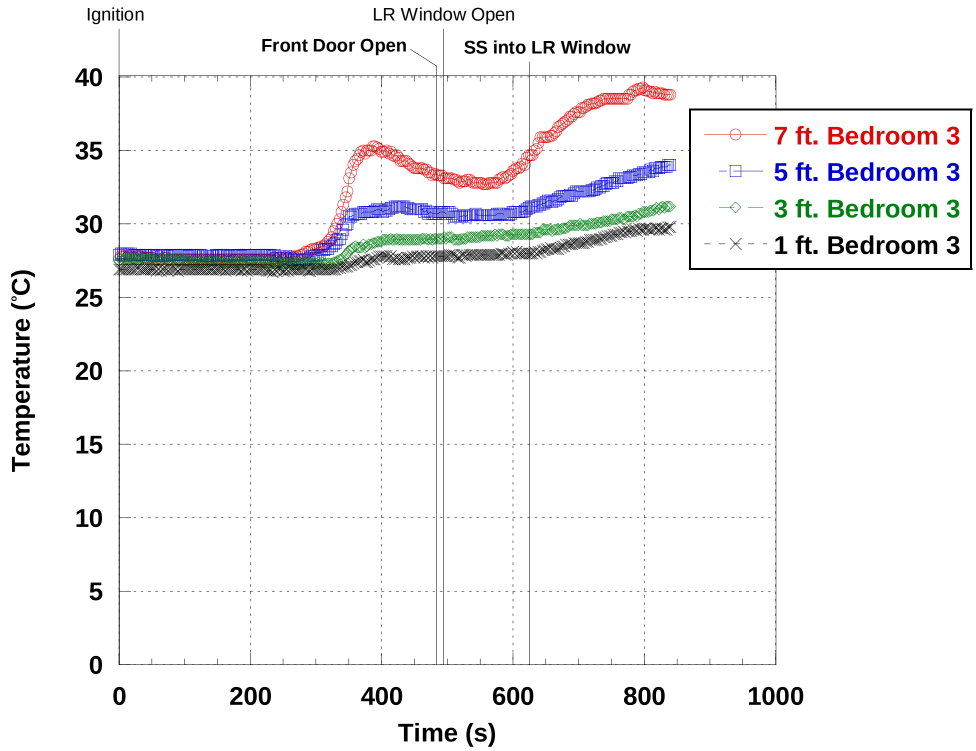


Figure 585. Experiment 3 - Bedroom 3

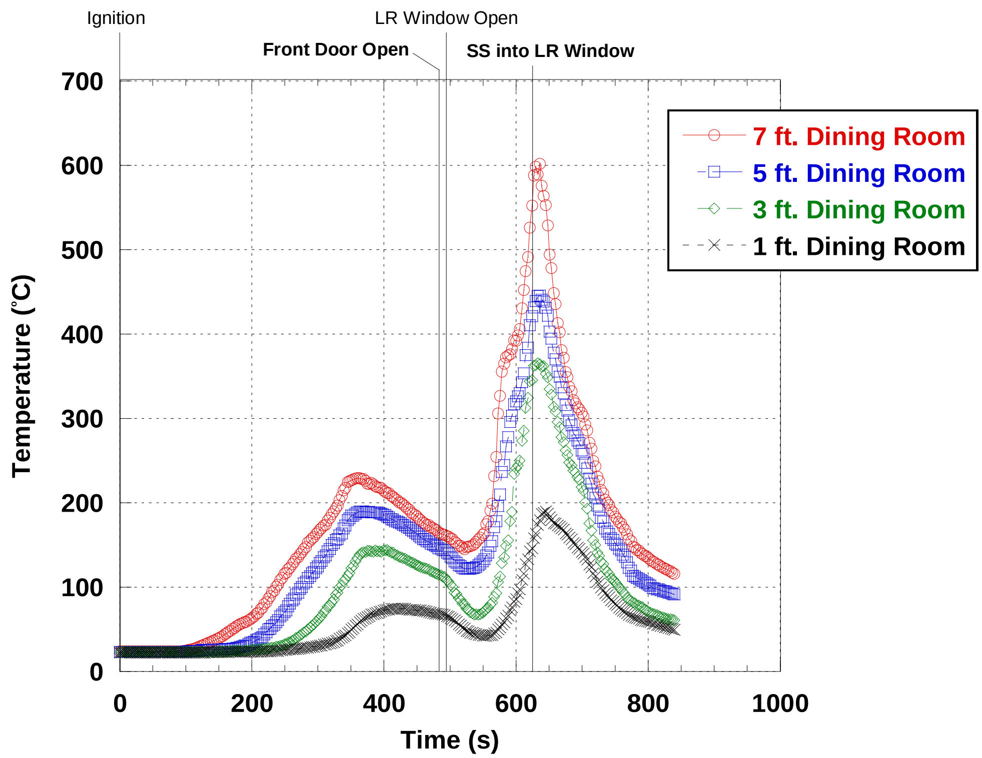


Figure 586. Experiment 3 - Dining Room

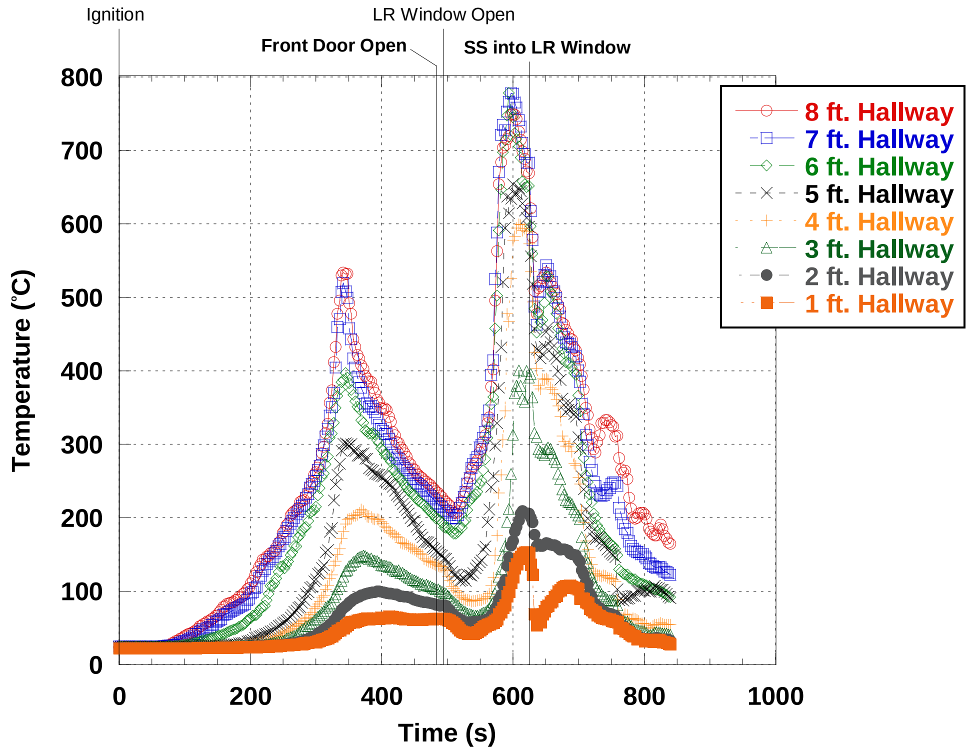


Figure 587. Experiment 3 – Hallway

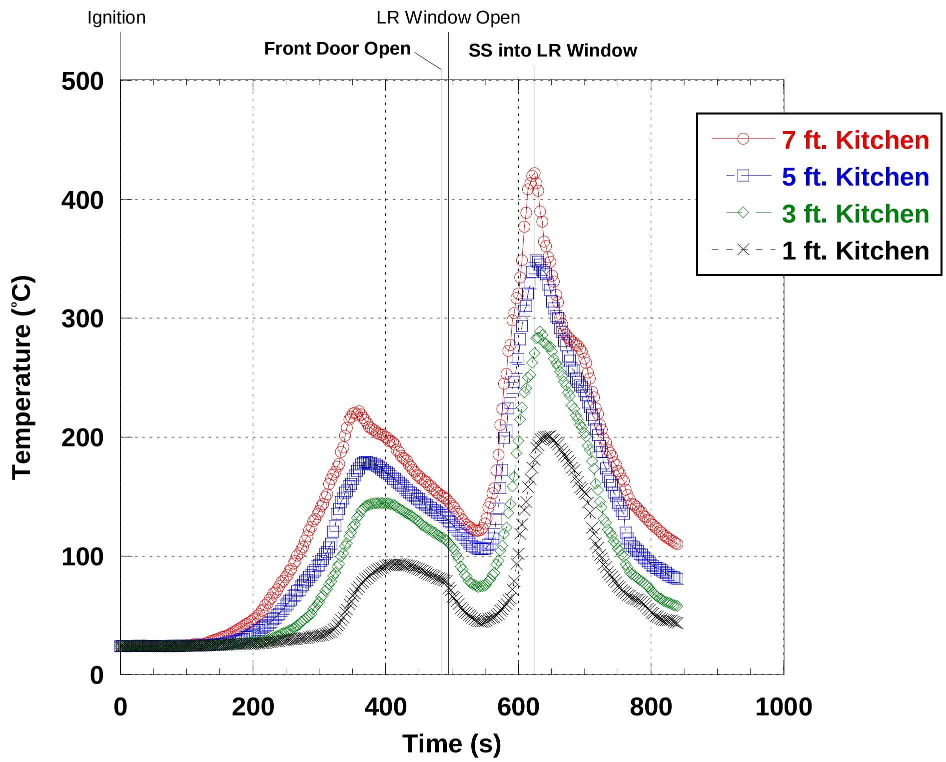


Figure 588. Experiment 3 - Kitchen

Experiment 4

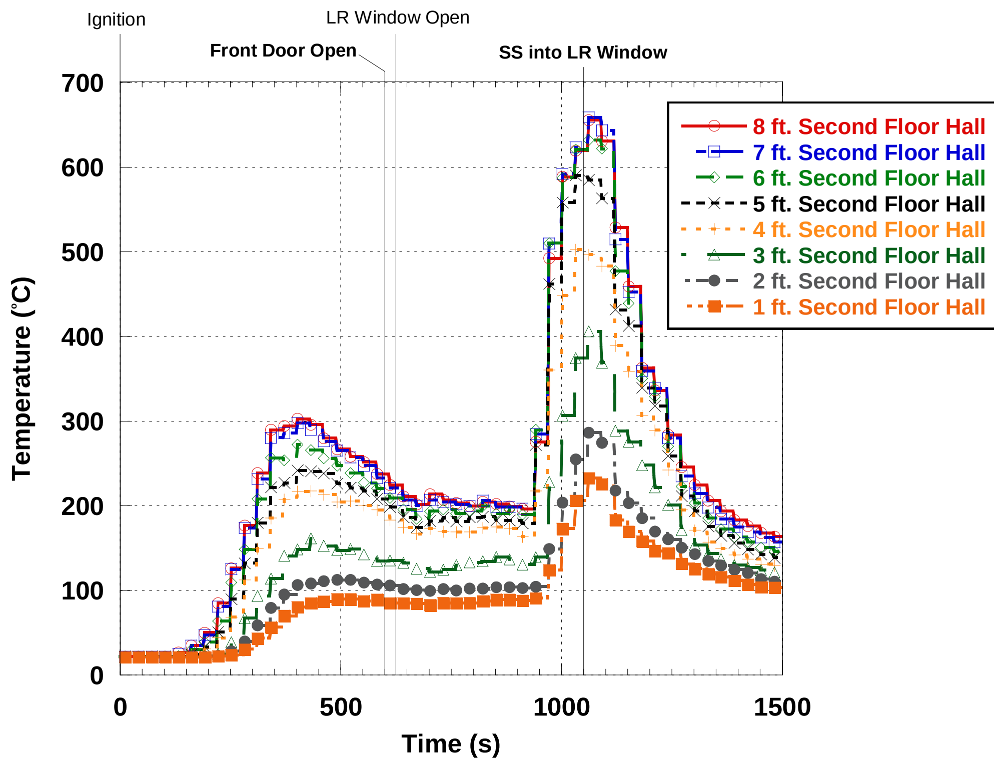


Figure 589. Experiment 4 - Second Floor Hall

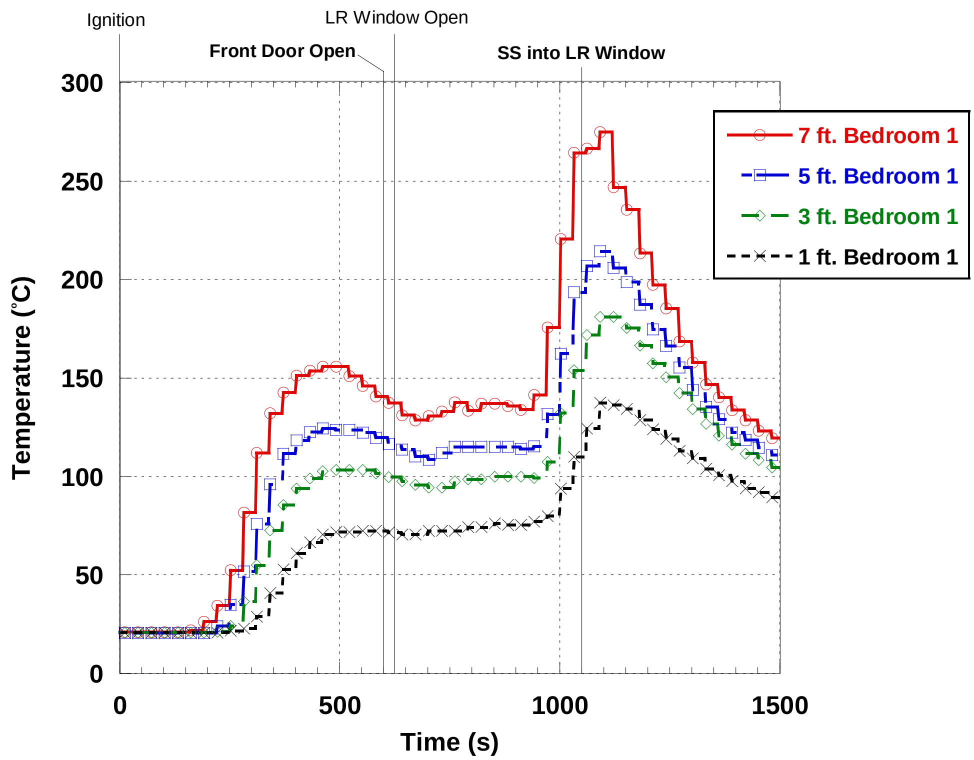


Figure 590. Experiment 4 - Bedroom 1

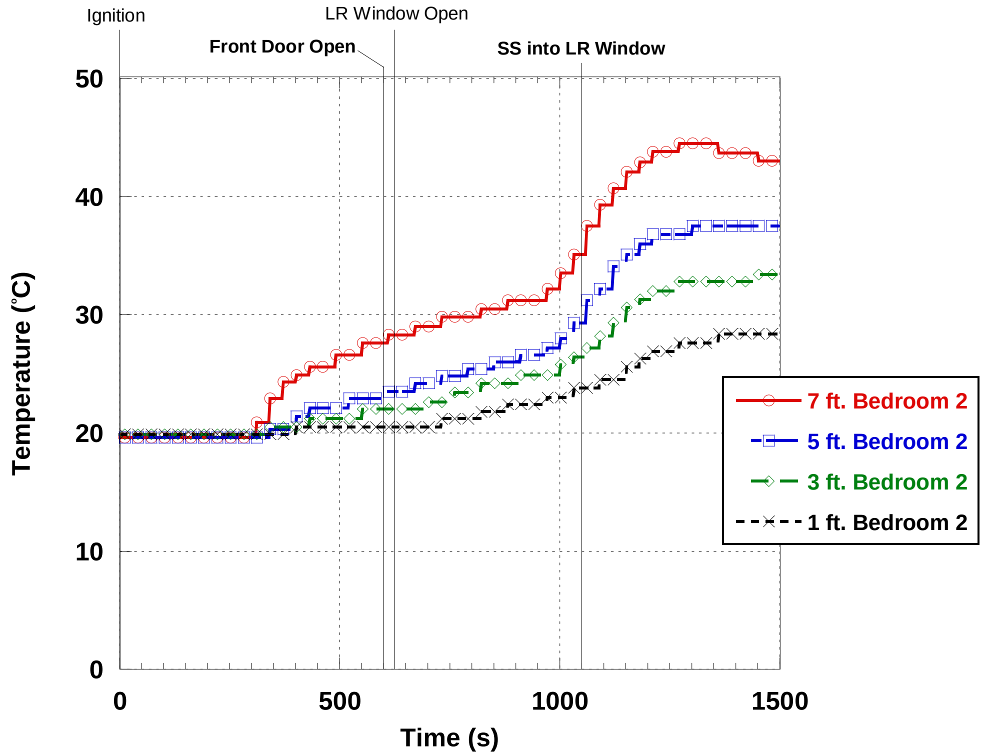


Figure 591. Experiment 4 - Bedroom 2

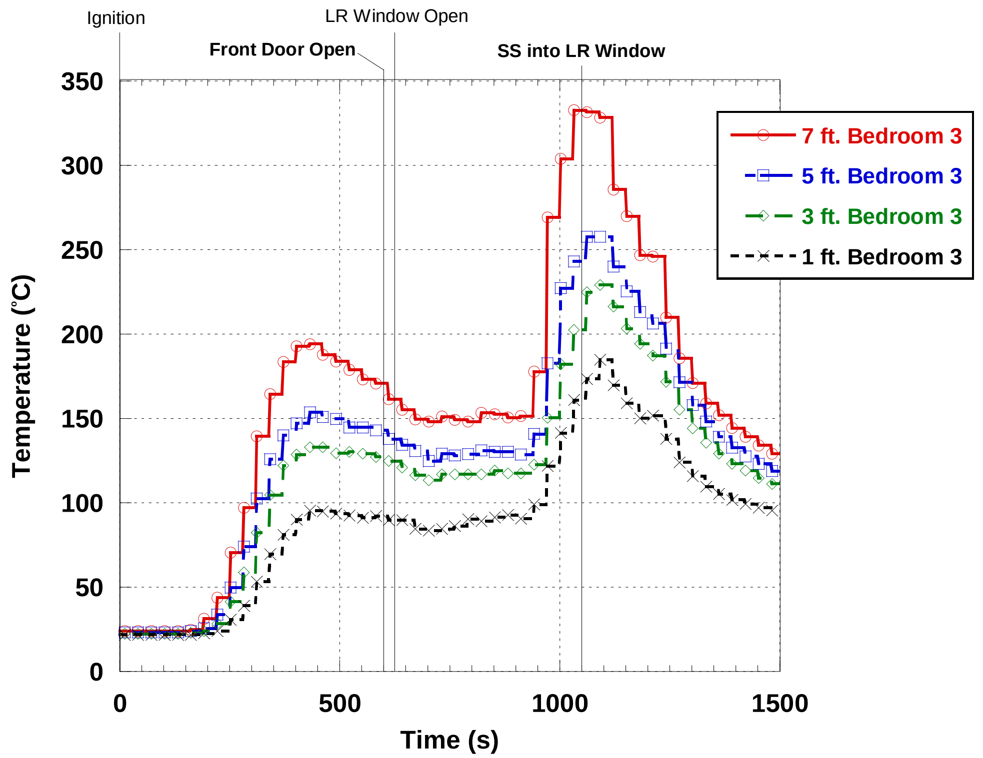


Figure 592. Experiment 4 - Bedroom 3

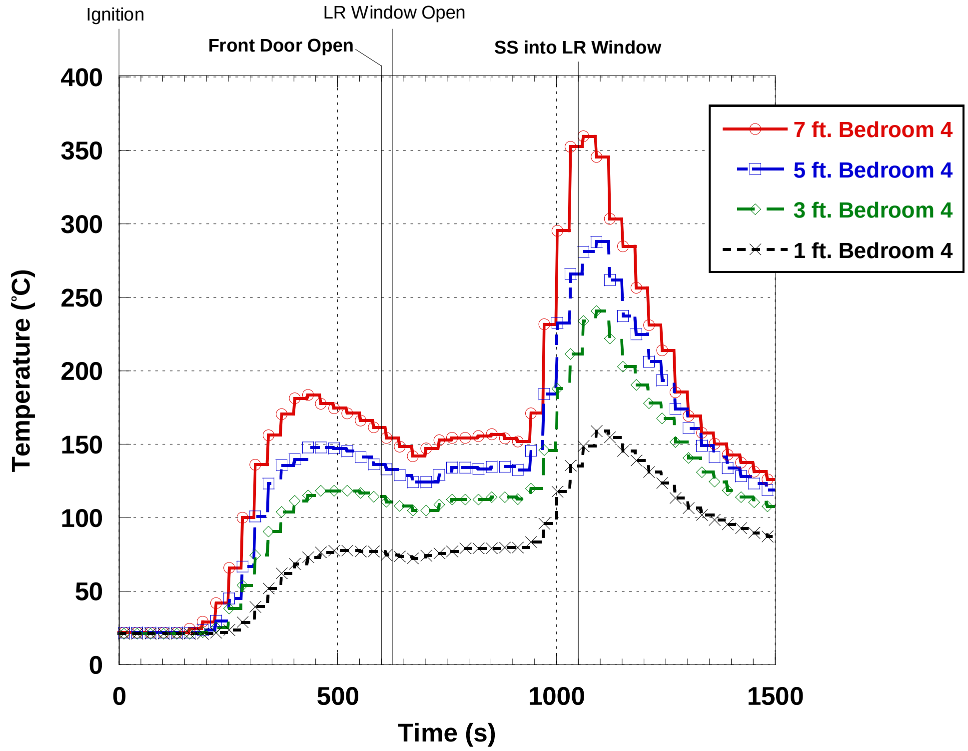


Figure 593. Experiment 4 - Bedroom 4

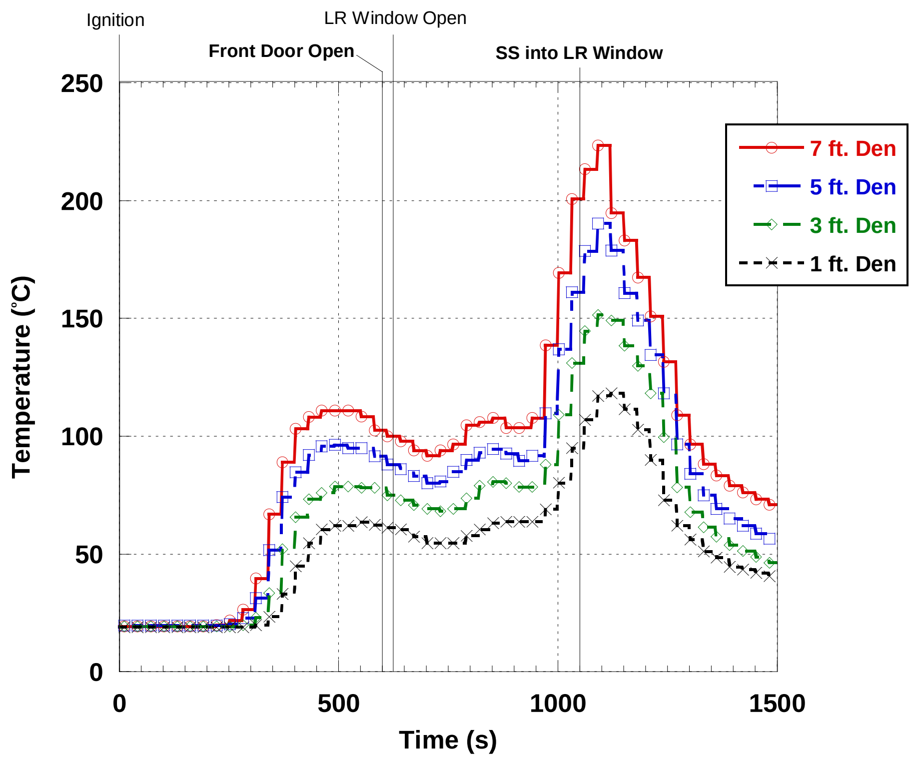


Figure 594. Experiment 4 - Den

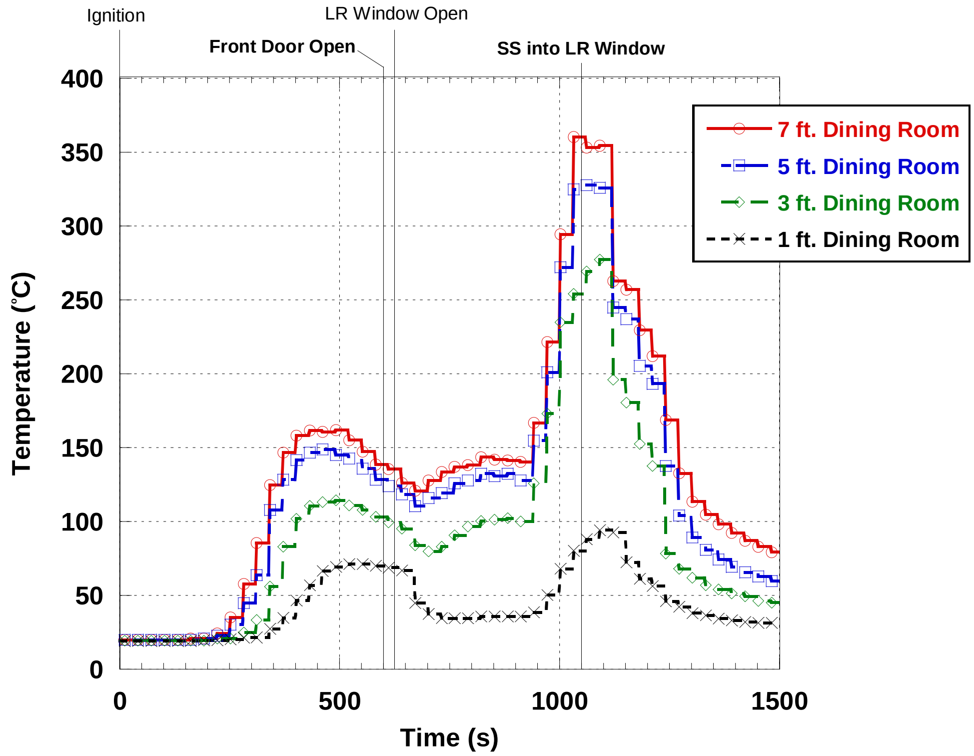


Figure 595. Experiment 4 - Dining Room

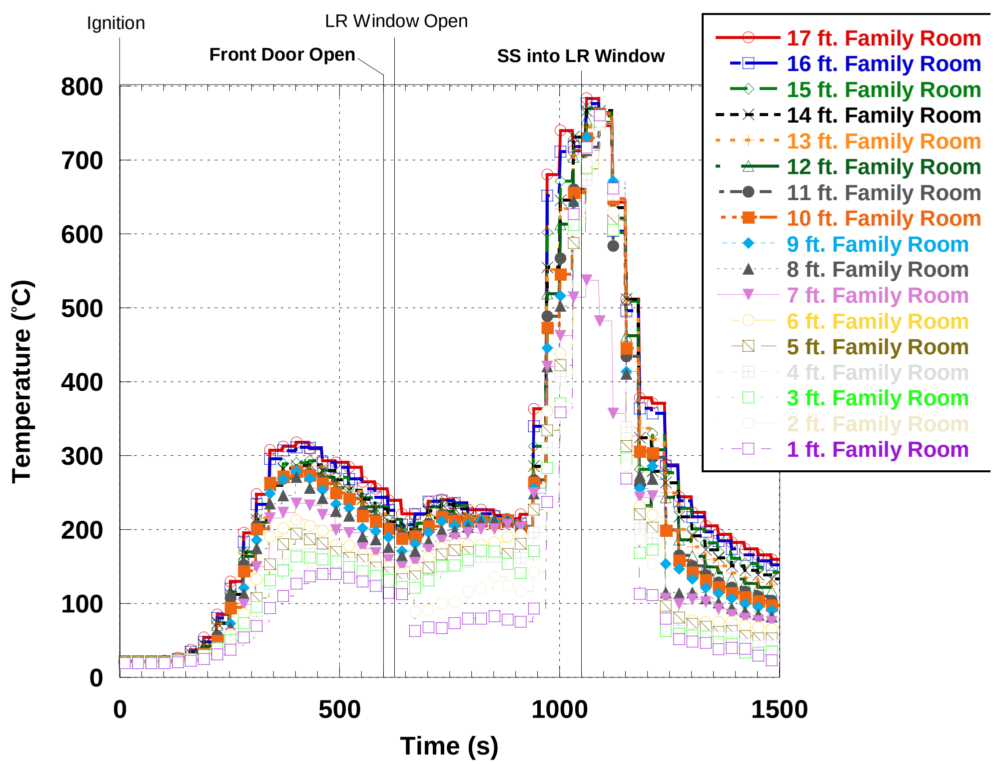


Figure 596. Experiment 4 - Family Room

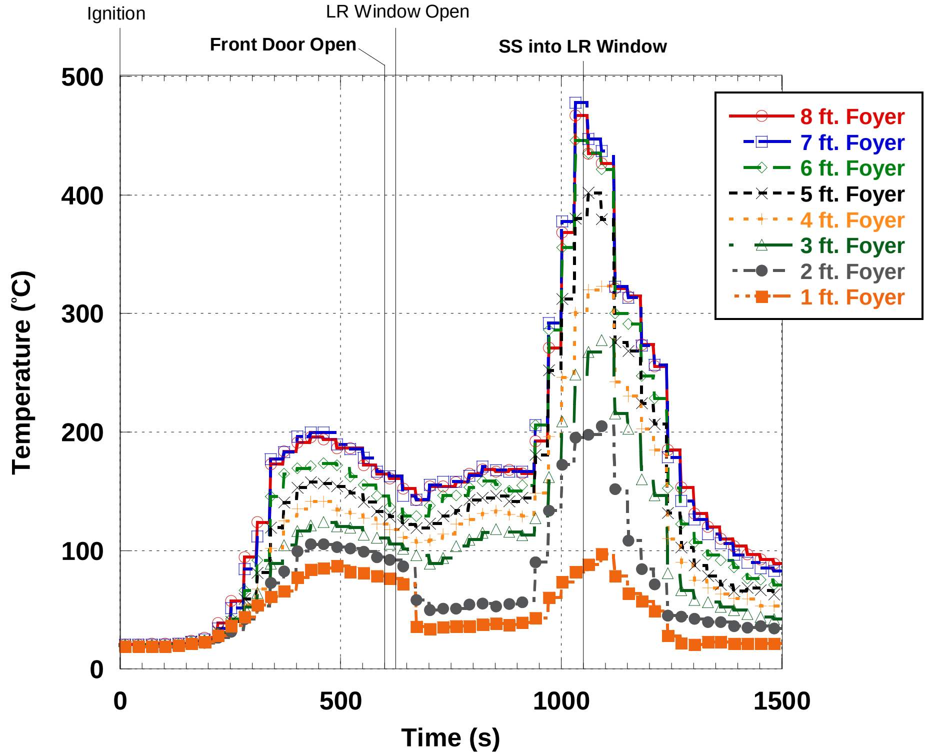


Figure 597. Experiment 4 - Foyer

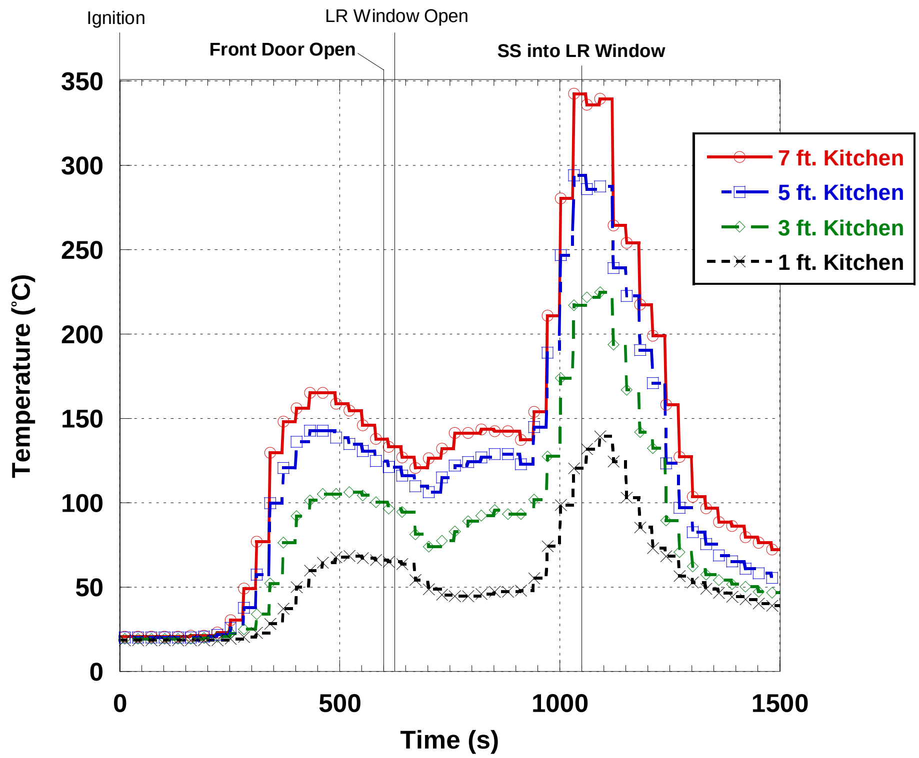


Figure 598. Experiment 4 - Kitchen

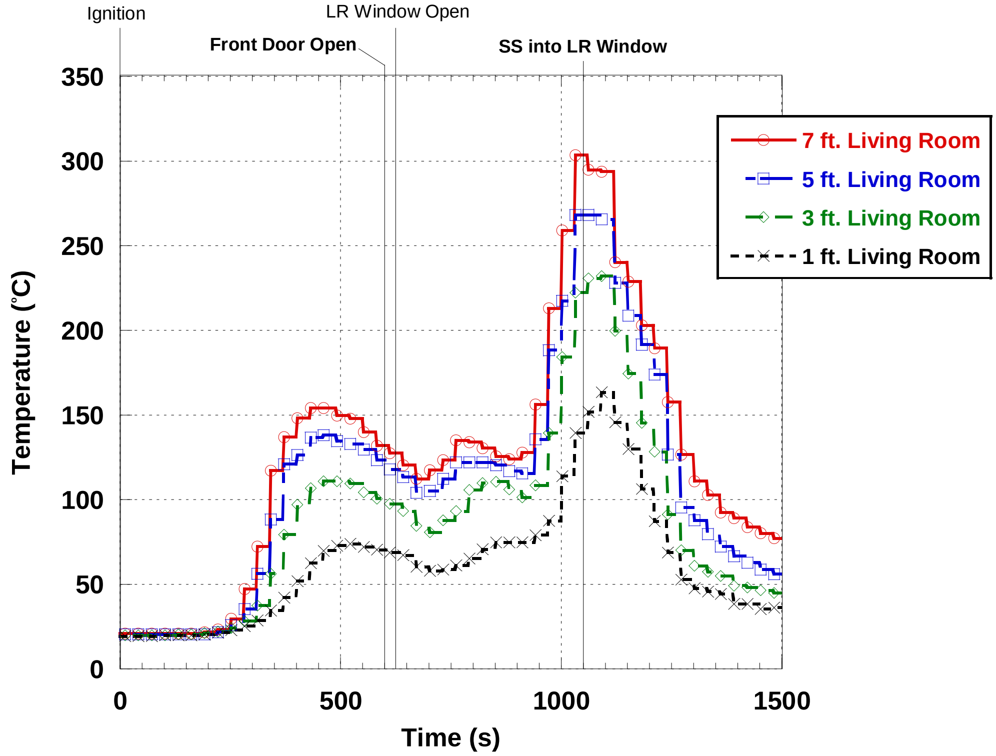


Figure 599. Experiment 4 - Living Room

Experiment 5

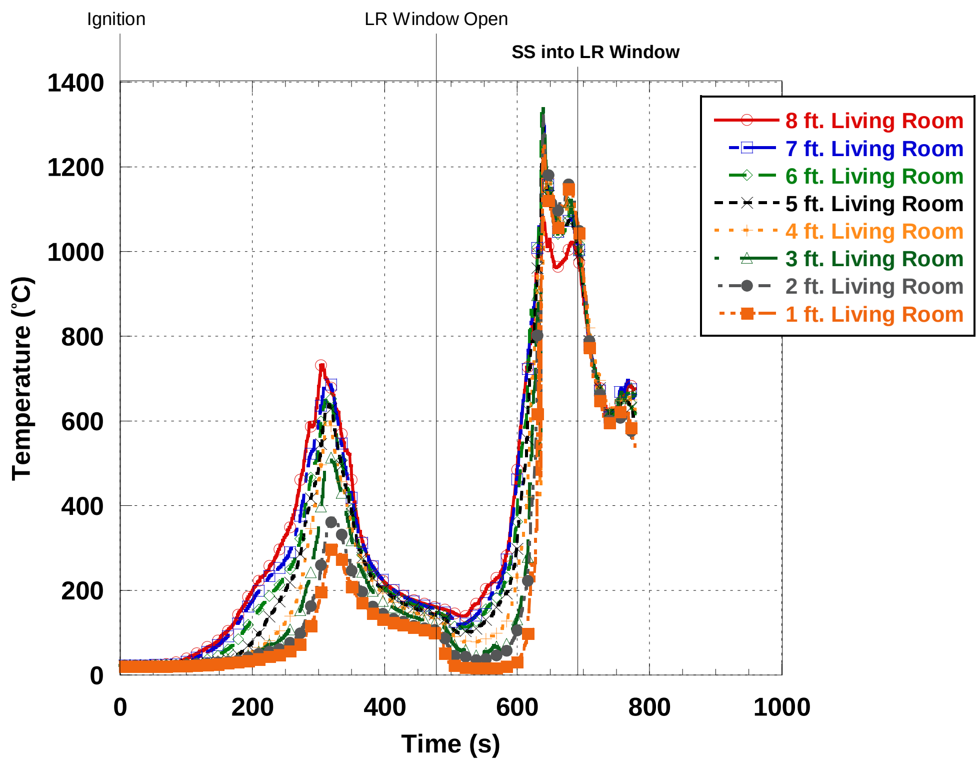


Figure 600. Experiment 5 - Living Room

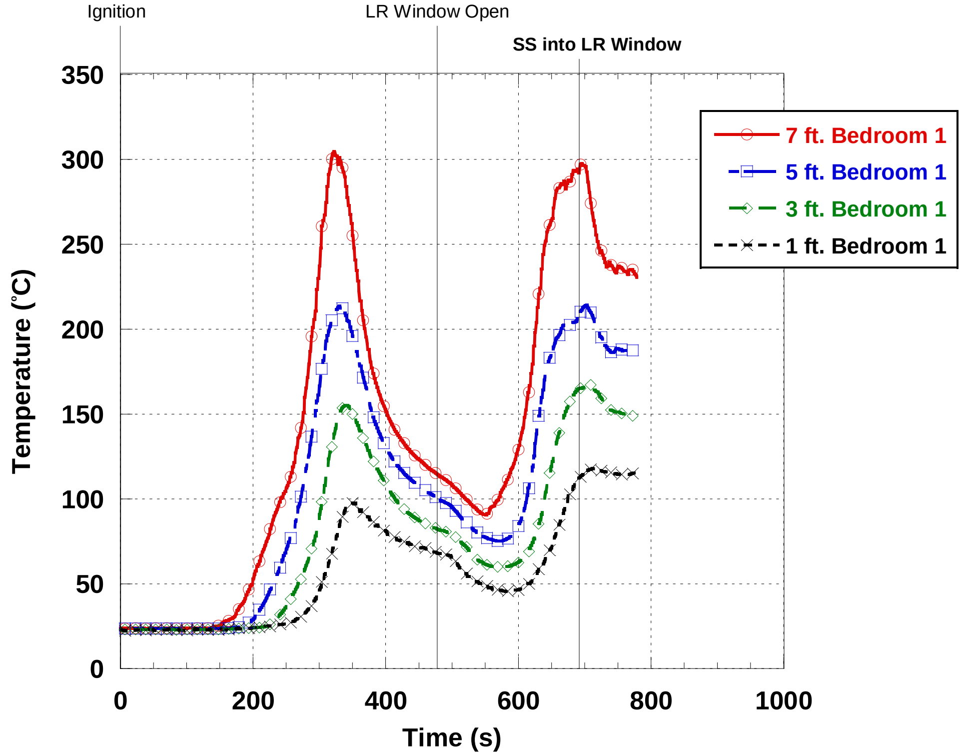


Figure 601. Experiment 5 - Bedroom 1

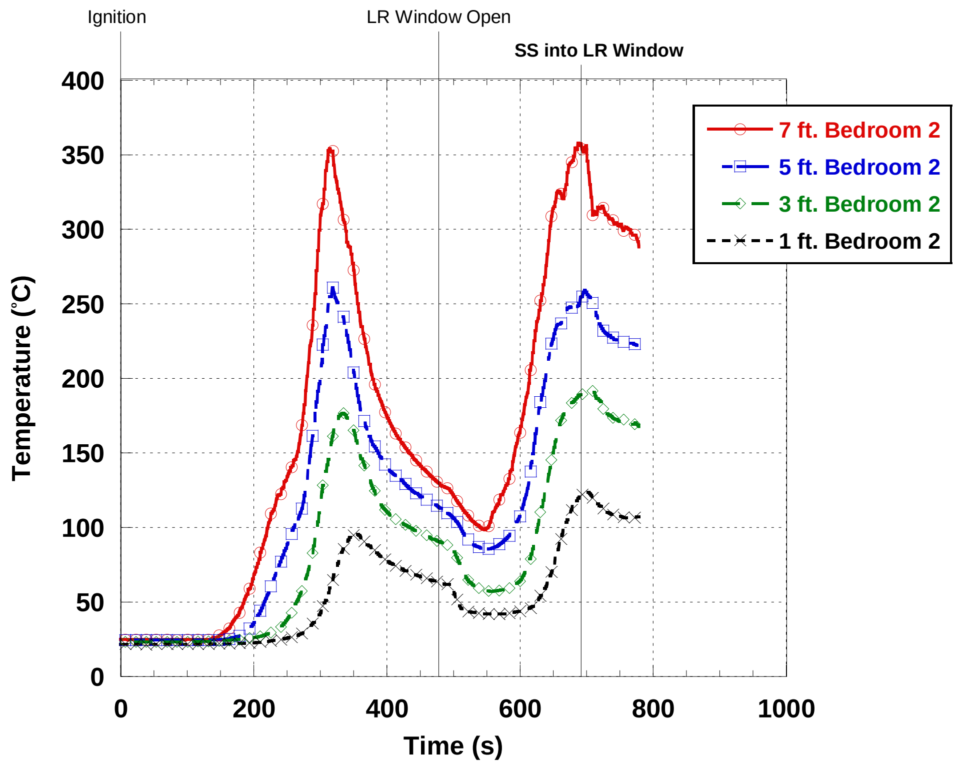


Figure 602. Experiment 5 - Bedroom 2

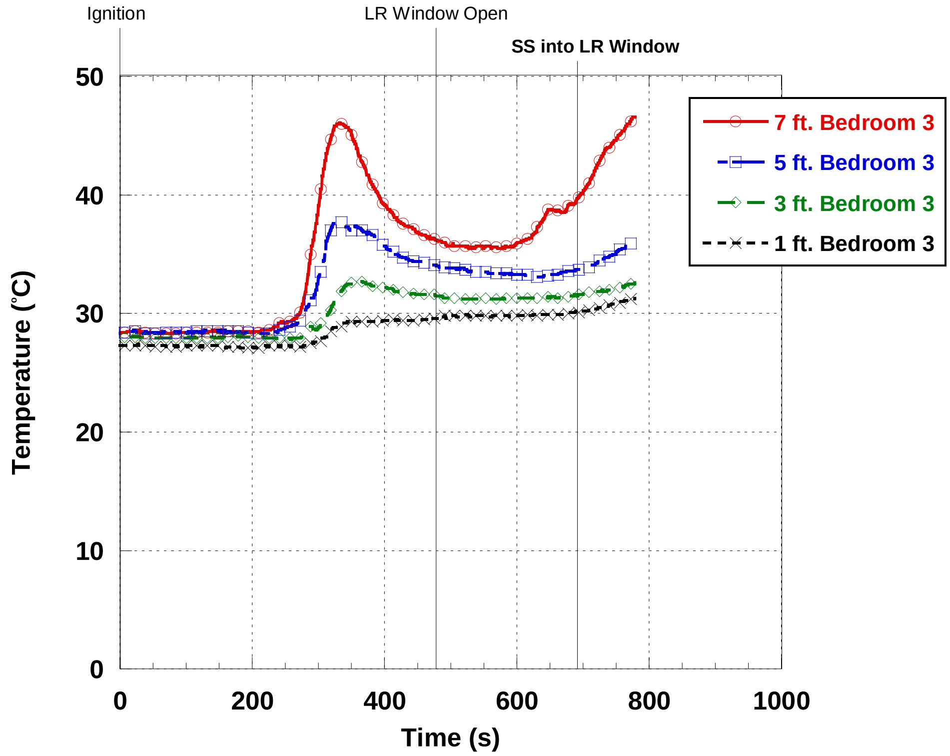


Figure 603. Experiment 5 - Bedroom 3

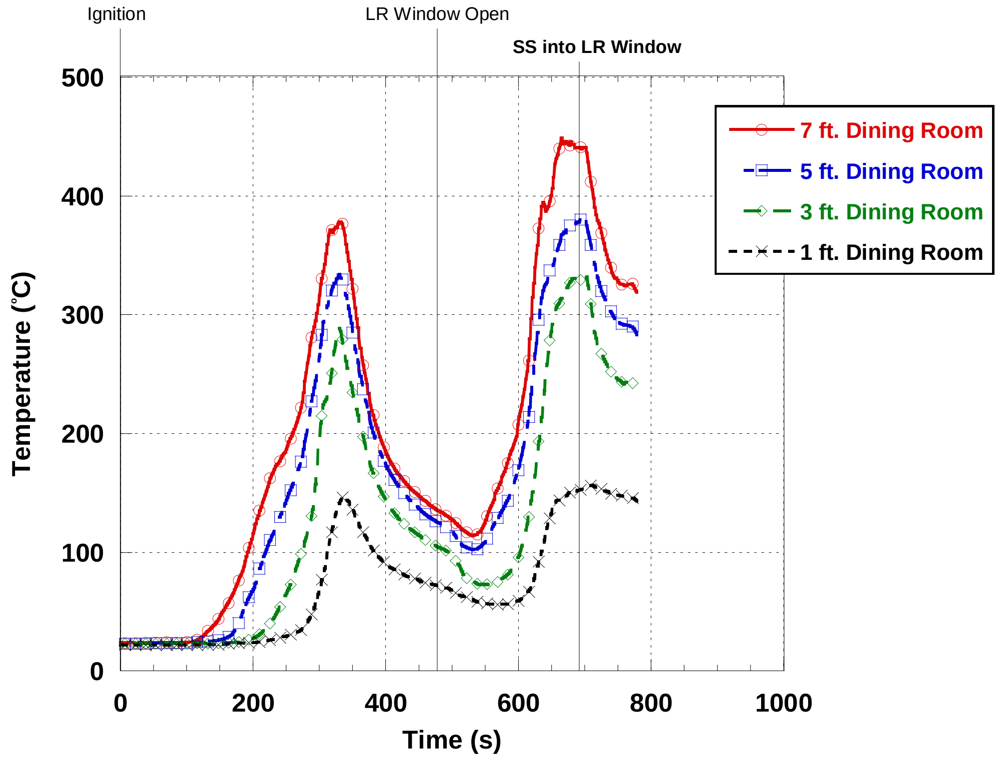


Figure 604. Experiment 5 - Dining Room

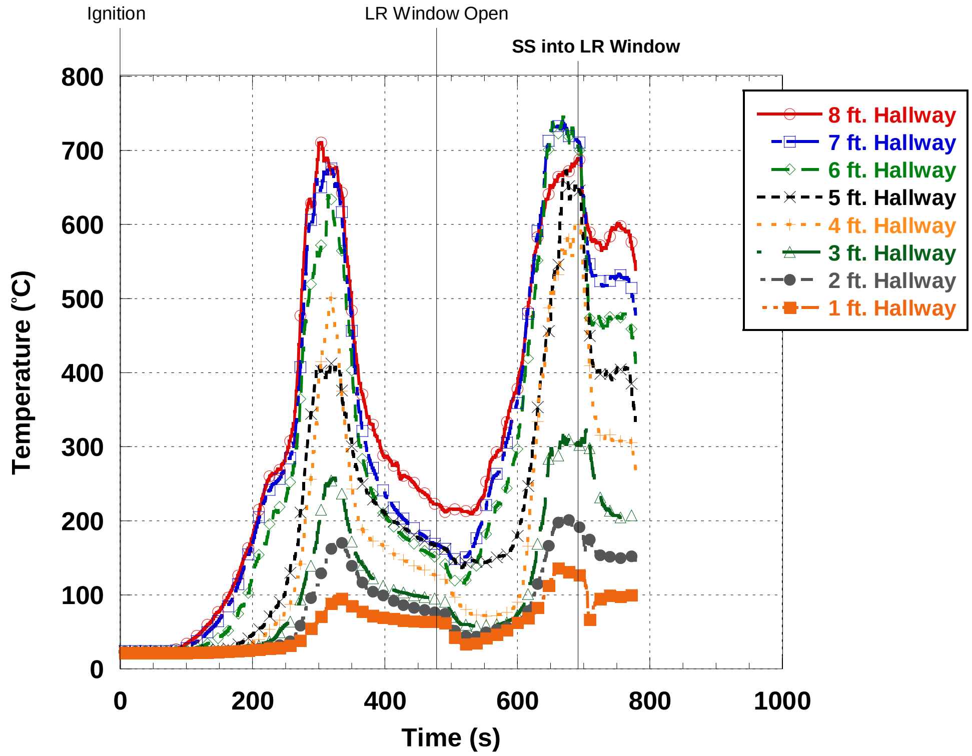


Figure 605. Experiment 5 - Hallway

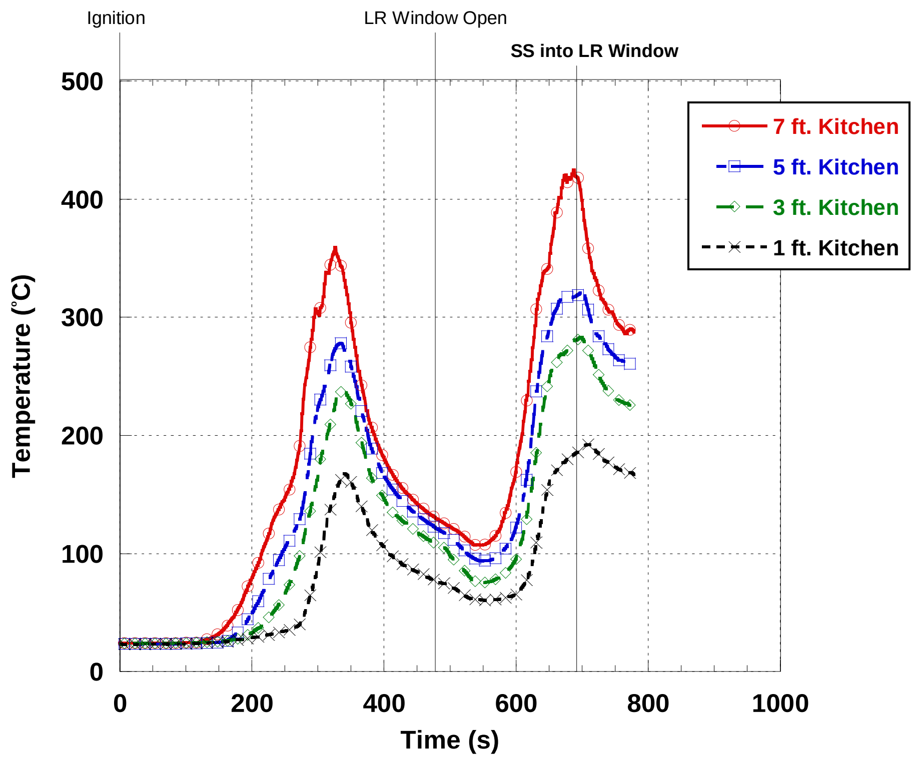


Figure 606. Experiment 5 - Kitchen

Experiment 6

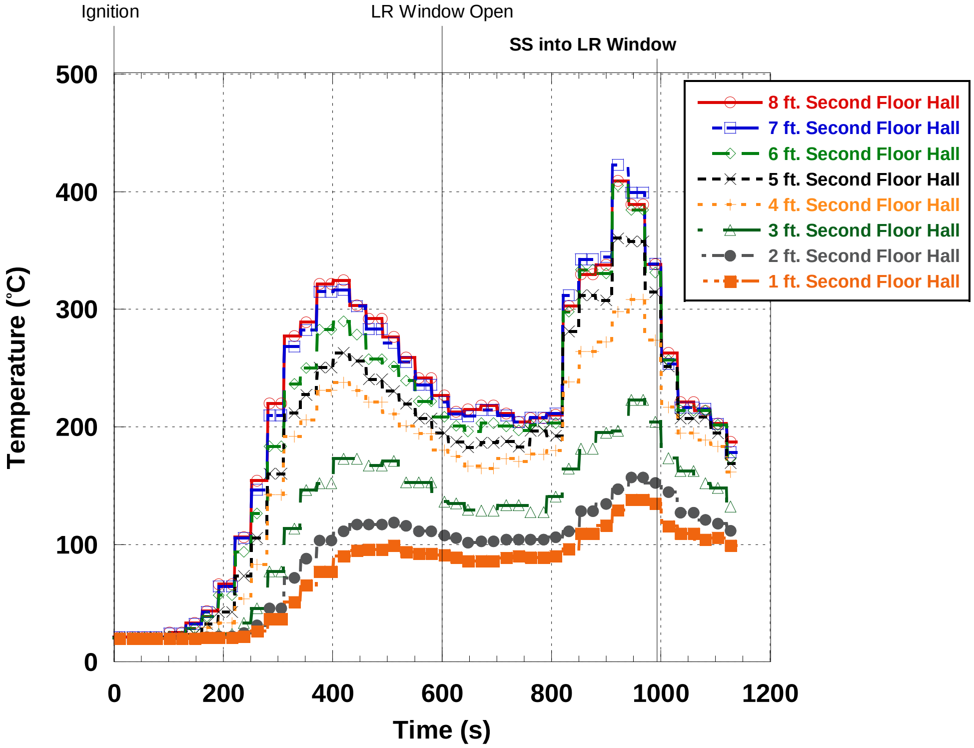


Figure 607. Experiment 6 - Second Floor Hall

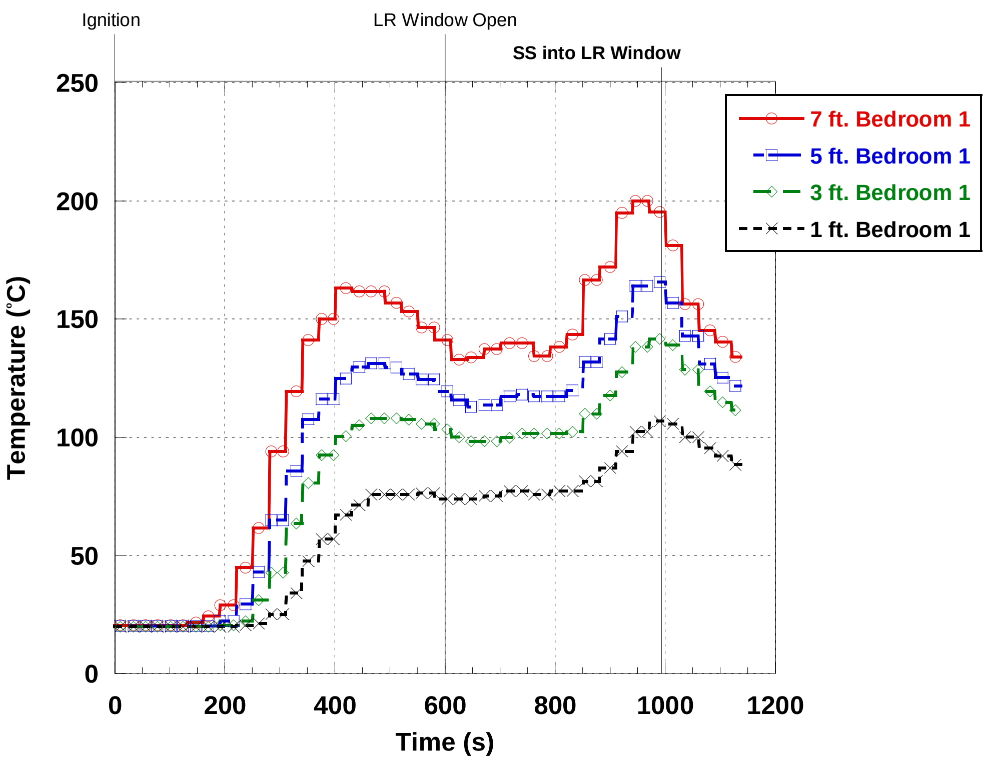


Figure 608. Experiment 6 - Bedroom 1

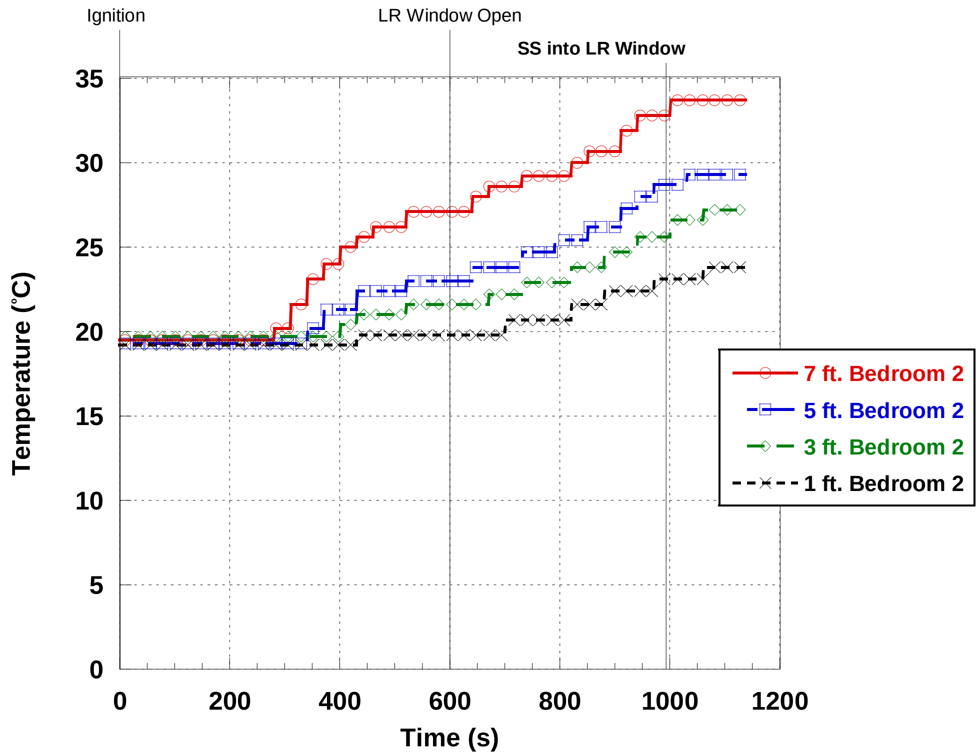


Figure 609. Experiment 6 - Bedroom 2

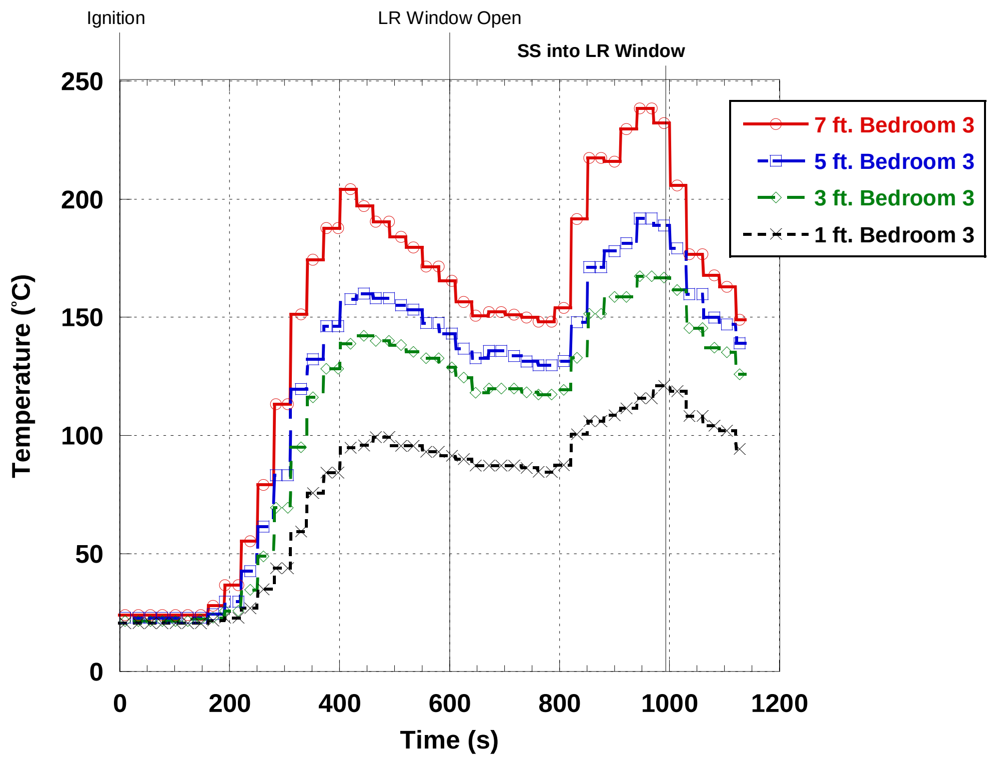


Figure 610. Experiment 6 - Bedroom 3

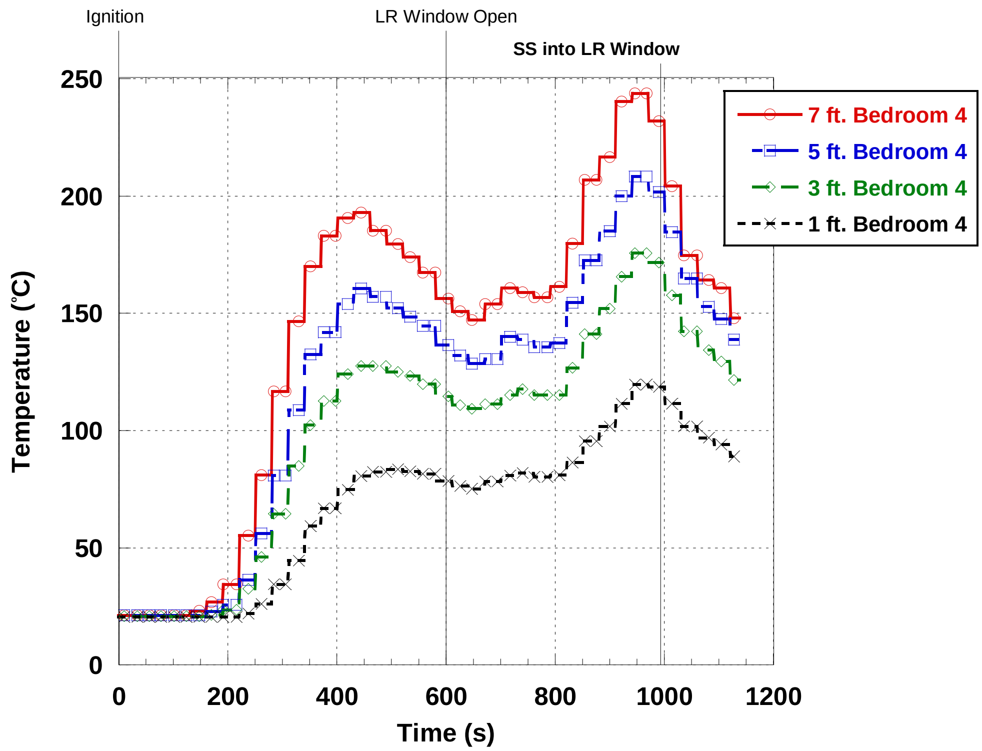


Figure 611. Experiment 6 - Bedroom 4

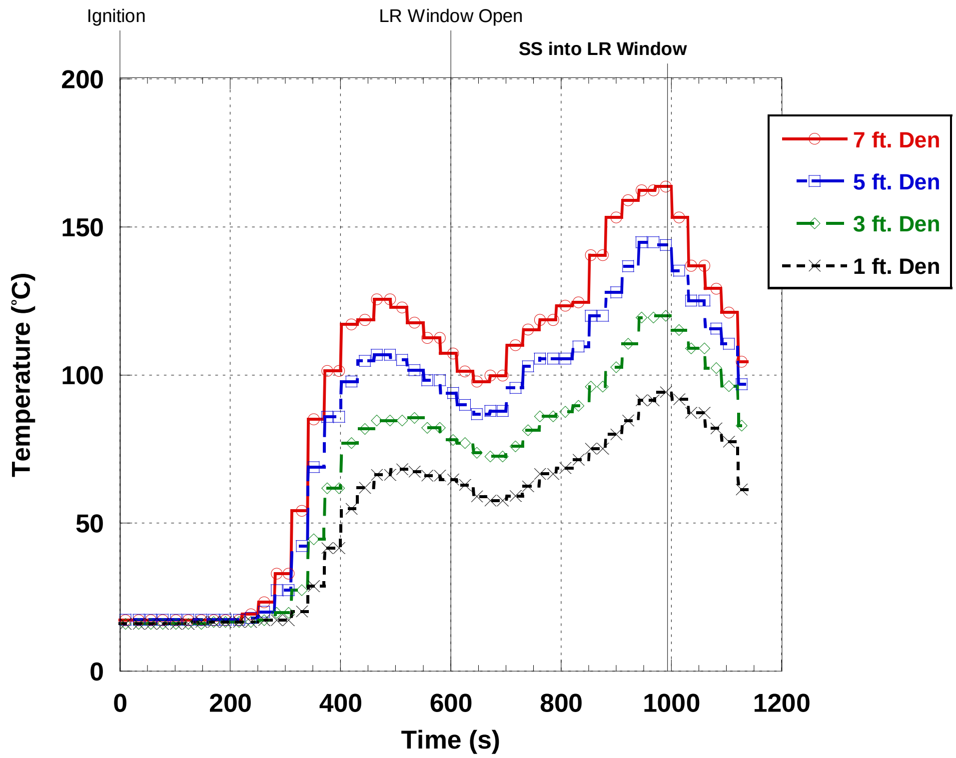


Figure 612. Experiment 6 - Den

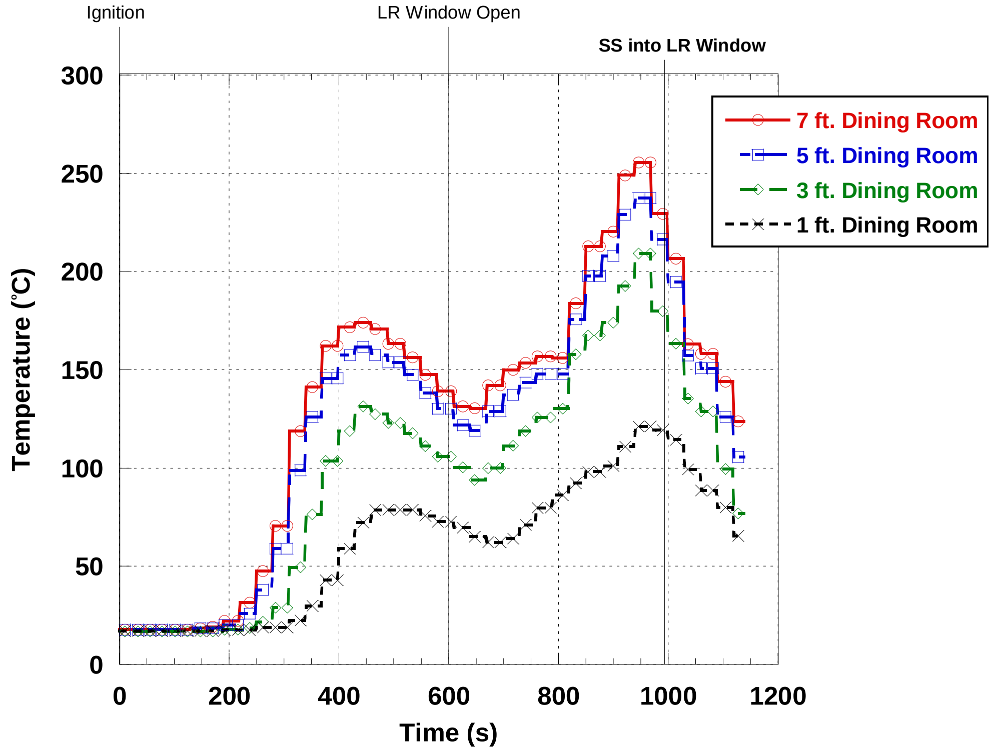


Figure 613. Experiment 6 - Dining Room

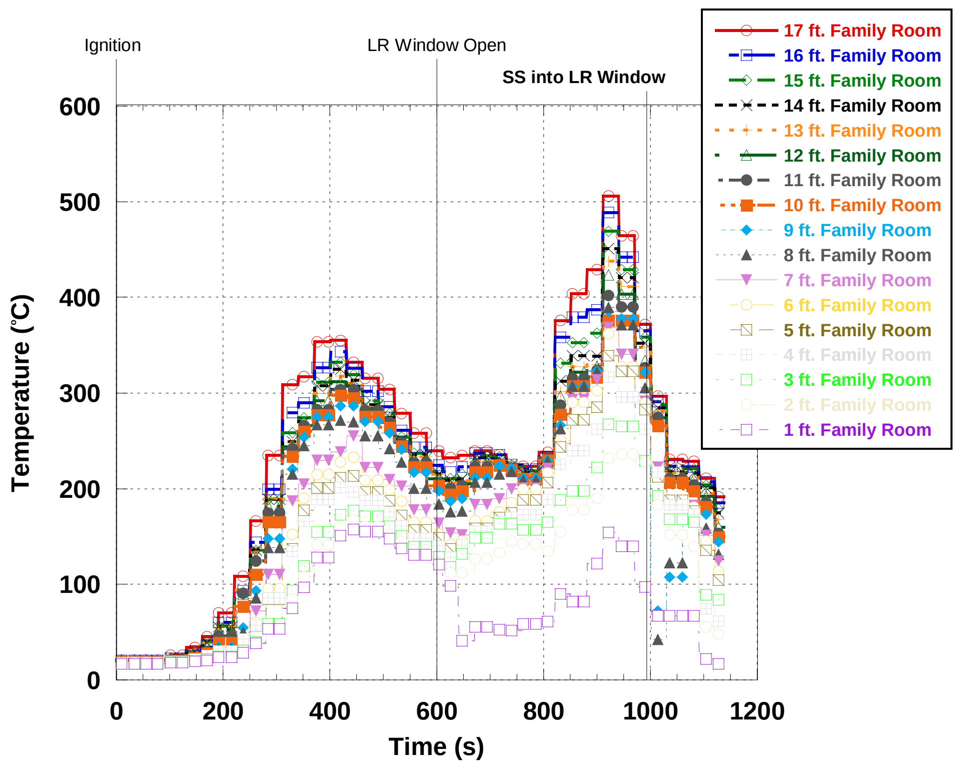


Figure 614. Experiment 6 - Family Room

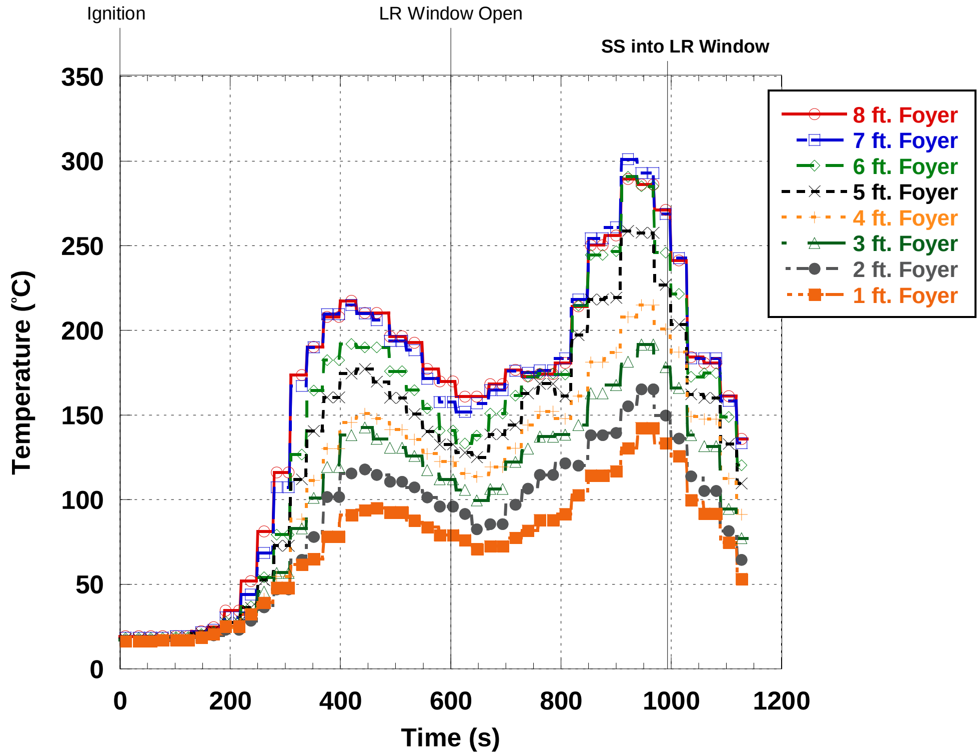


Figure 615. Experiment 6 - Foyer

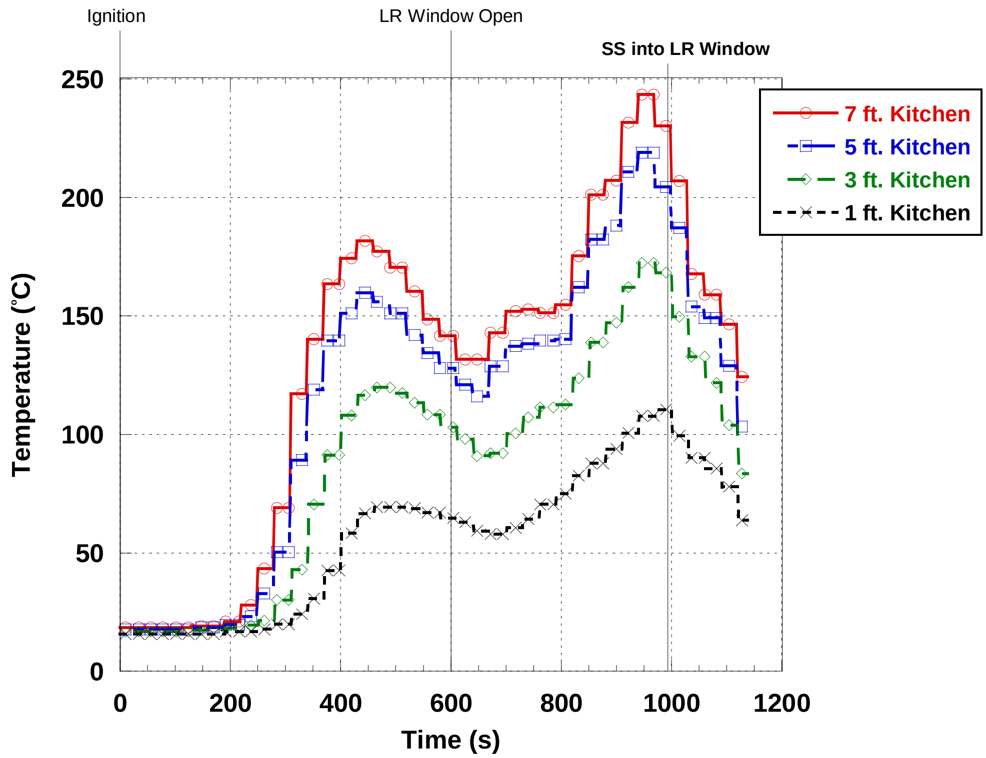


Figure 616. Experiment 6 - Kitchen

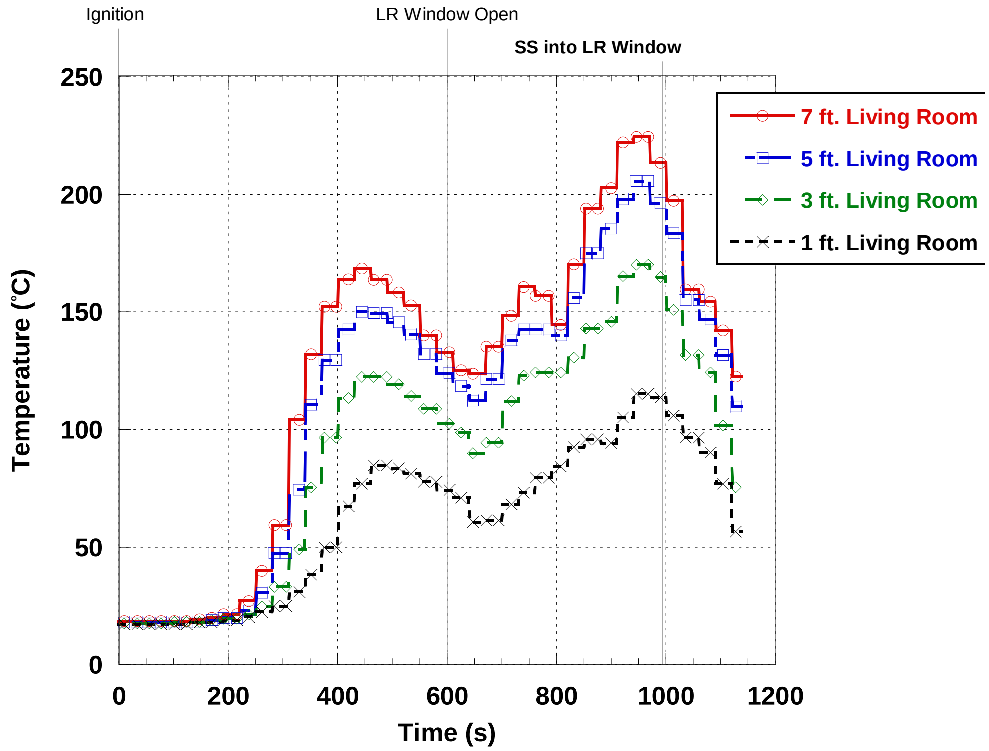


Figure 617. Experiment 6 - Living Room

Experiment 7

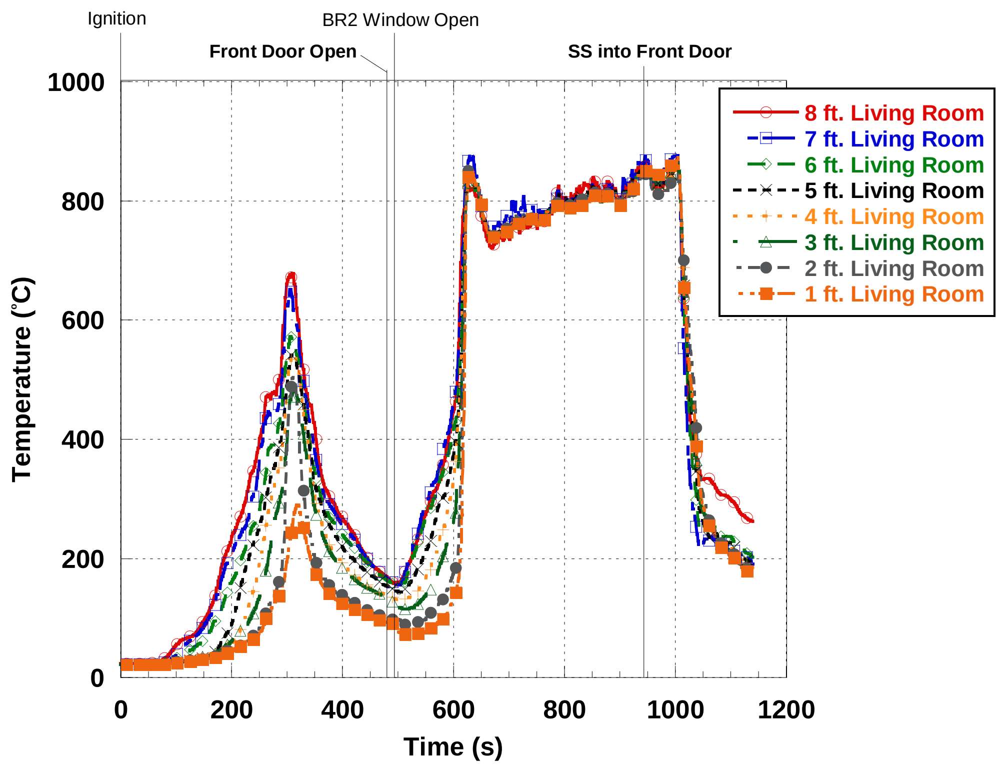


Figure 618. Experiment 7 - Living Room

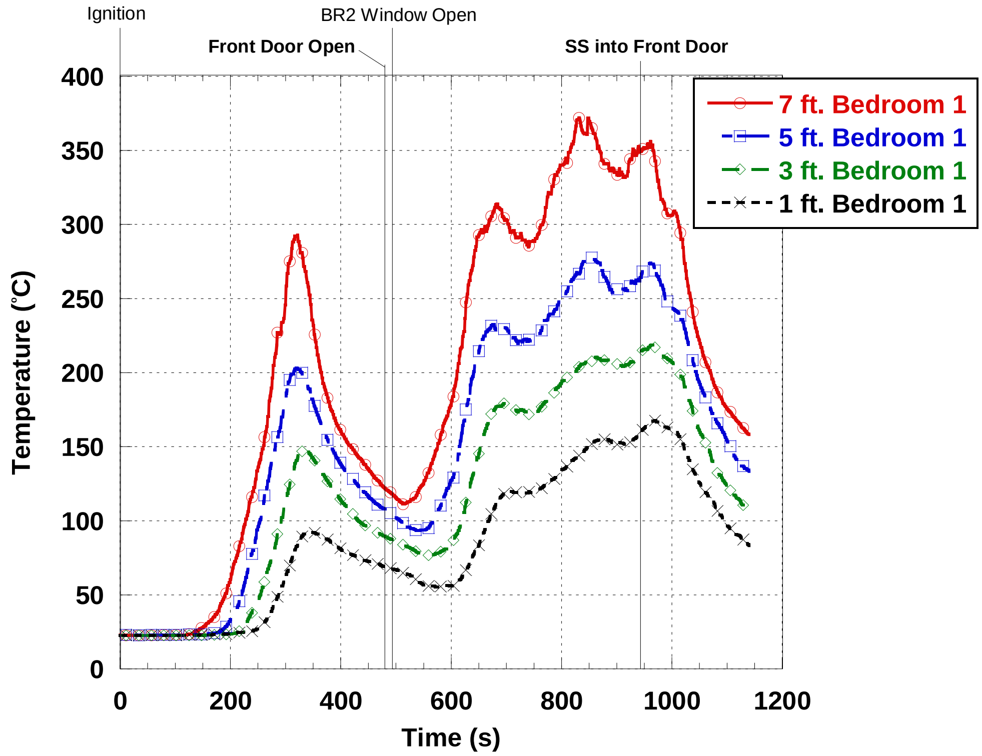


Figure 619. Experiment 7 - Bedroom 1

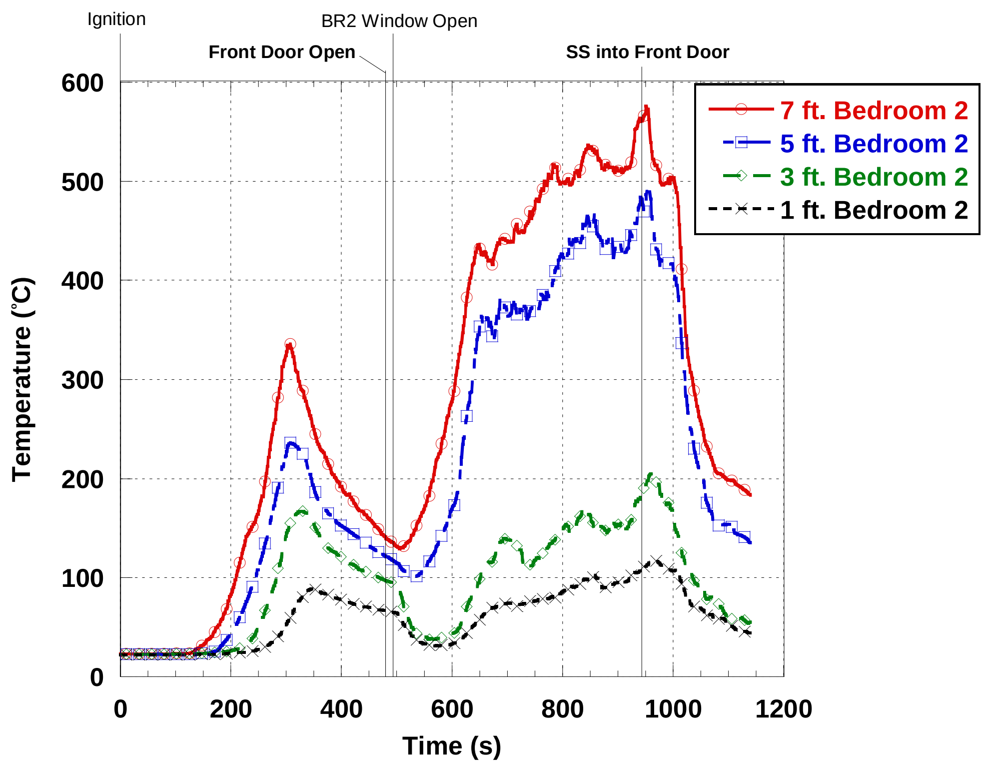


Figure 620. Experiment 7 - Bedroom 2

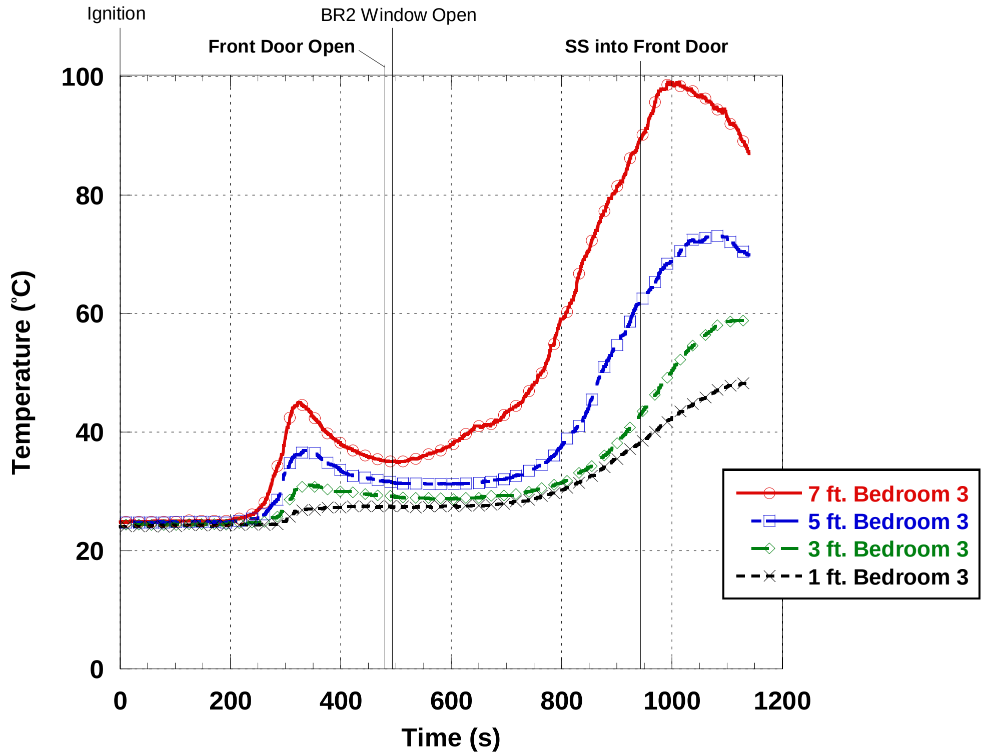


Figure 621. Experiment 7 - Bedroom 3

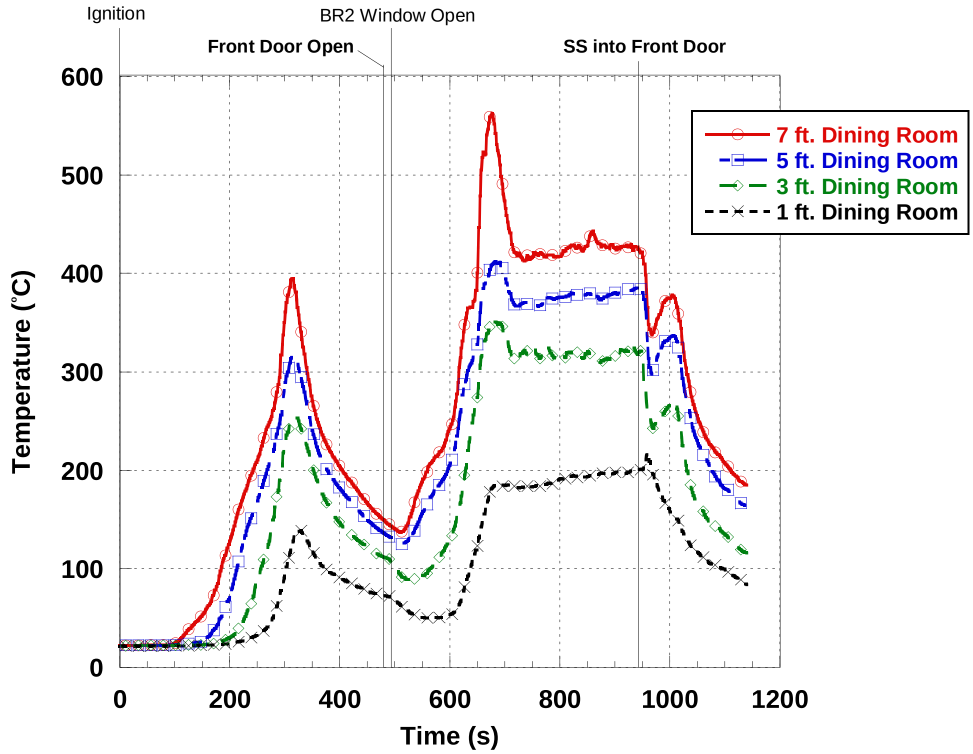


Figure 622. Experiment 7 - Dining Room

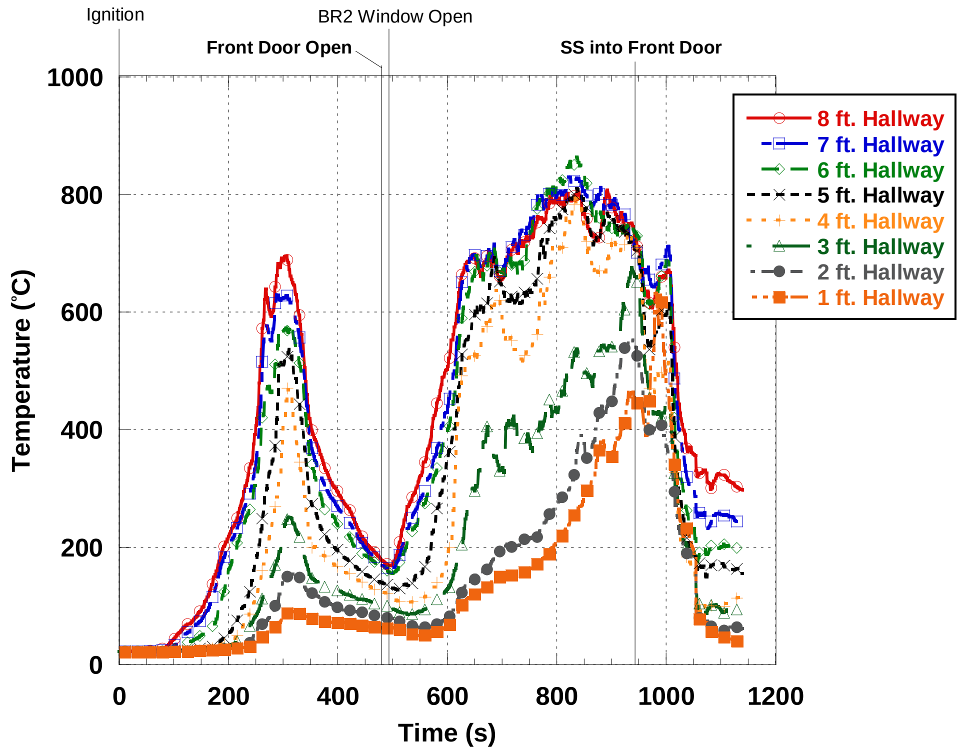


Figure 623. Experiment 7 - Hallway

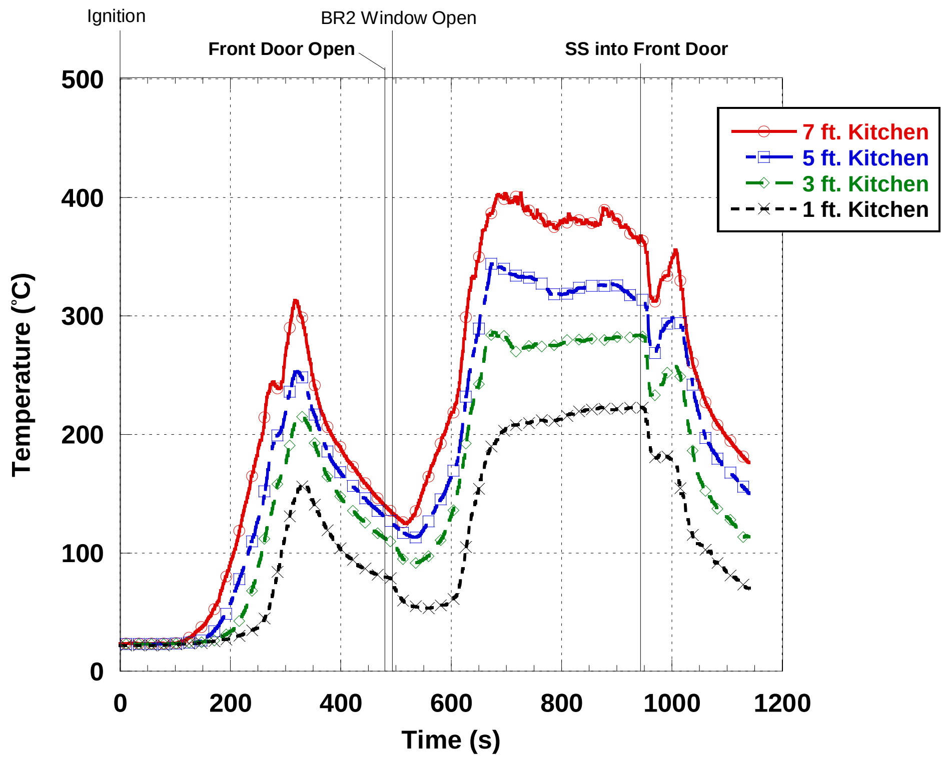


Figure 624. Experiment 7 - Kitchen

Experiment 8

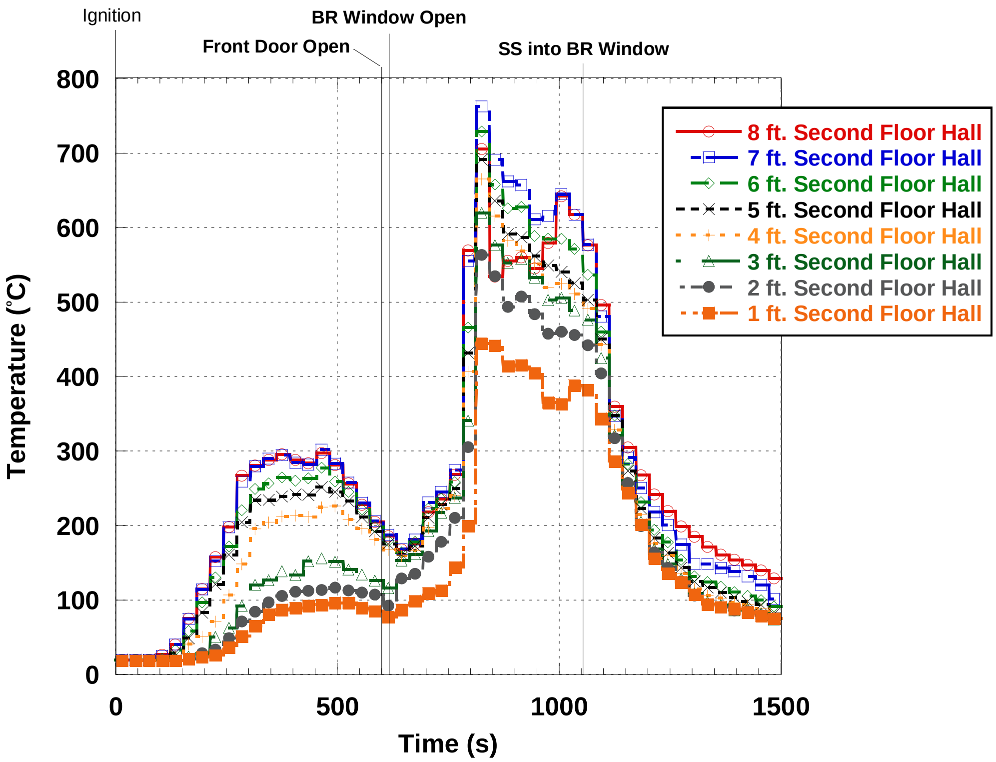


Figure 625. Experiment 8 - Second Floor Hall

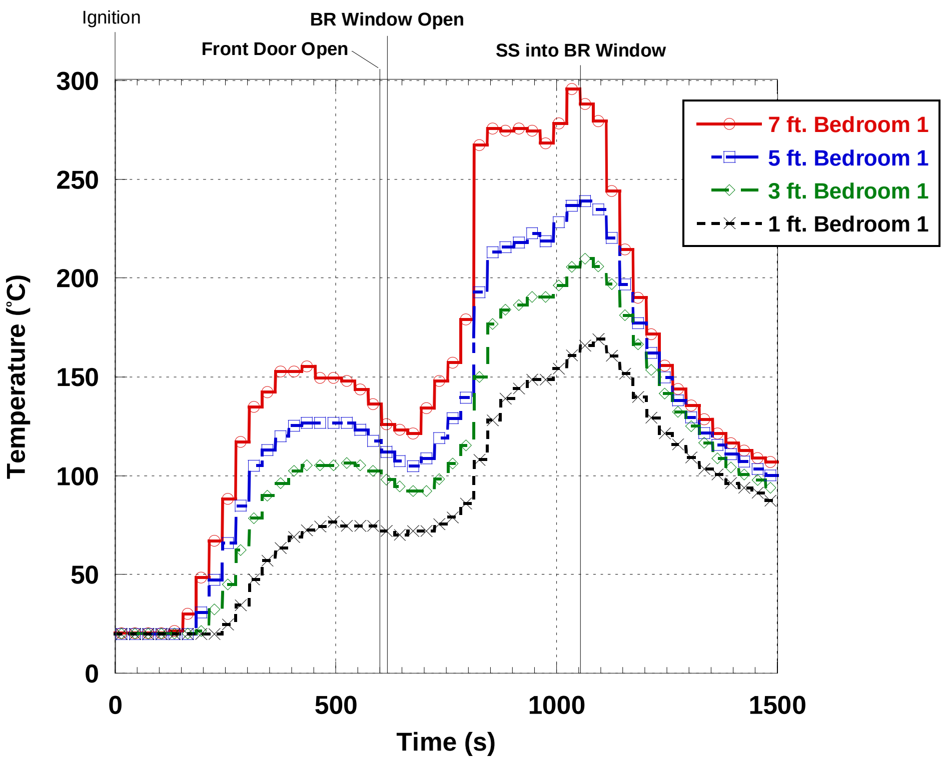


Figure 626. Experiment 8 - Bedroom 1

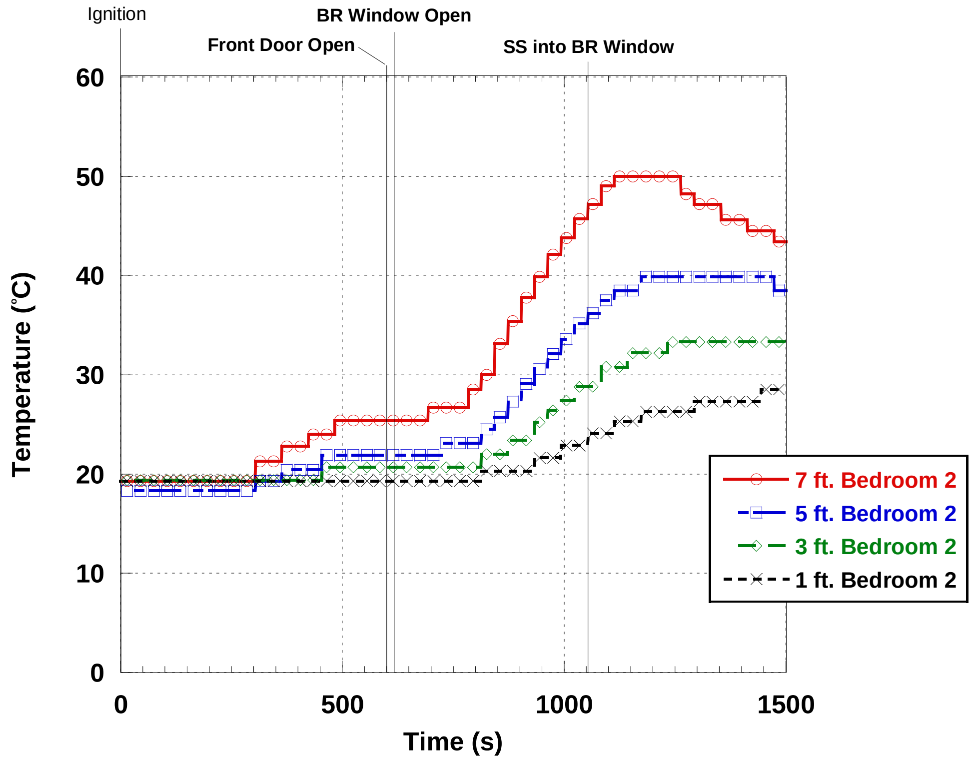


Figure 627. Experiment 8 - Bedroom 2

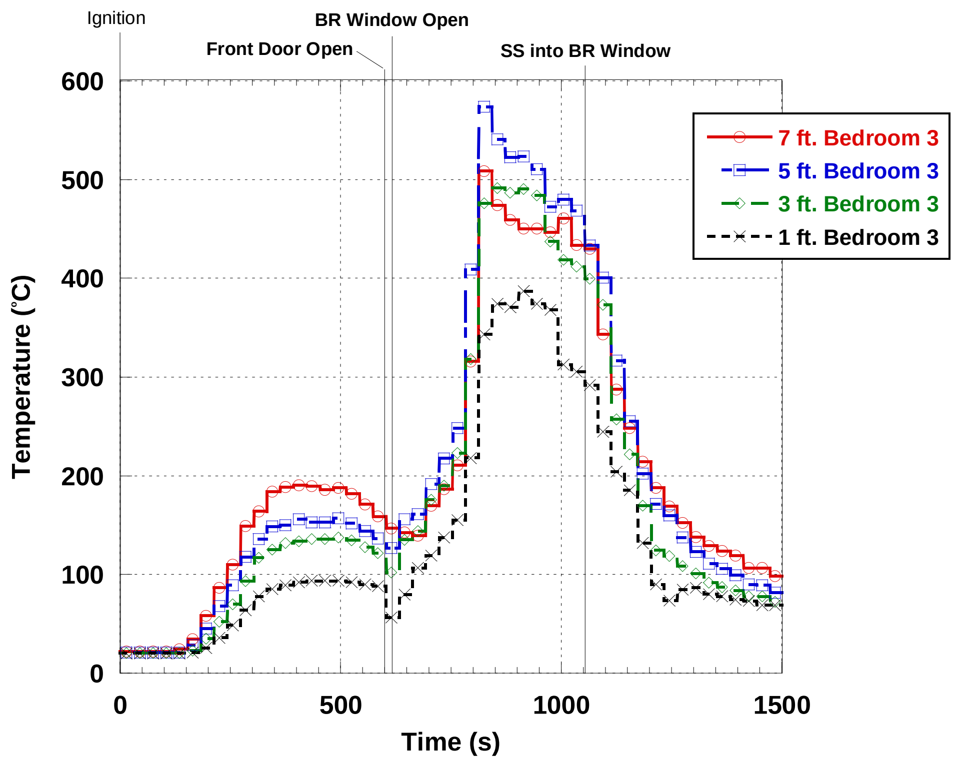


Figure 628. Experiment 8 - Bedroom 3

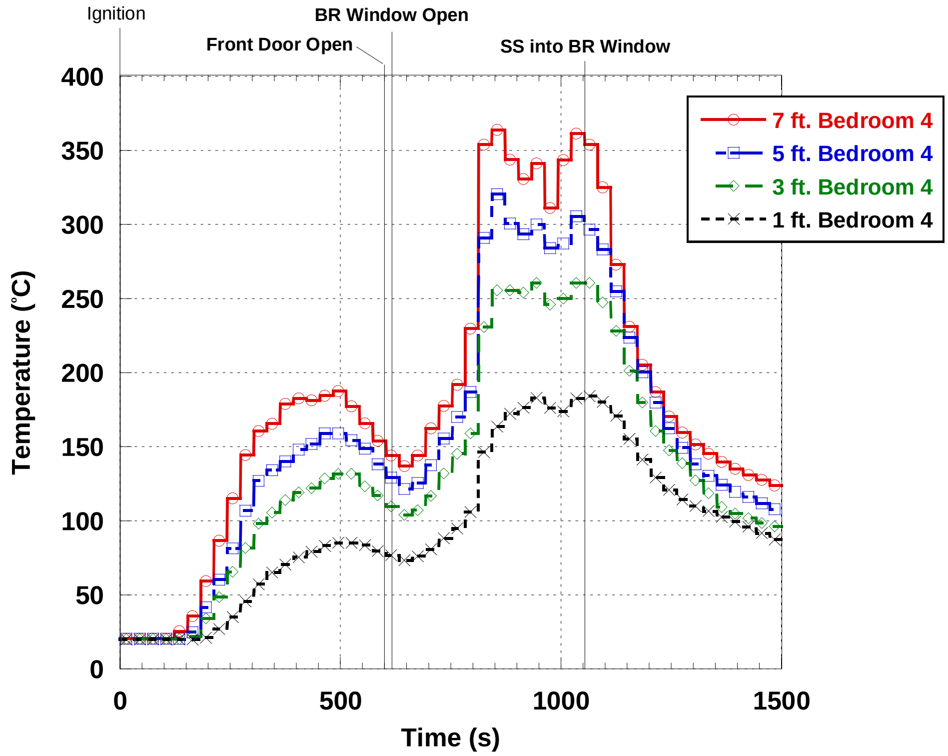


Figure 629. Experiment 8 - Bedroom 4

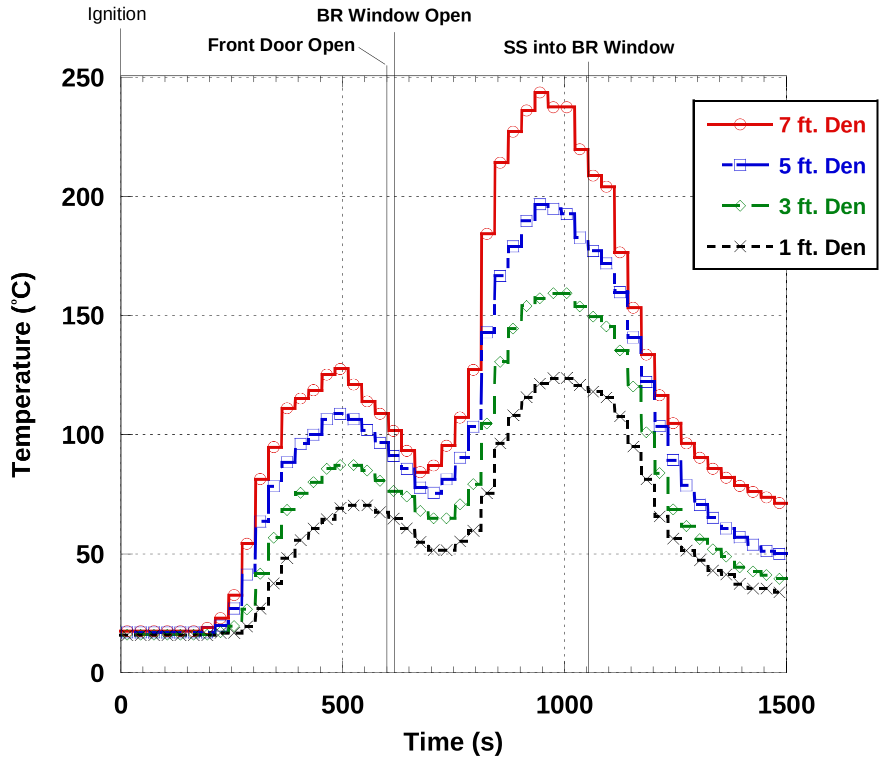


Figure 630. Experiment 8 - Den

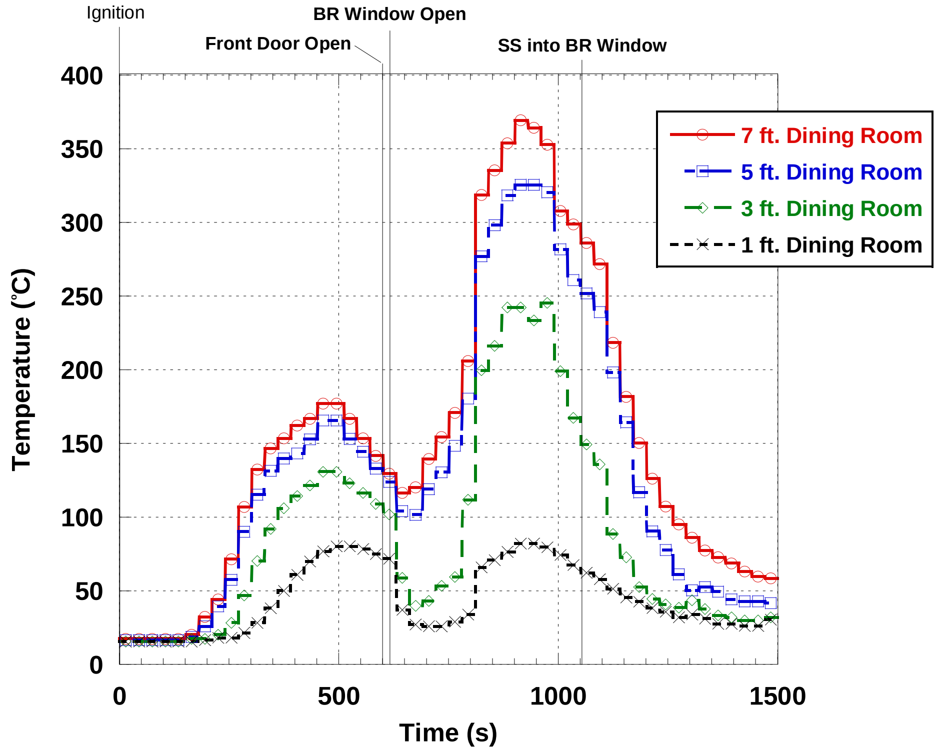


Figure 631. Experiment 8 - Dining Room

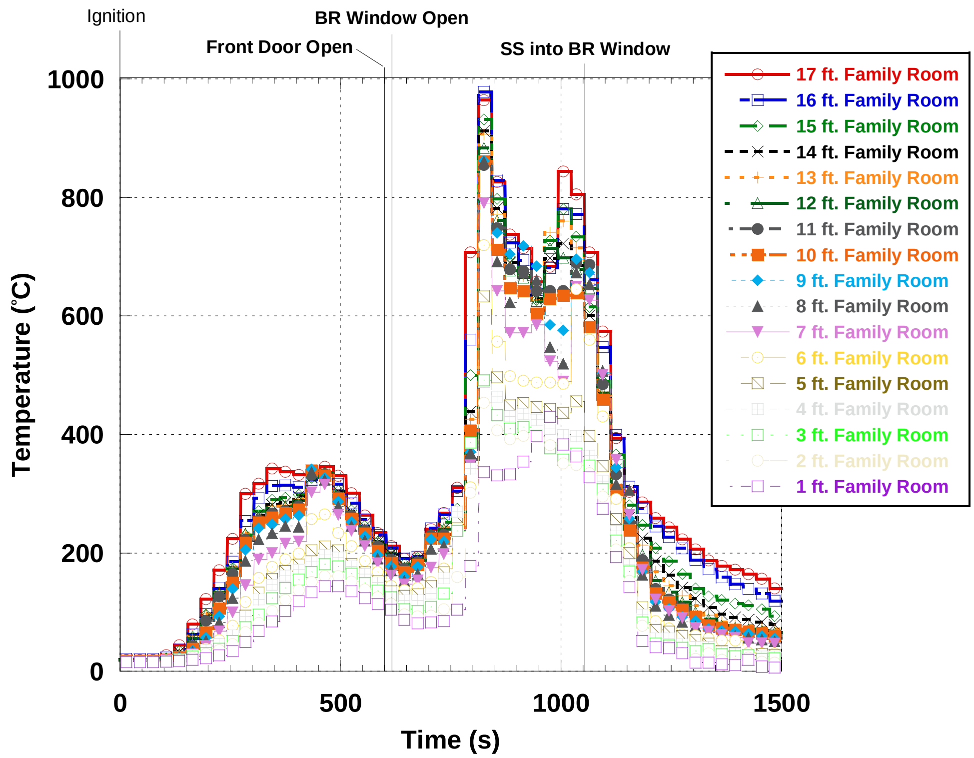


Figure 632. Experiment 8 - Family Room

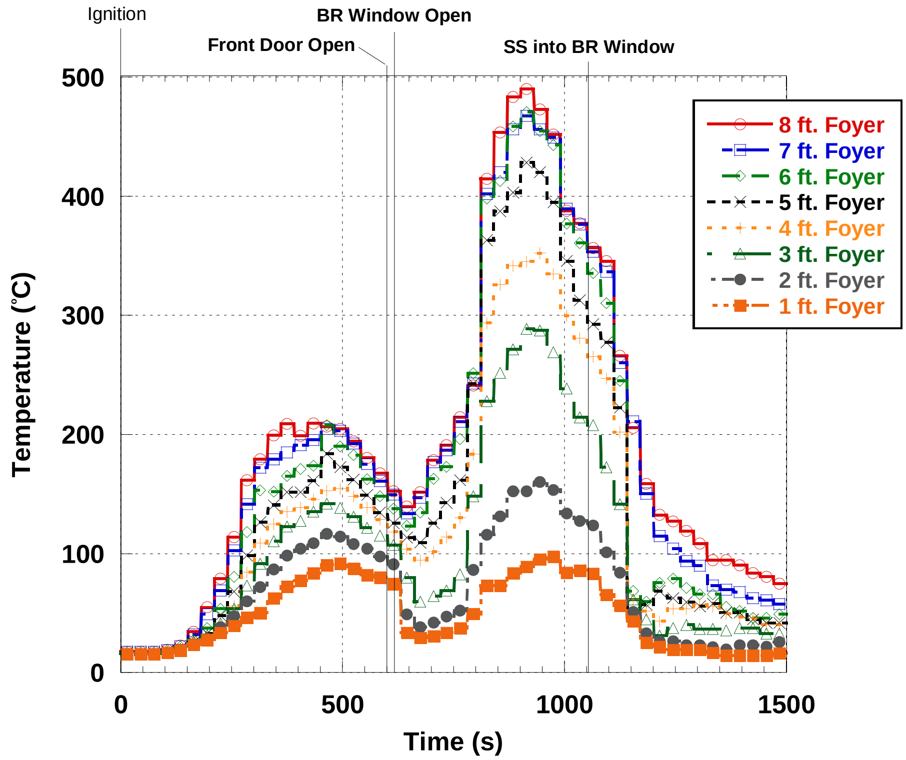


Figure 633. Experiment 8 - Foyer

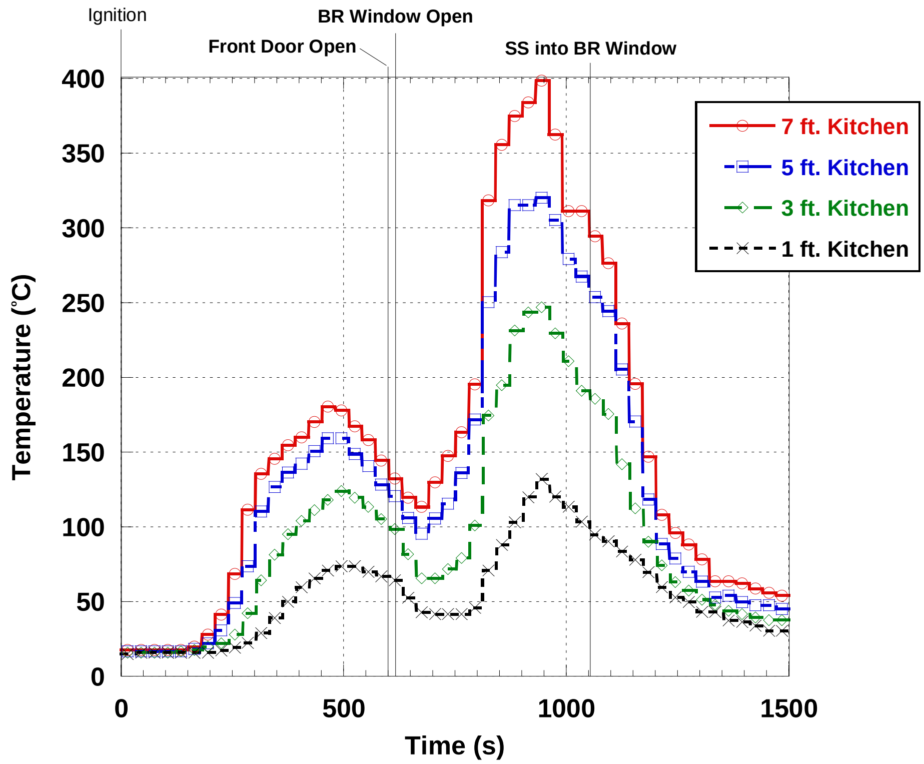


Figure 634. Experiment 8 - Kitchen

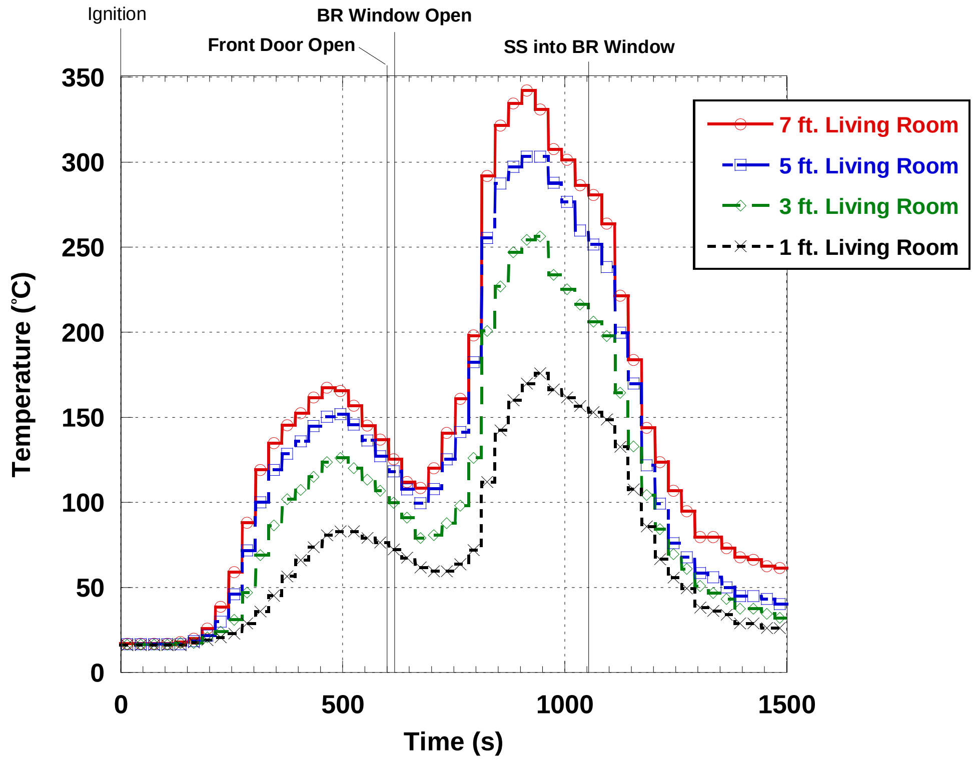


Figure 635. Experiment 8 - Living Room

Experiment 9

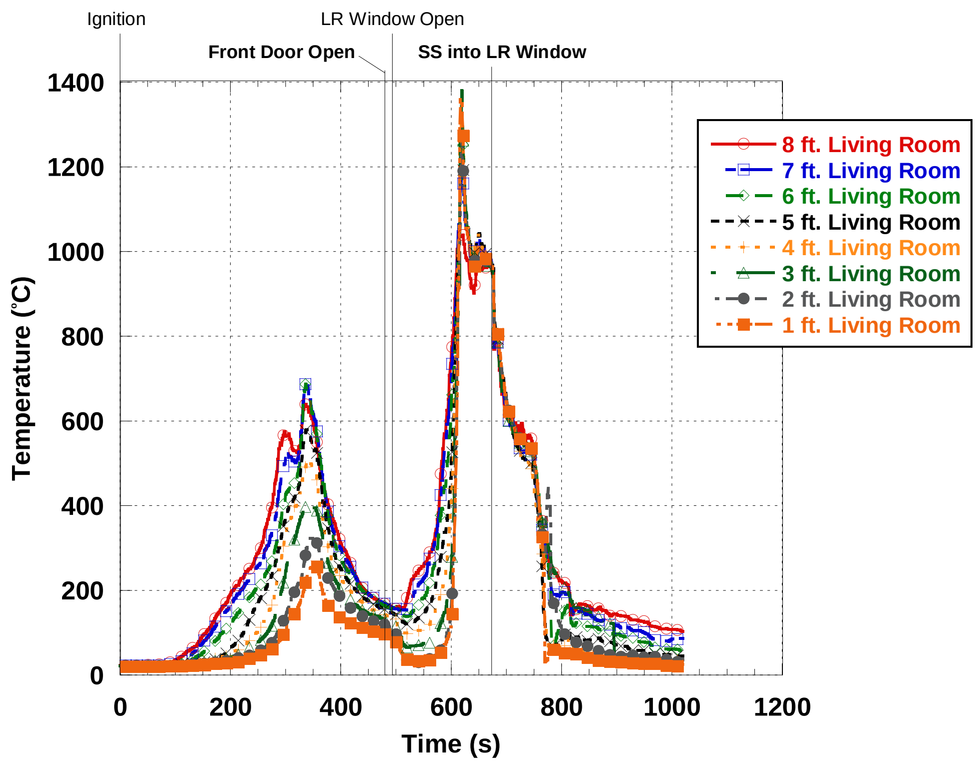


Figure 636. Experiment 9 - Living Room

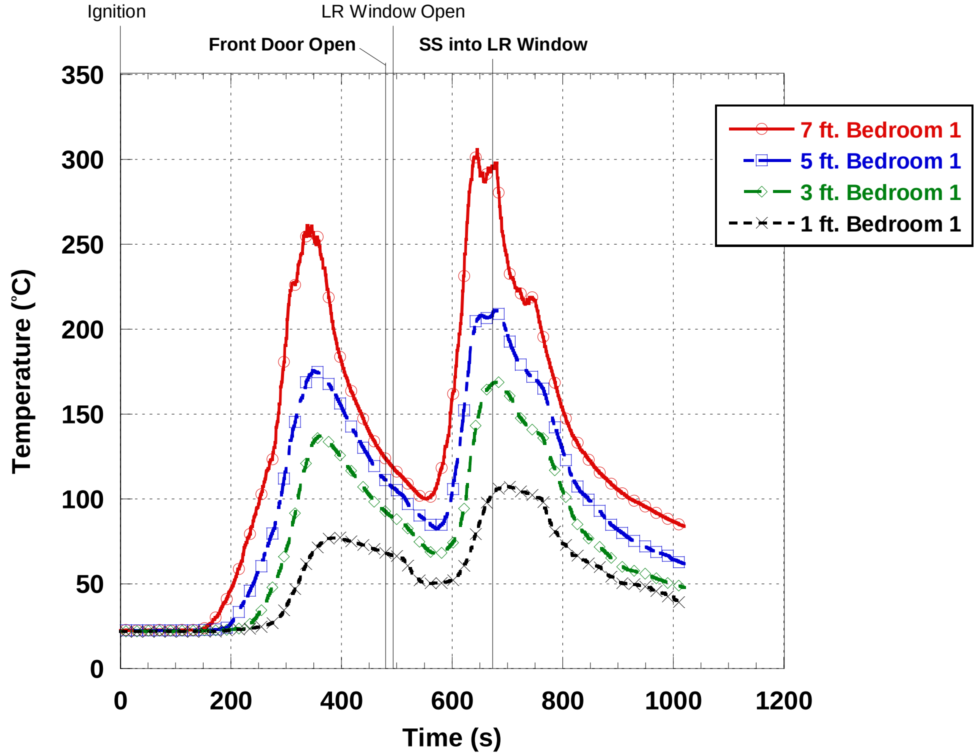


Figure 637. Experiment 9 - Bedroom 1

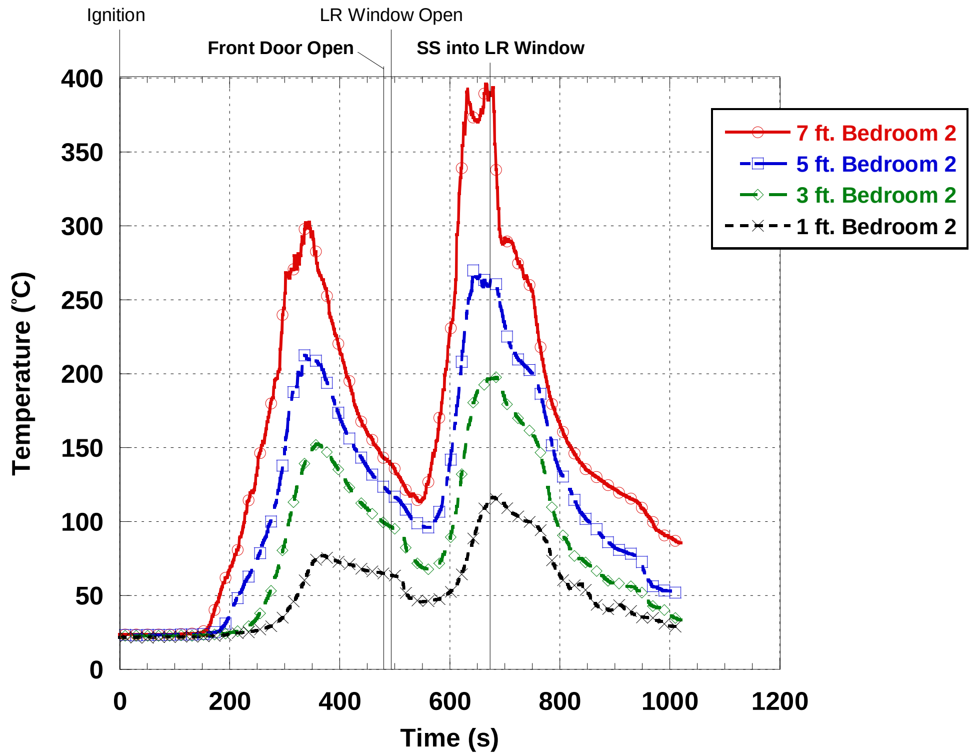


Figure 638. Experiment 9 - Bedroom 2

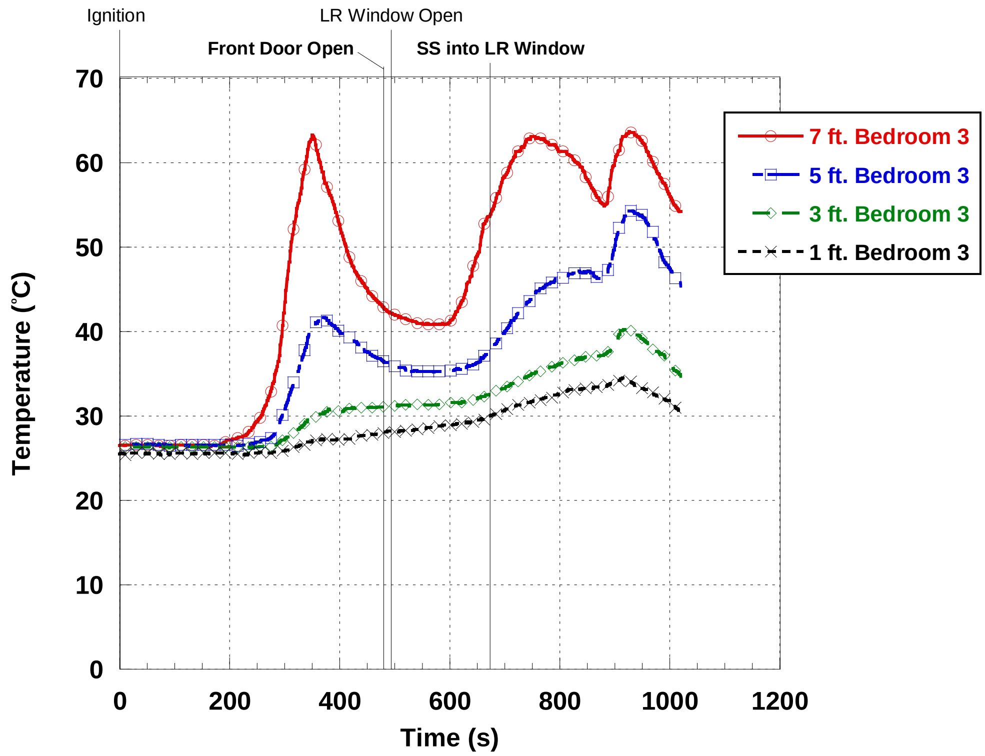


Figure 639. Experiment 9 - Bedroom 3

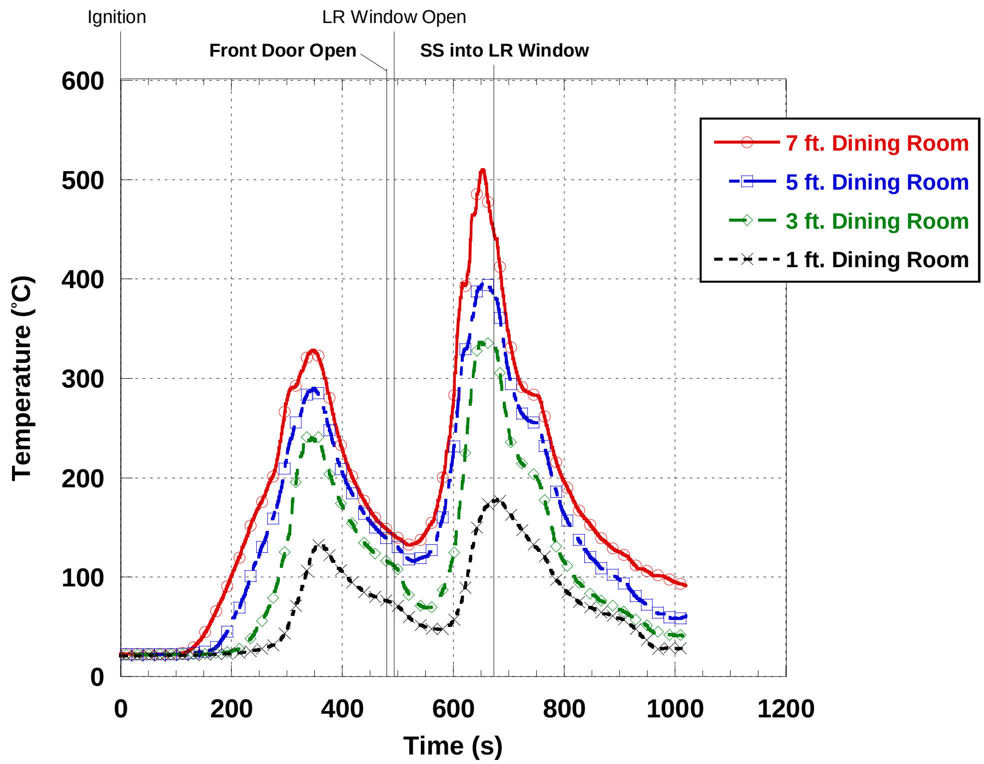


Figure 640. Experiment 9 - Bedroom 4

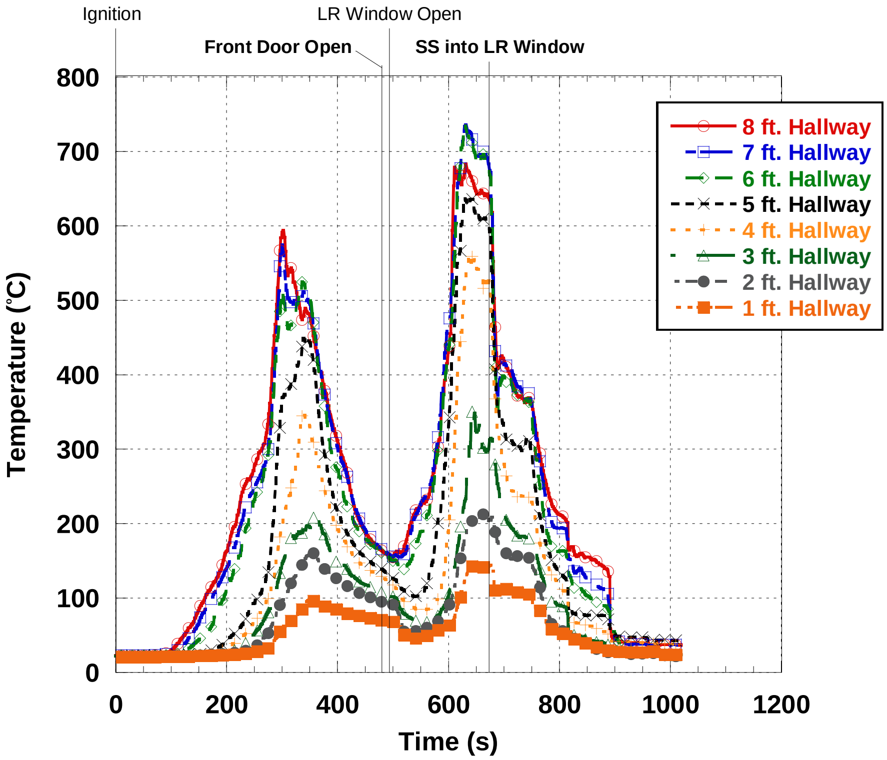


Figure 641. Experiment 9 - Hallway

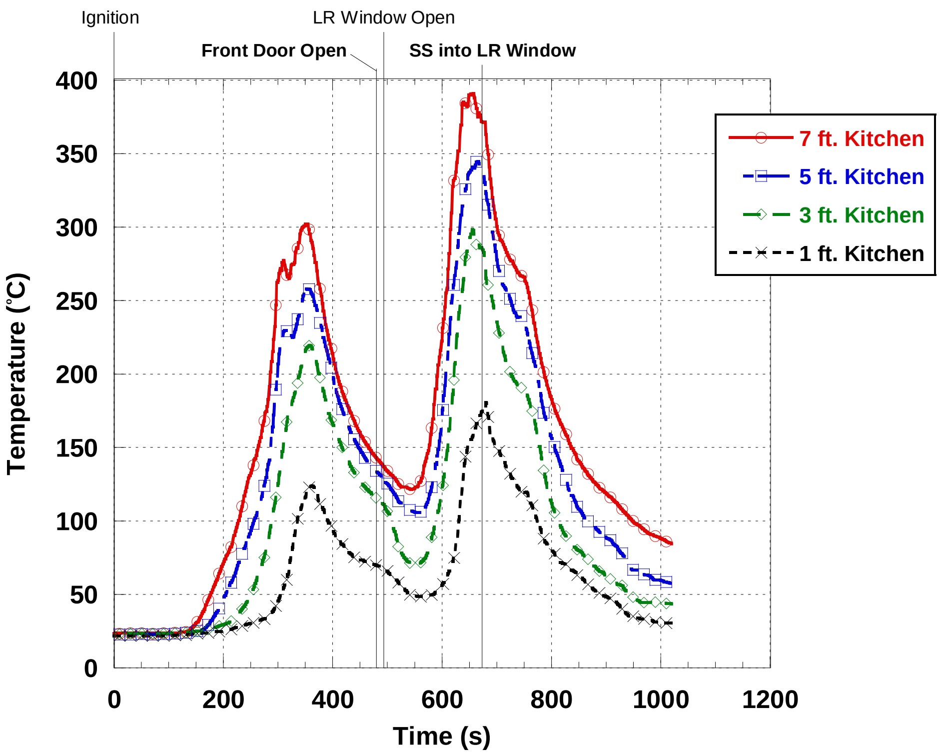


Figure 642. Experiment 9 - Kitchen

Experiment 10

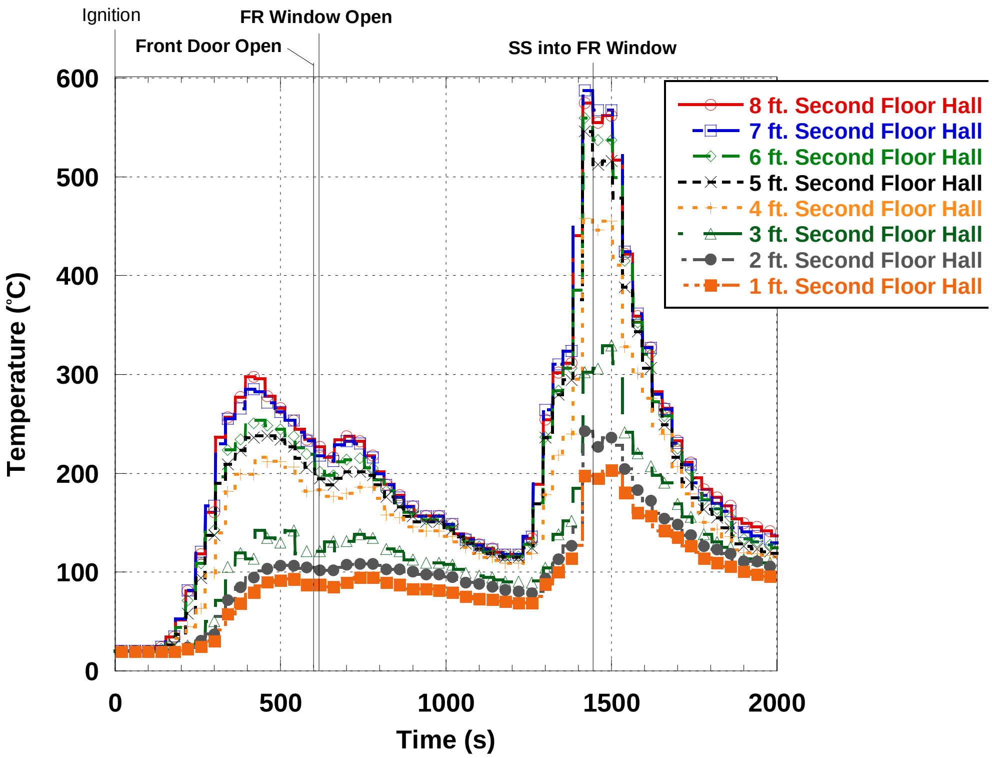


Figure 643. Experiment 10 - Second Floor Hall

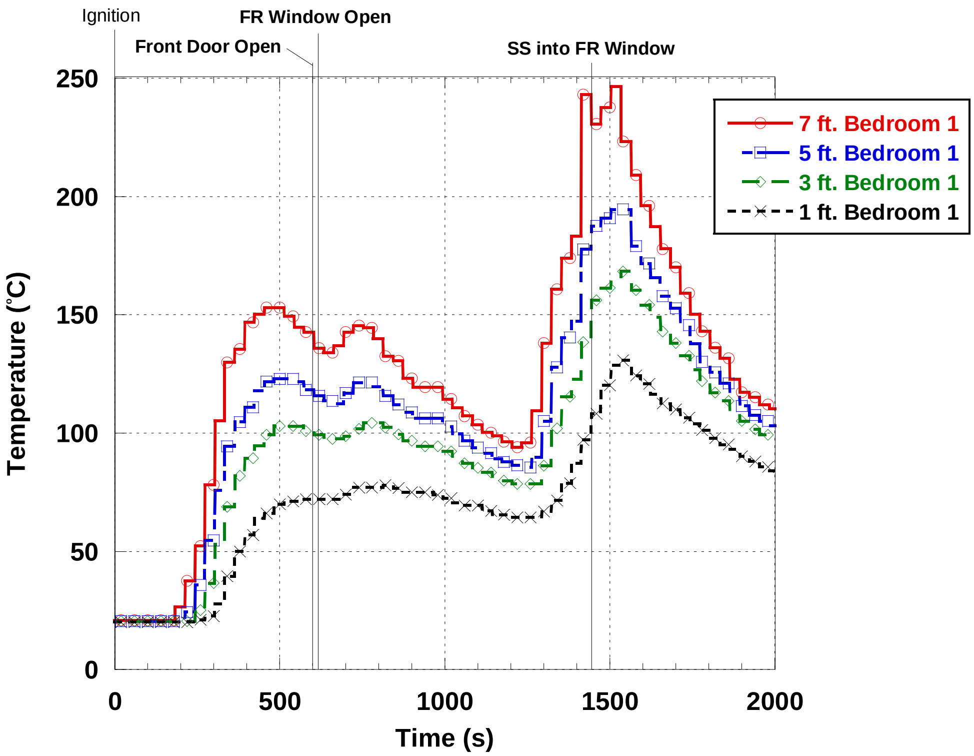


Figure 644. Experiment 10 - Bedroom 1

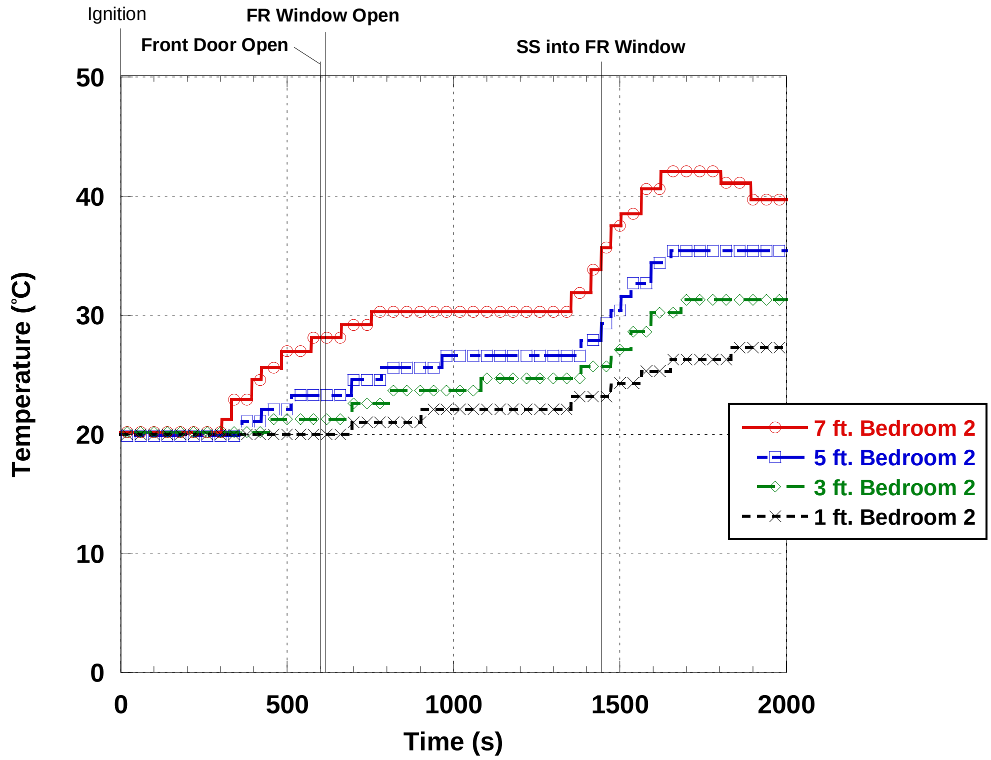


Figure 645. Experiment 10 - Bedroom 2

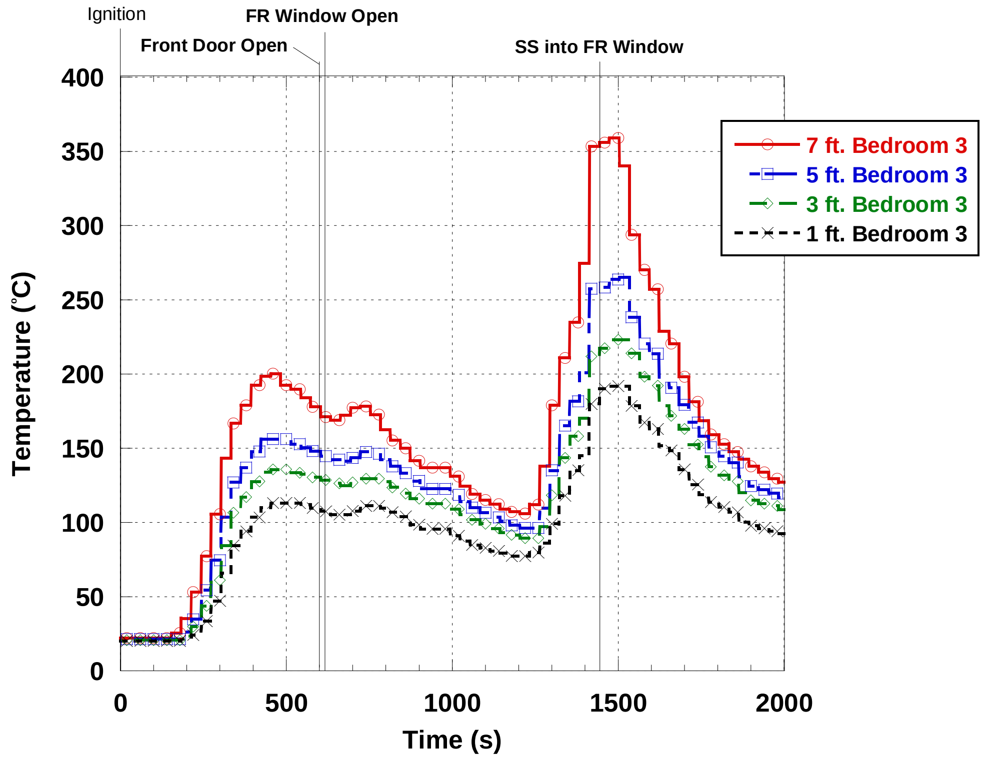


Figure 646. Experiment 10 - Bedroom 3

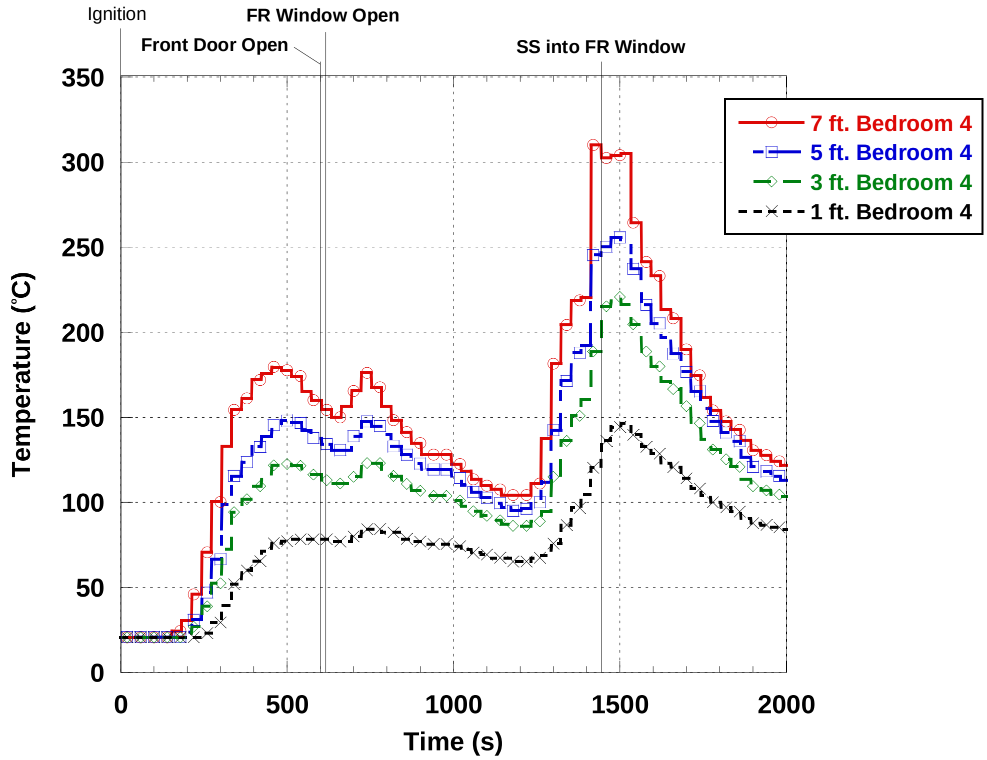


Figure 647. Experiment 10 - Bedroom 4

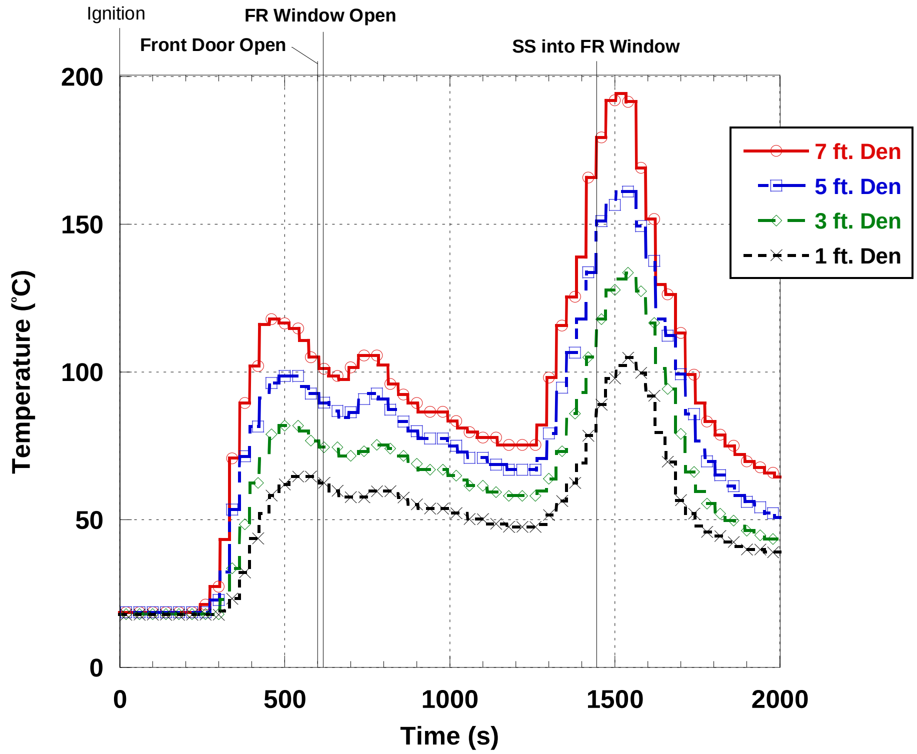


Figure 648. Experiment 10 - Den

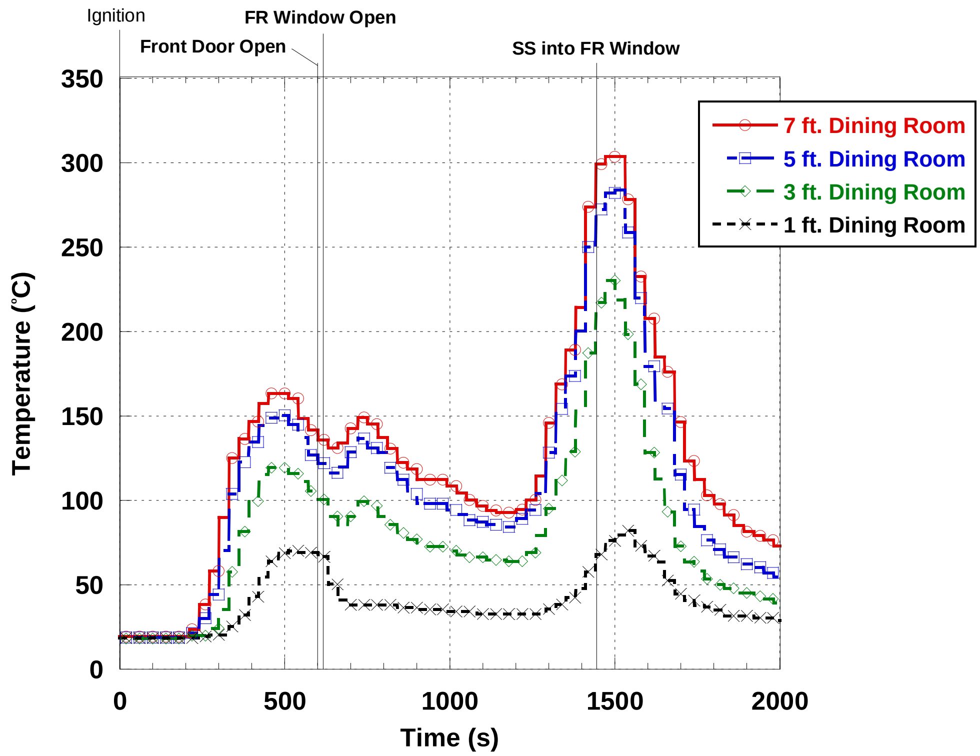


Figure 649. Experiment 10 - Dining Room

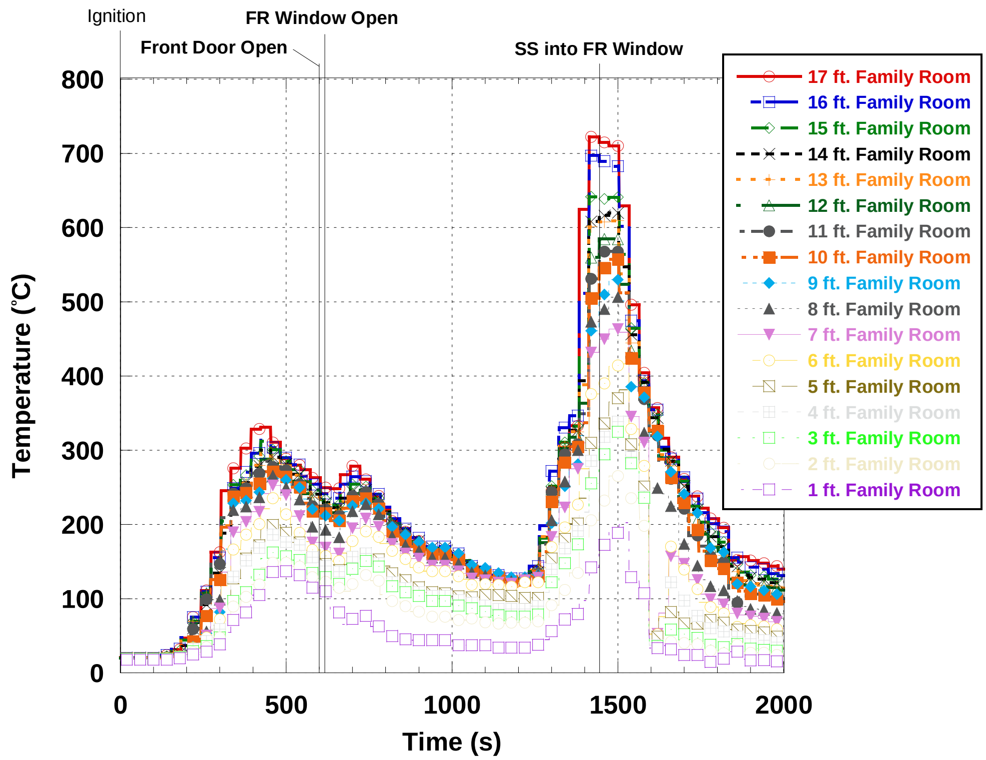


Figure 650. Experiment 10 - Family Room

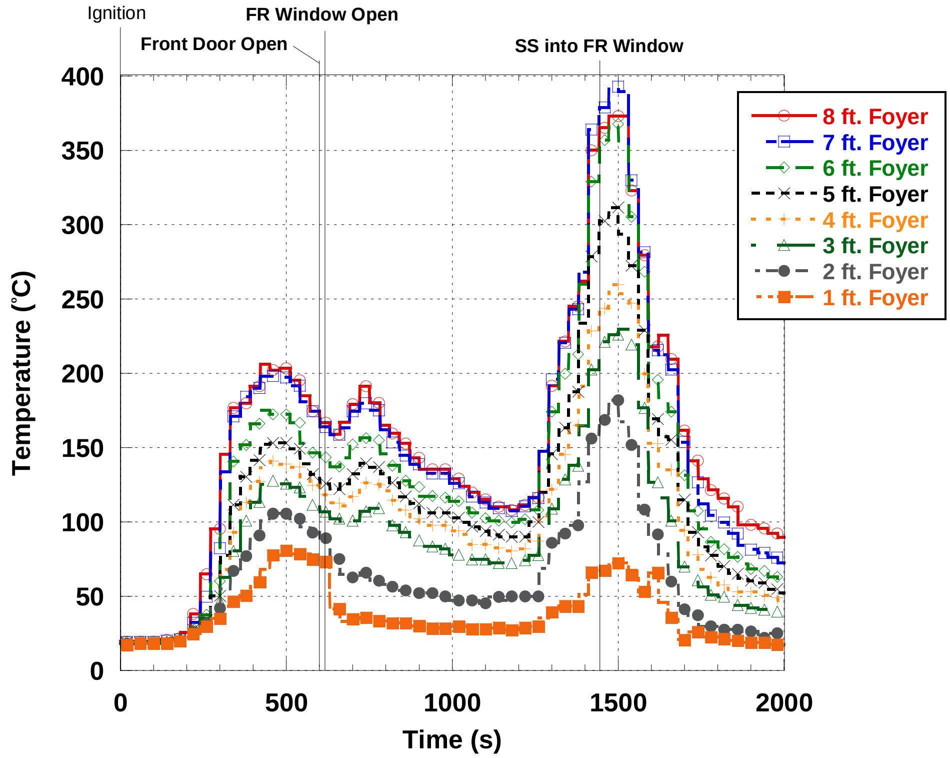


Figure 651. Experiment 10 - Foyer

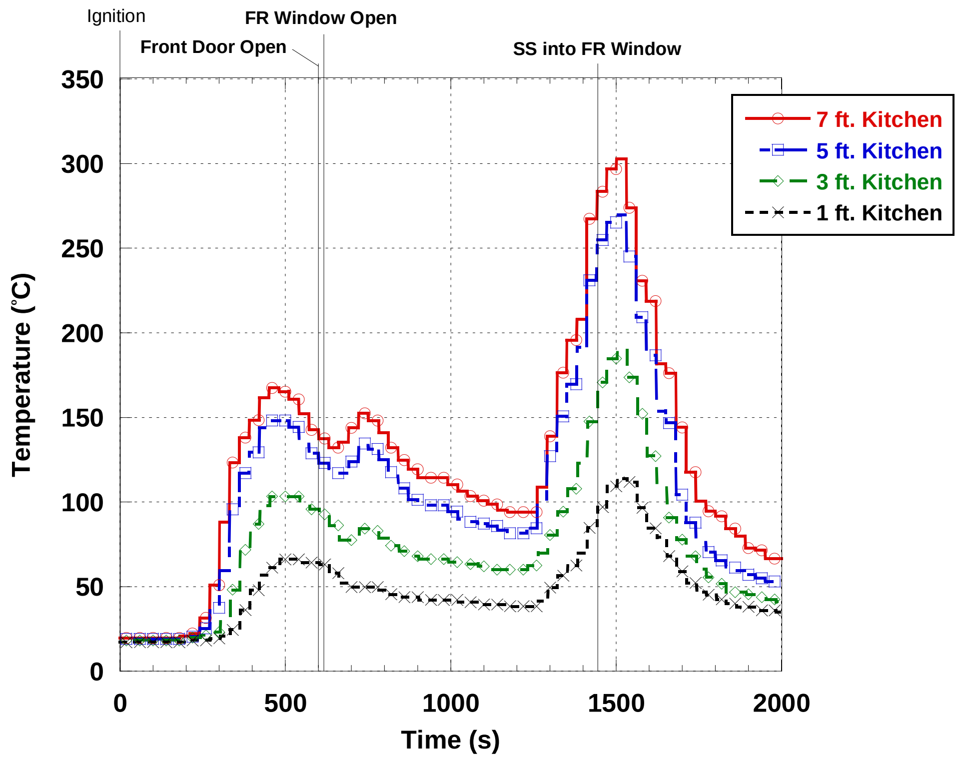


Figure 652. Experiment 10 - Kitchen

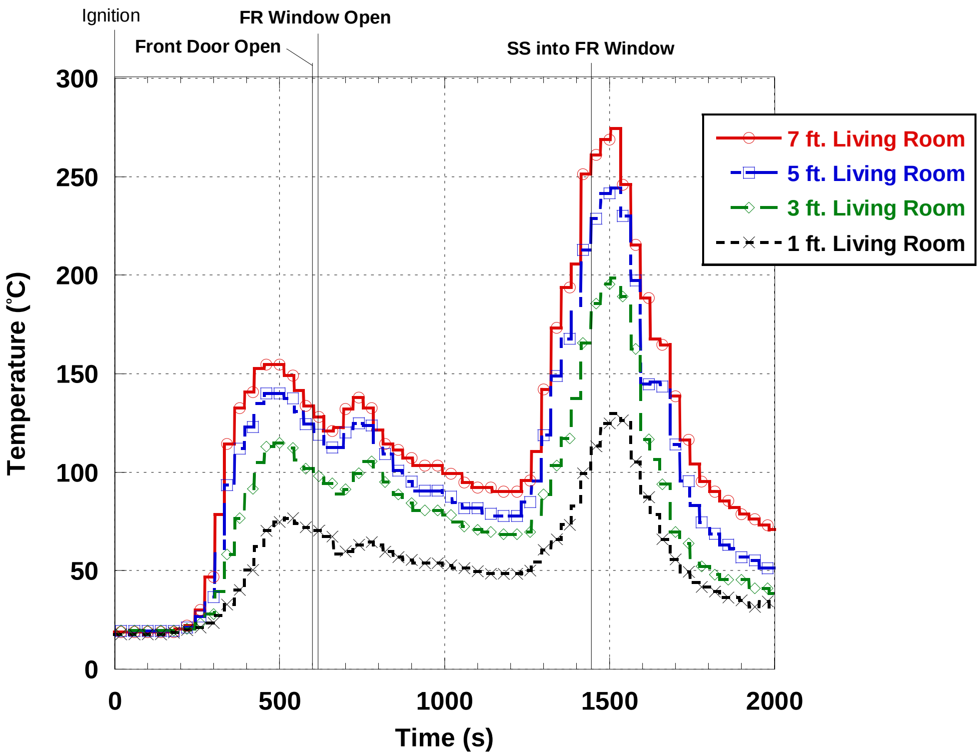


Figure 653. Experiment 10 - Living Room

Experiment 11

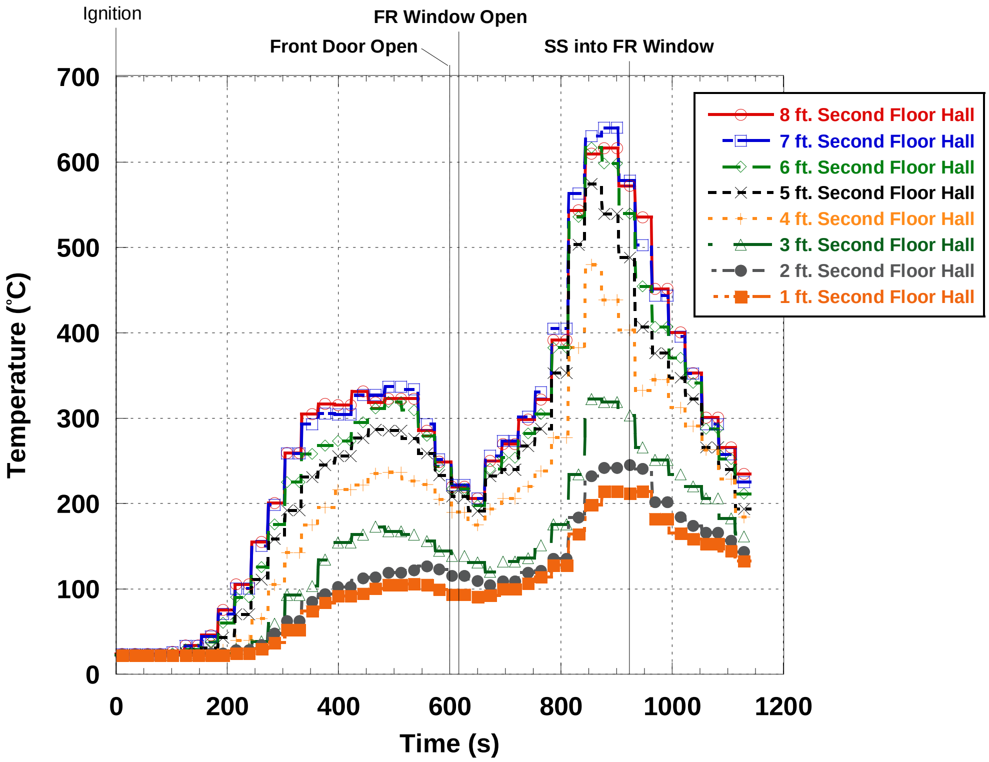


Figure 654. Experiment 11 - Second Floor Hall

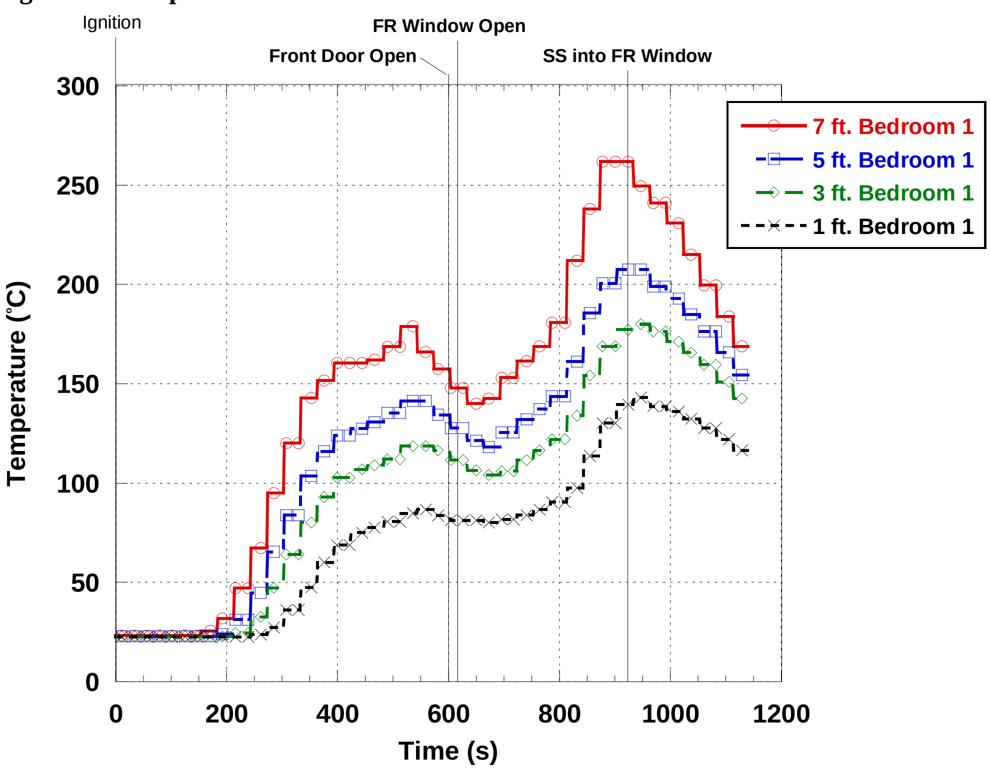


Figure 655. Experiment 11 - Bedroom 1

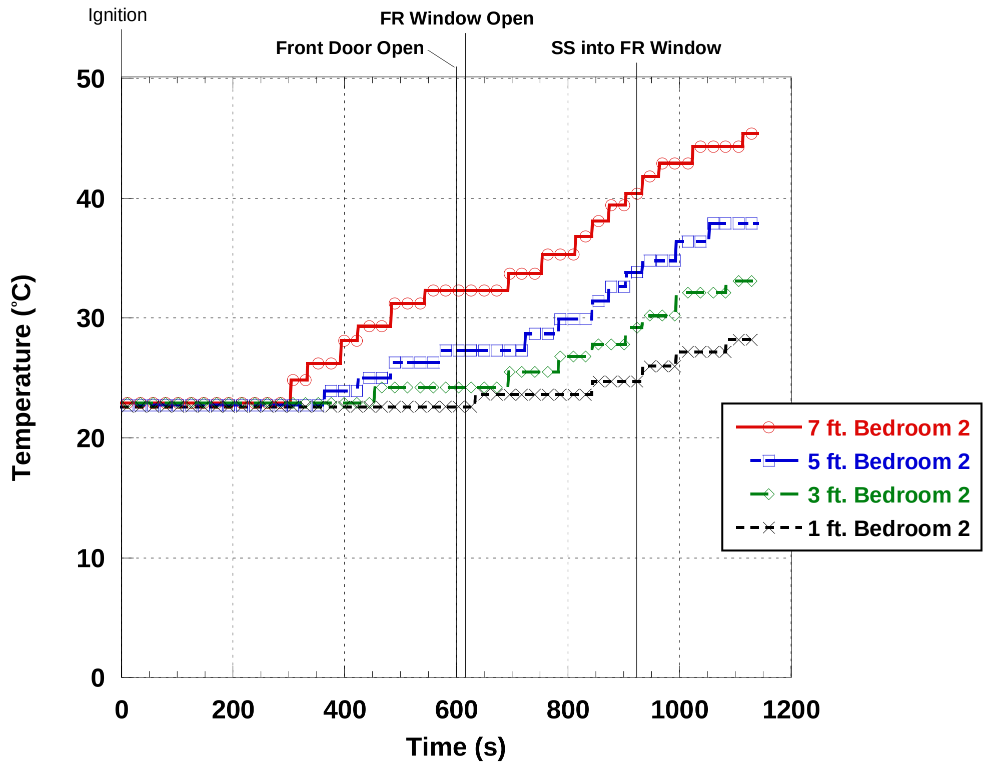


Figure 656. Experiment 11 - Bedroom 2

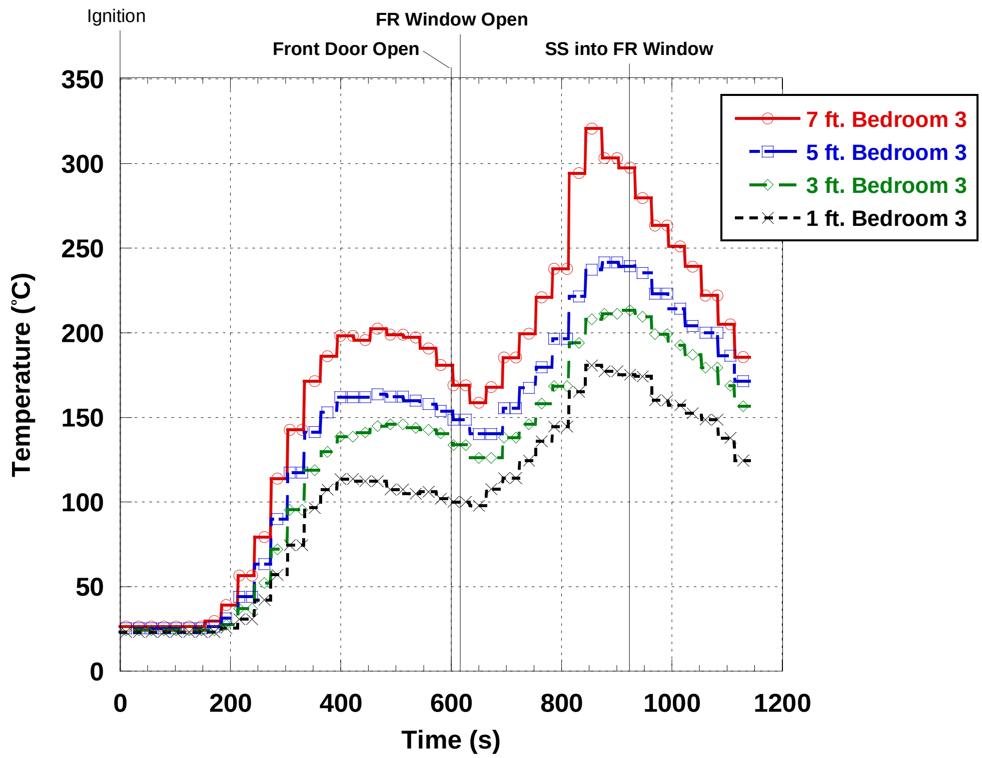


Figure 657. Experiment 11 - Bedroom 3

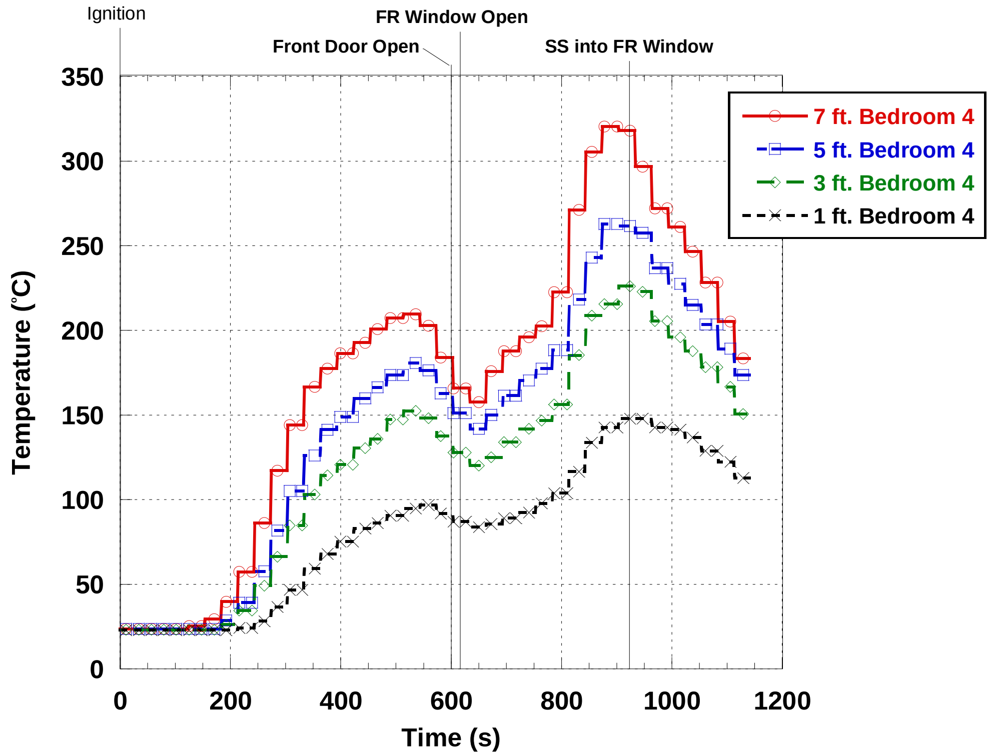


Figure 658. Experiment 11 - Bedroom 4

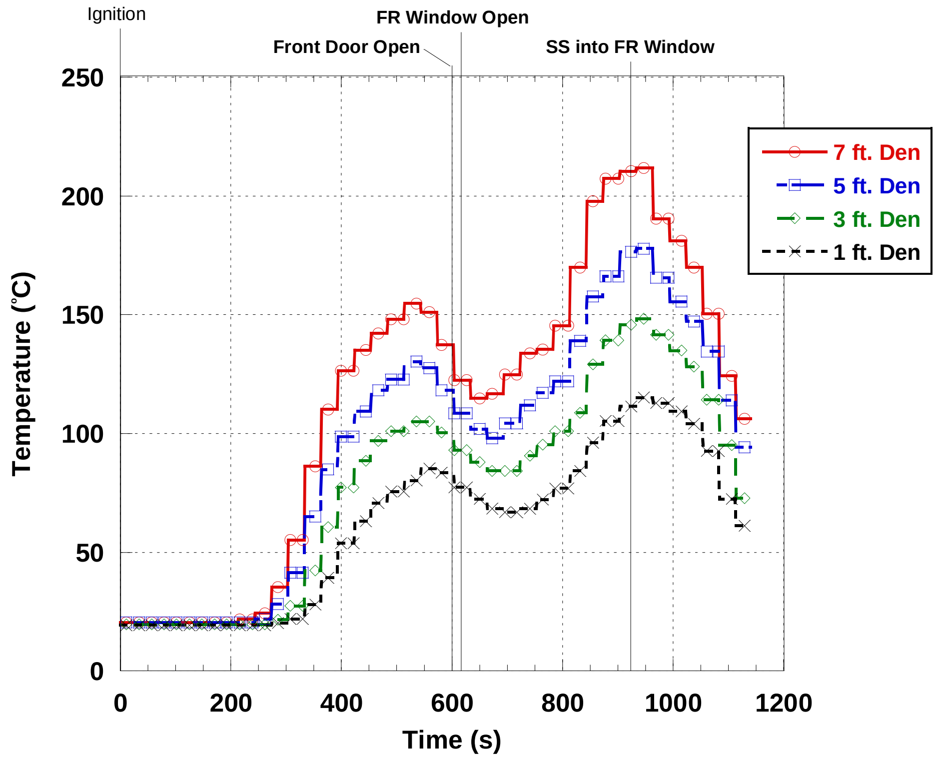


Figure 659. Experiment 11 - Den

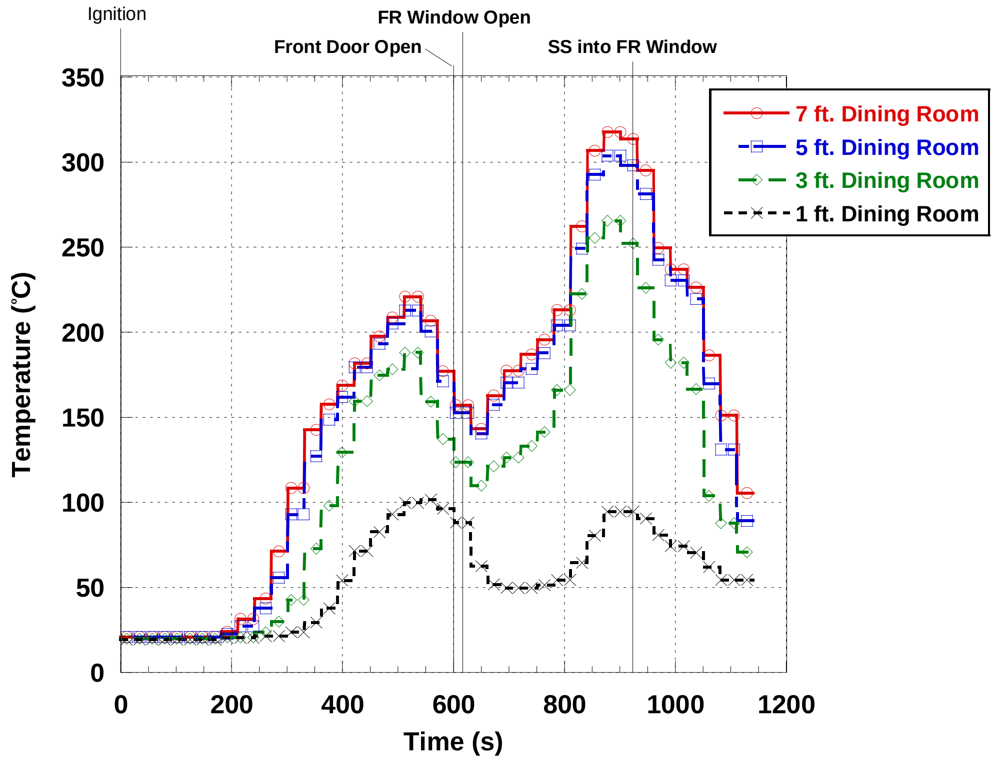


Figure 660. Experiment 11 - Dining Room

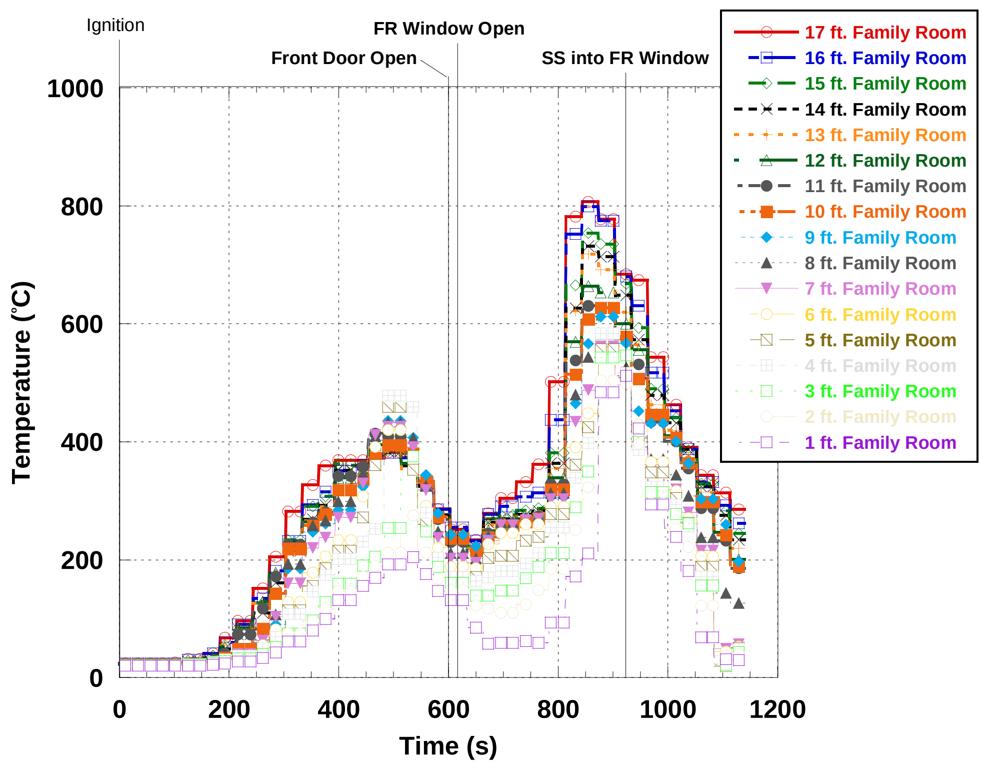


Figure 661. Experiment 11 - Family Room

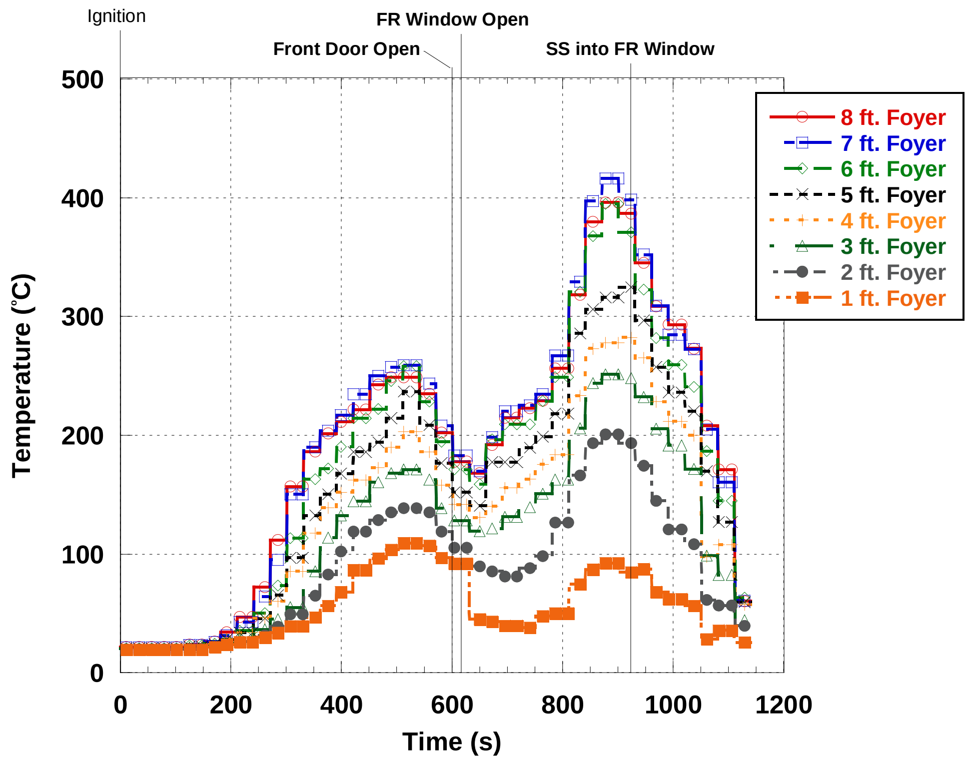


Figure 662. Experiment 11 - Foyer

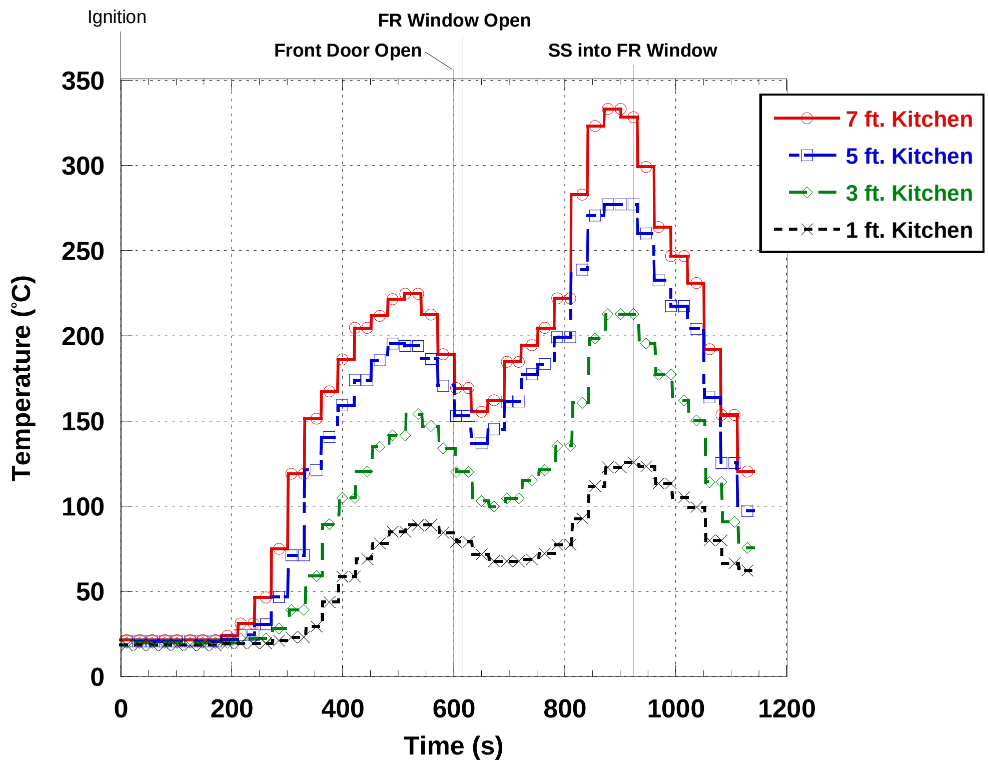


Figure 663. Experiment 11 - Kitchen

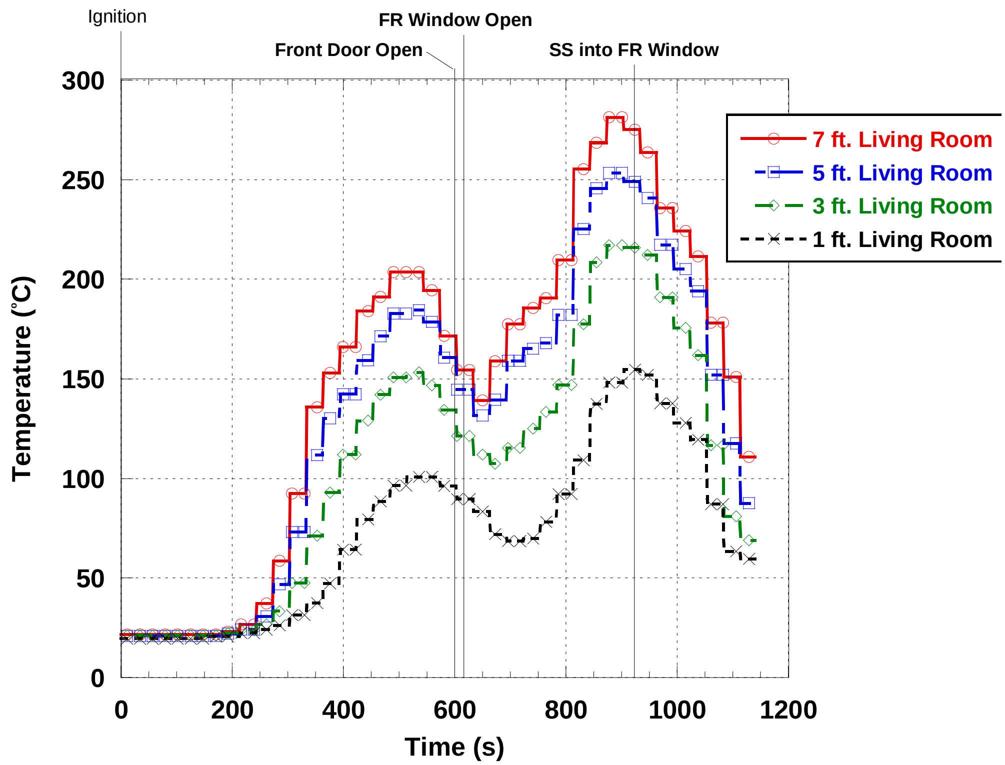


Figure 664. Experiment 11 - Living Room

Experiment 12

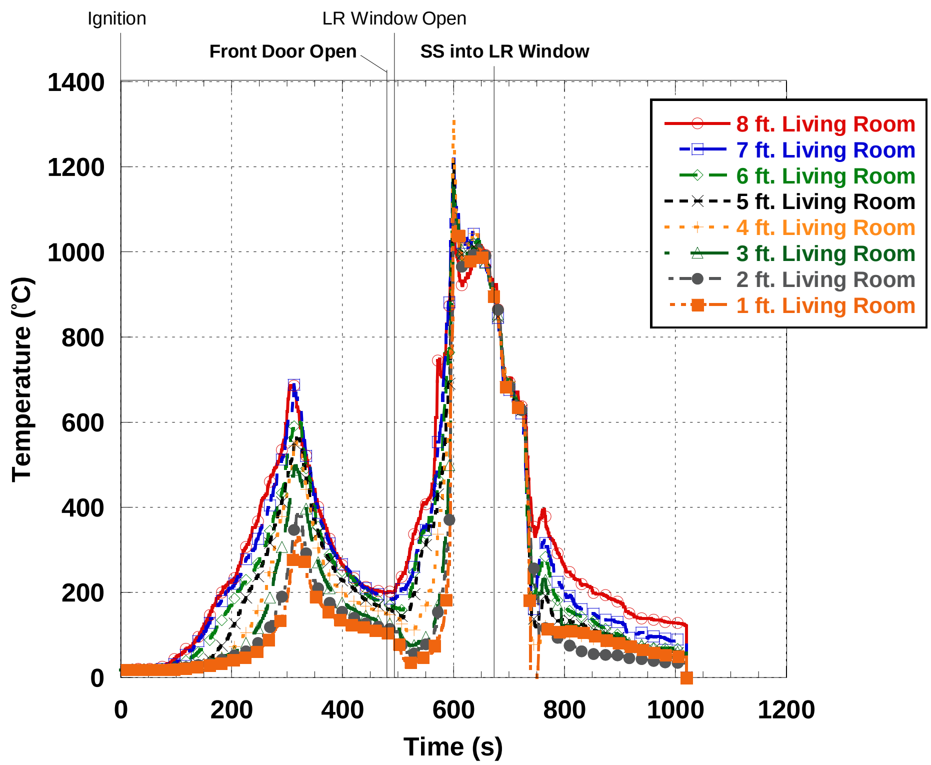


Figure 665. Experiment 12 - Living Room

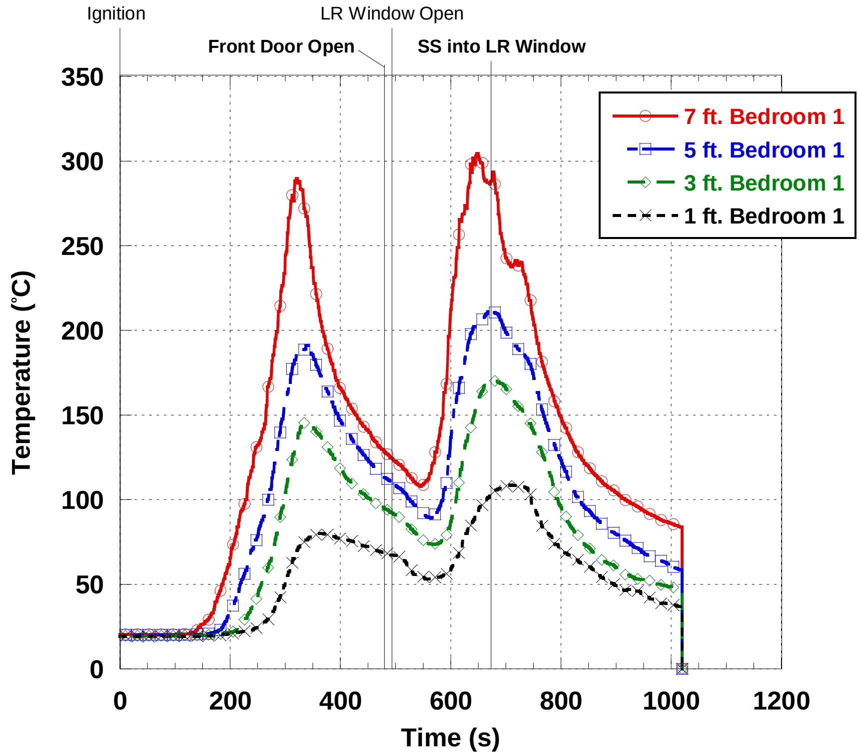


Figure 666. Experiment 12 - Bedroom 1

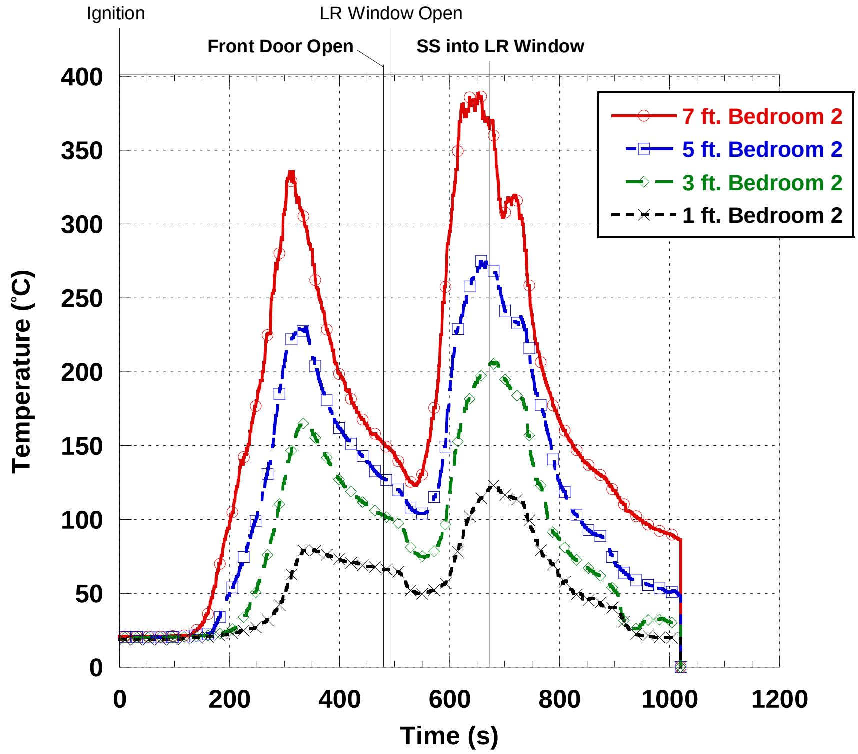


Figure 667. Experiment 12 - Bedroom 2

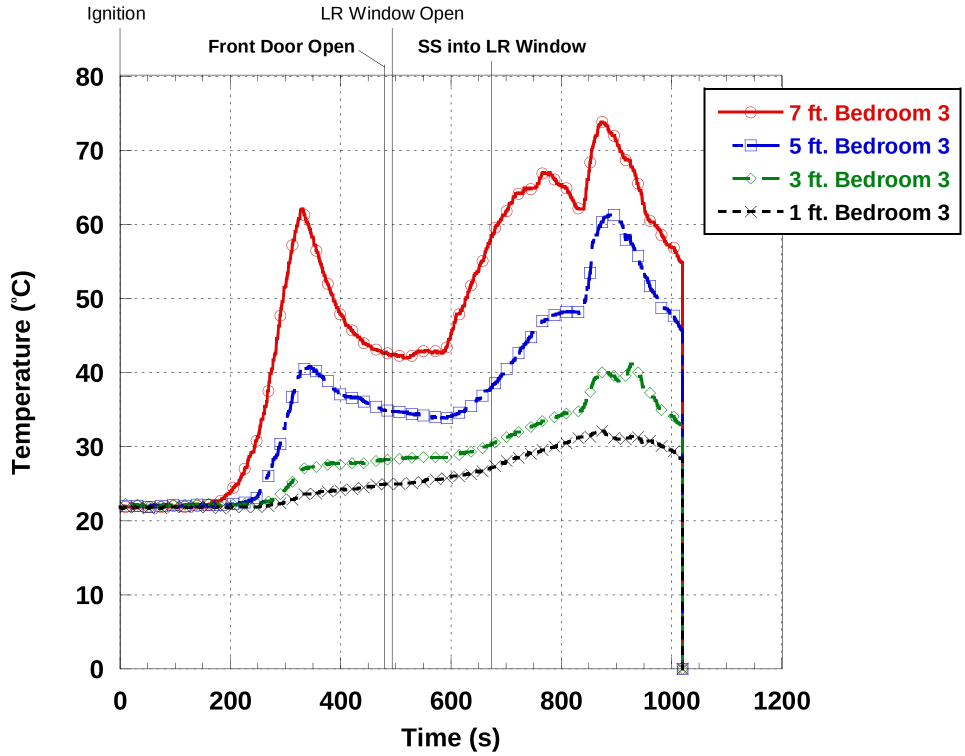


Figure 668. Experiment 12 - Bedroom 3

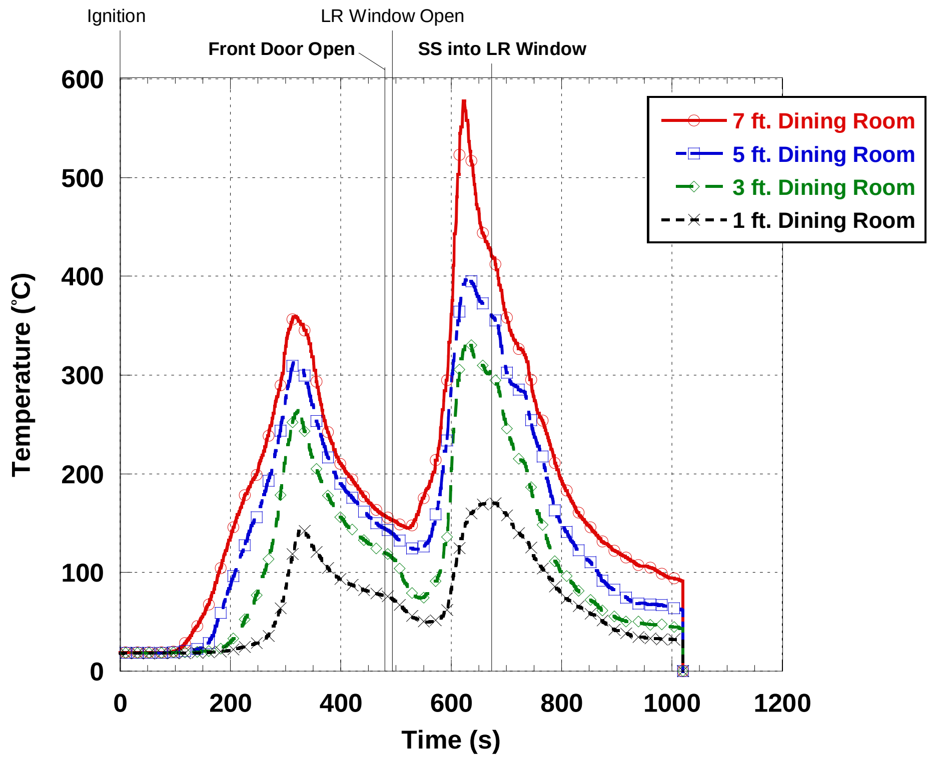


Figure 669. Experiment 12 - Dining Room

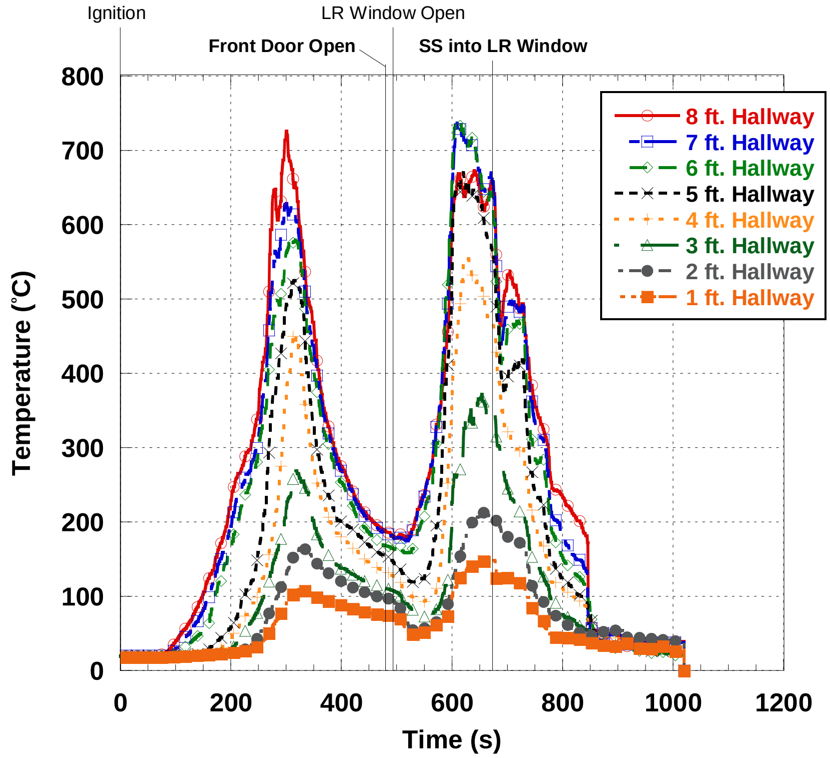


Figure 670. Experiment 12 - Hallway

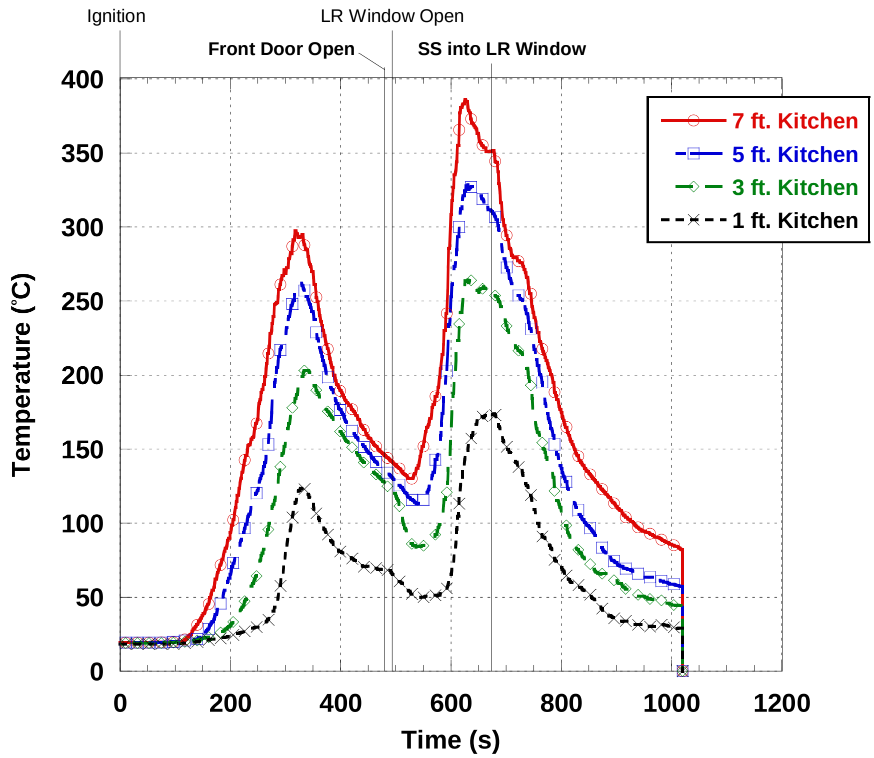


Figure 671. Experiment 12 - Kitchen

Experiment 13

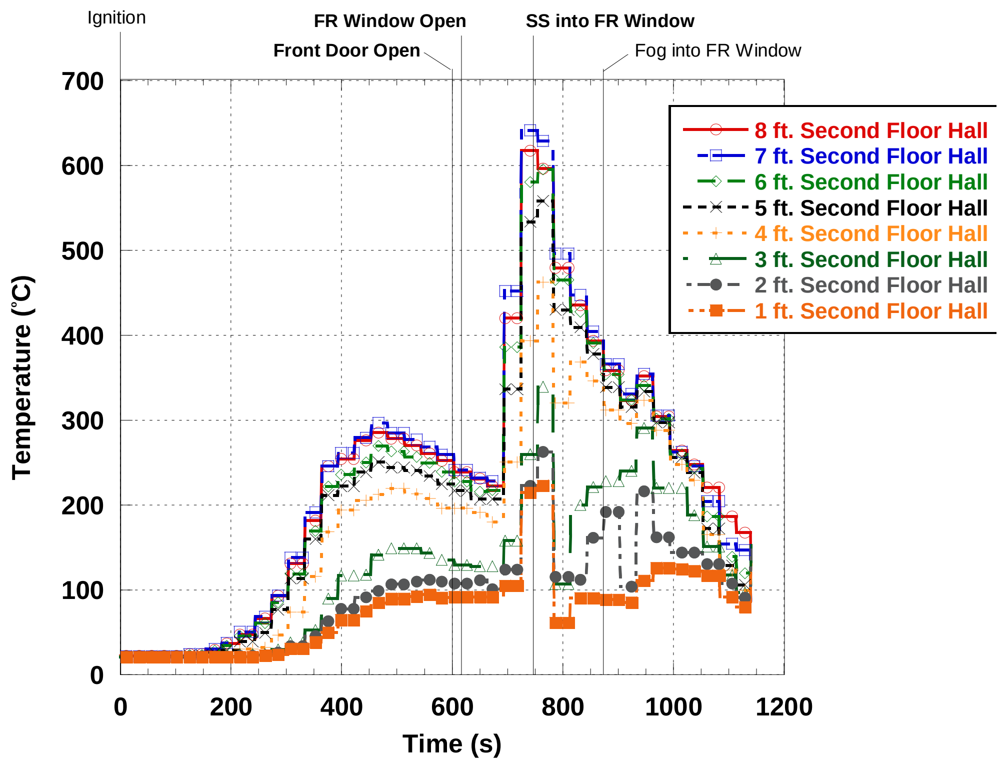


Figure 672. Experiment 13 - Second Floor Hall

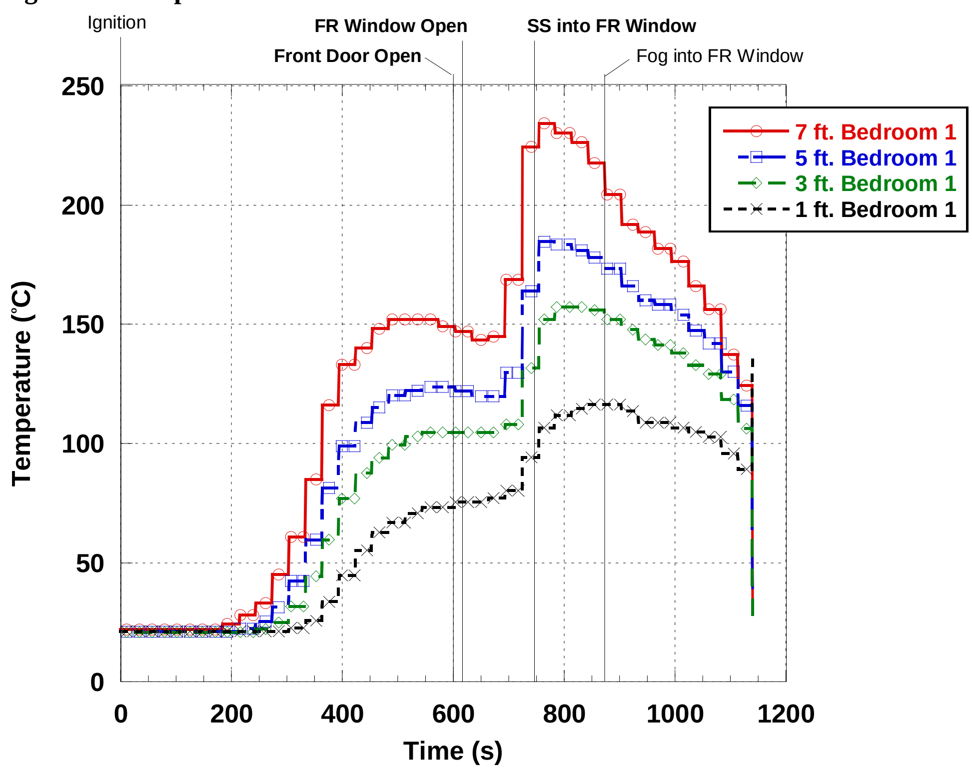


Figure 673. Experiment 13 - Bedroom 1

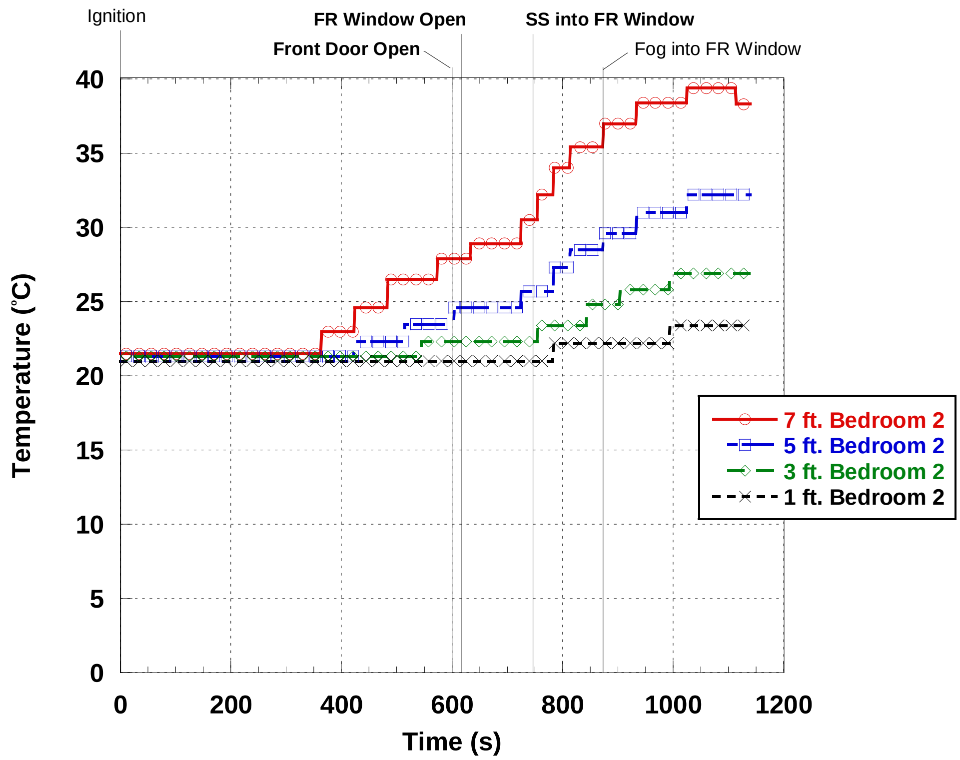


Figure 674. Experiment 13 - Bedroom 2

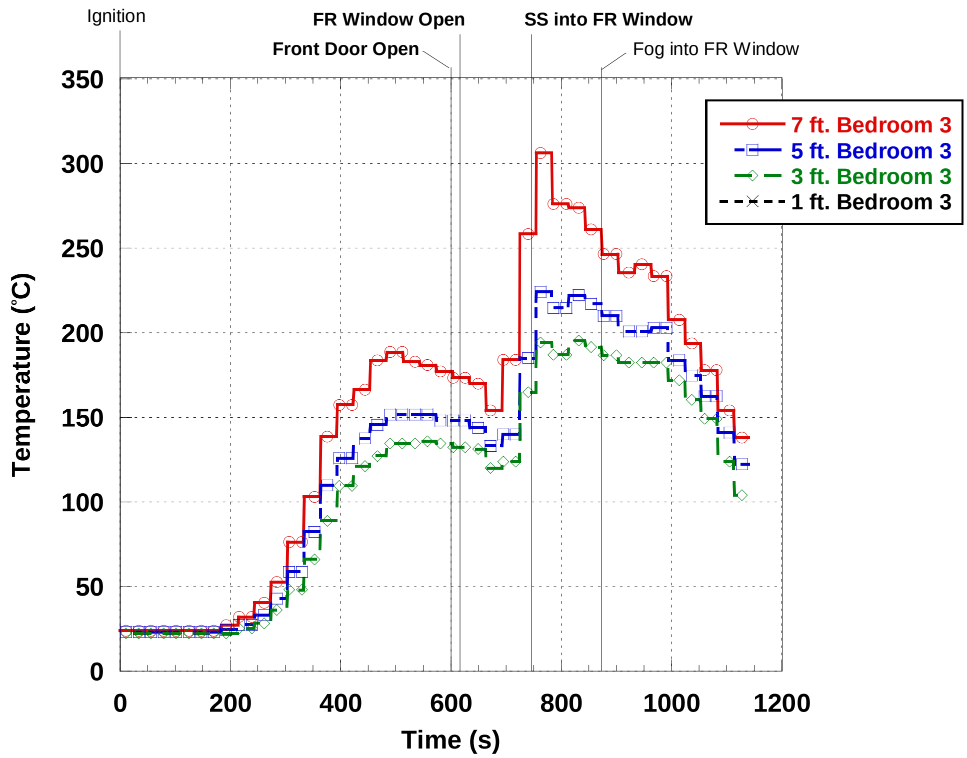


Figure 675. Experiment 13 - Bedroom 3

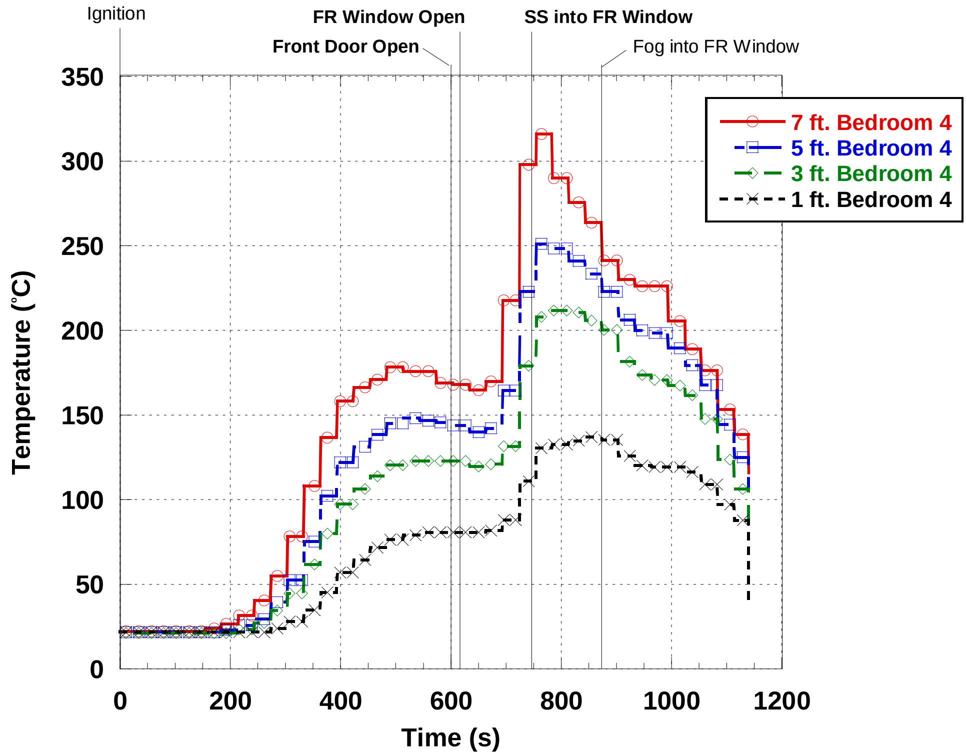


Figure 676. Experiment 13 - Bedroom 4

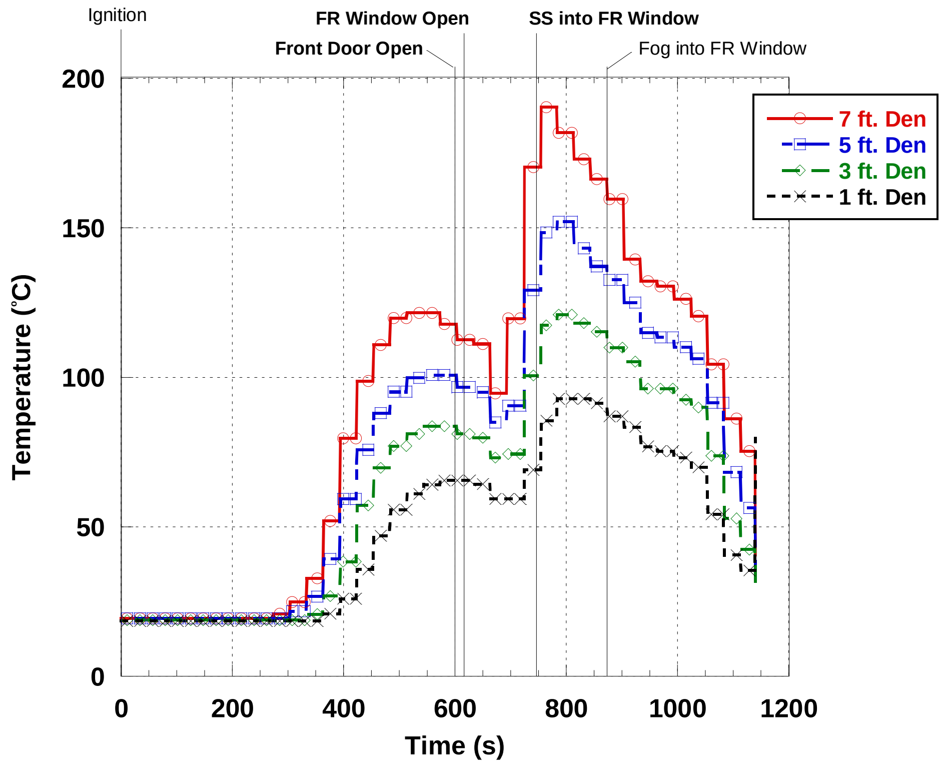


Figure 677. Experiment 13 - Den

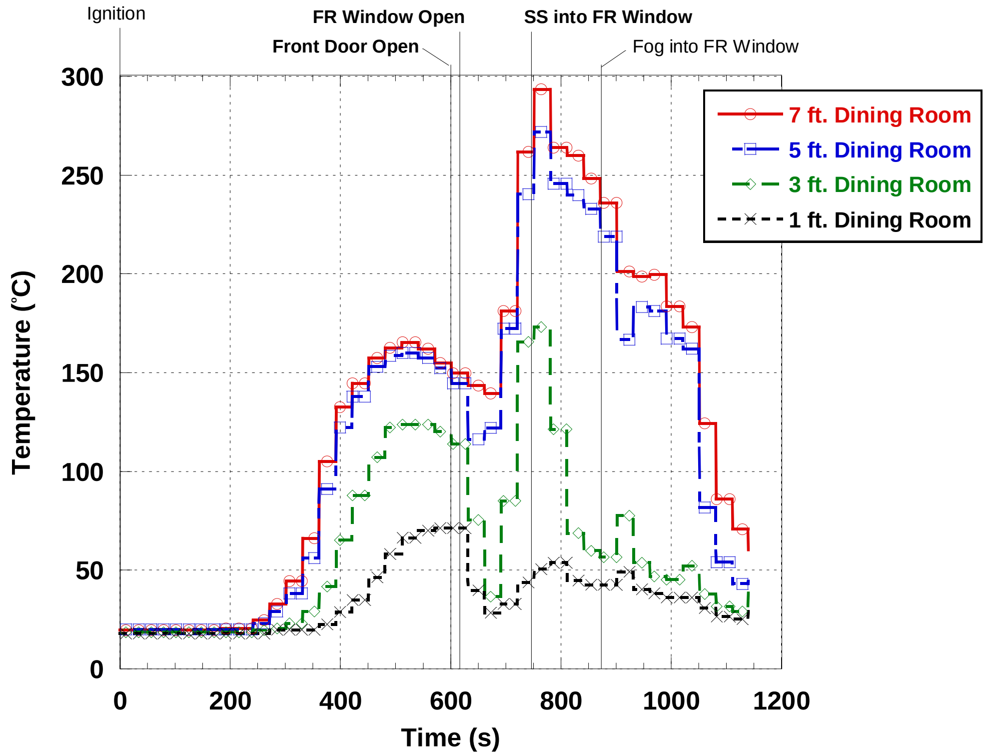


Figure 678. Experiment 13 - Dining Room

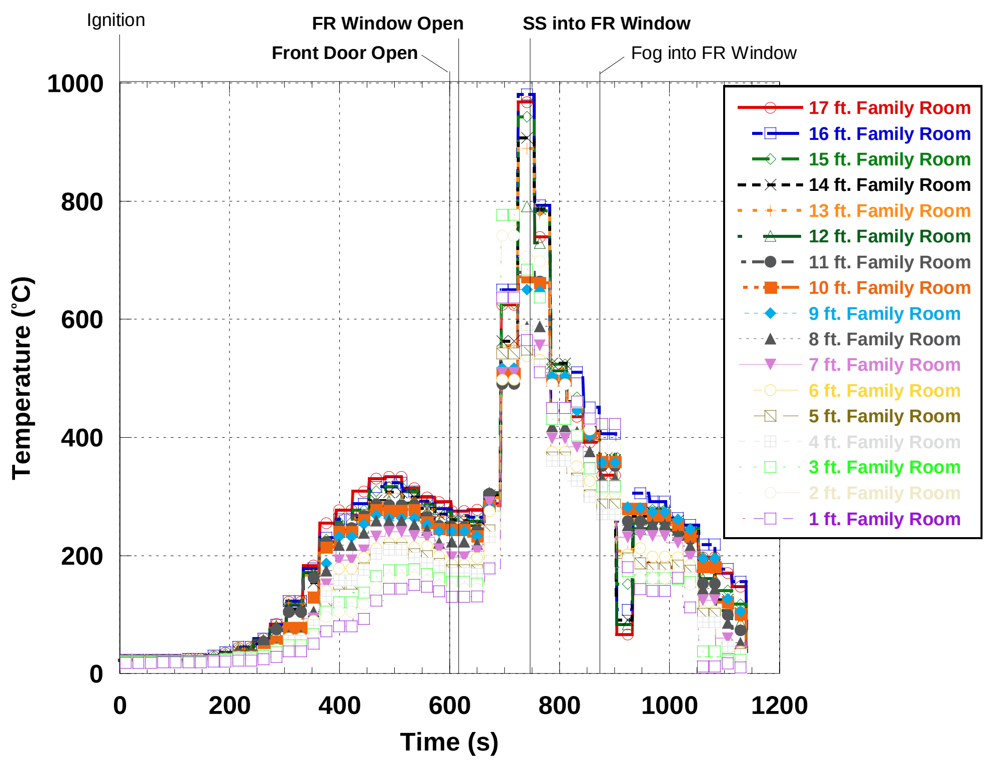


Figure 679. Experiment 13 - Family Room

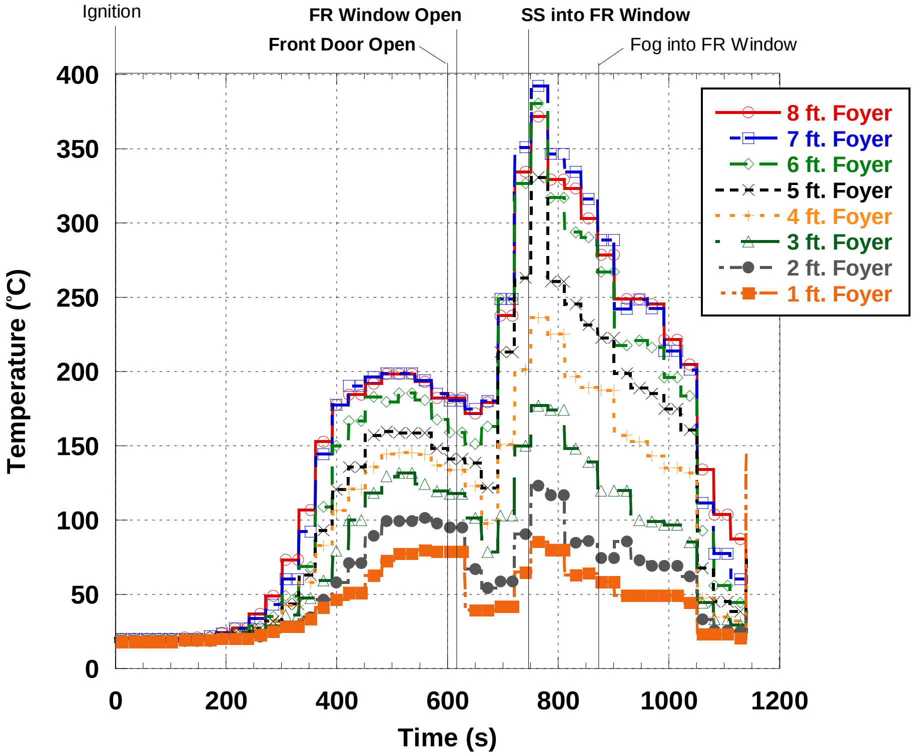


Figure 680. Experiment 13 - Foyer

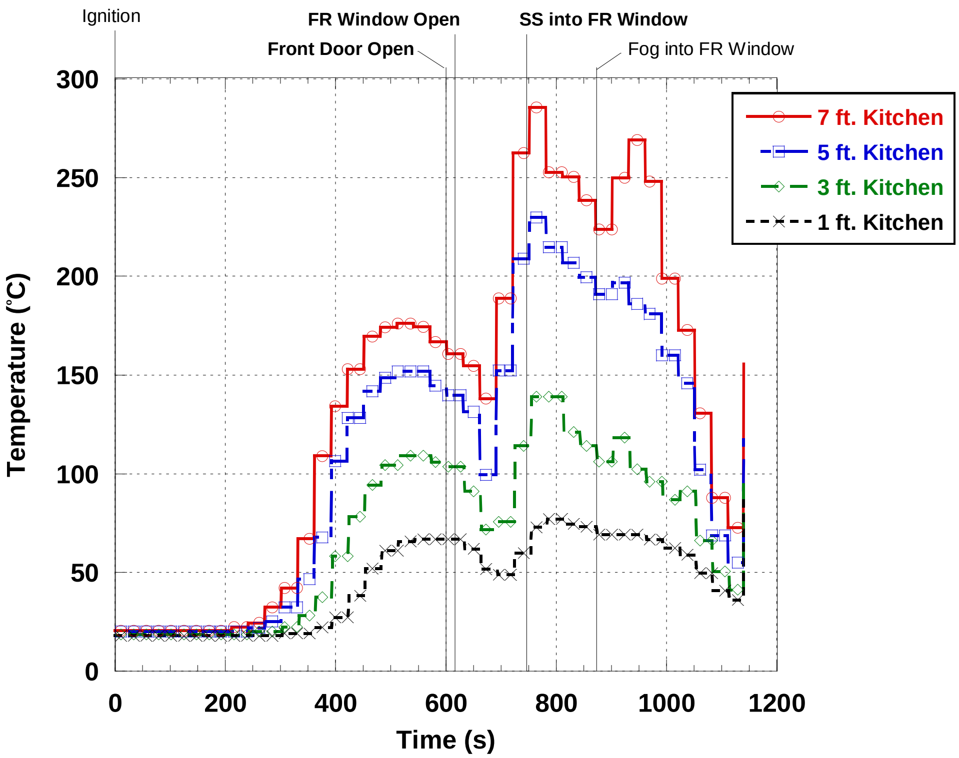


Figure 681. Experiment 13 - Kitchen

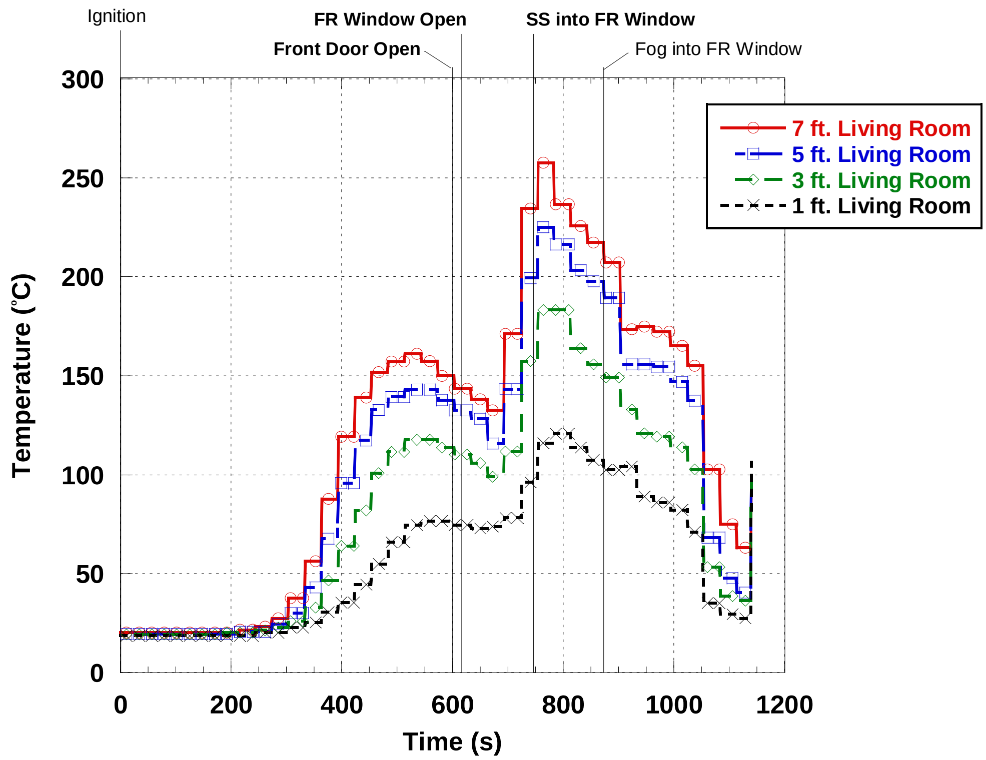


Figure 682. Experiment 13 - Living Room

Experiment 14

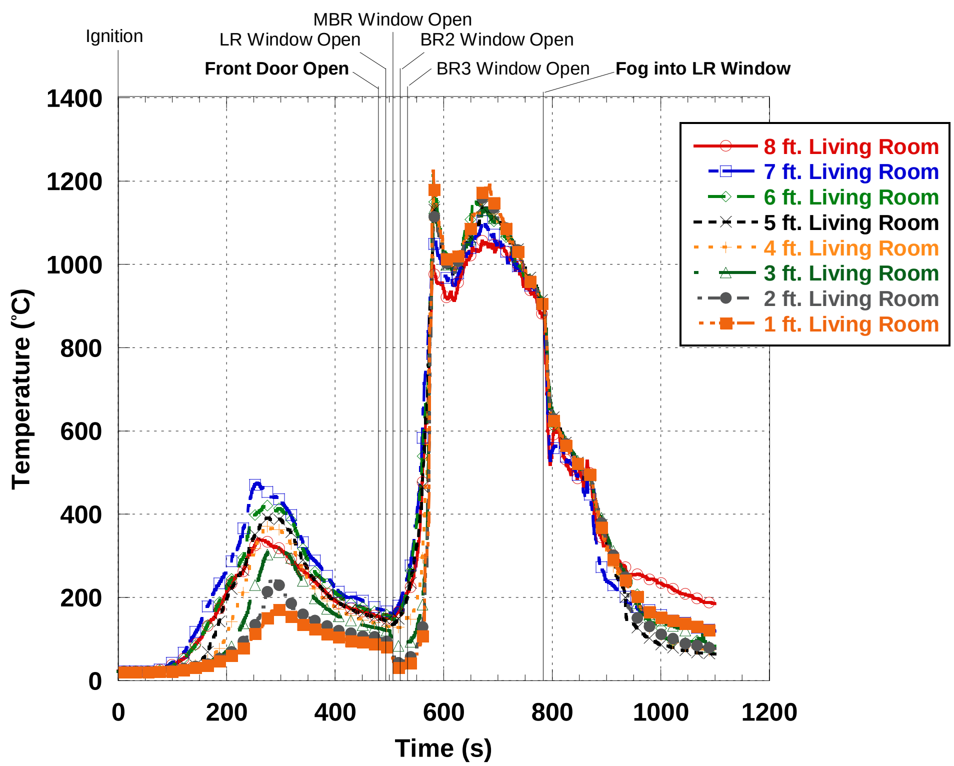


Figure 683. Experiment 14 - Living Room

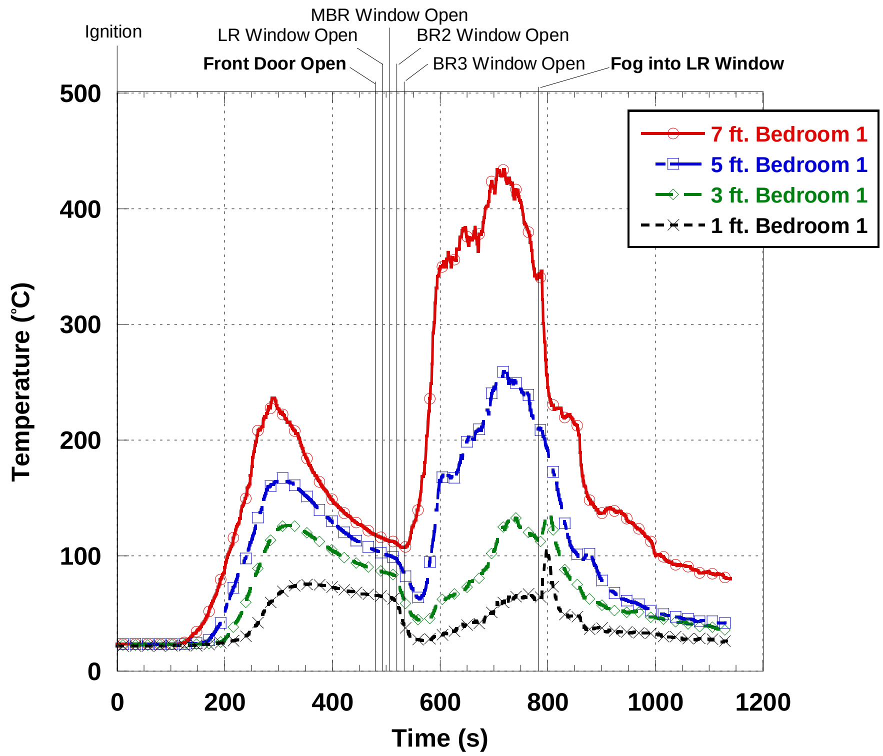


Figure 684. Experiment 14 - Bedroom 1

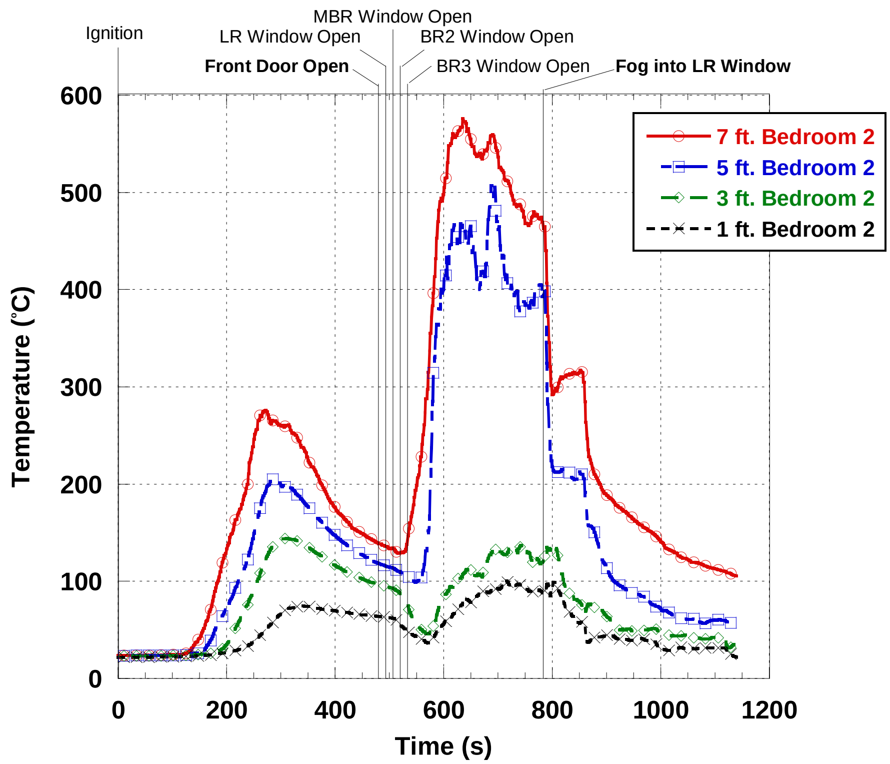


Figure 685. Experiment 14 - Bedroom 2

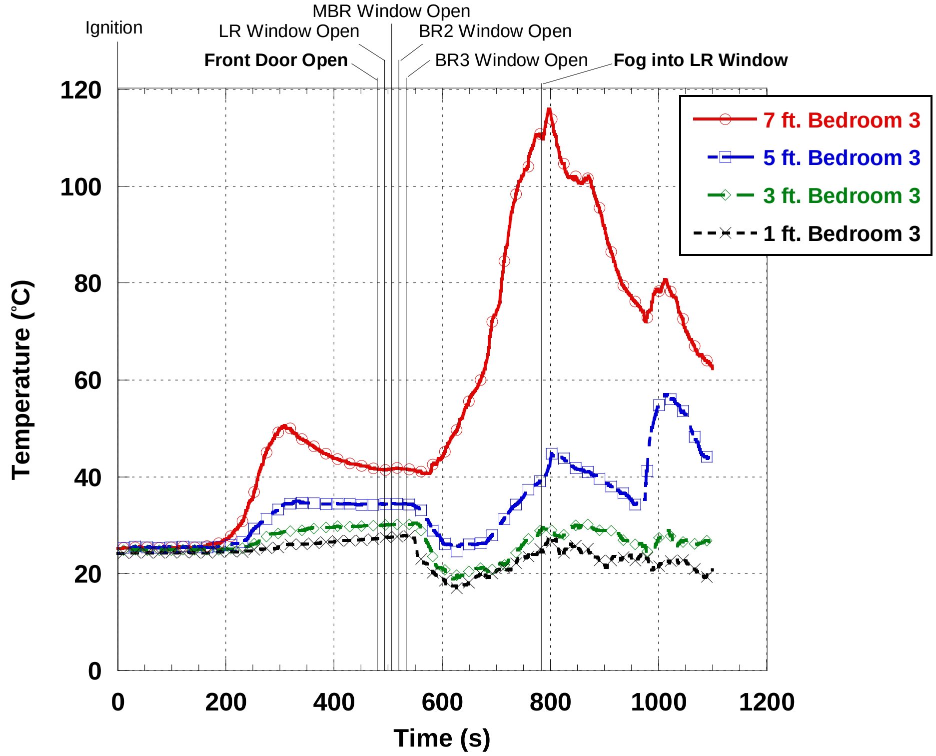


Figure 686. Experiment 14 - Bedroom 3

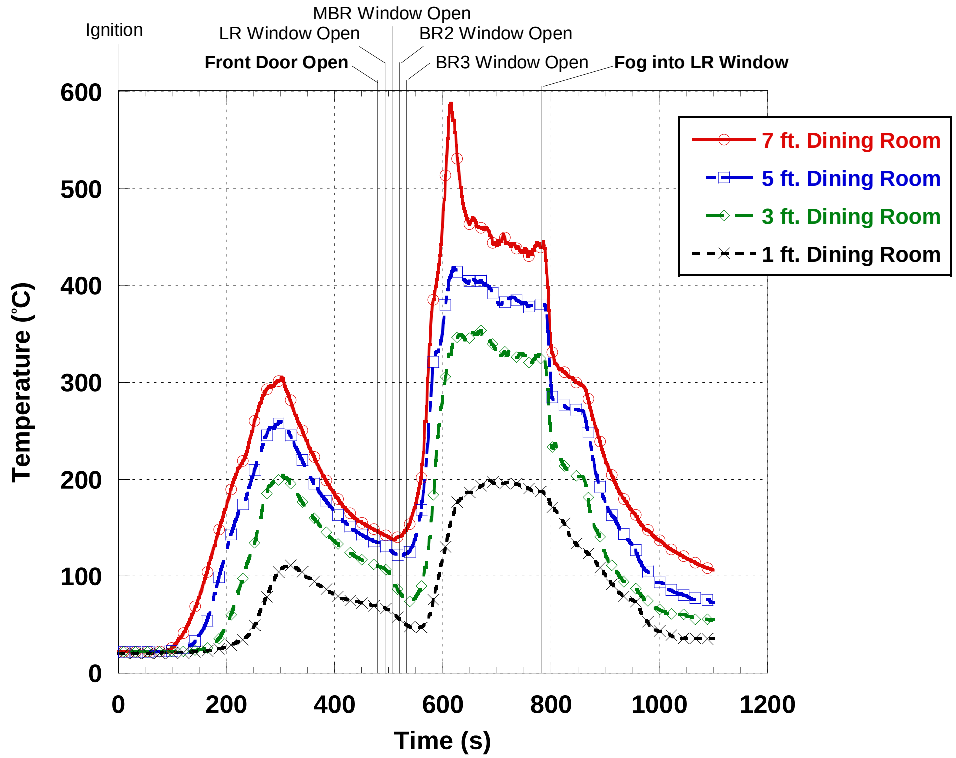


Figure 687. Experiment 14 - Dining Room

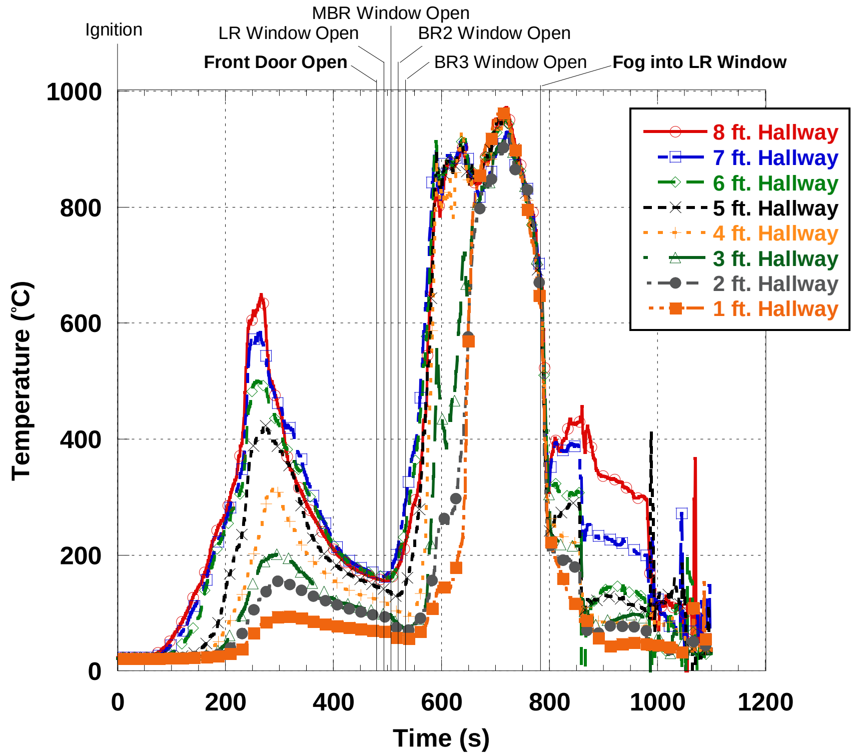


Figure 688. Experiment 14 - Hallway

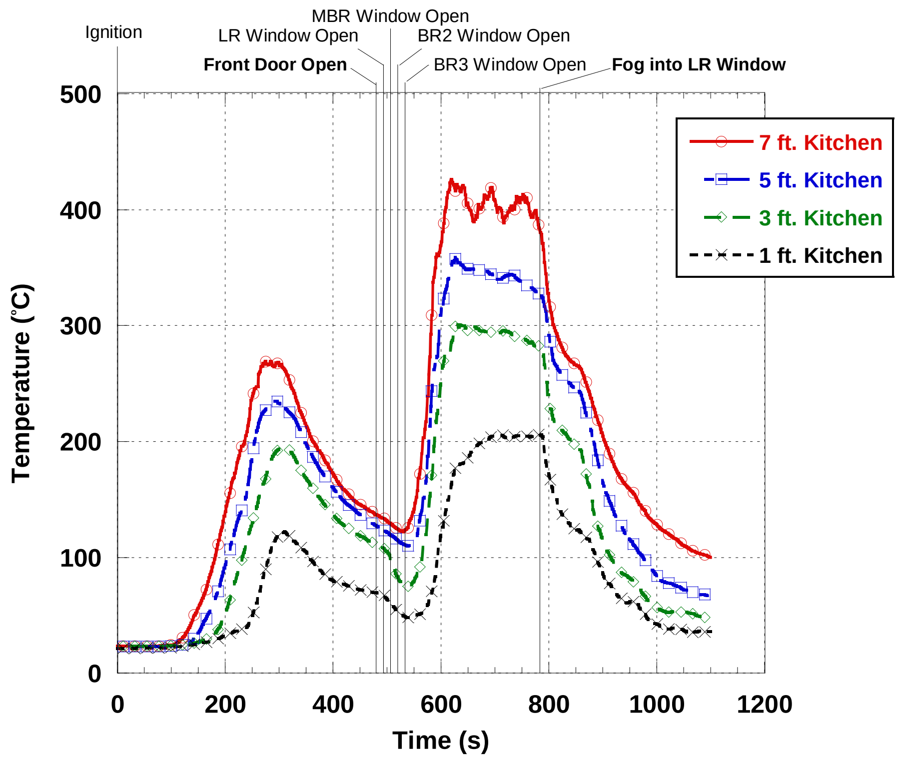


Figure 689. Experiment 14 - Kitchen

Experiment 15

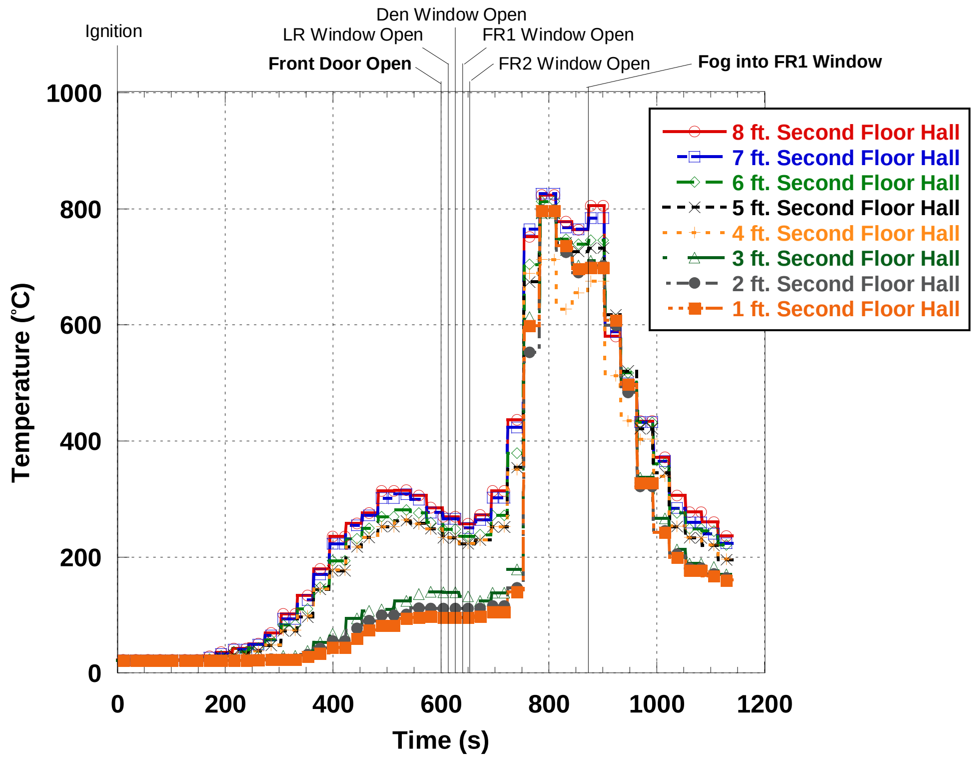


Figure 690. Experiment 15 - Second Floor Hall

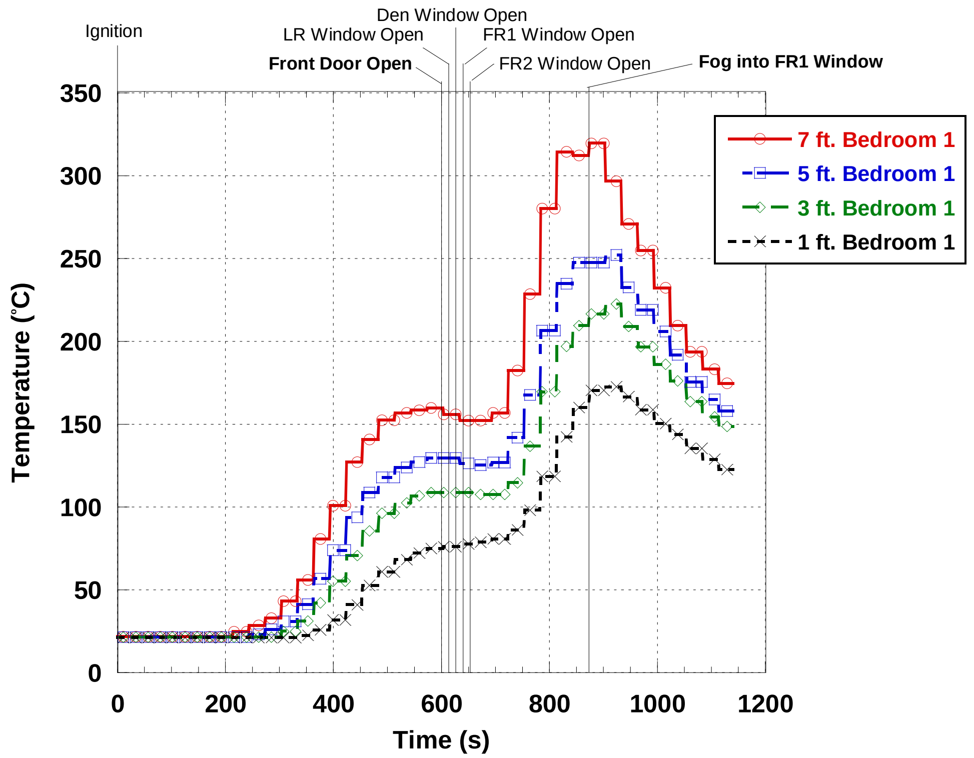


Figure 691. Experiment 15 - Bedroom 1

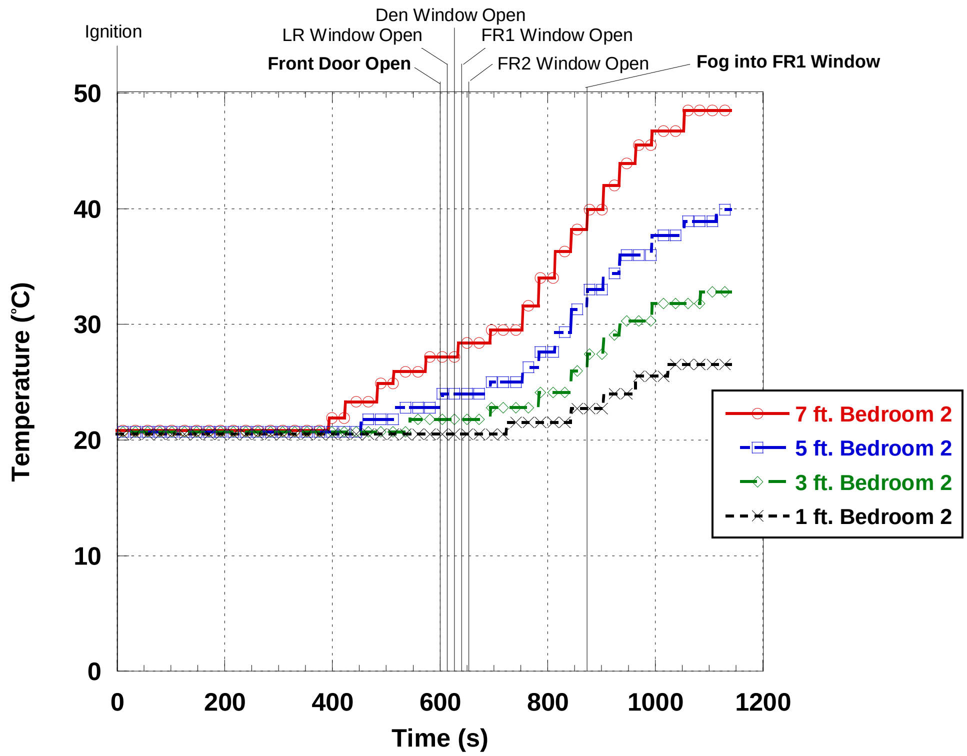


Figure 692. Experiment 15 - Bedroom 2

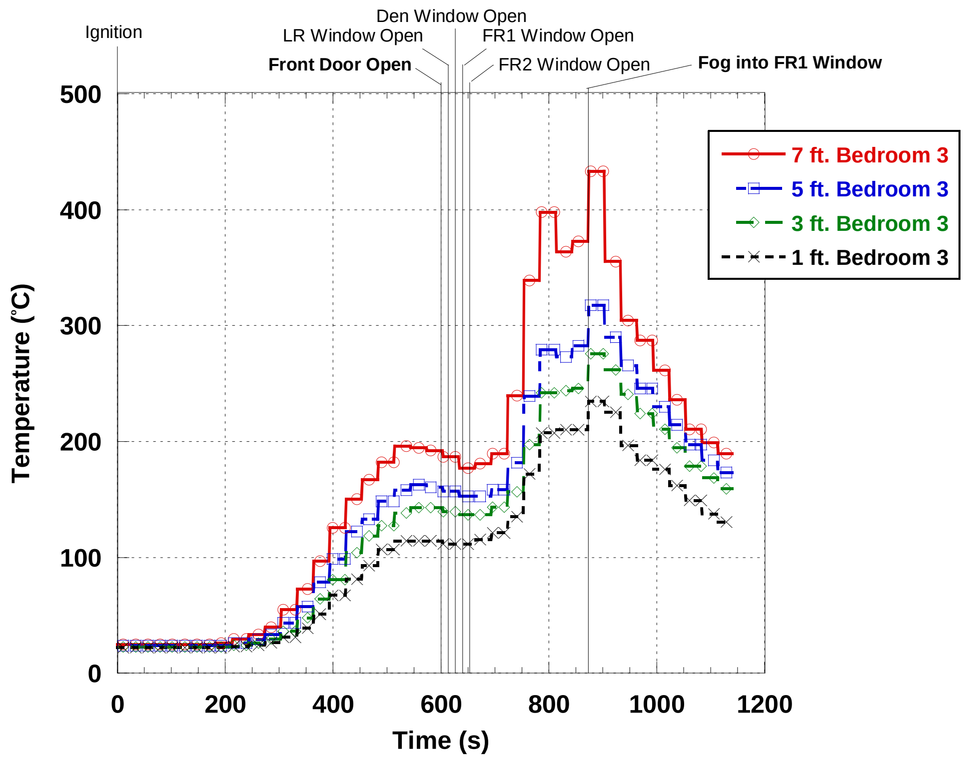


Figure 693. Experiment 15 - Bedroom 3

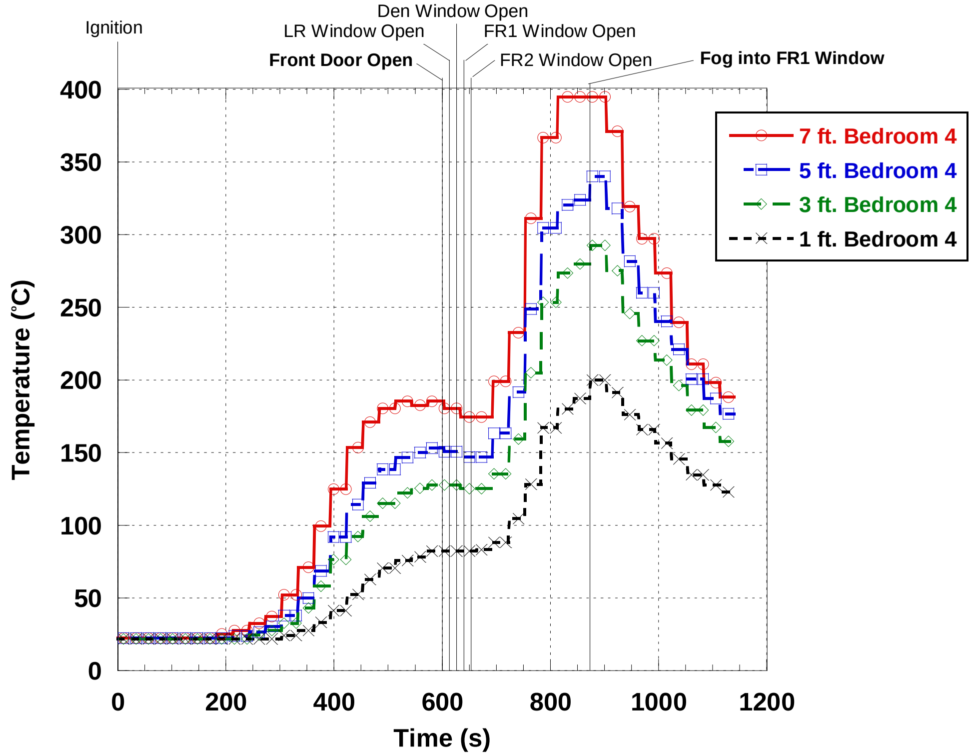


Figure 694. Experiment 15 - Bedroom 4

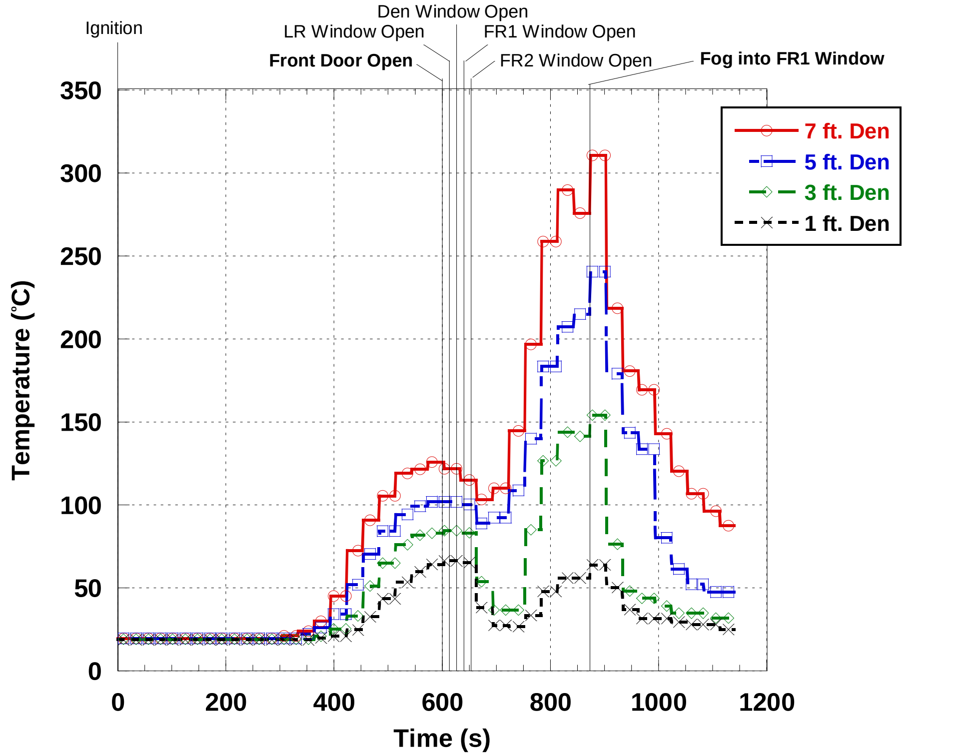


Figure 695. Experiment 15 - Den

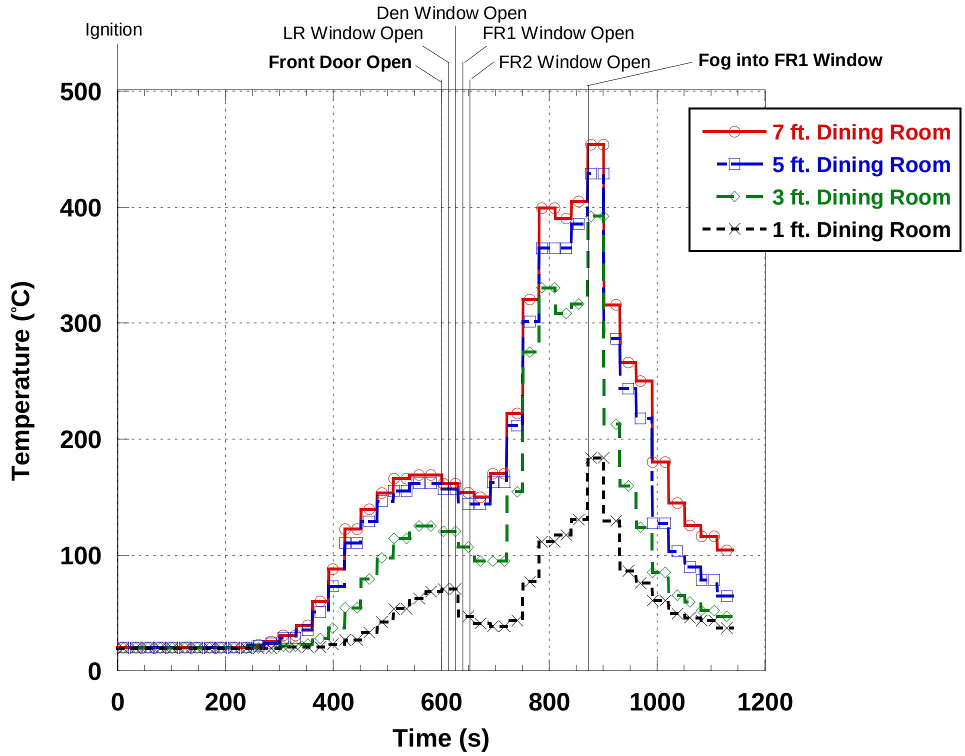


Figure 696. Experiment 15 - Dining Room

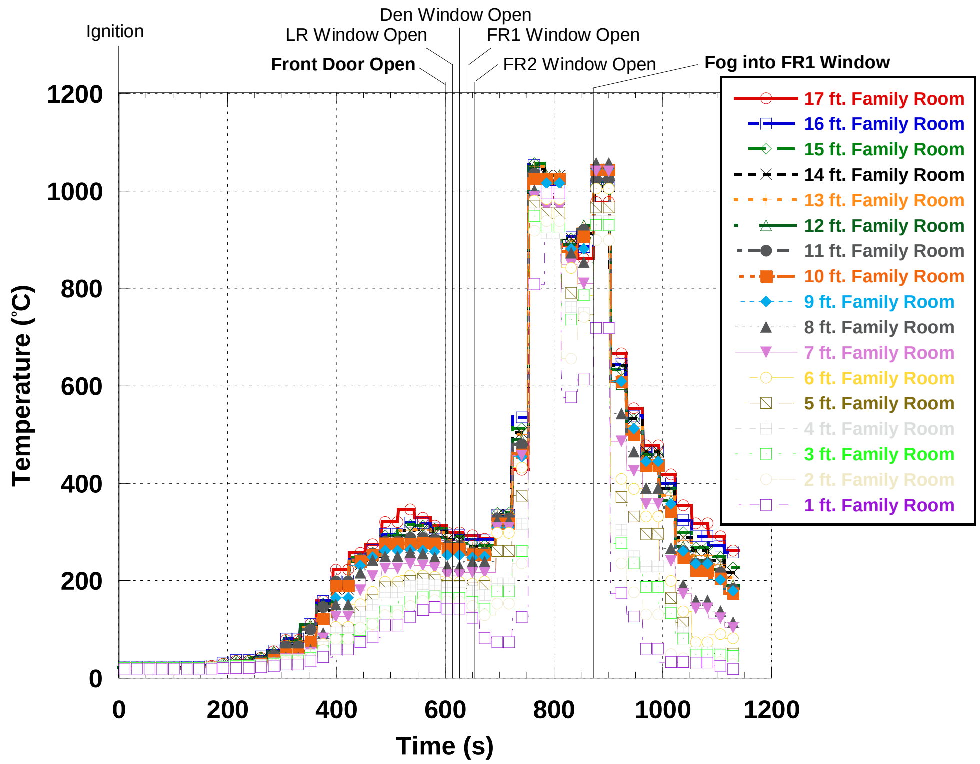


Figure 697. Experiment 15 - Family Room

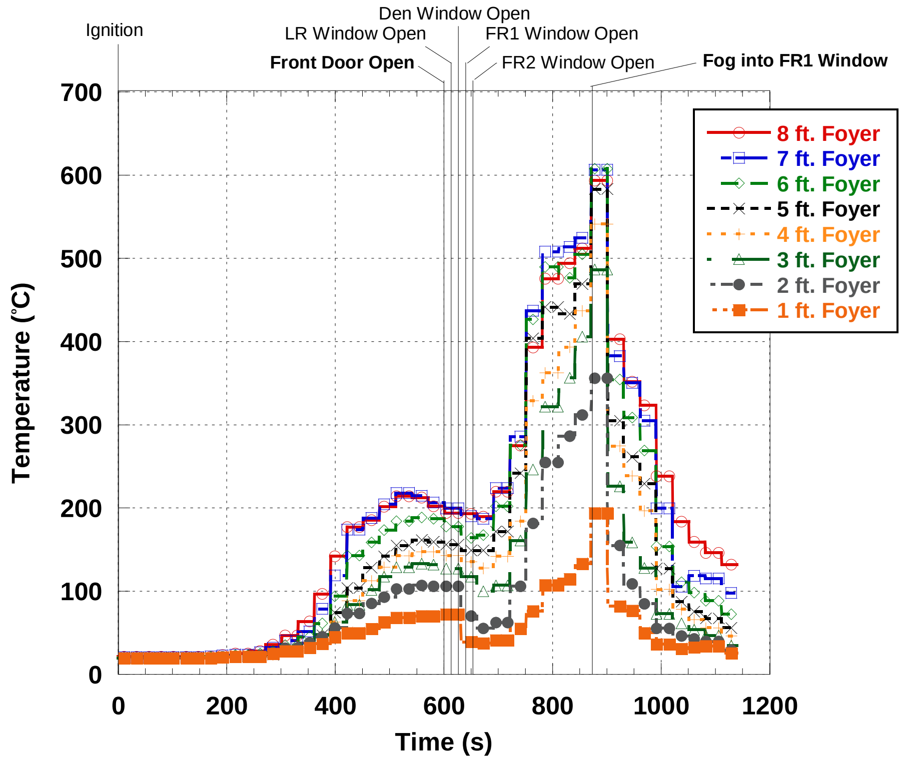


Figure 698. Experiment 15 - Foyer

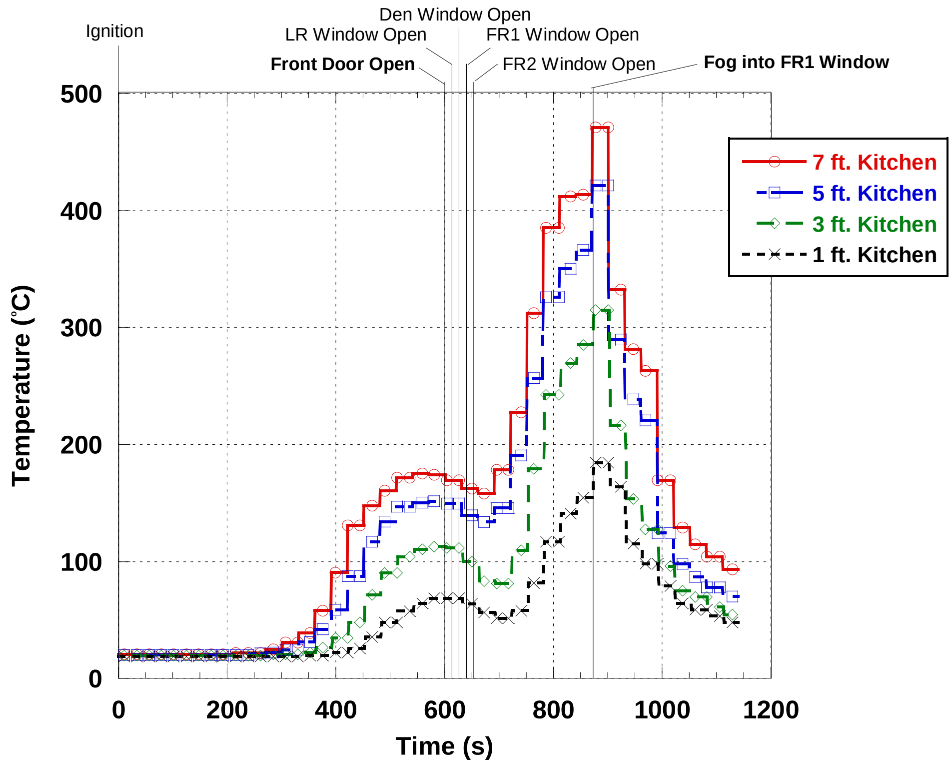


Figure 699. Experiment 15 - Kitchen

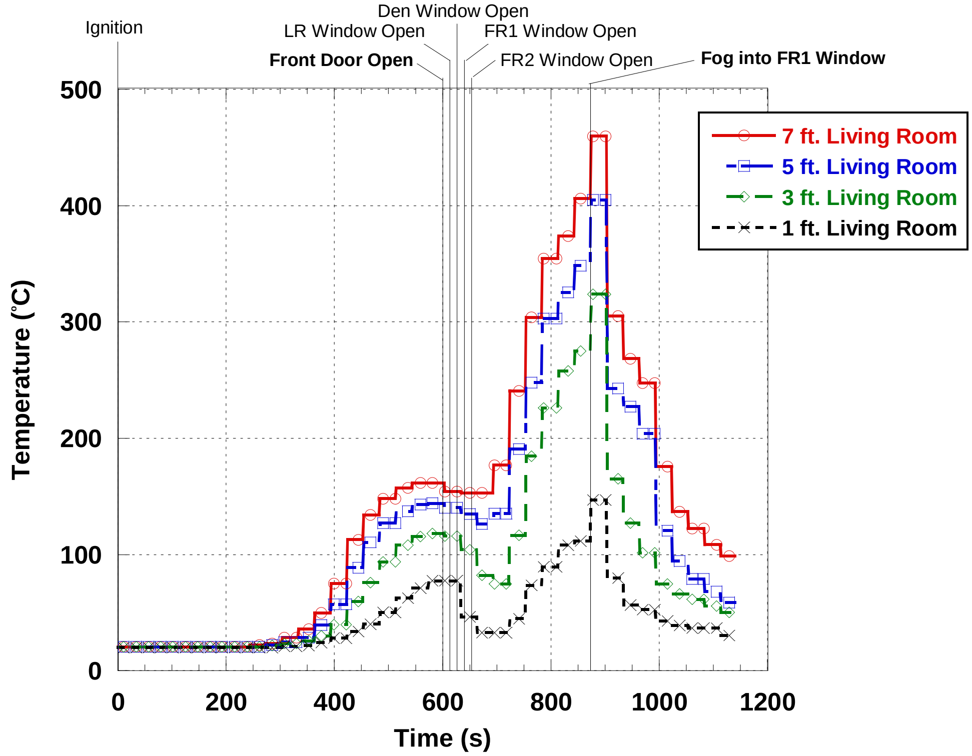


Figure 700. Experiment 15 - Living Room