Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes

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Document Information

Release Type	□ Internal □ External (Confidential) X External (Public)	
UL Distribution	UL Firefighter Safety Research Institute	
External Distribution		
Date: June 15, 2013	**Keywords:** Vertical Ventilation, Firefighting, Fire Dynamics, Suppression, Single Family House	
Title: **: Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes**		
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EXECUTIVE SUMMARY

Under the United States Department of Homeland Security (DHS) Assistance to Firefighter Grant Program, Underwriters Laboratories examined fire service ventilation and suppression 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 investigation examined the influence of these changes to the fire behavior and subsequent impact on firefighter tactics relative to horizontal and vertical ventilation and suppression. It is anticipated that the results of this investigation will be incorporated into improved firefighting tactics and decision making to reduce firefighter injuries and fatalities.

Vertical ventilation has been used successfully but also resulted in firefighter fatalities in the past, as it is not easily coordinated with suppression and other fire ground tasks such as horizontal ventilation. It is not straightforward for firefighters to train on the effects of vertical ventilation since fire service training structures and props do not allow for ventilation-limited fire conditions with representative fuel loads and floor plans that will be encountered on the fire ground. Thus, guidance on the effectiveness of vertical ventilation comes from experience gained during real incidents, but under many different fire ground conditions. This has made it difficult to develop comprehensive guidance on the coordination of vertical ventilation with other firefighter tactics, and how these tactics may influence the fire dynamics in the burning home. The purpose of this study was to improve the understanding of the fire dynamics associated with the use of vertical ventilation so that it may be more effectively deployed on the fire ground.

Two houses were constructed in the large fire facility of Underwriters Laboratories in Northbrook, IL. The first house was a one-story house (1200 ft^2, three bedrooms, one bathroom) with a total of 8 rooms. The second house was a two-story house (3200 ft^2, four bedrooms, two and a half bathrooms) with a total of 12 rooms. The second house featured a modern open floor plan, two-story great room and open foyer.

A total of seventeen experiments were conducted varying the ventilation locations and the number of ventilation openings. Ventilation scenarios included ventilating the front door and a window near the seat of the fire (with modern and legacy furnishings) to link to the previous research on horizontal ventilation, opening the front door and ventilating over the fire and remote from the fire. Additional experiments examined controlling the front door, making different sized ventilation holes in the roof and the impact of exterior hose streams.

The results from the experiments led to identification of tactical considerations for the fire service to integrate into their education and fire ground strategies and tactics where applicable. These tactical considerations include:

- **Today's Firefighter Workplace**

The fire service's workplace has changed and one of several significant factors is home furnishings. As compared to legacy furnishings, the modern home furnishings are made of synthetic materials that have significantly higher heat release rates. This shift speeds up the stages of fire development creating an increased potential for ventilation-limited fire conditions prior to fire department arrival. Most importantly, the time between tactical ventilation and flashover are 2 minutes for the modern fire and over 8 minutes in the legacy fire. The legacy fire could be described as forgiving as it pertains to ventilation. The firefighter has time to recover after poorly timed ventilation or an uncoordinated attack as they have approximately 8 minutes to adapt prior to flashover. The time to recover in the modern fire was approximately 2 minutes or 25% of the legacy time. This data supports the statement that, "You are not fighting your grandfather's fire anymore."

- **Control the Access Door**

Tactically, there are several considerations for door control. Most importantly, it is a temporary action. You have to open a door to gain access into a burning home, but if you limit the air inlet you limit the fire's ability to grow. The fire dynamics of door control are fairly simple. If you have a ventilation-limited fire and you limit the air, then you limit the heat that is able to be released. While this does not completely cut off the oxygen supply, it slows it, which slows fire growth. In these experiments, flashover was delayed for minutes by limiting the air supply. The longer and further the door is closed, the slower the fire will grow. The door should be controlled until water is applied to the fire. Once water goes on the fire and the attack crew has the upper hand, meaning more energy is being absorbed by the water than is being created by the fire, and then the door may be fully opened by firefighters to ventilate.

- **Coordinated Attack Includes Vertical Ventilation**

"Taking the lid off" does not guarantee positive results. Vertical ventilation is the most efficient type of natural ventilation. While it allows the largest amount of hot gases to exit the structure, it also allows the most air to be entrained into the structure. Coordination of vertical ventilation must occur with fire attack just like with horizontal ventilation. The way to make sure that the fire does not get larger and that ventilation works as intended is to take the fire from ventilation-limited (needs air to grow) to fuel-limited by applying water. As soon as the water has the upper hand (more energy is being absorbed by the water than is being created by the fire), ventilation will begin to work as intended. With vertical ventilation this will happen faster than with horizontal ventilation assuming similar vent sizes.

- **How big of a hole?**

A 4 ft. by 8 ft. hole over a ventilation-limited fire does not allow more smoke and hot gases to exit than it creates. A 4 ft. by 8 ft. hole above the fire in each of the houses alone did not improve conditions or make ventilation-limited fire conditions into fuel-limited conditions. When water was applied to the fire to reduce the burning rate, the fire became a fuel-limited fire. Once the fire was fuel-limited, the larger the hole the better conditions became for any potential victims or firefighters operating inside the structure.

- **Where do you vent?**

Ventilating over the fire is the best choice if your fire attack is coordinated. The closer the source of the air to the seat of the fire, the quicker it will increase in size. Placement of vertical ventilation can be a complex situation, especially if you do not know where the fire is in the house. Optimally, where you vertically ventilate depends on the room geometry, door locations, air inlet location, and subsequent flow paths. If you ventilate in coordination with fire attack (the hose stream is removing more energy than is being created), then it does not matter where you ventilate, but the closer to the seat of the fire, the more efficient the vent will be in removing heat and smoke, which will improve conditions for the remainder of the operations taking place on the fire ground. Ventilating remote from the fire can be effective under some circumstances. If the fire is in a room that is connected to the rest of the house by a doorway, ventilating the roof outside of that room could allow for smoke to be cleared from the rest of the house. However, as air is entrained to the room, fire will increase in size, while visibility may improve in the flow path leading from the air inlet to the fire room. This is an example where the vertical ventilation may improve visibility even though the fire may grow and local temperatures may increase.

- **Stages of Fire Growth and Flow Paths**

The stage of the fire (i.e., ventilation or fuel limited), the distance from the inlet (door or window) air to the fire, the distance from the fire to the outlet (door, window, roof vent), the shape of the inlet and outlet, and the type and shape of items (furniture or walls) or openings (interior doors) in the flow paths all play key roles in the availability of oxygen to the fire, and ultimately firefighter safety. Operations conducted in the flow path can place firefighters at significant risk due to the increased flow of fire, heat, and smoke toward their position.

- **Timing is Everything**

The purpose of venting is to improve the conditions for firefighters to operate. Some of these improved conditions are cooling, increased visibility, and useful flow paths opposite a hose line to release steam expansion. It is not possible to make statements about the effectiveness of ventilation unless one includes timing. Venting does not always lead to cooling; well-timed and coordinated ventilation leads to improved conditions. That same ventilation action 30 seconds earlier or later could have a dramatically different outcome. This is especially true for vertical ventilation. Vertical ventilation is efficient in venting heat and smoke but also causes rapid changes in the conditions in the home. Additional considerations about timing include (i) the fire does not react to additional oxygen instantaneously; (ii) the higher the interior temperatures the faster the fire reacts; (iii) the closer the air is to the fire the faster it reacts; (iv) the higher the ventilation the faster the fire reacts; (v) the more air the faster the fire reacts, the more exhaust the more air that is able to be entrained.

- **Reading Smoke**

Looking at smoke conditions is a very important component of size-up, but firefighters should not get complacent if there is nothing showing on arrival. In many of the experiments the smoke color changed from black to grey as the fire became ventilation-limited and the pressure within the house decreased. Ten seconds later there was no visible smoke showing at all. No or little smoke showing could mean a fuel-limited fire that is producing little smoke or it could mean a ventilation-limited fire that is in the initial decay stage and starved for air. In order to increase firefighter safety, consider treating every fire like it is ventilation-limited until proven otherwise.

- **Impact of Shut Door on Victim Tenability and Firefighter Survivability**

Behind a closed door is the most likely place to find a victim that can be rescued. 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. Every experiment included one closed bedroom next to an open bedroom. In every experiment a victim in the closed bedroom was survivable and able to function well through every experiment and well after fire department arrival. In the open bedroom potential victims would be unconscious if not deceased prior to fire department arrival or as a result of fire ventilation actions.

- **Softening the Target**

Applying water into the fire compartment as quickly as possible, regardless of where it is from, can make conditions in the entire structure better. During these experiments water was applied into a door or window with fire coming from it or with access to the fire from the exterior for approximately 15 seconds. This small amount of water had a positive impact on conditions within the houses increasing the potential for victim survivability and firefighter safety. This included stopping water flow for 60 seconds while conditions were monitored. If a firefighter crew had moved in and continued to suppress fire, the conditions would have improved that much faster. During size-up firefighter crews should assess the fastest and safest way to apply water to the fire. This could be by applying water through a window, through a door, from the exterior or from the interior.

- **You Can't Push Fire**

You cannot push fire with water. The previous UL study (Kerber S. , 2010) discussed the concept of pushing fire in the data analysis. Since the release of that study there has been a lot of discussion about this and stories from well-respected fire service members where this did happen or was perceived to happen. The specific fires that were being recalled by the firefighters were discussed in detail. In many of these conversations the firefighters were in the structure and in the flow path opposite the hoseline. In most cases where firefighters experienced fire moving over their heads, fire attack crews were advancing on the inside and not applying water from the outside into a fully developed fire. All of the current experiments described in this report were designed to examine the operations and the impact of the initial arriving fire service units so we did not, do not, and will not suggest that firefighters should be in the position where they are in a flow path opposite the hoseline. However, there are times when this may happen, so the experience of these firefighters should not be discounted. During our discussions, four events could have been witnessed which may have had the appearance of pushing fire: 1) a flow path is changed with ventilation and not water application. 2) A flow path is changed with water application. 3) Turnout gear becomes saturated with energy and passes through to the firefighter

4) One room is extinguished, which allows air to entrain into another room, causing the second room to ignite or increase in burning.

- **Big volume, apply water to what is burning**

In larger volume spaces, such as the family room/great room in the 2-story house, it is important to put water on what is burning. In modern floor plans with open floor plans and great rooms, there is a very large volume, so water application is not the same as a legacy home with smaller rooms and eight foot ceilings. Much of the water applied to a flashover condition in a small room will be applied to burning surfaces and the gases will be cooled as the water is converted to steam. In modern floor plans a stream of water can end up several rooms away from the room that has flashed over. The same open floor plan that can allow water to flow beyond the fire room can allow for suppression of a fire that is several rooms away. In open floor plan houses, the reach of a hose stream can be beneficial where in an older home that is divided, it may not be as useful. In a 2-story floor plan like the one used in these experiments, water can be applied into any room from more than 20 ft. away with some open lines of sight longer than 35 ft. This allows the fire to be knocked down from a safer distance without needing to be in the room or right next to the room to begin suppression. In addition, every bedroom on the second floor could have water flowed into it from the first floor before proceeding up the stairs.

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1. Introduction

There is a continued tragic loss of firefighter and civilian lives, as shown by fire statistics. One significant contributing factor is the lack of understanding of fire behavior in residential structures resulting from the use of ventilation as a firefighter practice on the fire ground. The changing dynamics of residential fires as a result of the changes in home construction materials, contents, size and geometry over the past 30 years compounds our lack of understanding of the effects of ventilation on fire behavior (Kerber S. , 2012). If used properly, ventilation improves visibility and reduces the chance of flashover or back draft. If a fire is not properly ventilated, it could result in an anticipated flashover, greatly reducing firefighter safety (Kerber S. , 2012).

This fire research project developed empirical data from full-scale house fire experiments to examine vertical ventilation, suppression techniques and the resulting fire behavior. The purpose of this study was to improve firefighter knowledge of the effects of vertical ventilation and the impact of different suppression techniques. The experimental results may be used to develop tactical considerations outlining firefighting ventilation and suppression practices to reduce firefighter death and injury. This fire research project will further work from previous DHS AFG sponsored research (EMW-2008-FP-01774), which studied the impact of horizontal ventilation through doors and windows (Kerber S. , 2010).

1.1. Background

NFPA estimates that from 2002-2011 (Karter, 2012), U.S. fire departments responded to an average of 398,000 residential fires annually. These fires caused an estimated annual average of 2,820 civilian deaths and 13,780 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 2006-2009 period, there were an estimated annual average 35,743 firefighter fire ground injuries in the U.S. (Michael J. Karter & Molis, 2010) The rate of traumatic firefighter deaths 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 (Fahy, LeBlanc, & Molis, 2007). Improper ventilation tactics are believed to be a significant contributing factor to the increase in firefighter injuries and deaths.

Ventilation is frequently used as a firefighting tactic to control and fight fires. In firefighting, ventilation refers to the process of creating openings to remove smoke, heat and toxic gases from a burning structure and replacing them with fresh air. If used properly, ventilation improves visibility and reduces the chance of flashover or back draft. If a large fire is not properly ventilated, not only will it be much harder to fight, but it could also build up enough poorly burned smoke to create a back draft or smoke explosion, or enough heat to create flashover. Poorly placed or timed ventilation may increase the fire's air supply, causing it to grow and spread rapidly. 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) 2 NIOSH fatality investigation reports, 98-FO7 (NIOSH, 1998) and F2004-14 (NIOSH, 2005) involved “offensive entry (that) was not coordinated with ventilation that was complete and effective” that resulted in multiple firefighter fatalities;

2) “While attempting to assess the extent of the fire in the attic, one of the firefighters operating on the roof fell through the weakened roof decking.” The firefighter suffered burn injuries as a result of this fall. His SCBA and face piece were torn off by the rafters during the fall.” (National Firefighter Near Miss Reporting System, 2009)

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”. (NIOSH, 2008) ;

4) 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.” (NIOSH, 2008);

5) 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.” (NIOSH, 2009)

6) A recent NIOSH publication documents the extent of the situation “Lives will continue to be lost unless fire departments make appropriate fundamental changes in fire-fighting tactics involving trusses. These fundamental changes include the following: Venting the roof using proper safety precautions.” (NIOSH, 2010)

As fire grows from the single 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. At this 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. However, if ventilation is increased, either through tactical action of the firefighters or unplanned ventilation resulting from effects of the fire (e.g., failure of a window, ceiling, roof) 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 new contemporary home construction including new building materials, contents, size and layout. Many contemporary homes are larger than older homes built before 1980. Newer homes tend to incorporate open floor plans, with large spaces that contribute to rapid fire spread. The challenge of rapid fire spread is exacerbated by the use of modern building materials, construction practices, and contents. The rising cost of energy and developments of “green” building design have resulted in a significant change in attic design. Emerging trends, such as tempered attic spaces, have resulted in a shift from traditional cellulosic and fiberglass batting installed in the attic floor joists to spray applied foams installed to the underside of the roof deck.

Previous research developed experimental fire test data and was used to demonstrate fire behavior resulting from varied horizontal ventilation opening locations (doors and windows) in legacy residential structures compared to modern residential structures. This project advances knowledge by investigating the effect of vertical ventilation through ceiling / attic / roofs. Many positive responses were received from firefighters following the release of the previous research project’s online training program. In addition, it was requested that UL address vertical ventilation and further address suppression tactics. This study will address these requests and the lack of available data. The data will be used to provide education and guidance to the fire service in proper use of vertical ventilation as a firefighting tactic that will result in mitigation of the firefighter injury and death risk associated with improper use of ventilation.

There are several high importance issues identified in the National Fallen Firefighter Foundation’s National Fire Service Research Agenda (National Fallen Firefighters Foundation, 2005) that this study addresses.

The first issue is the “Analysis of fire service culture.” Some practices in the fire service culture have never been justified scientifically and therefore they may be dangerous or provide little benefit to the outcome of an incident. For example the general practice of cutting roof ventilation opening size of 4 ft. by 4 ft. appears to be based on experience and not on systematic study. Many fire service tactics are taught with the justification of “...that is the way it has always been done.” Over the past several decades the fire environment has changed and in turn the fire behavior has changed. The fire service’s tactics have not been reevaluated to see if they need to change. This study will evaluate the current practice of firefighters’ vertical ventilation.

A second issue this study addresses is “Identify Fire Ground Factors that Contribute to Fire Service Injuries and Fatalities.” Several line of duty deaths and injuries have occurred because of rapid fire changes due to ventilation and as a result of the dangerous practice of operating on the roof of a home and either falling off of the roof or falling into the roof after collapse. This study provides scientific data that can be used to determine the benefits of vertical ventilation tactics.

1.2. Understanding Limitations

Every fire event that the fire service responds to is unique, as the range of fire ground variables at each fire event makes firefighting complex. In this investigation, key variables were identified and bounded to develop the data under controlled conditions. These variables included house geometry, fuel loading, fire department arrival time, tactical choices, hose stream flow rates, and ventilation locations. By bounding these variables and controlling the test conditions during firefighting operations, the impact of vertical ventilation operations and fire suppression tactics on fire dynamics and conditions in two types of single family homes was examined. The results enable the establishment of a scientific basis that may be used for other types of structures that are not single family homes, different sized rooms, different fuel loads, different interior geometries, different timing of operations, etc.

The purpose of this study is not to establish if vertical ventilation or exterior suppression is more effective. The purpose is to increase the fire service's knowledge of the impact of these tactics under specific conditions. Since all fire ground circumstances cannot be analyzed, it is anticipated that the data developed and this analysis enable firefighters to complement their previous observations and experiences.

This study does not consider the safety of physically conducting vertical ventilation operations. As shown in previous UL studies, wood roof systems burn and collapse which makes operating on top of a roof on fire a dangerous operation that should only be done with a risk/benefit analysis by the firefighters. Many firefighters have lost their lives due to collapse of a roof system while performing vertical ventilation. The information from this report can be incorporated into the size-up considerations of the fire service so that vertical ventilation is used to the best benefit possible when it is determined to be an appropriate tactic.

The fires in this study, where vertical ventilation was used, were content fires and represented a fire event within the living space of the home, and not a structure fire with fire extension into the attic space. These experiments were also meant to simulate initial fire service operations by an engine company or engine and truck company arriving together in short order with approximately national average response times. Additional experiments have been conducted to begin to examine vertically ventilating an attic fire and will be documented separately.

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 of changes in residential construction such as those created by open floor plans on fire behavior.
- Increase firefighter knowledge of the impact of different suppression techniques on conditions throughout a structure.
- 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 2.1.

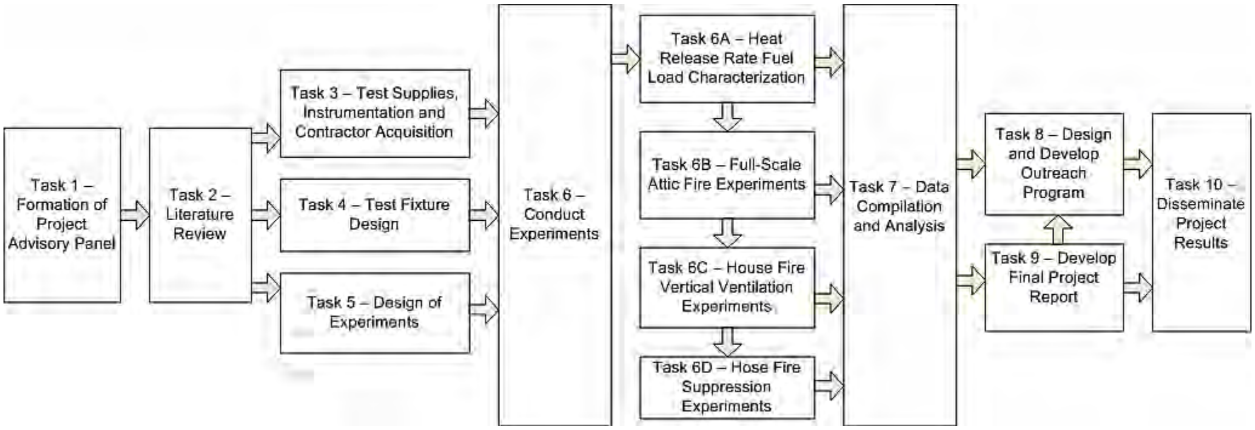


Figure 2.1: Project Technical Plan

- In Task 1, an advisory panel of technical experts in the fire engineering, fire service, and fire science fields was established. This enabled UL to ensure that the research was directed to the target audiences and that the results of the research may be disseminated into practice. The members of the panel are identified in the next section.
- In Task 2, literature pertinent to the research topic was documented.
- In Task 3, UL purchased appropriate research equipment and supplies for this project. In addition, UL identified a contractor to build the test structures.
- In Task 4, test fixtures to be used in the experiments were designed. The main test fixtures were two single family residential homes constructed in UL's Large Fire Facility. These were identical to homes built for a previous grant to allow for continuity to the previous results, and to expand the knowledge of fire dynamics.
- Task 5 consisted of design of experiment and included identification of the experimental variables, measurements, equipment, personnel, infrastructure resources, and scheduling to provide the largest return to the fire community. The established advisory panel guided the UL team with this task.
- Task 6 was the execution of the designed experiments. These experiments were divided into four sub-tasks as follows:
    - In Task 6A, heat release rate experiments in the calorimeter room of UL's Large Fire Facility were conducted to characterize modern furnishings and to understand the heat release in today's fire environment.
    - In Task 6B, fire experiments were performed to examine current attic construction practices with focus on spray applied foam insulation.
    - In Task 6C, full-scale house fire experiments were performed. Previous investigation (Kerber S. , 2010) examined fire service horizontal ventilation tactics. In this investigation, vertical ventilation tactics commonly used by the fire service as well as suppression tactics once the fire has reached flashover were examined.

  - Task 6D focused on suppression experiments that "push fire". This is a concern of the fire service as they apply water during fire mitigation. These experiments provide the information needed to address their concerns.
- In Task 7, the experimental results are compiled, analyzed and discussed with fire service as the target audience.
- In Task 8, results from Task 7 were used to design and develop an interactive training program for the fire community. In this task, instructional designers developed a course that is shared via the www.ULfirefightersafety.com website free of charge.
- In Task 9, details from all the experiments and results were documented in a final report. This was delivered to the DHS.
- The results of this investigation will be shared with the fire service in Task 10 by presenting at numerous venues that are attended by fire service leaders from across the country.

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:

- Josh Blum, Deputy Chief, Loveland – Symmes (OH) Fire Department
- John Ceriello, Lieutenant, Fire Department of New York
- James Dalton, Coordinator of Research, Chicago Fire Department
- Ed Hadfield, Division Chief, City of Coronado (CA) Fire Department
- Todd Harms, Assistant Chief, Phoenix Fire Department
- Ed Hartin, Chief, Central Whidbey Island Fire Rescue Department
- George Healy, Battalion Chief, Fire Department of New York
- Otto Huber, Fire Chief, Loveland – Symmes (OH) Fire Department
- Dan Madrzykowski, Fire Protection Engineer, National Institute of Standards and Technology
- Mark Nolan, Fire Chief, City of Northbrook (IL)
- David Rhodes, Battalion Chief, Atlanta Fire Department
- David Rickert, Firefighter, Milwaukee Fire Department
- Andy Rick, Firefighter, Lake Forest (IL) Fire Department
- Pete Van Dorpe, Chief of Training, Chicago Fire Department
- Sean DeCrane, Battalion Chief, Cleveland Fire Department
- Bobby Halton, Editor, Fire Engineering Magazine
- Harvey Eisner, Editor, Firehouse Magazine
- Tim Sendelbach, Editor, Fire Rescue Magazine

4. Heat Release Rate Experiments

Prior to conducting the full-scale house experiments a fuel load needed to be established. 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, three 18 ft. by 13 ft. rooms were constructed in UL's large fire test building. One room characterized a living room fuel package, a second room characterized a bedroom fuel package and the final room characterized a living room with a 16 ft. ceiling. Another important purpose of these experiments was to compare the fuel load of these experiments to the fuel load used for the previous horizontal ventilation research program (Kerber 2010).

4.1. Experimental Setup and Furnishings

The experimental room dimensions, 18 ft. wide by 13 ft. deep by 8 ft. or 16 ft. tall, were similar to those of the living rooms in the experimental houses. The opening on the front of the room measured 10 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, television stand, television, carpet and carpet padding in the living rooms, and a queen bed comprised of a mattress, box spring, wood frame, two pillows and comforter, dresser, television stand, television, carpet padding, and carpet. All furnishings in the room were positioned similar to that of the rooms in the houses. For more details on the furniture and its positioning, refer to Section 5.3.

Figure 4.1: Living Room

Figure 4.2: Bedroom

Figure 4.3: Tall Living Room

4.2. Experimental Procedure

Ignition was enabled, remotely, using stick matches on the left side of the sofa facing the opening of the room for both living room fires and in a plastic trashcan full of shredded paper (0.5 lb.) on the left side of the bed in the bedroom fire. 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.

4.3. Instrumentation

The rooms and individual components were positioned in the nominal 50 by 50-ft. fire test cell equipped with a 25-ft. diameter heat release rate measurement hood. Four inlet ducts provided make up air in the test facility and were 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.

4.4. Results

The heat release rate versus time and images of every minute of each experiment are shown for the three room experiments.

4.4.1. Living Room

The heat release rate data for the living room burn can be seen in Figure 4.4. Figure 4.5 through Figure 4.14 show each minute up to the first ten minutes of the living room experiment.

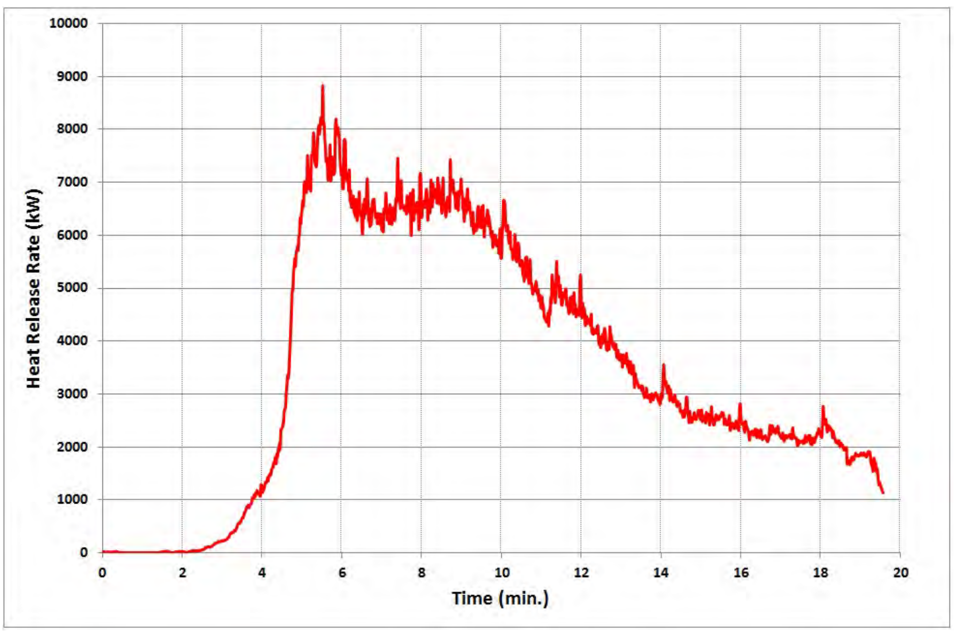


Figure 4.4: Living Room Heat Release Rate vs. Time


Figure 4.5: One Minute After Ignition


Figure 4.6: Two Minutes After Ignition


Figure 4.7: Three Minutes After Ignition


Figure 4.8: Four Minutes After Ignition


Figure 4.9: Five Minutes After Ignition


Figure 4.10: Six Minutes After Ignition

Figure 4.11: Seven Minutes After Ignition

Figure 4.12: Eight Minutes After Ignition

Figure 4.13: Nine Minutes After Ignition

Figure 4.14: Ten Minutes After Ignition

4.4.2. Bedroom Burn

The heat release rate data for the bedroom burn can be seen in Figure 4.15. Figure 4.16 through Figure 4.25 show each minute up to the first ten minutes of the bedroom experiment.

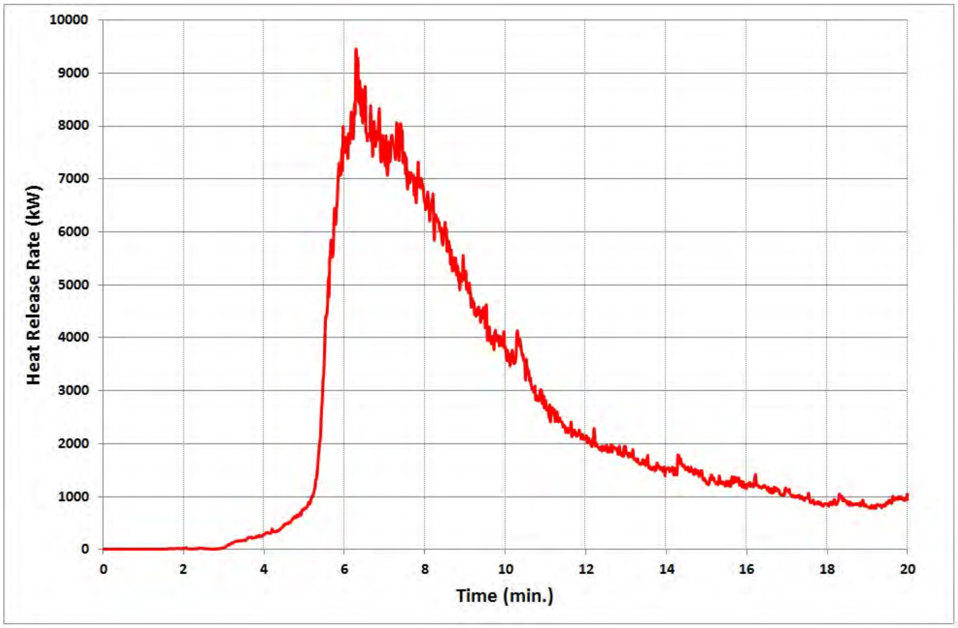


Figure 4.15: Bedroom Burn Heat Release Rate vs. Time

Figure 4.16: One Minute After Ignition

Figure 4.17: Two Minutes After Ignition

Figure 4.18: Three Minutes After Ignition

Figure 4.19: Four Minutes After Ignition


Figure 4.20: Five Minutes After Ignition


Figure 4.21: Six Minutes After Ignition


Figure 4.22: Seven Minutes After Ignition


Figure 4.23: Eight Minutes After Ignition


Figure 4.24: Nine Minutes After Ignition


Figure 4.25: Ten Minutes After Ignition

4.4.3. Tall Living Room Burn

The heat release rate data for the tall living room burn can be seen in Figure 4.26. Figure 4.27 through Figure 4.36 show each minute up to the first ten minutes of the tall living room experiment.

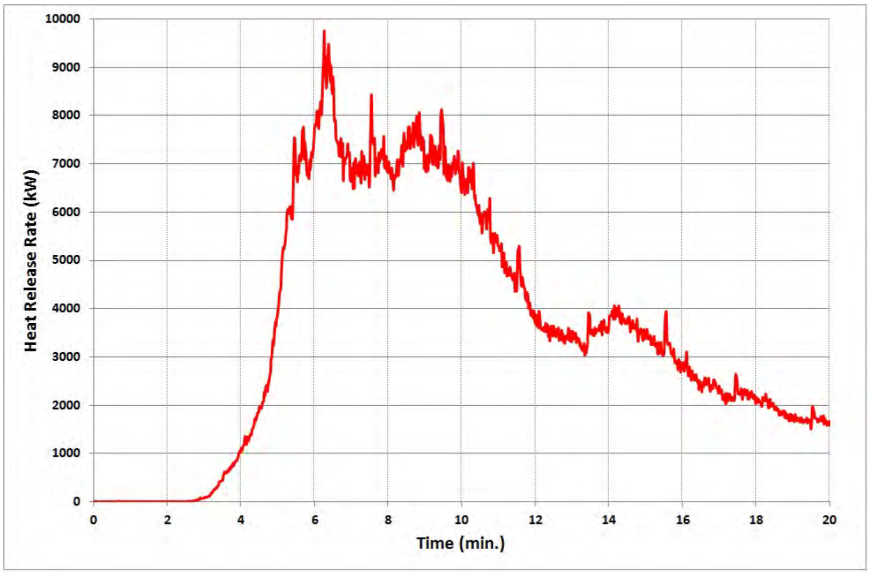


Figure 4.26: Tall Living Room Heat Release Rate vs. Time

Figure 4.27: One Minute After Ignition

Figure 4.28: Two Minutes After Ignition

Figure 4.29: Three Minutes After Ignition

Figure 4.30: Four Minutes After Ignition


Figure 4.31: Five Minutes After Ignition


Figure 4.32: Six Minutes After Ignition


Figure 4.33: Seven Minutes After Ignition


Figure 4.34: Eight Minutes After Ignition


Figure 4.35: Nine Minutes After Ignition


Figure 4.36: Ten Minutes After Ignition

4.5. Discussion

Three measurements were compared between the experiments to examine the fuel packages selected for the full-scale house experiments: time to flashover, heat release rate, and total heat released. These measurements were also compared to the fuel package used in the previous horizontal ventilation experiments in Table 4.1. All of the rooms transitioned to flashover and all of the flashover times were within 45 seconds of each other. This indicates that underventilated fire conditions can be achieved, even with the ventilation provided by a 70 ft^2

opening in the room of fire origin. Comparing the maximum heat release rates shows that the opening size, or amount of air, limited the maximum heat release rate possible, approximately 9.3 ± 0.5 MW. The maximum heat release rate from the previous study was higher because the opening on the front was 2 ft. wider allowing more air to increase the burning rate. The final measurement was the total heat released. This value was also similar for each of the experiments with an average value of 3905 ± 425 MJ. Most importantly, the values between this living room fuel package and the 2008 study fuel package are within 10%, which allows us to compare both experimental series.

Another comparison can be made between the living room with the 8 ft ceiling and the one with the 16 ft ceiling. Even though the tall living room was double the volume, flashover only occurred 35 seconds later than the 8 ft. ceiling room with nearly identical fuel loads. This is indicative of the rapid increase in heat release rate that occurs just prior to flashover and the ventilation-limited condition.

Table 4.1: Experiment Result Comparison

	Living Room	Living Room (2008)*	Bedroom	Tall Living Room
Time to Flashover (m:ss)	4:45	5:00	5:30 (3:20**)	5:20
Maximum Heat Release Rate (MW)	8.8	11.5	9.4	9.8
Total Heat Released (MJ)	4060	3650	3580	4330

*Front Opening was 12 ft wide by 7 ft tall (2 ft wider than other rooms)
**Trashcan did not transition to flaming until 2:10 after ignition

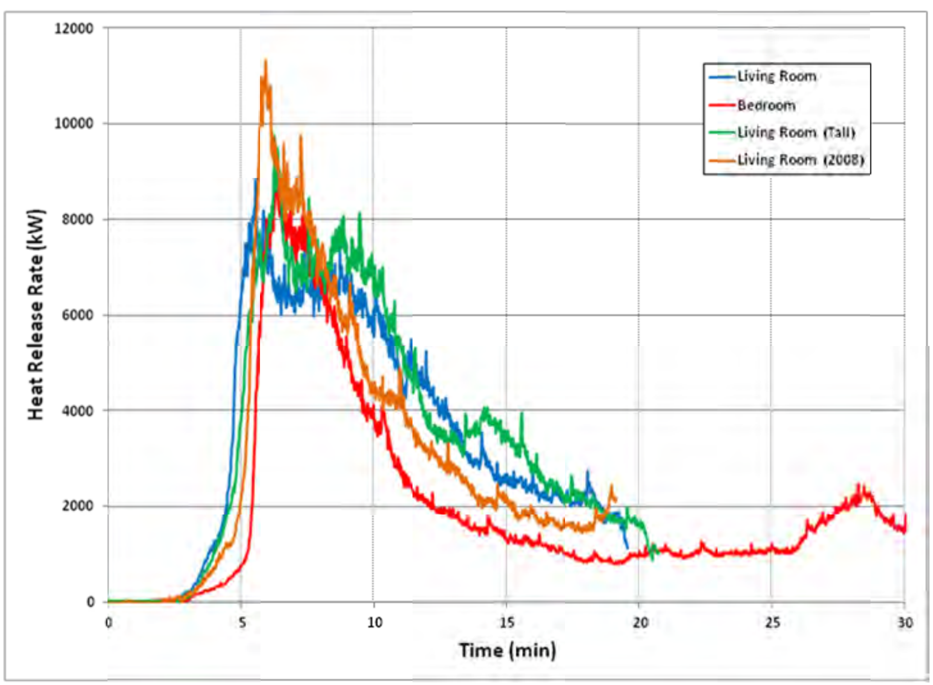


Figure 4.37: Heat Release Rate Comparison

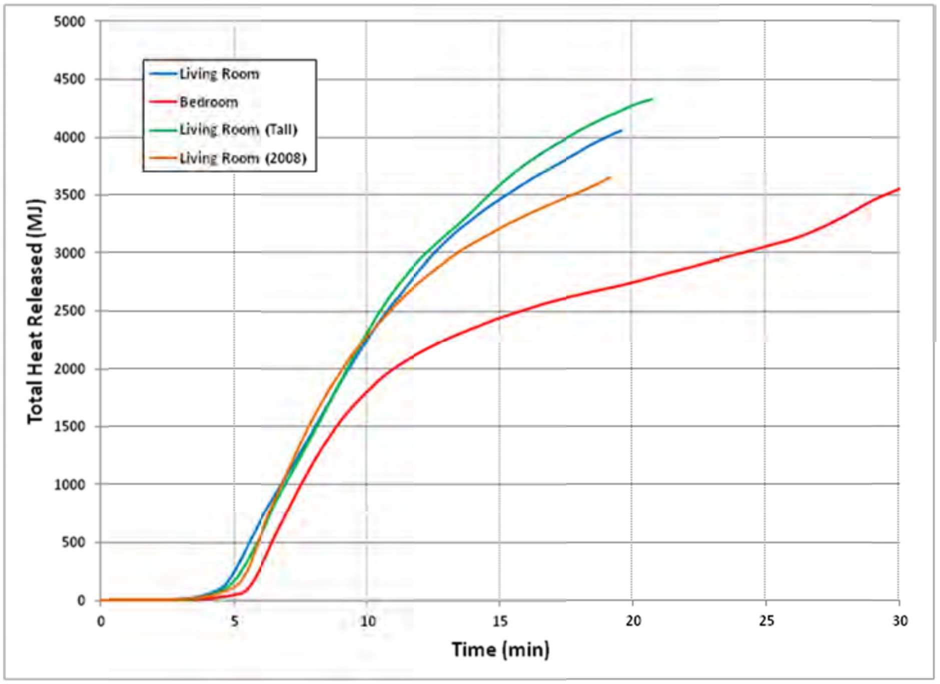


Figure 4.38: Total Heat Released Comparison

4.6. Conclusion

The fuel loads acquired for these experiments were able to produce enough energy to create the necessary ventilation-limited conditions in both houses. Additionally, the heat release rate and total heat released from the living room fuel load is within 10% of that of the fuel load used in the previous study on horizontal ventilation such that the experiments can be compared for various horizontal and vertical ventilation scenarios. Finally, doubling the volume of the fire room while maintaining the same amount of ventilation does not significantly slow down the time to flashover due to the rapid increase in heat release rate that occurs prior to flashover.

5. Full-Scale House Experiments

The project technical panel designed a series of 17 experiments to examine several scenarios that were identified as gaps in current fire service knowledge of fire dynamics, ventilation and suppression. These gaps include:

- Impact of door control
- Impact of vertical ventilation hole size
- Impact of vertical ventilation hole location
- Impact of different flow paths between fire location and ventilation location
- Impact of modern and legacy fuel loads in a structure
- Impact of exterior suppression with various flow path configurations

To examine these knowledge gaps in vertical ventilation practices, suppression practices as well as the impact of changes in modern house geometries and contents, two houses were constructed in the large fire facility of Underwriters Laboratories in Northbrook, IL. Seventeen experiments were conducted, varying the ventilation locations, fire ignition location and the timing of ventilation openings (Table 5.1 and Table 5.2).

Ventilation scenarios included ventilating the front door and a window near the seat of the fire to link these experiments to previous horizontal ventilation experiments, opening the front door and a ventilation hole above the seat of the fire and remote from the seat of the fire, and opening the front door and opening a large hole above the fire. Suppression scenarios included igniting a fire in the kitchen, opening the front door and flowing water into the kitchen with the dining room window closed and open. Another suppression experiment included igniting a fire in the living room, creating a flow path from the front door through Bedroom 1 and flowing water through the front door. A final scenario in the 1-story house examined opening the front door and living room window while the living room was furnished with legacy fuel. Details of the structures, instrumentation, fuel load and results follow in this section.

Table 5.1: One-Story Experimental Details

Experiment #	Structure	Location of Ignition	Ventilation Parameters
1	1-Story	Living Room	Front Door + Living Room Window
3	1-Story	Living Room	Front Door Partially Open + Roof (4' by 4')
5	1-Story	Living Room	Front Door + Roof (4' by 4')
7	1-Story	Living Room	Front Door + Roof (4' by 8')
9	1-Story	Bedroom 1	Front Door + Roof (4' by 4') + Bedroom 1 Window
11	1-Story	Bedroom 1	Bedroom 1 Window + Front Door + Roof (4' by 4')
13	1-Story	Kitchen	Front Door + Dining Room Window
15	1-Story	Living Room	Living Room + Bedroom 1 Window
17	1-Story	Living Room	Front Door + Living Room Window

Table 5.2: Two-story Experimental Details

Experiment #	Structure	Location of Ignition	Ventilation Parameters
2	2-Story	Family Room	Front Door + Family Room Window
4	2-Story	Family Room	Front Door Partially Open + Roof (4' by 4')
6	2-Story	Family Room	Front Door + Roof (4' by 4')
8	2-Story	Family Room	Front Door + Roof (4' by 8')
10	2-Story	Bedroom 3	Front Door + Roof (4' by 4') + Bedroom 3 Window
12	2-Story	Family Room	Family Room Window + Front Door + Roof (4' by 4')
14	2-Story	Bedroom 3	Bedroom 3 Window + Front Door + Roof (4' by 4')
16	2-Story	Kitchen	Family Room Window (nearer Kitchen) + Bedroom 3 Window

5.1. One-Story Structure

Seven of the 17 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 5.1 through Figure 5.4). 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 metal truss construction and was lined with ½ in. cement board to provide a volume to represent an attic void. A roof ventilation system was created above the Living Room to allow for remote roof ventilation. Hinged openings were able to be opened simulating a roof cut being "pulled" and a section of ceiling was able to be removed simulating the ceiling being "pushed" through from above. The front and rear of the structure were covered with cement board to limit exterior fire spread. Figure 5.5 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 show the cement floor or simulated tile locations.


Figure 5.1: One-Story Front


Figure 5.3: One-Story Rear


Figure 5.2: One-Story Roof

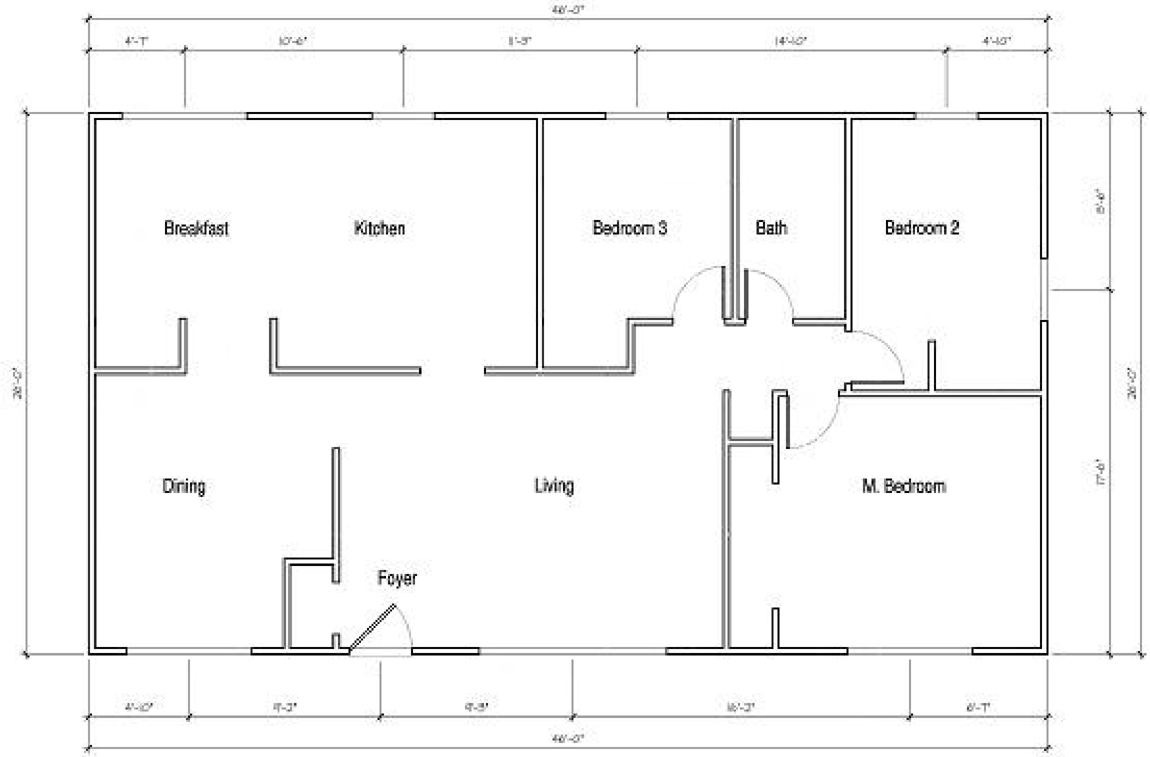


Figure 5.4: One-Story House Floor Plan

Figure 5.5: 3D Rendering of the One-Story House from the Front

5.2. 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 5.6 through Figure 5.12). This 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 engineered I-joist construction but not sheathed because the fires were content fires only and not structure fires. A roof ventilation system was created above the Family Room to allow for remote roof ventilation. Hinged sections of roof could be opened to simulate a roof cut being completed. This section did not have an interior ceiling to be "pushed" because this section of the roof above the great room was simulated to be a cathedral style ceiling, having no void below the roof. The front and rear of the structure were covered with cement board to limit exterior fire spread.

Figure 5.6: Two-Story Front

Figure 5.7: Two-Story Rear

Figure 5.8: Two-Story Roof

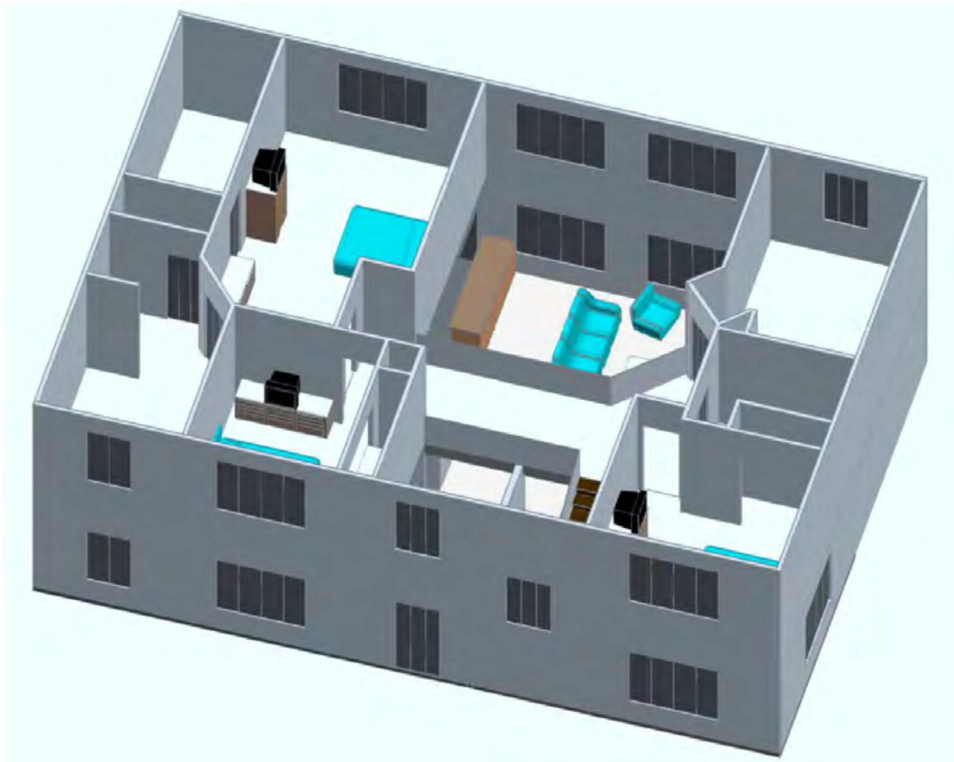


Figure 5.9. 3D Rendering of the 2-Story House from the Front

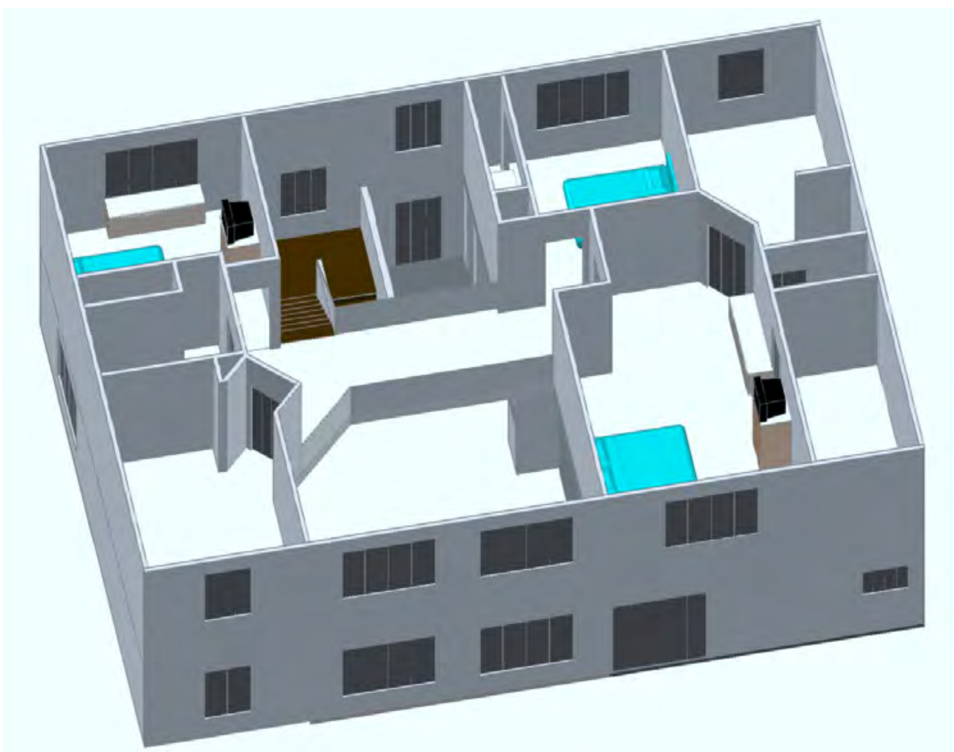


Figure 5.10. 3D Rendering of the 2-Story House from the Back

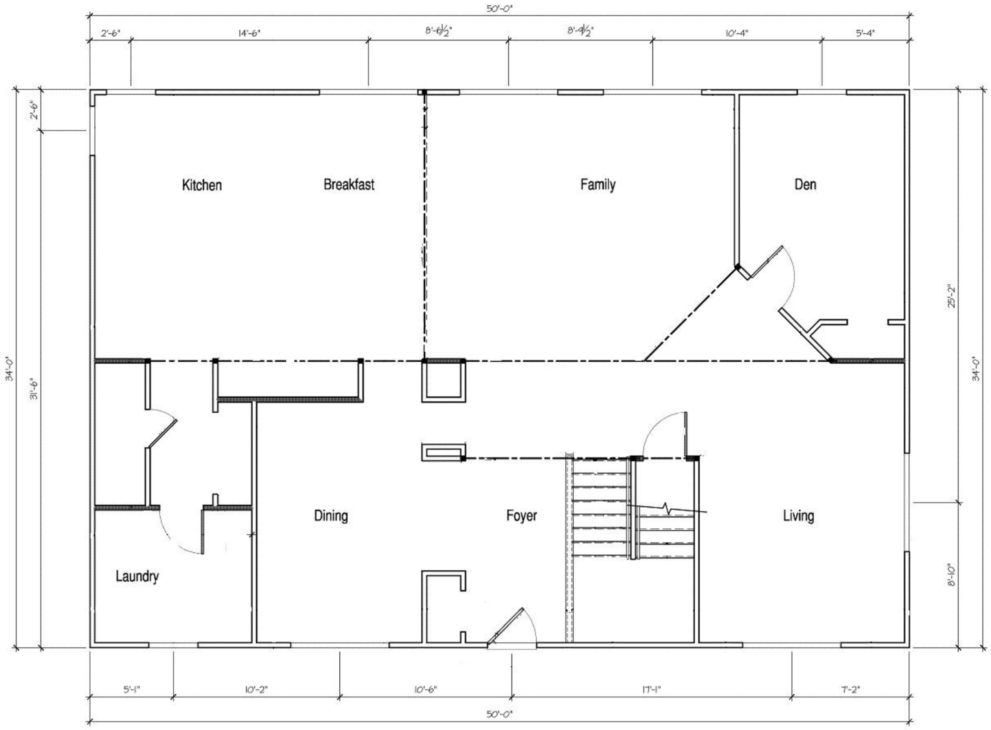


Figure 5.11. Two-Story House First Floor Plan

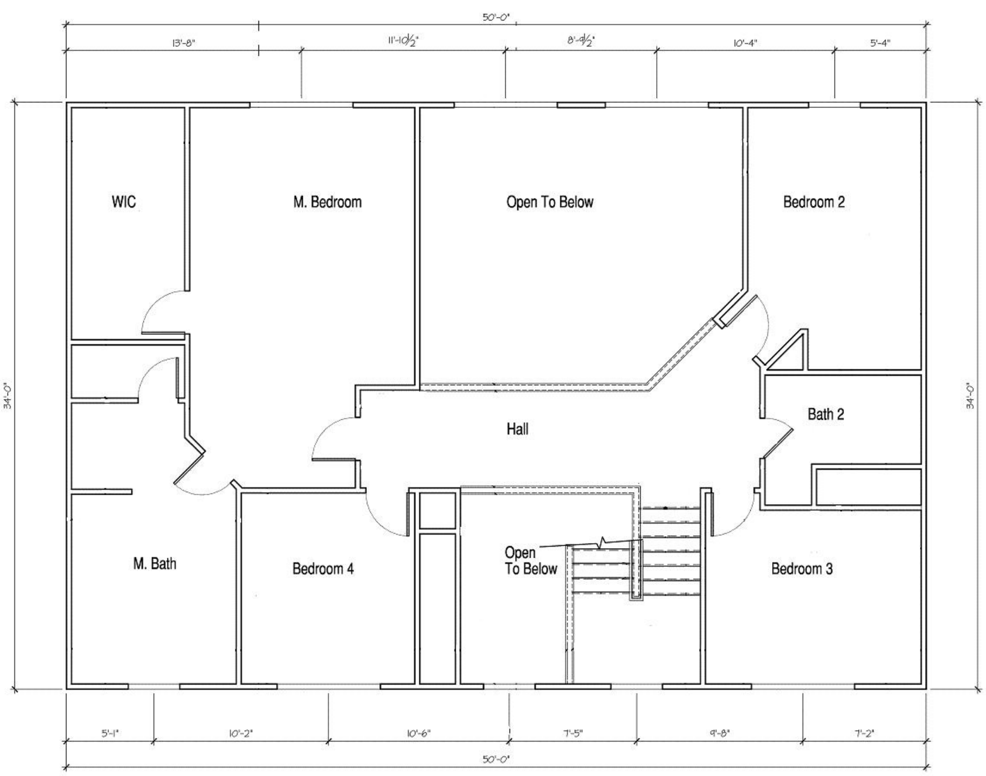


Figure 5.12. Two-Story House Second Floor Plan

5.3. 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 5.3. 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, television stand, television, end table, coffee table, chair, ottoman, two pictures, lamp with shade, and two curtains (Figure 5.13 through Figure 5.15). 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 4.

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, television stand and television. The floor was covered with polyurethane foam padding and polyester carpet (Figure 5.16 and Figure 5.17). The remainder of the bedrooms in both houses were furnished with the same bed, television stand, television, and flooring compliment as well as a light brown dresser, headboard, framed mirror (Figure 5.18).

The dining room of both houses was furnished with a solid wood table and six upholstered chairs (Figure 5.19). The kitchens were furnished with the same table and chairs as the dining room, a dishwasher, stove, refrigerator, and kitchen cabinets with cement board counters. The floors of both rooms were also cement board to simulate a tile floor (Figure 5.20 and Figure 5.21). The two-story house also had a den on the first floor in which a stuffed chair was placed as a target fuel.

Figure 5.22 through Figure 5.24 show the locations of the furniture within the houses. The fuel loading for both houses is calculated in Table 5.4. All rooms were conservatively loaded to less than 5 lb/ft^2. While the kitchens had the highest fuel load because of the cabinets, the rooms with the largest heat release rate potential were the living rooms and bedrooms with the foam cushioned furniture.

Table 5.3: Furniture Dimensions and Weight

Item	Length (in.)	Width (in.)	Height (in.)	Weight (lbs.)
4 Drawer Chest	44	24	35	214.7
Green Stripe Sofa	70	36	35.5	178.1
Rose Chair	34	34	30	48.6
Rose Autumn	28	20	16	19.4
Coffee Table	42	20	19	36.9
Table Lamp w/ Shade	4	4	28	6.7
TV Set	38	5	25	47.3
End Table	26	26	25.75	28.9
Picture	31	1.5	21.5	7.1
Drapes (one panel)	94	132		17.9
Queen Mattress	79	59	7.75	64.6
Queen Box Spring	79	59	7.5	69.8
Full Mattress	74	53	7.25	54.1
Full Box Spring	74	52	7.75	57.5
Nightstand	22	18	25	19.8
2 Drawer Chest	23.75	18.5	23.75	57.5
6 Drawer Wood Dresser	54	18	32	124.7
Mirror for Wood Dresser	28	1	48	28.8
Headboard	72	1.25	26	40.2
Pillow	24	16	3	1.5
Sheets	98	83		3.5
Mattress Pad	75	69		2.3
Memory Foam Mattress Top	56	75	1.5	4.2
Bed Skirt (Bed in a Bag)	60	81	14 drop	1.2
Fitted Sheet (Bed in a Bag)	60	80	14 drop	1.5
Flat Sheet (Bed in a Bag)	120	90		1.2
Comforter (Bed in a Bag)	90	86		4.5
Pillow Cases (Bed in a Bag)	30	24		0.5
Kitchen Table	30	30	29.5	49
Dining Room Table Top (one kitchen table used for base)	96	30	1.75	107.7
Stack Chairs	18	22	38	16.9
Dishwasher (in cabinet style)	24	25	34	85.2
Refrigerator	30	24.5	64	201.2
Stove	30	25	44	160.6
Microwaves	30	15	16	52.9
Kitchen Cabinet-SB60-Sink Base (Unfinished Oak)	24 (deep)	60	34.5	93.2
Base Kitchen Cabinet-B36 (Unfinished Oak)	24 (deep)	36	34.5	70.7
Base Kitchen Cabinet-B24 (Unfinished Oak)	24 (deep)	24	34.5	55.1
Wall Kitchen Cabinet-W2430 (Unfinished Oak)	12 (deep)	24	30	34.6

Figure 5.13: One-Story Living Room

Figure 5.14: Two-Story Family Room

Figure 5.15: Two-Story Living Room

Figure 5.16: Two-Story Master Bedroom

Figure 5.17: One-Story Master Bedroom

Figure 5.18: Two-Story Bedroom 3


Figure 5.19: One-Story Dining Room


Figure 5.20: One-Story Kitchen


Figure 5.21: Two-Story Kitchen

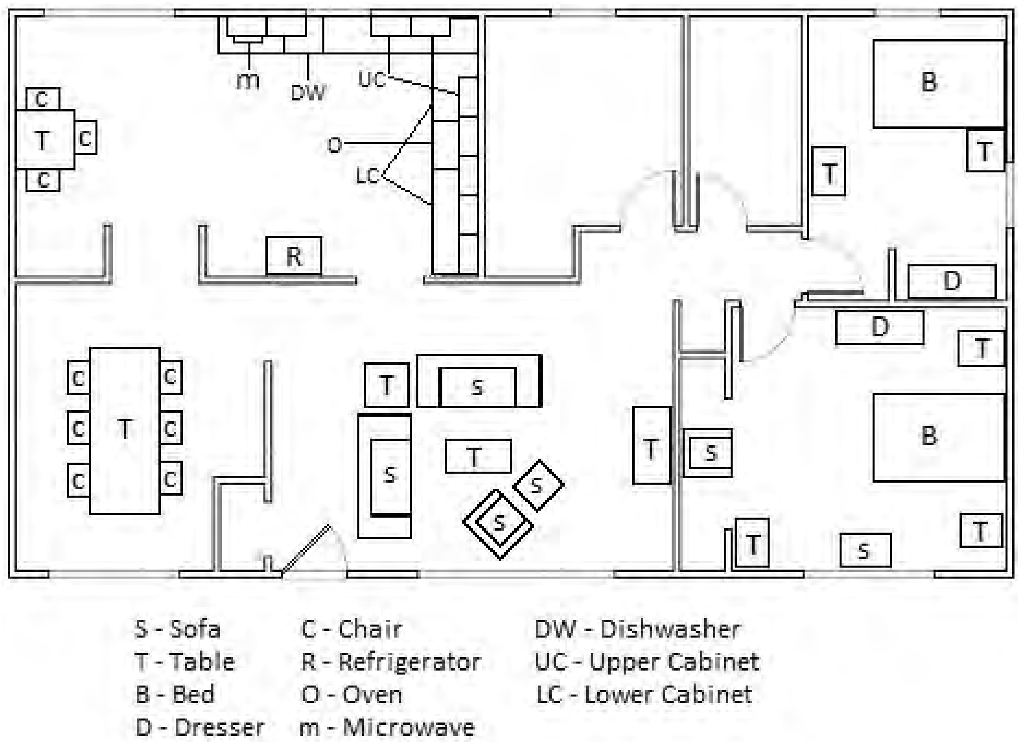


Figure 5.22: One-Story Furniture Locations

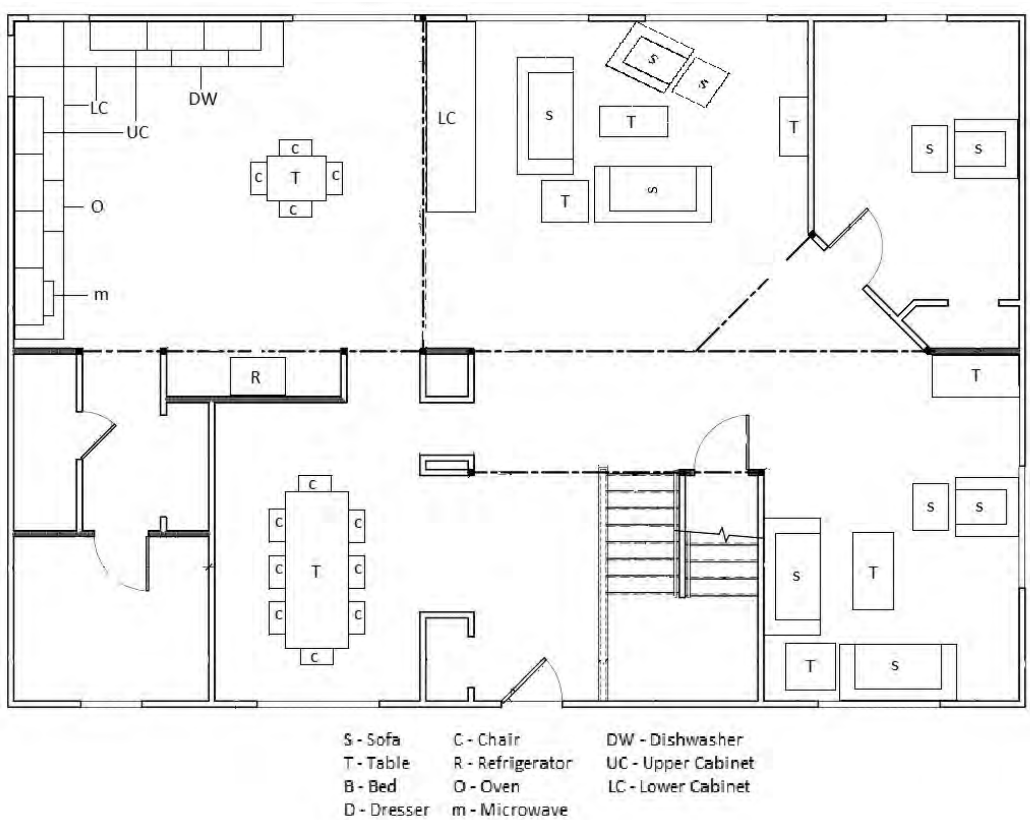


Figure 5.23: Two-Story First Floor Furniture Locations

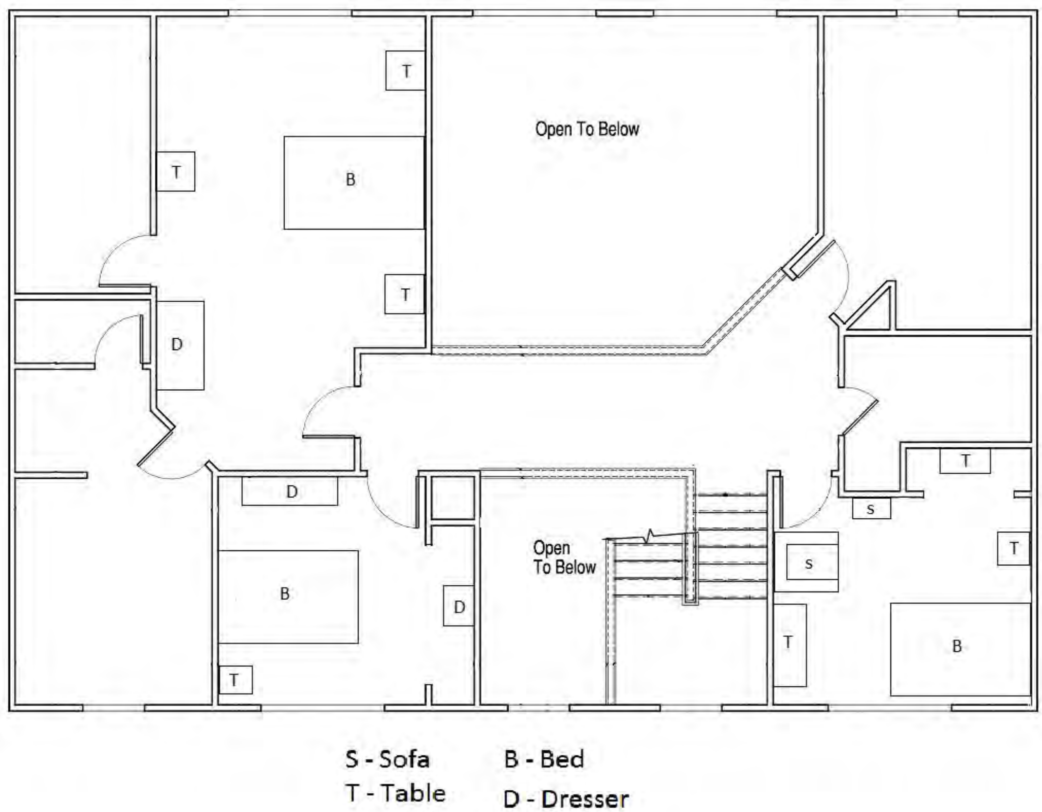


Figure 5.24: Two-Story Second Floor Furniture Locations

Table 5.4: Fuel Loading for both Houses

One-Story Structure		
Room	**Total Fuel (lb.)**	**Fuel Load (lb/ft^2)**
Living Room	772.9	3.19
Dining Room	209.1	1.49
Kitchen	1223.2	4.71
Bedroom 1	560.9	3.25
Bedroom 2	413	3.49
Two-Story Structure		
Room	**Total Fuel (lb.)**	**Fuel Load (lb/ft^2)**
Family Room	758.7	2.68
Dining Room	242.9	1.64
Kitchen	1397.3	4.29
Den	68	0.47
Living Room	758.7	3.55
Bedroom 1	473.1	1.79
Bedroom 3	538.1	3.82
Bedroom 4	450.3	3.47

5.4. Instrumentation

The measurements taken during the experiments included gas temperature, gas velocity, gas concentrations, pressure, thermal imaging, 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, family room, hallway, Bedroom 1 (1-story), and Bedroom 3 (2-story) 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 5.25). The thermocouple locations in the dining room, kitchen, and other 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 5.26 through Figure 5.28). These probes were located in the front doorway and the roof ventilation opening. 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 flows into the houses.

Gas concentrations of oxygen, carbon monoxide, and carbon dioxide were measured in 4 locations in the structure. Concentrations were measured at 3 ft. from the floor adjacent to the front door and in bedrooms 1, 2 and 3 for both houses (Figure 5.29 and Figure 5.30). Gas concentration measurements after water flow into the structure may not be accurate due to the impact of moisture on the gas measurement equipment.

Pressure measurements were made in several rooms in both houses at 3 elevations, 1 ft., 4 ft., and 7 ft. above the floor. The family room in the 2-story house was the exception, where measurements were made at 1 ft., 8 ft. and 16 ft. above the floor. In the 1-story house, measurements were made in the living room, kitchen, Bedroom 1, and Bedroom 2. In the 2-story house, measurements were made at the front door, living room, kitchen, family room, Bedroom 2, and Bedroom 3 (Figure 5.28 and Figure 5.31). The pressure was a differential pressure between the inside of the structure and outside of the structure.

Video cameras and a thermal imaging camera were placed inside and outside the building to monitor both smoke and fire conditions throughout each experiment (Figure 5.32). Seven video camera views and one thermal imaging view were recorded during each experiment. The views recorded are detailed in Table 5.5.

Figure 5.33 through Figure 5.35 show the location of the instrumentation within the houses.

Table 5.5: Video camera views

One-Story	Two-Story
Outside front	Outside front
Inside front door	Inside front door
From dining room looking into the living room	Inside front door (Thermal)
Looking across the Kitchen	Family Room looking toward front door
Bedroom 1 looking toward the bed	From kitchen looking into the family room
Bedroom 2 looking toward hallway	From living room looking toward family room
Bedroom 2 looking toward hallway (Thermal)	Bedroom 3 looking toward hallway
Bedroom 3 looking at closed door	From master bedroom looking toward hallway

Figure 5.25: Thermocouple Array

Figure 5.26: Doorway Velocity Probes

Figure 5.27: Roof Velocity Probes

Figure 5.28: Pressure Transducers

Figure 5.29: Gas Sampling Tube

Figure 5.30: Gas Sampling Instruments

Figure 5.31: Pressure Measuring Tube

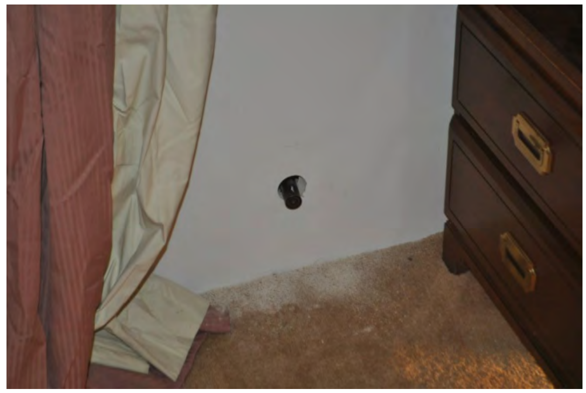


Figure 5.32: Interior Video Cameras

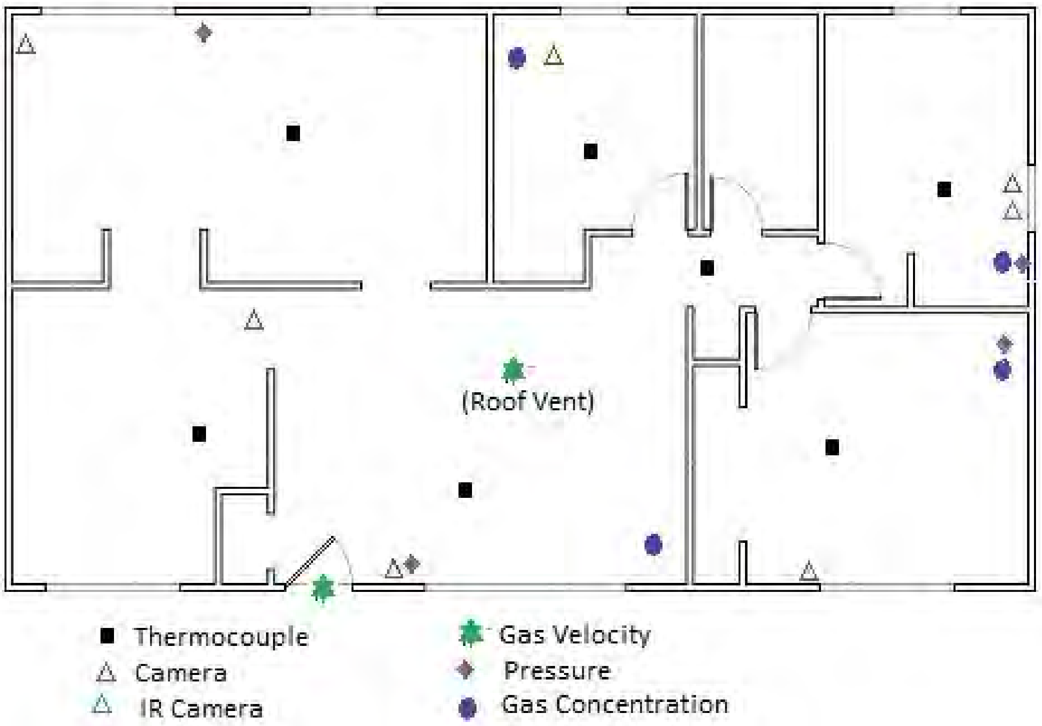


Figure 5.33: One-Story Instrument Locations

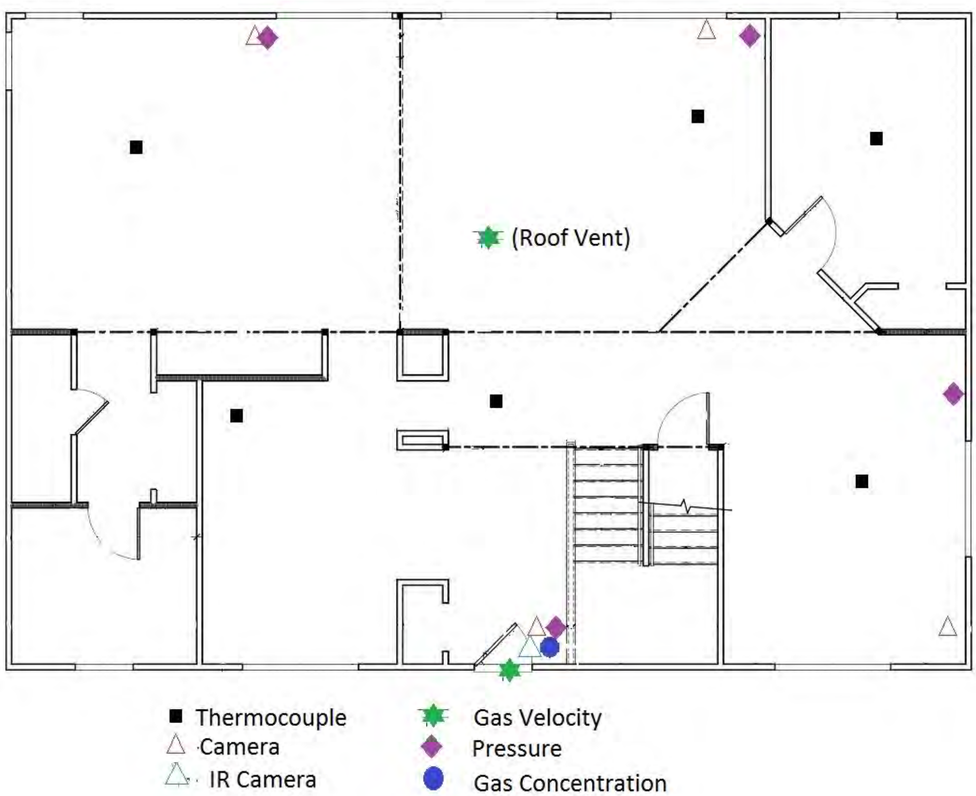


Figure 5.34: Two-Story First Floor Instrumentation

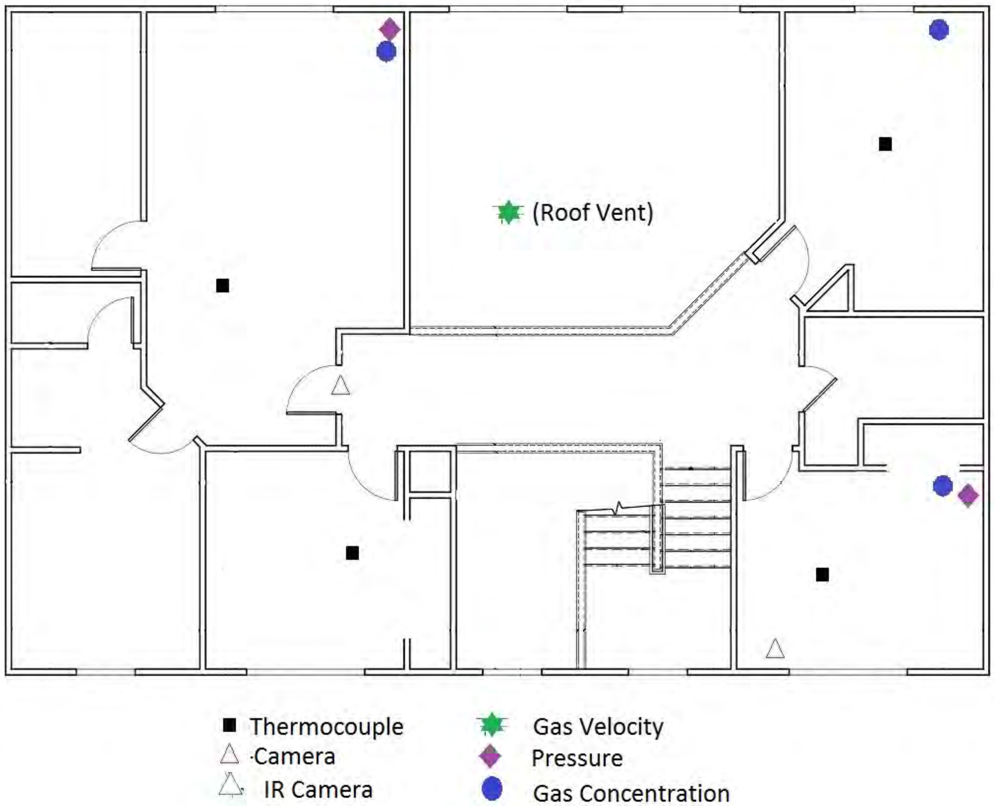


Figure 5.35: Two-Story Second Floor Instrumentation Locations

5.5. Experimental Methodology

All of the experiments started with the exterior doors and windows closed, the roof vents closed, and all of the interior doors in the same locations (i.e., either open or closed). The fire was ignited using a remote ignition device comprising of five stick matches (Figure 5.36) and electrically energized with a fine wire to heat the match heads, and create a small flaming ignition source. The ignition locations are shown in Figure 5.37 through Figure 5.39.

Figure 5.36: Ignition Matches

Figure 5.37: One-Story Living Room Ignition Location

Figure 5.38: Two-Story Family Room Ignition Location

Figure 5.39: Bedroom Ignition Location

The flaming fire was allowed to grow until ventilation operations were performed by making openings. The one story house was ventilated 8 minutes after ignition. This was determined based on two factors: time to achieve ventilation-limited conditions in the house and potential response and intervention times of the fire service. 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. The same fuel package was used in the two-story family room with a 17 ft. ceiling and open floor plan as was used in the one-story house with an 8 ft ceiling and compartmented floor plan therefore the two-story house required a longer time to become ventilation-limited.

Ventilation scenarios included ventilating the front door and a window near the seat of the fire to link these experiments to previous horizontal ventilation experiments, opening the front door and a ventilation hole above the seat of the fire and remote from the seat of the fire, and opening the front door and opening a large hole above the fire. Suppression scenarios included igniting a fire in the kitchen, opening the front door and flowing water into the kitchen with the dining room window closed and open. Another suppression experiment included igniting a fire in the living room, creating a flow path from the front door through Bedroom 1 and flowing water through the front door. A final scenario in the 1-story house examined opening the front door and living room window while the living room was furnished with legacy fuel.

In most cases in the field vertical ventilation and horizontal ventilation are performed at different time scales. There is an obvious difference between ventilating a glass window with a tool from the ground versus climbing to the roof and creating a ventilation hole through the roof membrane. Therefore, the timing of the vertical ventilation openings was done based on interior conditions and not a certain time. The most frequent criteria chosen was a 3 ft. temperature of 400 °F in the area that a firefighting crew could be operating. This approach may be justified by the fact that a crew operating in that area could request that vertical ventilation is completed to improve the conditions in the area in which they were operating. The timing of these openings will be explained and examined for each experiment in the discussion section of the report.

After ventilation, the fire was allowed to grow until flashover or perceived maximum burning rate occurred. This was 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 (prior to transition from a content fire to a structure fire), a hose stream was flowed in through an external opening.

Incorporated into every experiment was a stream of water directed into a ventilation opening for approximately 15 seconds. The hose line used was a 1 ¾ inch with a combination nozzle with approximately 100 psi nozzle pressure, creating a flow of 100 gpm (Figure 5.40). 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 into the structure with the guidance of putting water on what was burning, so the nozzle was not held stationary (Figure 5.41). During the fog stream application the nozzle was adjusted to create an approximate 30 degree fog pattern and also directed into the structure with the intent to extinguish the visible fire while not holding the nozzle stationary (Figure 5.42).

The flow rate of the nozzle was 100 gpm resulting in approximately 25 gallons of water delivered through the opening into the house during the 15 second flow. The purpose of this flow was not to enable firefighters to move into the structure and extinguish the fire but to suppress as much fire as possible and to observe the conditions in the surrounding rooms . This has an impact on the tactical considerations as discussed later in the report. This would allow the potential fire attack crew to slow the fire down, or soften the target, prior to making entry, therefore make entry into a safer environment. The experiment was terminated at least one minute after the hose stream, and suppression was completed by the firefighting crew.

Figure 5.40: Suppression Nozzle

Figure 5.41: Straight Stream Application

Figure 5.42: Fog Stream Application

5.6. One-Story Experimental Results

Nine experiments were conducted in the one-story house (Table 5.6).

Table 5.6: One-Story Experimental Details

Experiment #	Structure	Location of Ignition	Ventilation Parameters
1	1-Story	Living Room	Front Door + Living Room Window
3	1-Story	Living Room	Front Door Partially Open + Roof (4' by 4')
5	1-Story	Living Room	Front Door + Roof (4' by 4')
7	1-Story	Living Room	Front Door + Roof (4' by 8')
9	1-Story	Bedroom 1	Front Door + Roof (4' by 4') + Bedroom 1 Window
11	1-Story	Bedroom 1	Bedroom 1 Window + Front Door + Roof (4' by 4')
13	1-Story	Kitchen	Front Door + Dining Room Window
15	1-Story	Living Room	Living Room + Bedroom 1 Window
17	1-Story	Living Room	Front Door + Living Room Window

In the discussion below, the purpose for each experiment's purpose is described. Each experiment's results include:

- A table showing the timeline;
- A series of figures covering an overview of the experiment;
- The data from each experiment are included on graphs that have the timeline detail included at the top of each graph with a vertical line indicating when the event occurred.

The results of each experiment are then examined in further detail in the discussion section.

5.6.1. Experiment 1

Experiment 1 was designed to simulate a crew making entry through the front door and then further ventilating the living room window. Ignition occurred in the living room. The fire was allowed to grow unventilated until 8:00, when the front door was opened, and then 15 seconds later the living room window was opened. The fire was then allowed to grow until 11:10, post-flashover, when 13 seconds of water were applied to the living room with a combination nozzle positioned in the straight stream pattern. The experiment was terminated at 12:20, and the crew extinguished the fire. Figure 5.44 through Figure 5.50 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.51 through Figure 5.61 detail the temperatures, pressures, gas concentrations and gas velocities during the experiments.

Table 5.7: Experiment 1 Timeline

Time	Description
0:00	Ignition
8:00	Front Door Open
8:15	Living Room Window Open
11:10	Straight Stream into Living Room Window
12:20	Final Suppression (End of Experiment)

Figure 5.43: Experiment 1 Scenario

Figure 5.44: Experiment 1 - 0:00

Figure 5.45: Experiment 1 - 4:56

Figure 5.46: Experiment 1 - 8:05

Figure 5.47: Experiment 1 - 8:20

Figure 5.48: Experiment 1 - 10:35

Figure 5.49: Experiment 1 - 11:12

Figure 5.50: Experiment 1 - 12:00

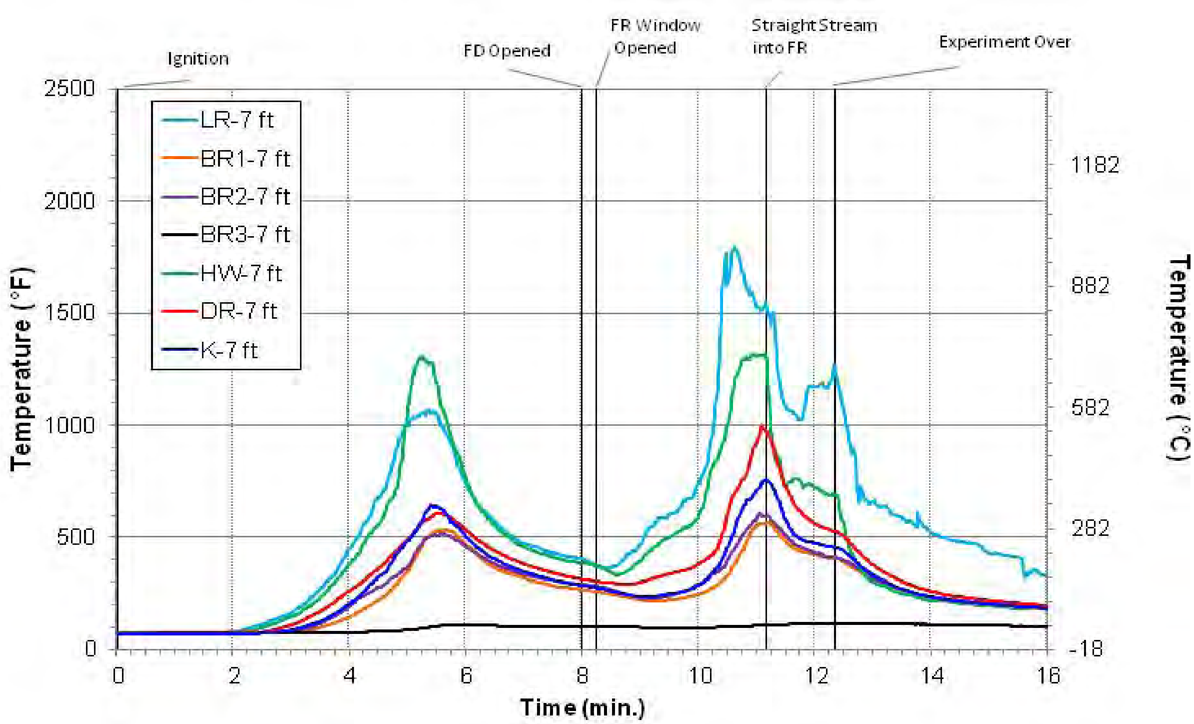


Figure 5.51: Experiment 1 - 7 ft. Temperatures

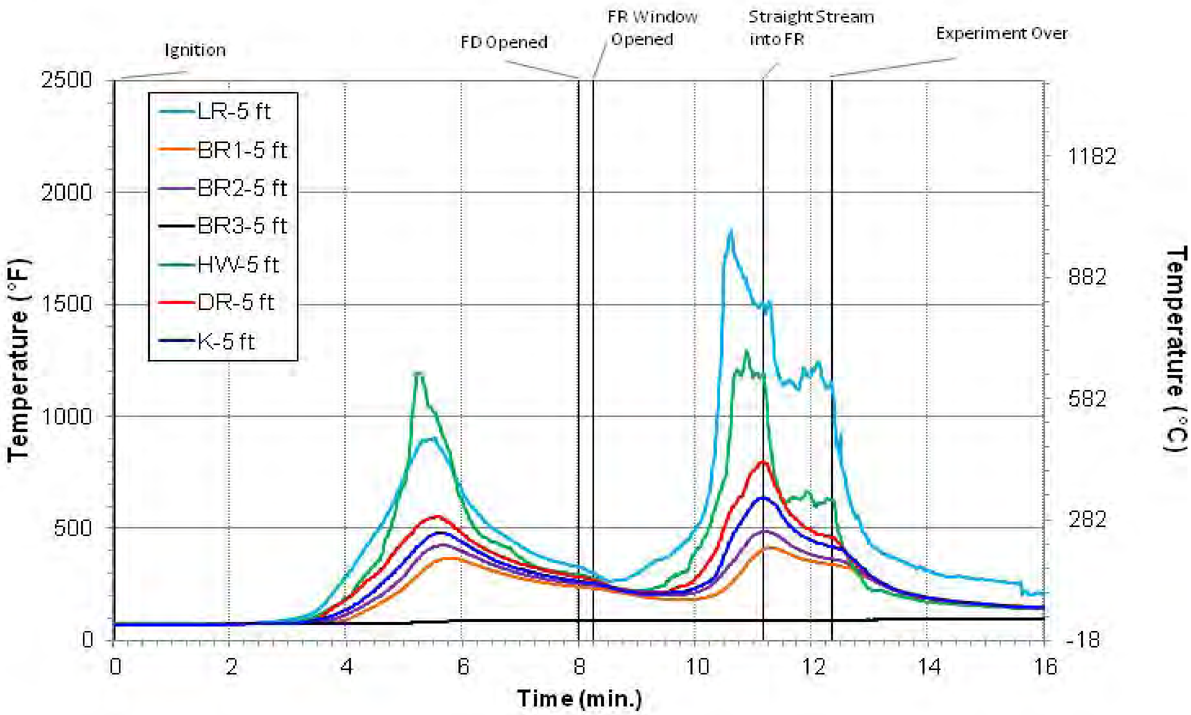


Figure 5.52: Experiment 1 - 5 ft. Temperatures

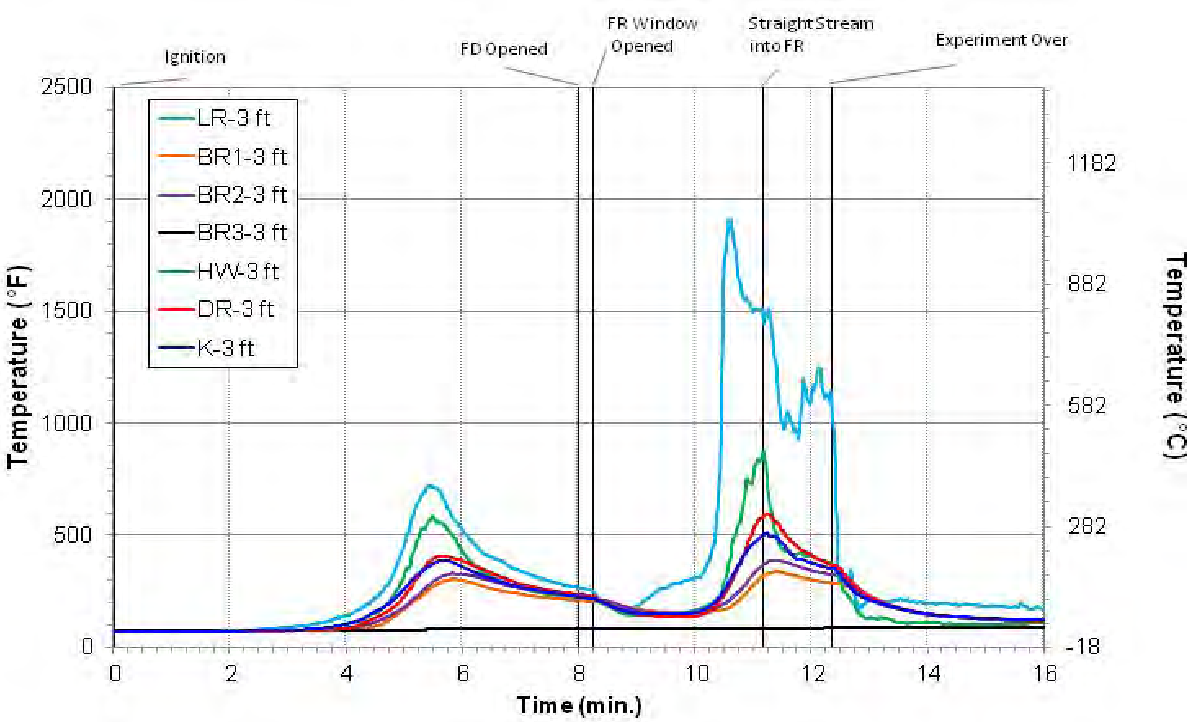


Figure 5.53: Experiment 1 - 3 ft. Temperatures

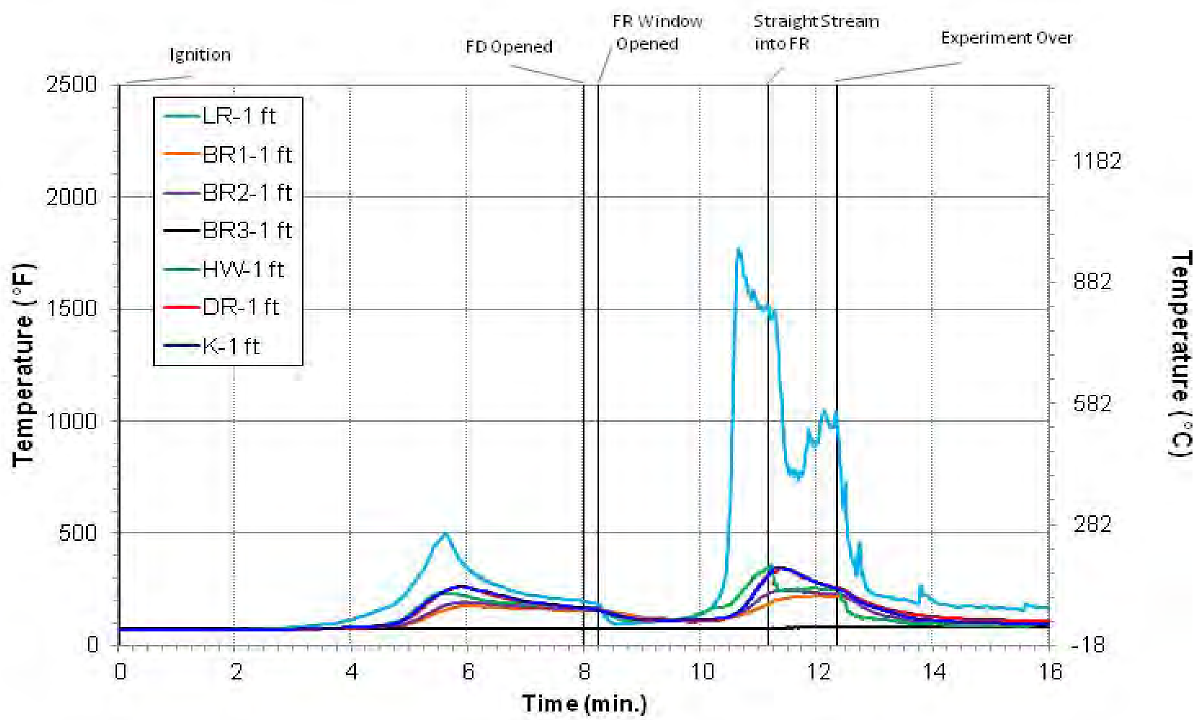


Figure 5.54: Experiment 1 - 1 ft. Temperatures

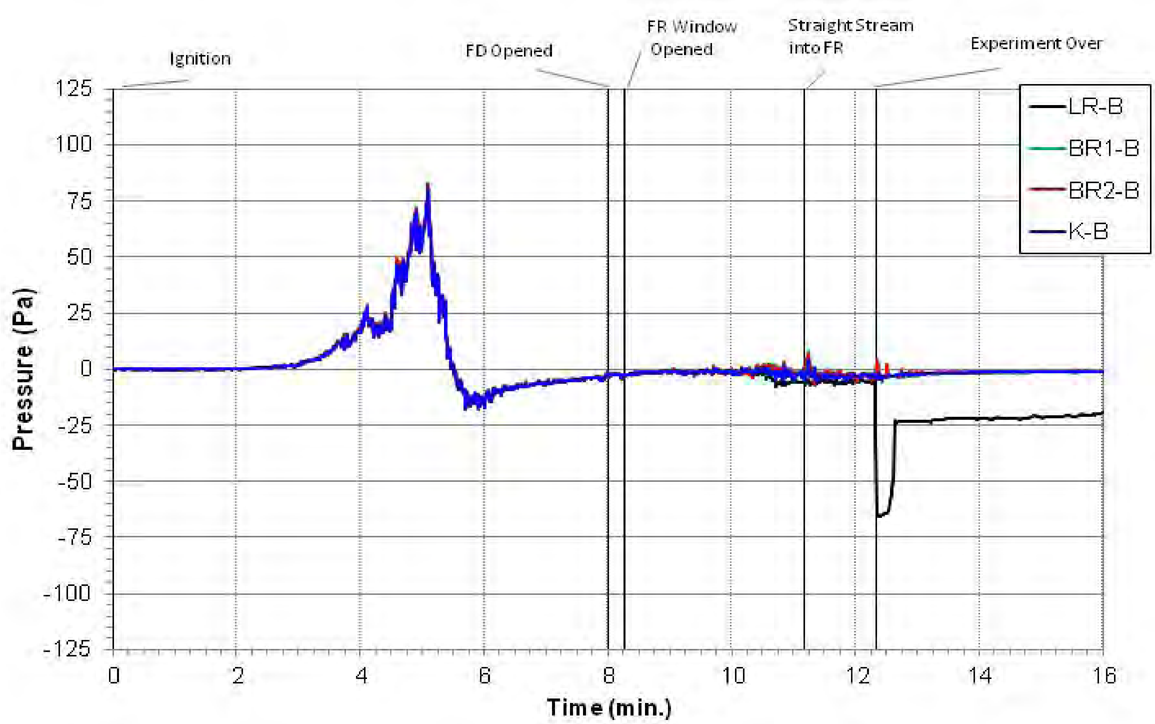


Figure 5.55: Experiment 1 - Bottom Pressure

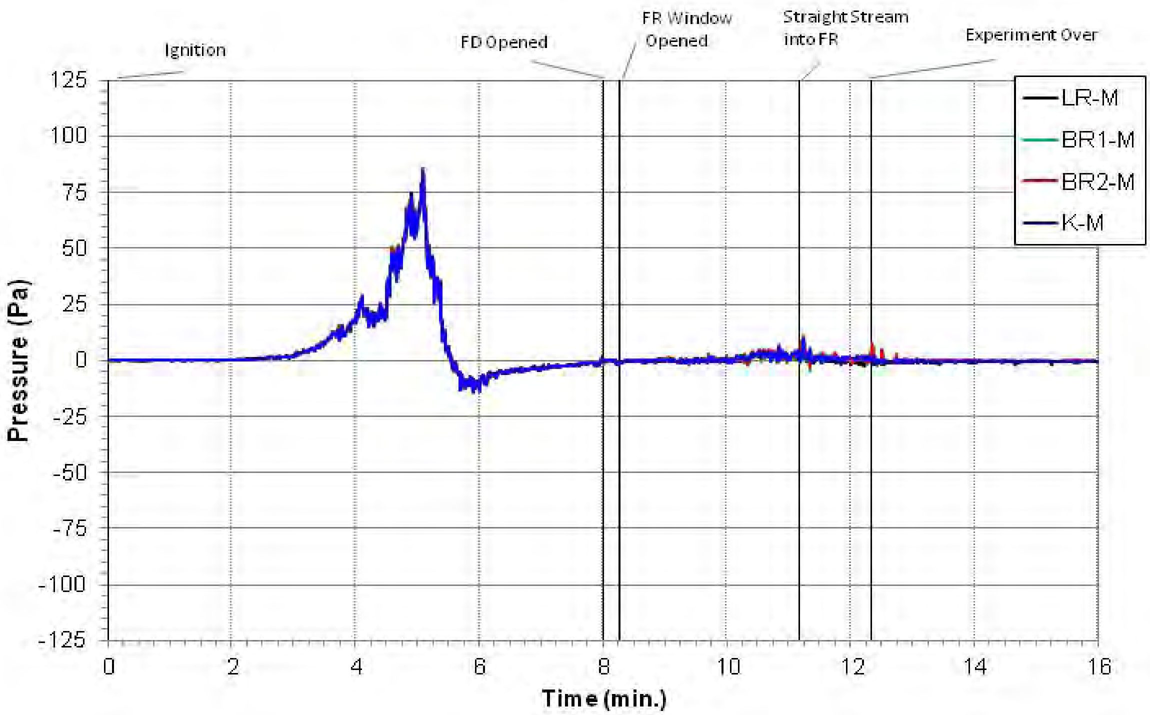


Figure 5.56: Experiment 1 - Middle Pressure

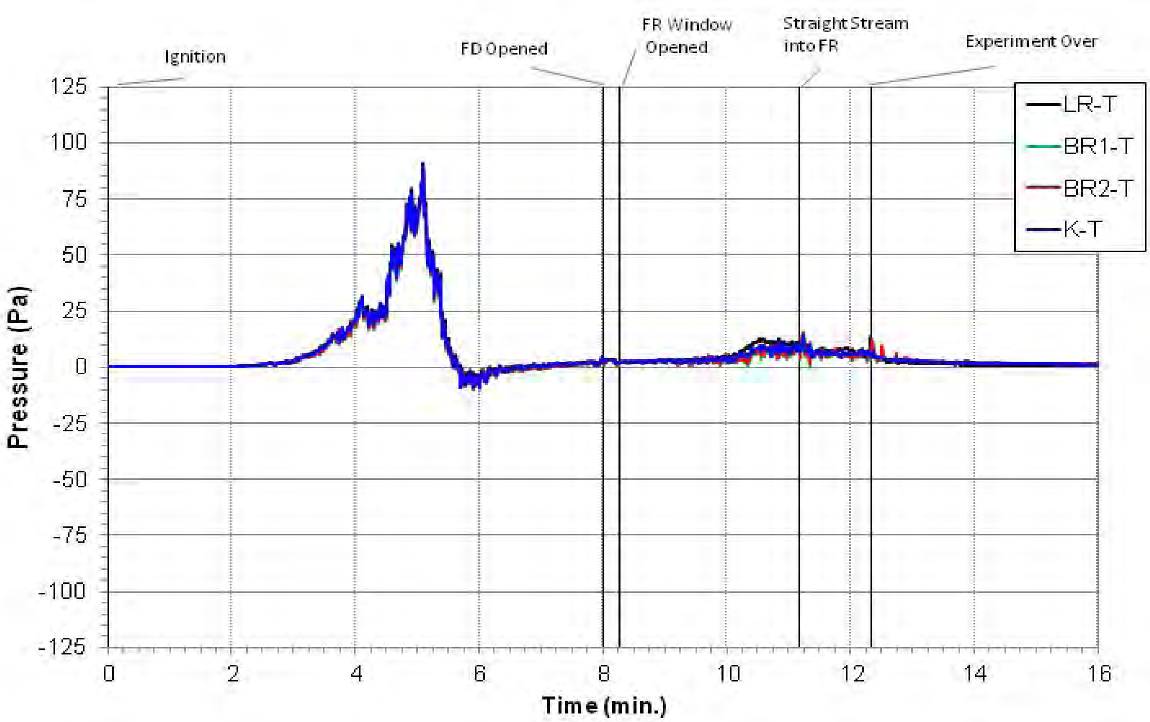


Figure 5.57: Experiment 1 - Top Pressure

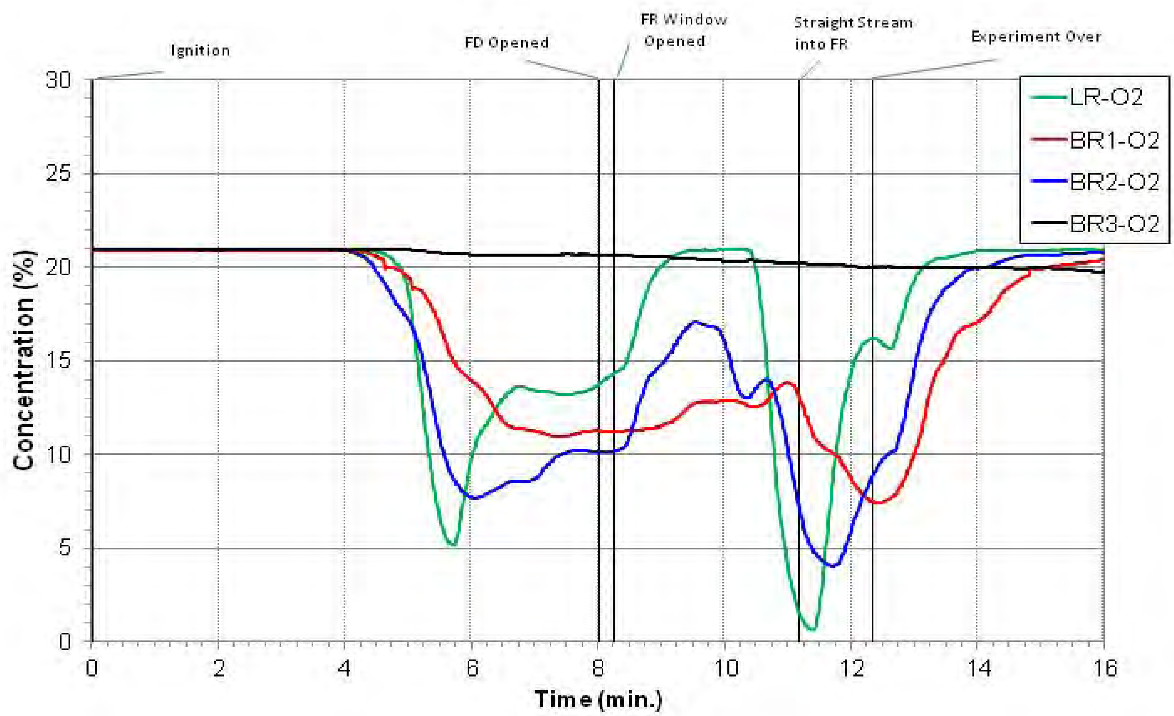


Figure 5.58: Experiment 1 - Oxygen Concentration

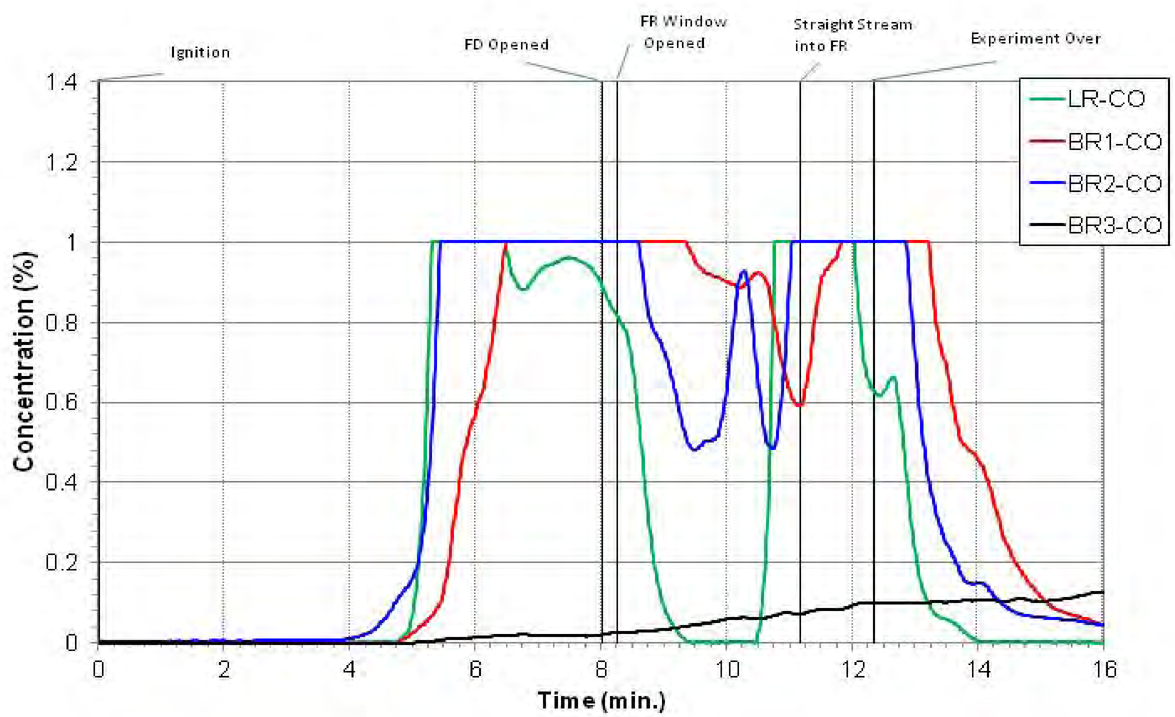


Figure 5.59: Experiment 1 - Carbon Monoxide Concentration

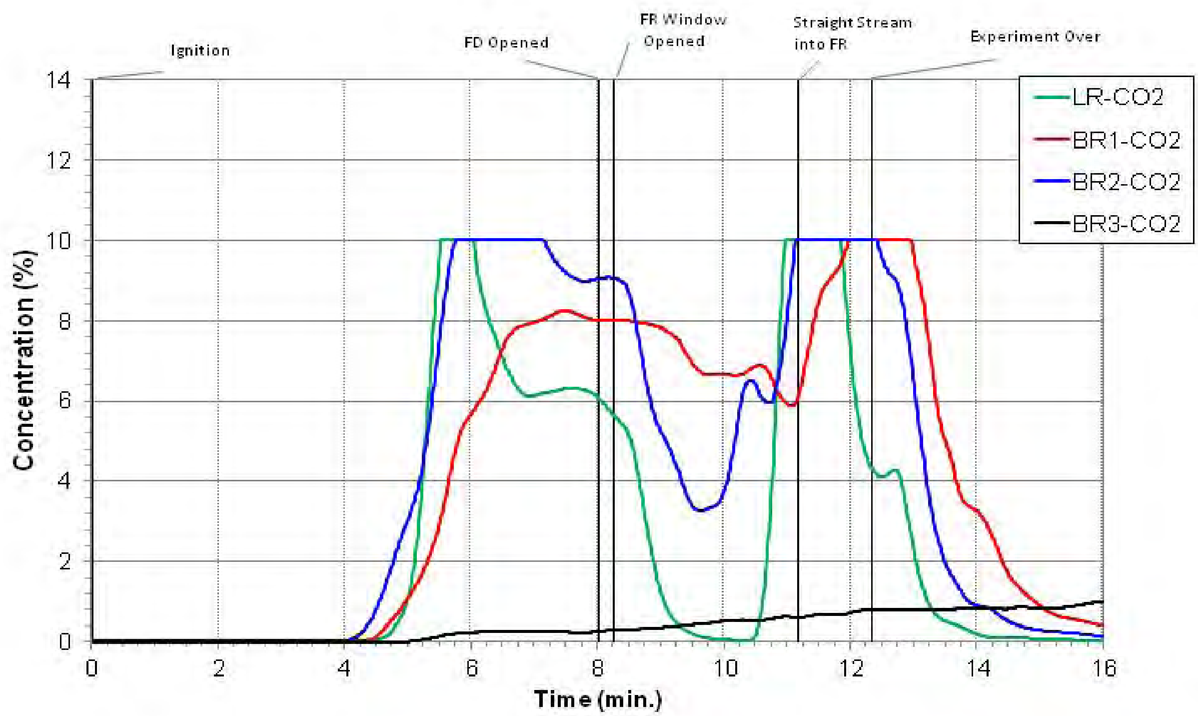


Figure 5.60: Experiment 1 - Carbon Dioxide Concentration

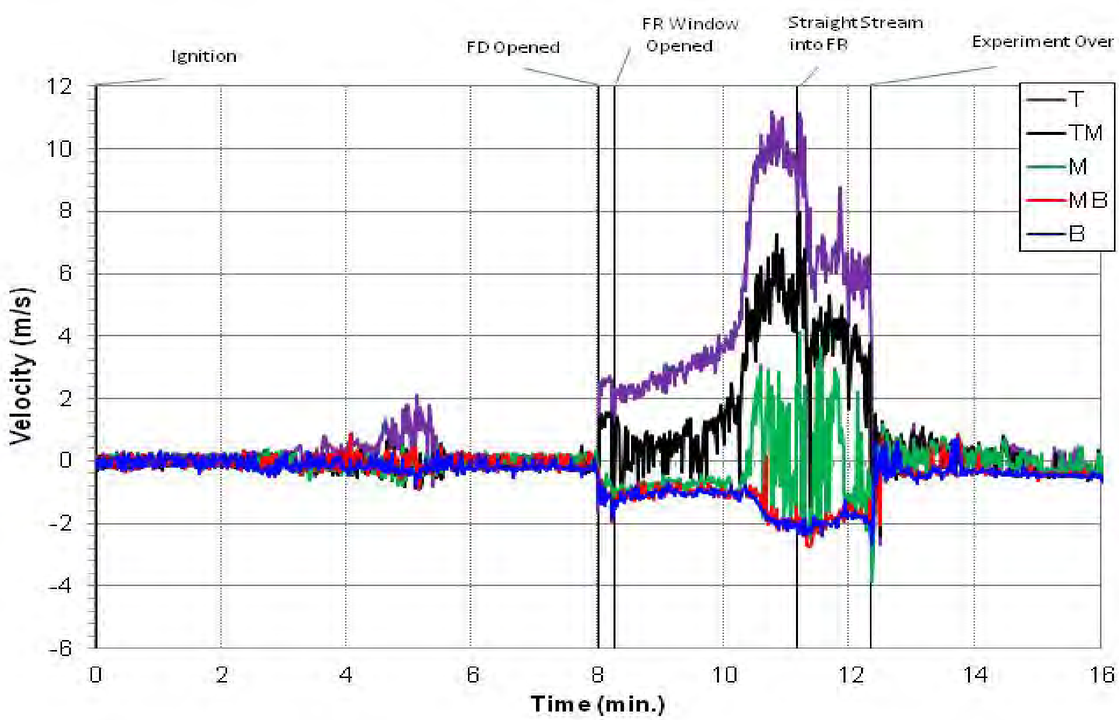


Figure 5.61: Experiment 1 - Front Door Velocity

5.6.2. Experiment 3

Experiment 3 was designed to simulate a fire crew entering the structure and then controlling the door behind them by closing the width of a hoseline, followed by vertically ventilating above the living room fire. Ignition occurred in the living room. The fire was allowed to grow until 8:00, when the front door was opened and then returned to partially open at 8:15. At 12:05, the fire was further ventilated by opening a 4' by 4' hole on the roof. The fire was again allowed to grow until 15:07, post-flashover, when the front door was fully opened. Several seconds later, at 15:25, 11 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern. The experiment ended at 17:00, when the crew extinguished the fire. Figure 5.63 through Figure 5.71 show images of the house velocities during certain times of the experiment, which highlight the events in the timeline. Figure 5.72 through Figure 5.83 detail the temperatures, pressures, gas concentrations and gas velocities during the experiments.

Table 5.8: Experiment 3 Timeline

Time	Description
0:00	Ignition
8:00	Front Door Open
8:15	Front Door Partially Open
12:05	4 ft. by 4 ft. Vertical Vent Open
15:07	Front Door Fully Open
15:25	Straight Stream into Front Door
17:00	Final Suppression (End of Experiment)

Figure 5.62: Experiment 3 Scenario

Figure 5.63: Experiment 3 - 0:00

Figure 5.64: Experiment 3 - 5:00

Figure 5.65: Experiment 3 - 8:05

Figure 5.66: Experiment 3 - 8:20

Figure 5.67: Experiment 3 - 12:10

Figure 5.68: Experiment 3 - 13:25

Figure 5.69: Experiment 3 - 15:10

Figure 5.70: Experiment 3 - 15:29

Figure 5.71: Experiment 3 - 16:10

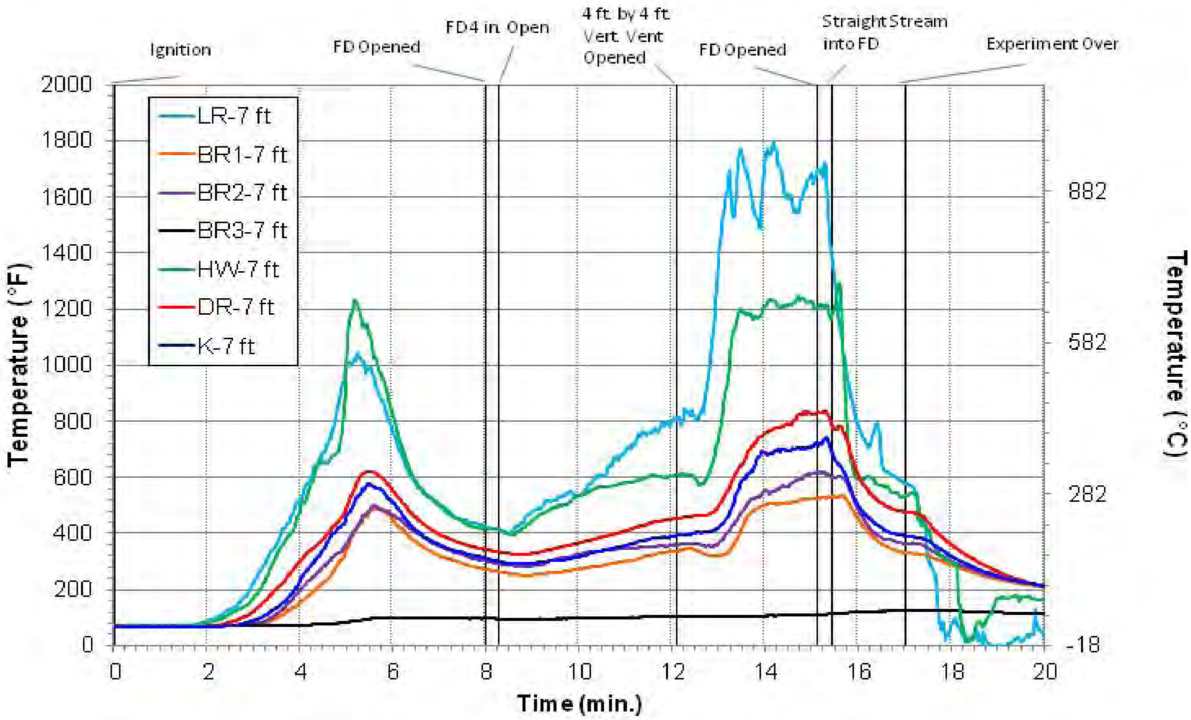


Figure 5.72: Experiment 3 - 7 ft. Temperatures

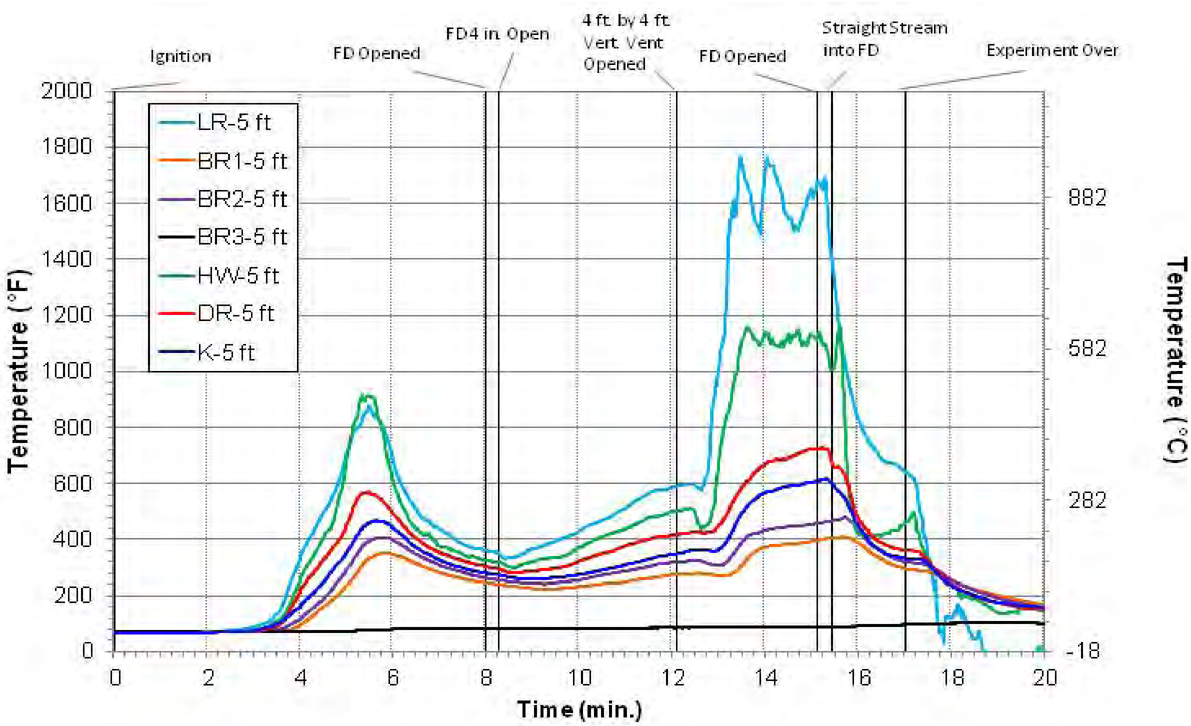


Figure 5.73: Experiment 3 - 5 ft. Temperatures

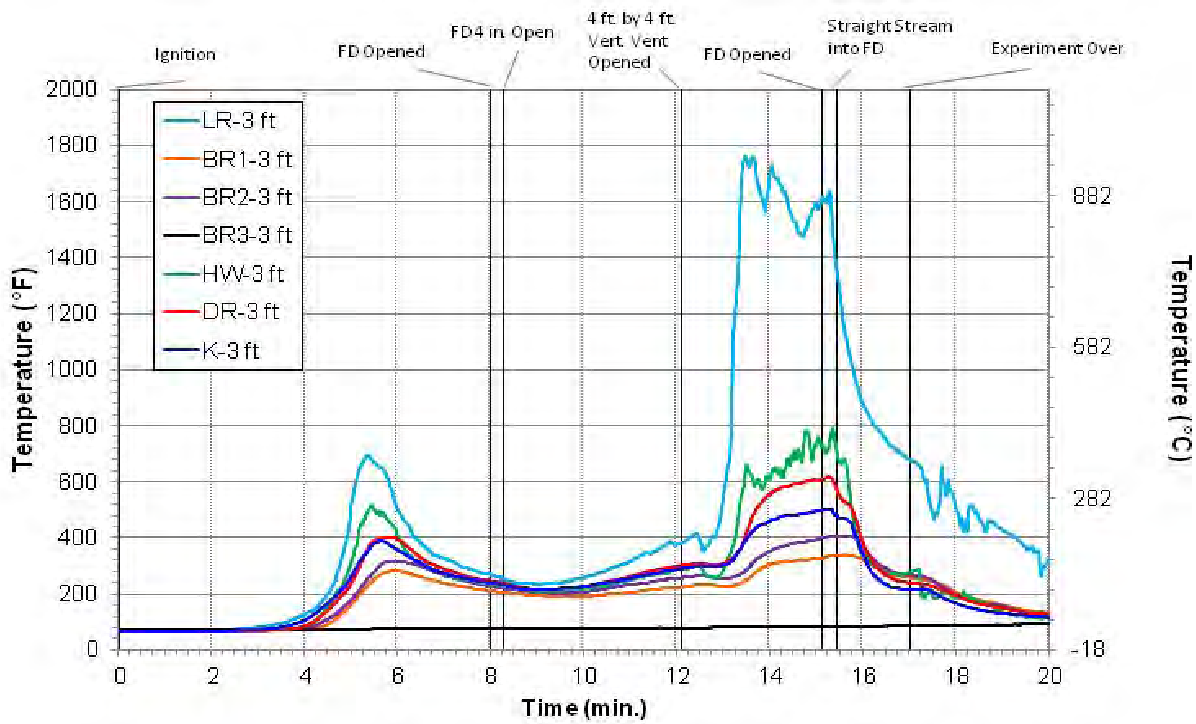


Figure 5.74: Experiment 3 - 3 ft. Temperatures

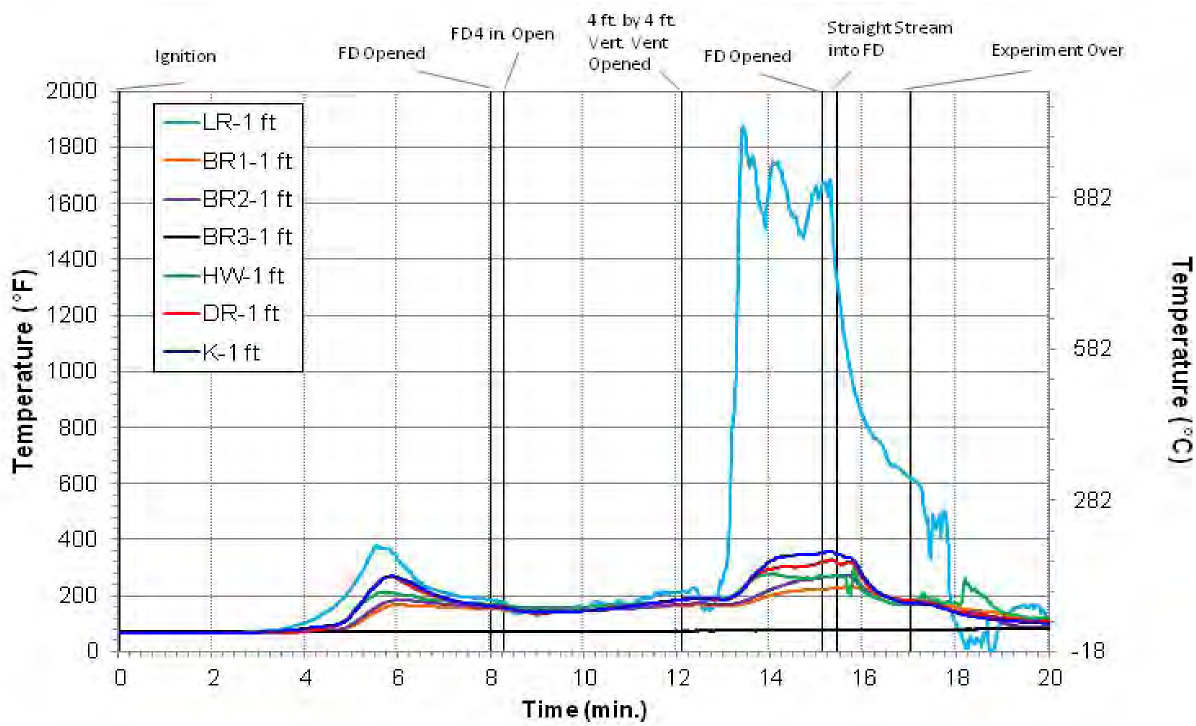


Figure 5.75: Experiment 3 - 1 ft. Temperatures

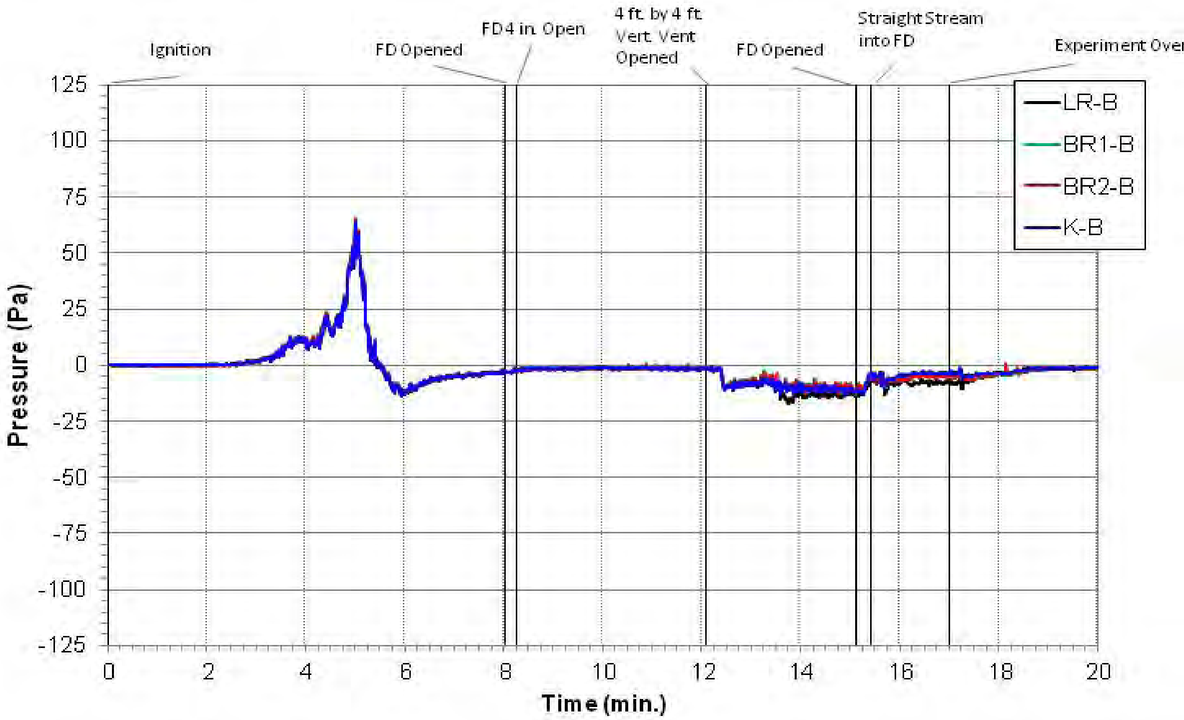


Figure 5.76: Experiment 3 - Bottom Pressure

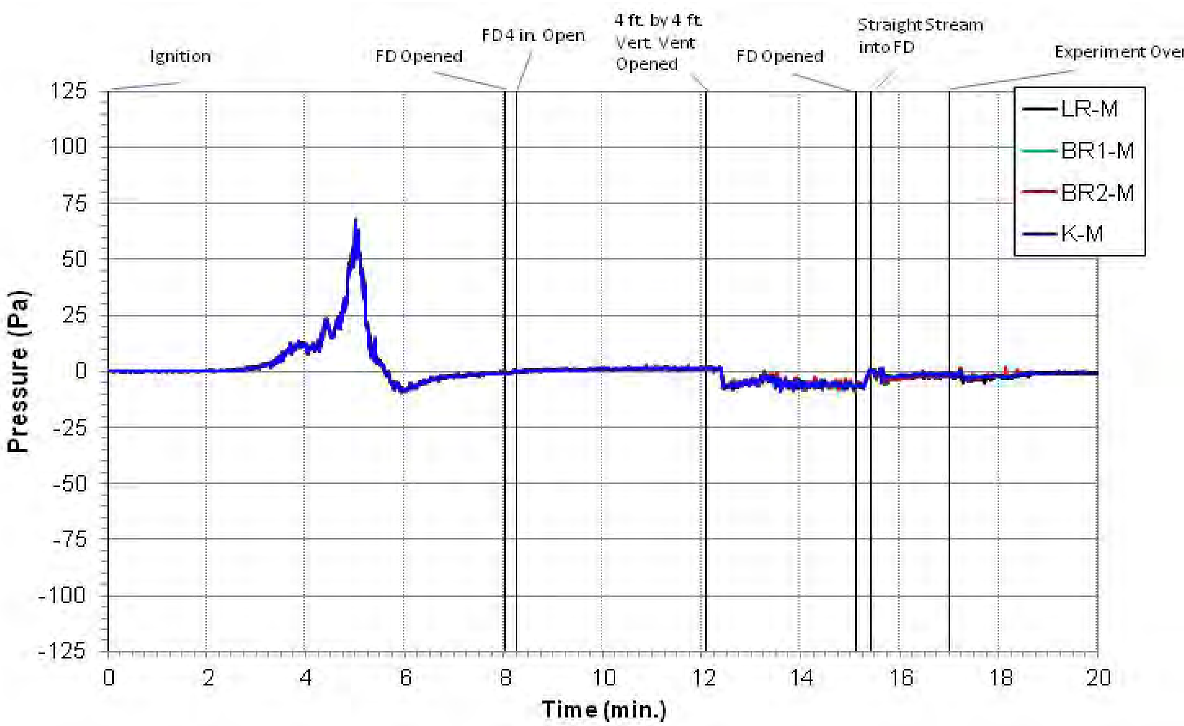


Figure 5.77: Experiment 3 - Middle Pressure

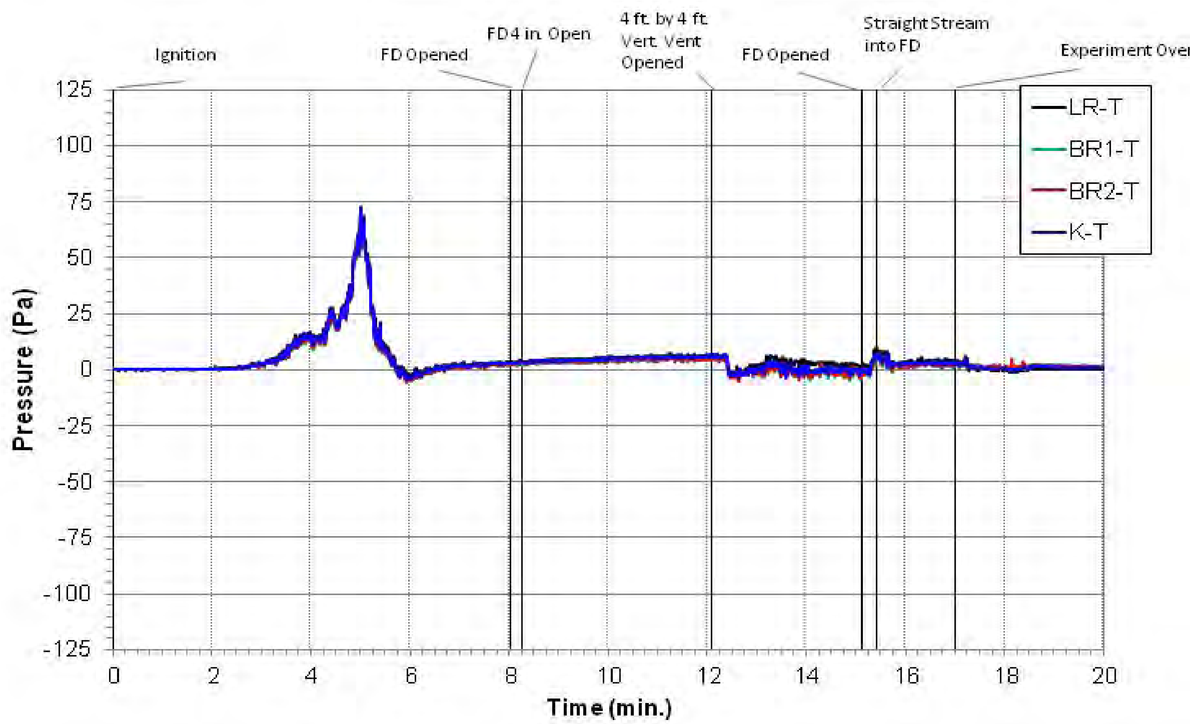


Figure 5.78: Experiment 3 - Top Pressure

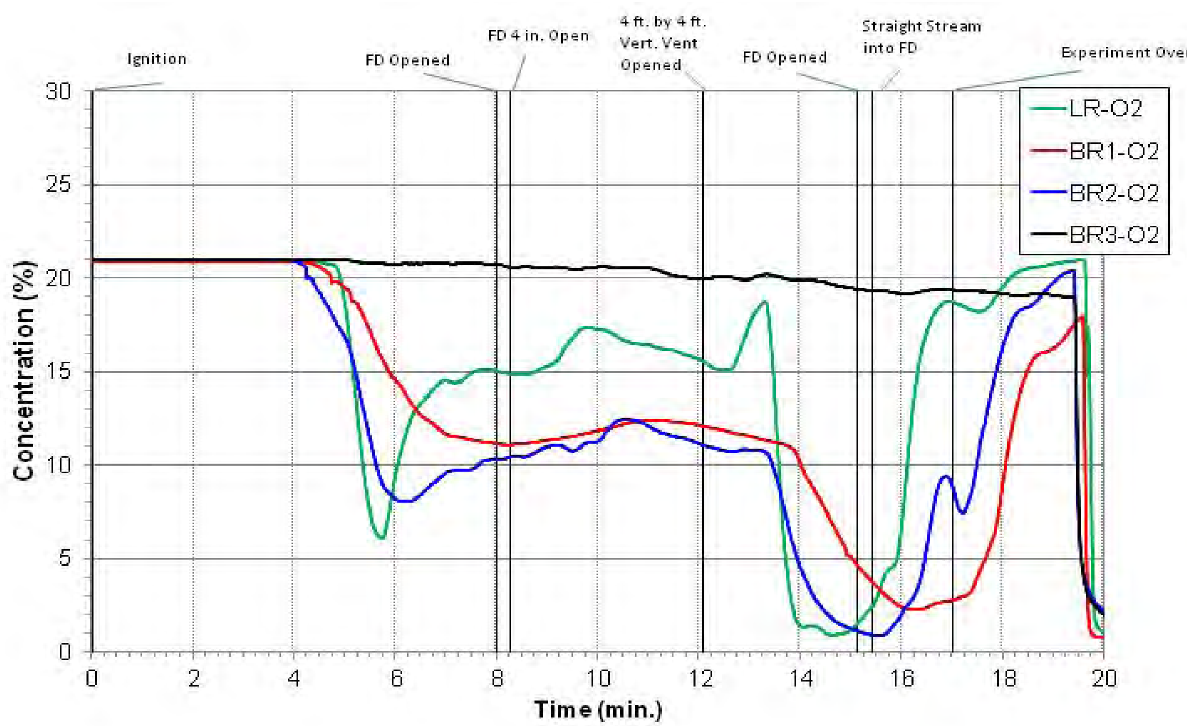


Figure 5.79: Experiment 3 - Oxygen Concentration

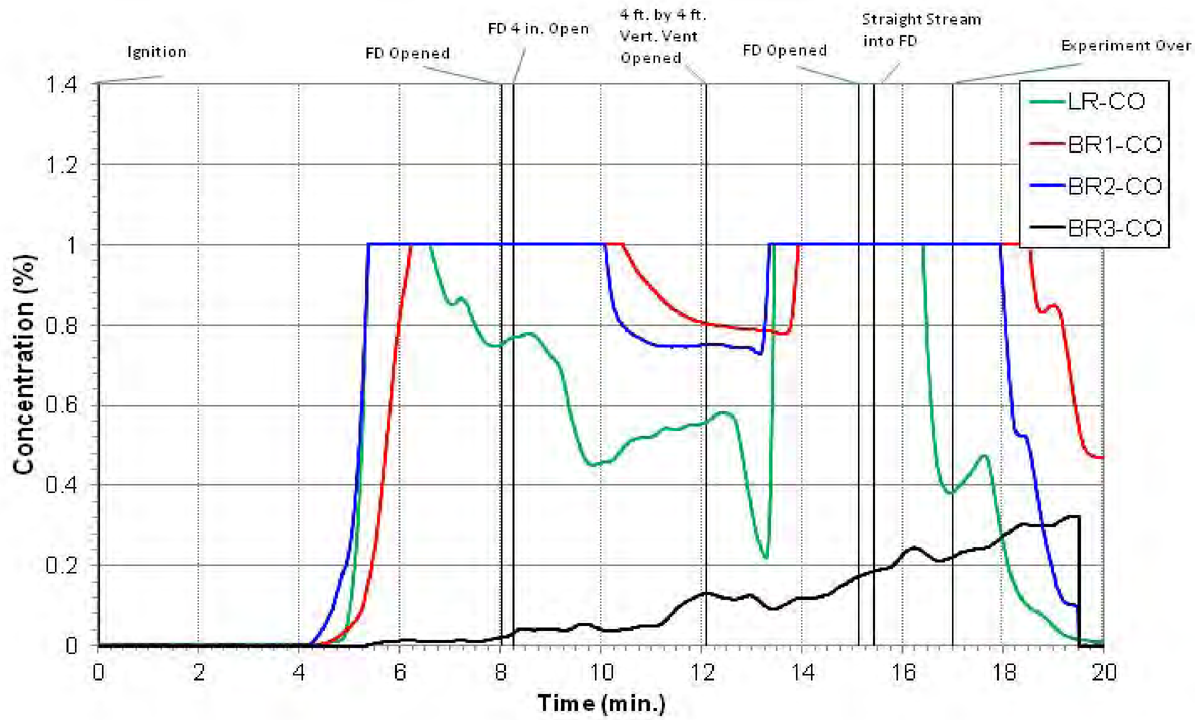


Figure 5.80: Experiment 3 - Carbon Monoxide Concentration

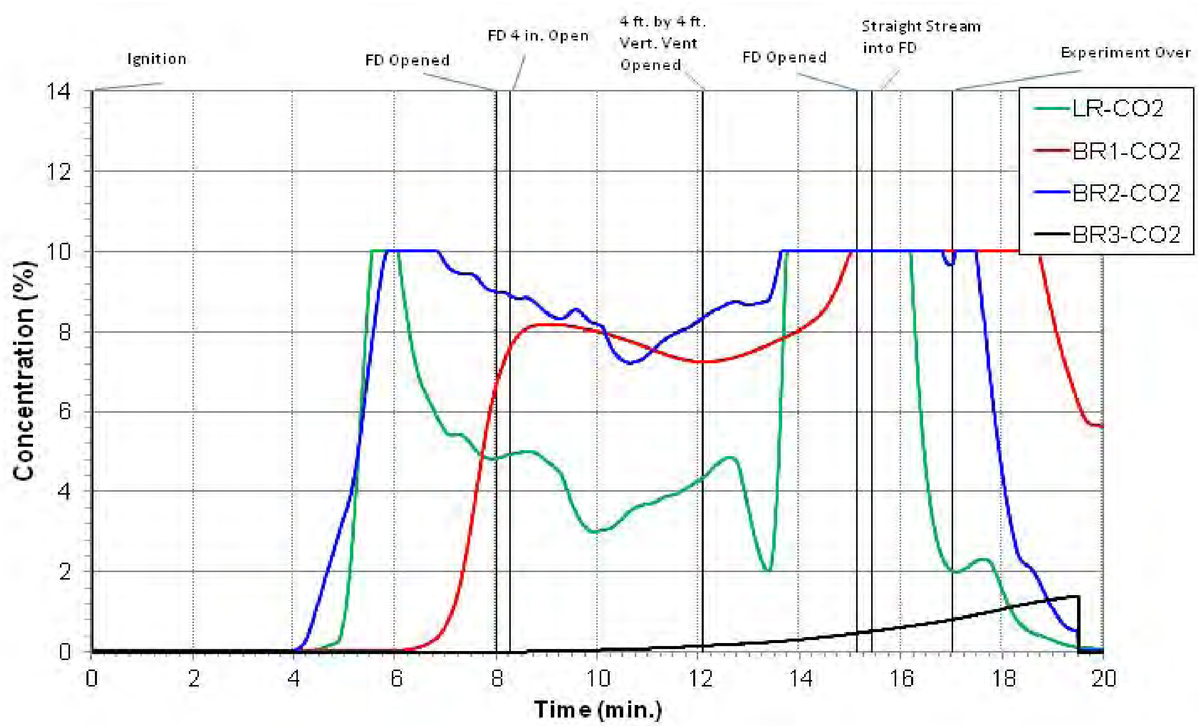


Figure 5.81: Experiment 3 - Carbon Dioxide Concentration

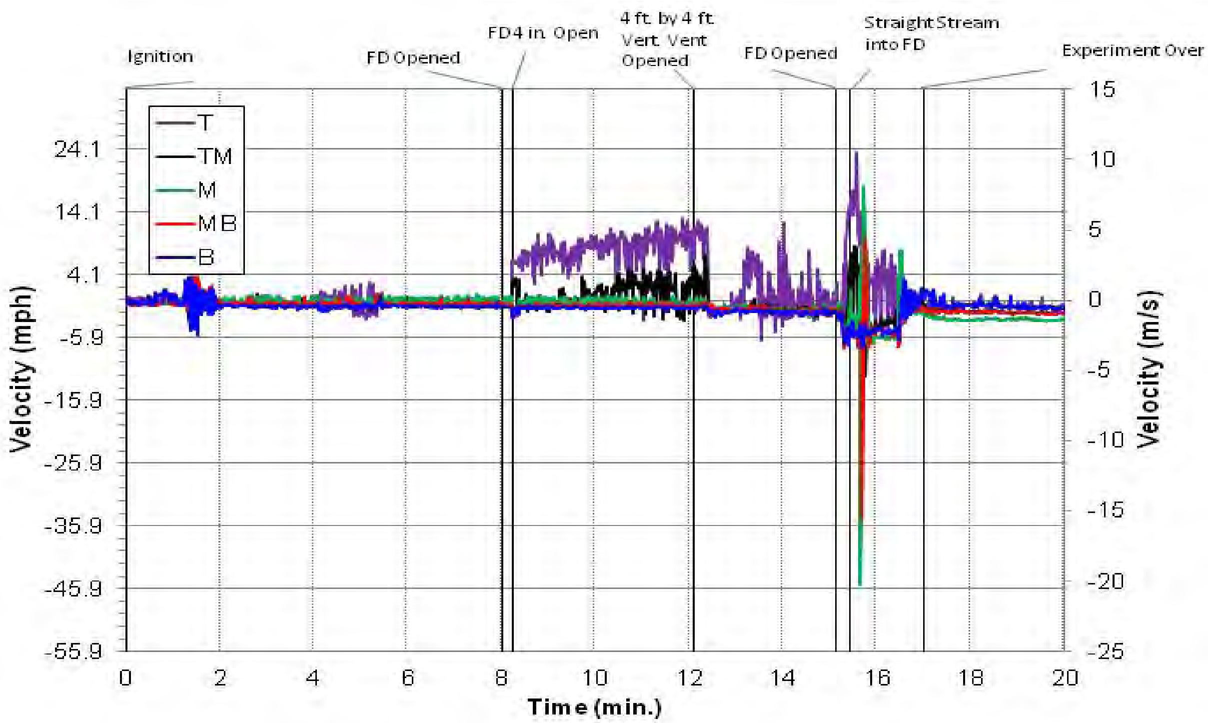


Figure 5.82: Experiment 3 - Front Door Velocity

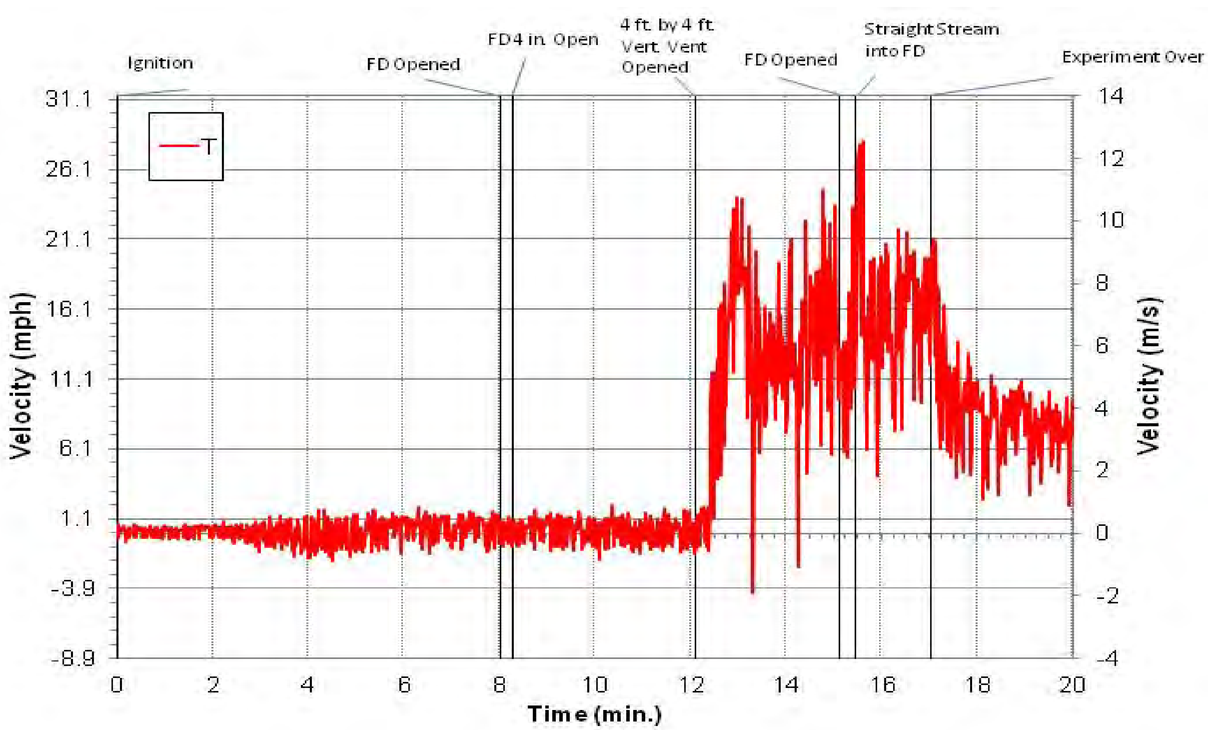


Figure 5.83: Experiment 3 - Roof Vent Velocity

5.6.3. Experiment 5

Experiment 5 was designed to simulate a crew ventilating the front door, chocking it completely open, and then ventilating vertically above the fire. Ignition occurred in the living room. The fire was allowed to grow until 8:00, when the front door was opened. At 9:45, a 4' by 4' hole in the roof was opened. The fire was allowed to grow to post-flashover conditions, and then, at 11:15, 17 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern. The experiment ended at 12:55, and the crew extinguished the fire. Figure 5.85 through Figure 5.91 show images of the house at certain times during the experiment that highlight the events in the timeline. Figure 5.92 through Figure 5.103 detail the temperatures, pressures, gas concentrations and gas velocities during the experiments.

Table 5.9: Experiment 5 Timeline

Time	Description
0:00	Ignition
8:00	Front Door Open
9:45	4 ft. by 4 ft. Vertical Vent Open
11:15	Straight Stream into Front Door
12:55	Final Suppression (End of Experiment)

Figure 5.84: Experiment 5 Scenario

Figure 5.85: Experiment 5 - 0:00

Figure 5.86: Experiment 5 - 4:30

Figure 5.87: Experiment 5 - 8:05

Figure 5.88: Experiment 5 - 9:50

Figure 5.89: Experiment 5 - 10:25

Figure 5.90: Experiment 5 - 11:17

Figure 5.91: Experiment 5 - 15:10

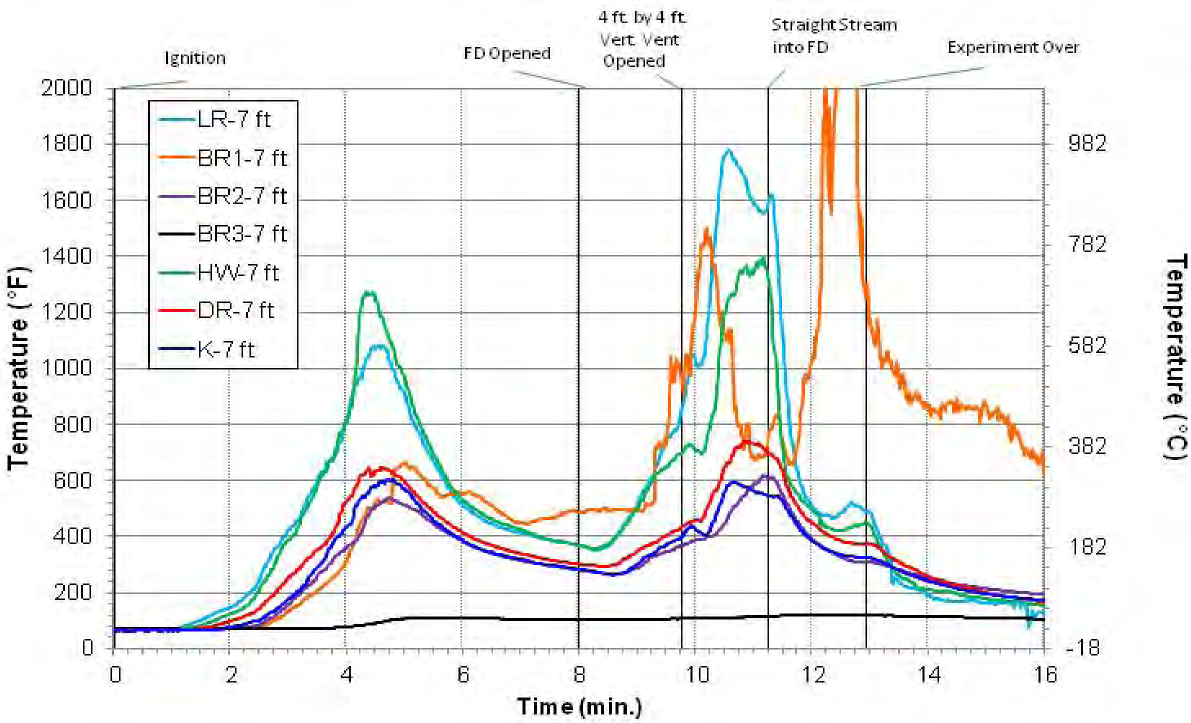


Figure 5.92: Experiment 5 - 7 ft. Temperatures

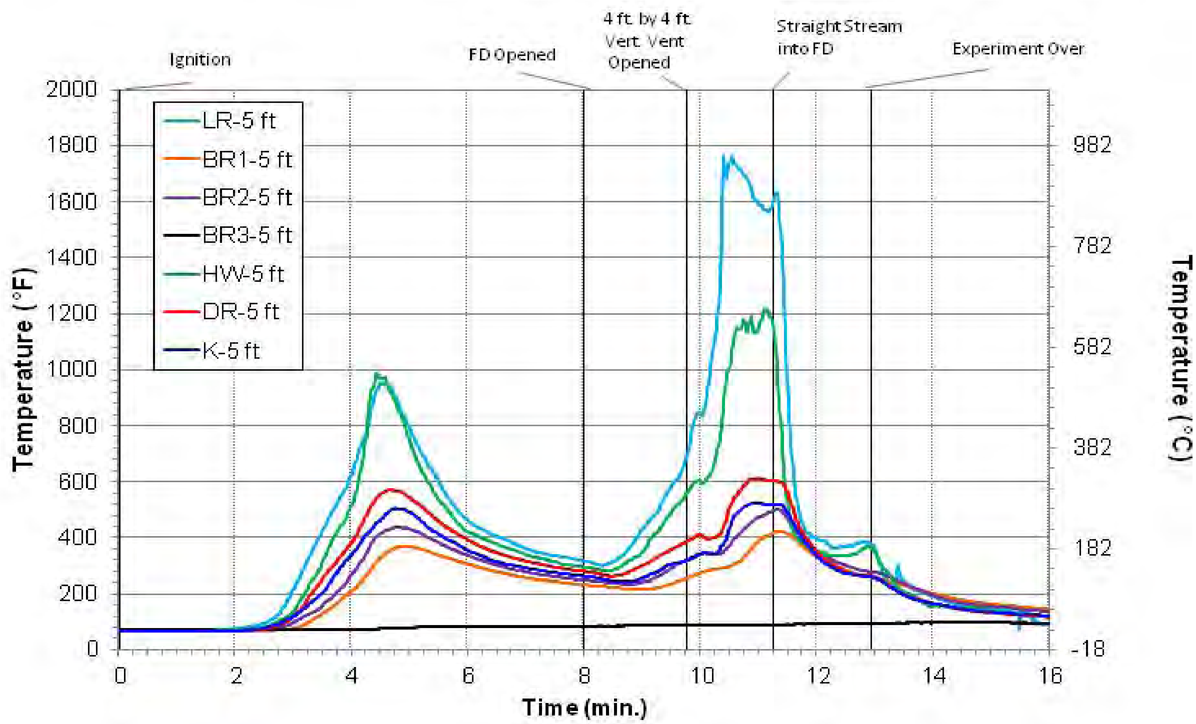


Figure 5.93: Experiment 5 - 5 ft. Temperatures

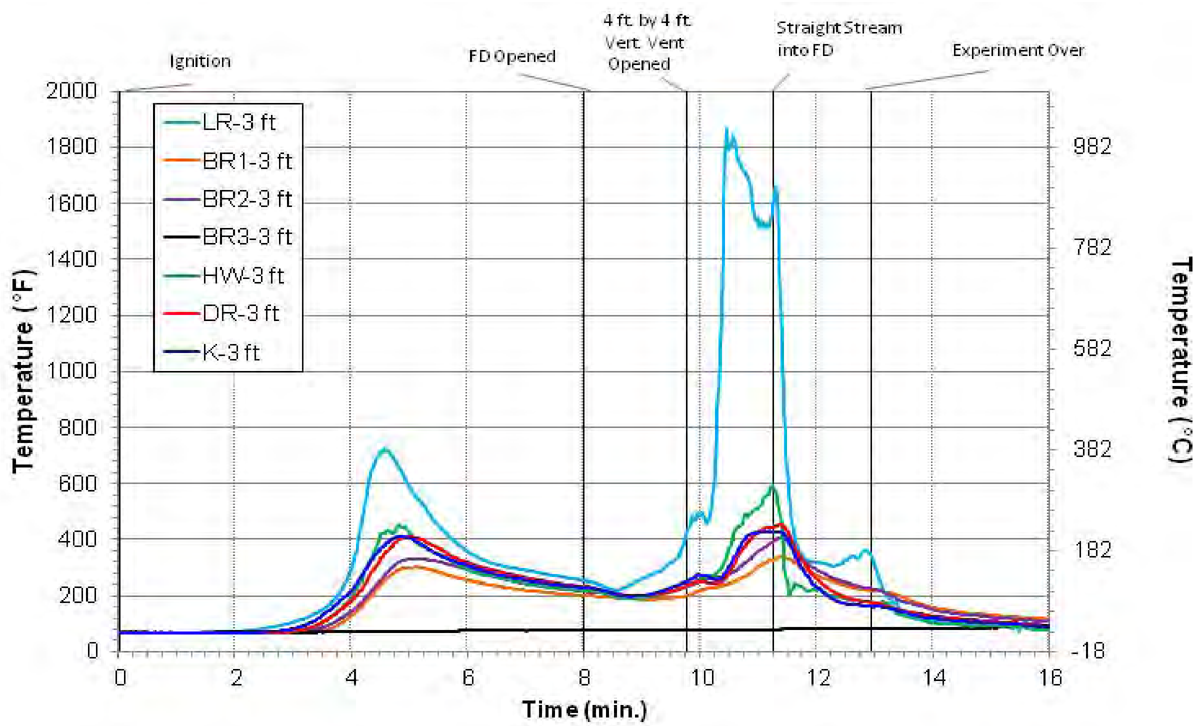


Figure 5.94: Experiment 5 - 3 ft. Temperatures

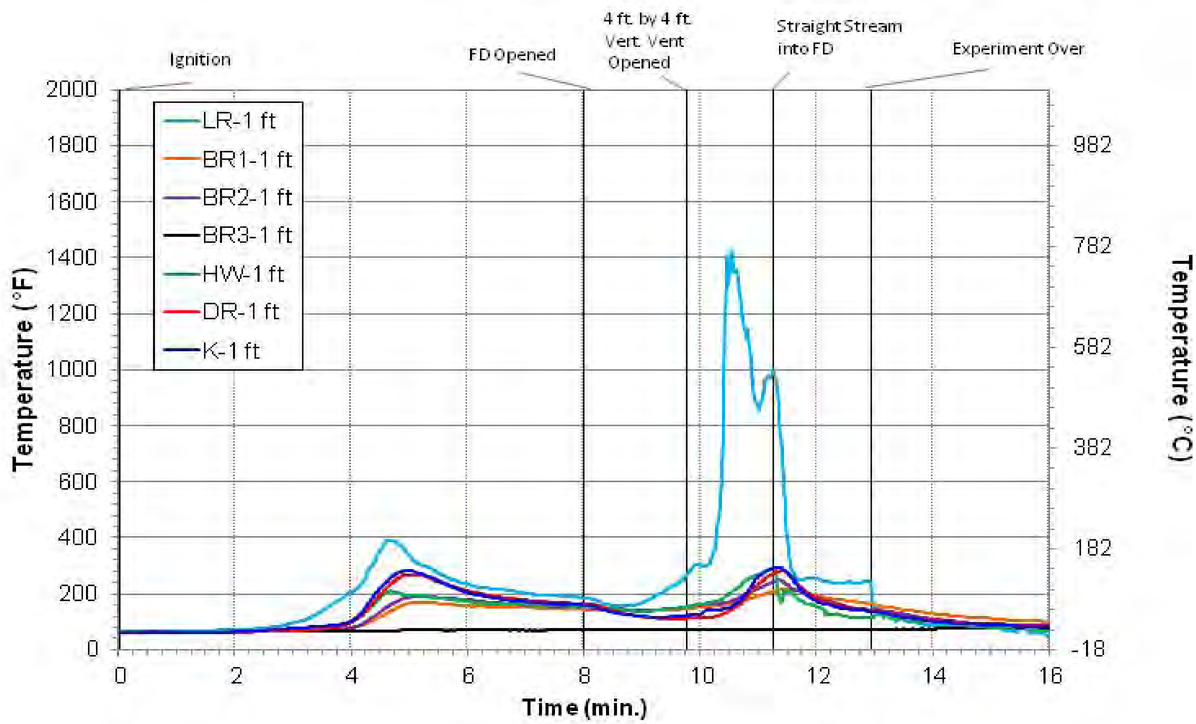


Figure 5.95: Experiment 5 - 1 ft. Temperatures

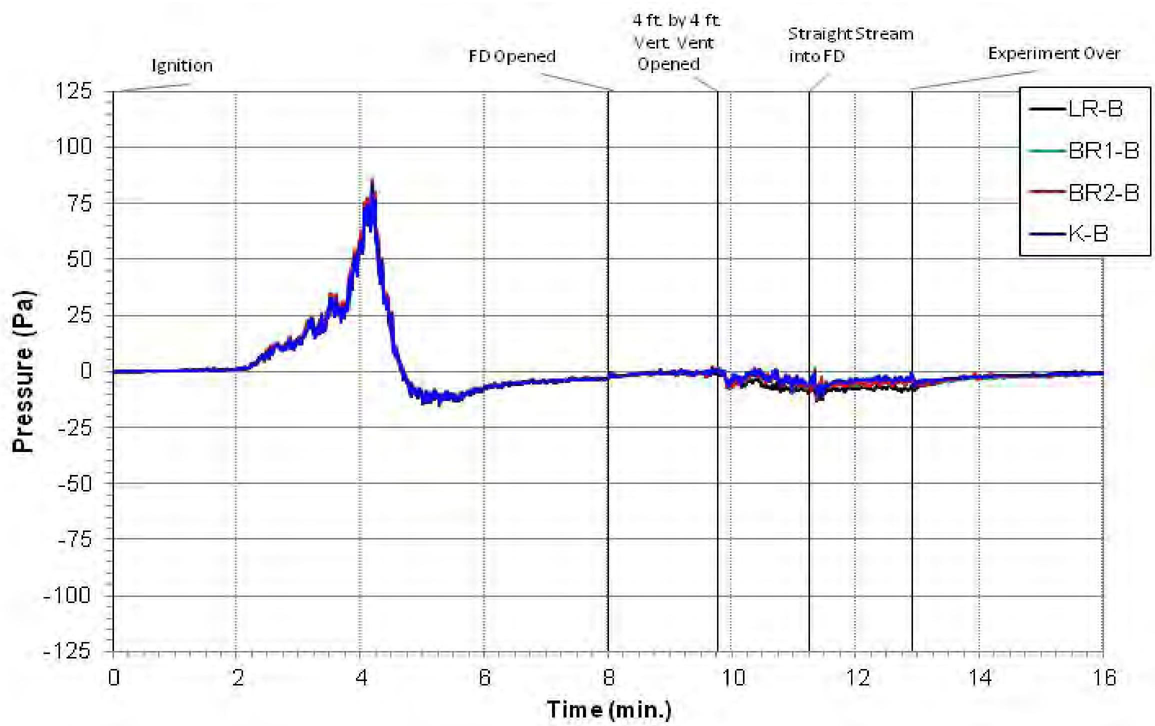


Figure 5.96: Experiment 5 - Bottom Pressure

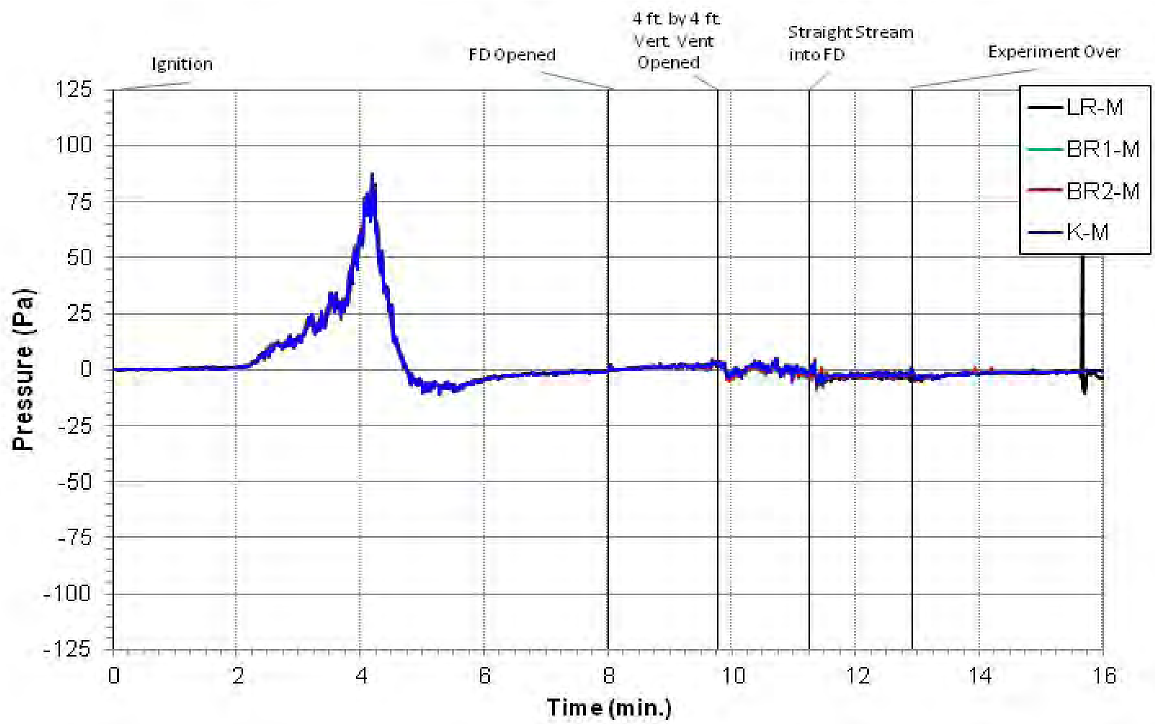


Figure 5.97: Experiment 5 - Middle Pressure

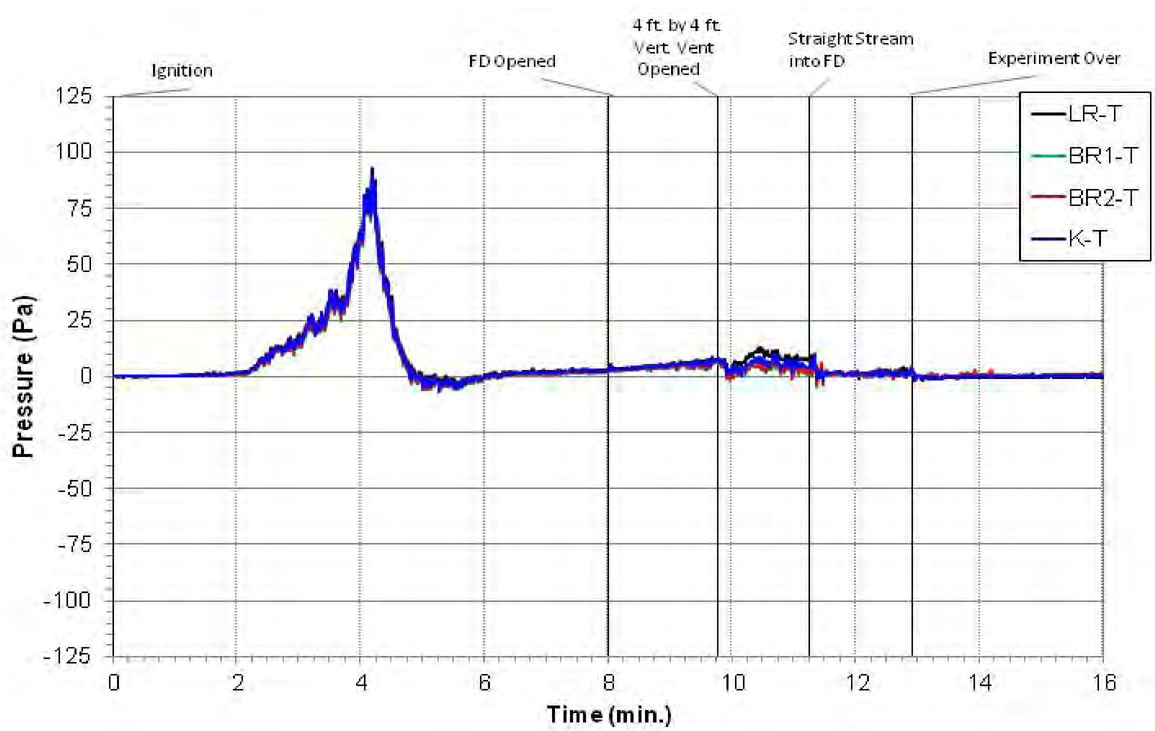


Figure 5.98: Experiment 5 - Top Pressure

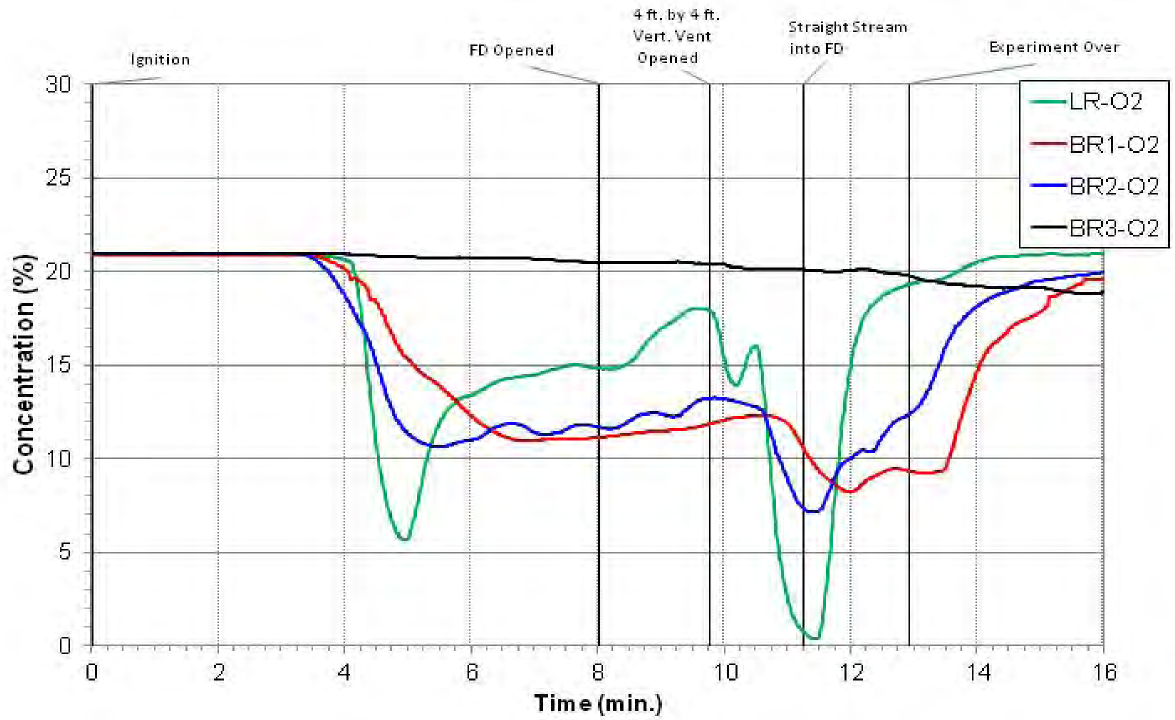


Figure 5.99: Experiment 5 - Oxygen Concentration

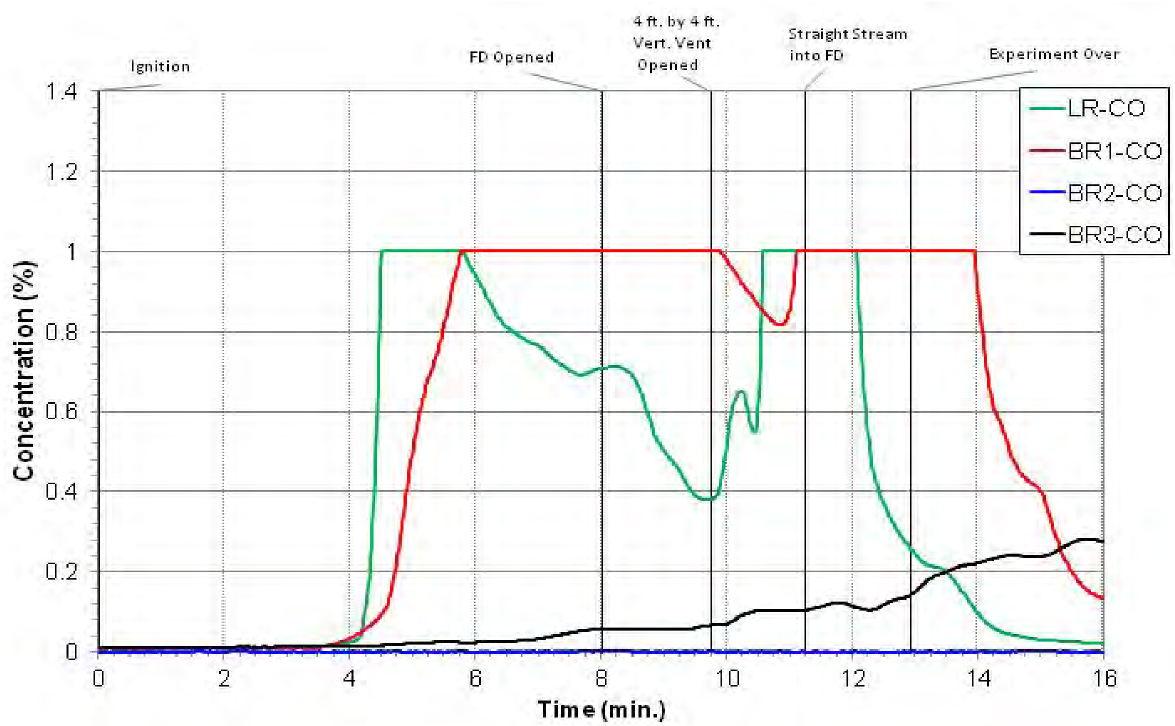


Figure 5.100: Experiment 5 - Carbon Monoxide Concentration

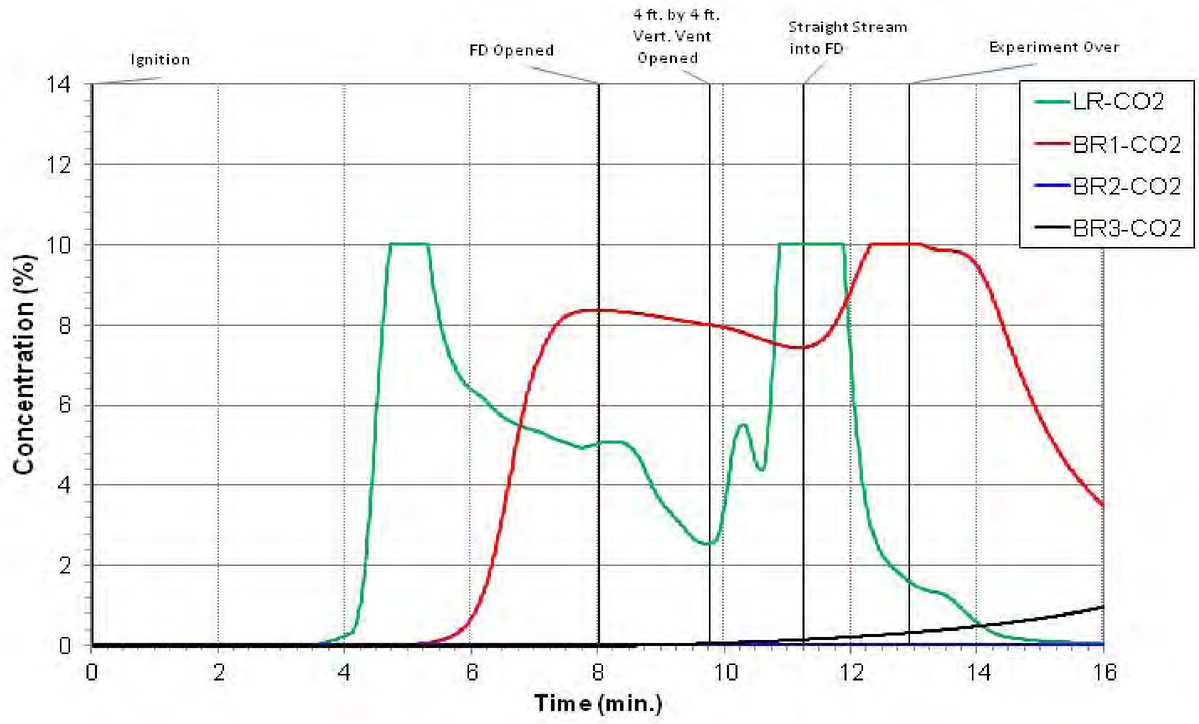


Figure 5.101: Experiment 5 - Carbon Dioxide Concentration

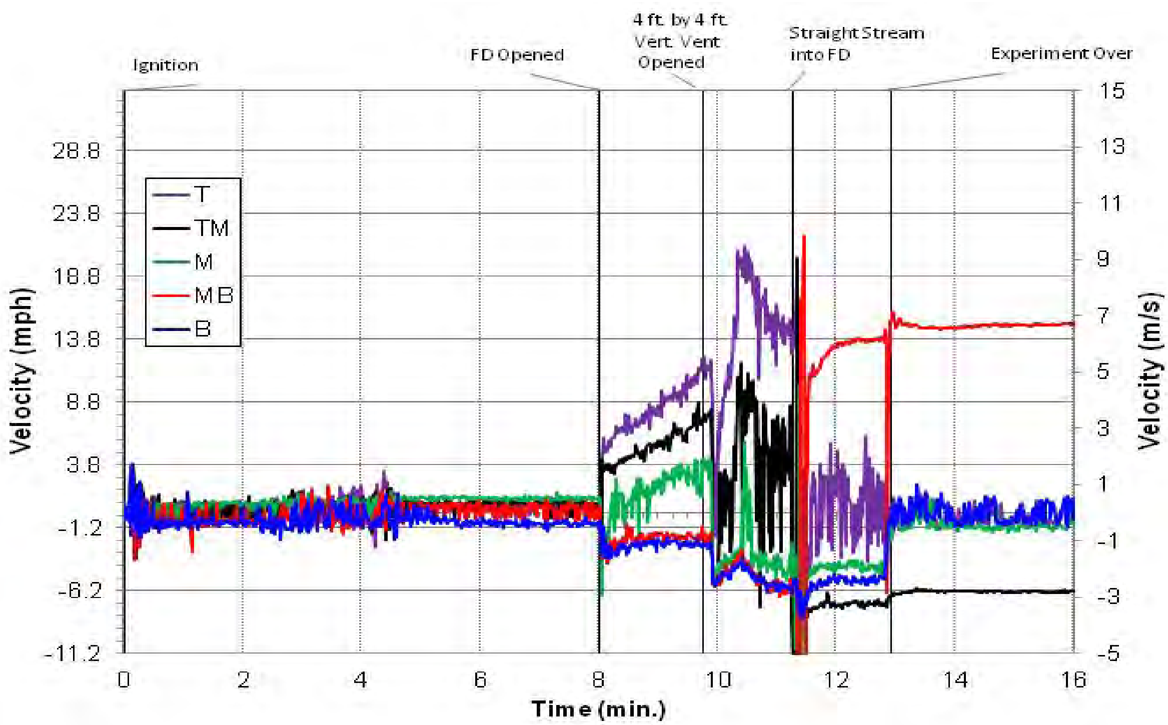


Figure 5.102: Experiment 5 - Front Door Velocity

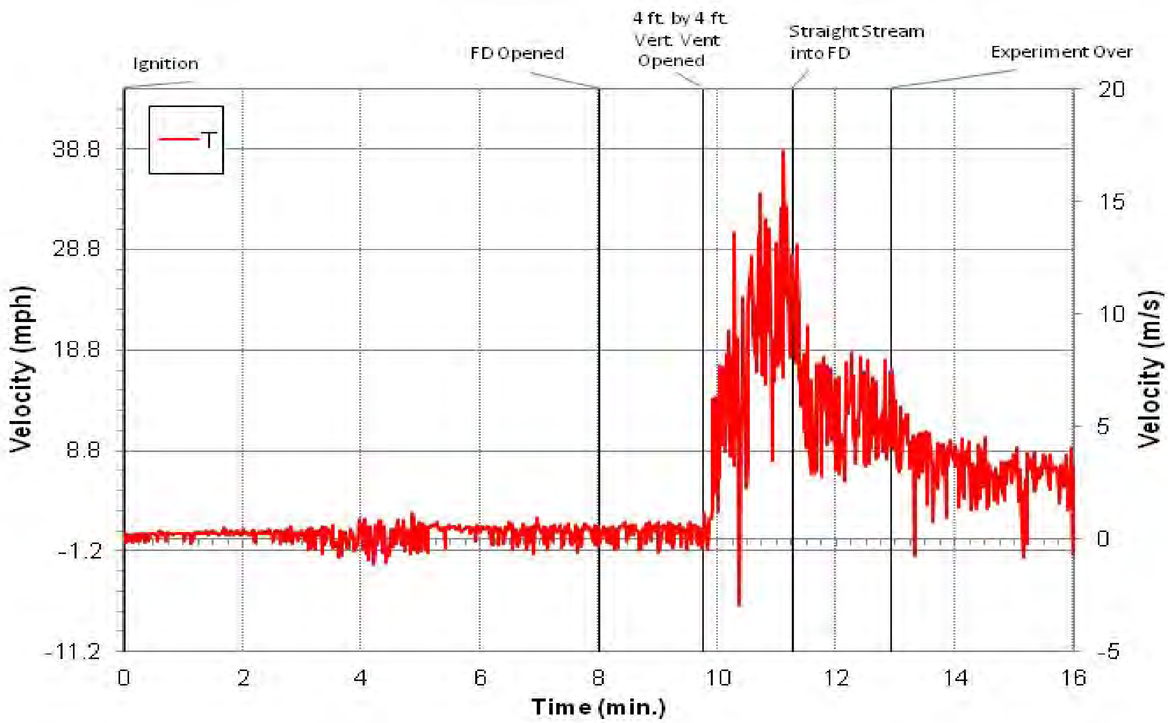


Figure 5.103: Experiment 5 - Roof Vent Velocity

5.6.4. Experiment 7

Experiment 7 was designed to simulate a crew ventilating the front door, chocking it open, and later ventilating vertically a hole twice the size of Experiment 5 (4 ft by 8 ft total). Ignition occurred in the living room. The fire was allowed to grow until 8:00, when the front door was opened. At 9:35 a 4' by 4' hole in the roof was opened and 10 seconds later an additional 4' by 4' hole in the roof was opened for a total ventilation area of 4 ft by 8 ft. The fire was then allowed to grow to post-flashover conditions and 15 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern at 11:10. The experiment ended at 13:05, and the crew extinguished the fire. Figure 5.105 through Figure 5.111 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.112 through Figure 5.123 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.10: Experiment 7 Timeline

Time	Description
0:00	Ignition
8:00	Front Door Open
9:35	4 ft. by 4 ft. Vertical Vent Open
9:45	4 ft. by 8 ft. Vertical Vent Open
11:10	Straight Stream into Front Door
13:05	Final Suppression (End of Experiment)

Figure 5.104: Experiment 7 Scenario

Figure 5.105: Experiment 7 - 0:00

Figure 5.106: Experiment 7 - 5:00


Figure 5.107: Experiment 7 - 8:05


Figure 5.108: Experiment 7 - 9:50


Figure 5.109: Experiment 7 - 10:20


Figure 5.110: Experiment 7 - 11:15


Figure 5.111: Experiment 7 - 12:00

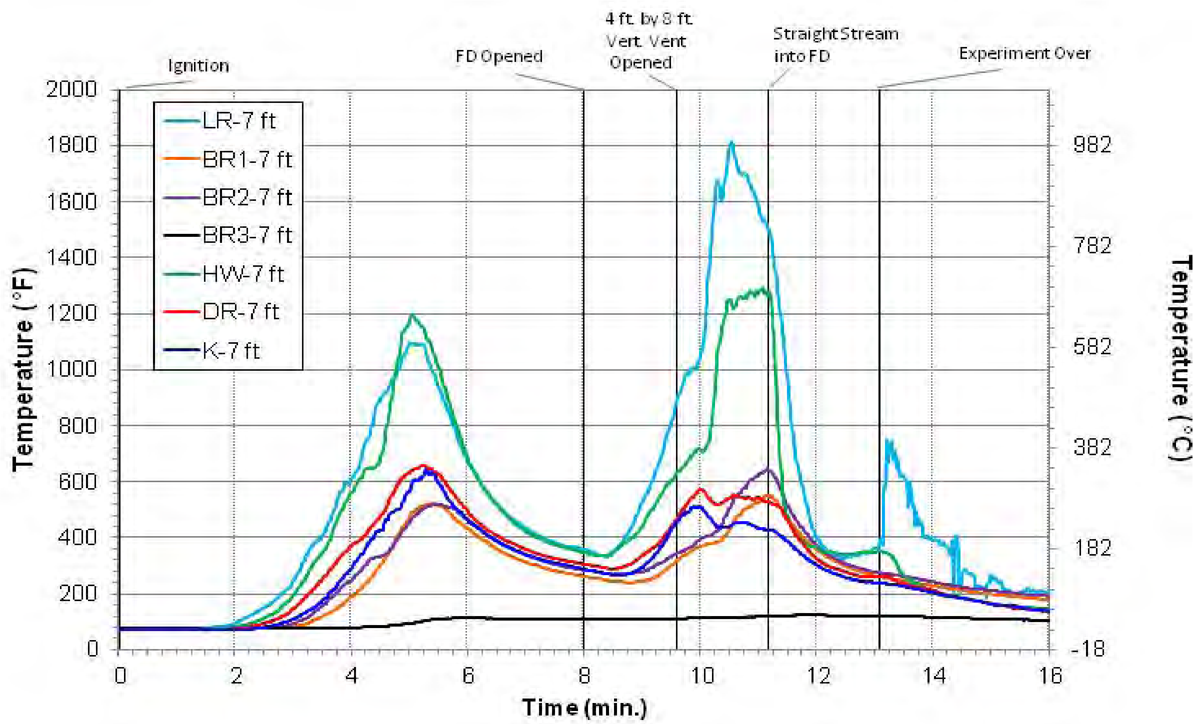


Figure 5.112: Experiment 7 - 7 ft. Temperatures

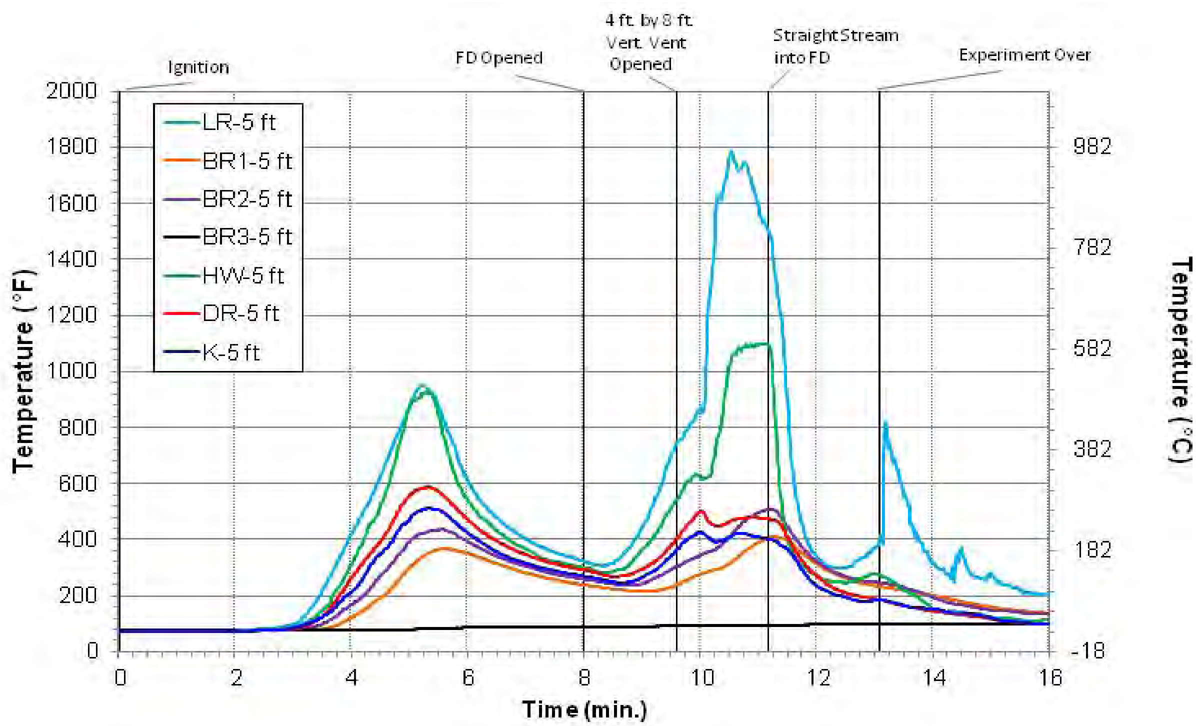


Figure 5.113: Experiment 7 - 5 ft. Temperatures

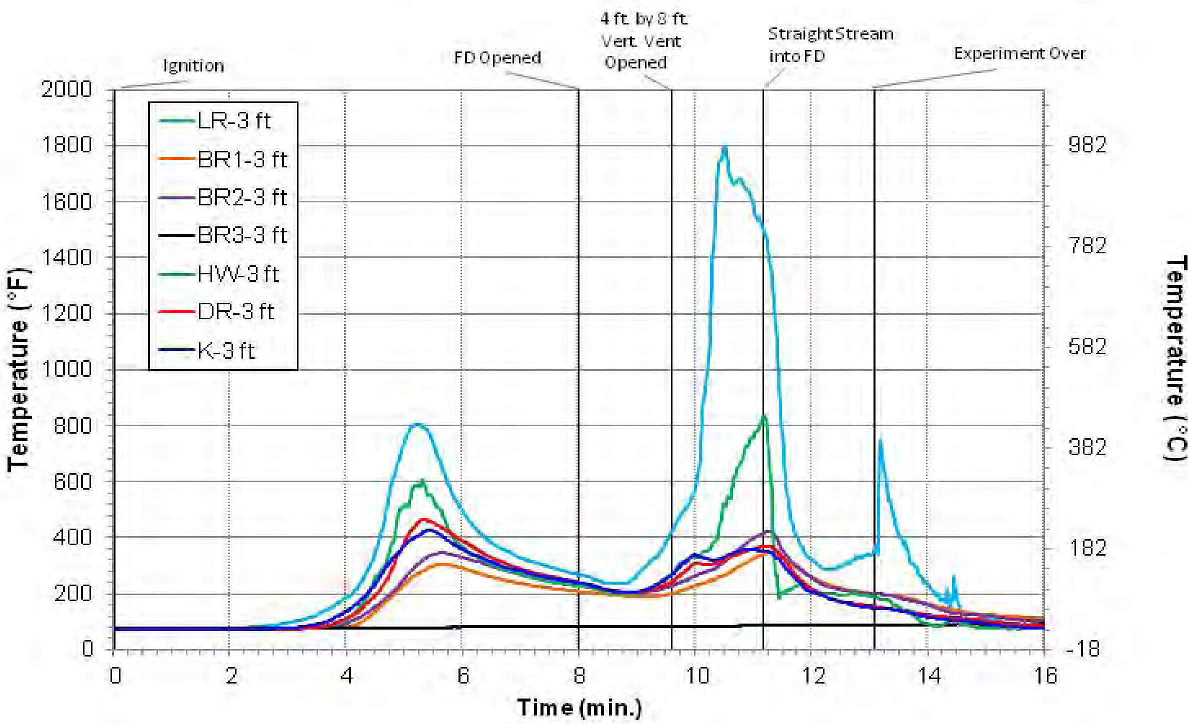


Figure 5.114: Experiment 7 - 3 ft. Temperatures

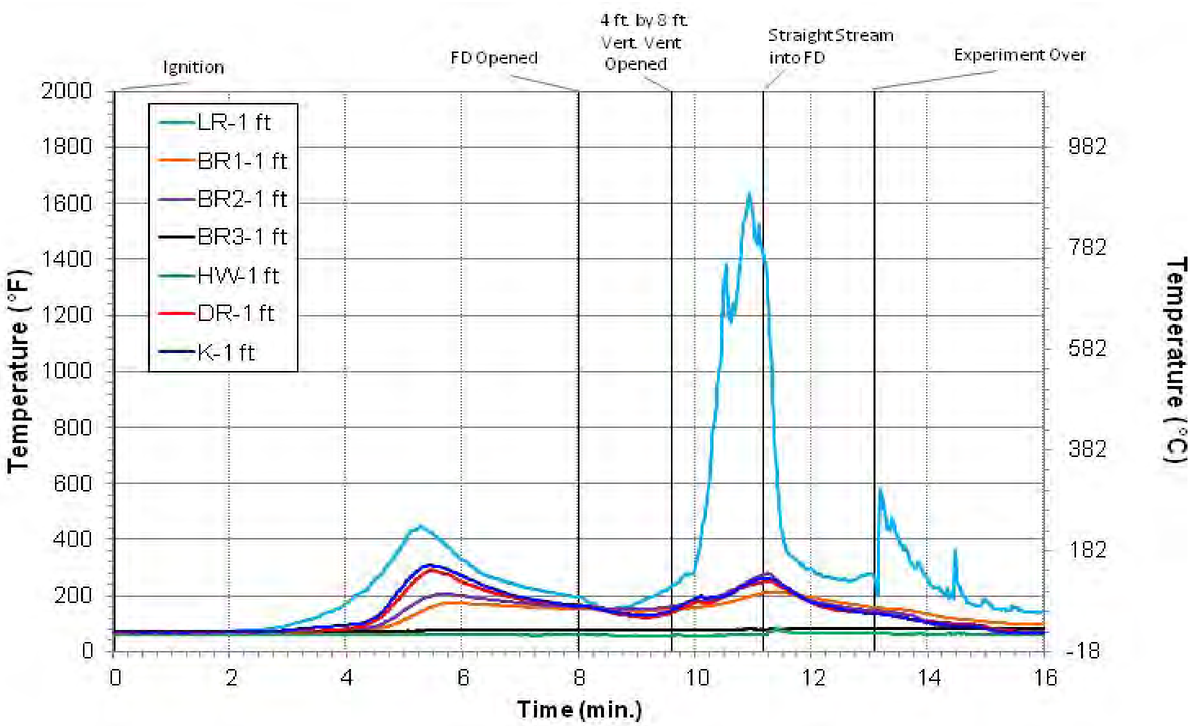


Figure 5.115: Experiment 7 - 1 ft. Temperatures

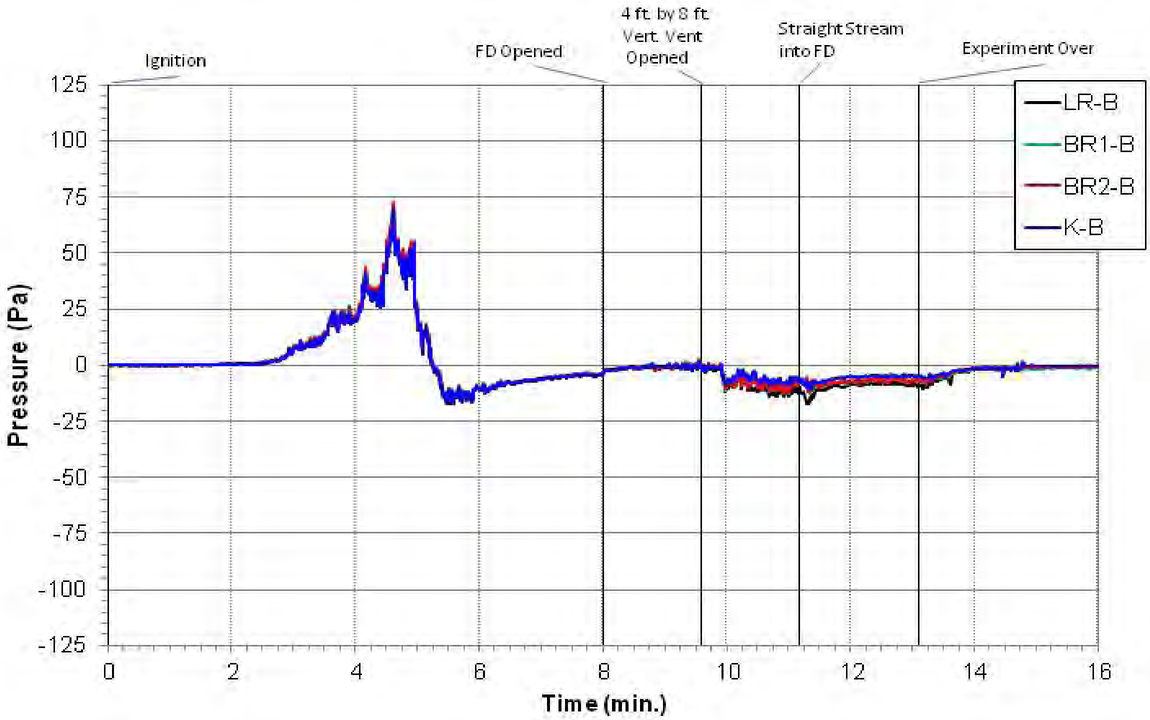


Figure 5.116: Experiment 7 - Bottom Pressure

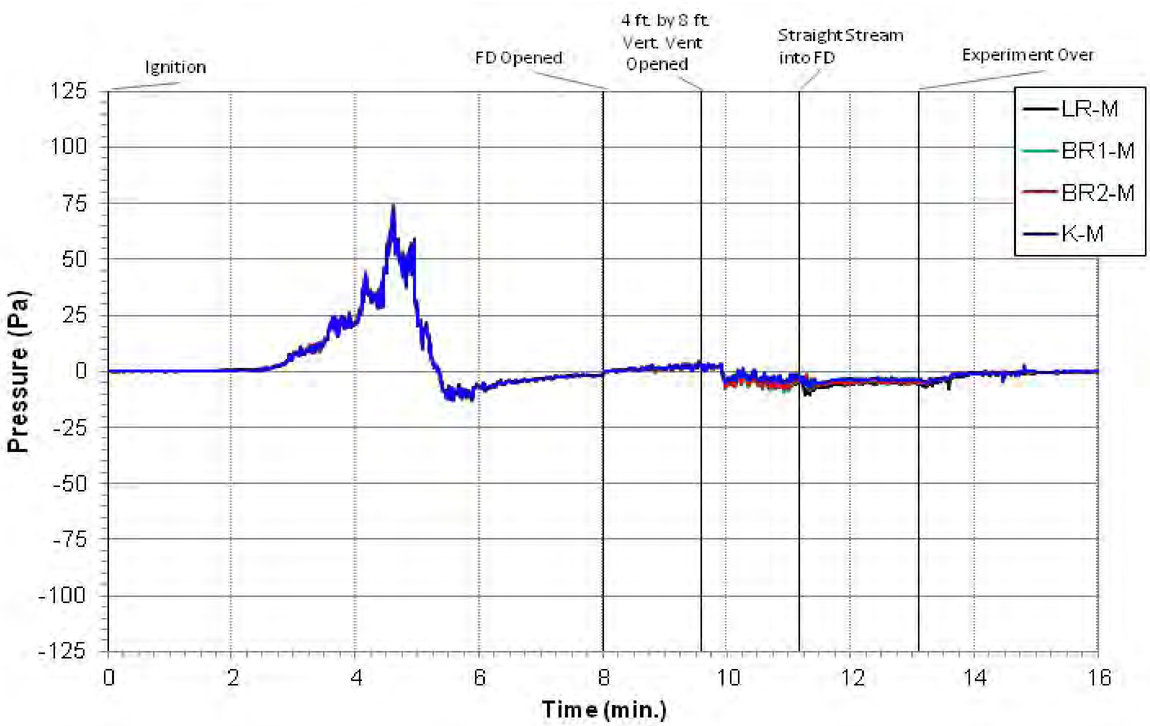


Figure 5.117: Experiment 7 - Middle Pressure

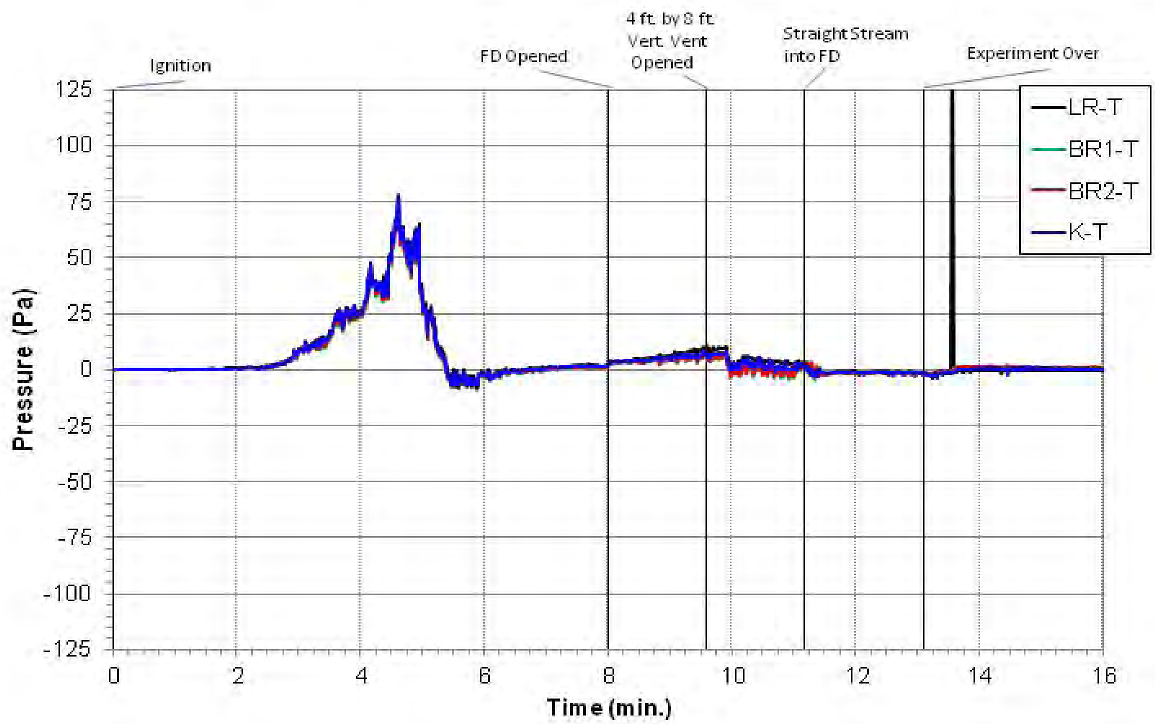


Figure 5.118: Experiment 7 - Top Pressure

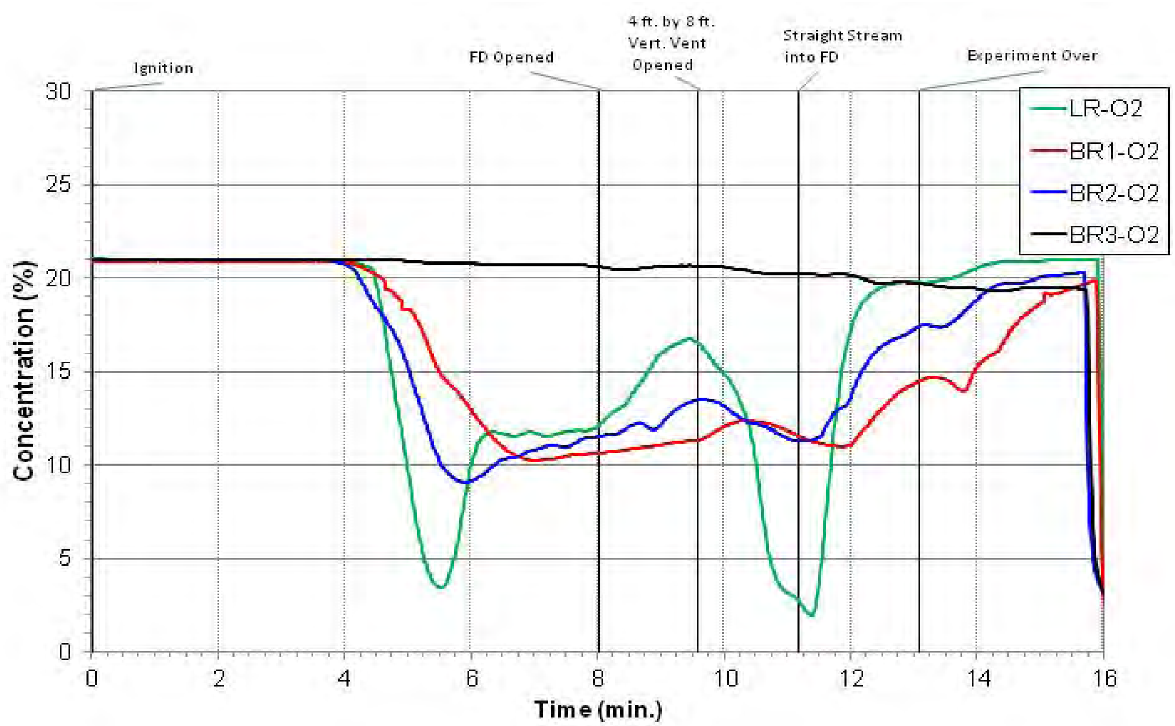


Figure 5.119: Experiment 7 - Oxygen Concentration

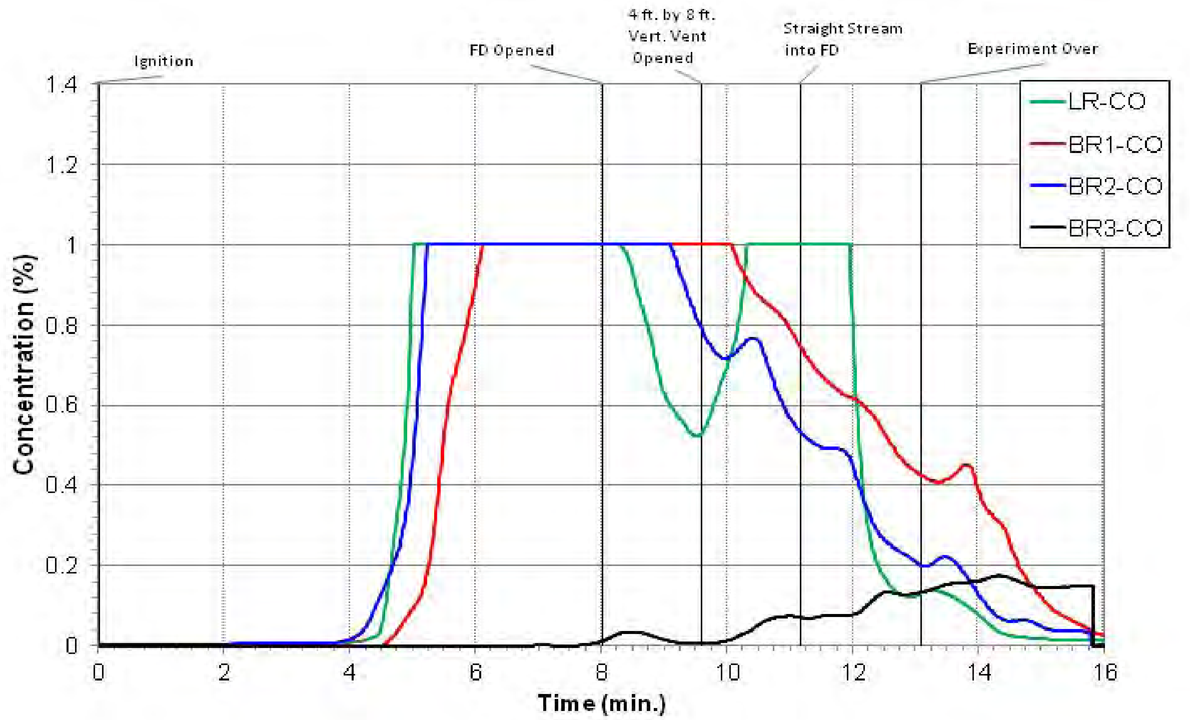


Figure 5.120: Experiment 7 - Carbon Monoxide Concentration

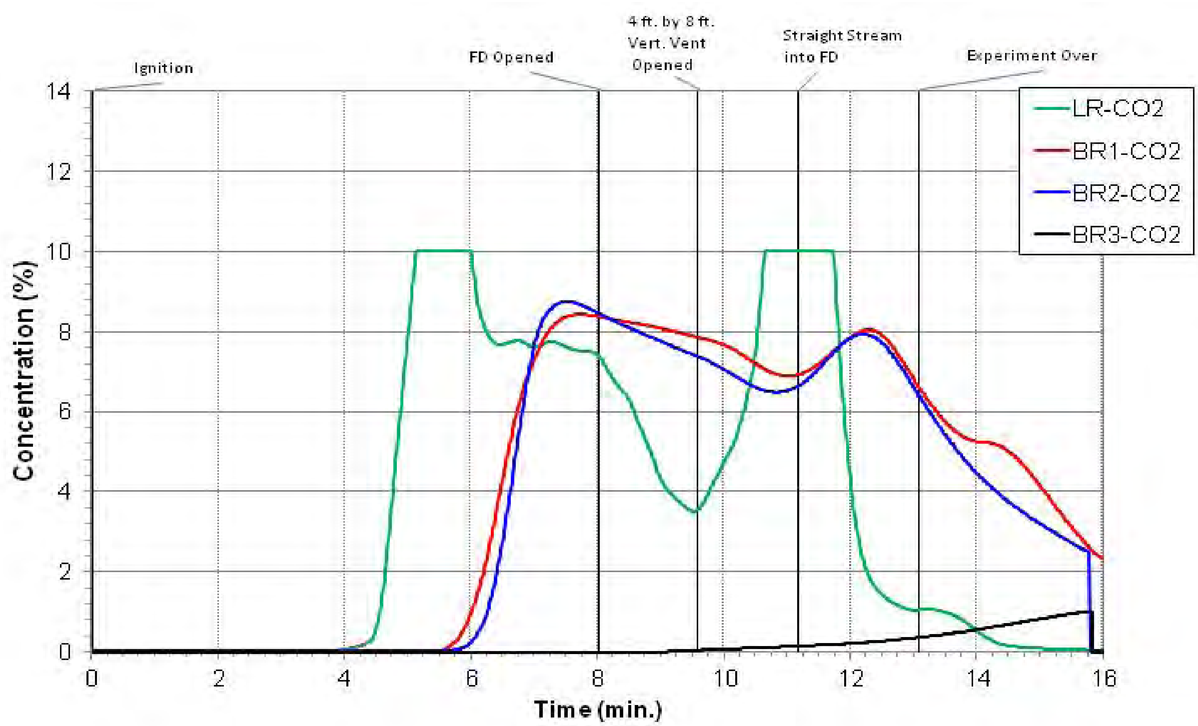


Figure 5.121: Experiment 7 - Carbon Dioxide Concentration

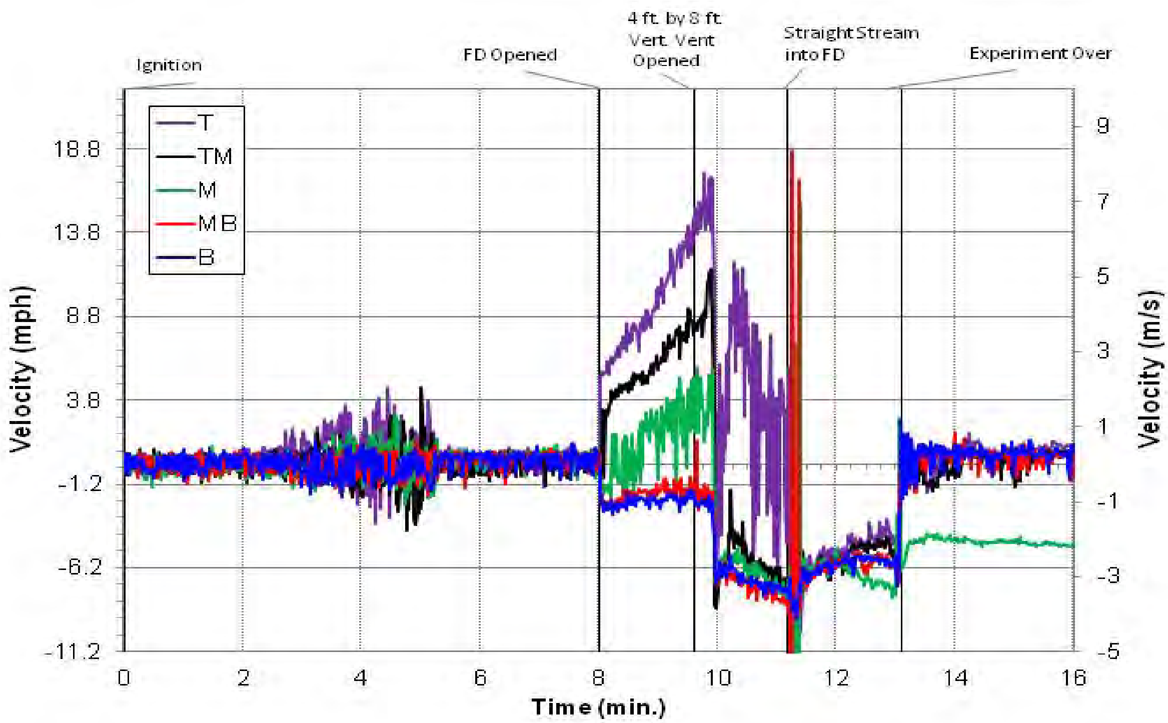


Figure 5.122: Experiment 7 - Front Door Velocity

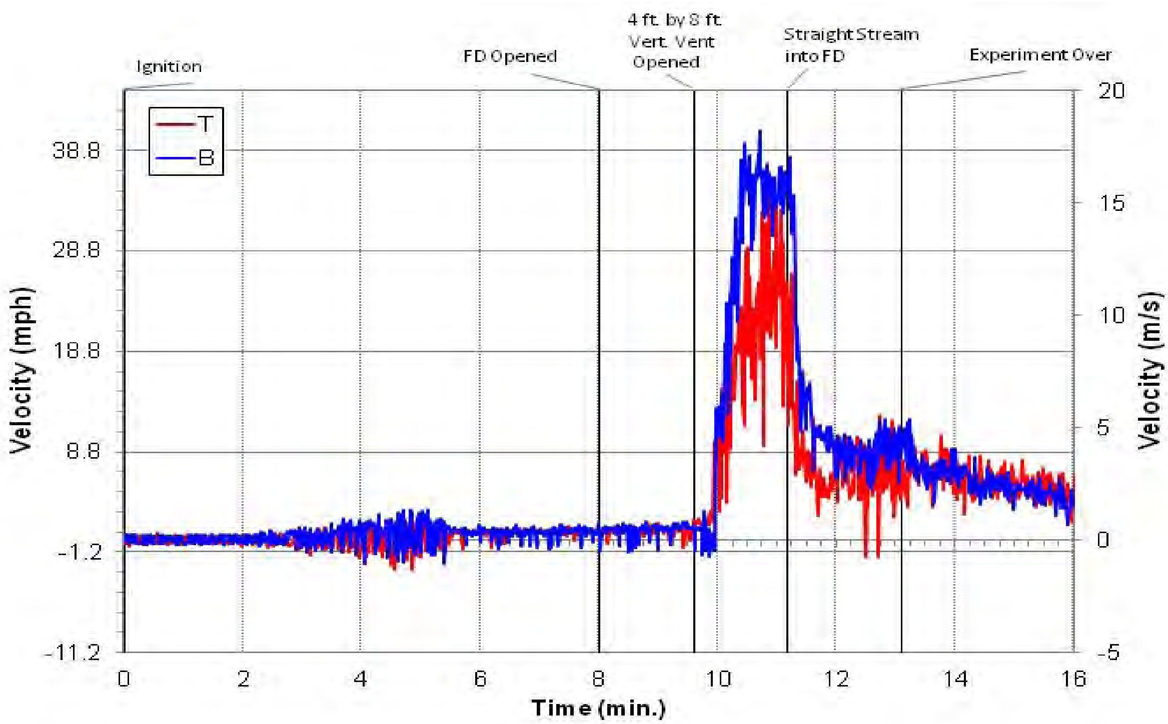


Figure 5.123: Experiment 7 - Roof Vent Velocity

5.6.5. Experiment 9

Experiment 9 was designed to simulate a fire in a bedroom with ventilation through the front door, then vertically in the living room (remote from the fire), and finally through a window near the seat of the fire. Ignition occurred in Bedroom 1. The fire was allowed to grow until 8:00, when the front door was opened. The fire was then allowed to grow for three more minutes until, at 11:00, a 4’ by 4’ hole was opened in the roof above the living room. The fire then grew to post-flashover conditions, although only for a short time. At 15:15, the window of Bedroom 1 was opened. The fire again grew to post-flashover conditions and the experiment ended at 16:30, when the crew extinguished the fire. Figure 5.125 through Figure 5.130 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.131 through Figure 5.142 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.11: Experiment 9 Timeline

Time	Description
0:00	Ignition
8:00	Front Door Open
11:00	4 ft. by 4 ft. Vertical Vent Open
15:15	Bedroom 1 Window Open
16:30	Final Suppression (End of Experiment)

Figure 5.124: Experiment 9 Scenario

Figure 5.125: Experiment 9 - 0:00

Figure 5.126: Experiment 9 - 5:00

Figure 5.127: Experiment 9 - 8:10

Figure 5.128: Experiment 9 - 11:05

Figure 5.129: Experiment 9 - 15:25

Figure 5.130: Experiment 9 - 13:25

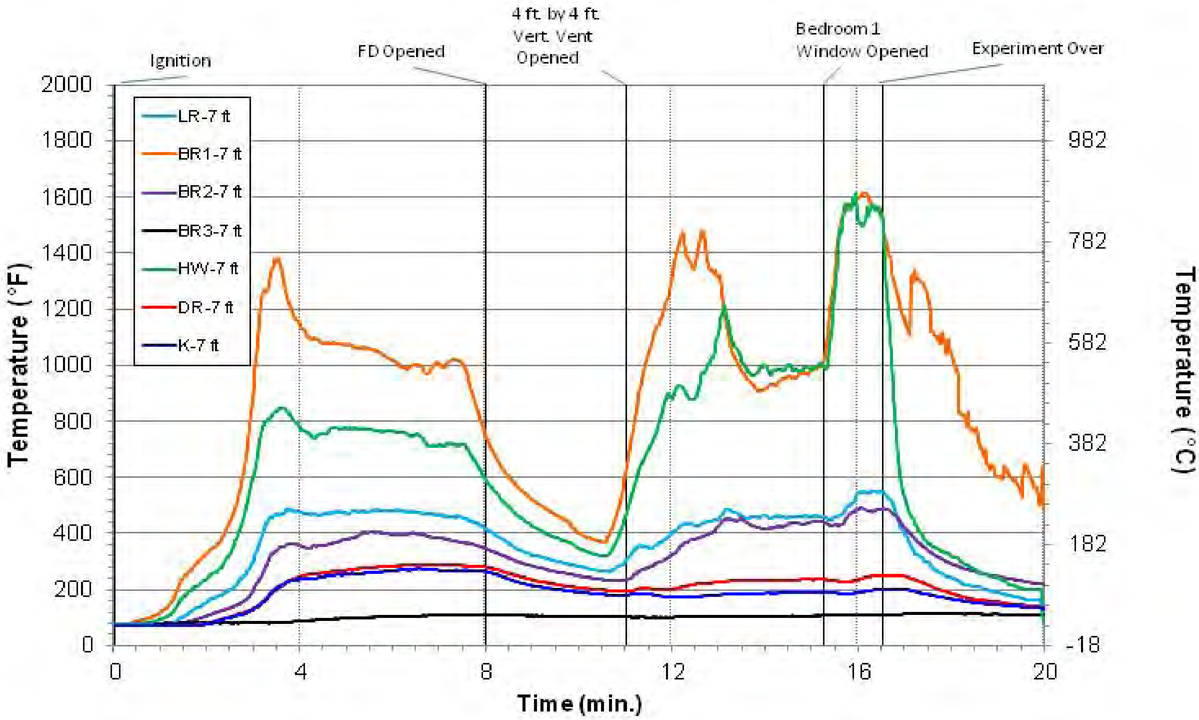


Figure 5.131: Experiment 9 - 7 ft. Temperatures

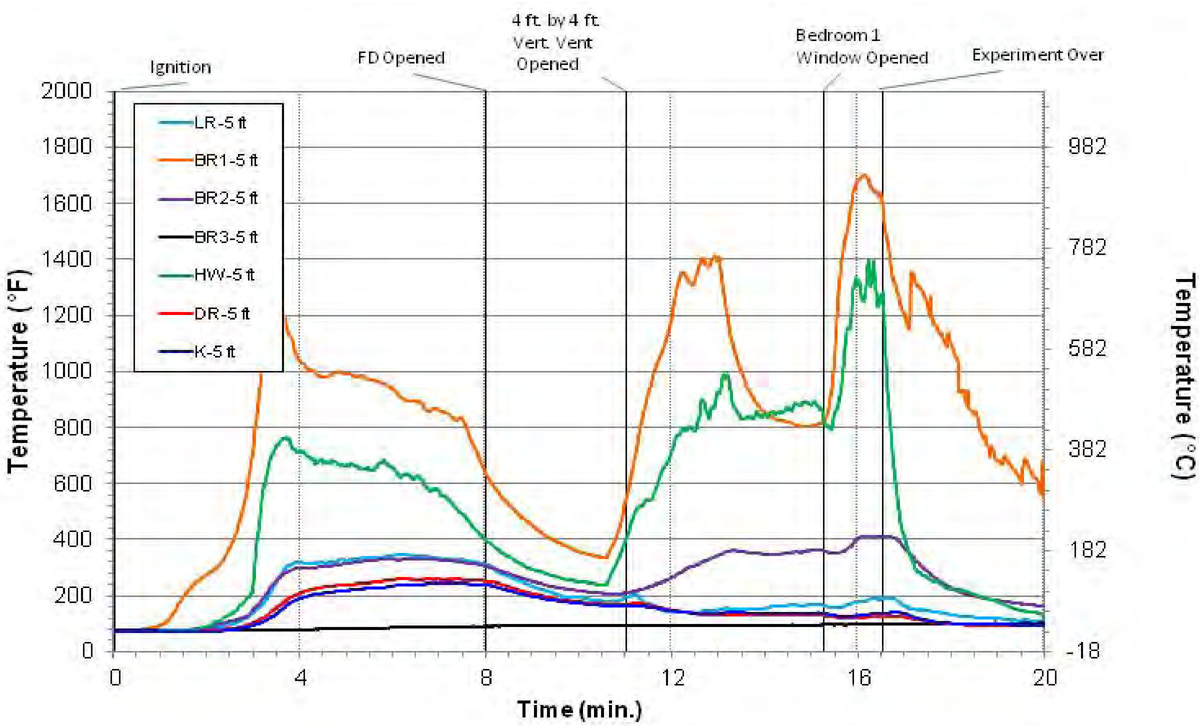


Figure 5.132: Experiment 9 - 5 ft. Temperatures

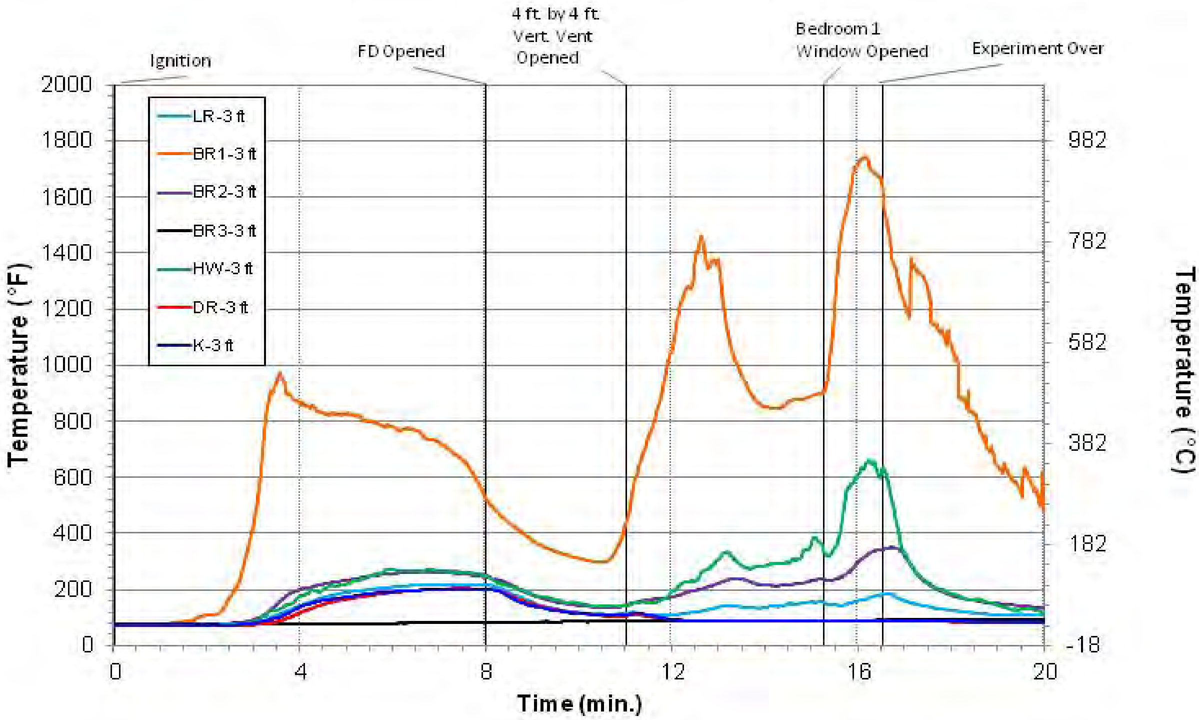


Figure 5.133: Experiment 9 - 3 ft. Temperatures

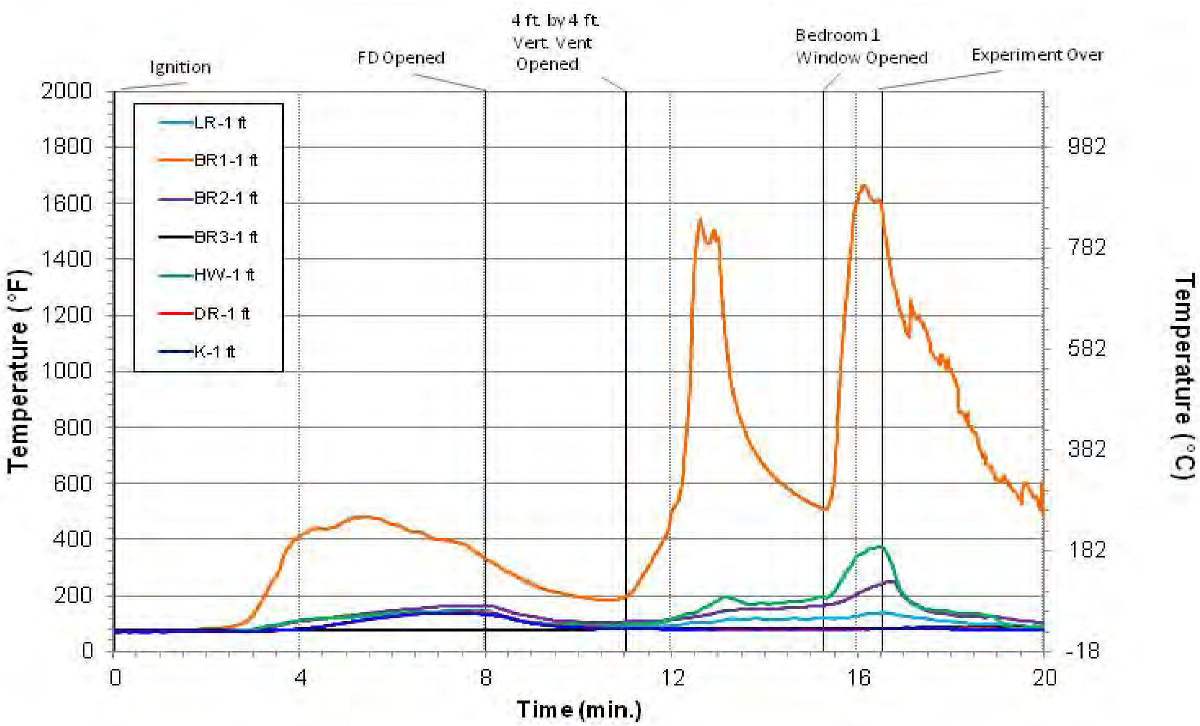


Figure 5.134: Experiment 9 - 1 ft. Temperatures

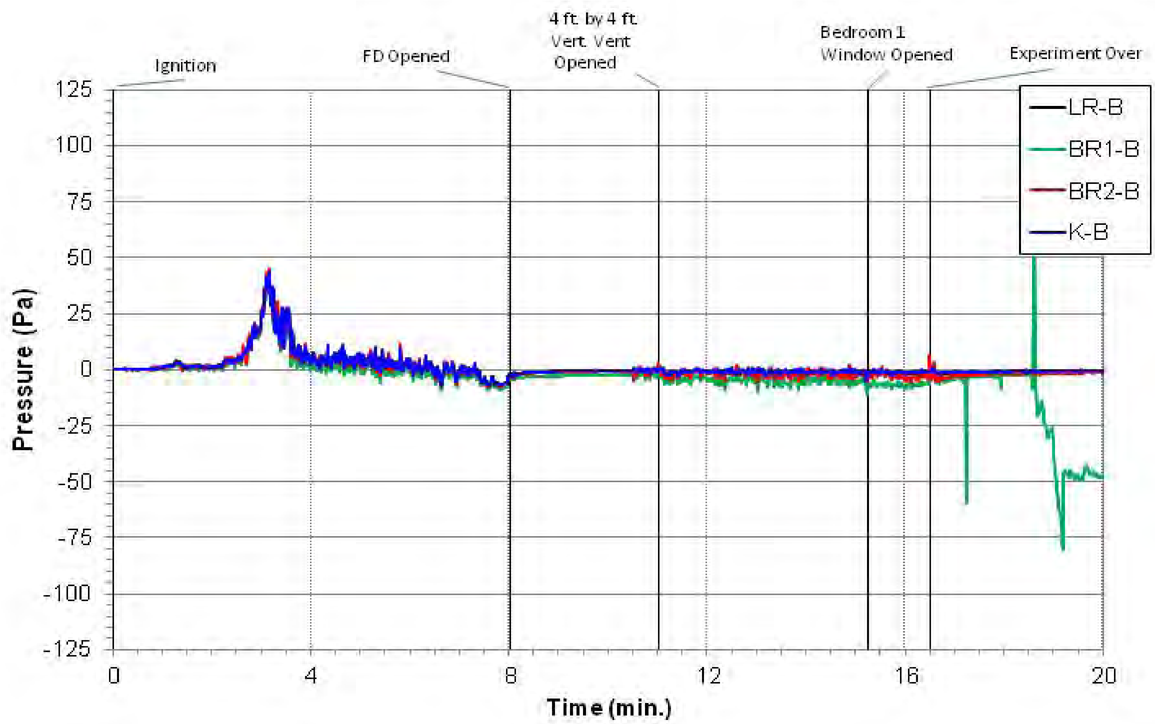


Figure 5.135: Experiment 9 - Bottom Pressure

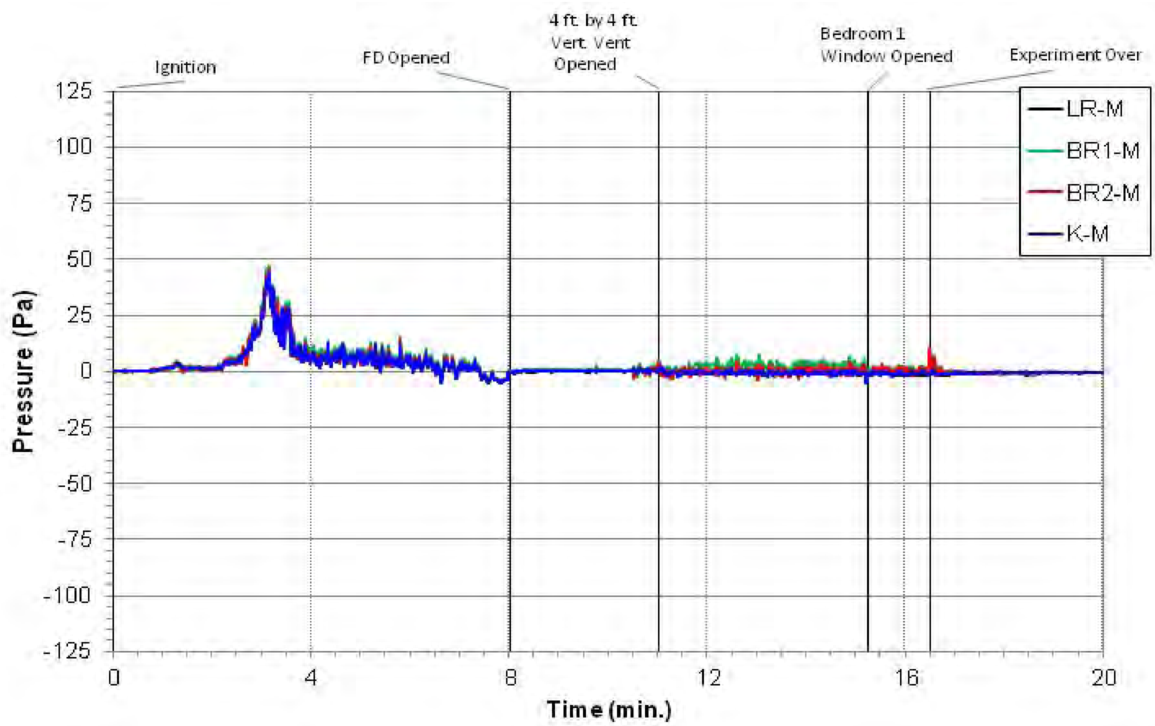


Figure 5.136: Experiment 9 - Middle Pressure

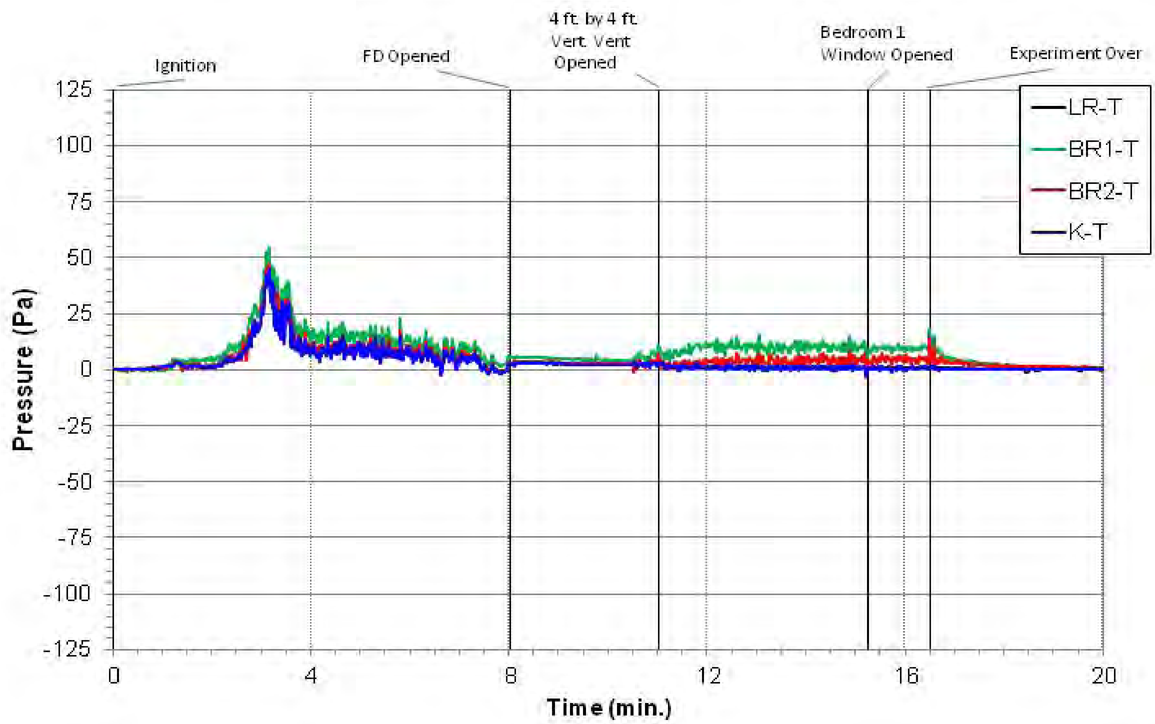


Figure 5.137: Experiment 9 - Top Pressure

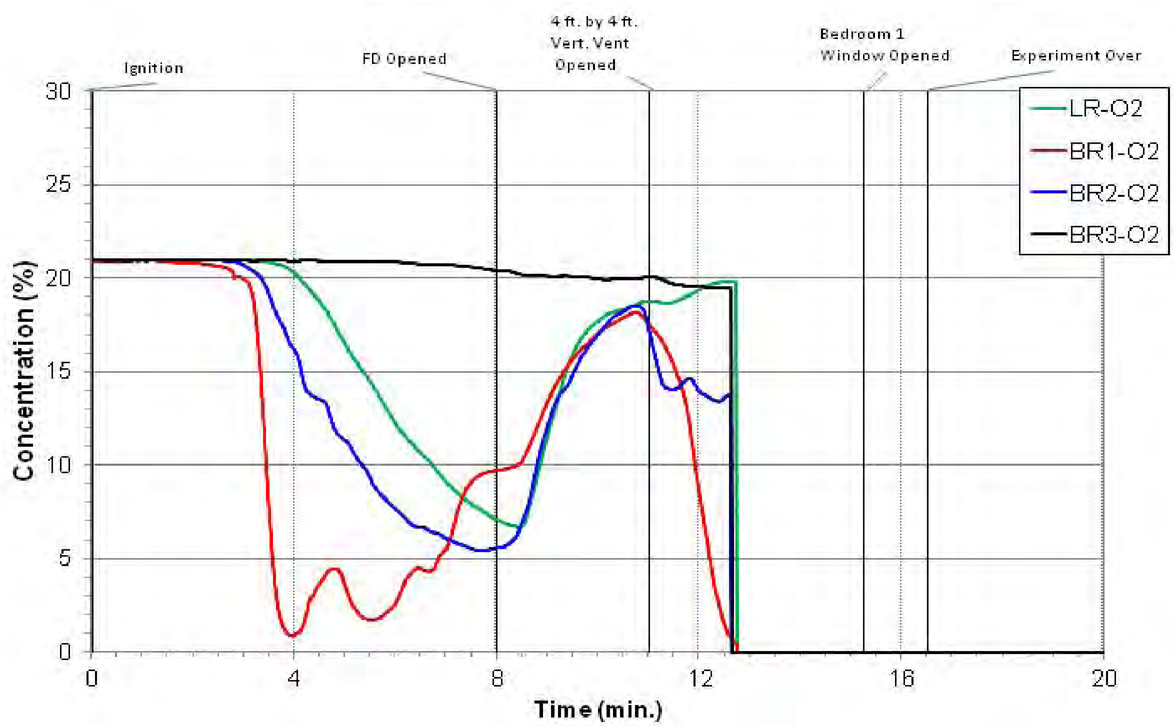


Figure 5.138: Experiment 9 - Oxygen Concentration

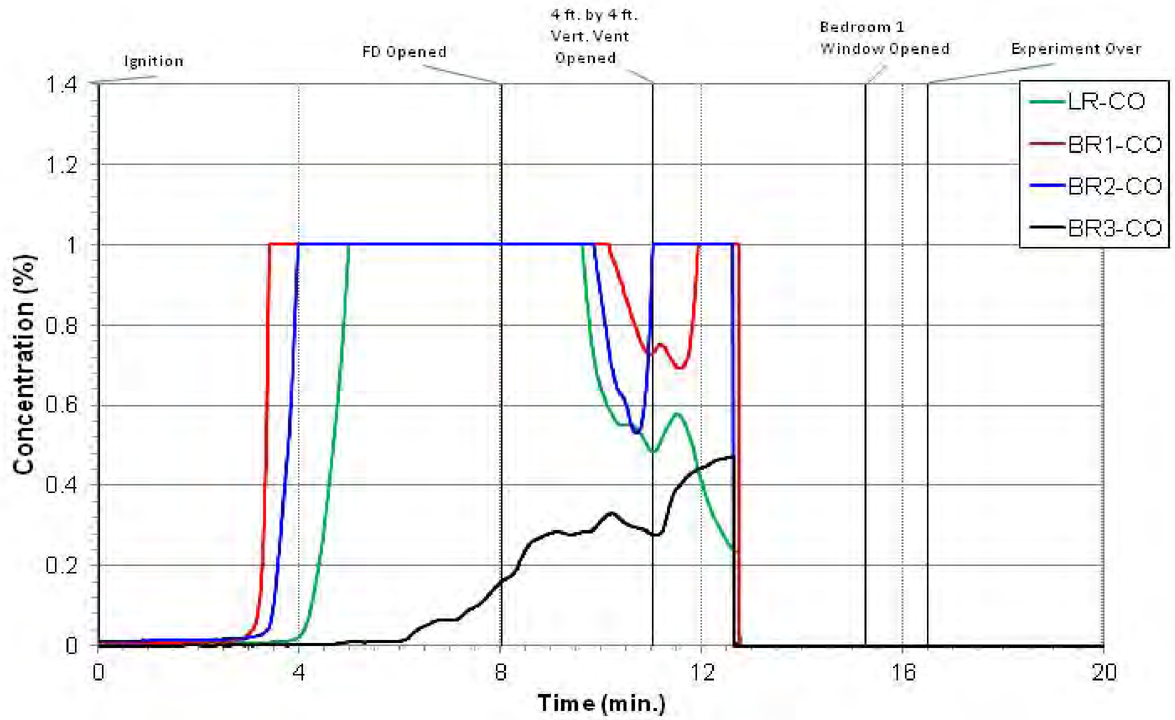


Figure 5.139: Experiment 9 - Carbon Monoxide Concentration

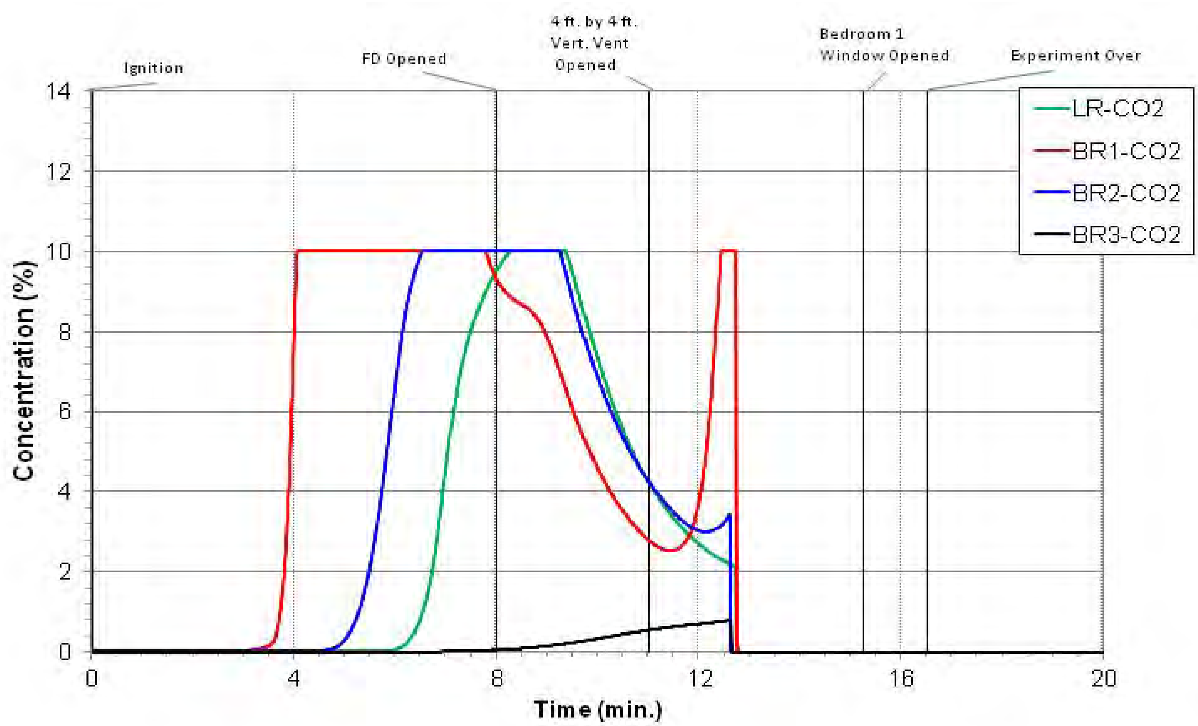


Figure 5.140: Experiment 9 - Carbon Dioxide Concentration

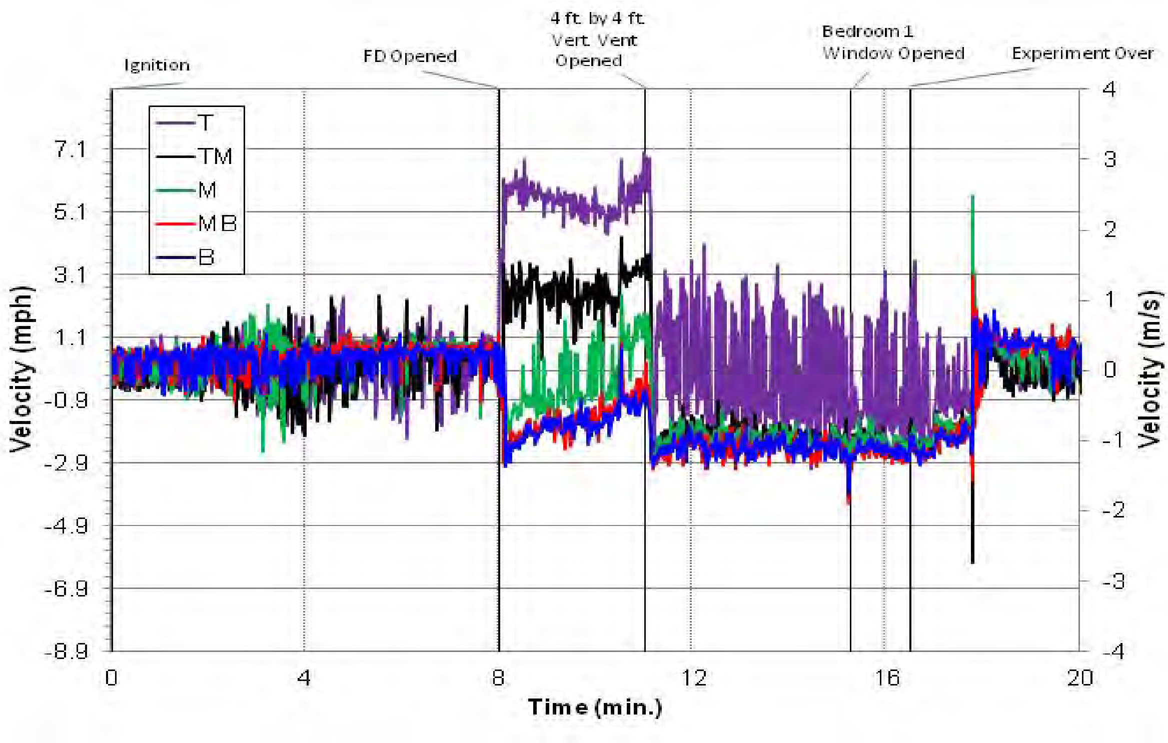


Figure 5.141: Experiment 9 - Front Door Velocity

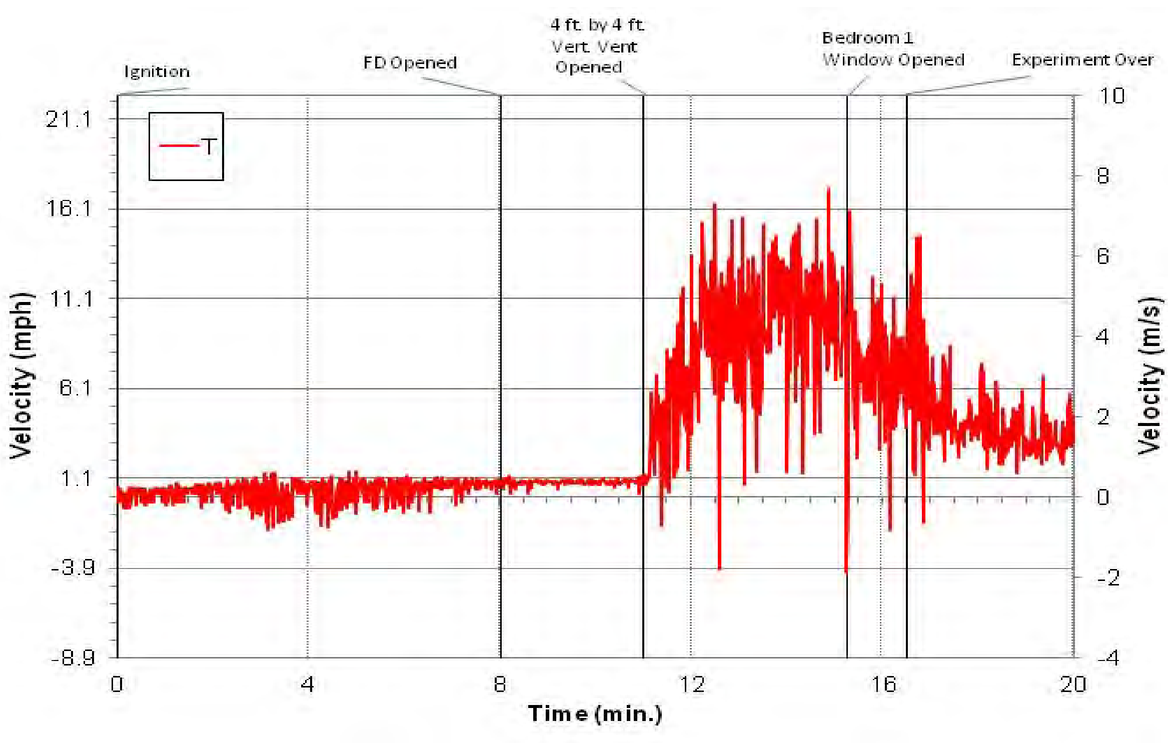


Figure 5.142: Experiment 9 - Roof Vent Velocity

5.6.6. Experiment 11

Experiment 11 was designed to simulate a window failing in the fire room prior to fire department arrival, and then a crew arriving and venting the door and the roof. Ignition occurred in Bedroom 1. The fire was allowed to grow until 6:00, when the Bedroom 1 window was opened. The fire then grew to the condition of post-flashover and at 8:00 the front door was opened. The fire was then ventilated even further at 9:20 when the 4' by 4' vertical vent was opened. At 10:45, 16 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern. The experiment ended at 12:20, and the crew extinguished the fire. Figure 5.144 through Figure 5.151 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.152 through Figure 5.163 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.12: Experiment 3 Timeline

Time	Description
0:00	Ignition
6:00	Bedroom 1 Window Open
8:00	Front Door Open
9:20	4 ft. by 4 ft. Vertical Vent Open
10:45	Straight Stream into Bedroom 1 Window
12:20	Final Suppression (End of Experiment)

Figure 5.143: Experiment 11 Scenario

Figure 5.144: Experiment 11 - 0:00

Figure 5.145: Experiment 11 - 5:00

Figure 5.146: Experiment 11 - 6:05

Figure 5.147: Experiment 11 - 6:15

Figure 5.148: Experiment 11 - 8:05

Figure 5.149: Experiment 11 - 9:25

Figure 5.150: Experiment 11 - 10:50

Figure 5.151: Experiment 11 - 11:30

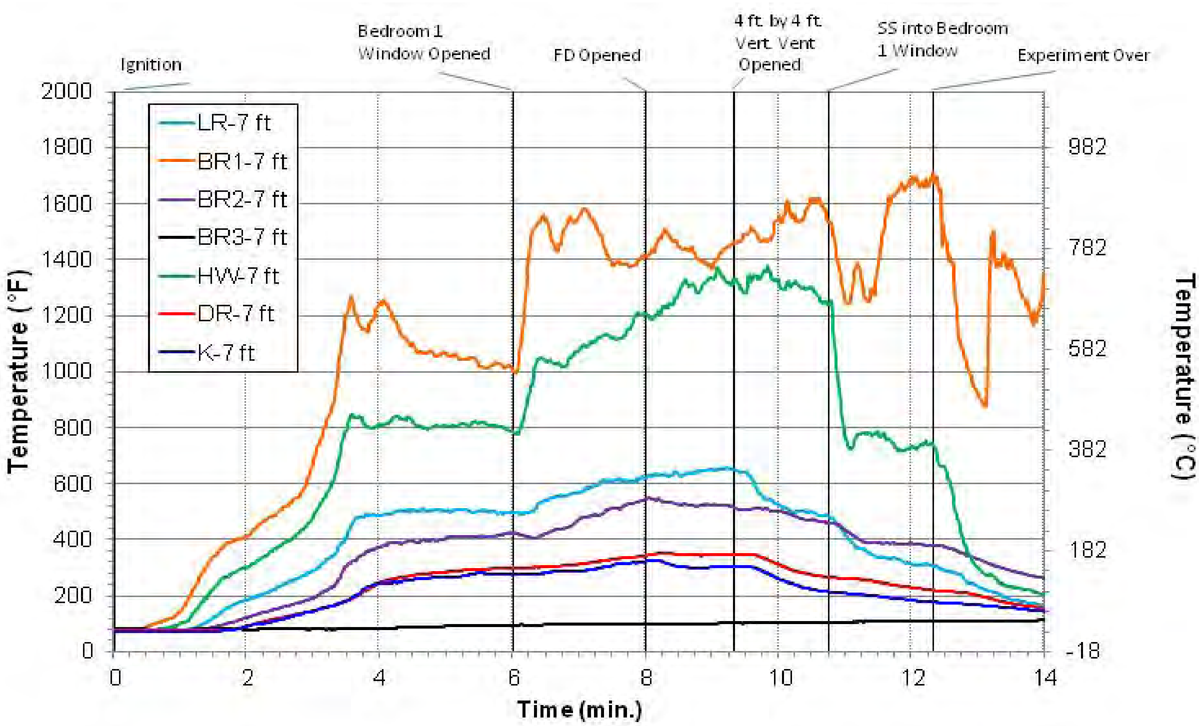


Figure 5.152: Experiment 11 - 7 ft. Temperatures

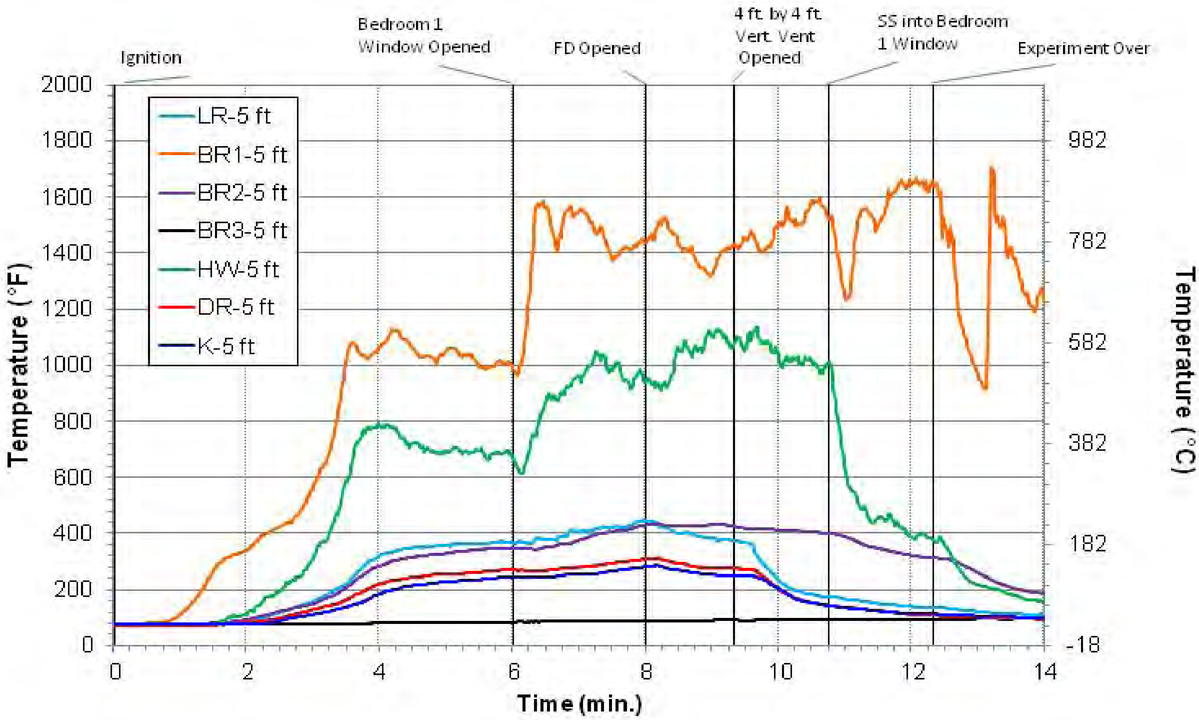


Figure 5.153: Experiment 11 - 5 ft. Temperatures

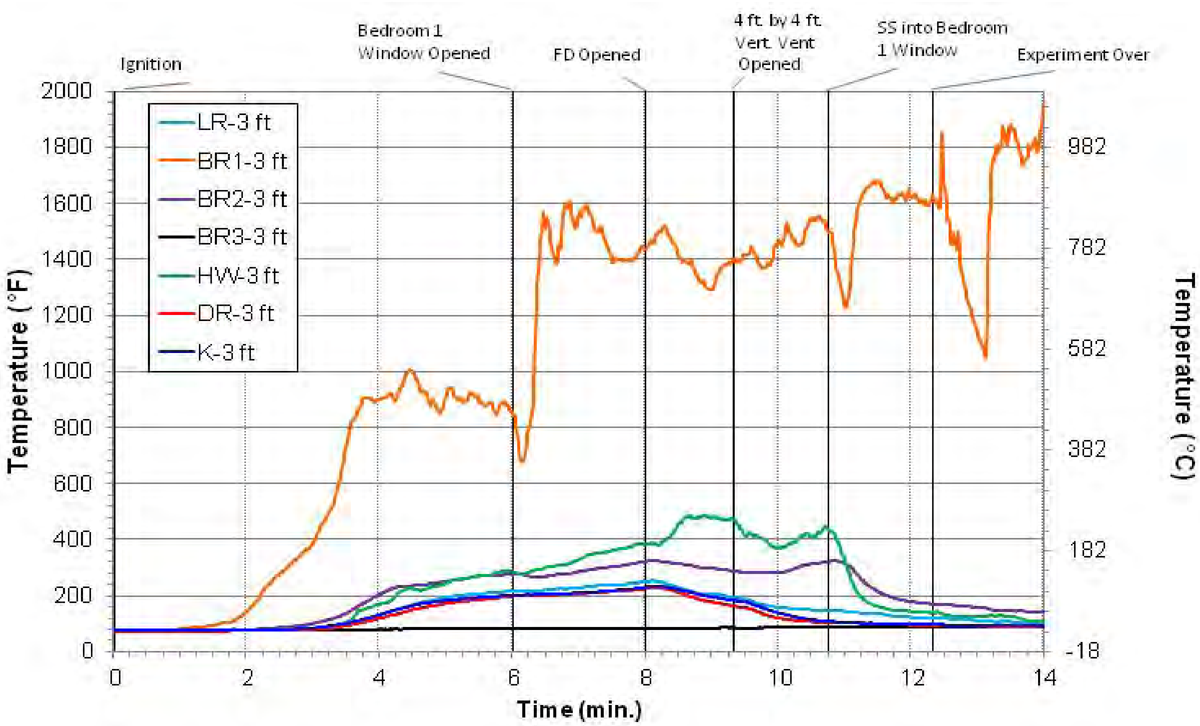


Figure 5.154: Experiment 11 - 3 ft. Temperatures

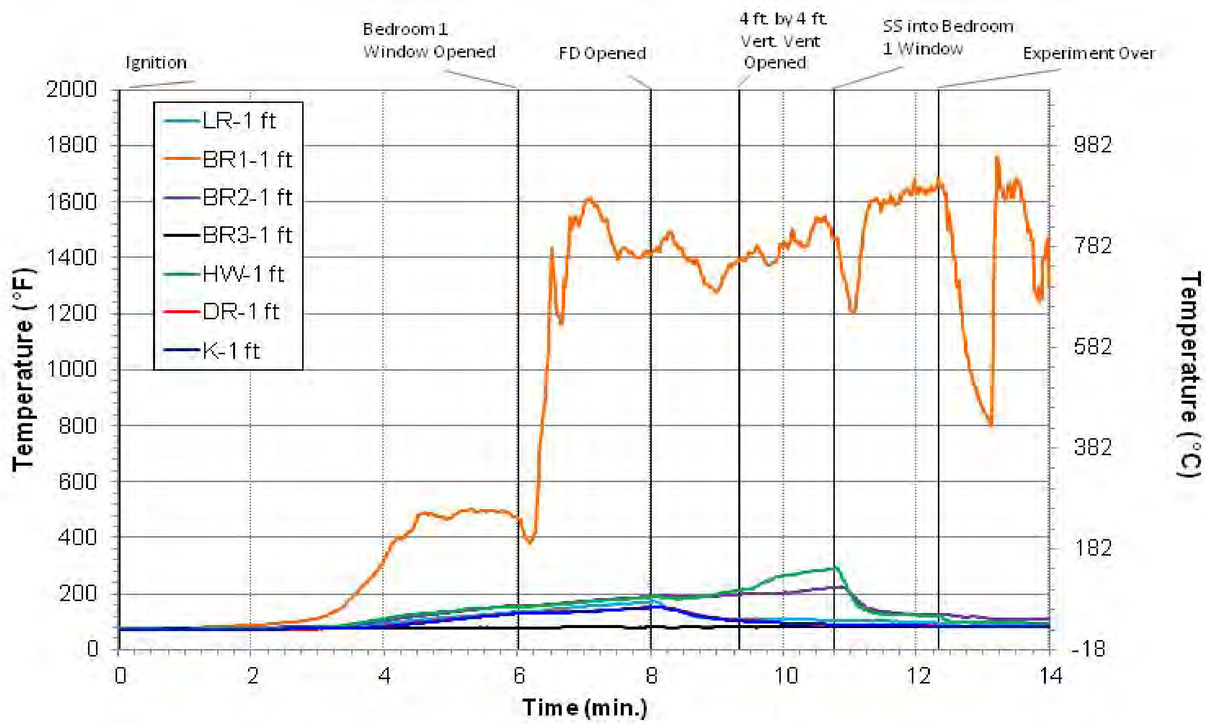


Figure 5.155: Experiment 11 - 1 ft. Temperatures

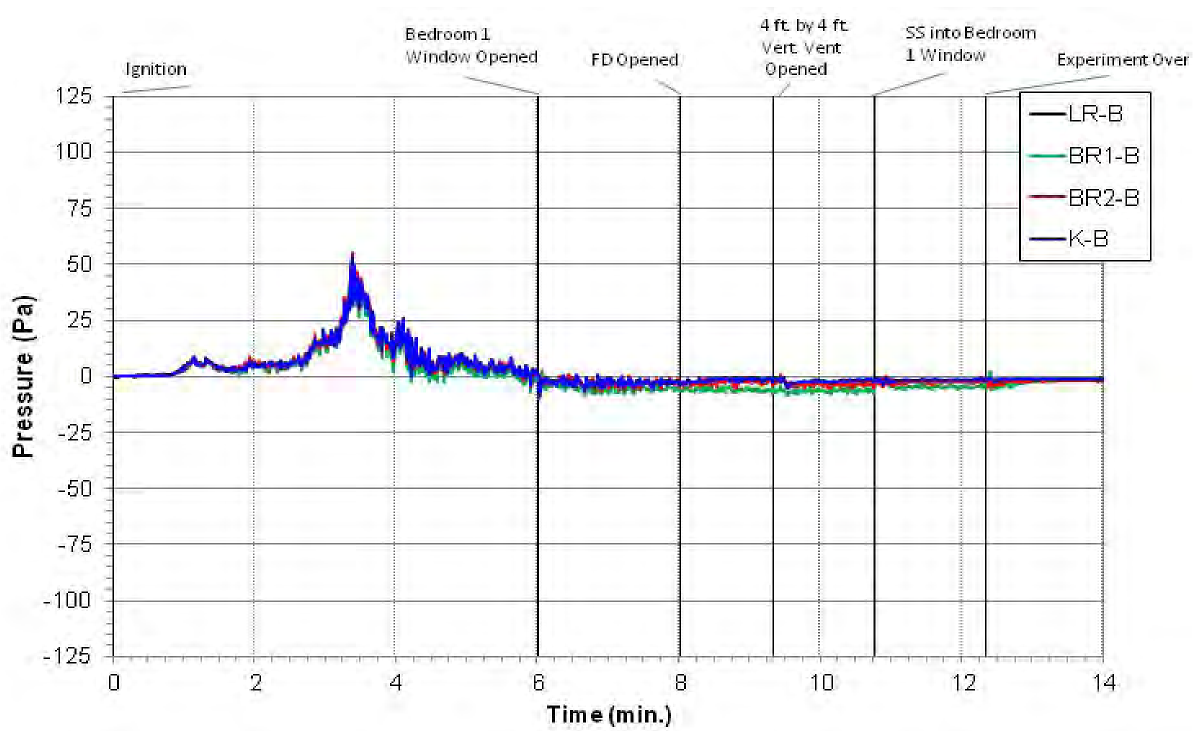


Figure 5.156: Experiment 11 - Bottom Pressure

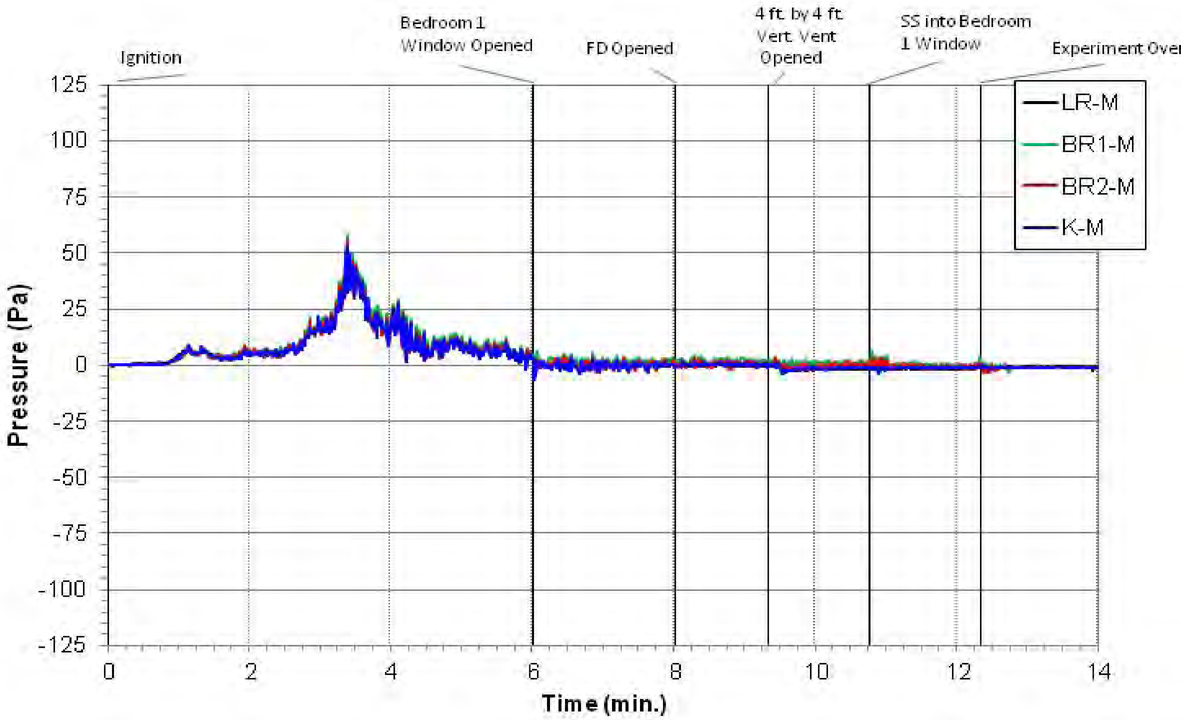


Figure 5.157: Experiment 11 - Middle Pressure

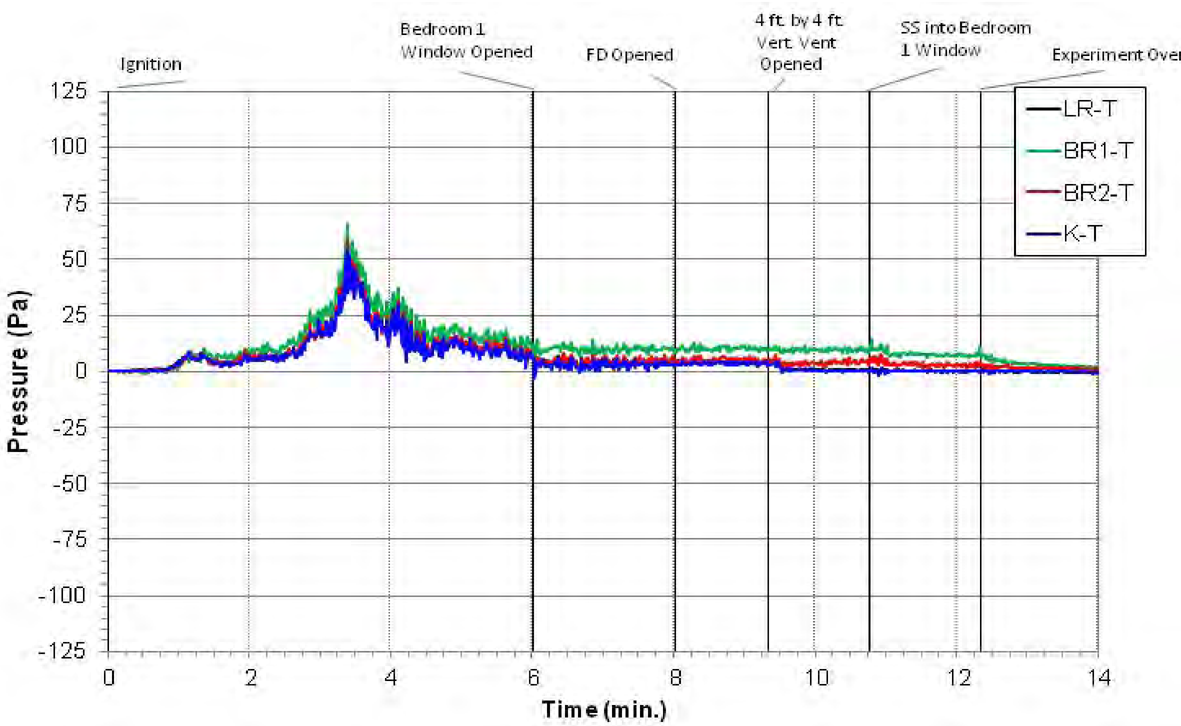


Figure 5.158: Experiment 11 - Top Pressure

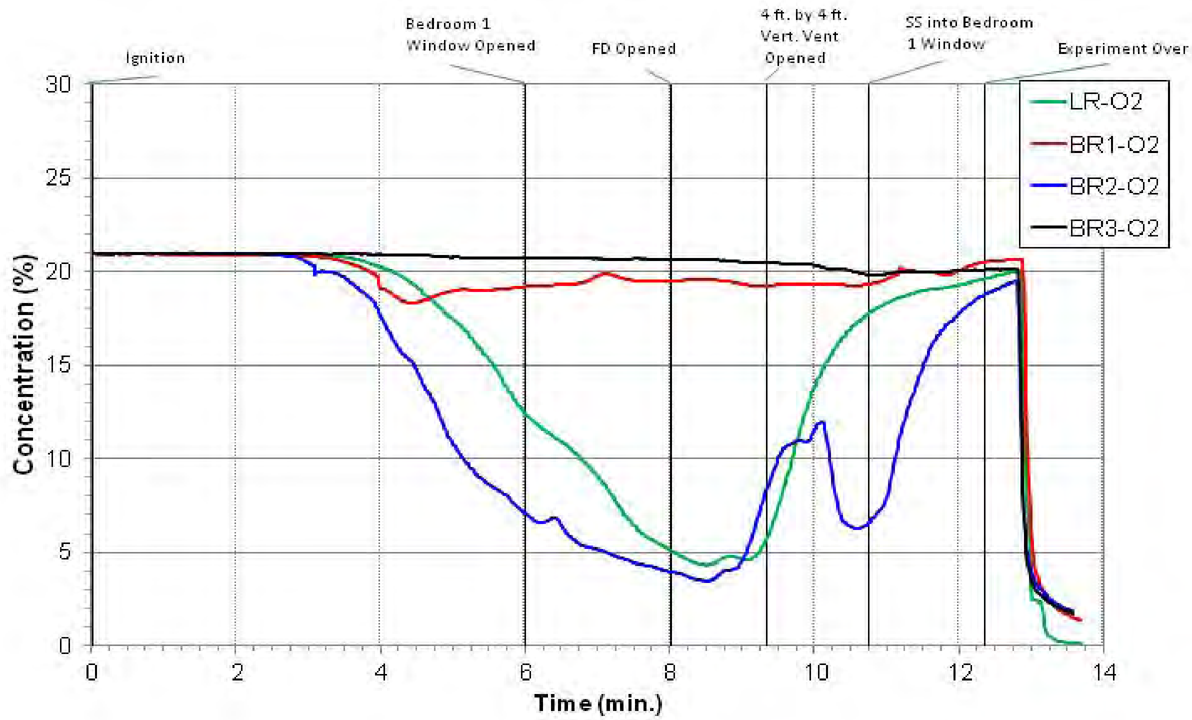


Figure 5.159: Experiment 11 - Oxygen Concentration

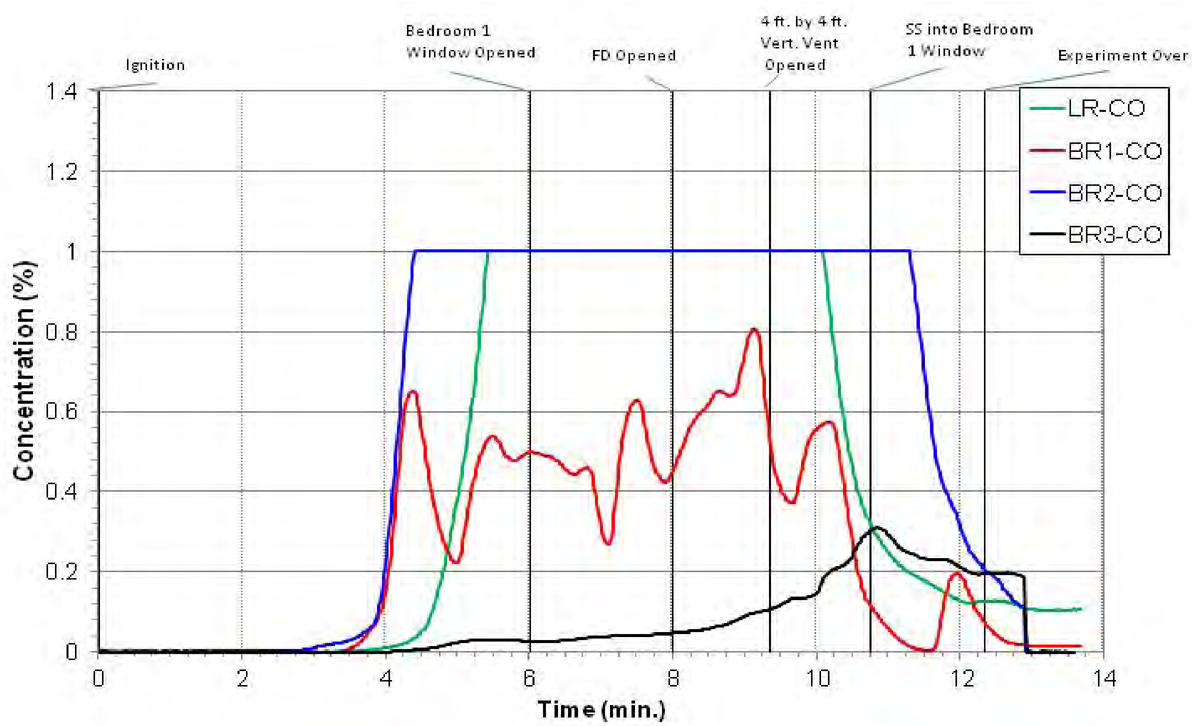


Figure 5.160: Experiment 11 - Carbon Monoxide Concentration

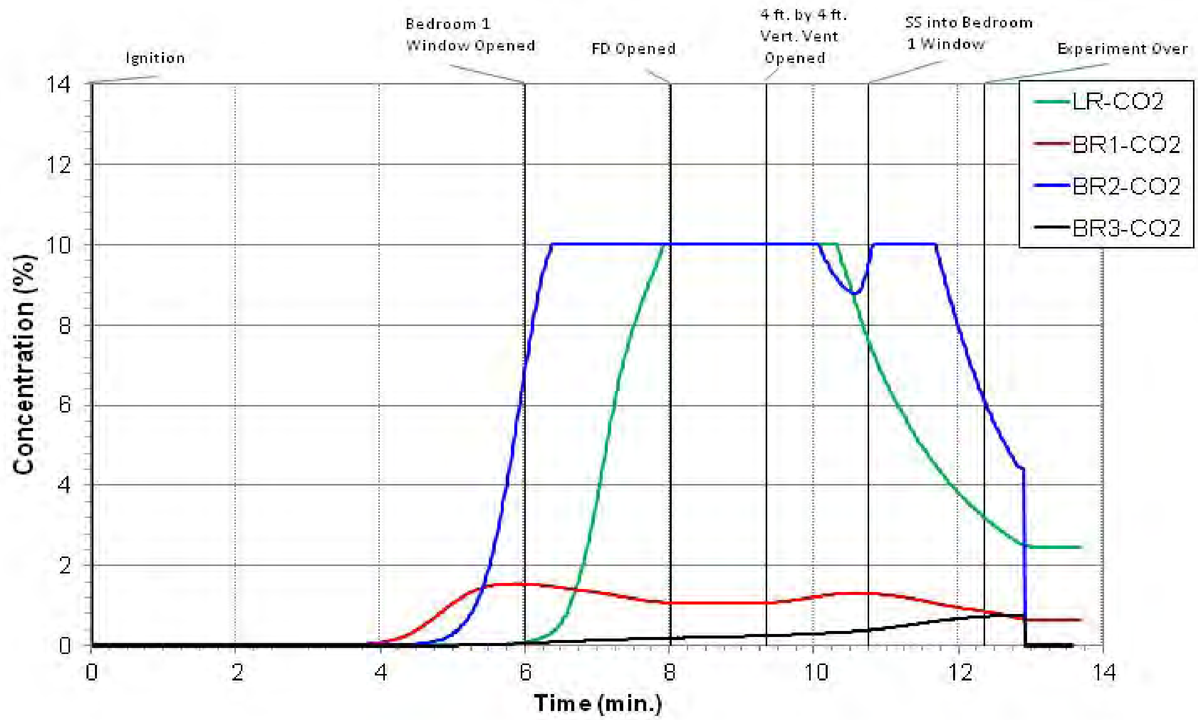


Figure 5.161: Experiment 11 - Carbon Dioxide Concentration

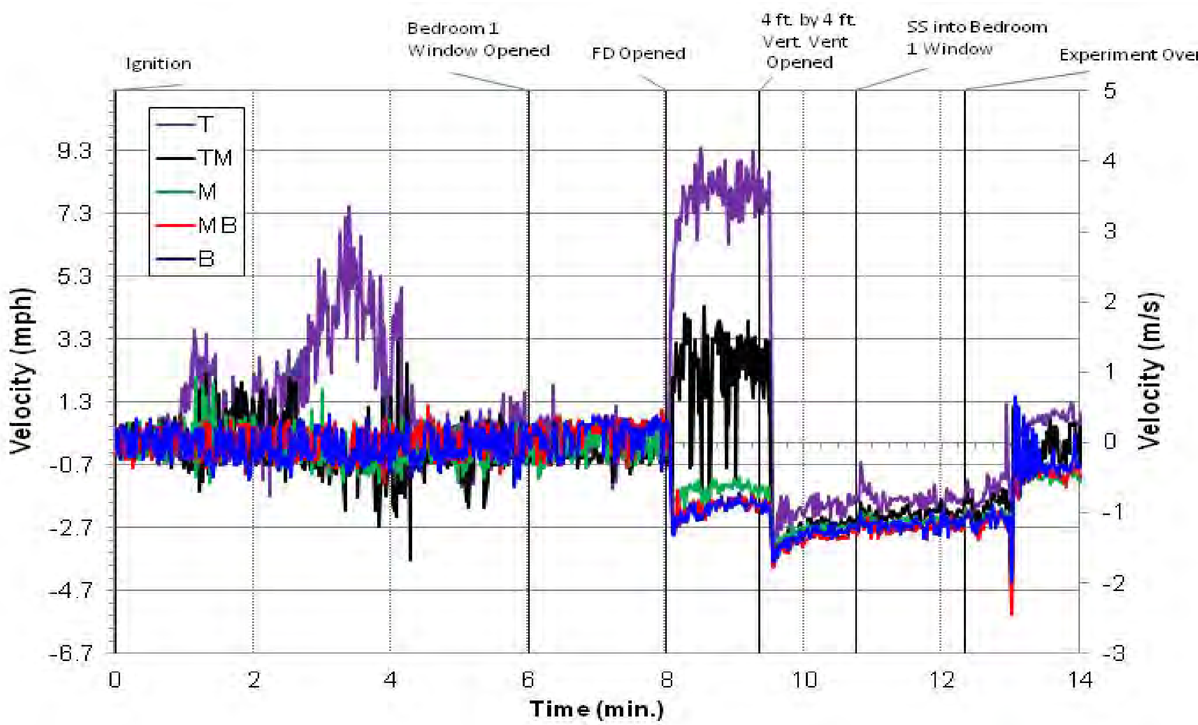


Figure 5.162: Experiment 11 - Front Door Velocity

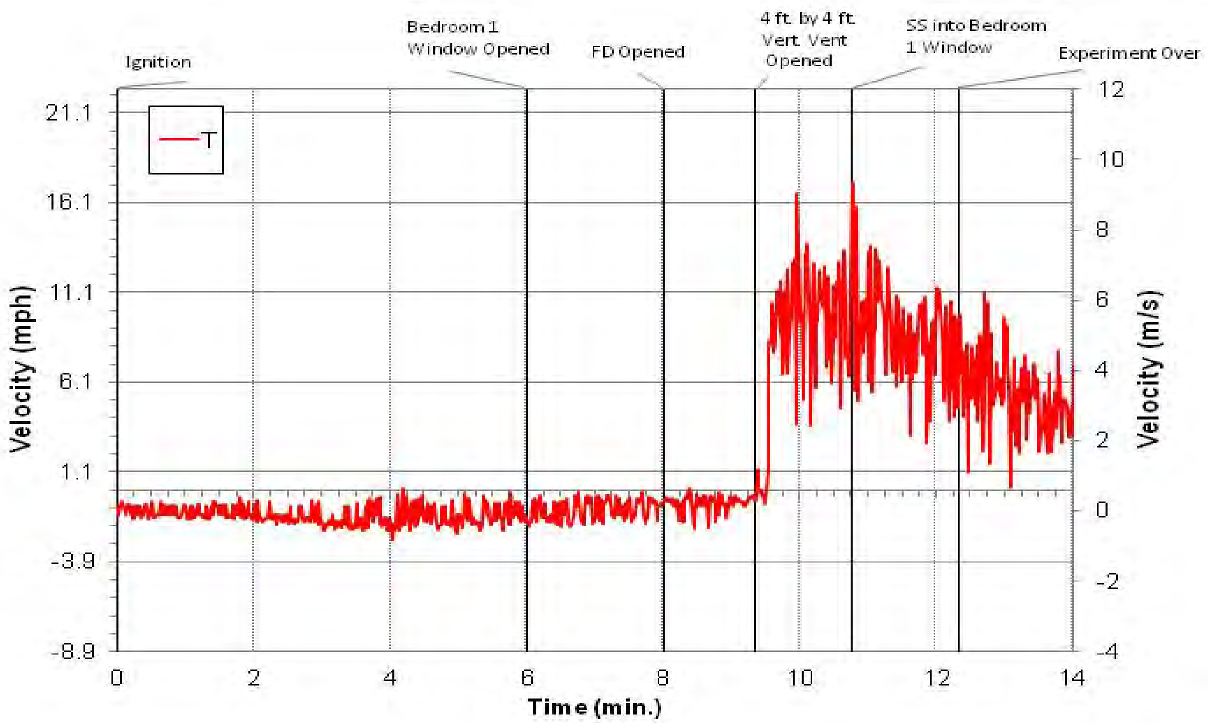


Figure 5.163: Experiment 11 - Roof Vent Velocity

5.6.7. Experiment 13

Experiment 13 was designed to simulate a fire in the kitchen and its development. Ignition occurred in the kitchen. A simulated fire crew arrived and ventilated the front door, flowed water through the front door into the kitchen and then ventilated the dining room and continued to flow water into the kitchen to examine the impact of steam production and conditions in the structure. The fire grew until 10:00, when the front door was opened. At 13:45, 6 seconds of water was applied through the front door with a combination nozzle positioned in a straight stream pattern. At 19:00, 7 seconds of water was applied through the front door with a combination nozzle positioned in a fog stream pattern. The dining room window was opened at 20:00. Water was again applied to the fire at 22:40 for 6 seconds with a combination nozzle positioned in a straight stream pattern. At 24:00, 41 seconds of water was applied to the fire with a combination nozzle positioned in a fog stream pattern. Water was applied to the fire for a fifth time at 25:35 for 12 seconds with a combination nozzle positioned in a straight stream pattern, this time through the dining room window rather than the front door. The experiment ended at 26:40, and the crew extinguished the fire. Figure 5.165 through Figure 5.174 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.175 through Figure 5.185 detail the temperatures, pressures, gas concentrations and gas velocities during the experiments.

Table 5.13: Experiment 13 Timeline

Time	Description
0:00	Ignition
10:00	Front Door Open
13:45	Straight Stream into Front Door
19:00-19:05	Fog Stream into Front Door
20:00	Dining Room Window Open
22:40	Straight Stream into Front Door
24:00-24:40	Fog Stream into Front Door
25:35	Straight Stream into Dining Room Window
26:40	Final Suppression (End of Experiment)

Figure 5.164: Experiment 13 Scenario

Figure 5.165: Experiment 13 - 0:00

Figure 5.166: Experiment 13 - 7:00

Figure 5.167: Experiment 13 - 10:05

Figure 5.168: Experiment 13 - 13:50

Figure 5.169: Experiment 13 - 19:00

Figure 5.170: Experiment 13 - 20:05

Figure 5.171: Experiment 13 - 22:50

Figure 5.172: Experiment 13 - 24:10

Figure 5.173: Experiment 13 - 25:45

Figure 5.174: Experiment 13 - 26:15

h

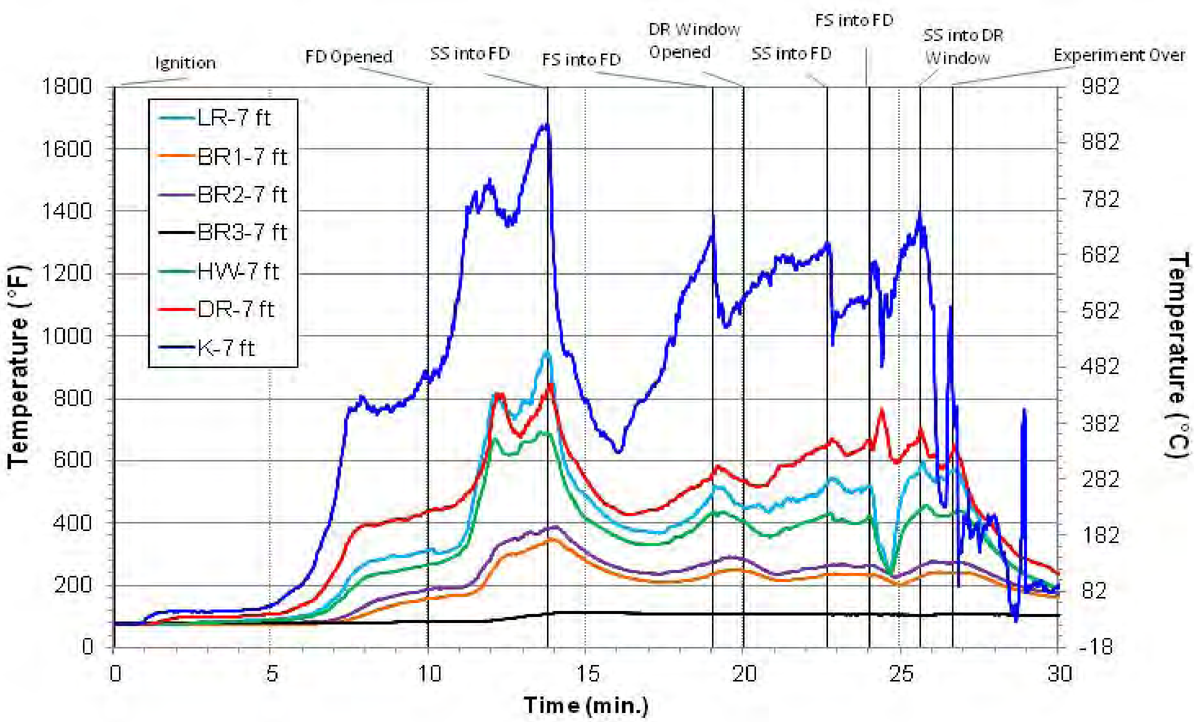


Figure 5.175: Experiment 13 - 7 ft. Temperatures

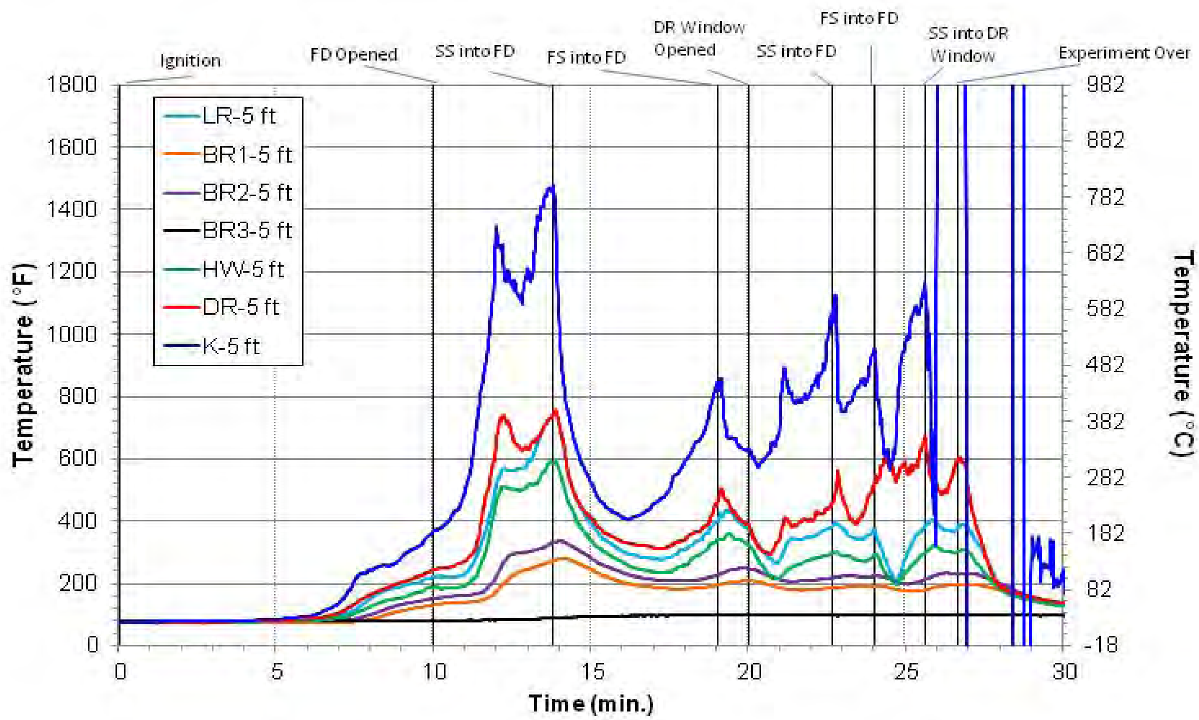


Figure 5.176: Experiment 13 - 5 ft. Temperatures

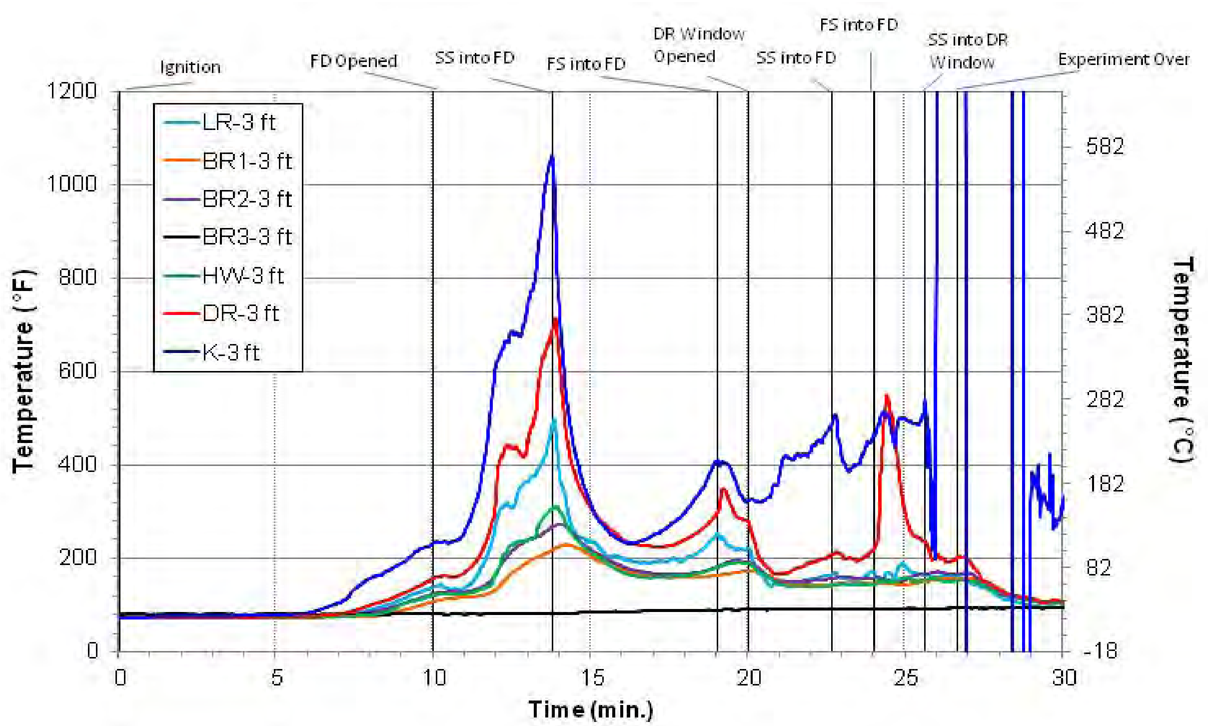


Figure 5.177: Experiment 13 - 3 ft. Temperatures

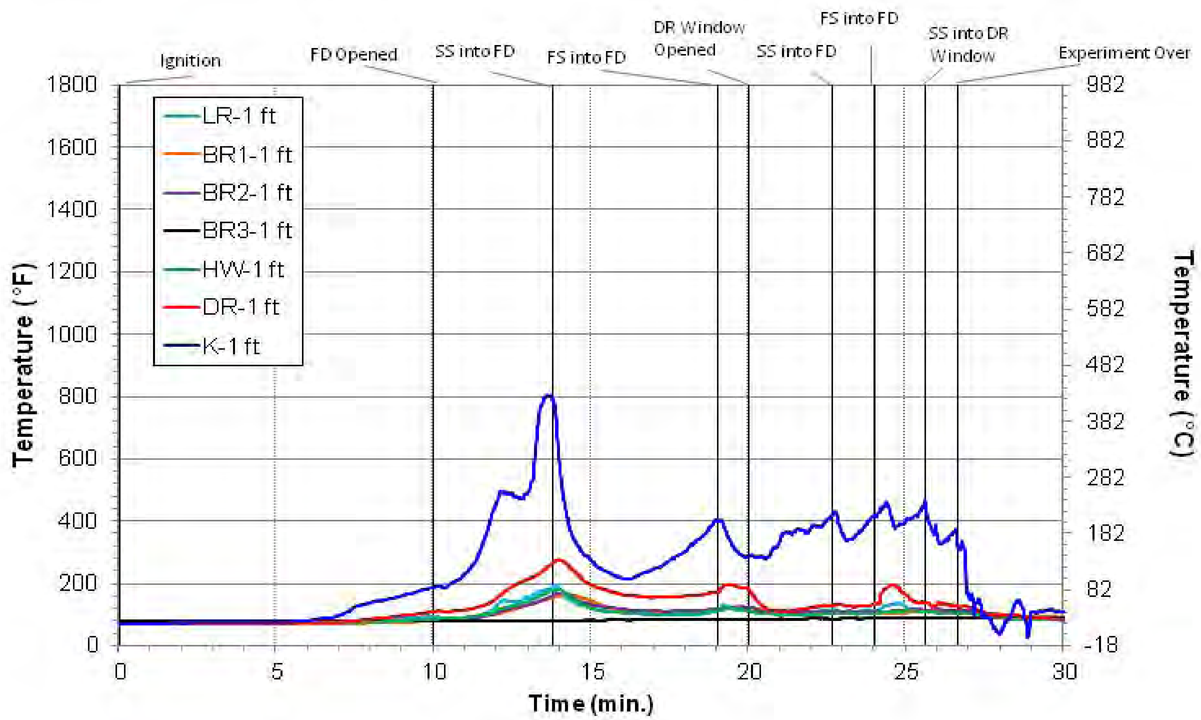


Figure 5.178: Experiment 13 - 1 ft. Temperatures

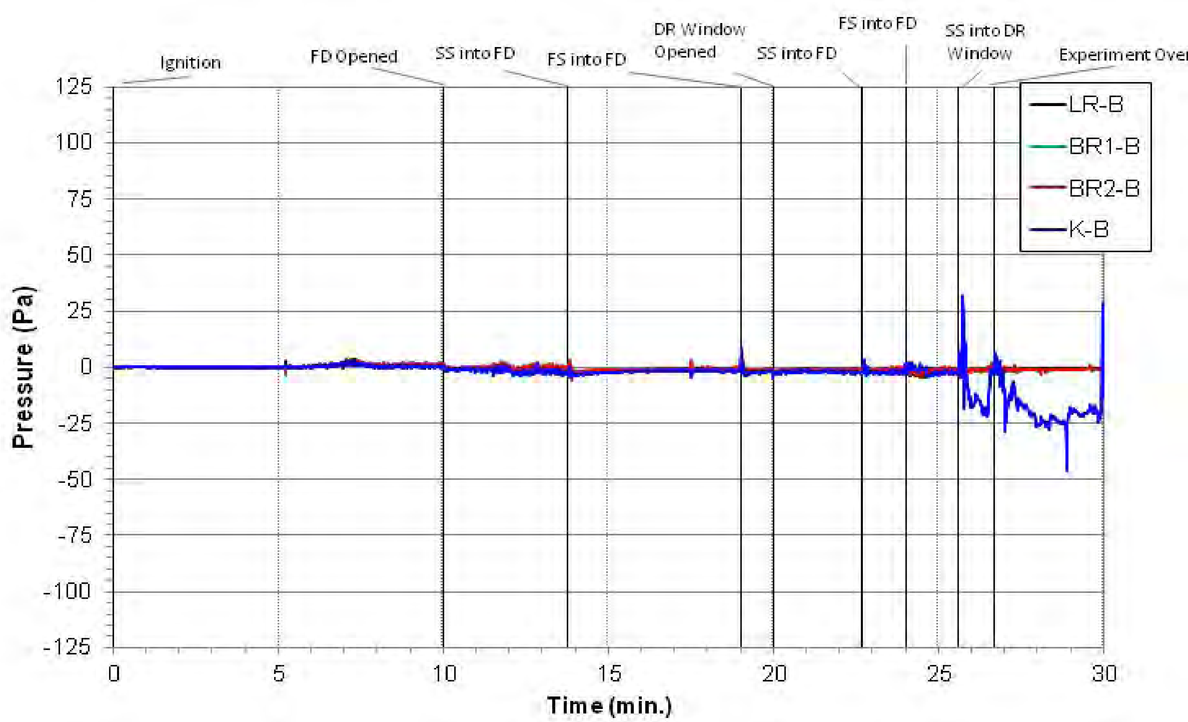


Figure 5.179: Experiment 13 - Bottom Pressure

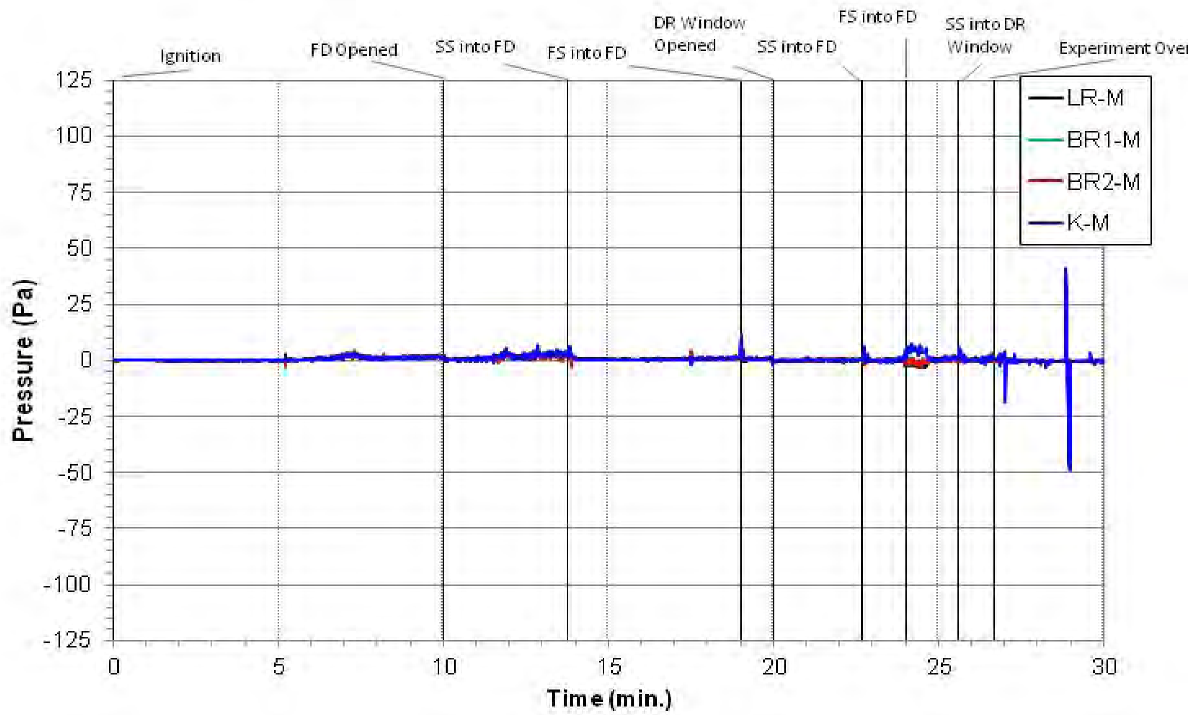


Figure 5.180: Experiment 13 - Middle Pressure

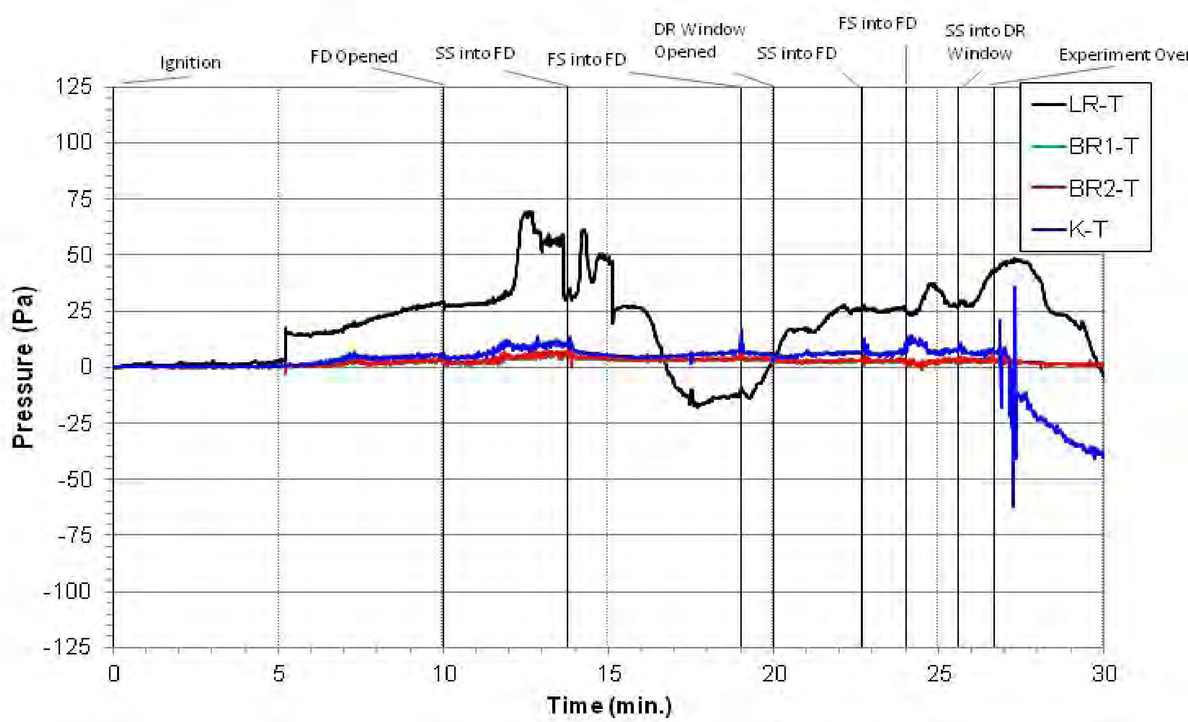


Figure 5.181: Experiment 13 - Top Pressure

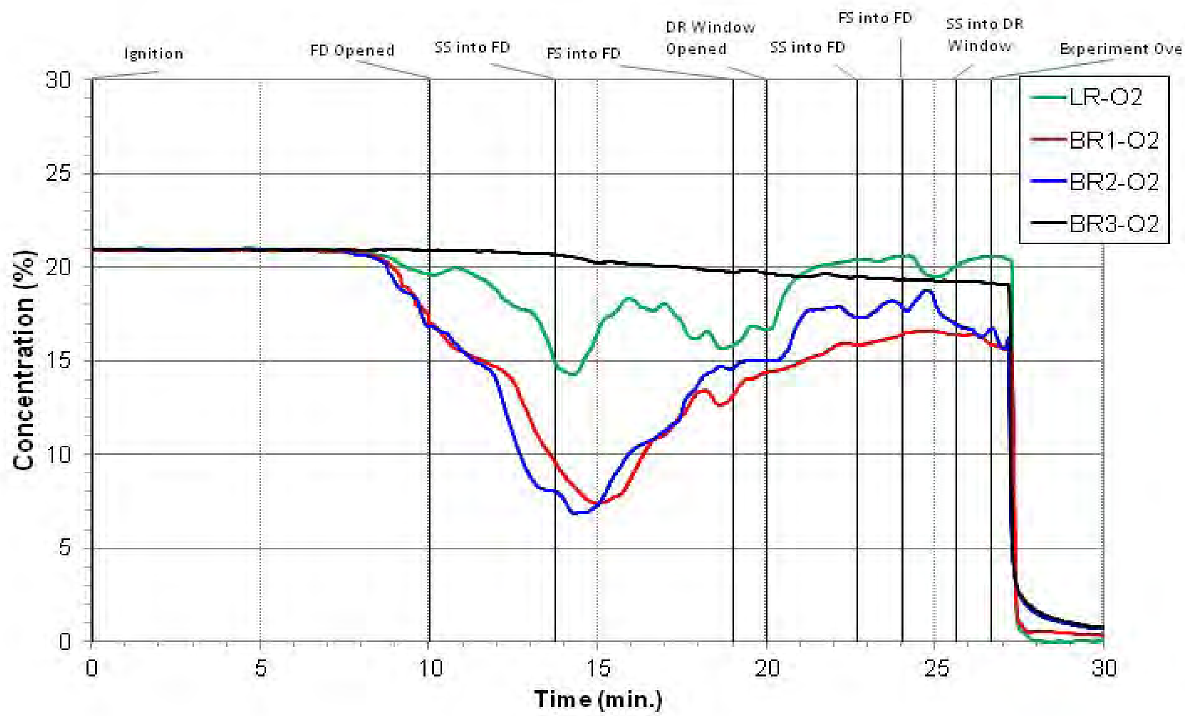


Figure 5.182: Experiment 13 - Oxygen Concentration

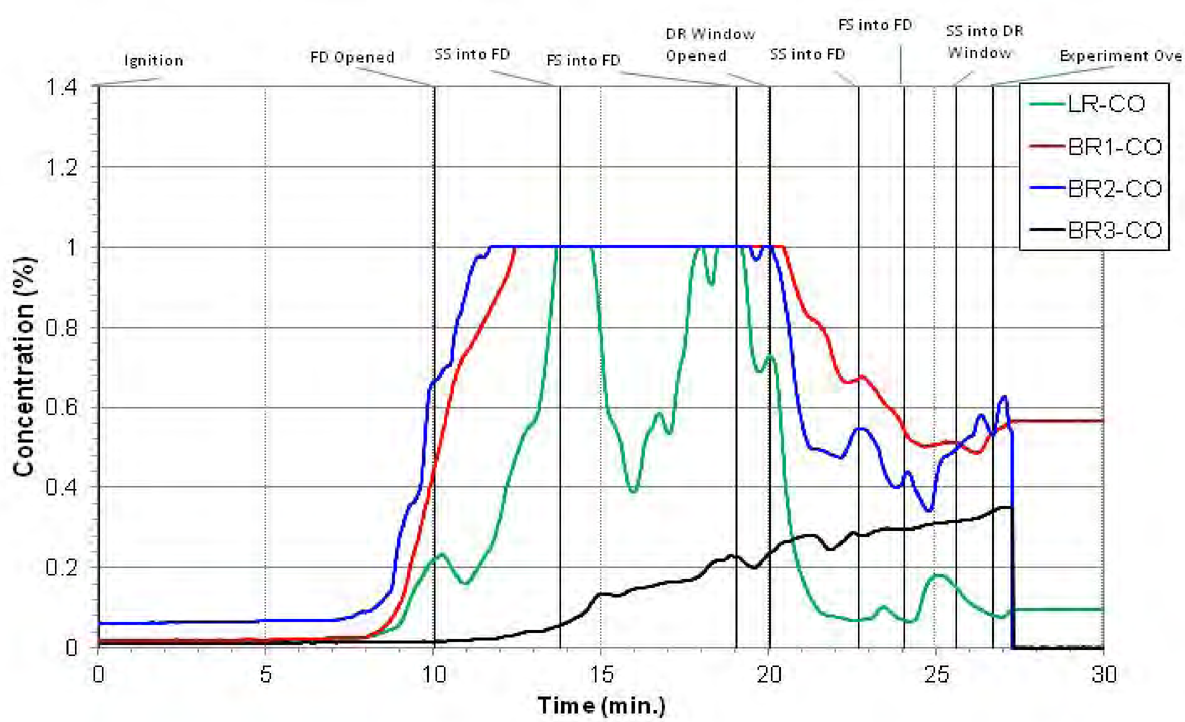


Figure 5.183: Experiment 13 - Carbon Monoxide Concentration

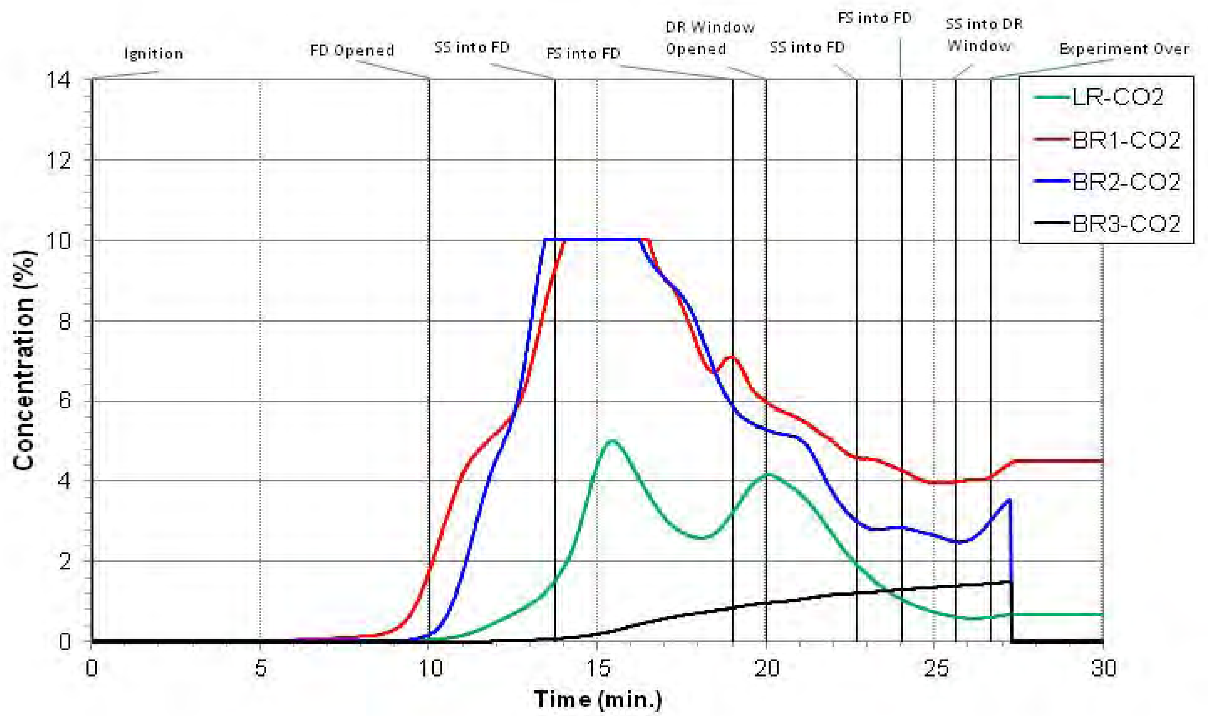


Figure 5.184: Experiment 13 - Carbon Dioxide Concentration

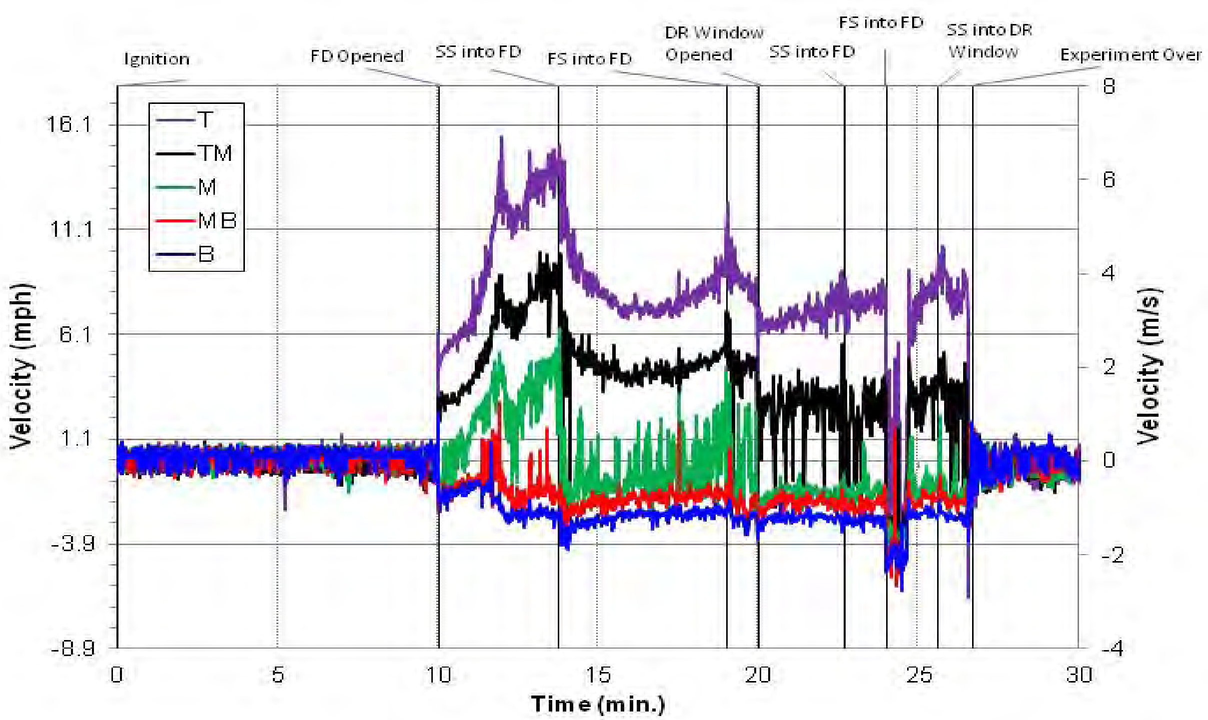


Figure 5.185: Experiment 13 - Front Door Velocity

5.6.8. Experiment 15

Experiment 15 was designed to simulate a fire with the possibility of pushing the fire to another room through ventilation tactics and suppression tactics. Ignition occurred in the living room. The fire was allowed to grow until 6:00, when the living room window was opened. The fire then continued to grow to post-flashover conditions and at 9:30 the Bedroom 1 window was opened. At 10:30, 11 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern. The fire was allowed to regrow and at 18:00, 13 seconds of water was applied to the fire with a combination nozzle positioned in a fog stream pattern to see if it had the effect of pushing the fire. The experiment ended at 20:05, and the crew extinguished the fire. Figure 5.187 through Figure 5.194 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.195 through Figure 5.204 detail the temperatures, pressures, gas concentrations and gas velocities during the experiments.

Table 5.14: Experiment 15 Timeline

Time	Description
0:00	Ignition
6:00	Living Room Window Open
9:30	Bedroom 1 Window Open
10:30	Straight Stream into Living Room Window
18:00	Fog Stream into Living Room Window
20:05	Final Suppression (End of Experiment)

Figure 5.186: Experiment 15 Scenario

Figure 5.187: Experiment 15 - 0:00

Figure 5.188: Experiment 15 - 4:30

Figure 5.189: Experiment 15 - 6:05

Figure 5.190: Experiment 15 - 8:55

Figure 5.191: Experiment 15 - 9:35

Figure 5.192: Experiment 15 - 10:35

Figure 5.193: Experiment 15 - 16:06

Figure 5.194: Experiment 15 - 19:00

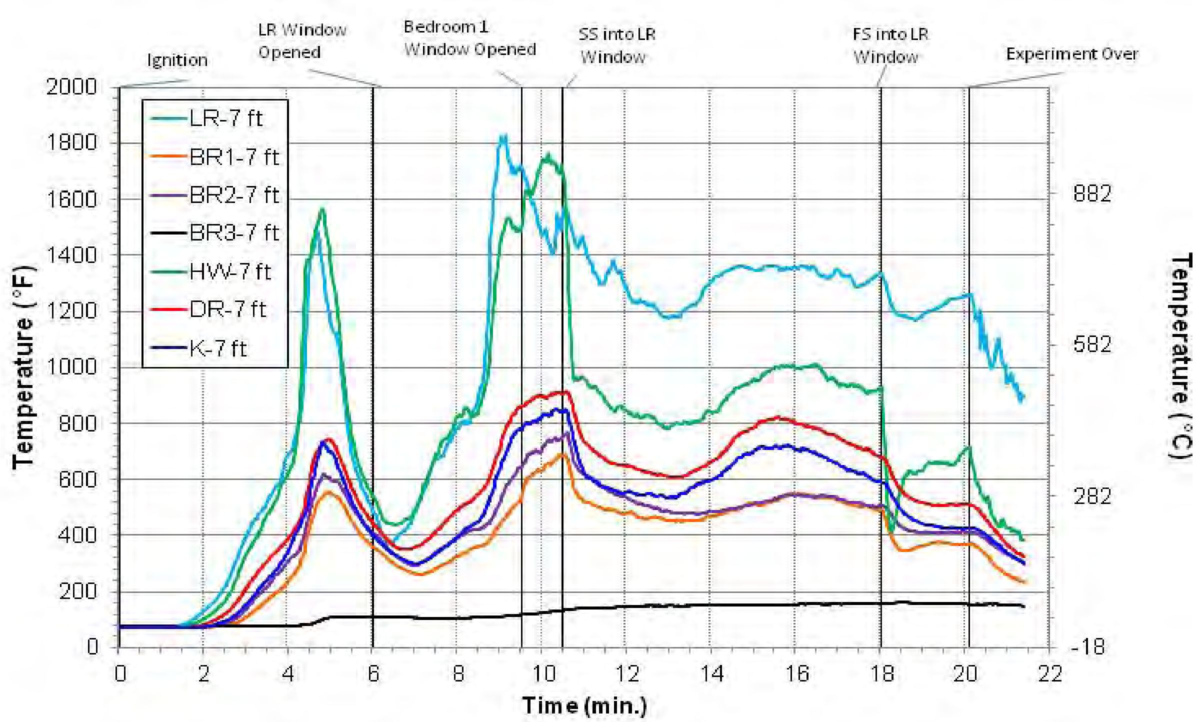


Figure 5.195: Experiment 15 - 7 ft. Temperatures

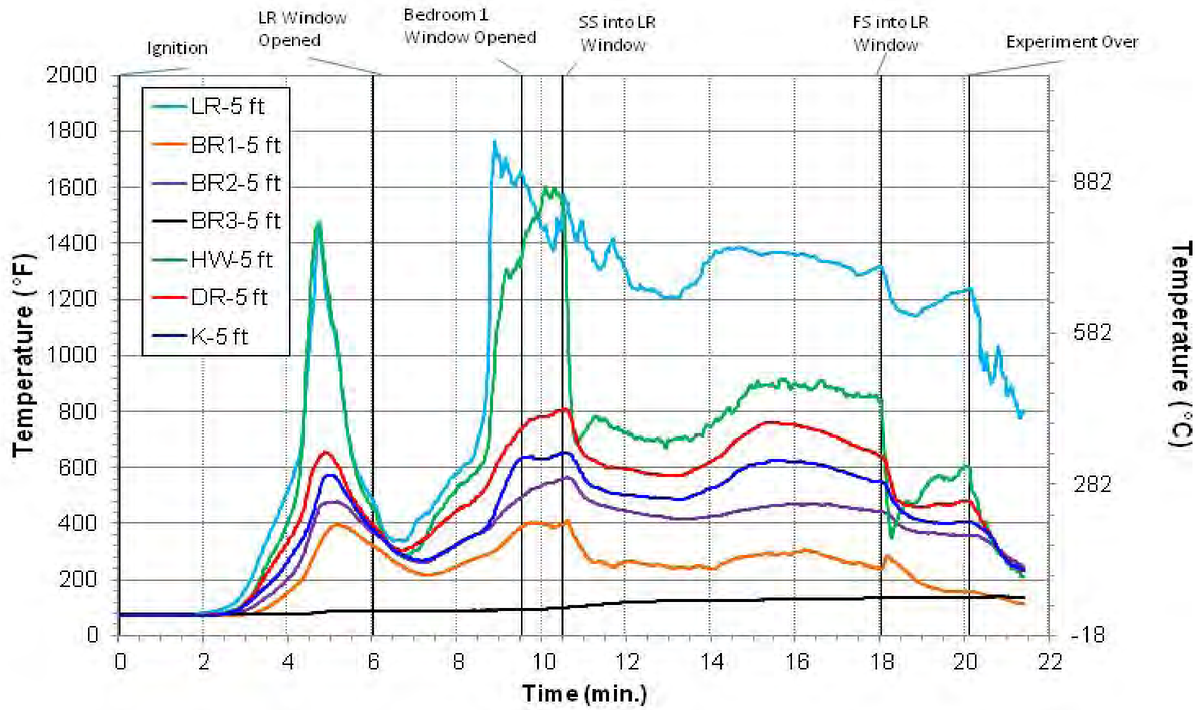


Figure 5.196: Experiment 15 - 5 ft. Temperatures

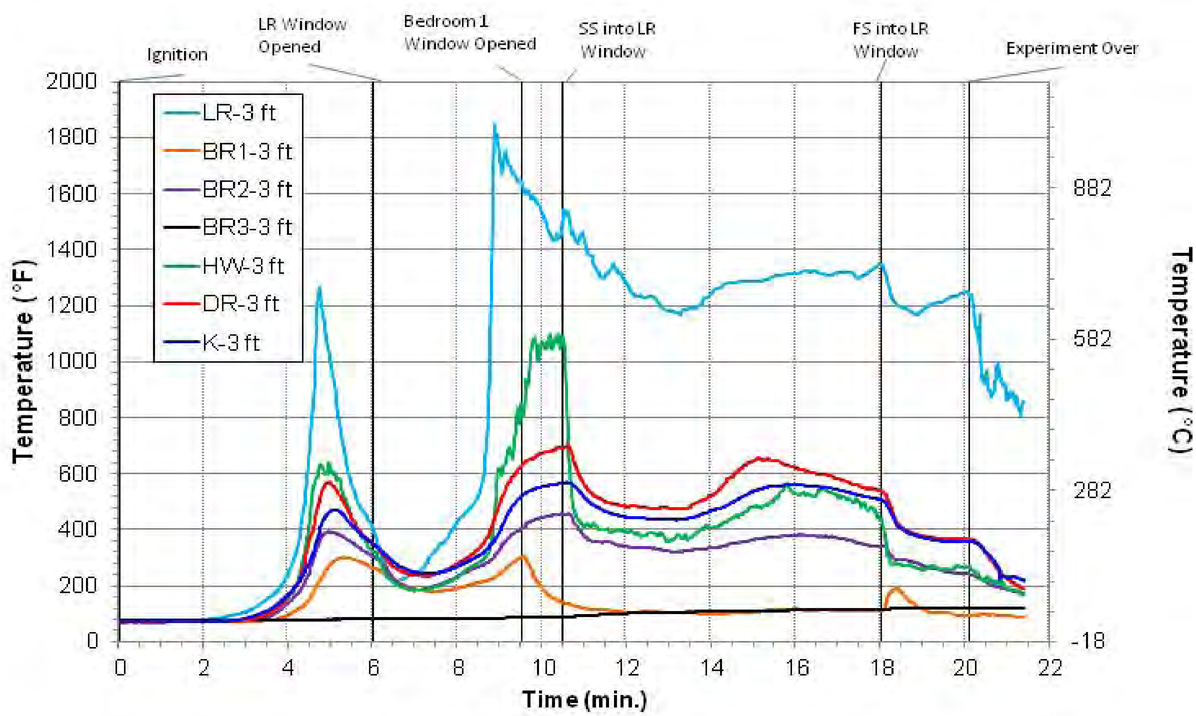


Figure 5.197: Experiment 15 - 3 ft. Temperatures

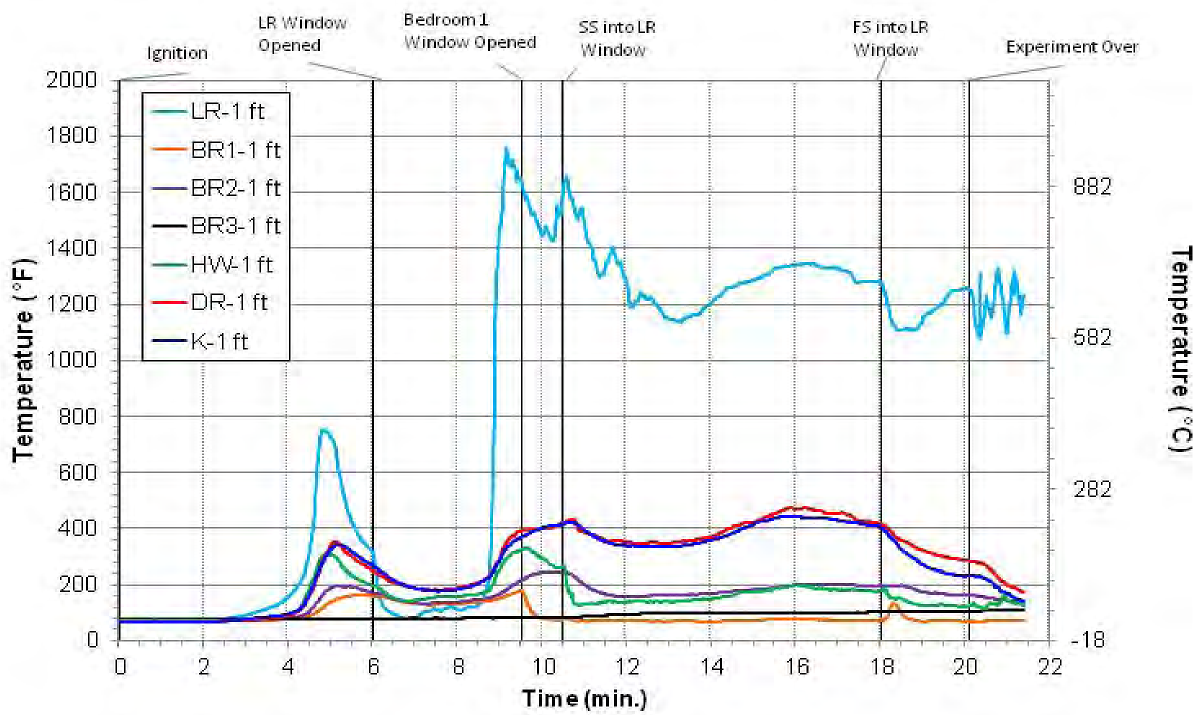


Figure 5.198: Experiment 15 - 1 ft. Temperatures

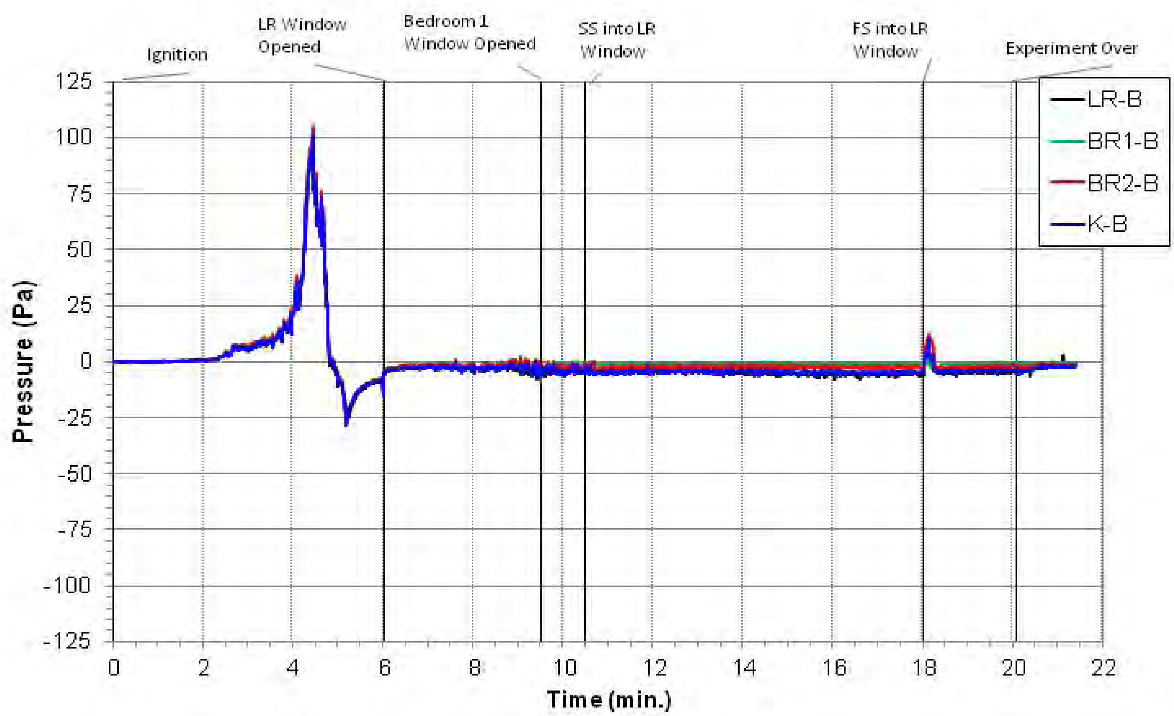


Figure 5.199: Experiment 15 - Bottom Pressure

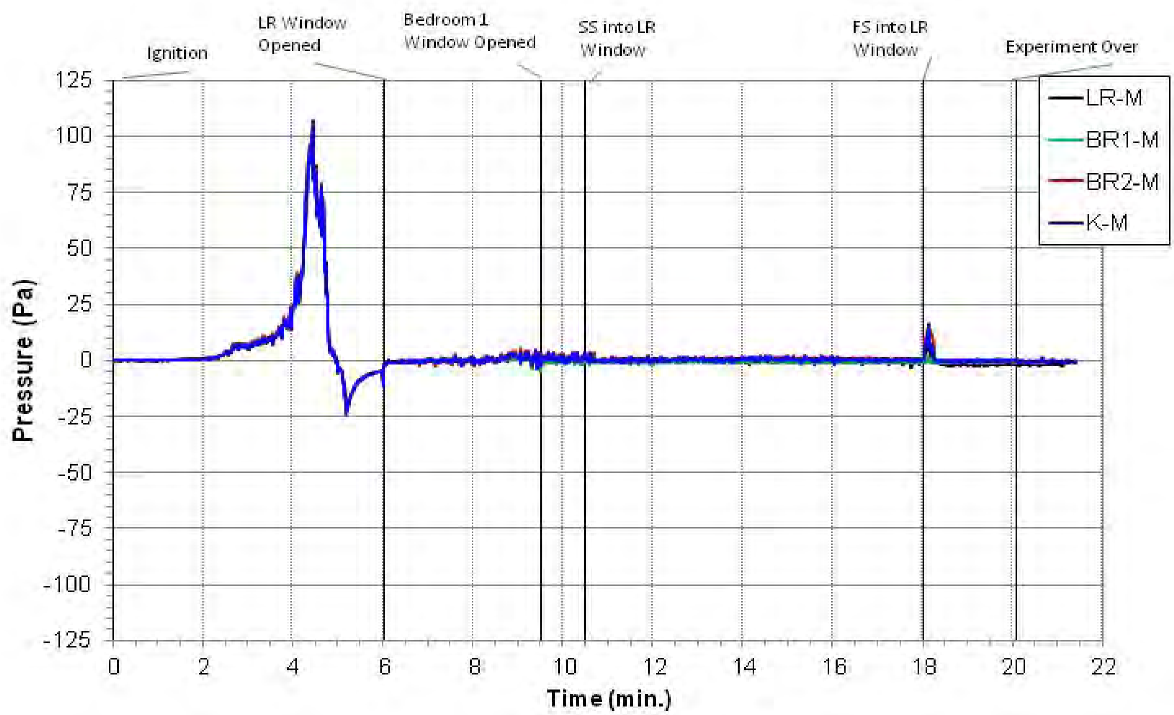


Figure 5.200: Experiment 15 - Middle Pressure

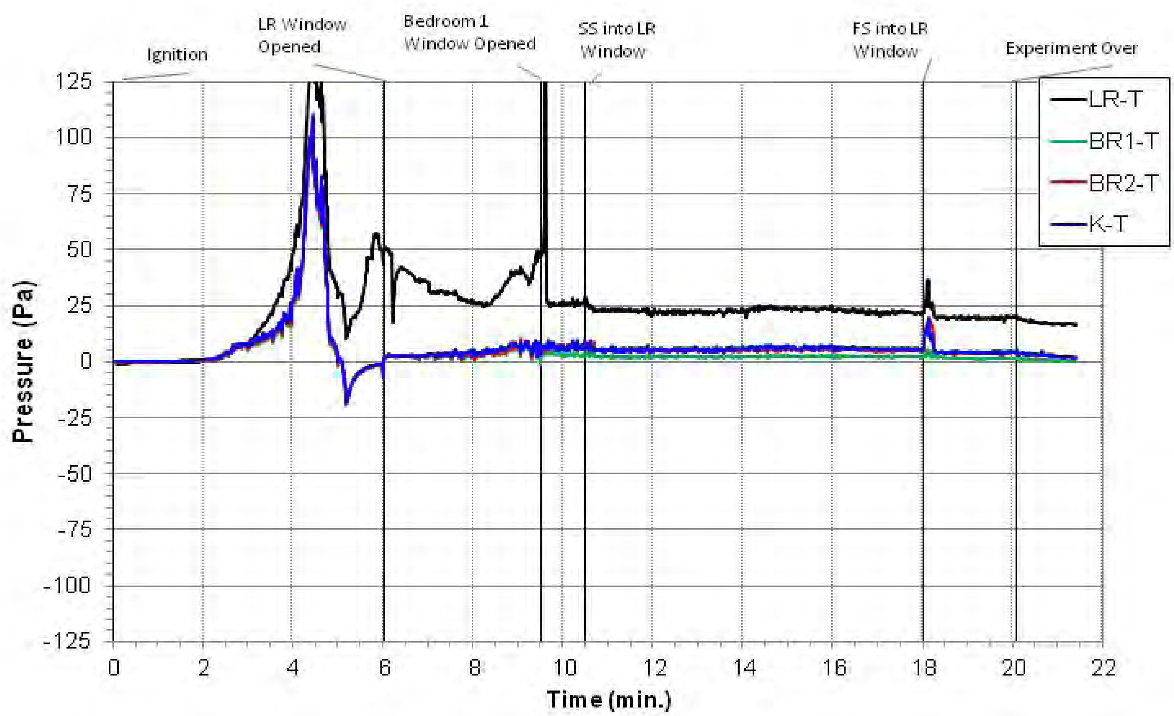


Figure 5.201: Experiment 15 - Top Pressure

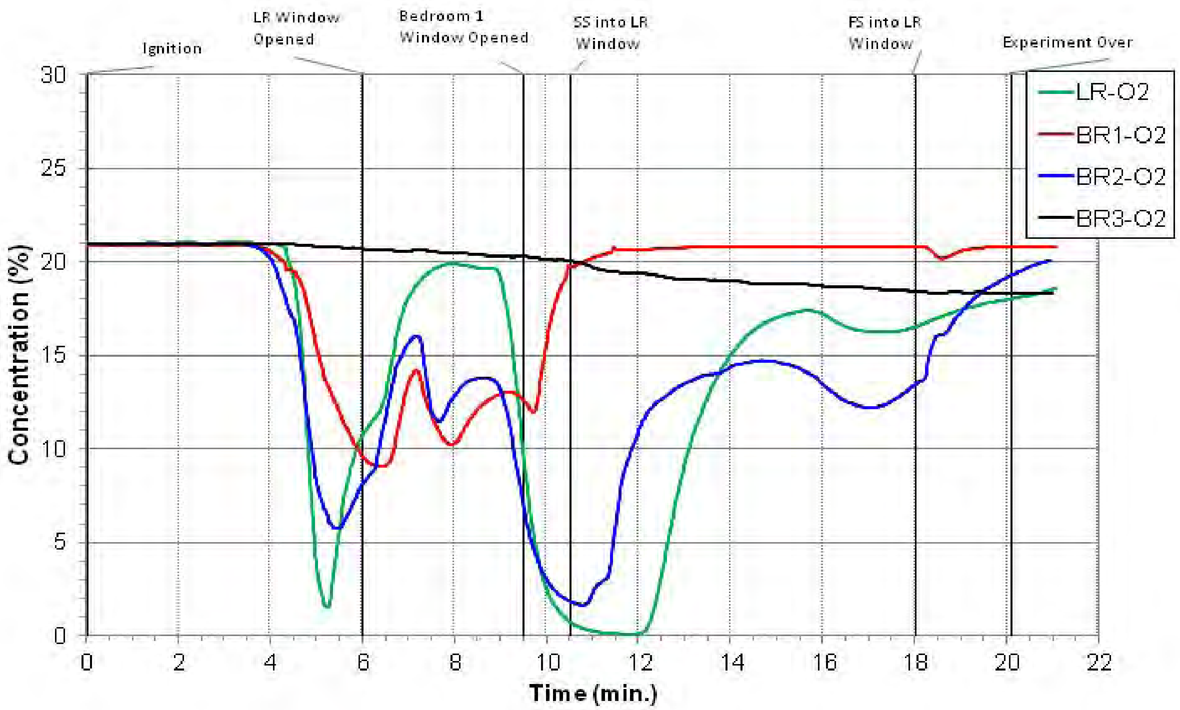


Figure 5.202: Experiment 15 - Oxygen Concentration

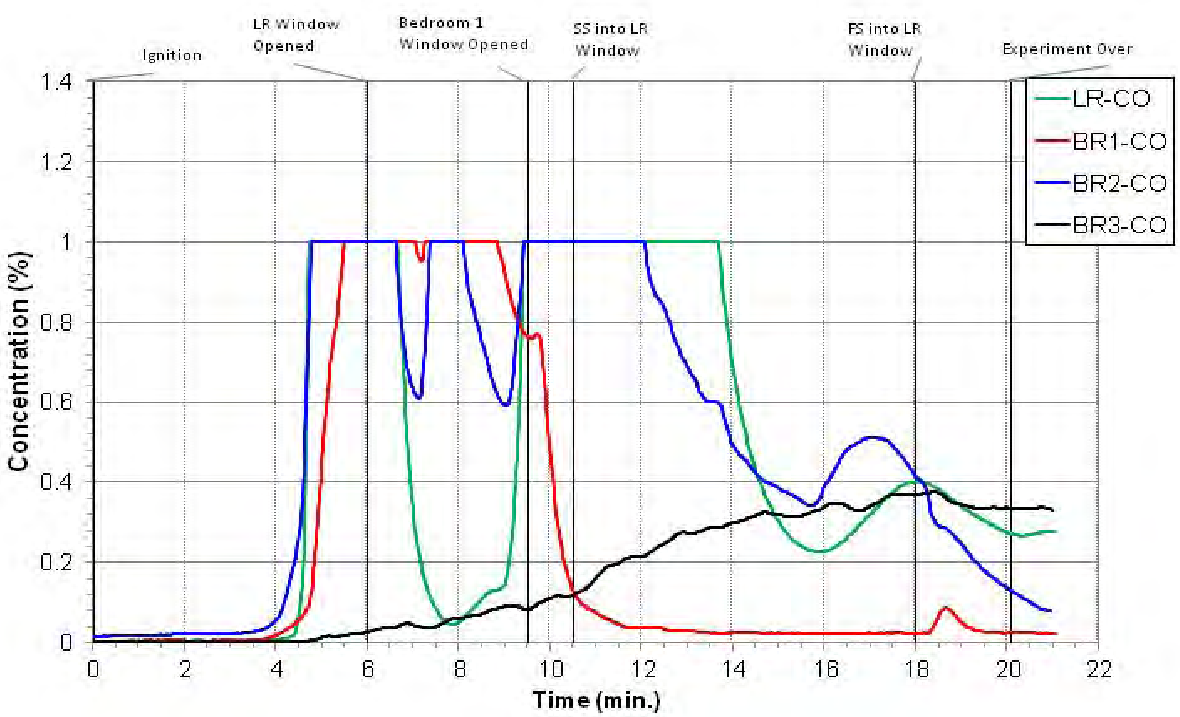


Figure 5.203: Experiment 15 - Carbon Monoxide Concentration

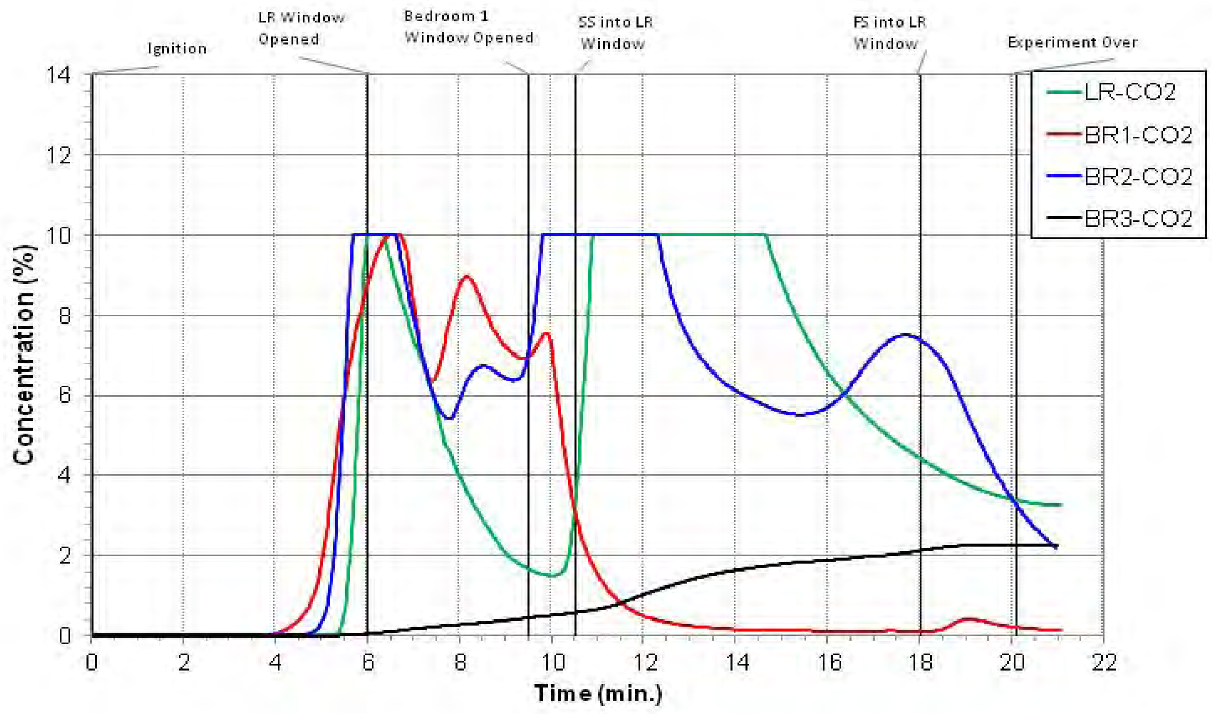


Figure 5.204: Experiment 15 - Carbon Dioxide Concentration

5.6.9. Experiment 17

Experiment 17 was designed to simulate a fire with legacy furniture being attacked by a fire crew in the same way as in Experiment 1. Ignition occurred in the living room. The fire was allowed to grow until 24:00, when the front door was opened and 15 seconds later, at 24:15, the living room window was opened. The fire then grew to post-flashover conditions and at 33:30, 15 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern. The experiment ended at 35:30, and the crew extinguished the fire. Figure 5.206 through Figure 5.212 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.213 through Figure 5.223 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.15: Experiment 17 Timeline

Time	Description
0:00	Ignition
24:00	Front Door Open
24:15	Living Room Window Open
33:30	Straight Stream into Family Room Window
35:30	Final Suppression (End of Experiment)

Figure 5.205: Experiment 17 Scenario

Figure 5.206: Experiment 17 - 0:00

Figure 5.207: Experiment 17 - 16:00

Figure 5.208: Experiment 17 - 24:05

Figure 5.209: Experiment 17 - 24:20

Figure 5.210: Experiment 17 - 27:30

Figure 5.211: Experiment 17 - 33:35

Figure 5.212: Experiment 17 - 34:30

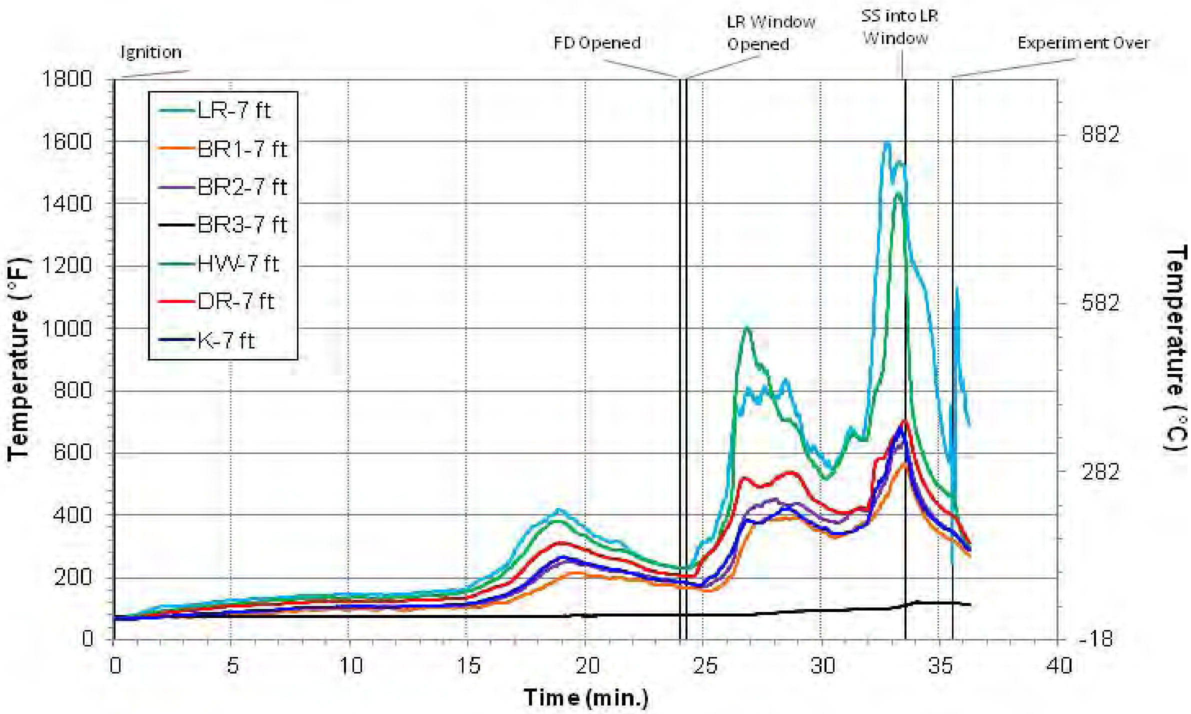


Figure 5.213: Experiment 17 - 7 ft. Temperatures

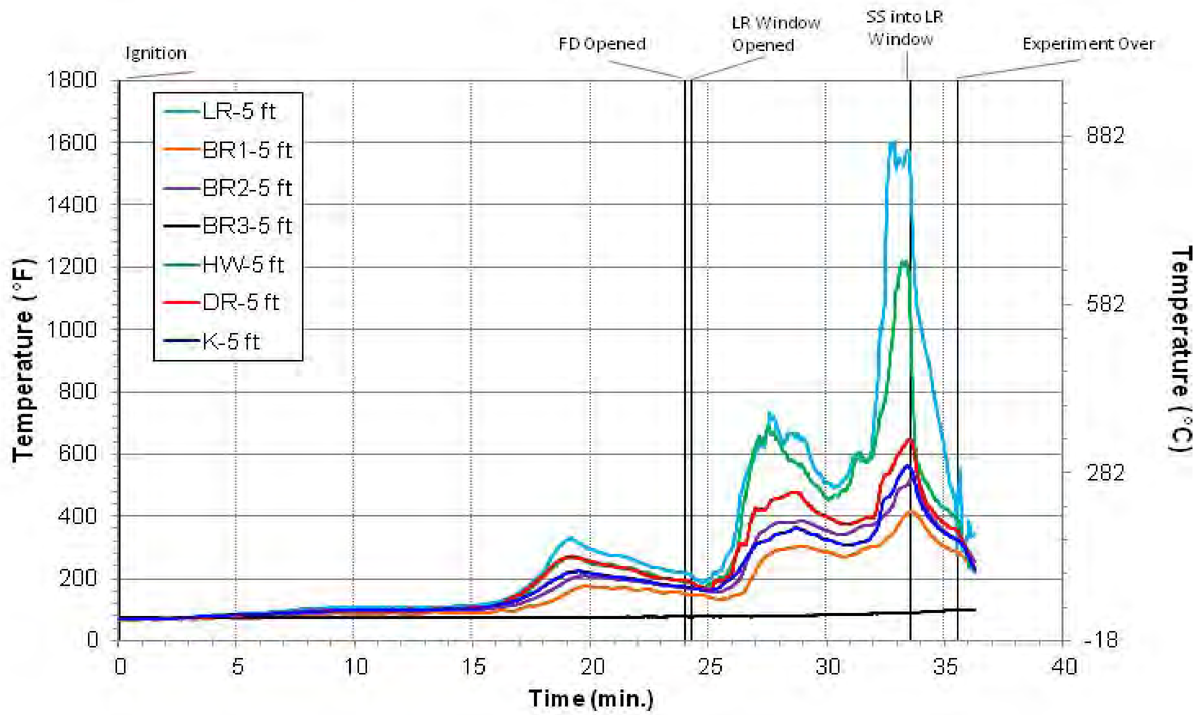


Figure 5.214: Experiment 17 - 5 ft. Temperatures

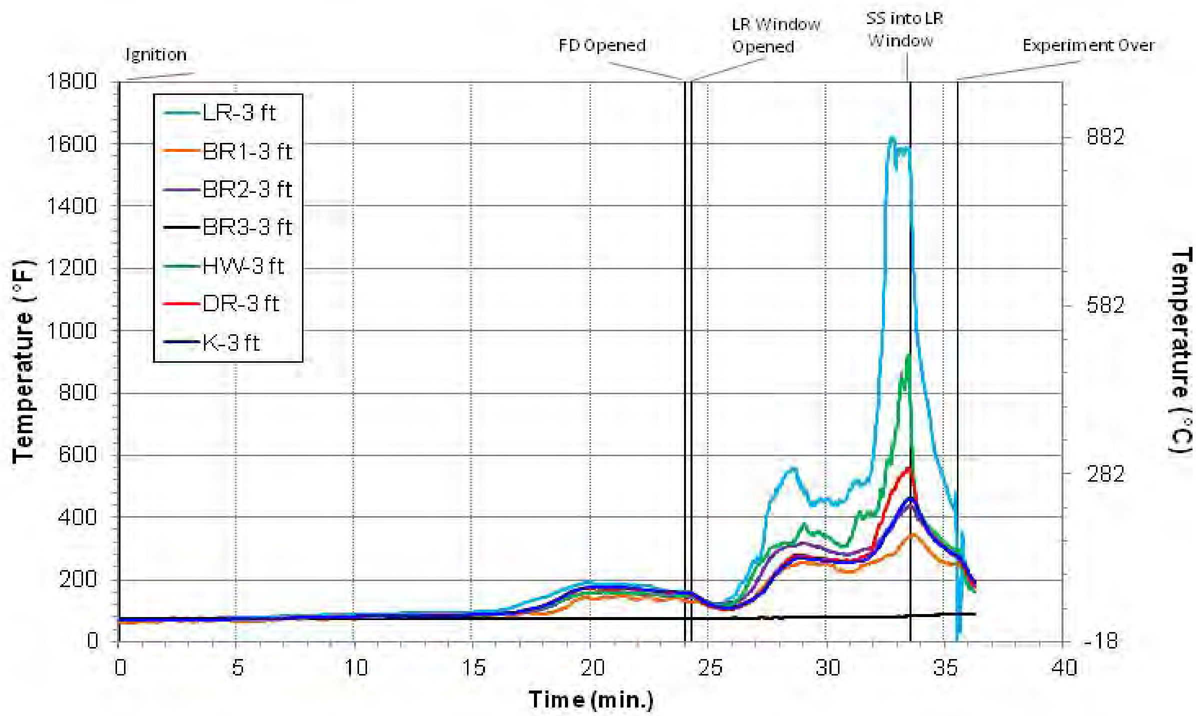


Figure 5.215: Experiment 17 - 3 ft. Temperatures

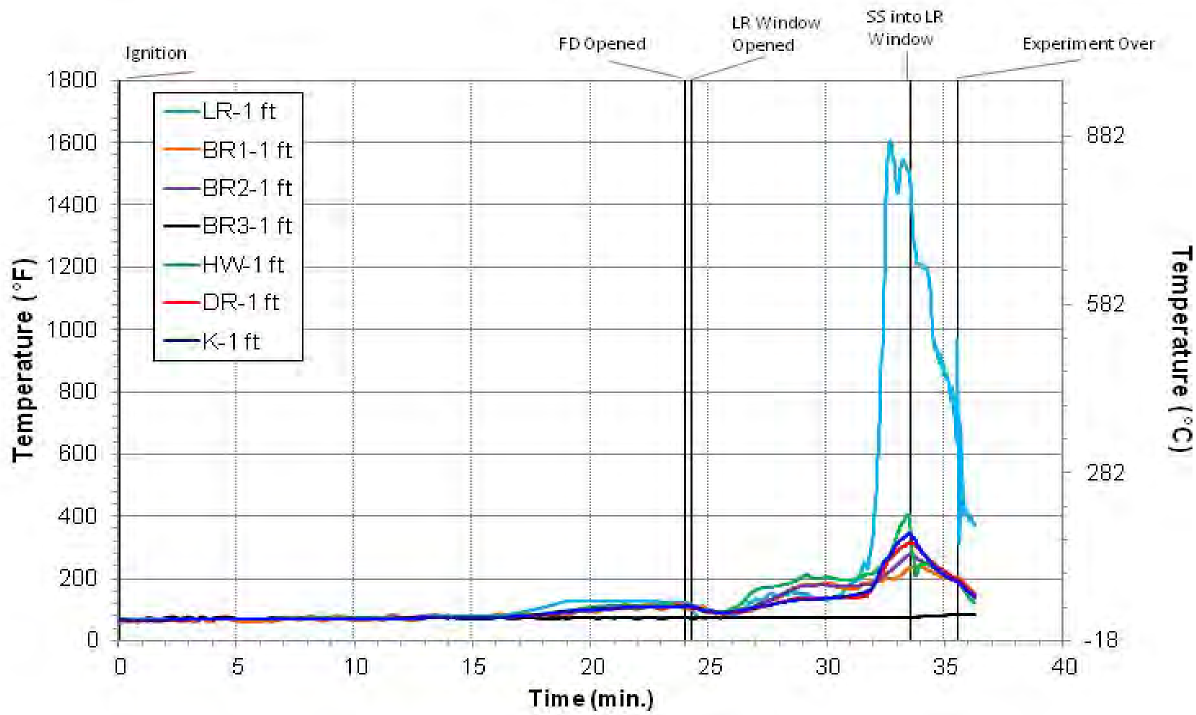


Figure 5.216: Experiment 17 - 1 ft. Temperatures

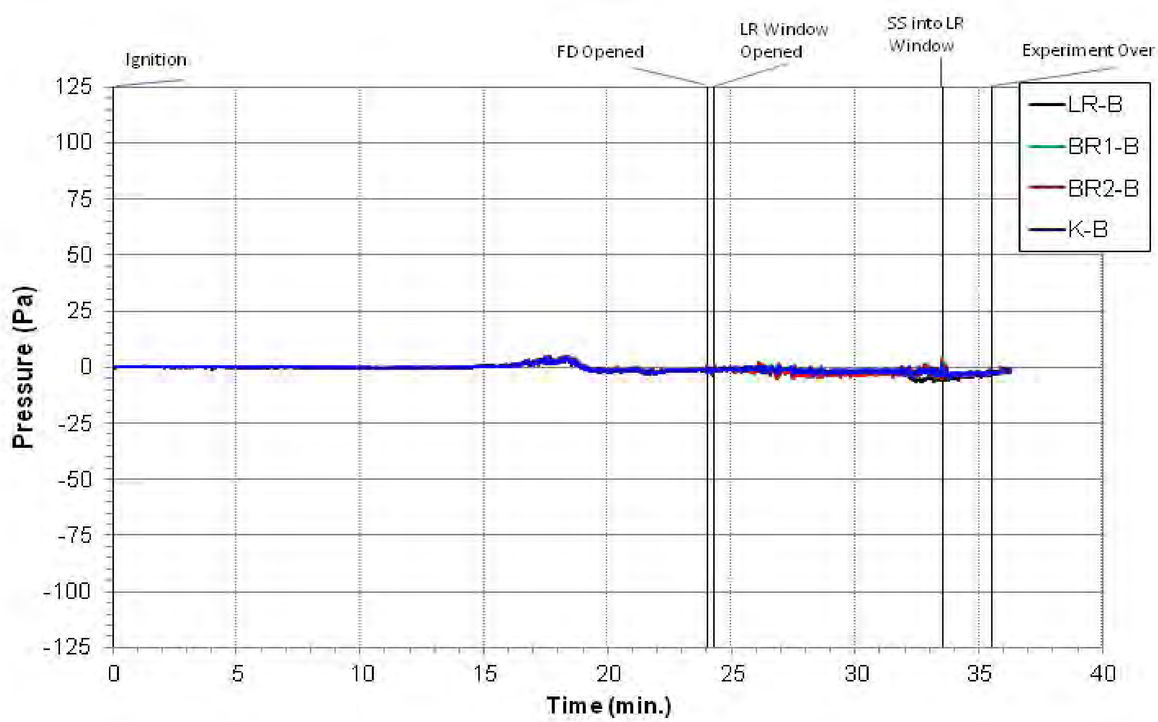


Figure 5.217: Experiment 17 - Bottom Pressure

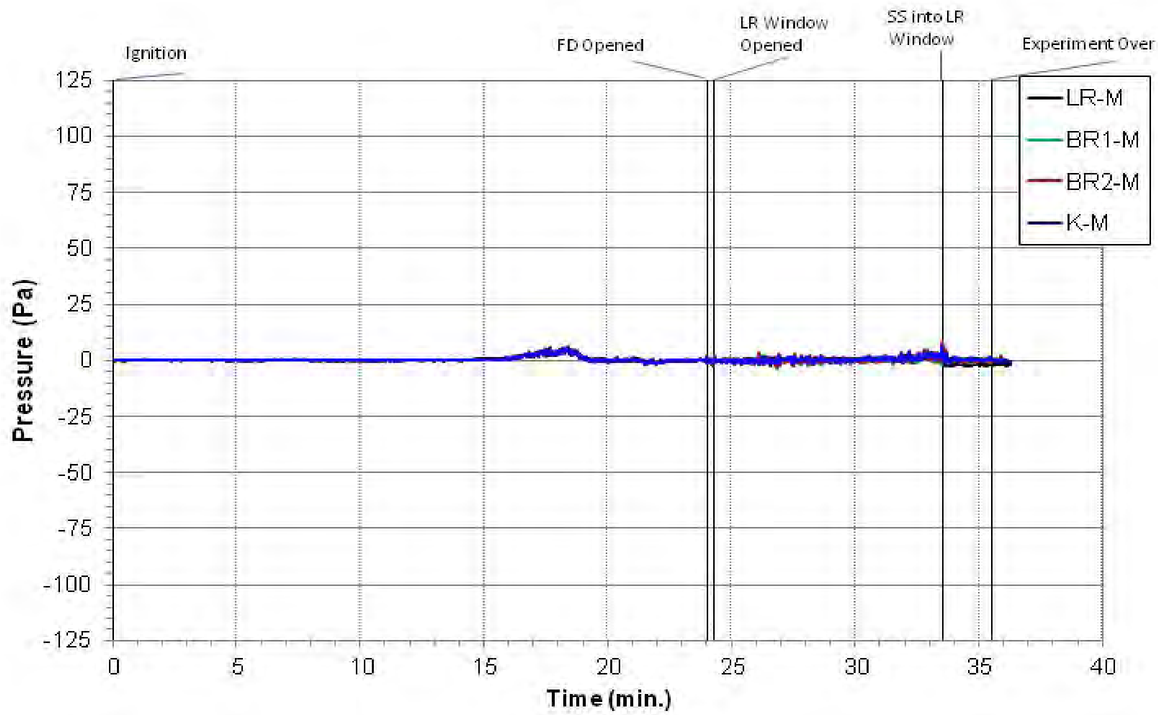


Figure 5.218: Experiment 17 - Middle Pressure

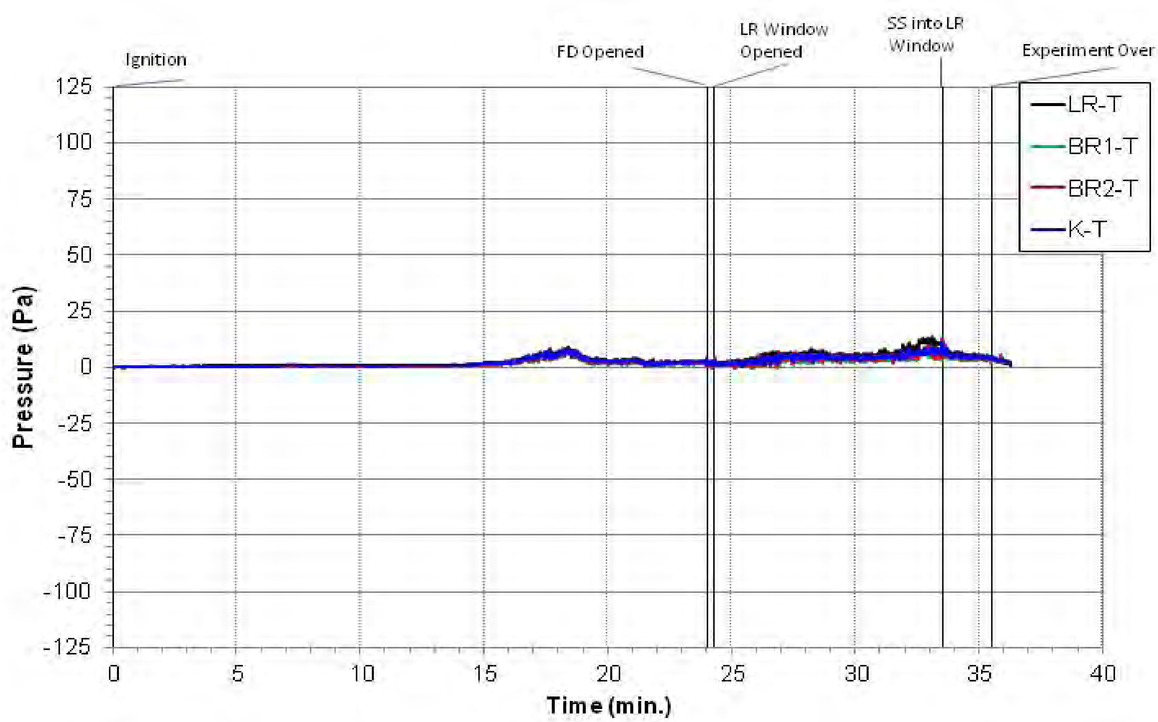


Figure 5.219: Experiment 17 - Top Pressure

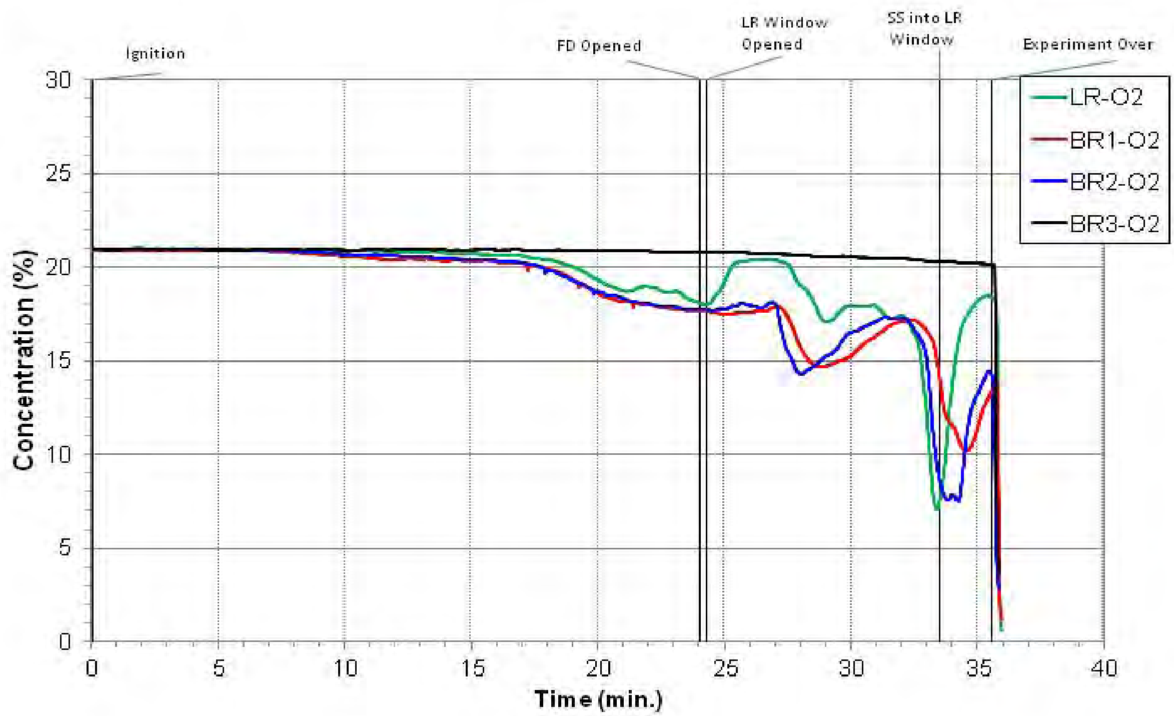


Figure 5.220: Experiment 17 - Oxygen Concentration

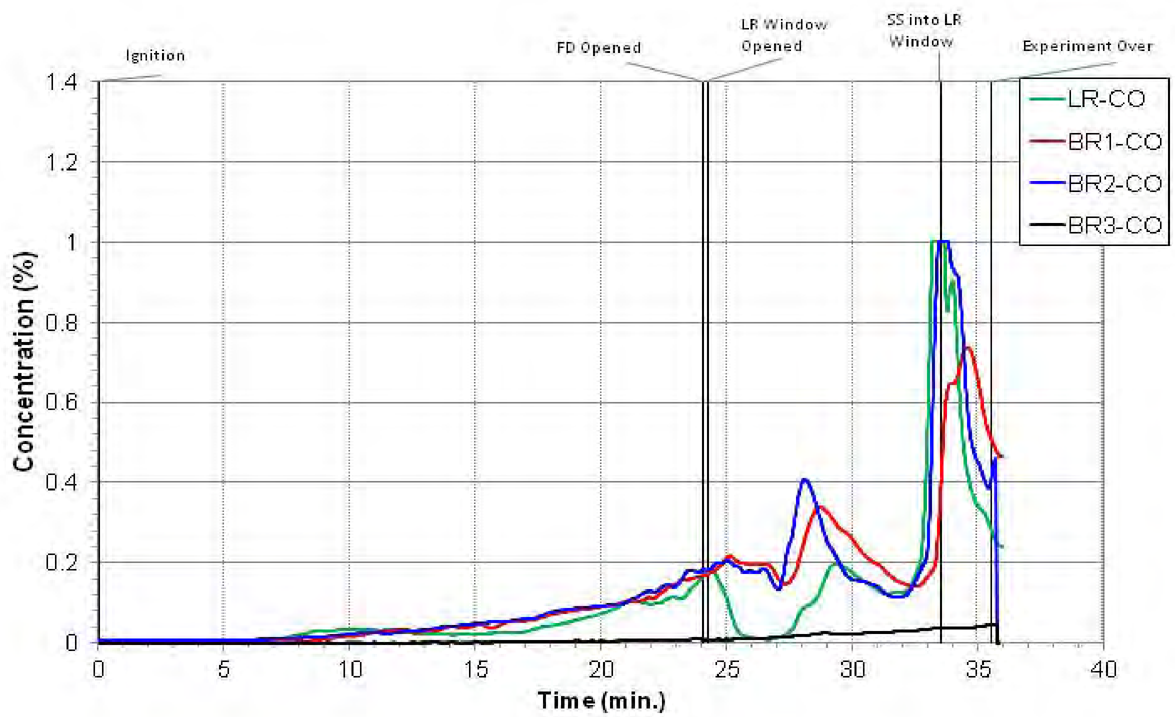


Figure 5.221: Experiment 17 - Carbon Monoxide Concentration

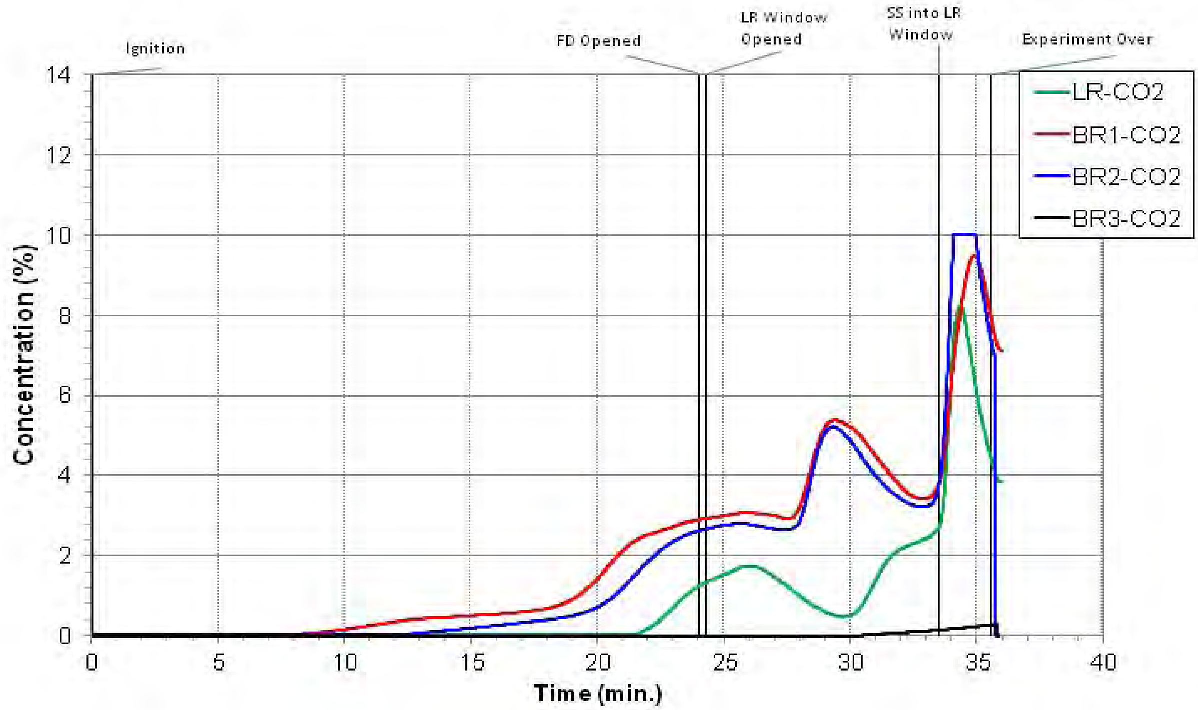


Figure 5.222: Experiment 17 - Carbon Dioxide Concentration

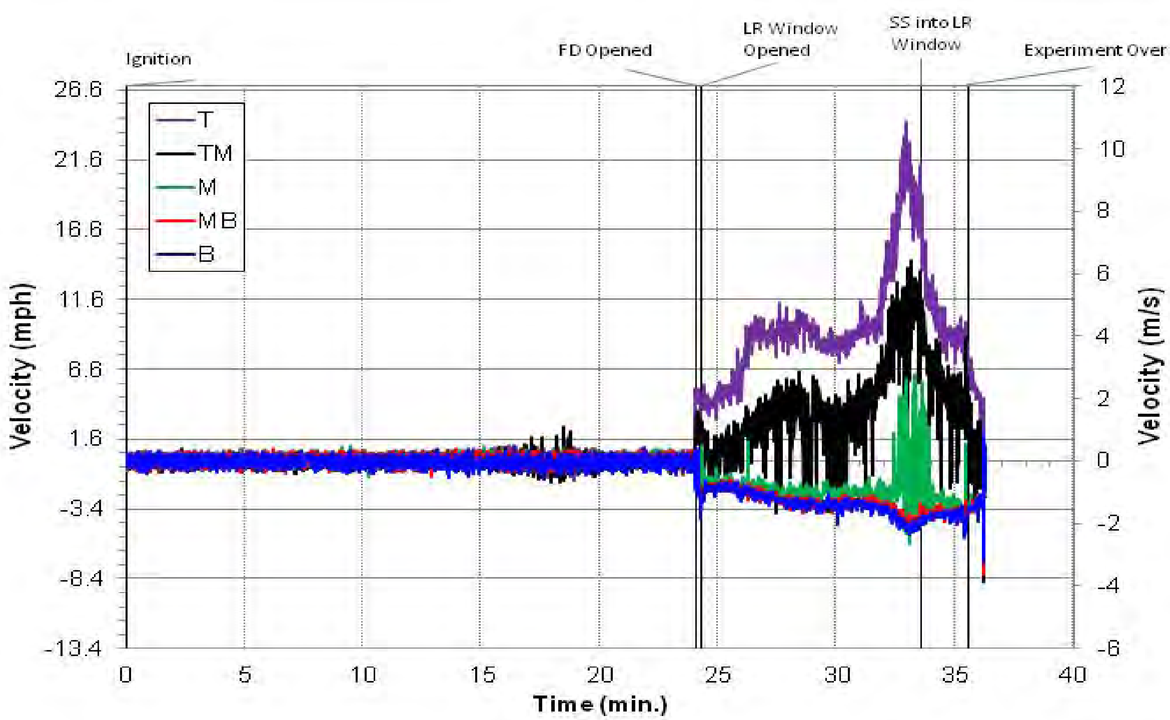


Figure 5.223: Experiment 17 - Front Door Velocity

5.7. Two-Story Experimental Results

Eight experiments were conducted in the two-story house (Table 5.16). In the following, each experiment is described and a table showing the timeline is provided. A series of figures provide an overview of the experiment; and the data from each experiment is included on graphs that have the timeline detail included at the top of each graph with a vertical line indicating when the event occurred. The results of each experiment are examined in further detail in the discussion section.

Table 5.16: Two-story Experimental Details

Experiment #	Structure	Location of Ignition	Ventilation Parameters
2	2-Story	Family Room	Front Door + Family Room Window
4	2-Story	Family Room	Front Door Partially Open + Roof (4' by 4')
6	2-Story	Family Room	Front Door + Roof (4' by 4')
8	2-Story	Family Room	Front Door + Roof (4' by 8')
10	2-Story	Bedroom 3	Front Door + Roof (4' by 4') + Bedroom 3 Window
12	2-Story	Family Room	Family Room Window + Front Door + Roof (4' by 4')
14	2-Story	Bedroom 3	Bedroom 3 Window + Front Door + Roof (4' by 4')
16	2-Story	Kitchen	Family Room Window (nearer Kitchen) + Bedroom 3 Window

5.7.1. Experiment 2

Experiment 2 was designed to simulate a crew entering through the front door, with a window near the seat of the fire being ventilated in coordination with access. Ignition occurred in the family room. The fire was allowed to grow until 10:00, when the front door was opened. 15 seconds later, at 10:15, the family room window was opened. The fire then grew to post-flashover conditions and at 14:20 water was applied for 12 seconds with a combination nozzle positioned in a straight stream pattern. The experiment ended at 15:40, and the crew extinguished the fire. Figure 5.225 through Figure 5.231 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.232 through Figure 5.242 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.17: Experiment 2 Timeline

Time	Description
0:00	Ignition
10:00	Front Door Open
10:15	Family Room Window Open
14:20	Straight Stream into Family Room Window
15:40	Final Suppression (End of Experiment)

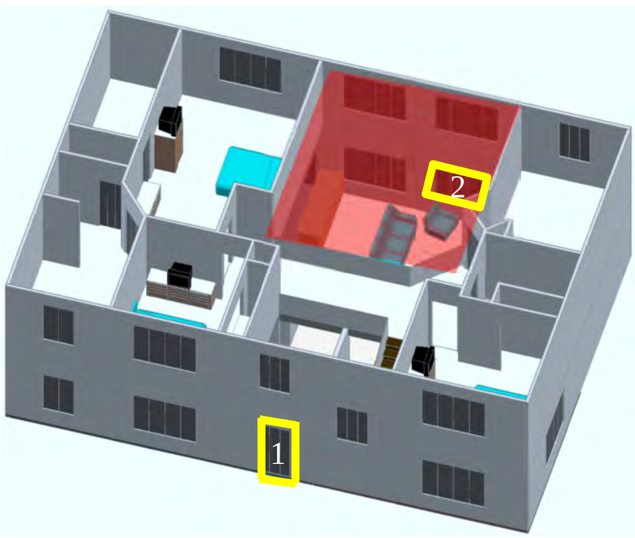


Figure 5.224: Experiment 2 Scenario

Figure 5.225: Experiment 2 - 0:00

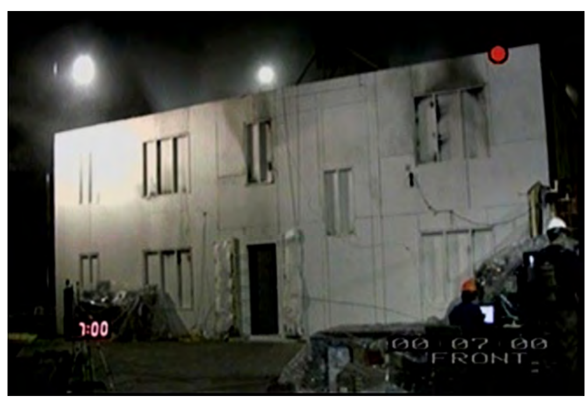


Figure 5.226: Experiment 2 - 7:00

Figure 5.227: Experiment 2 - 10:06

Figure 5.228: Experiment 2 - 10:23

Figure 5.229: Experiment 2 - 12:30

Figure 5.230: Experiment 2 - 14:21

Figure 5.231: Experiment 2 - 15:00

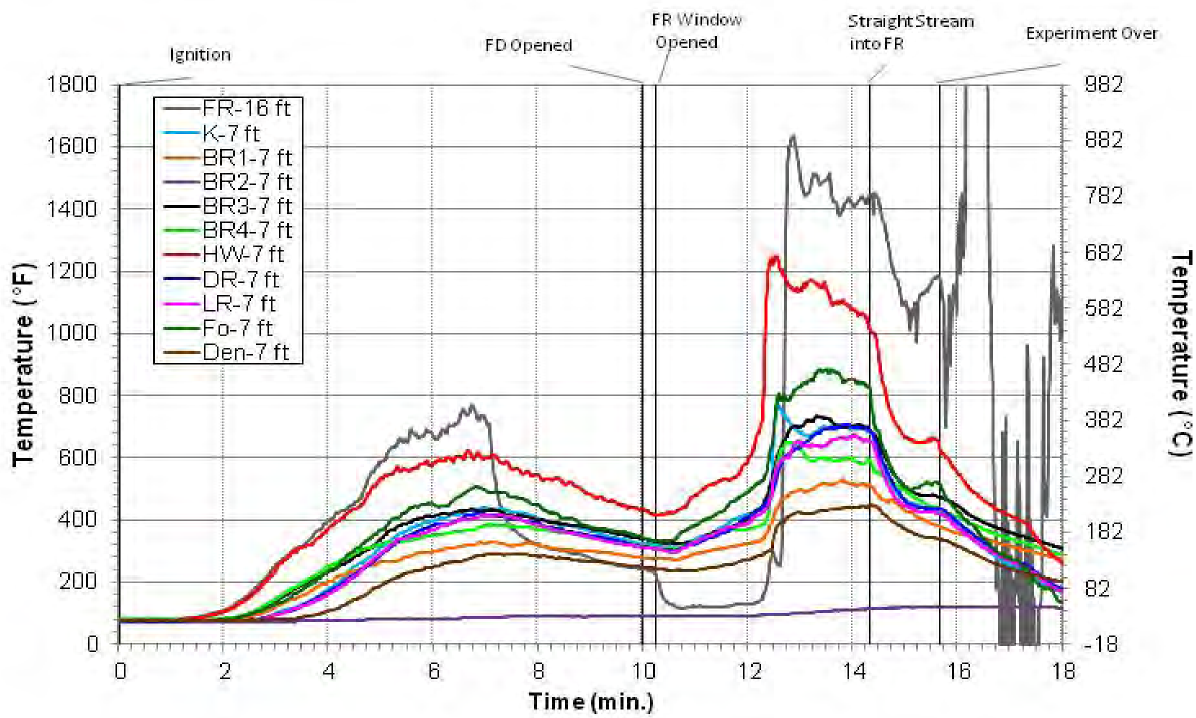


Figure 5.232: Experiment 2 - 7 ft. Temperatures

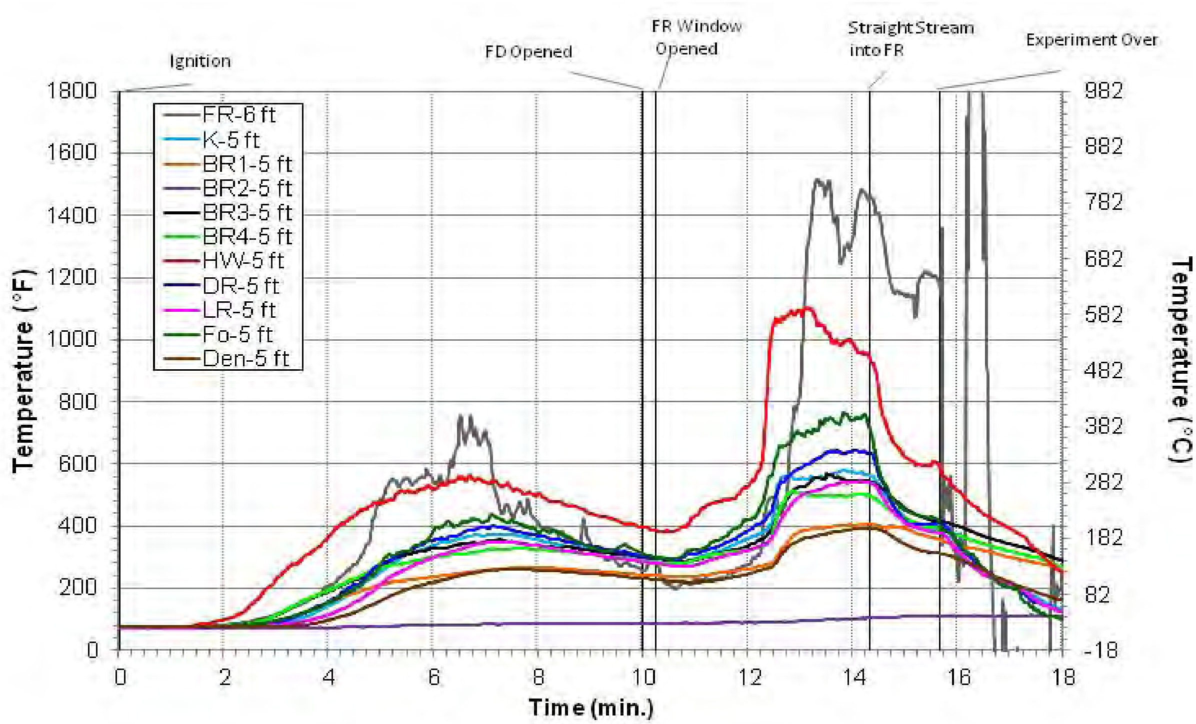


Figure 5.233: Experiment 2 - 5 ft. Temperatures

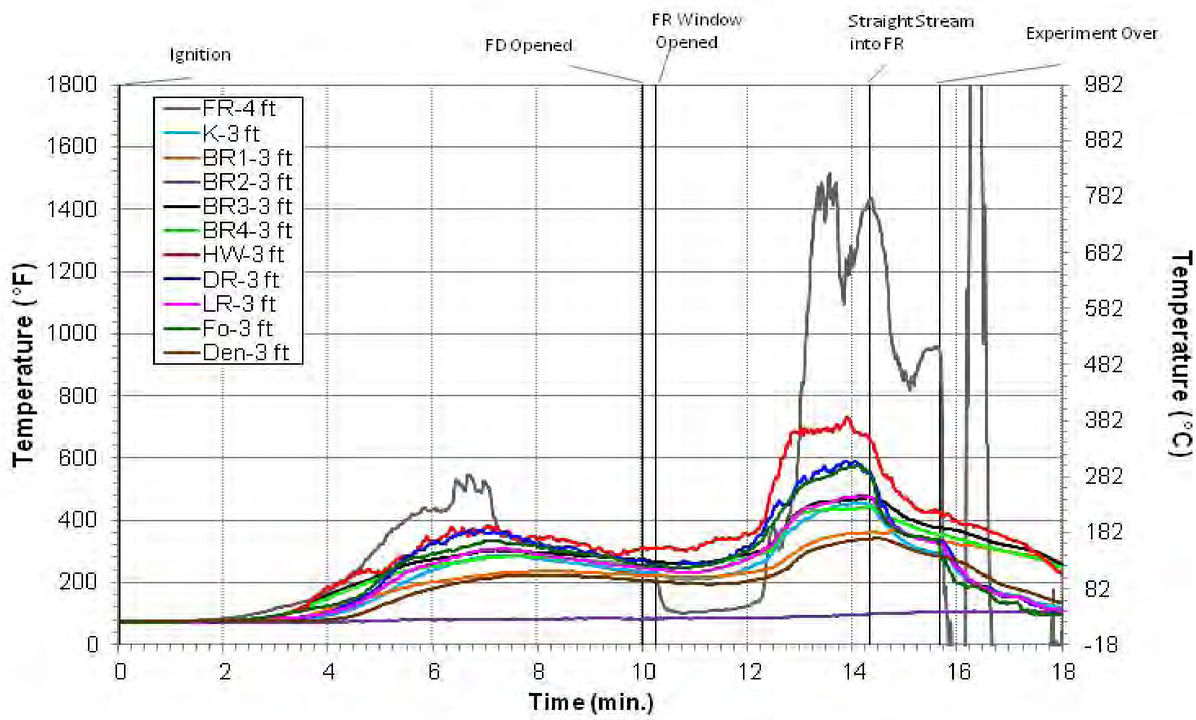


Figure 5.234: Experiment 2 - 3 ft. Temperatures

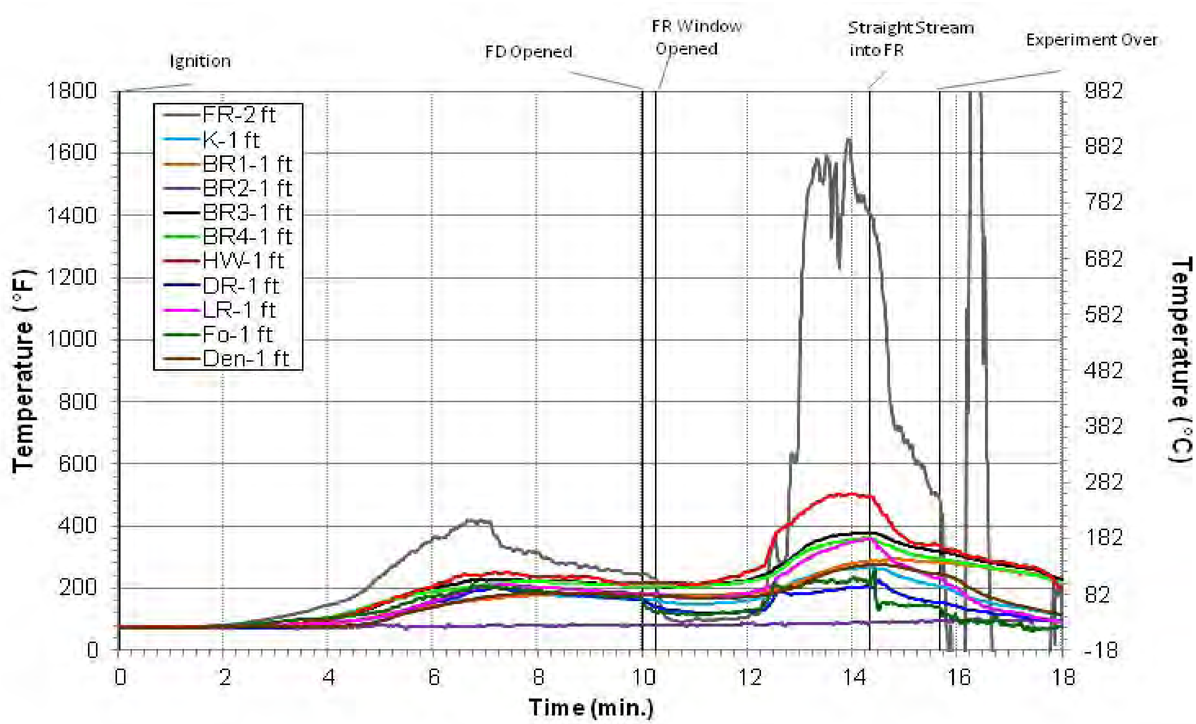


Figure 5.235: Experiment 2 - 1 ft. Temperatures

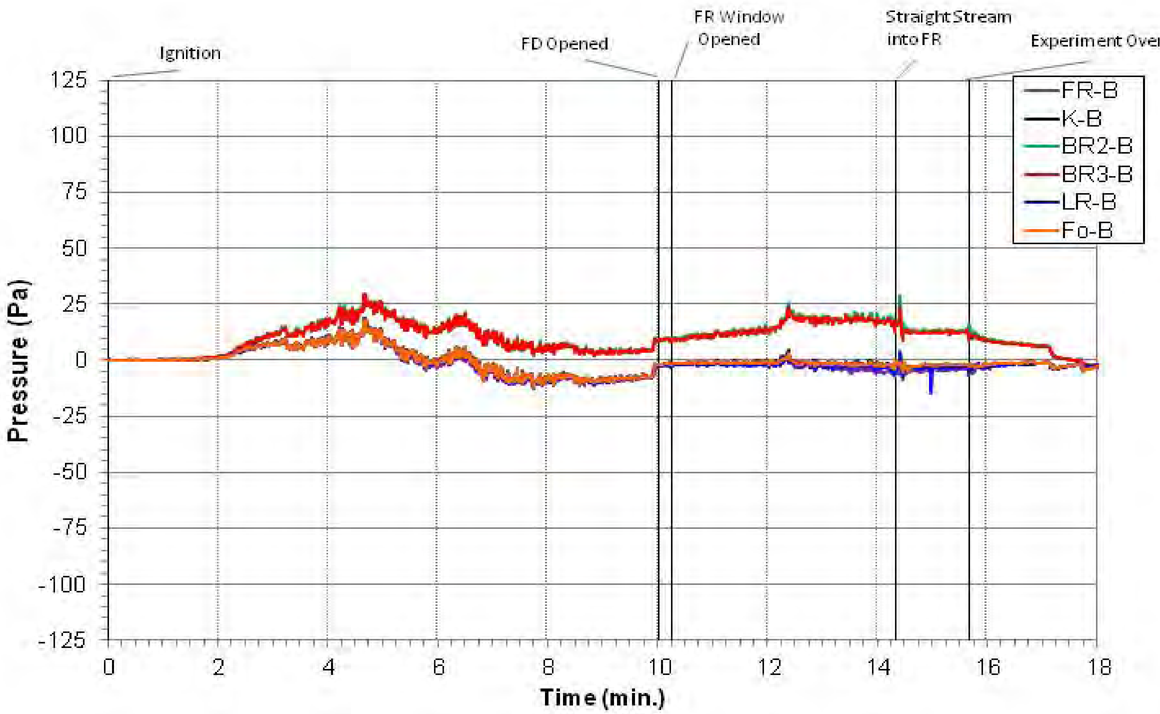


Figure 5.236: Experiment 2 - Bottom Pressure

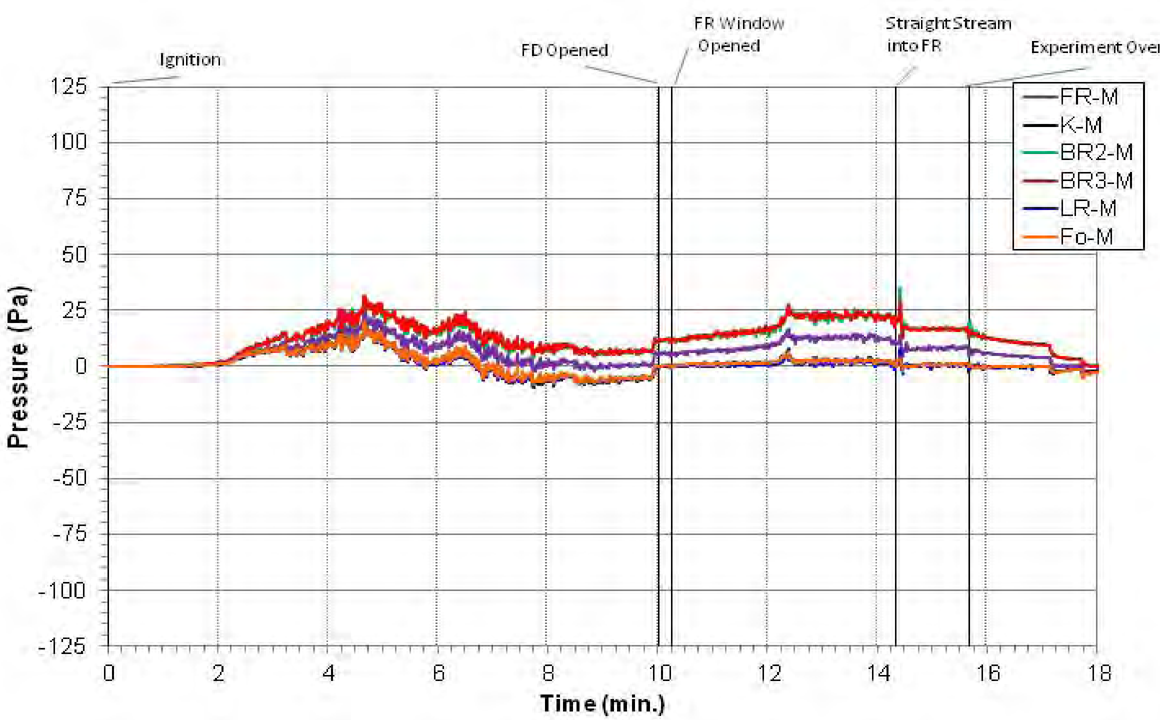


Figure 5.237: Experiment 2 - Middle Pressure

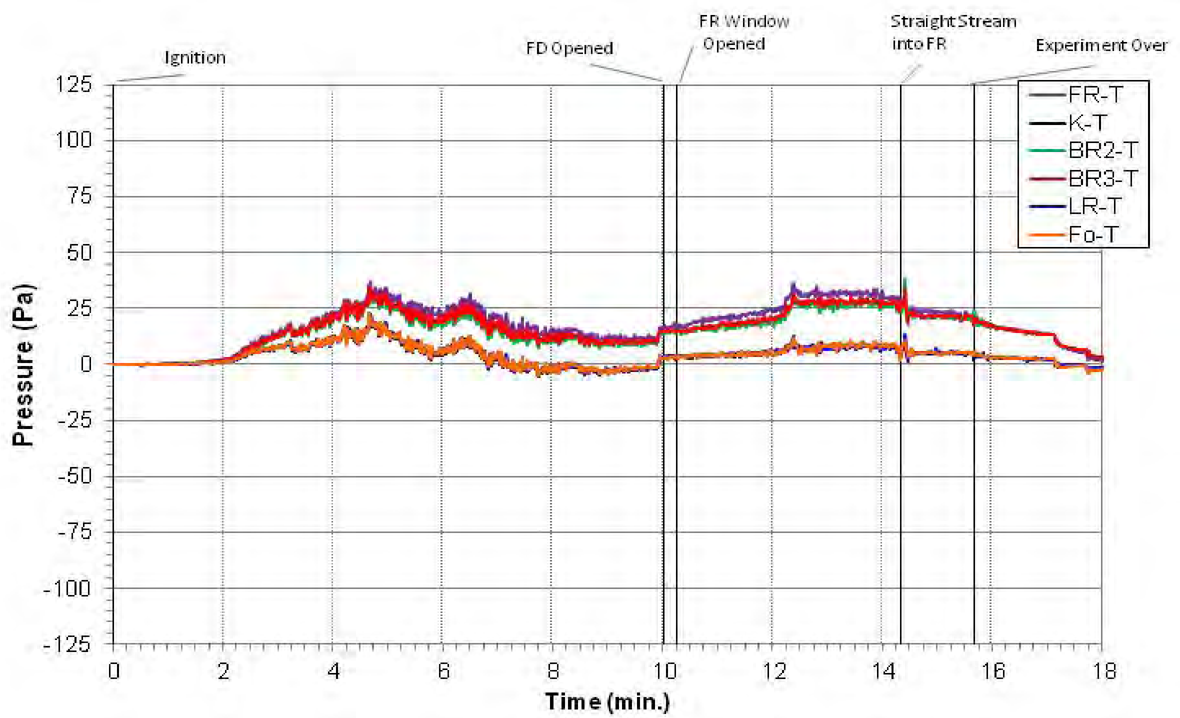


Figure 5.238: Experiment 2 - Top Pressure

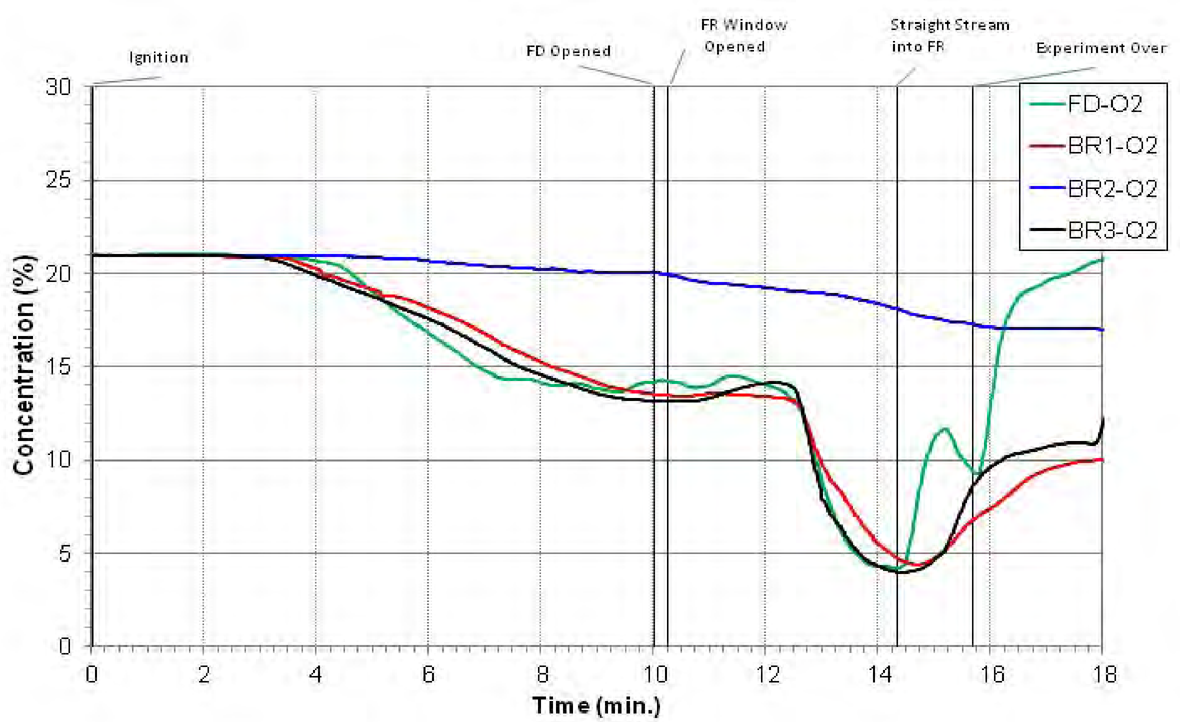


Figure 5.239: Experiment 2 - Oxygen Concentration

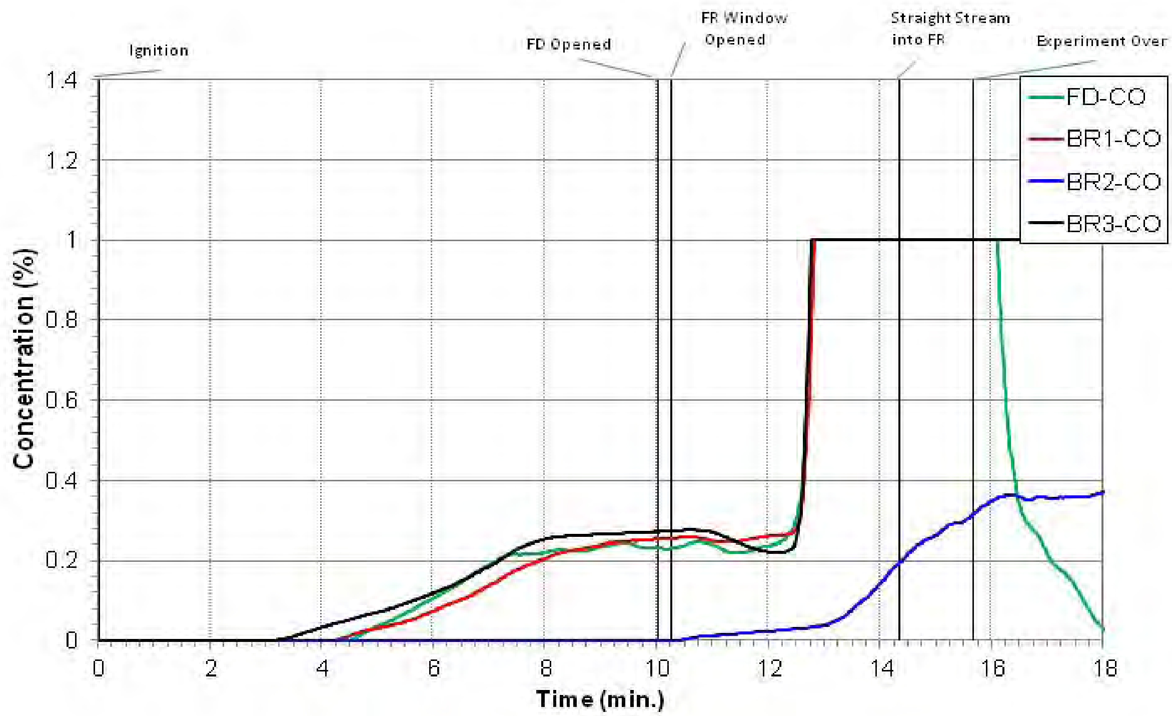


Figure 5.240: Experiment 2 - Carbon Monoxide Concentration

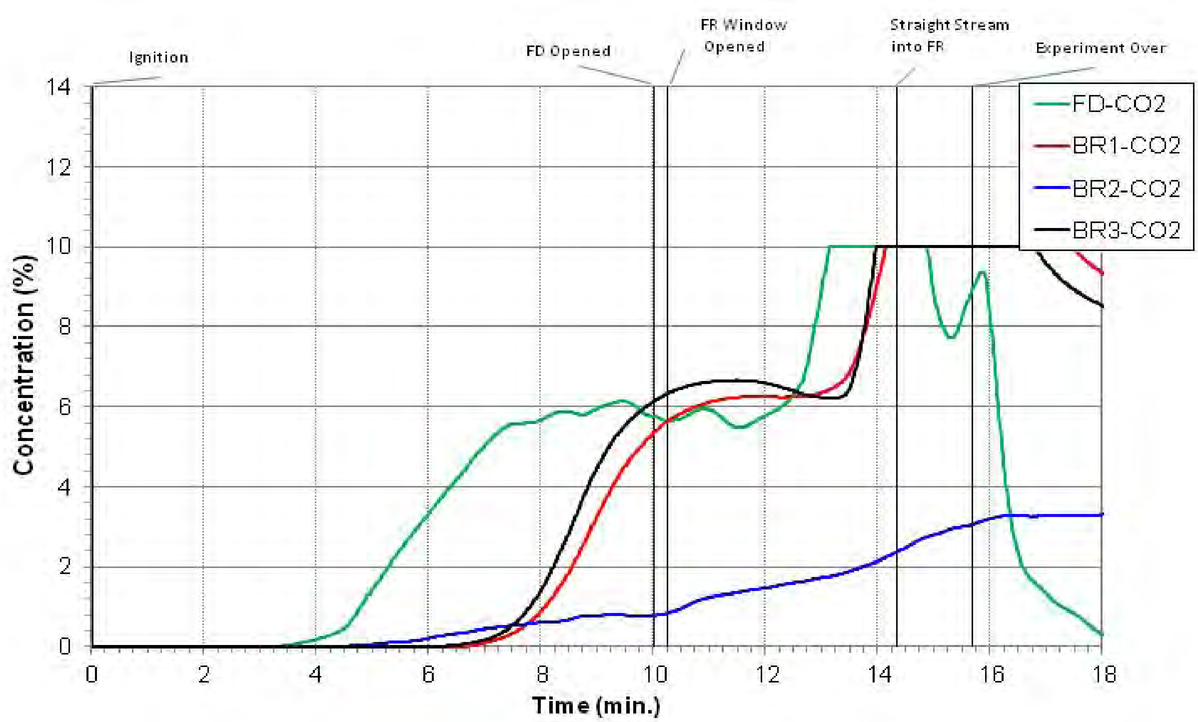


Figure 5.241: Experiment 2 - Carbon Dioxide Concentration

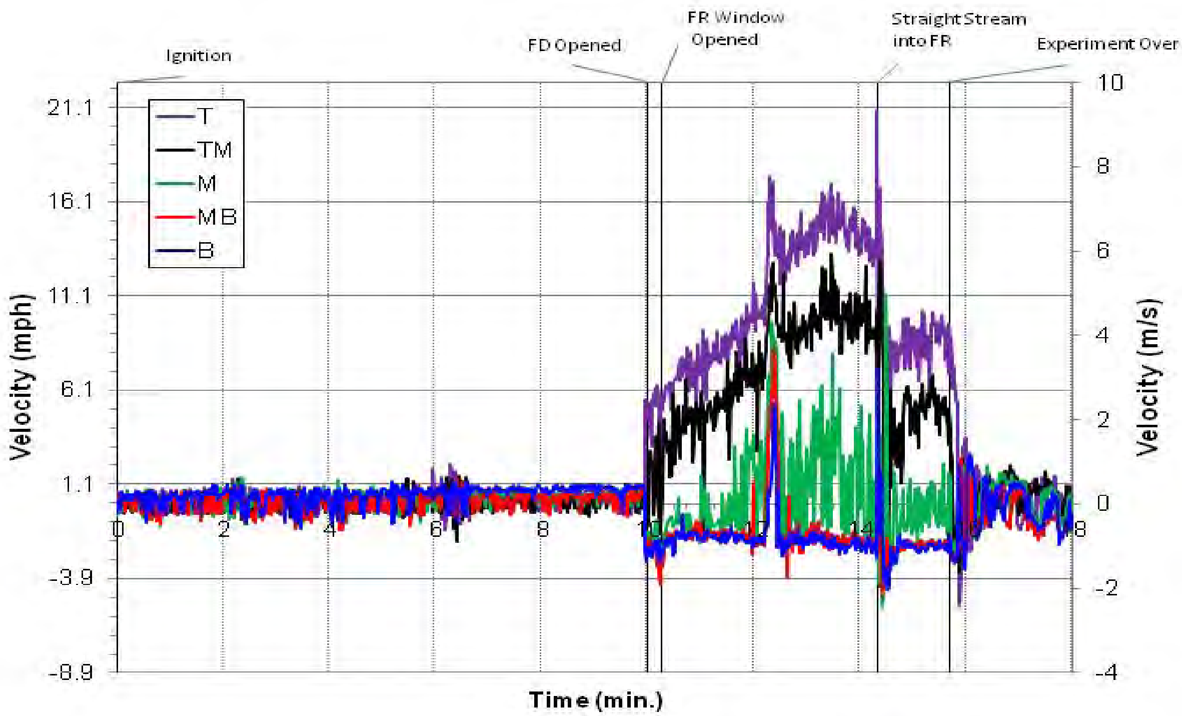


Figure 5.242: Experiment 2 - Front Door Velocity

5.7.2. Experiment 4

Experiment 4 was designed to simulate a fire crew entering the structure and then controlling the door behind them by closing the door to the width of a hoseline, followed by vertically ventilating above the family room fire. Ignition occurred in the family room. The fire was allowed to grow until 10:00, when the front door was opened and then returned to partially open at 10:15. At 13:30, a 4' by 4' hole in the roof was opened and the fire was allowed to grow to near flashover conditions. The front door was fully opened at 19:00, and 13 seconds of water was applied with a combination nozzle positioned in a straight stream pattern. The experiment ended at 20:30, and the crew extinguished the fire. Figure 5.244 through Figure 5.251 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.252 through Figure 5.263 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.18: Experiment 4 Timeline

Time	Description
0:00	Ignition
10:00	Front Door Open
10:15	Front Door Partially Open
13:30	4 ft. by 4 ft. Vertical Vent Open
19:00	Front Door Fully Open, Straight Stream into Front Door
20:30	Final Suppression (End of Experiment)

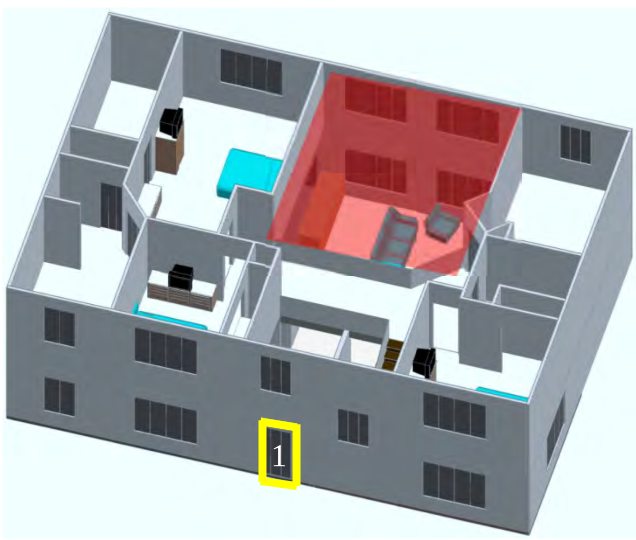


Figure 5.243: Experiment 4 Scenario

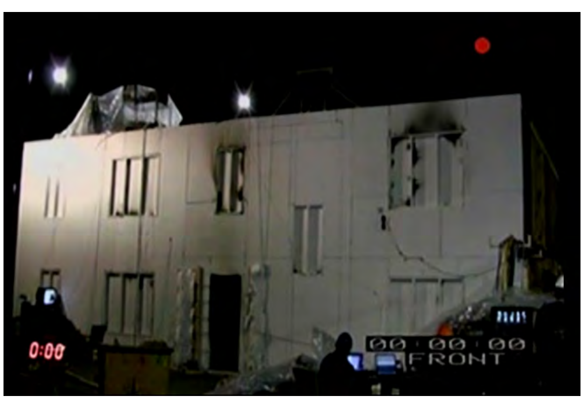


Figure 5.244: Experiment 4 - 0:00

Figure 5.245: Experiment 4 - 7:01

Figure 5.246: Experiment 4 - 10:05

Figure 5.247: Experiment 4 - 10:35

Figure 5.248: Experiment 4 - 13:35

Figure 5.249: Experiment 4 - 16:28

Figure 5.250: Experiment 4 - 19:03

Figure 5.251: Experiment 4 - 19:50

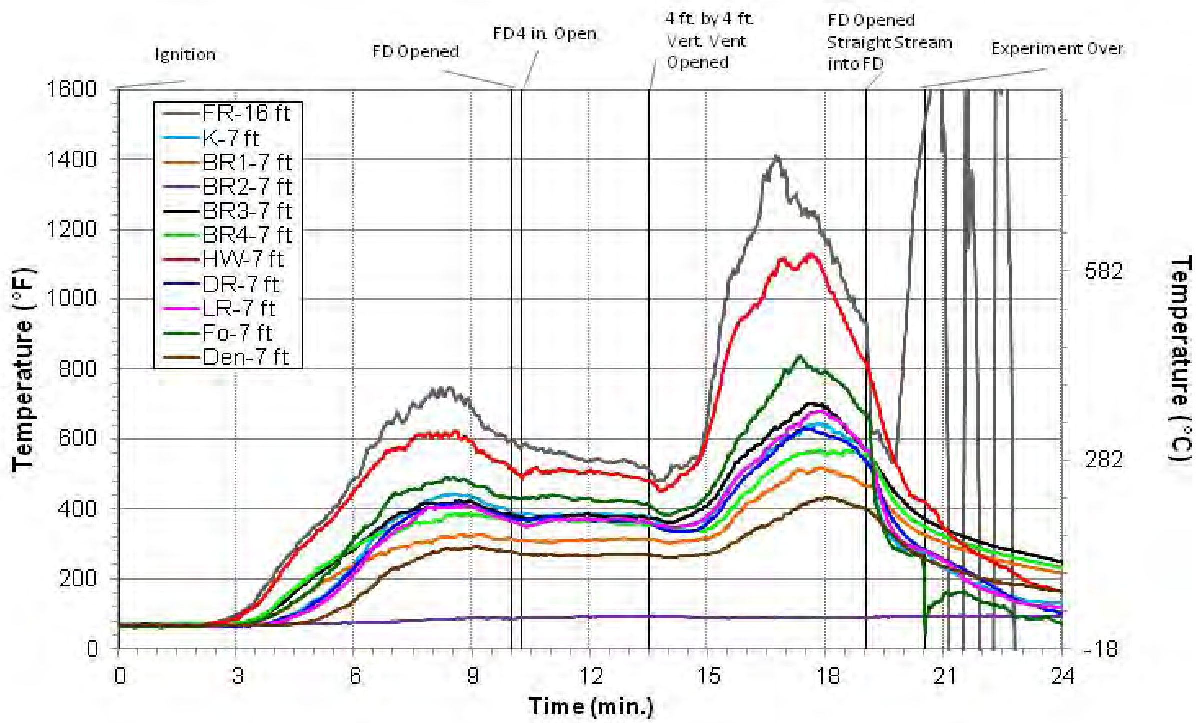


Figure 5.252: Experiment 4 - 7 ft. Temperatures

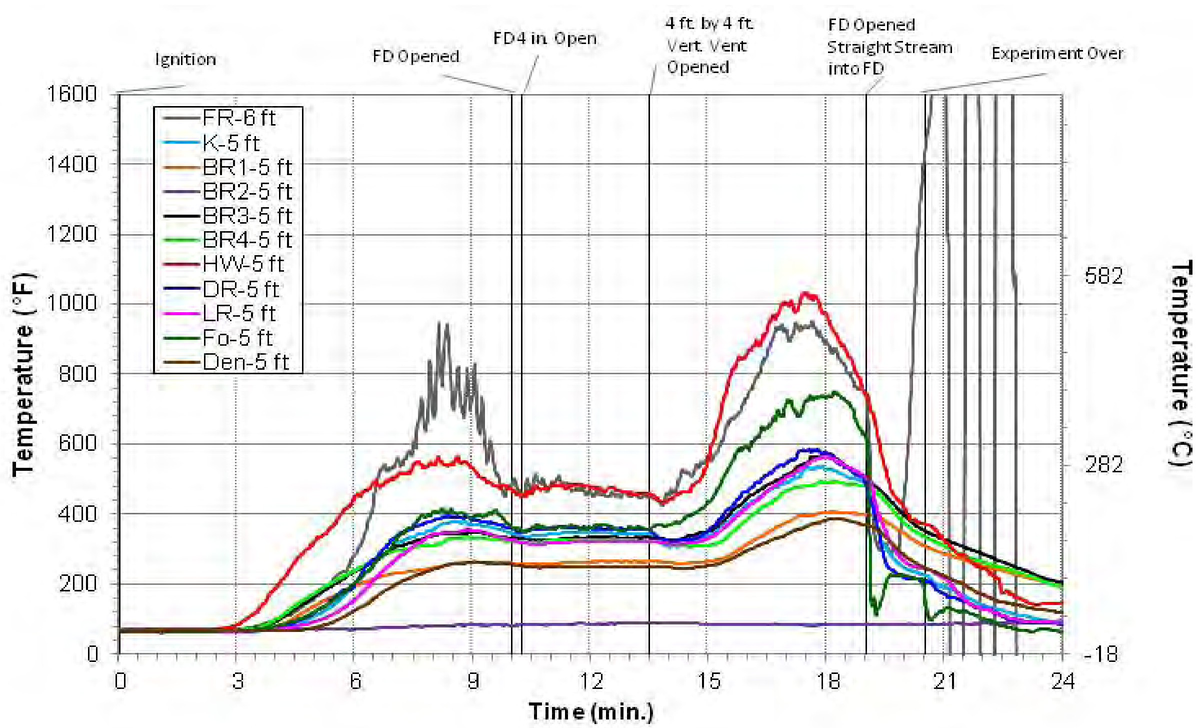


Figure 5.253: Experiment 4 - 5 ft. Temperatures

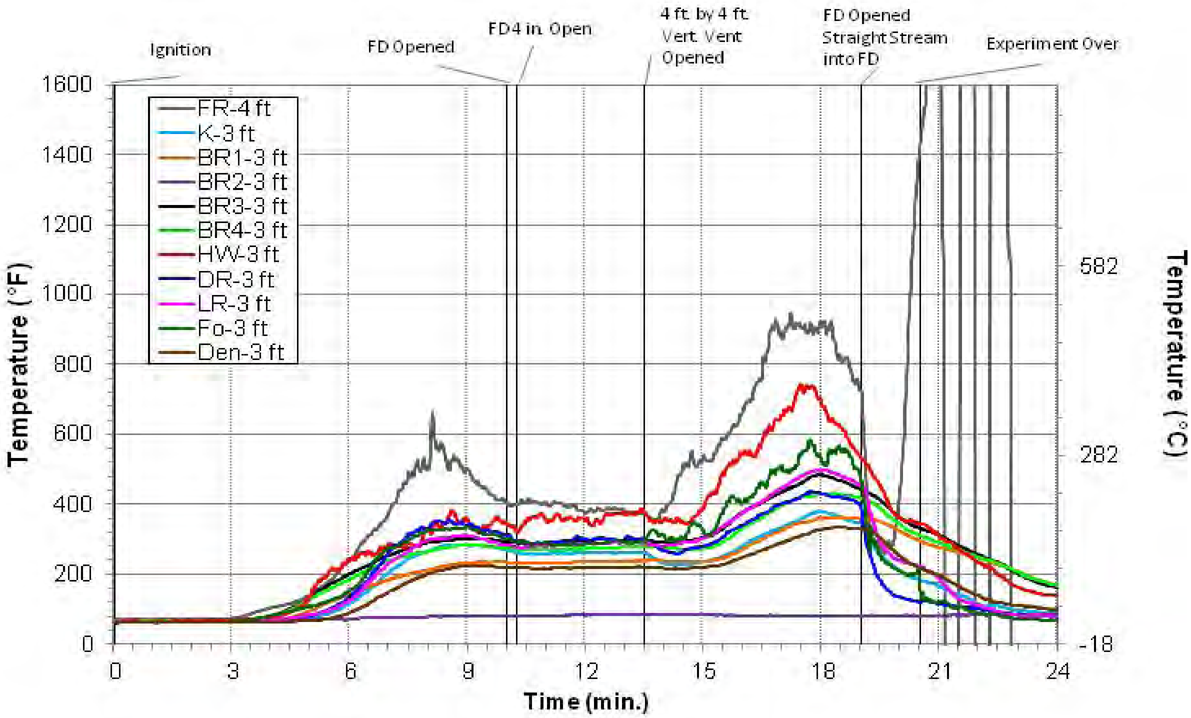


Figure 5.254: Experiment 4 - 3 ft. Temperatures

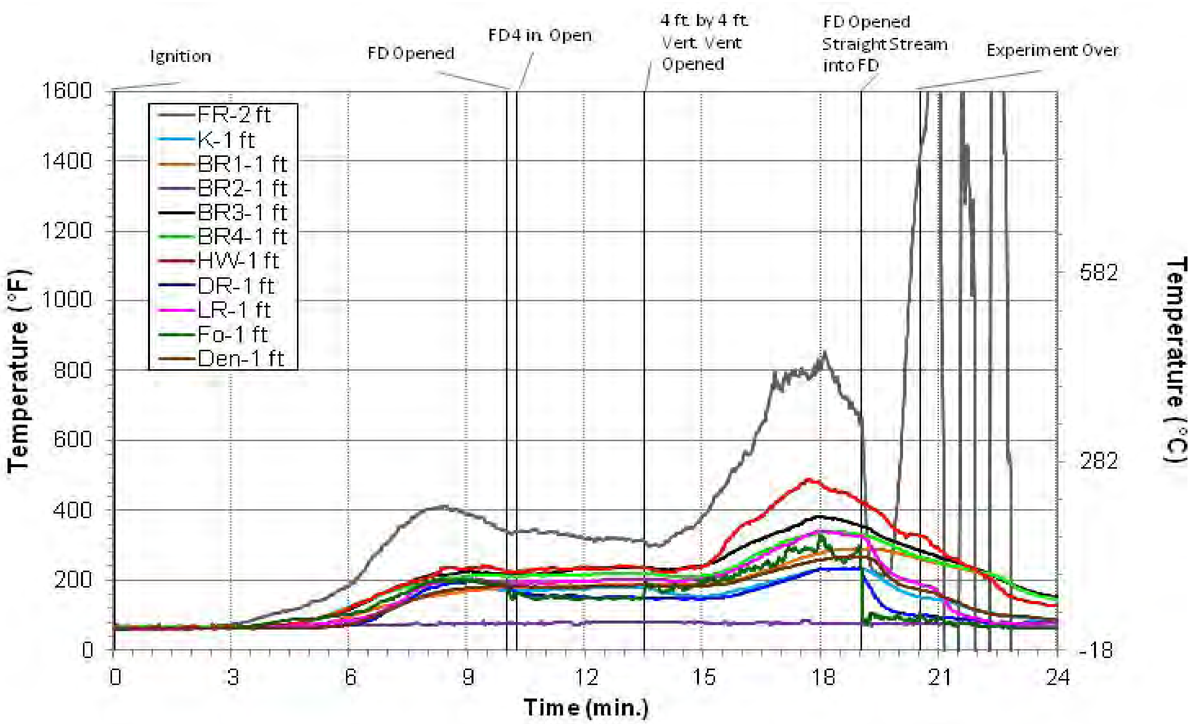


Figure 5.255: Experiment 4 - 1 ft. Temperatures

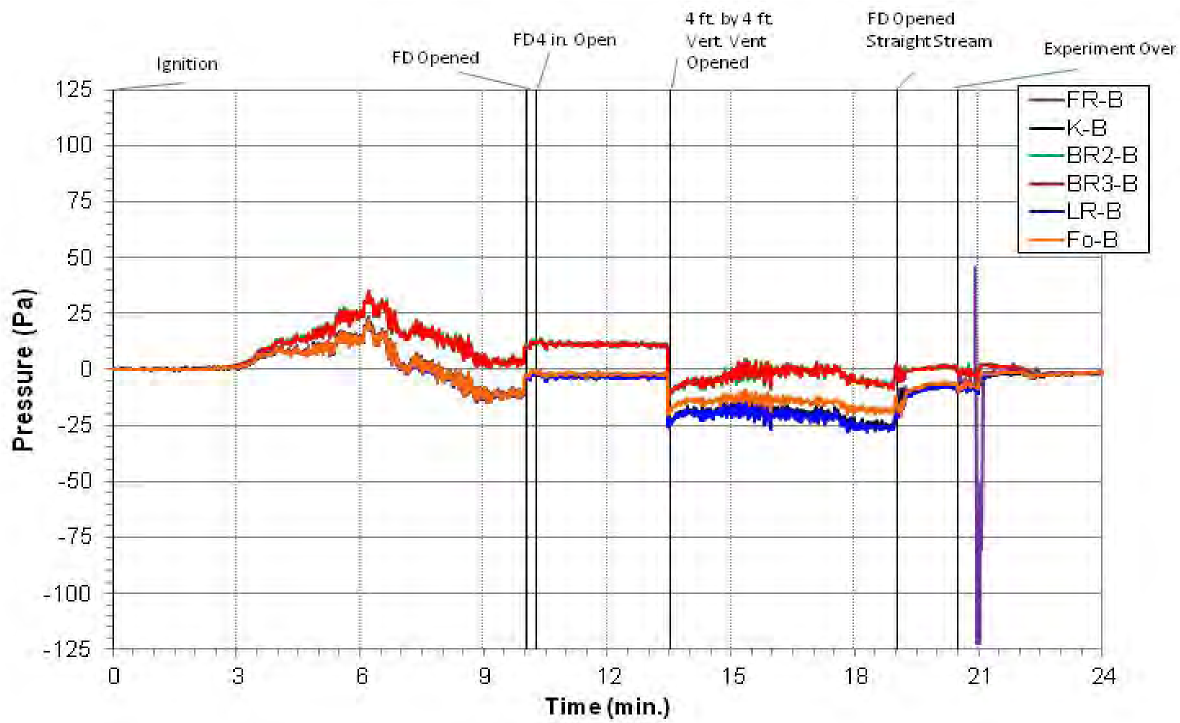


Figure 5.256: Experiment 4 - Bottom Pressure

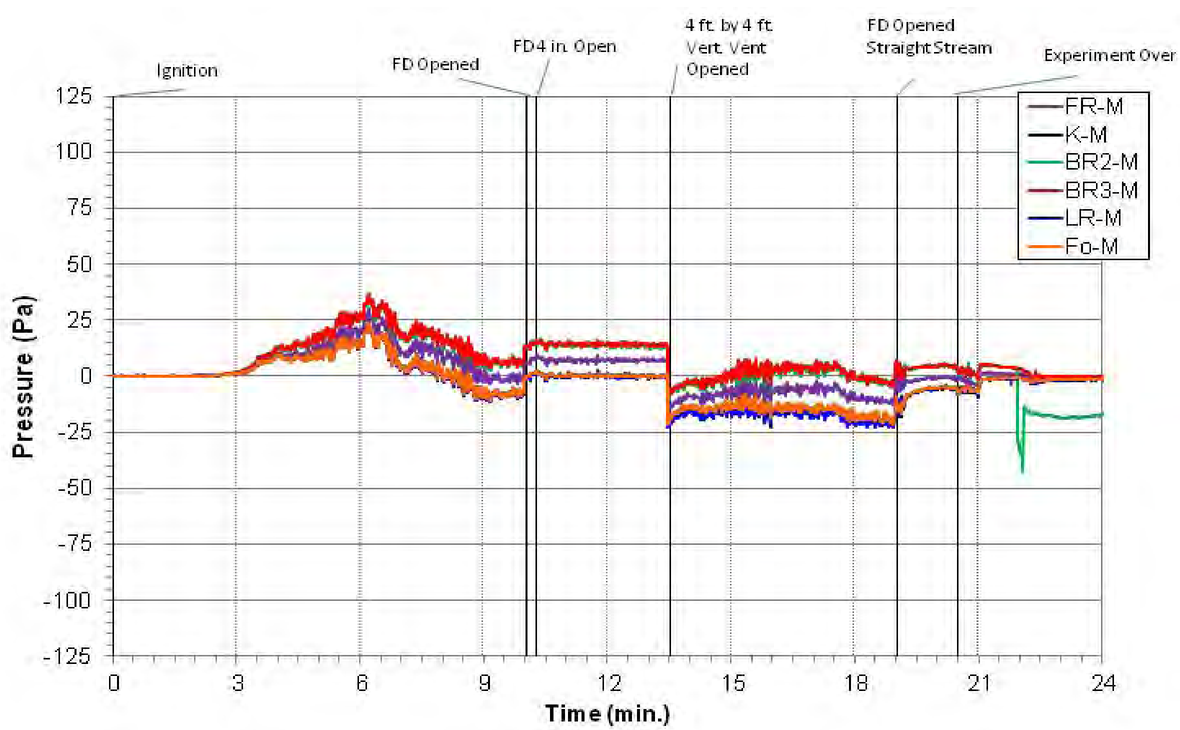


Figure 5.257: Experiment 4 - Middle Pressure

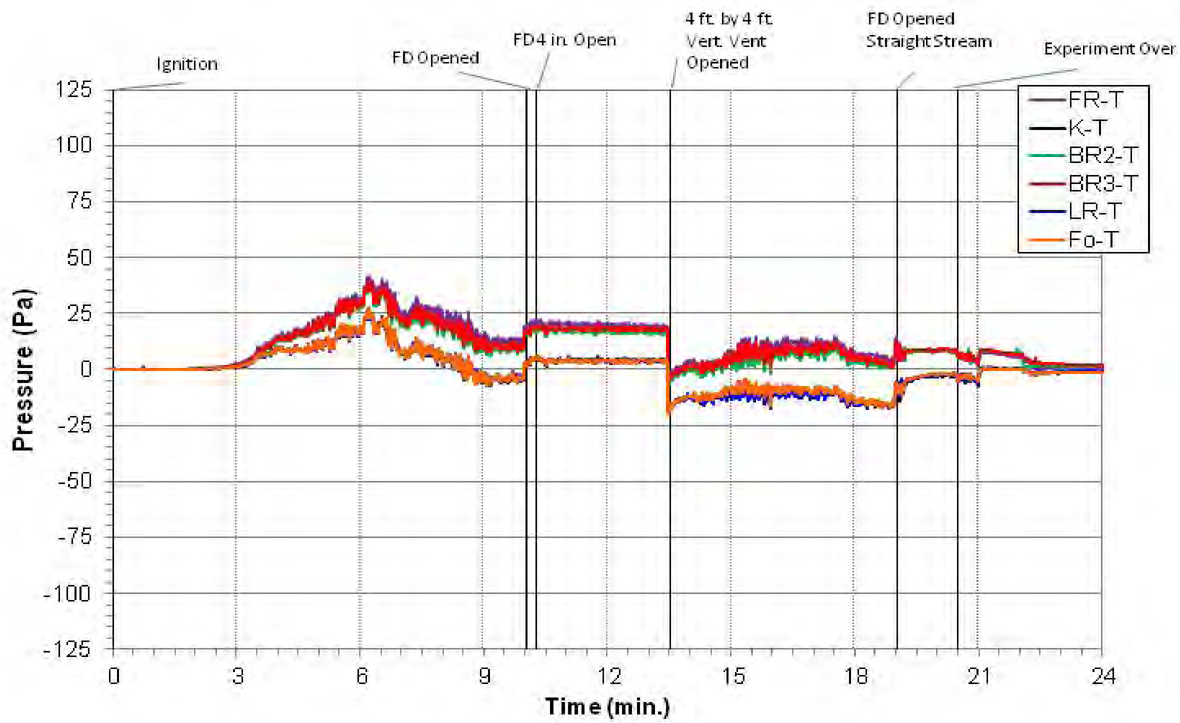


Figure 5.258: Experiment 4 - Top Pressure

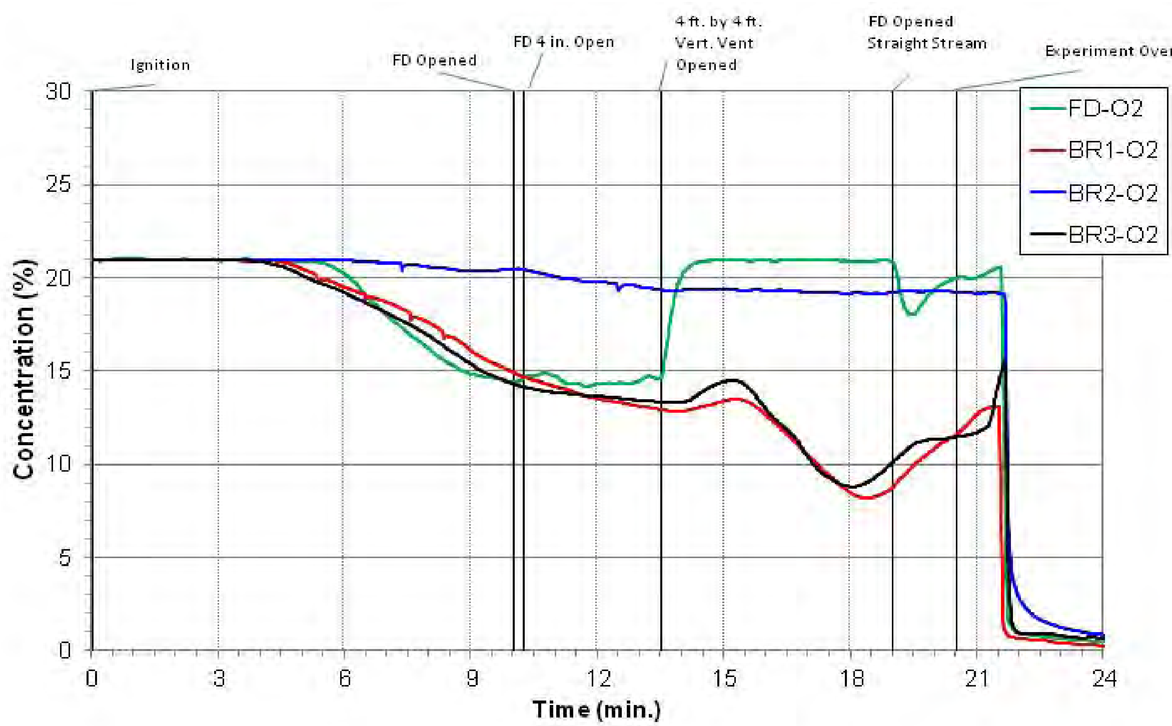


Figure 5.259: Experiment 4 - Oxygen Concentration

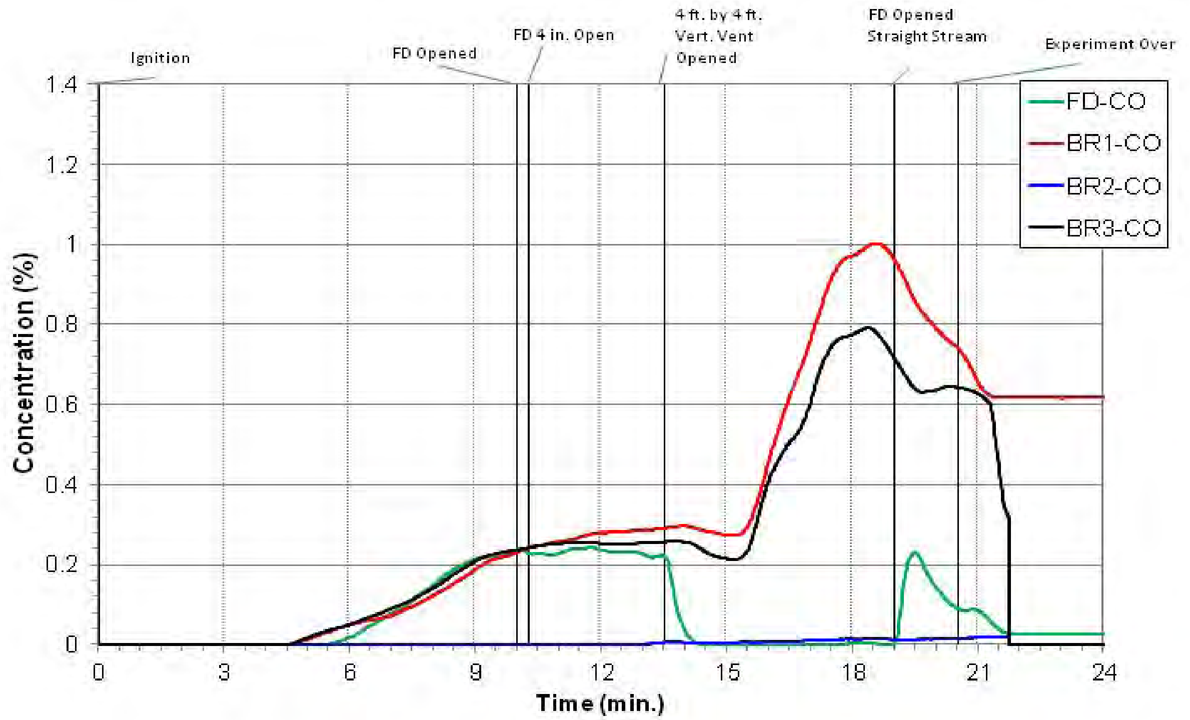


Figure 5.260: Experiment 4 - Carbon Monoxide Concentration

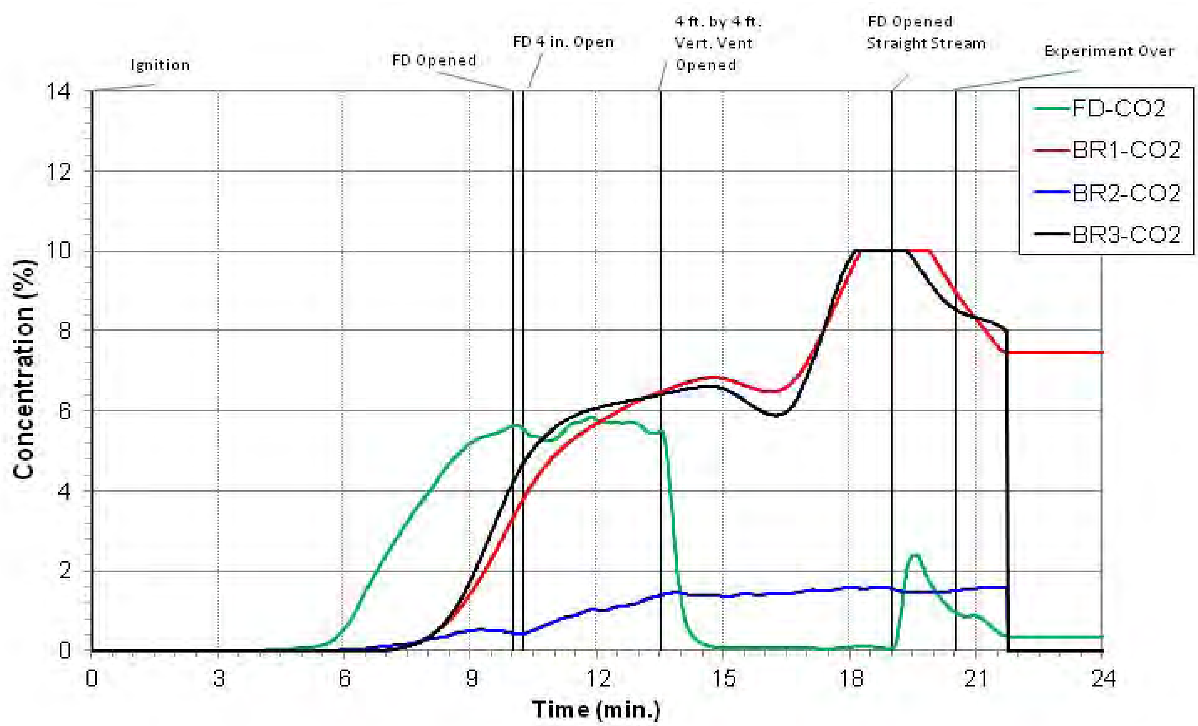


Figure 5.261: Experiment 4 - Carbon Dioxide Concentration

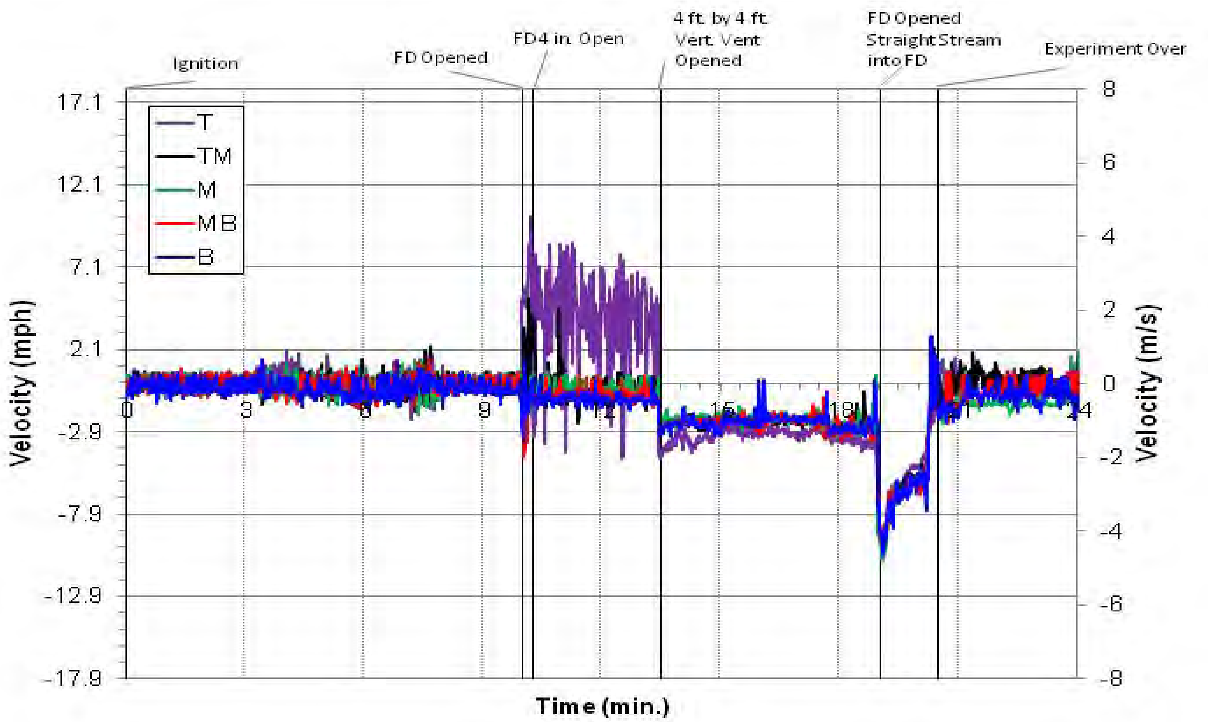


Figure 5.262: Experiment 4 - Front Door Velocity

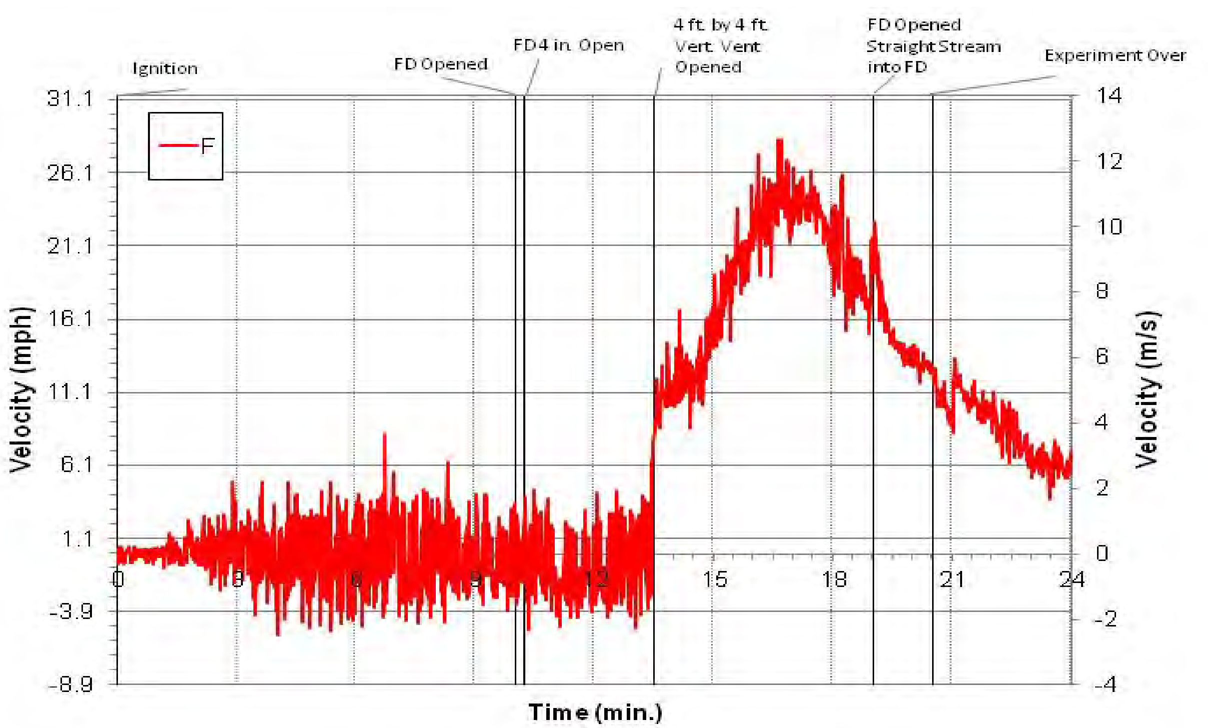


Figure 5.263: Experiment 4 - Roof Vent Velocity

5.7.3. Experiment 6

Experiment 6 was designed to simulate a crew ventilating the front door, chocking it completely open, and then ventilating vertically above the fire. Ignition occurred in the family room. The fire was allowed to grow until 10:00, when the front door was opened. At 11:45, the 4’ by 4’ hole in the roof was opened. The fire was allowed to grow to post-flashover conditions, and at 13:45, 15 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern. The experiment ended at 15:25, and the crew extinguished the fire. Figure 5.265 through Figure 5.271 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.272 through Figure 5.283 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.19: Experiment 6 Timeline

Time	Description
0:00	Ignition
10:00	Front Door Open
11:45	4 ft. by 4 ft. Vertical Vent Open
13:45	Straight Stream into Front Door
15:25	Final Suppression (End of Experiment)

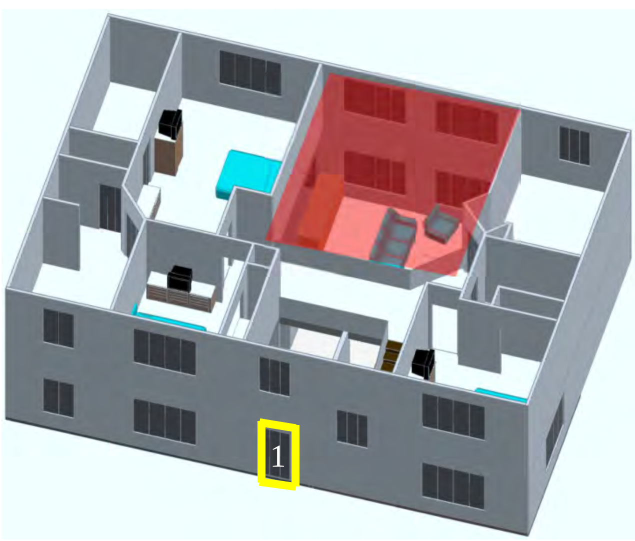


Figure 5.264: Experiment 6 Scenario

Figure 5.265: Experiment 6 - 0:00

Figure 5.266: Experiment 6 - 7:00

Figure 5.267: Experiment 6 - 10:05


Figure 5.268: Experiment 6 - 11:51


Figure 5.269: Experiment 6 - 12:11

Figure 5.270: Experiment 6 - 13:48

Figure 5.271: Experiment 6 - 14:30

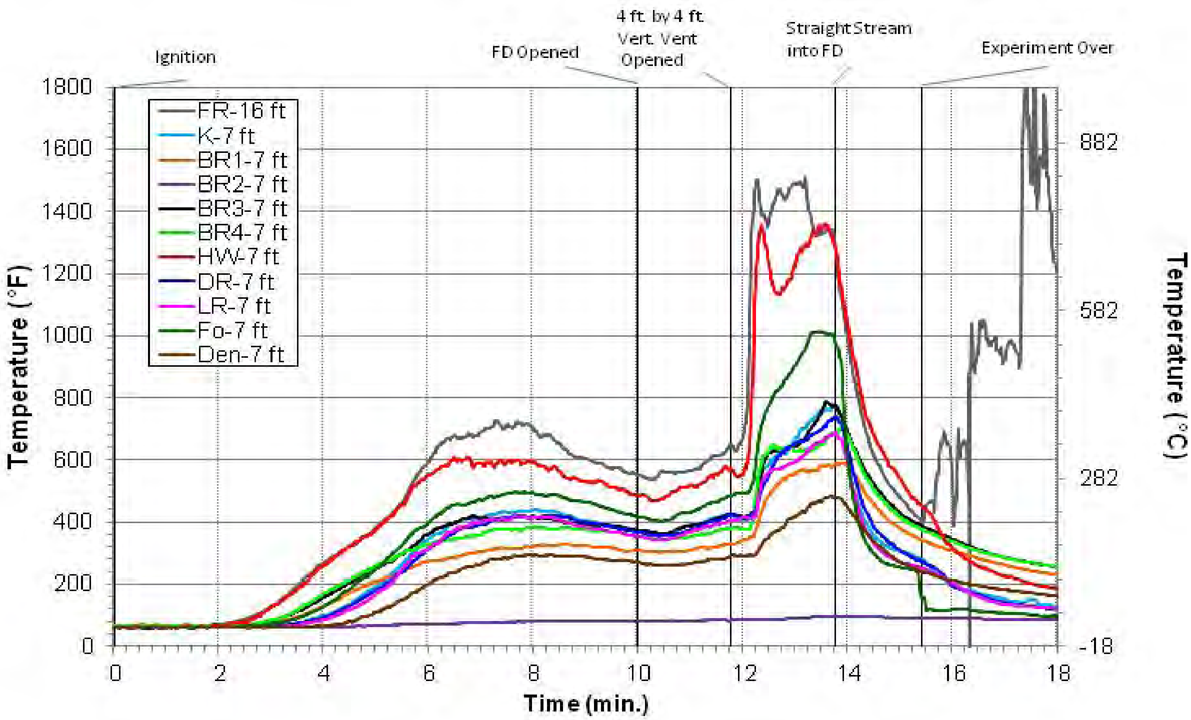


Figure 5.272: Experiment 6 - 7 ft. Temperatures

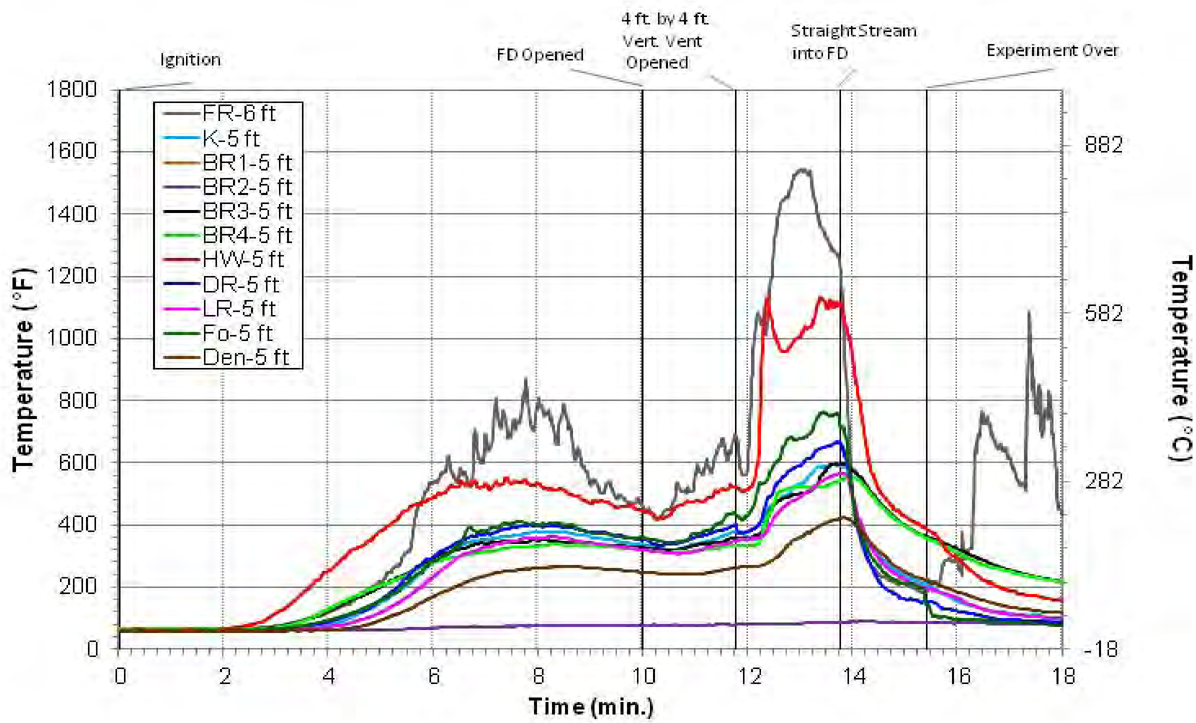


Figure 5.273: Experiment 6 - 5 ft. Temperatures

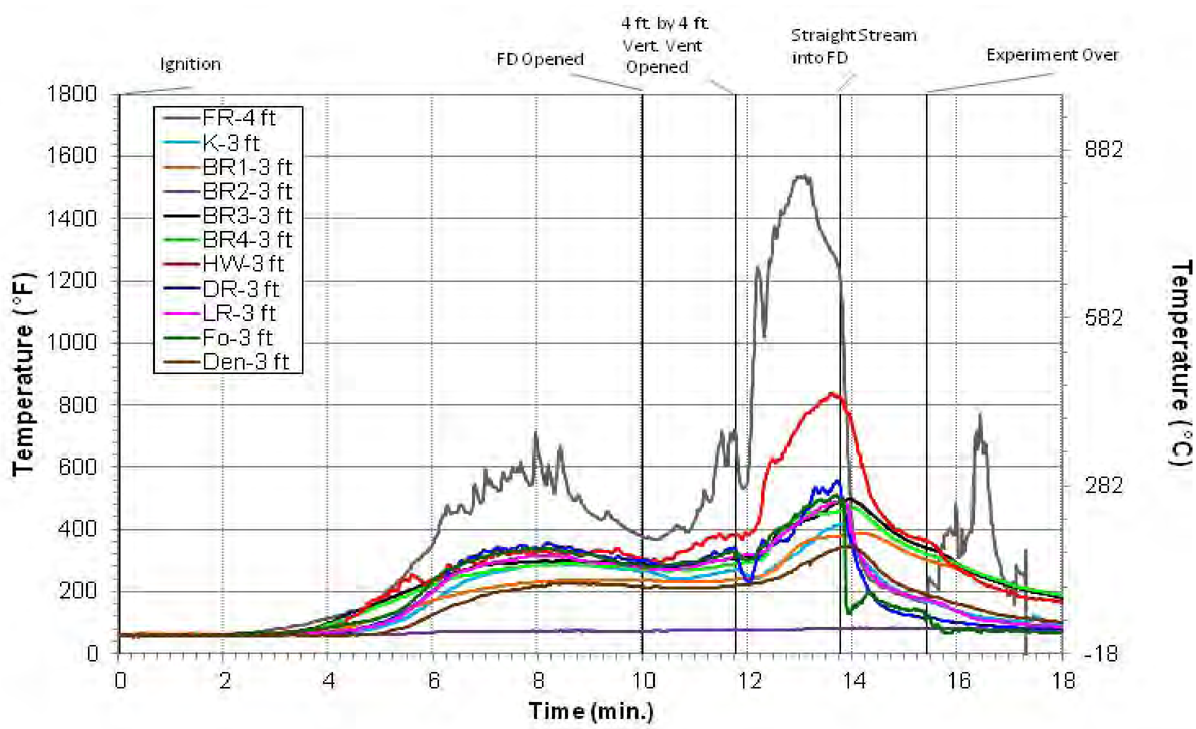


Figure 5.274: Experiment 6 - 3 ft. Temperatures

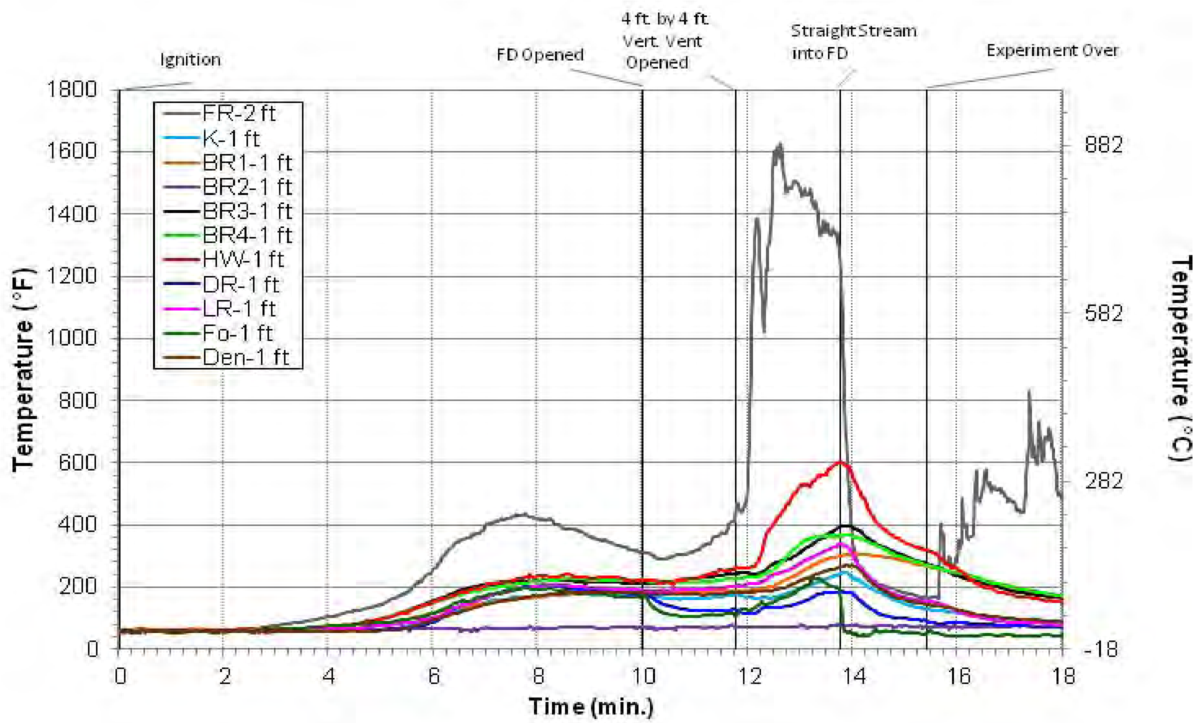


Figure 5.275: Experiment 6 - 1 ft. Temperatures

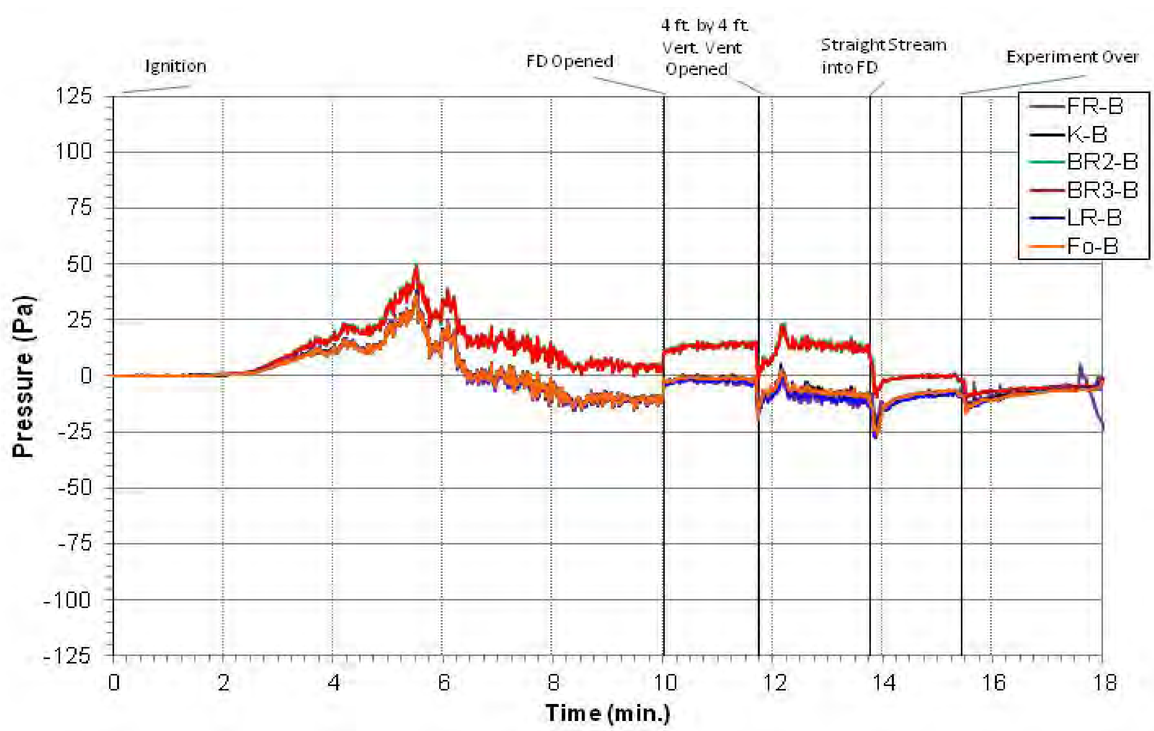


Figure 5.276: Experiment 6 - Bottom Pressure

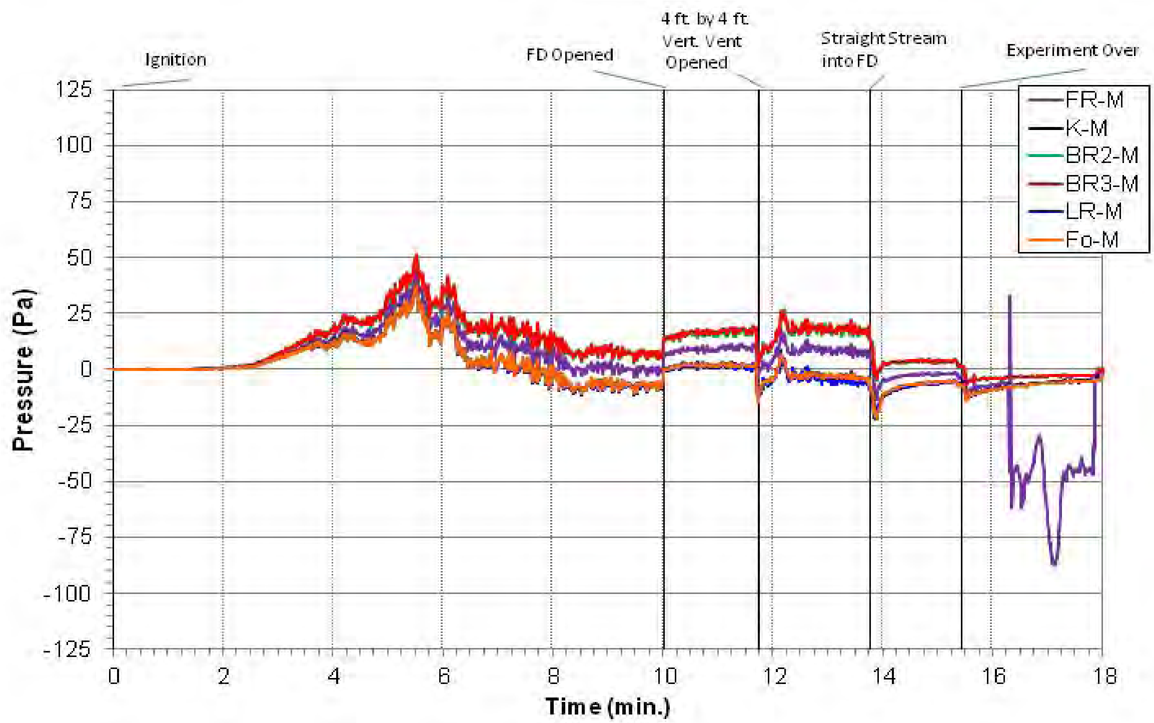


Figure 5.277: Experiment 6 - Middle Pressure

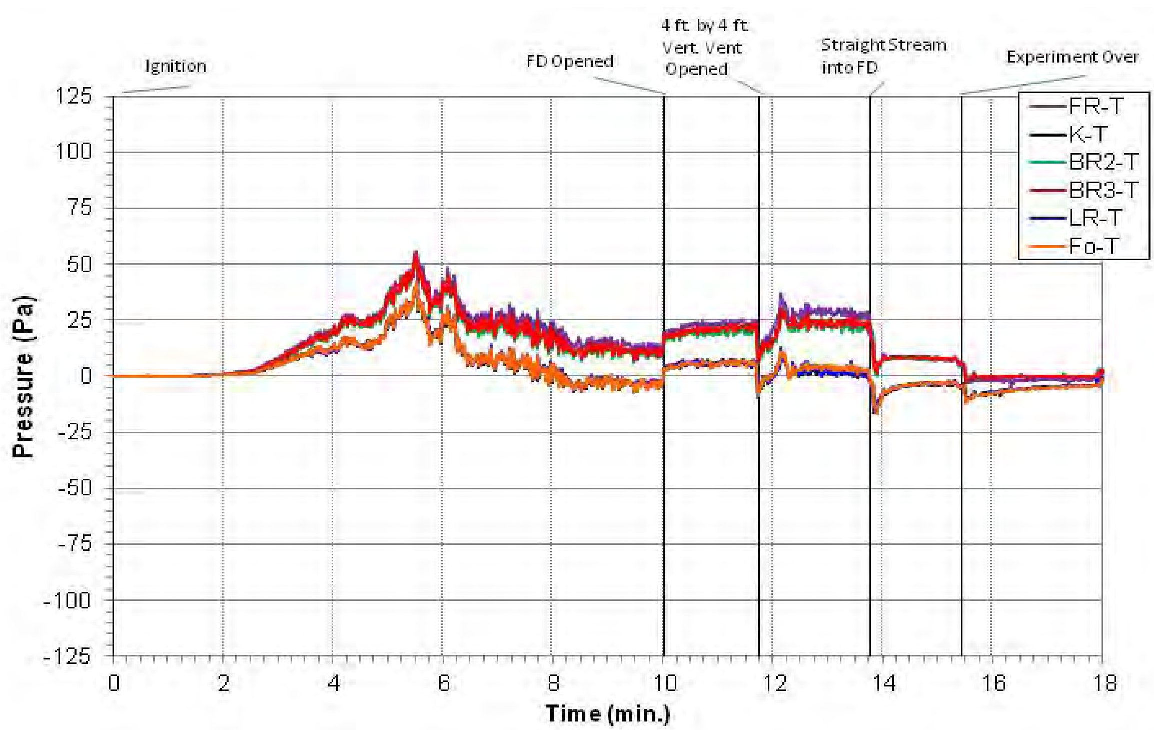


Figure 5.278: Experiment 6 - Top Pressure

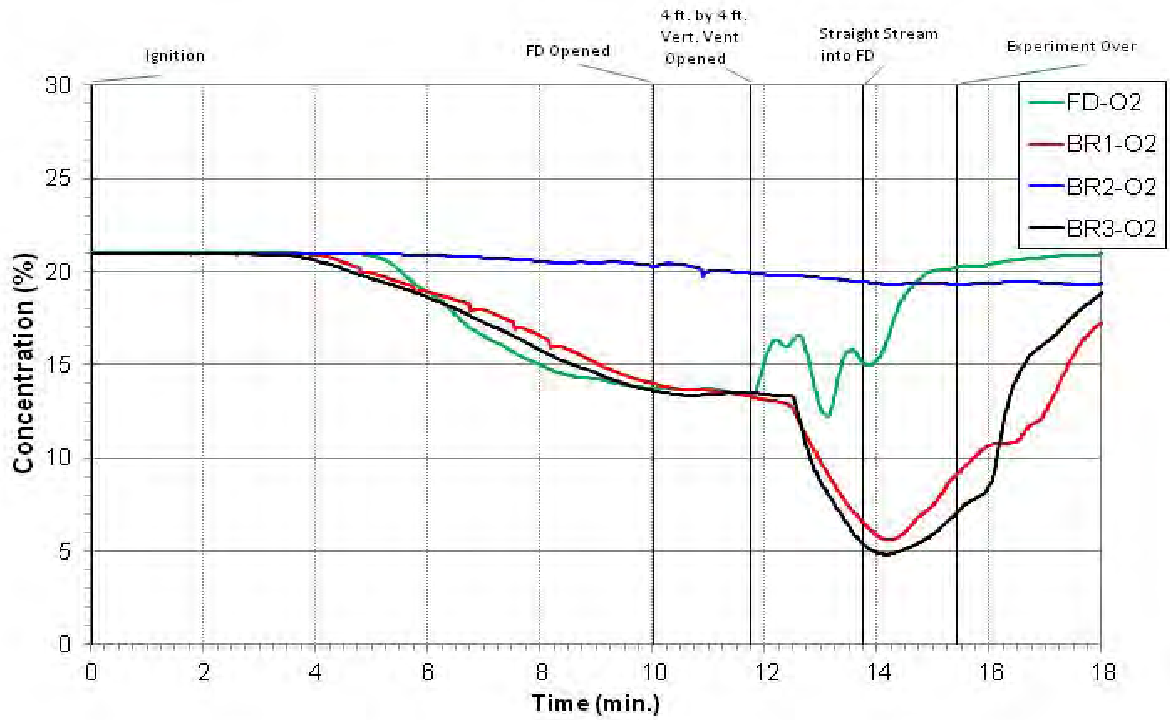


Figure 5.279: Experiment 6 - Oxygen Concentration

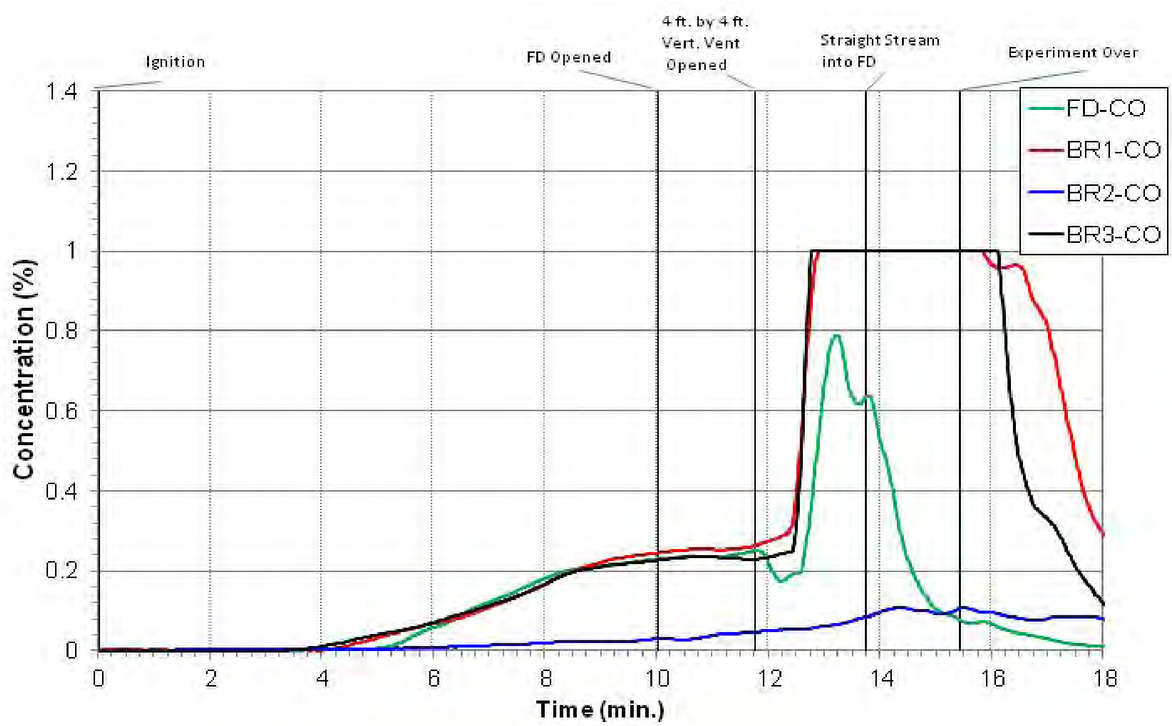


Figure 5.280: Experiment 6 - Carbon Monoxide Concentration

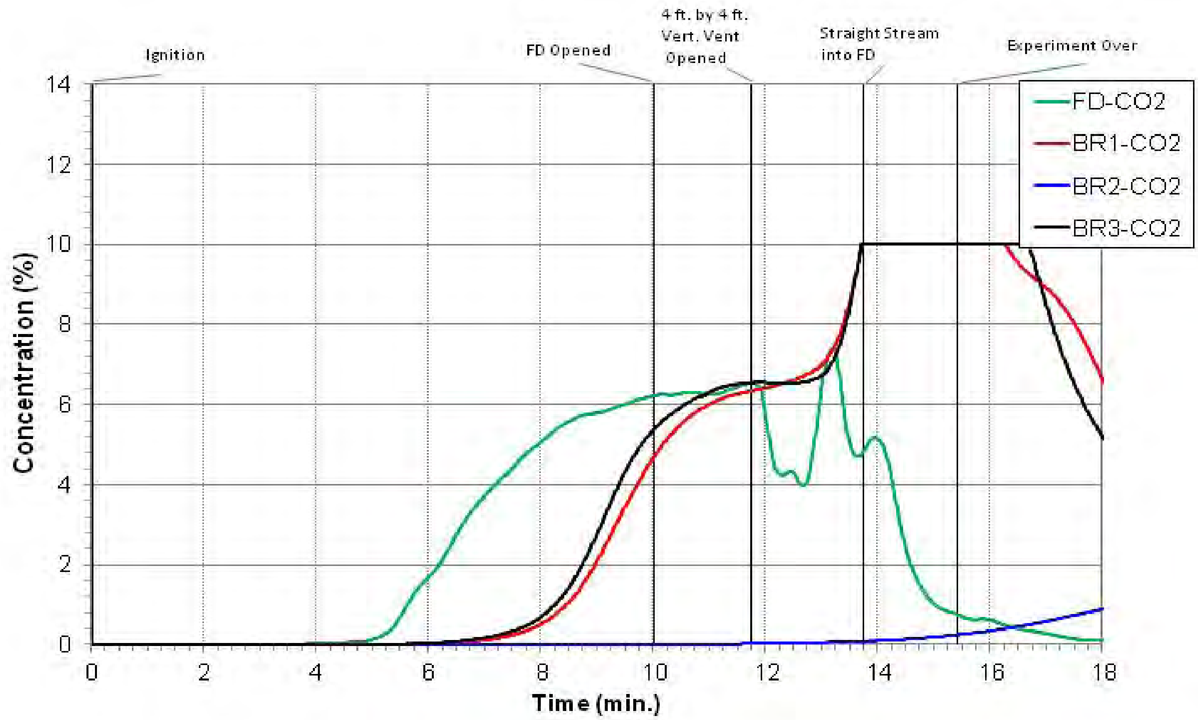


Figure 5.281: Experiment 6 - Carbon Dioxide Concentration

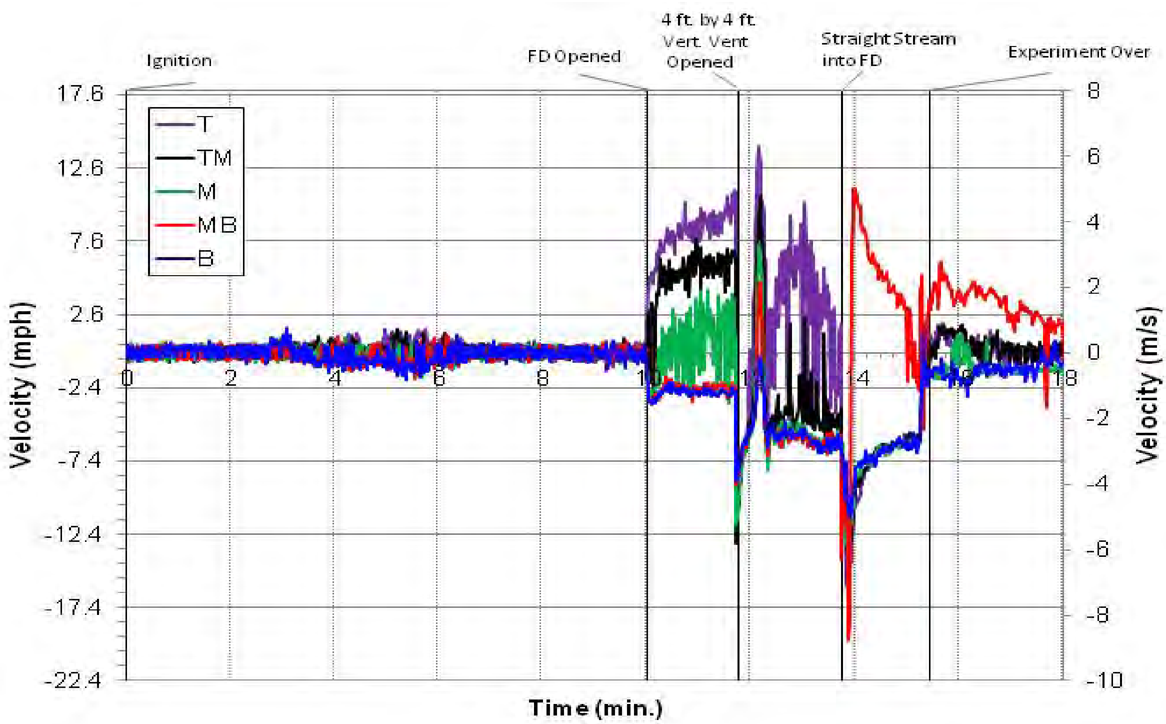


Figure 5.282: Experiment 6 - Front Door Velocity

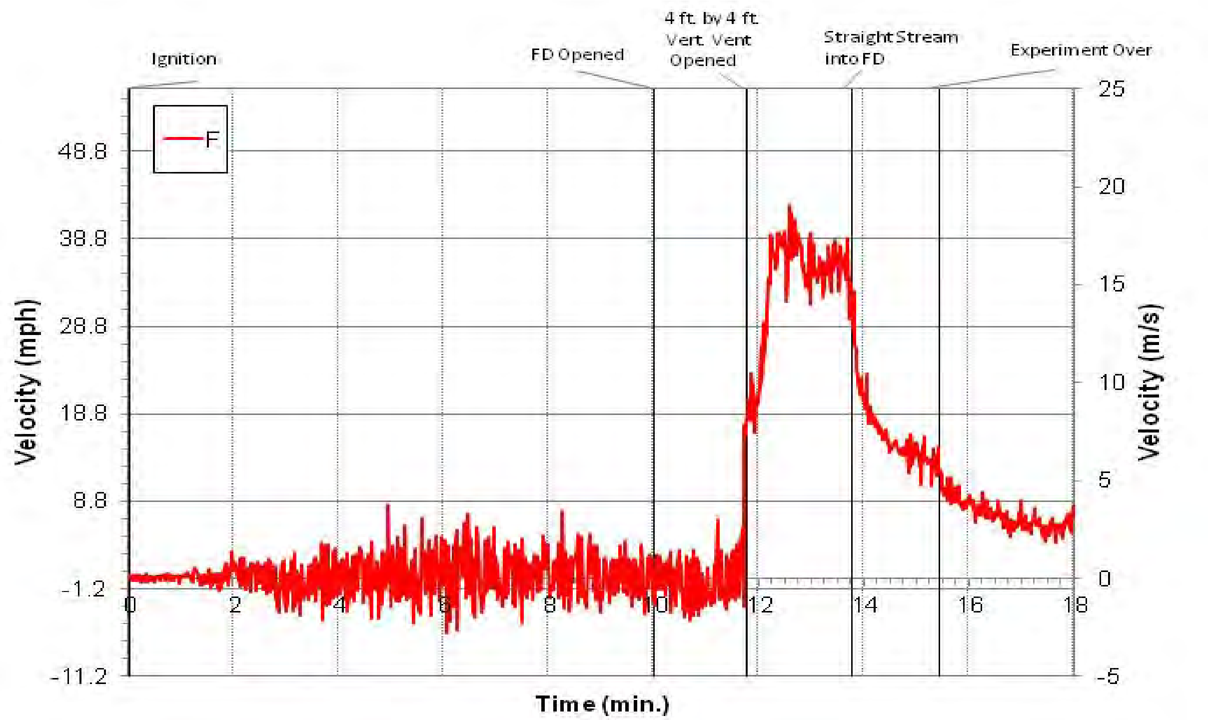


Figure 5.283: Experiment 6 - Roof Vent Velocity

5.7.4. Experiment 8

Experiment 8 was designed to simulate a crew ventilating the front door, chocking it open, and later ventilating vertically a hole twice the size of the hole in Experiment 6 (4 ft by 8 ft total). Ignition occurred in the living room.. Ignition occurred in the family room. The fire was allowed to grow until 10:00, when the front door was opened. At 11:15, a 4' by 8' hole in the roof was opened, and the fire was allowed to then continue to grow to post-flashover conditions. At 13:00, 15 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern. The experiment ended at 15:05, and the crew extinguished the fire. Figure 5.285 through Figure 5.291 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.292 through Figure 5.303 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.20: Experiment 8 Timeline

Time	Description
0:00	Ignition Occurs
10:00	Front Door Open
11:15	4 ft. by 8 ft. Vertical Vent Open
13:00	Straight Stream into Front Door
15:05	Final Suppression (End of Experiment)

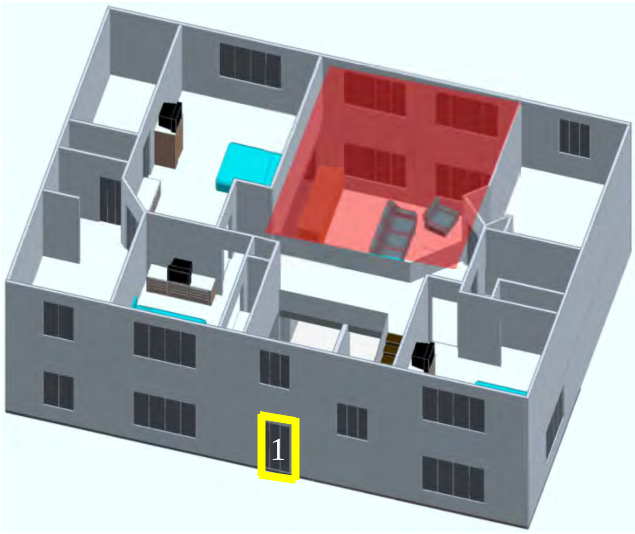


Figure 5.284: Experiment 8 Scenario

Figure 5.285: Experiment 8 - 0:00

Figure 5.286: Experiment 8 - 7:01

Figure 5.287: Experiment 8 - 10:05

Figure 5.288: Experiment 8 - 11:25

Figure 5.289: Experiment 8 - 12:20

Figure 5.290: Experiment 8 - 13:01

Figure 5.291: Experiment 8 - 13:45

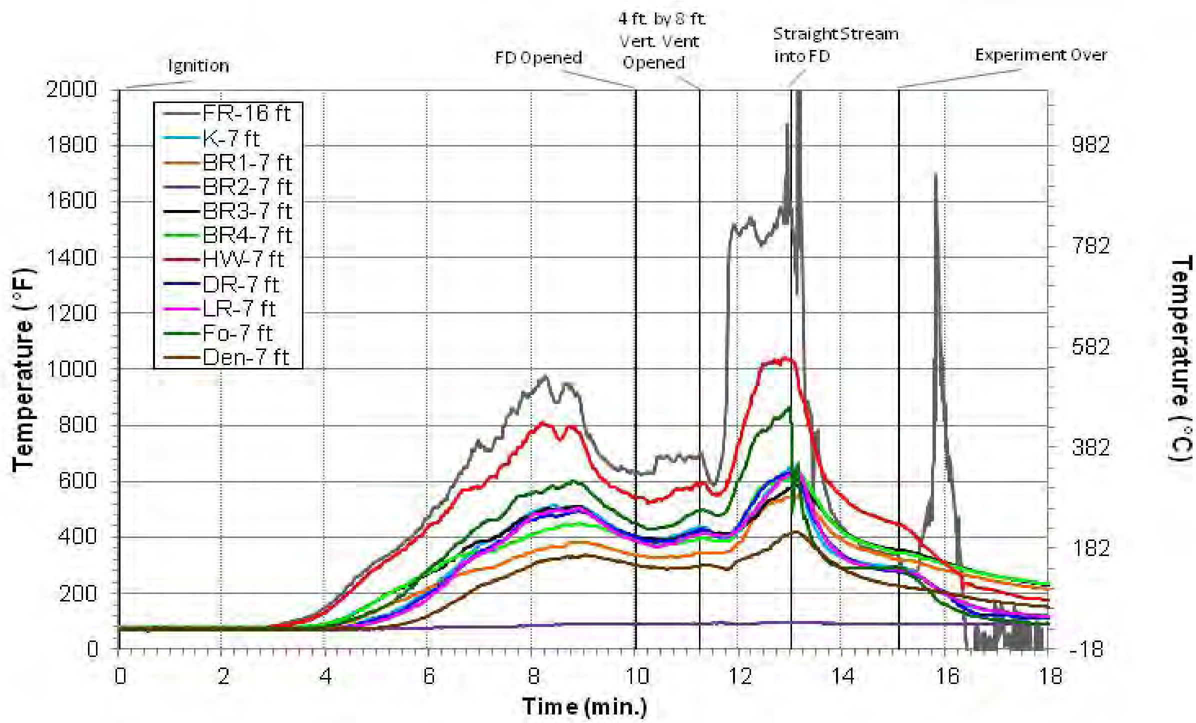


Figure 5.292: Experiment 8 - 7 ft. Temperatures

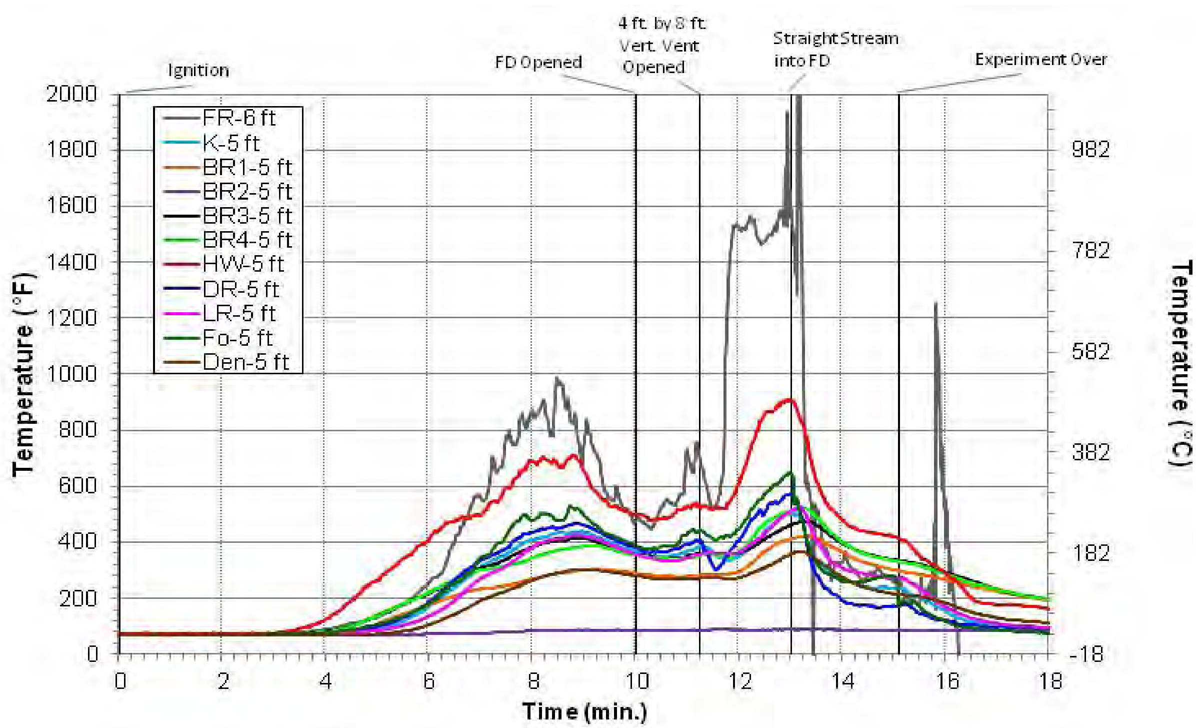


Figure 5.293: Experiment 8 - 5 ft. Temperatures

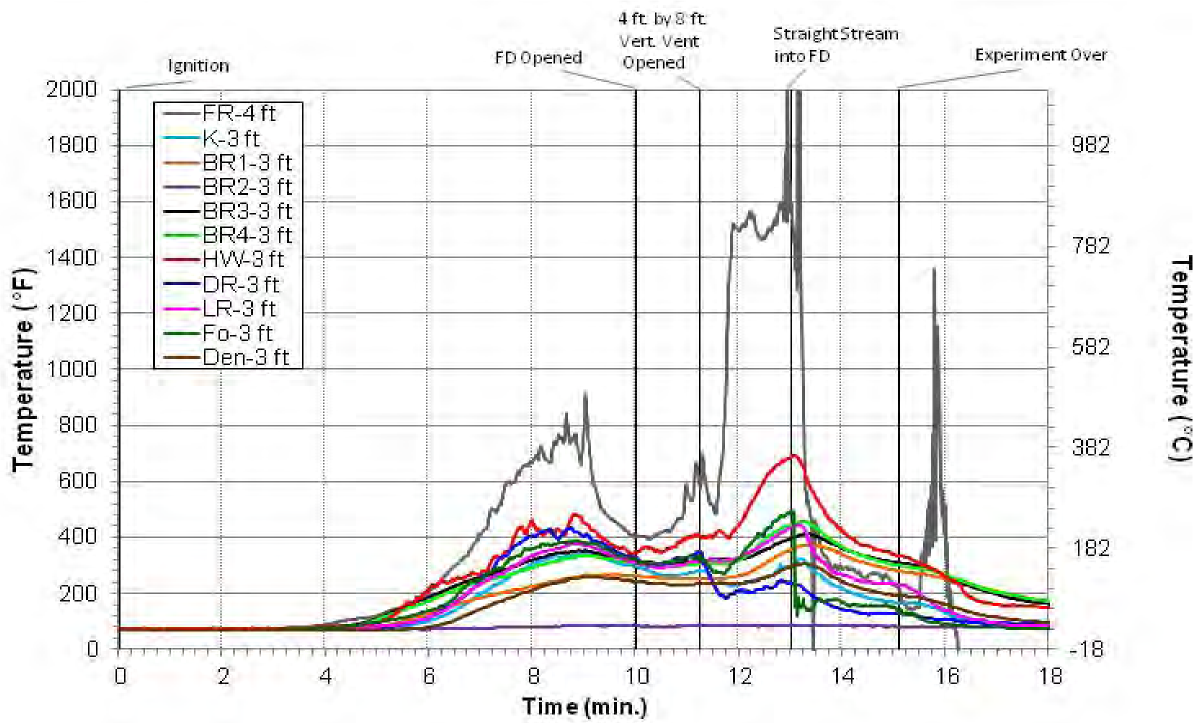


Figure 5.294: Experiment 8 - 3 ft. Temperatures

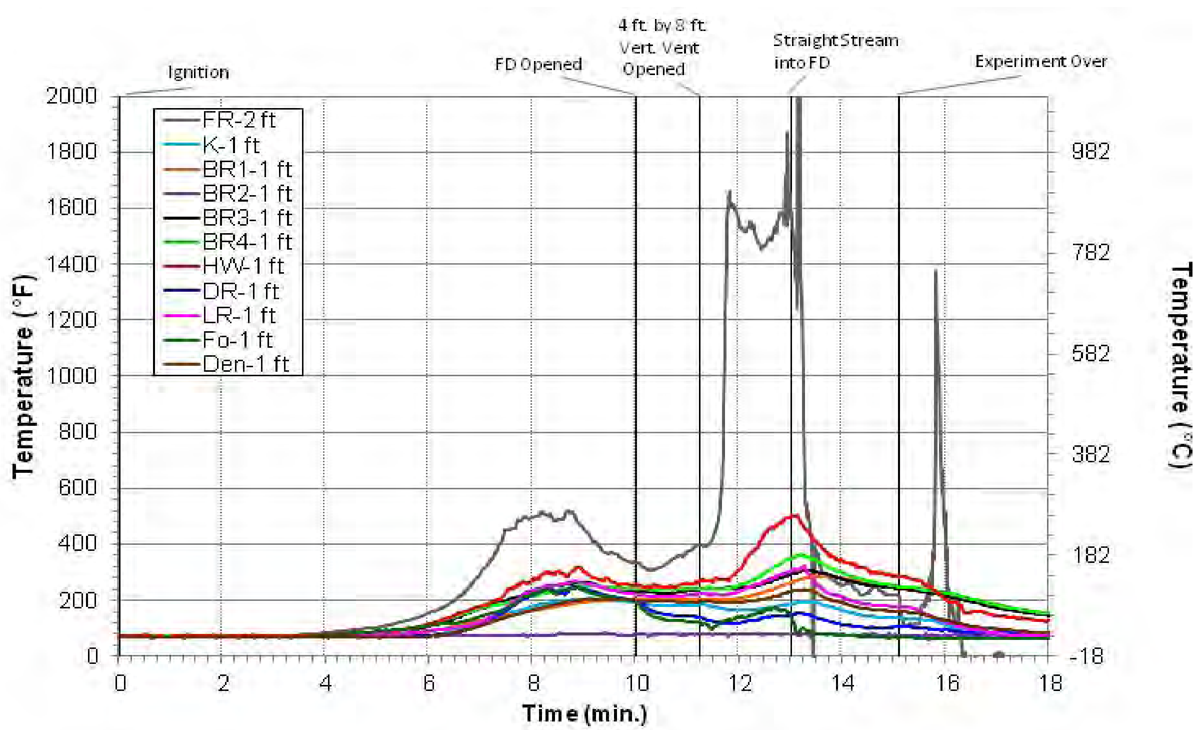


Figure 5.295: Experiment 8 - 1 ft. Temperatures

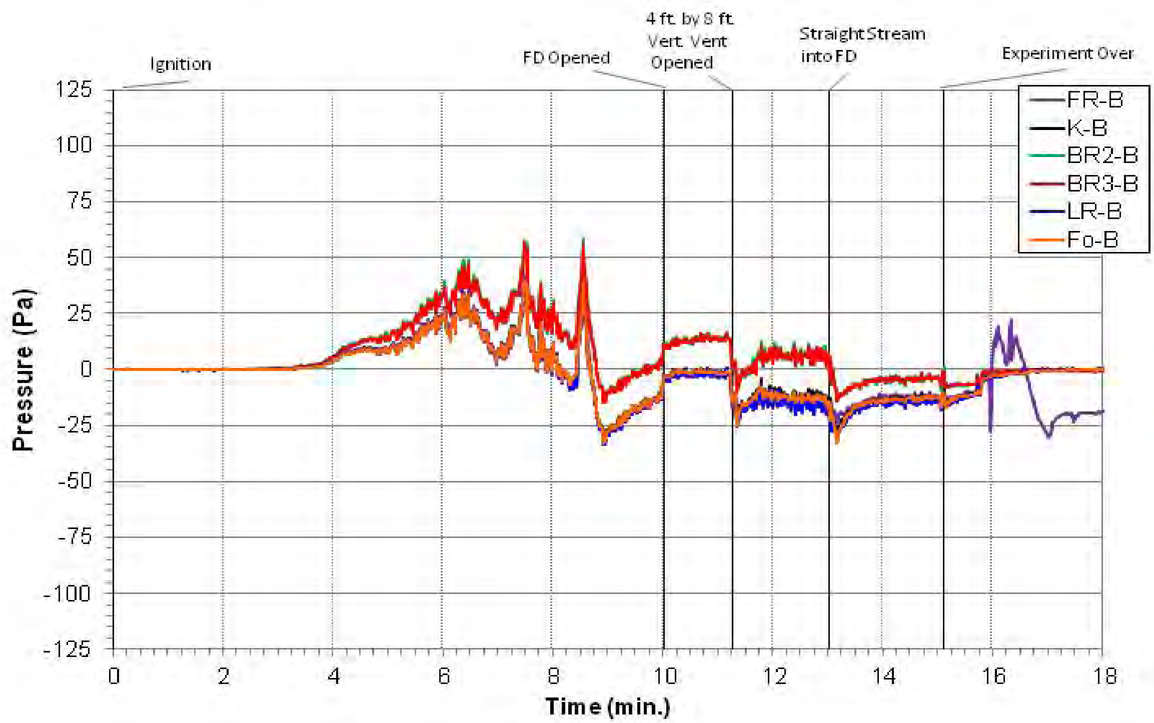


Figure 5.296: Experiment 8 - Bottom Pressure

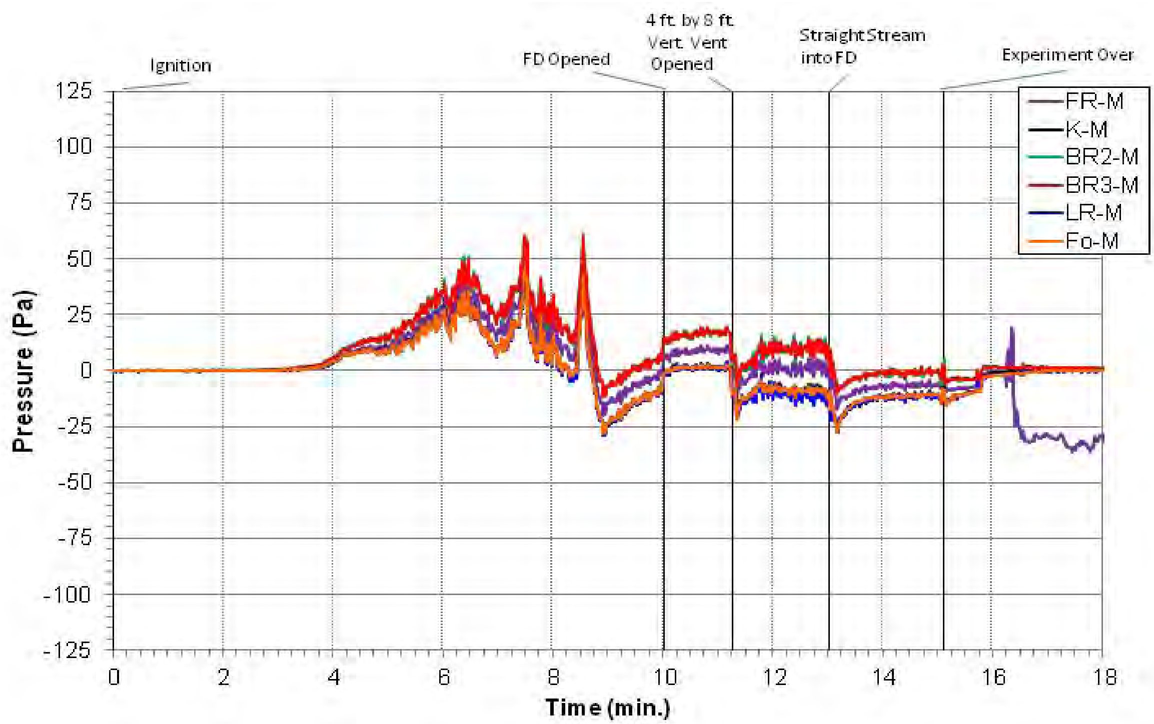


Figure 5.297: Experiment 8 - Middle Pressure

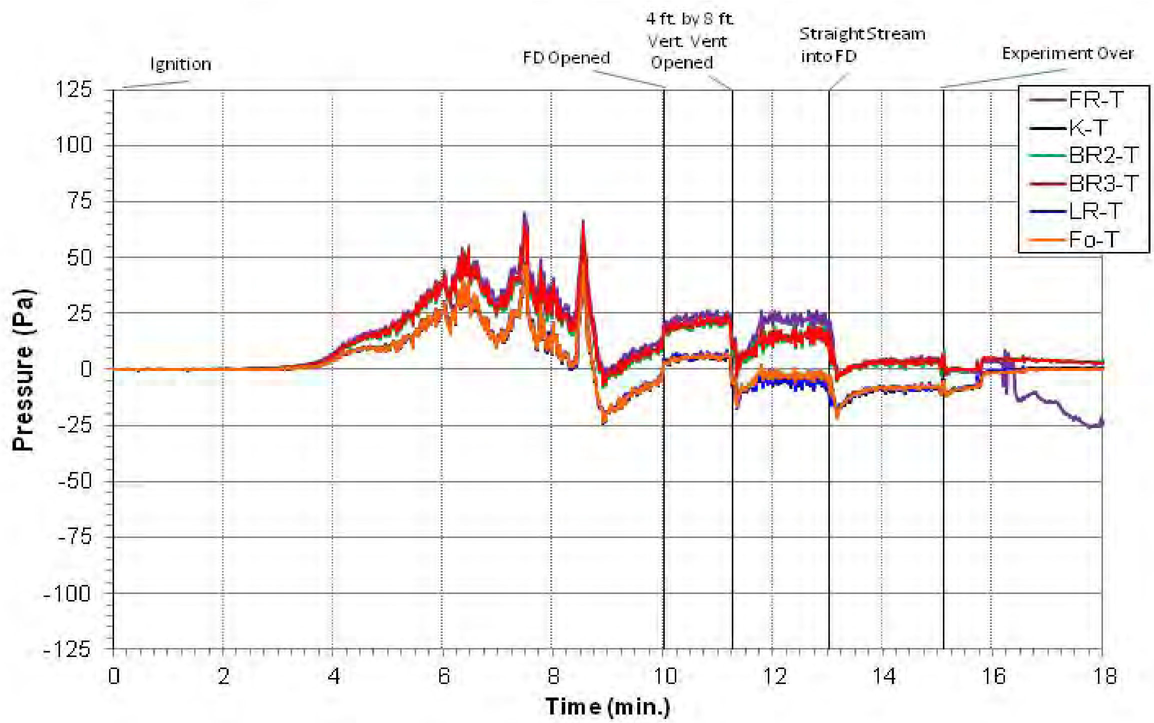


Figure 5.298: Experiment 8 - Top Pressure

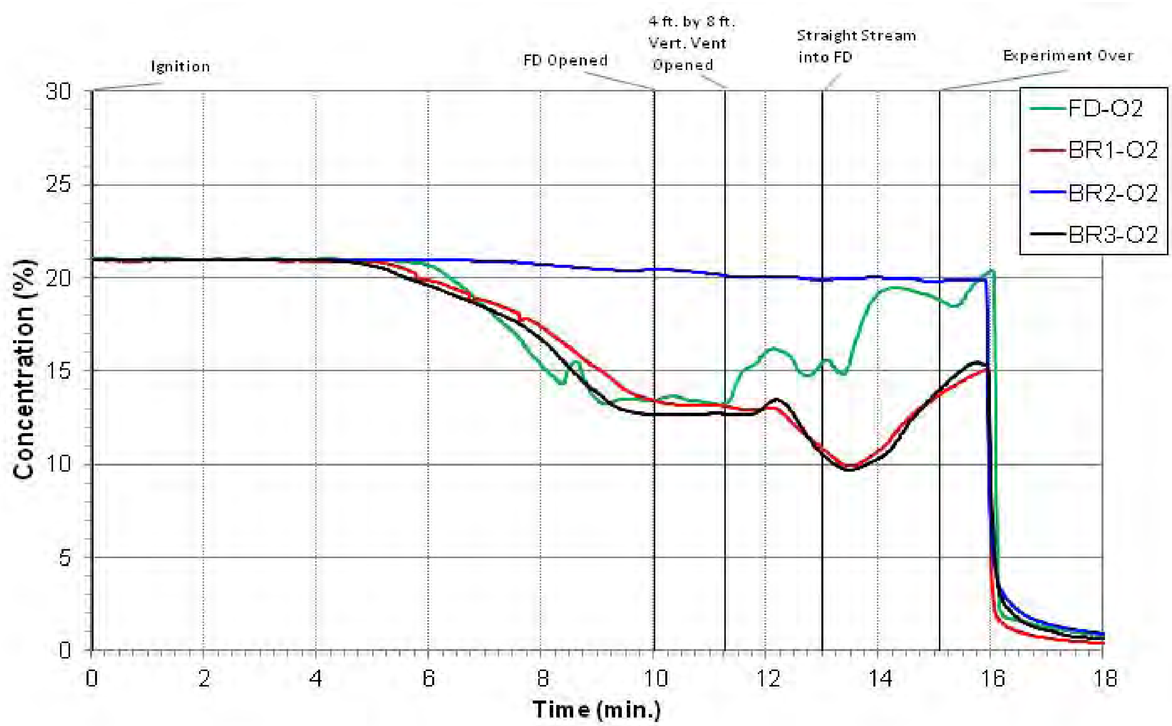


Figure 5.299: Experiment 8 - Oxygen Concentration

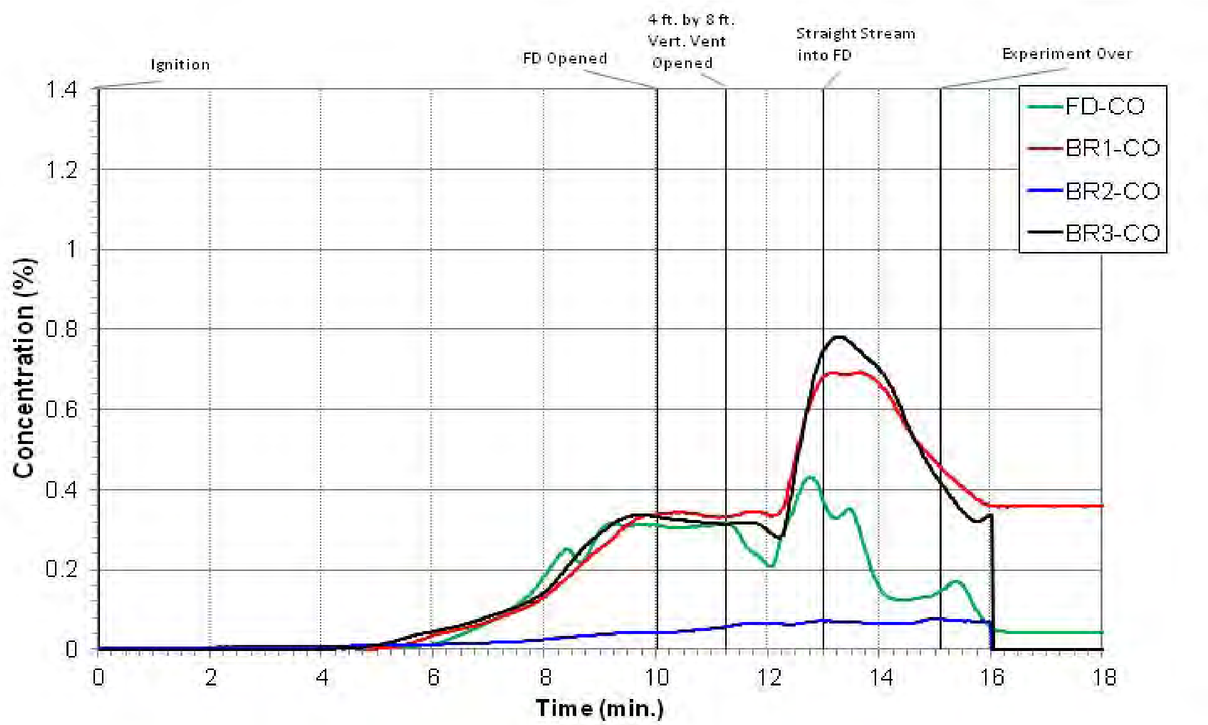


Figure 5.300: Experiment 8 - Carbon Monoxide Concentration

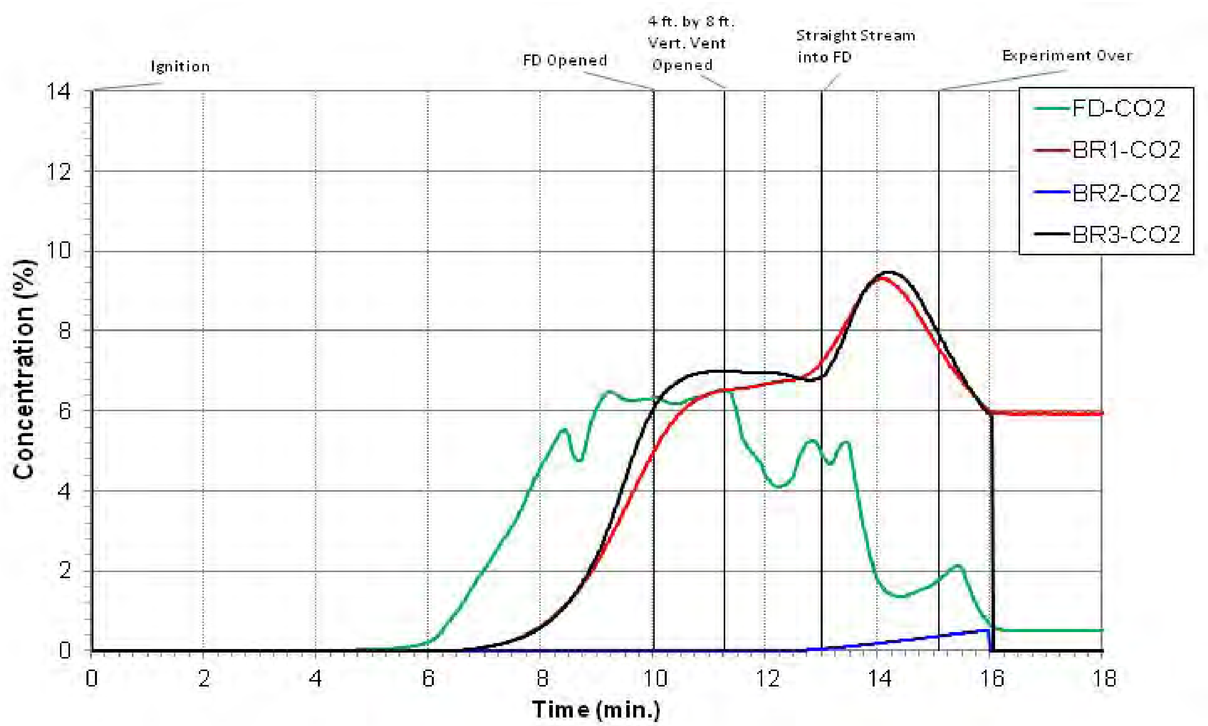


Figure 5.301: Experiment 8 - Carbon Dioxide Concentration

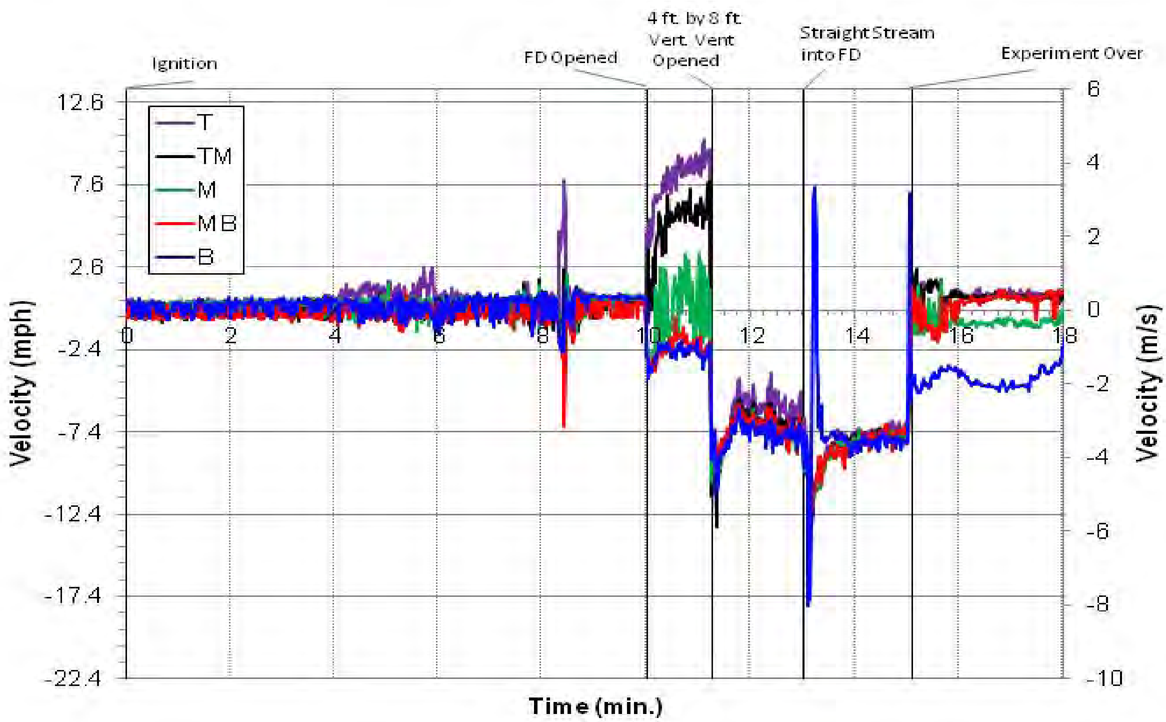


Figure 5.302: Experiment 8 - Front Door Velocity

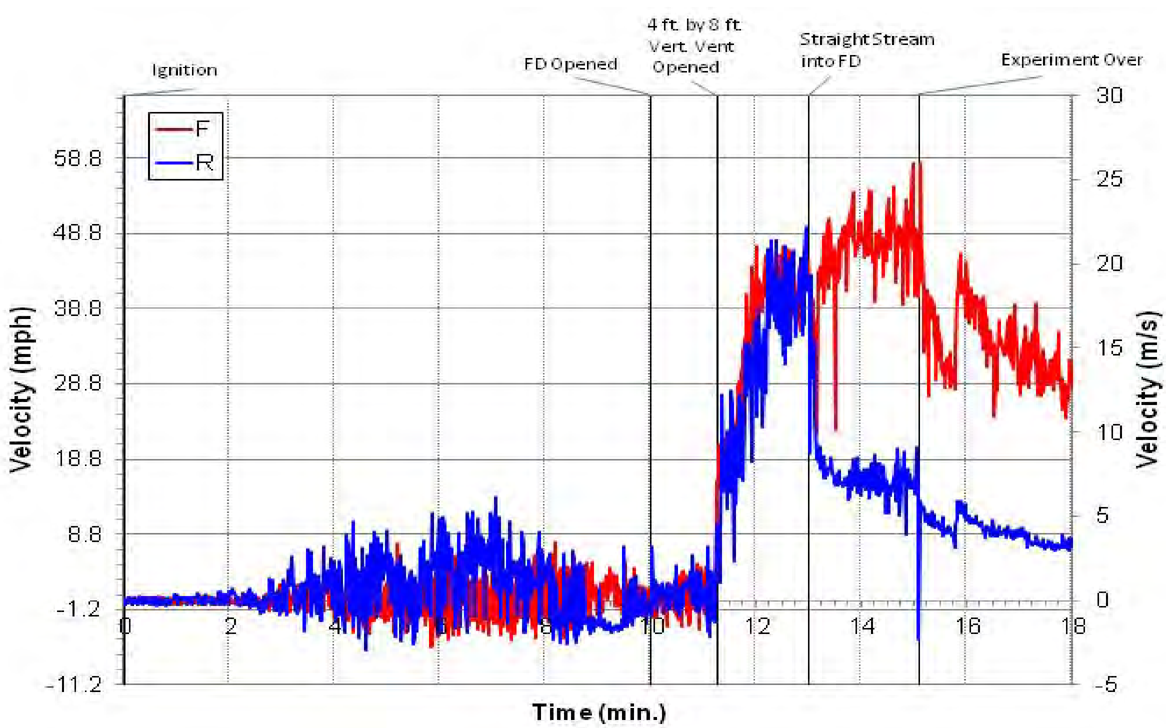


Figure 5.303: Experiment 8 - Roof Vent Velocity

5.7.5. Experiment 10

Experiment 10 was designed to simulate a fire in a second floor bedroom with ventilation through the front door, then vertically in the family room (remote from the fire), and finally through a window near the seat of the fire in the bedroom. Ignition occurred in Bedroom 3. The fire was allowed to grow until 10:00, when the front door was opened. At 11:30, a 4’ by 4’ hole was opened in the roof. The fire was then allowed to grow to post-flashover conditions, and then the Bedroom 3 window was opened at 16:35. Water was applied to the fire for 12 seconds with a combination nozzle positioned in a straight stream pattern at 17:30. The experiment ended at 19:00, and the crew extinguished the fire. Figure 5.305 through Figure 5.311 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.312 through Figure 5.323 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.21: Experiment 10 Timeline

Time	Description
0:00	Ignition
10:00	Front Door Open
11:30	4 ft. by 4 ft. Vertical Vent Open
16:35	Bedroom 3 Window Open
17:30	Straight Stream into Bedroom 3 Window
19:00	Final Suppression (End of Experiment)

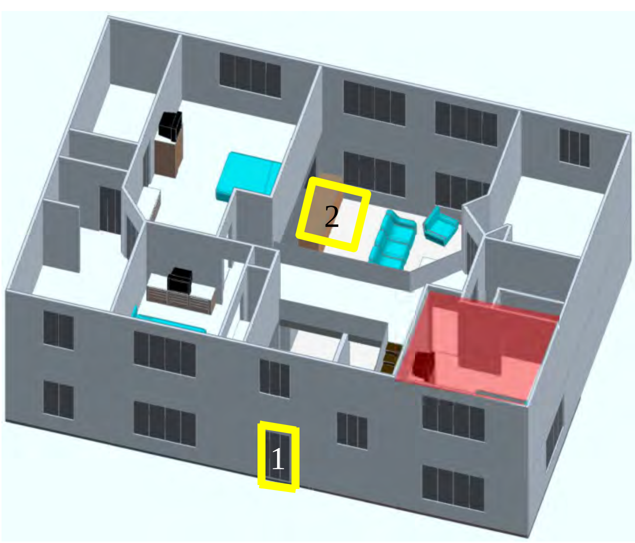


Figure 5.304: Experiment 10 Scenario

Figure 5.305: Experiment 10 - 0:00

Figure 5.306: Experiment 10 - 6:30

Figure 5.307: Experiment 10 - 10:05

Figure 5.308: Experiment 10 - 11:36

Figure 5.309: Experiment 10 - 16:45

Figure 5.310: Experiment 10 - 17:35

Figure 5.311: Experiment 10 - 18:20

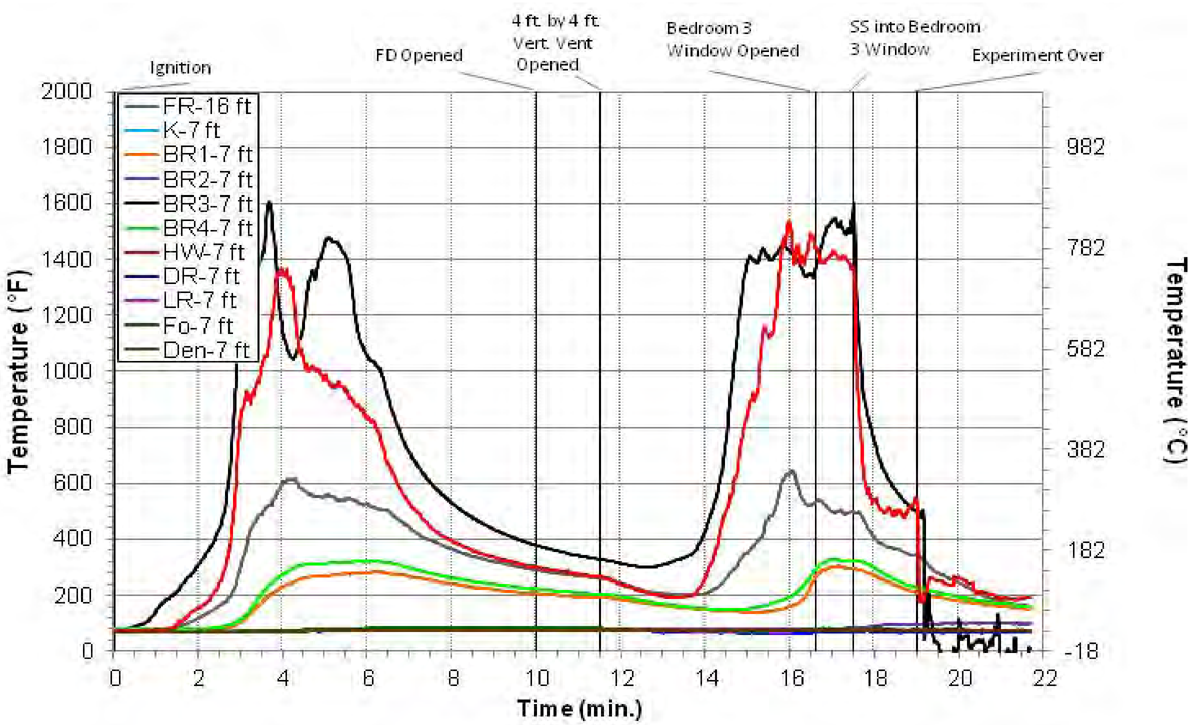


Figure 5.312: Experiment 10 - 7 ft. Temperatures

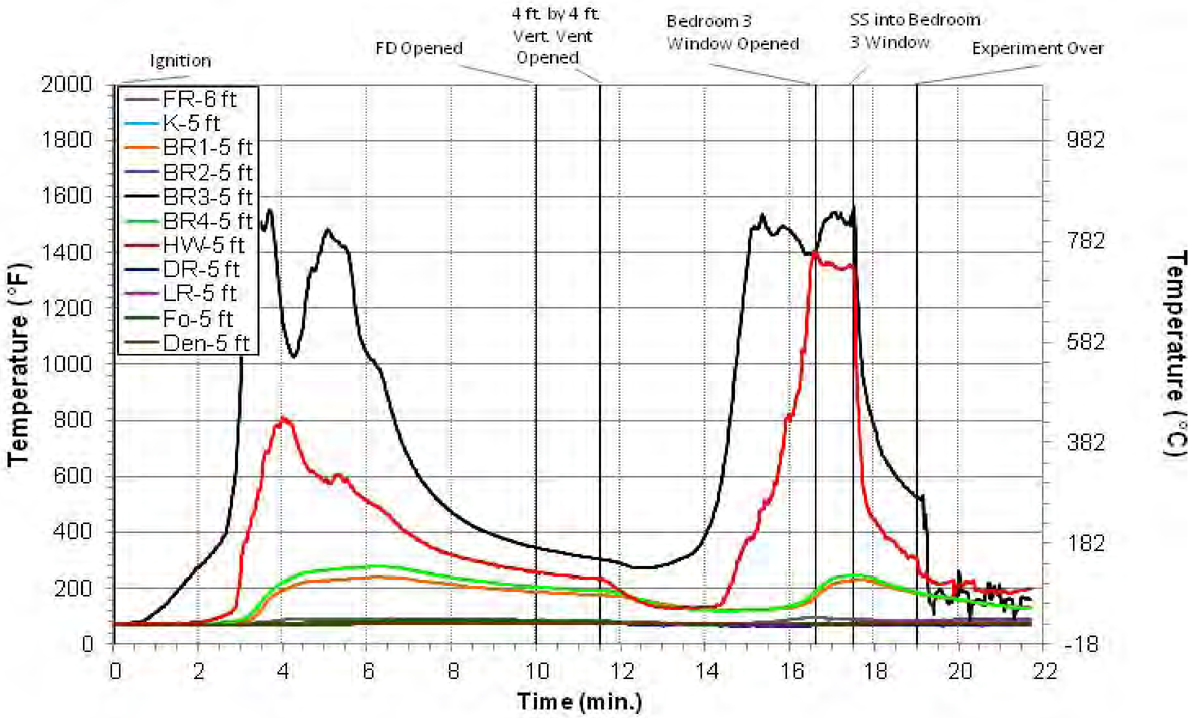


Figure 5.313: Experiment 10 - 5 ft. Temperatures

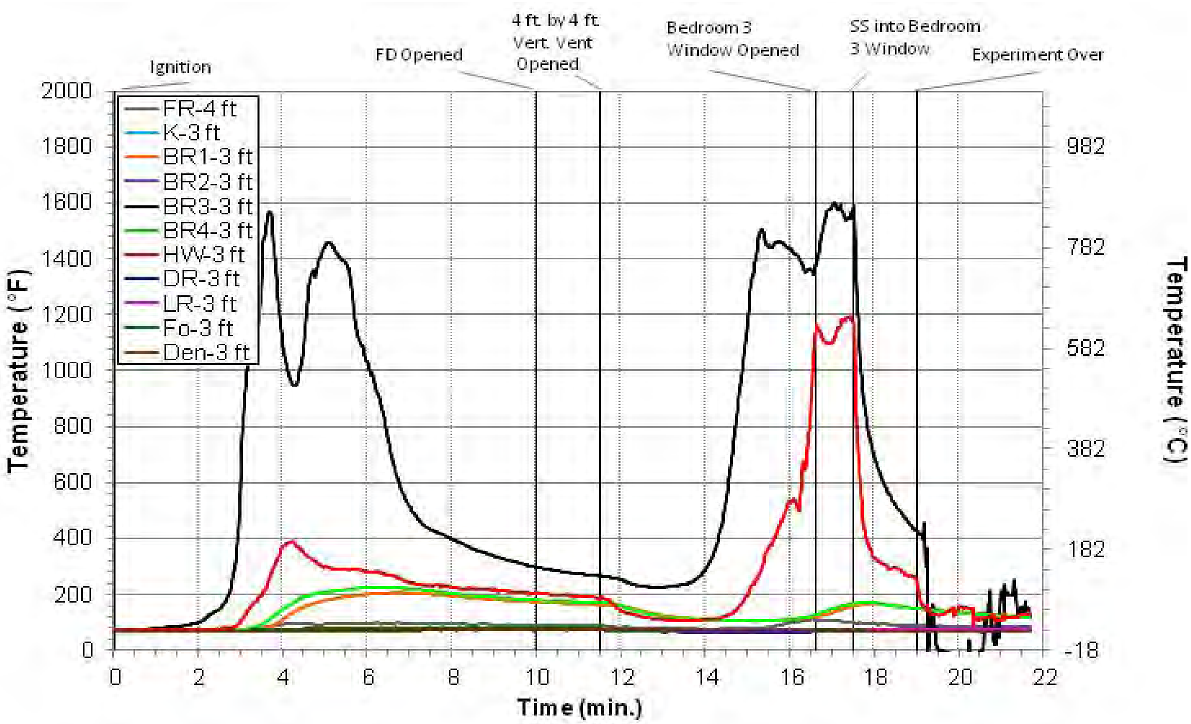


Figure 5.314: Experiment 10 - 3 ft. Temperatures

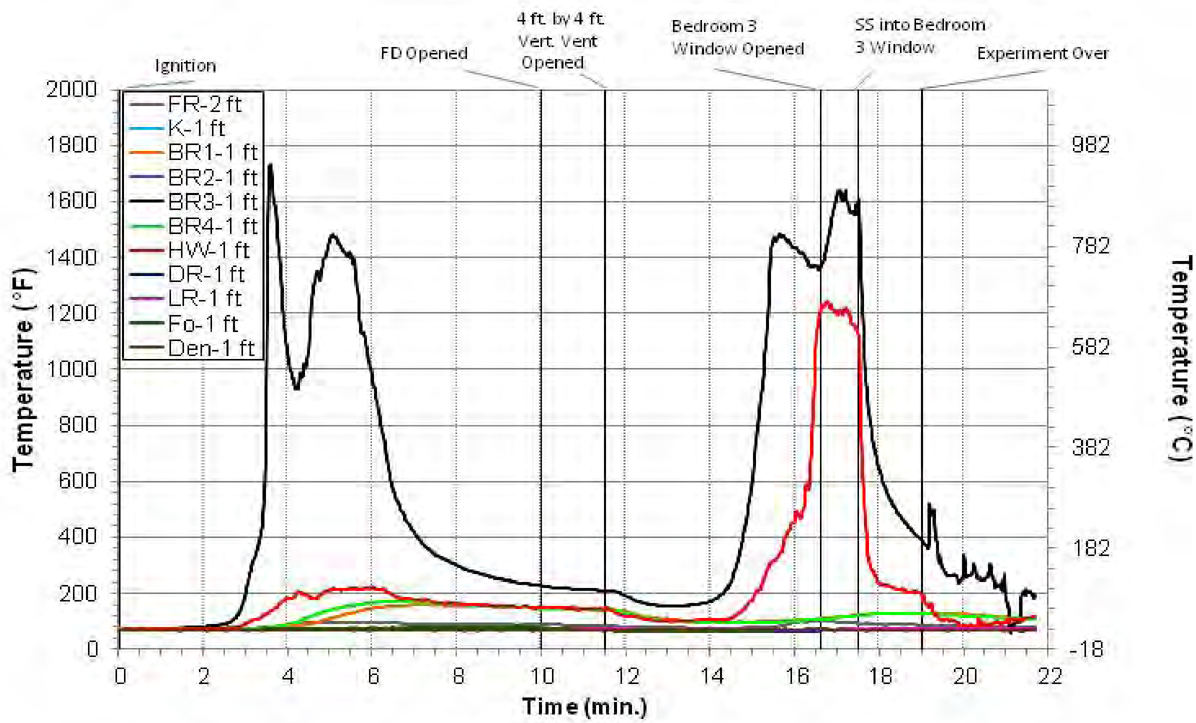


Figure 5.315: Experiment 10 - 1 ft. Temperatures

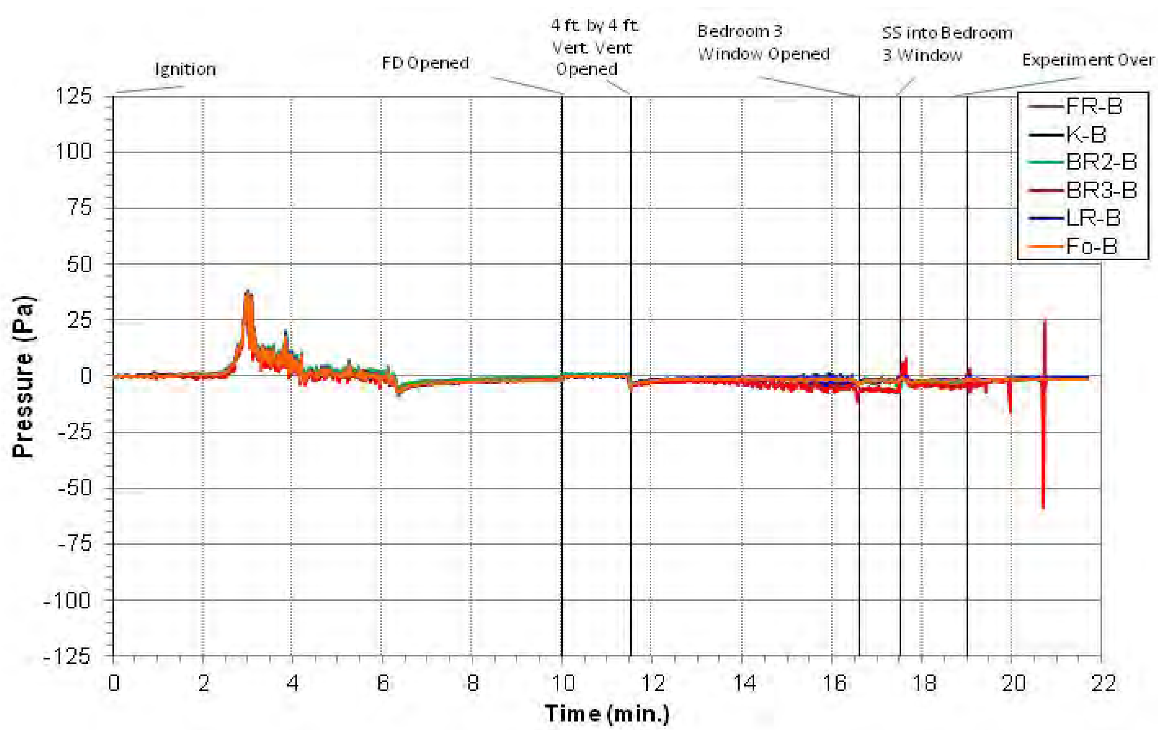


Figure 5.316: Experiment 10 - Bottom Pressure

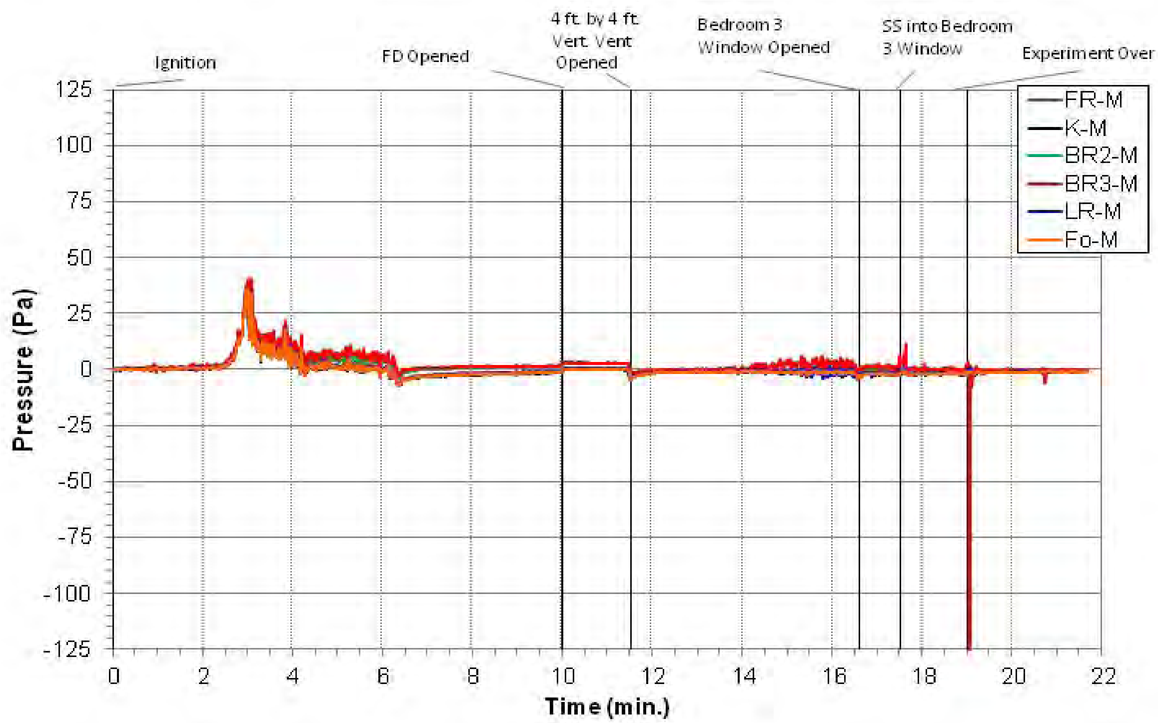


Figure 5.317: Experiment 10 - Middle Pressure

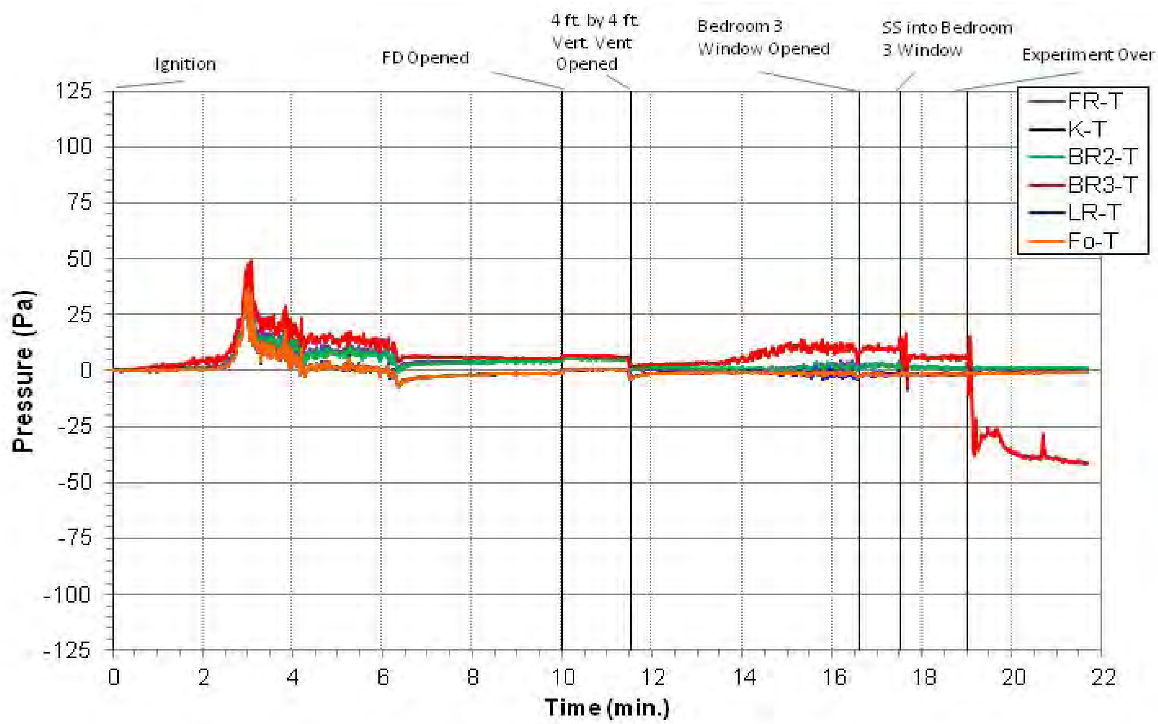


Figure 5.318: Experiment 10 - Top Pressure

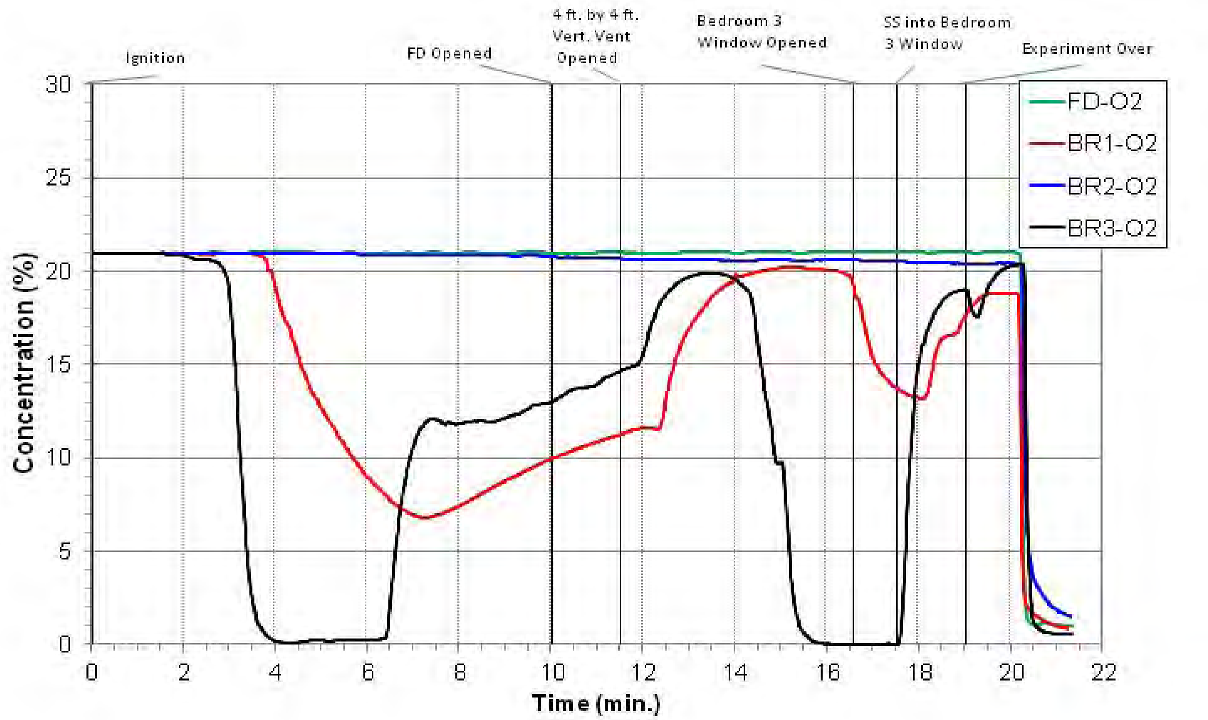


Figure 5.319: Experiment 10 - Oxygen Concentration

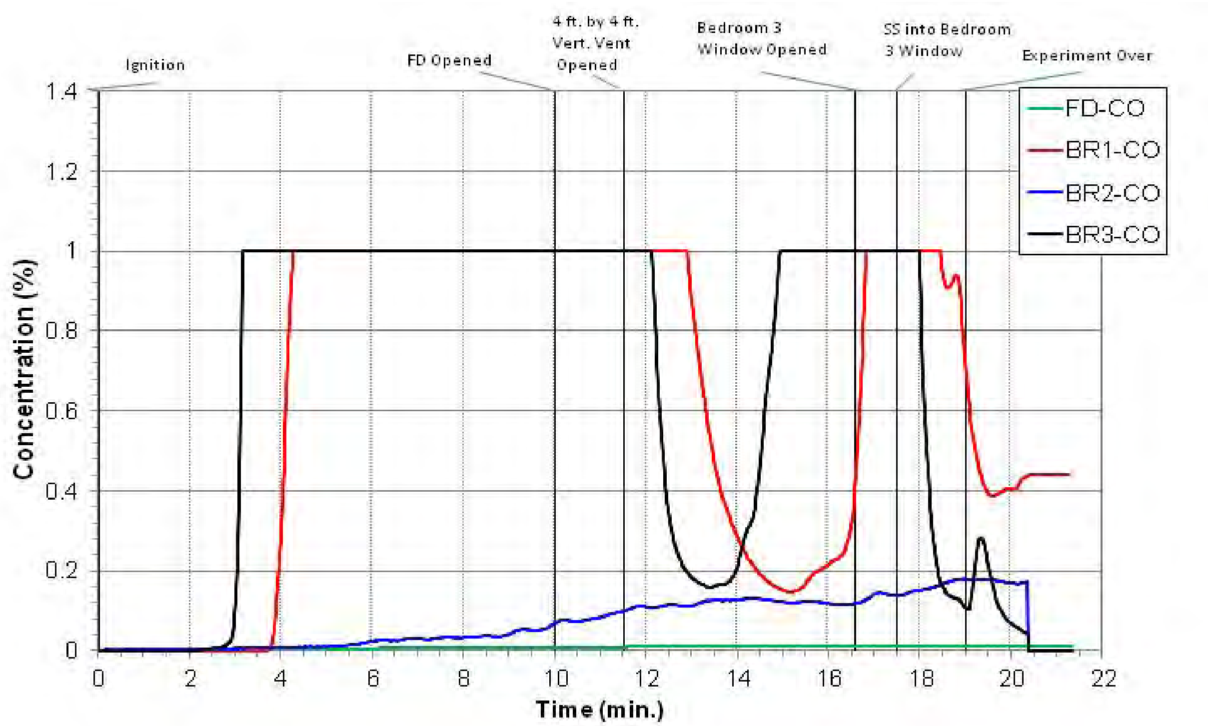


Figure 5.320: Experiment 10 - Carbon Monoxide Concentration

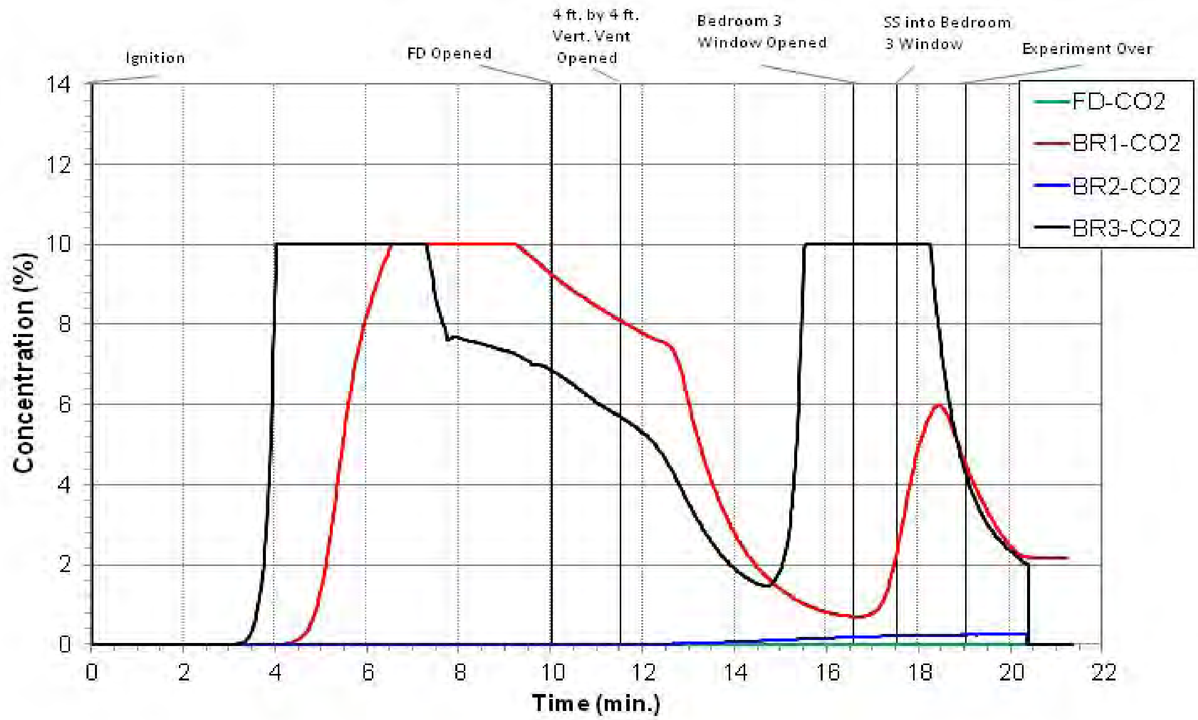


Figure 5.321: Experiment 10 - Carbon Dioxide Concentration

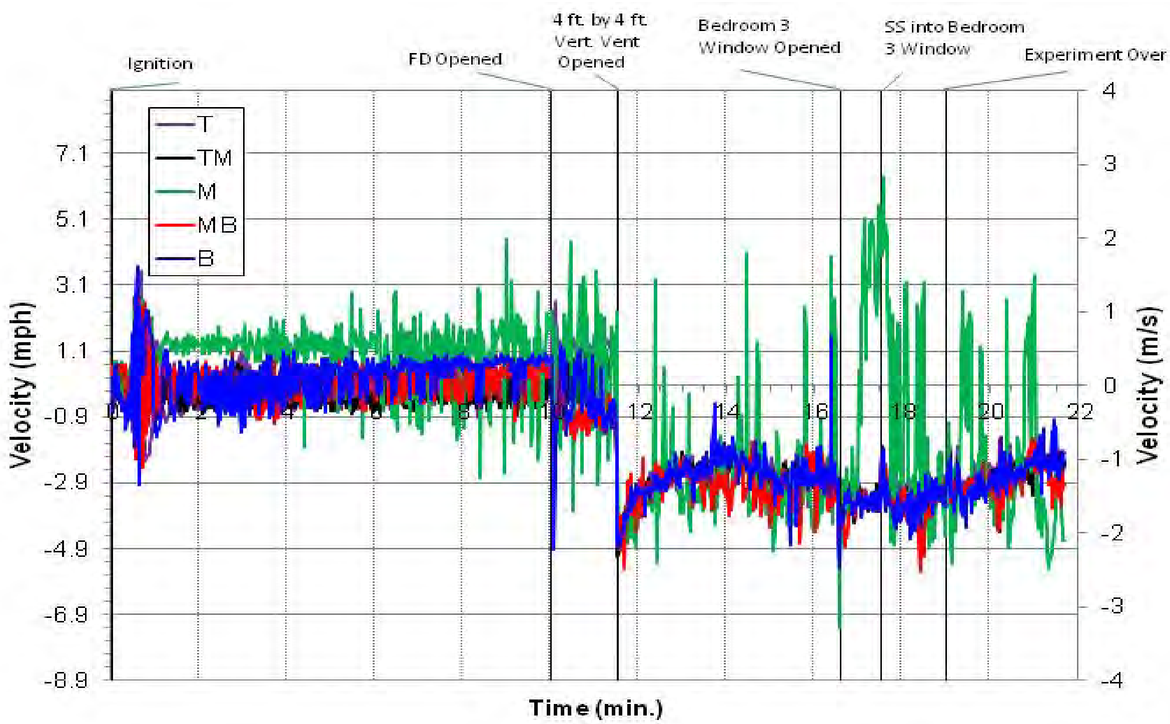


Figure 5.322: Experiment 10 - Front Door Velocity

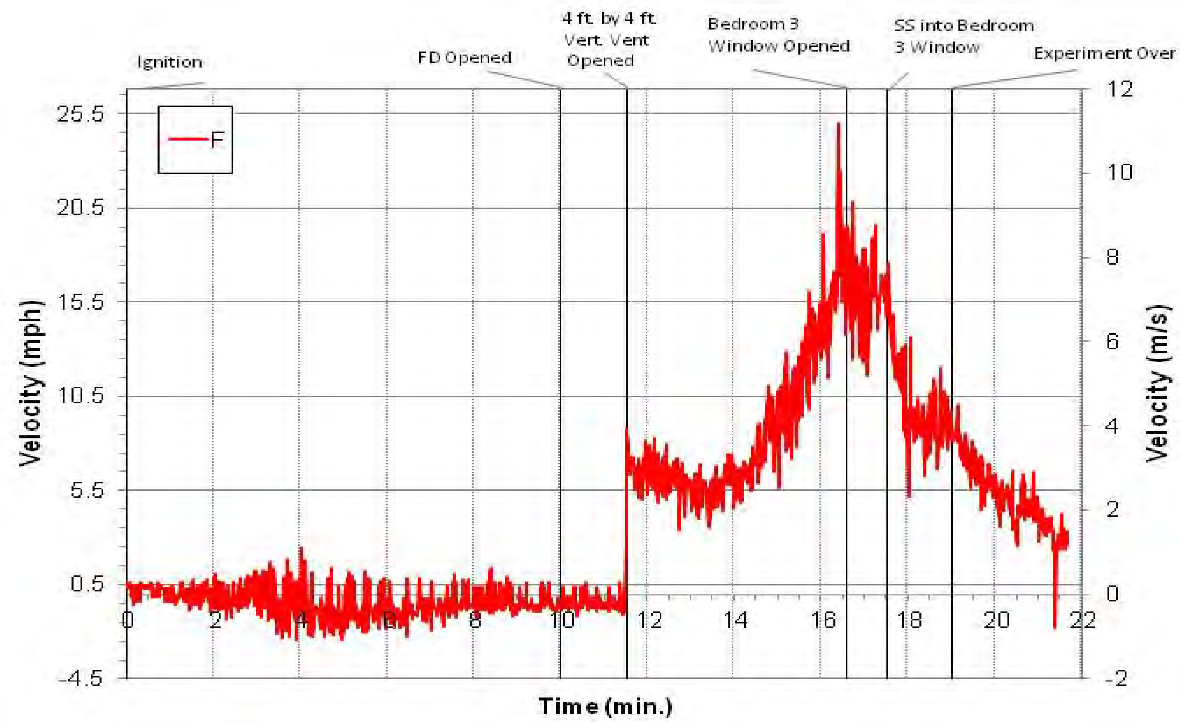


Figure 5.323: Experiment 10 - Roof Vent Velocity

5.7.6. Experiment 12

Experiment 12 was designed to simulate a window failing in the fire room prior to fire department arrival, and then a crew arriving and venting the door and the roof. Igntion occurred in the family room. The fire was allowed to grow until 8:00, when the family room window was opened. Then, at 10:00, the front door was opened. The fire was then allowed to continue to grow until 12:15, when a 4’ by 4’ hole was opened in the roof. The fire then reached post-flashover conditions, and at 14:00, 16 seconds of water was applied to the fire with a combination nozzle in a straight stream pattern. The experiment ended at 16:05, and the crew extinguished the fire. Figure 5.325 through Figure 5.332 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.333 through Figure 5.344 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.22: Experiment 12 Timeline

Time	Description
0:00	Ignition
8:00	Family Room Window Open
10:00	Front Door Open
12:15	4 ft. by 4 ft. Vertical Vent Open
14:00	Straight Stream into Family Room Window
16:05	Final Suppression (End of Experiment)

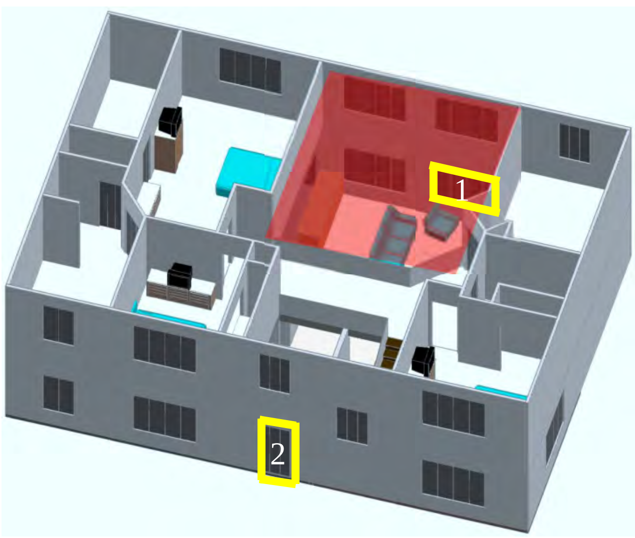


Figure 5.324: Experiment 12 Scenario

Figure 5.325: Experiment 12 - 0:00

Figure 5.326: Experiment 12 - 7:01

Figure 5.327: Experiment 12 - 8:05

Figure 5.328: Experiment 12 - 10:05

Figure 5.329: Experiment 12 - 11:15

Figure 5.330: Experiment 12 - 12:30

Figure 5.331: Experiment 12 - 14:05

Figure 5.332: Experiment 12 - 14:41

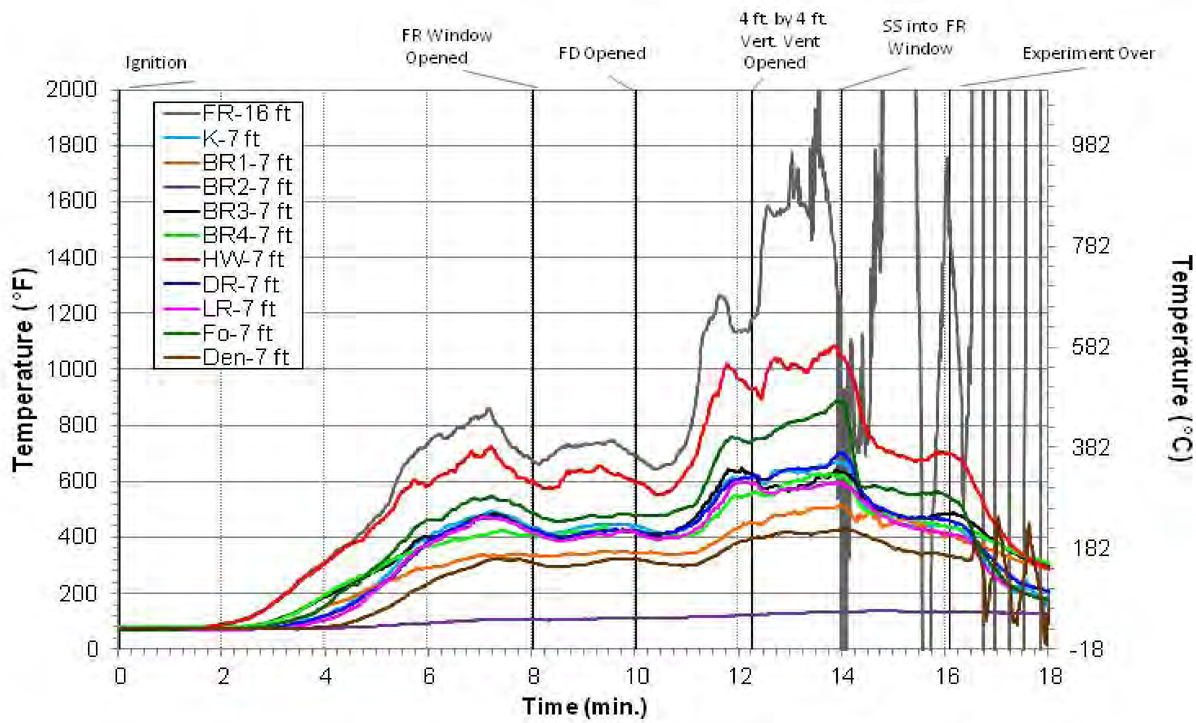


Figure 5.333: Experiment 12 - 7 ft. Temperatures

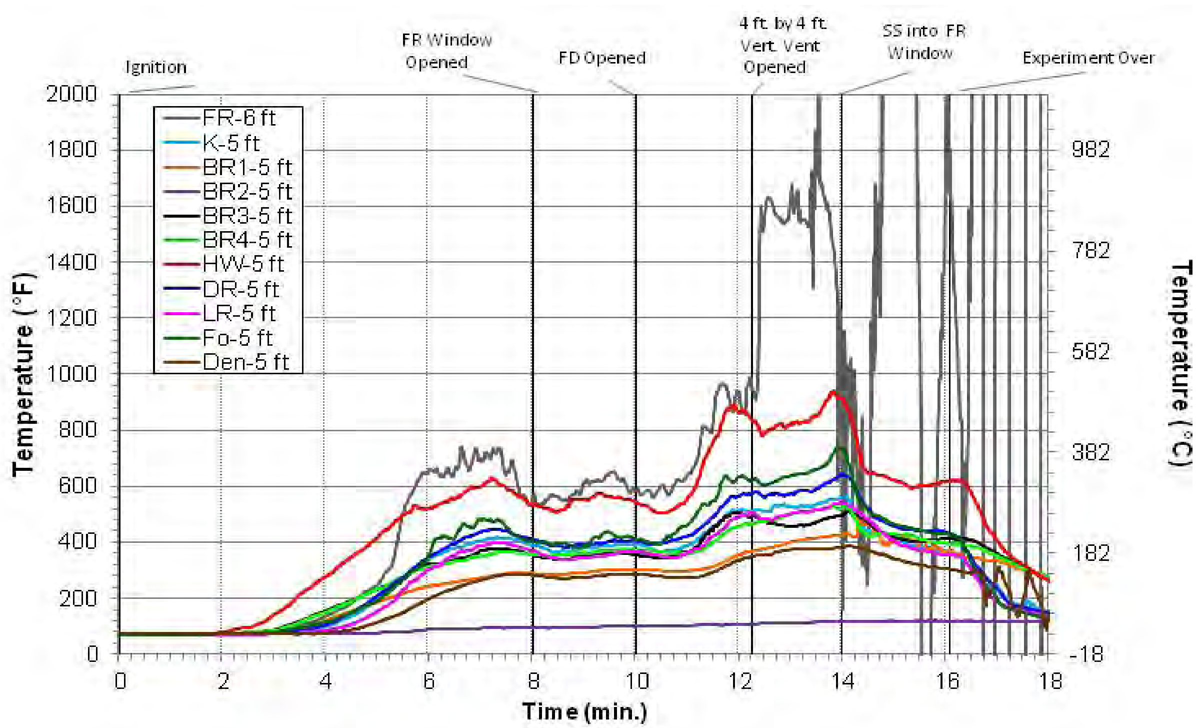


Figure 5.334: Experiment 12 - 5 ft. Temperatures

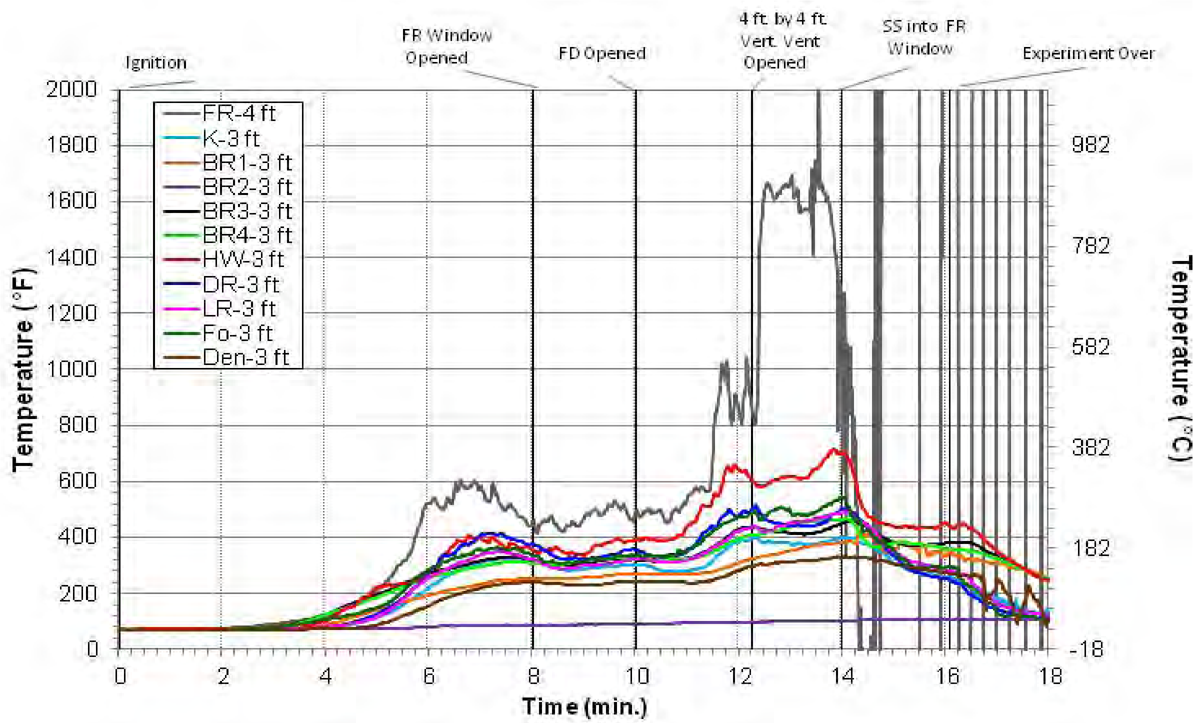


Figure 5.335: Experiment 12 - 3 ft. Temperatures

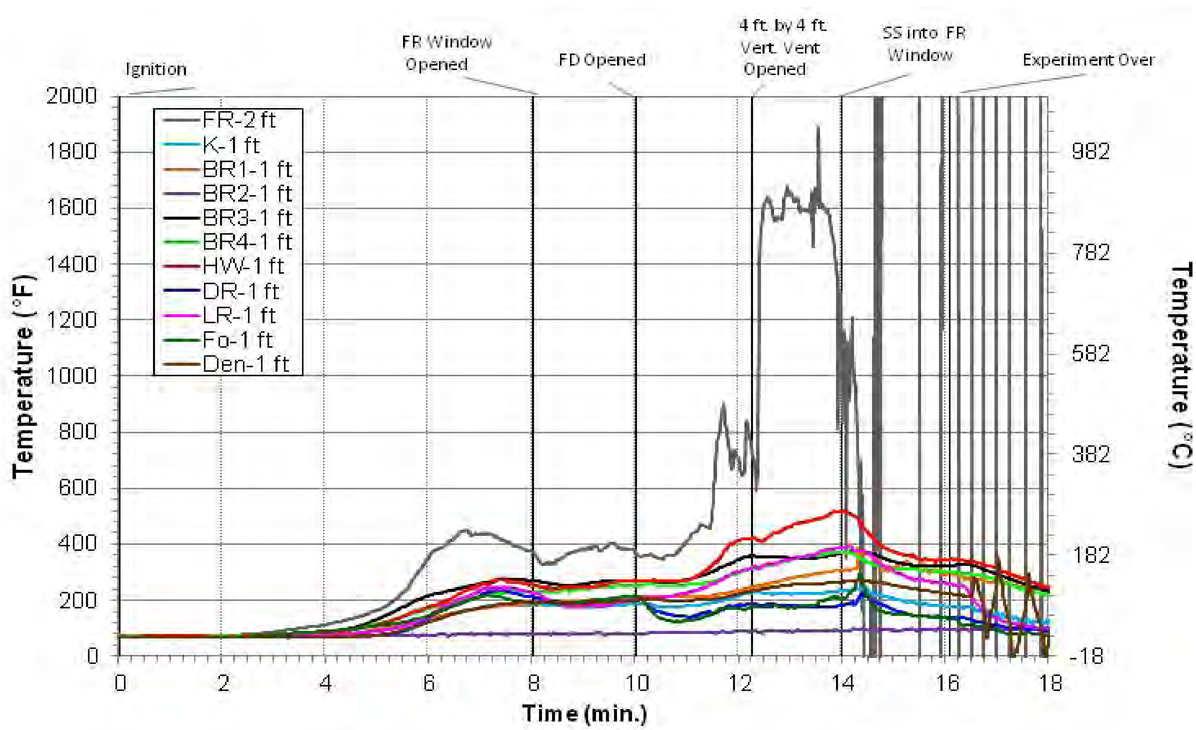


Figure 5.336: Experiment 12 - 1 ft. Temperatures

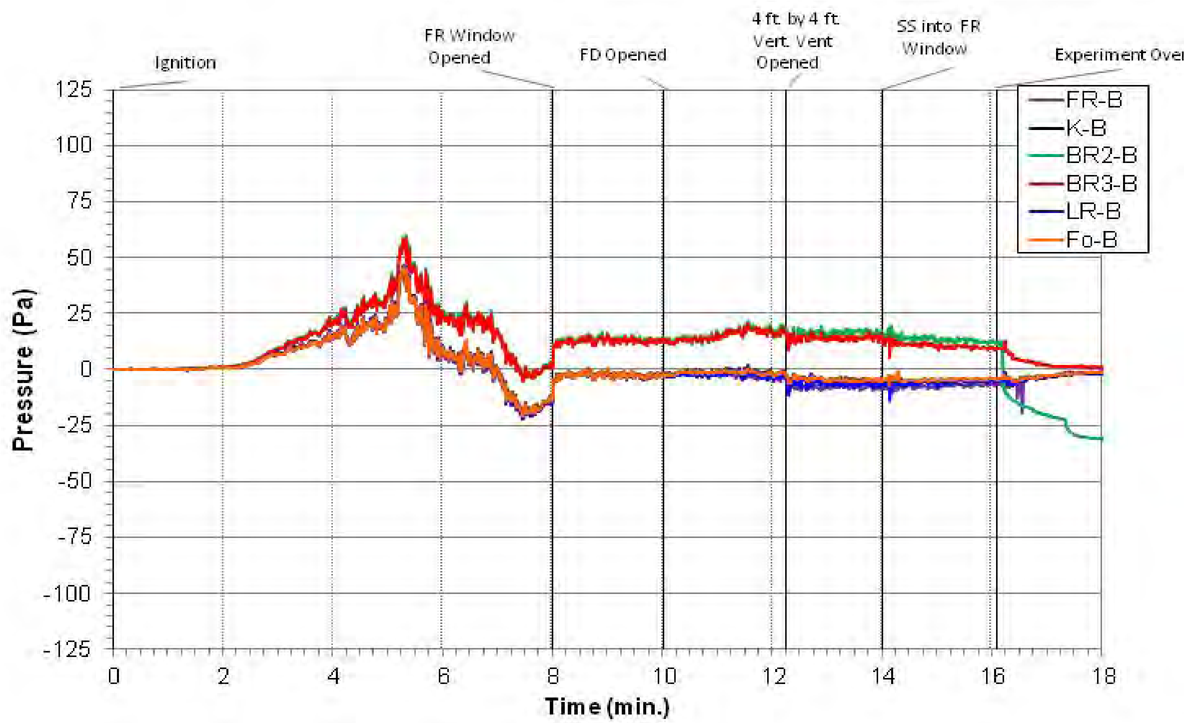


Figure 5.337: Experiment 12 - Bottom Pressure

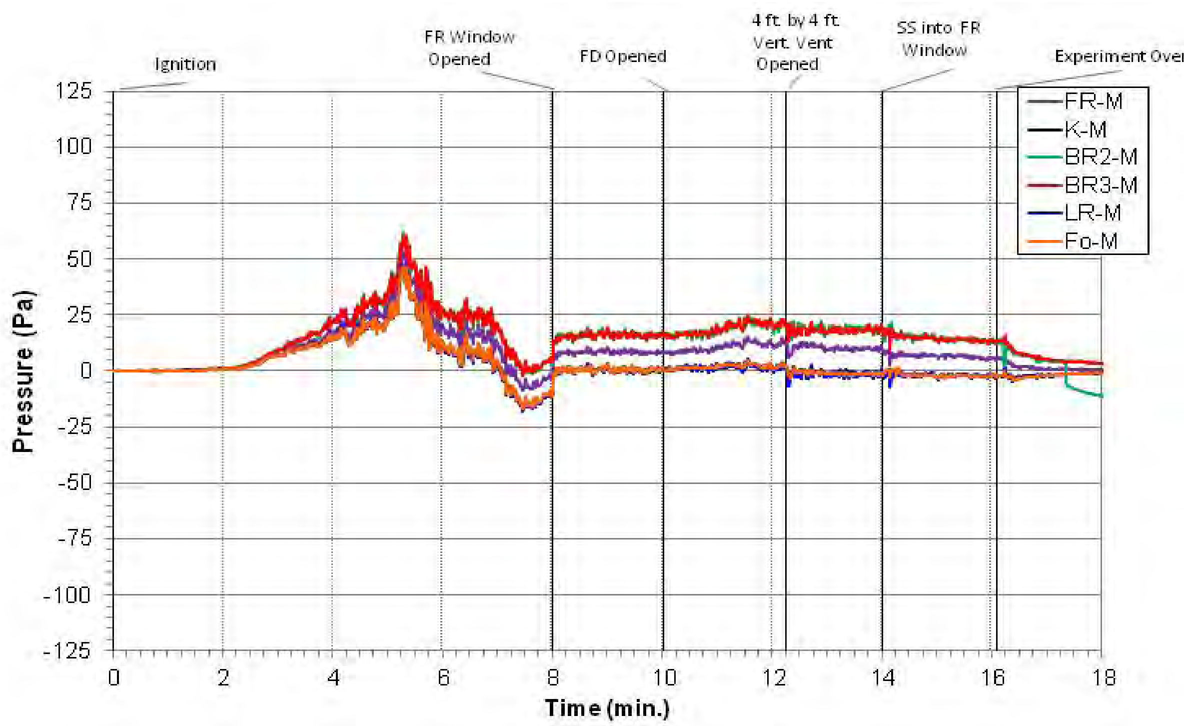


Figure 5.338: Experiment 12 - Middle Pressure

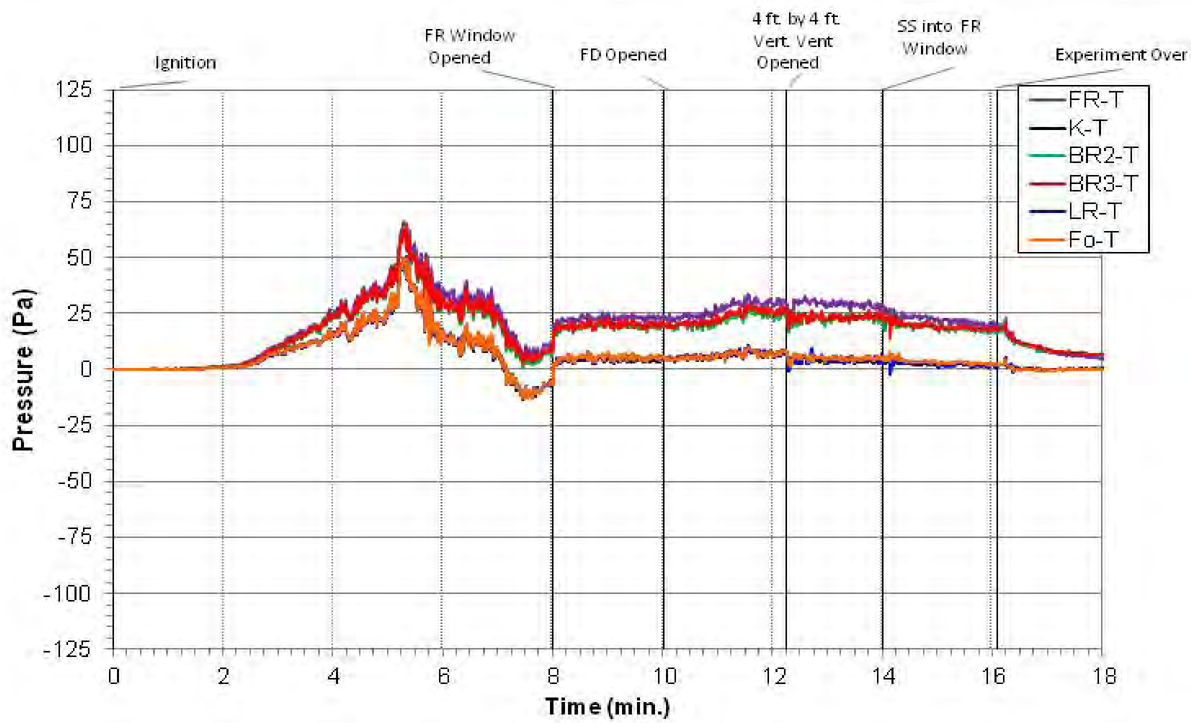


Figure 5.339: Experiment 12 - Top Pressure

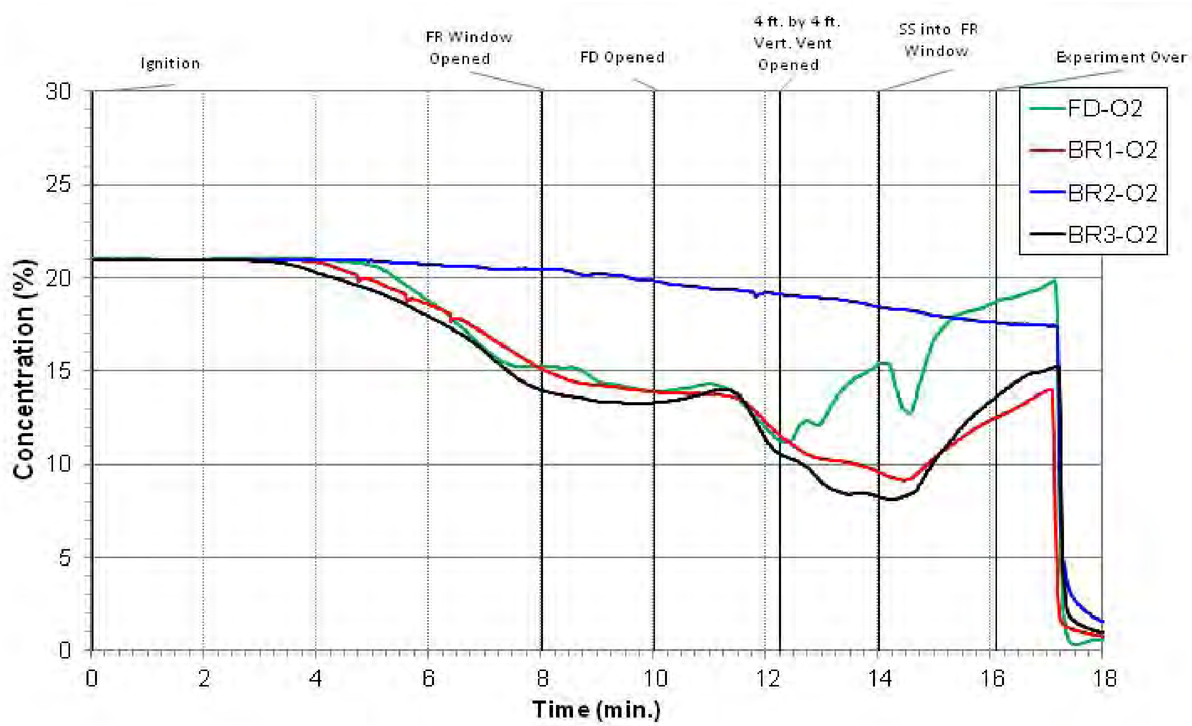


Figure 5.340: Experiment 12 - Oxygen Concentration

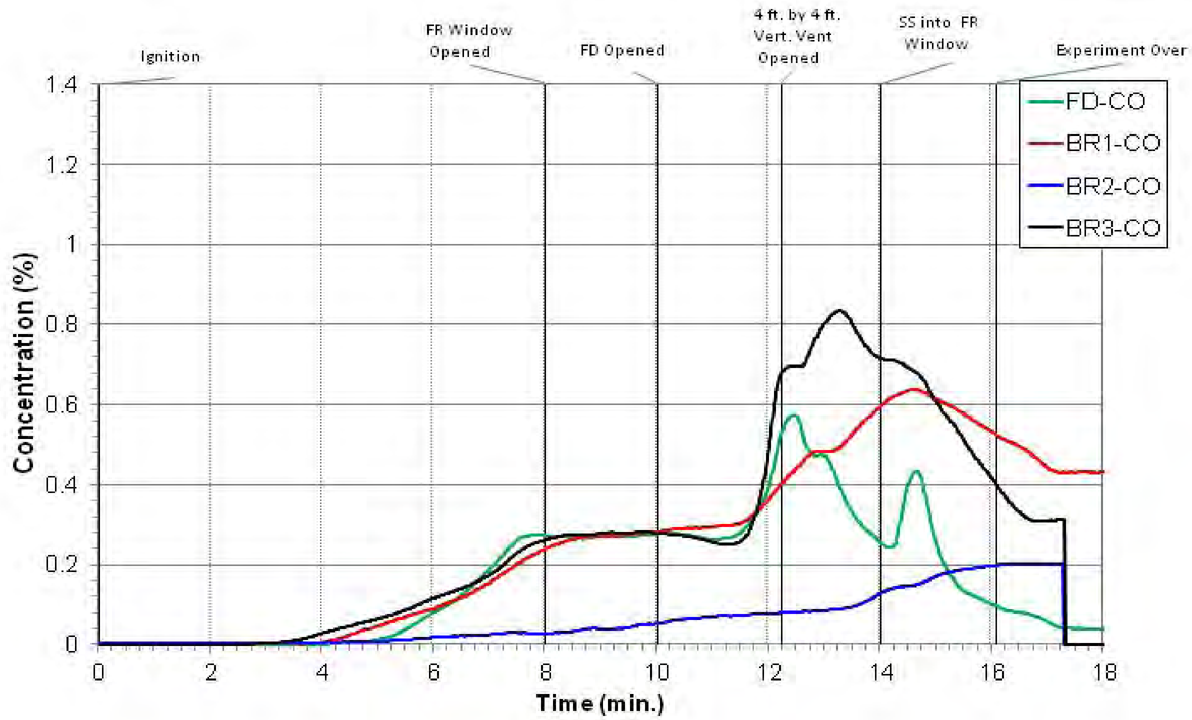


Figure 5.341: Experiment 12 - Carbon Monoxide Concentration

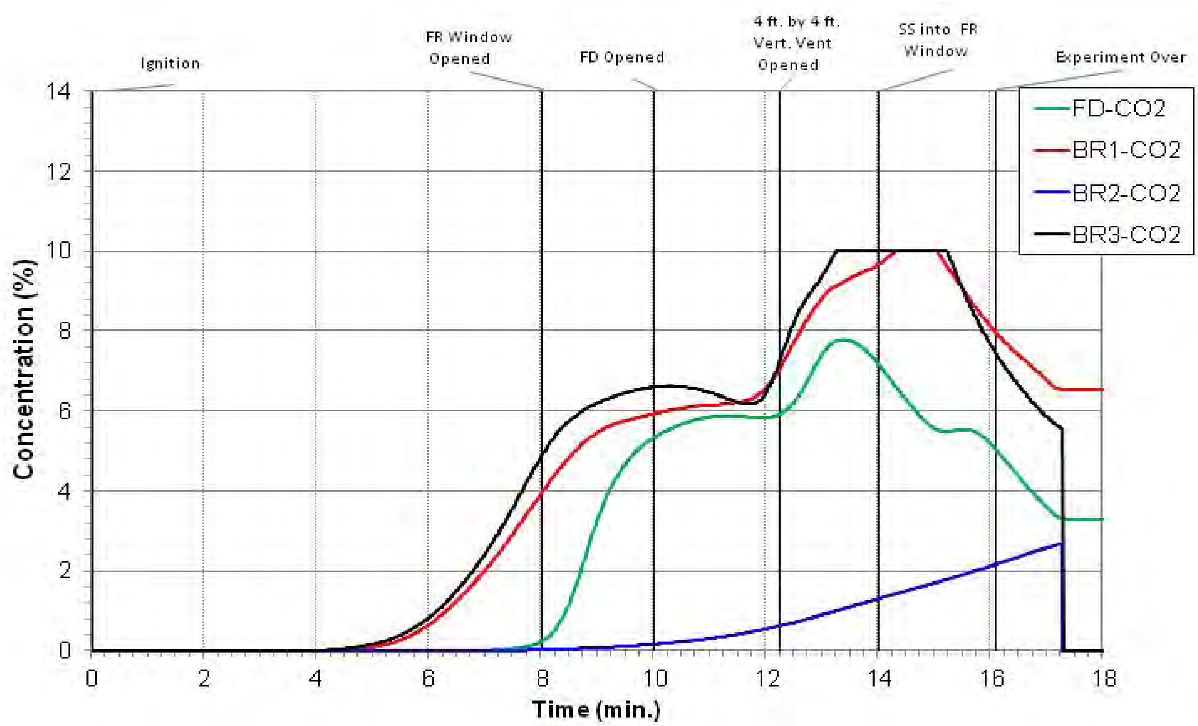


Figure 5.342: Experiment 12 - Carbon Dioxide Concentration

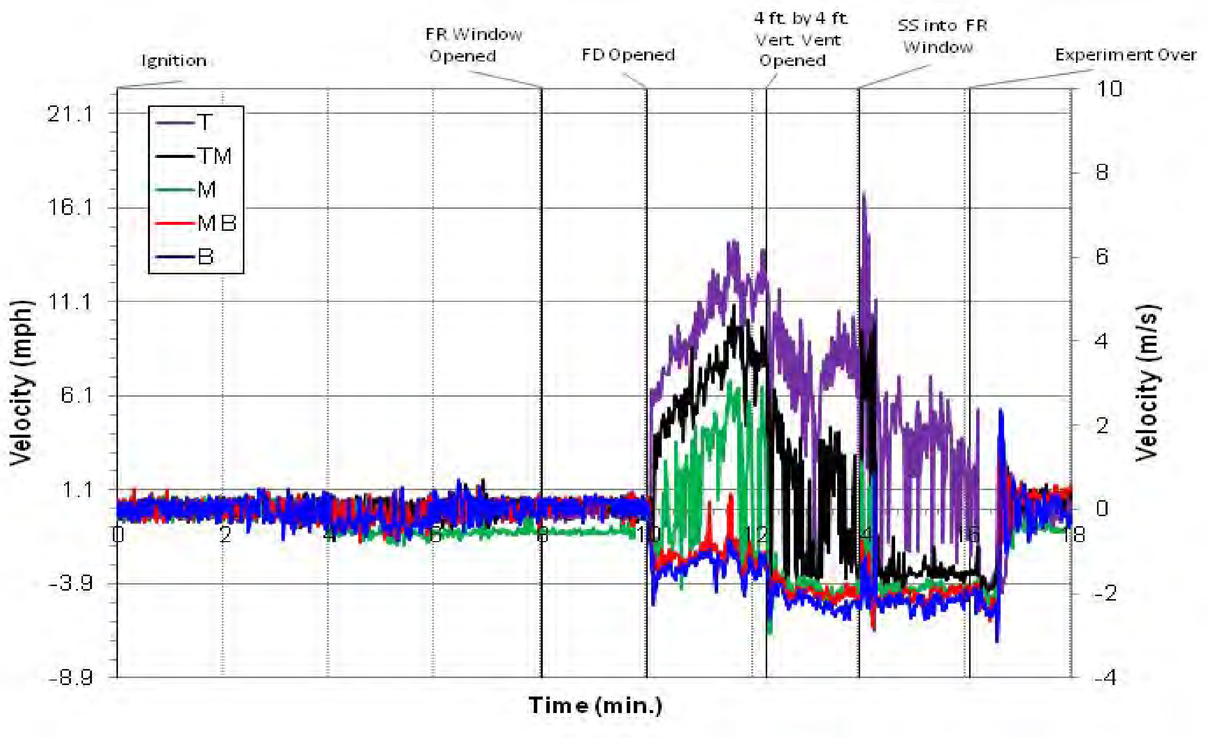


Figure 5.343: Experiment 12 - Front Door Velocity

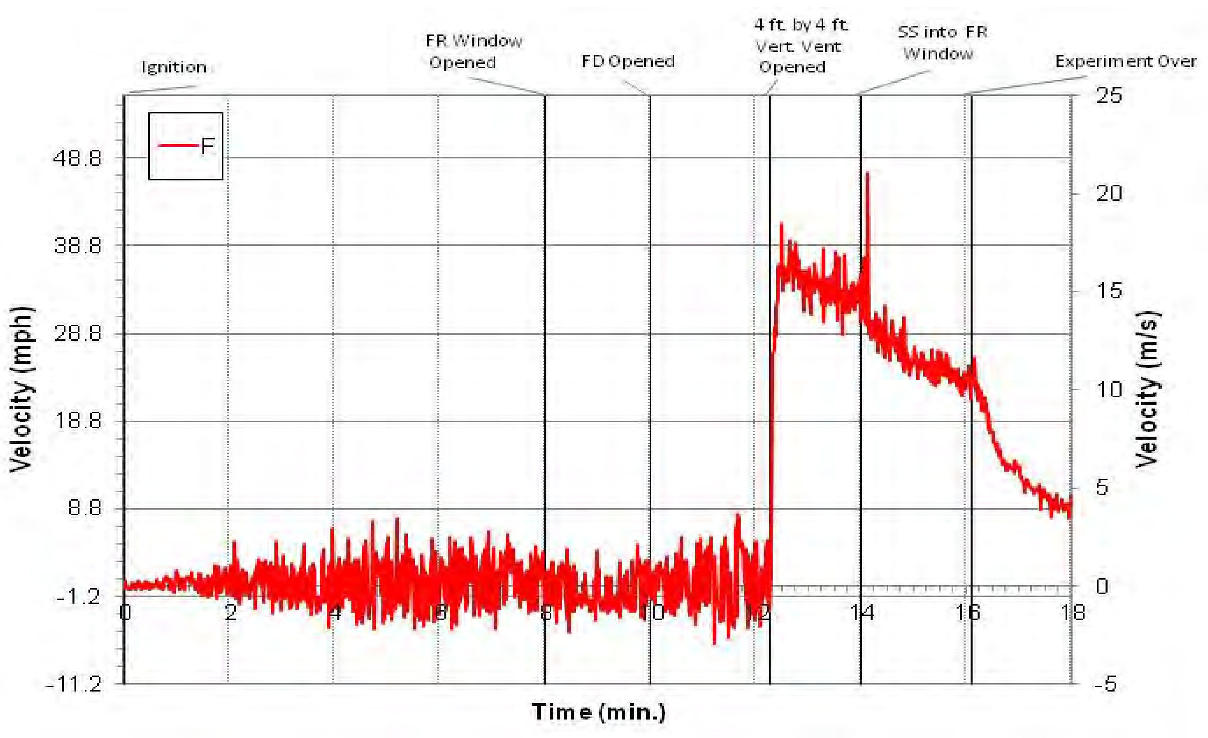


Figure 5.344: Experiment 12 - Roof Vent Velocity

5.7.7. Experiment 14

Experiment 14 was designed to simulate a fire in a two-story house on the second floor with initial ventilation near the seat of the fire, followed by ventilation for entry, and then vertical ventilation. Ignition occurred in Bedroom 3. The fire was allowed to grow until 8:35, when the Bedroom 3 window was opened. At 10:00, the front door was then opened. The fire then grew to post-flashover conditions, and at 11:00 a 4' by 4' hole was opened in the roof. Water was applied to the fire for 15 seconds with a combination nozzle positioned in a straight stream pattern at 12:30. The experiment ended at 14:35, and the crew extinguished the fire. Figure 5.346 through Figure 5.354 show images of the fire during certain times of the experiment that highlight the events in the timeline. Figure 5.355 through Figure 5.366 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.23: Experiment 14 Timeline

Time	Description
0:00	Ignition
8:35	Bedroom 3 Window Open
10:00	Front Door Open
11:00	4 ft. by 4 ft. Vertical Vent Open
12:30	Straight Stream into Bedroom 3 Window
14:45	Final Suppression (End of Experiment)

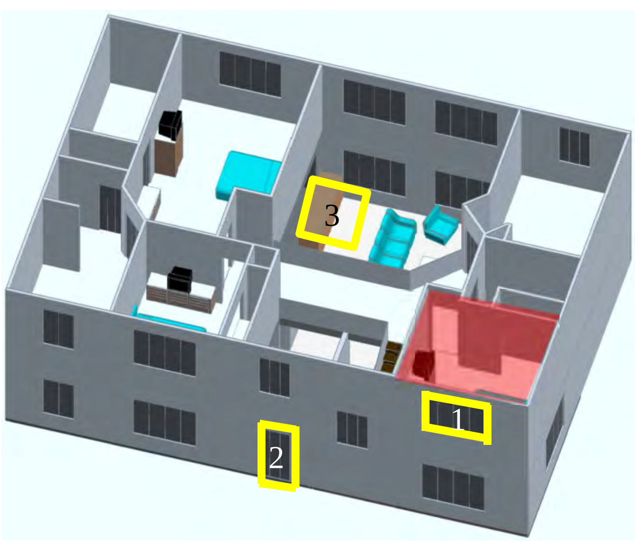


Figure 5.345: Experiment 14 Scenario

Figure 5.346: Experiment 14 - 0:01

Figure 5.347: Experiment 14 - 3:45

Figure 5.348: Experiment 14 - 8:40

Figure 5.349: Experiment 14 - 8:55

Figure 5.350: Experiment 14 - 10:05

Figure 5.351: Experiment 14 - 10:35

Figure 5.352: Experiment 14 - 11:05

Figure 5.353: Experiment 14 - 12:34

Figure 5.354: Experiment 14 - 13:00

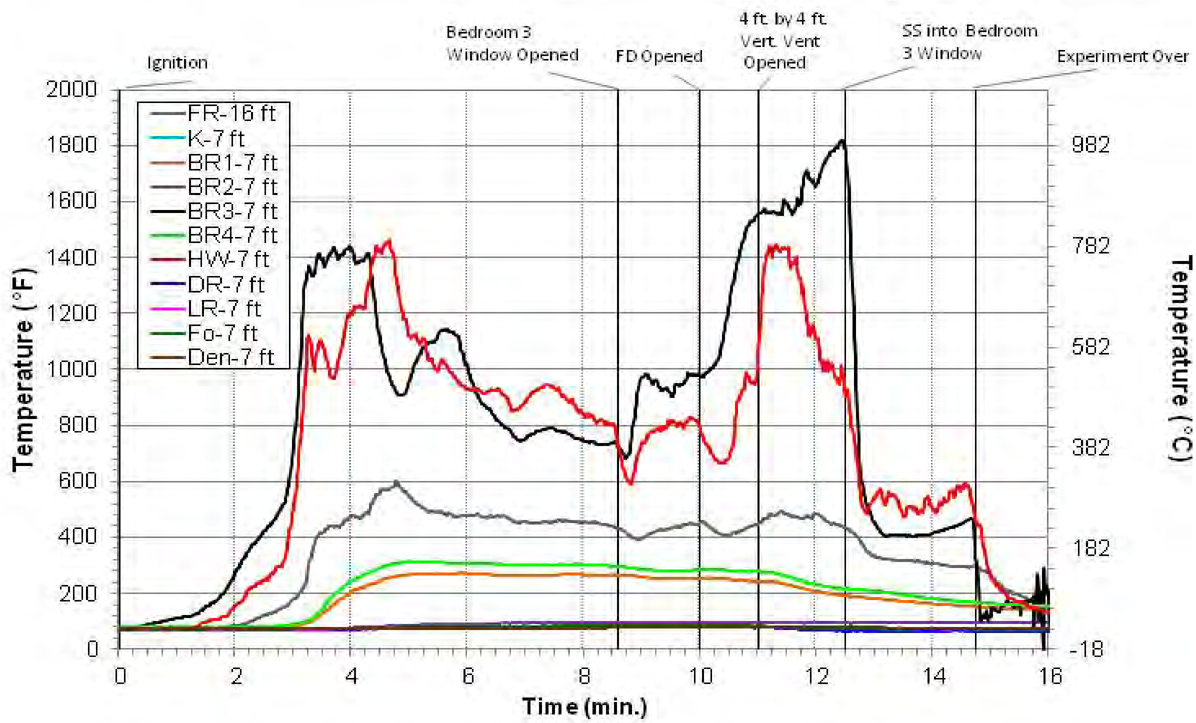


Figure 5.355: Experiment 14 - 7 ft. Temperatures

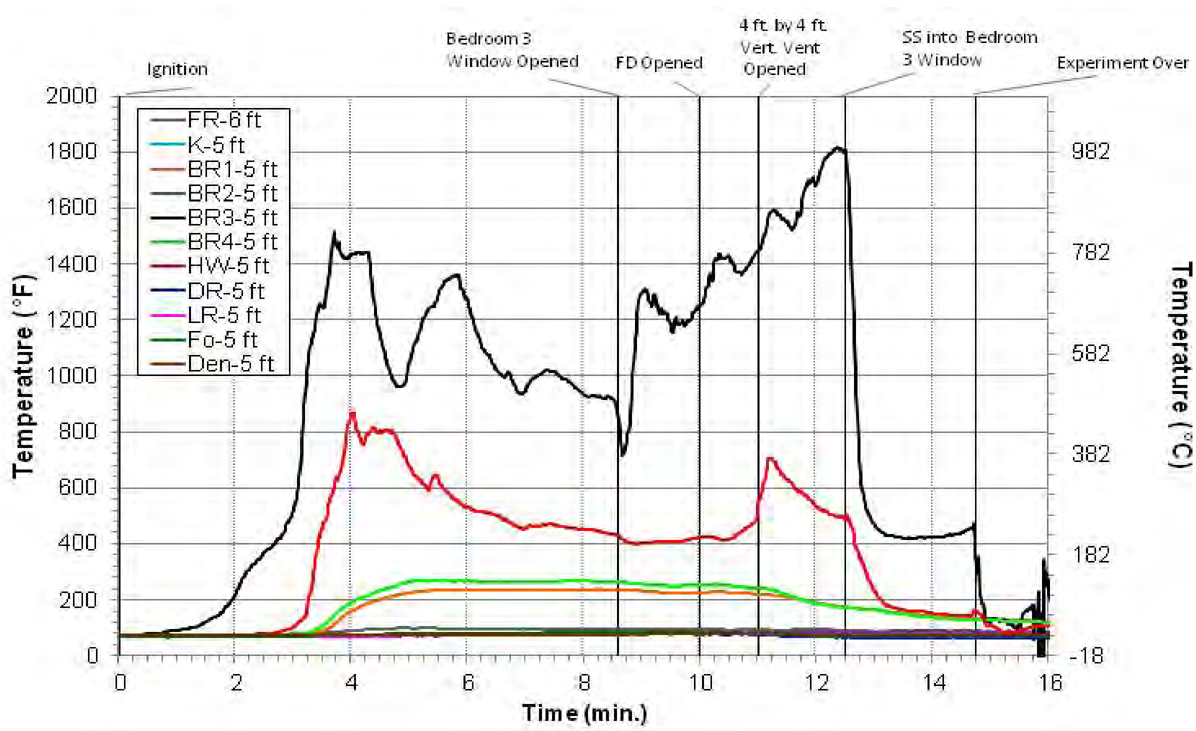


Figure 5.356: Experiment 14 - 5 ft. Temperatures

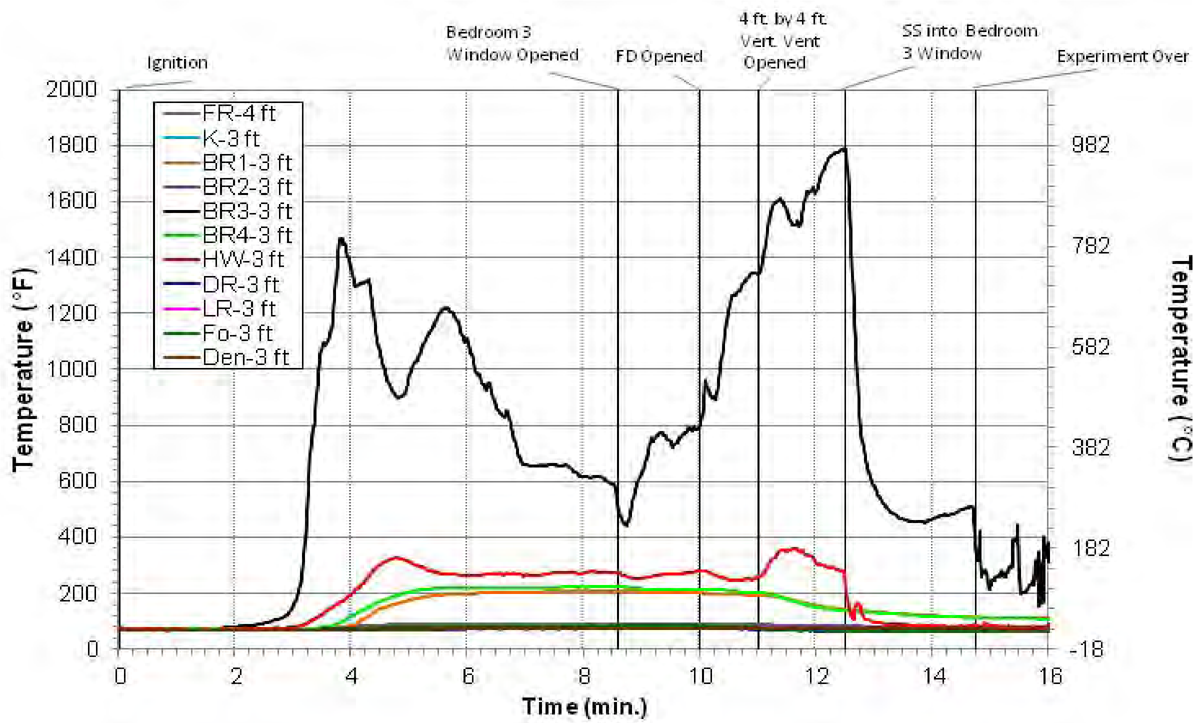


Figure 5.357: Experiment 14 - 3 ft. Temperatures

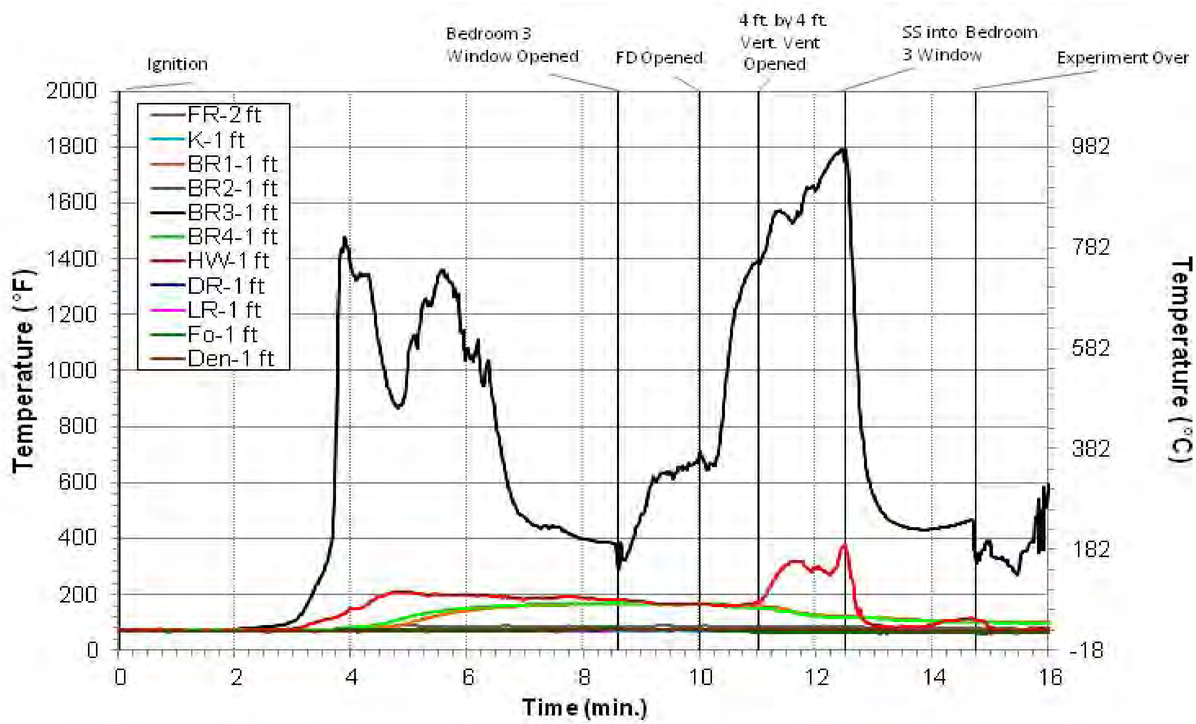


Figure 5.358: Experiment 14 - 1 ft. Temperatures

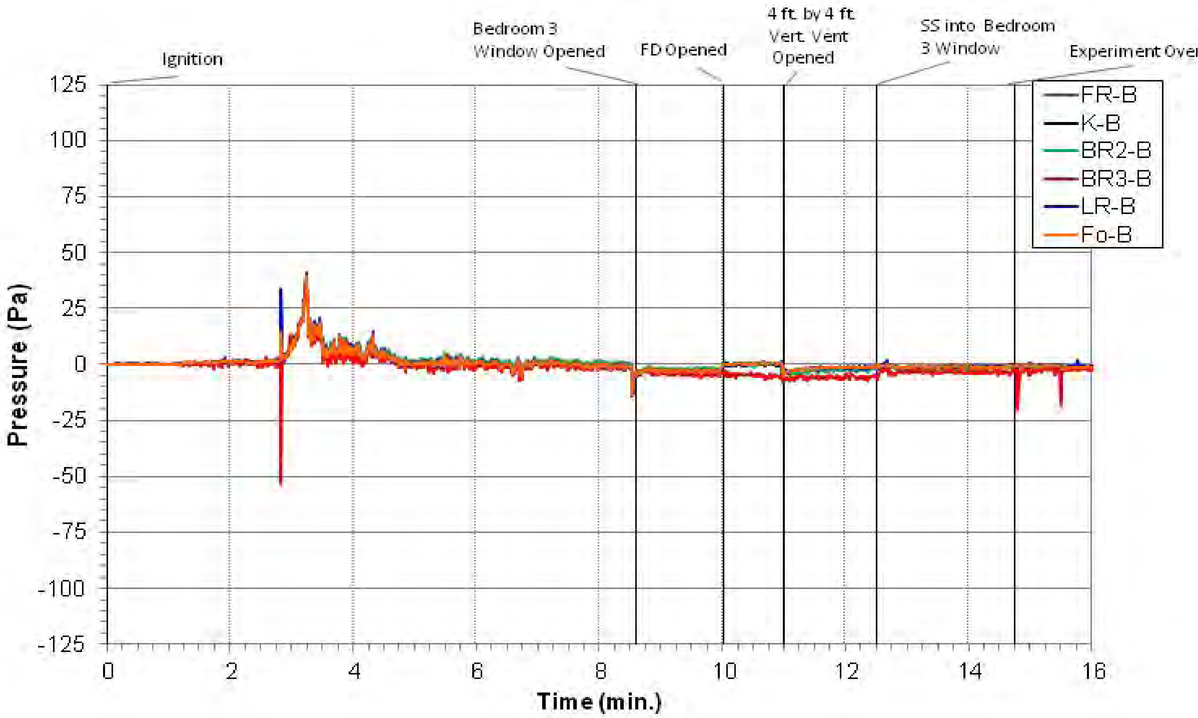


Figure 5.359: Experiment 14 - Bottom Pressure

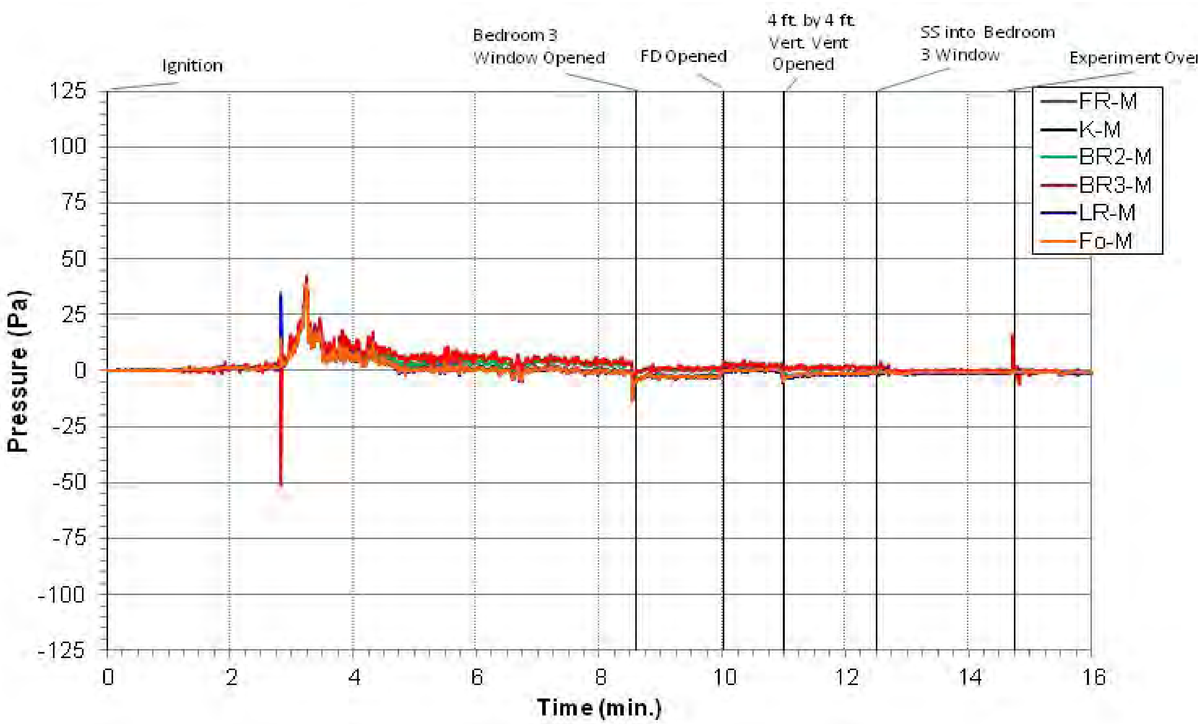


Figure 5.360: Experiment 14 - Middle Pressure

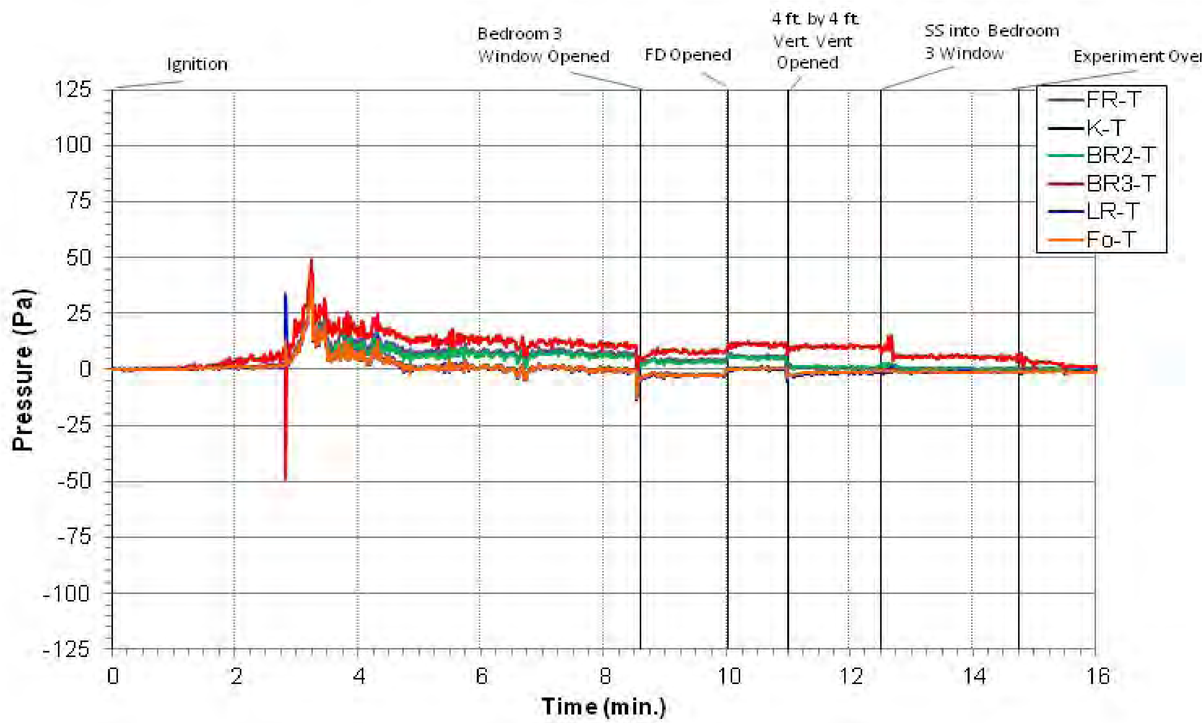


Figure 5.361: Experiment 14 - Top Pressure

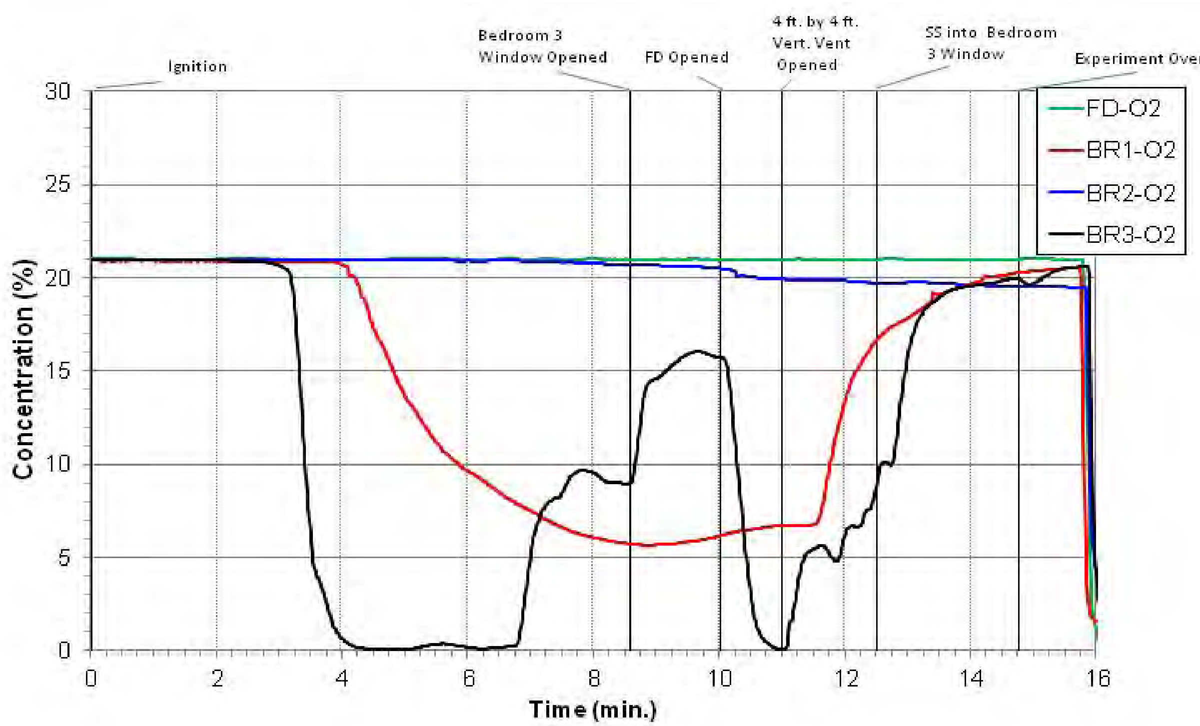


Figure 5.362: Experiment 14 - Oxygen Concentration

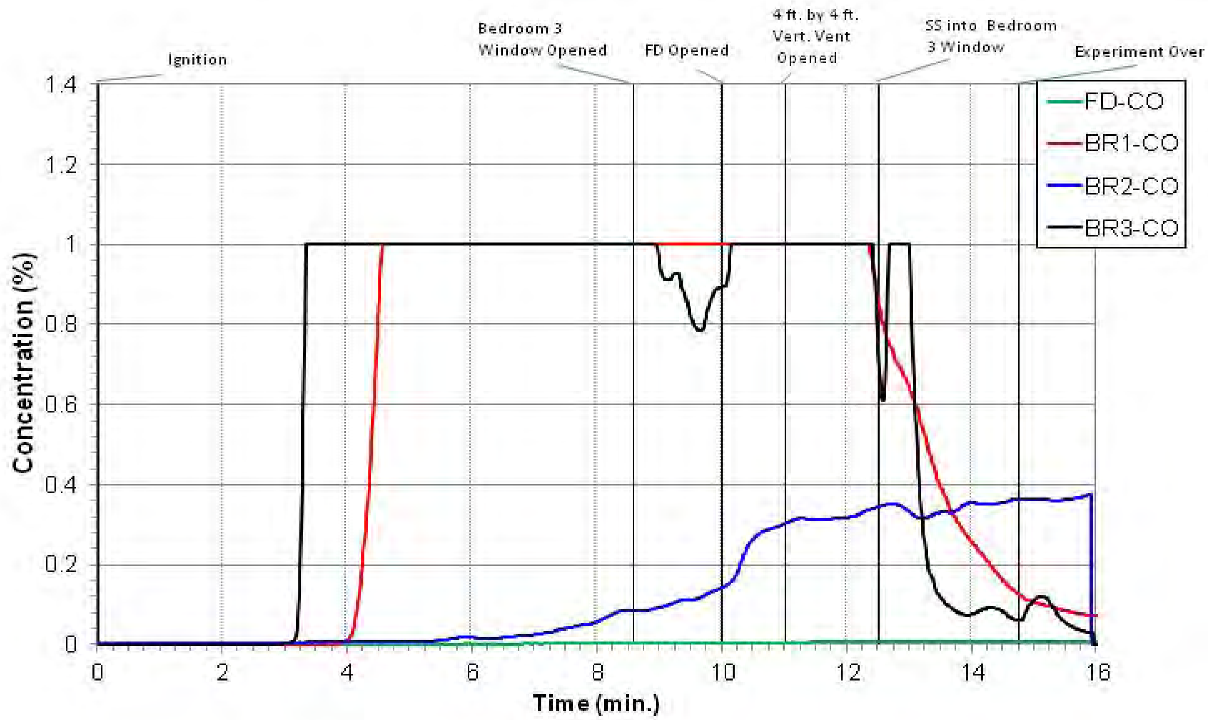


Figure 5.363: Experiment 14 - Carbon Monoxide Concentration

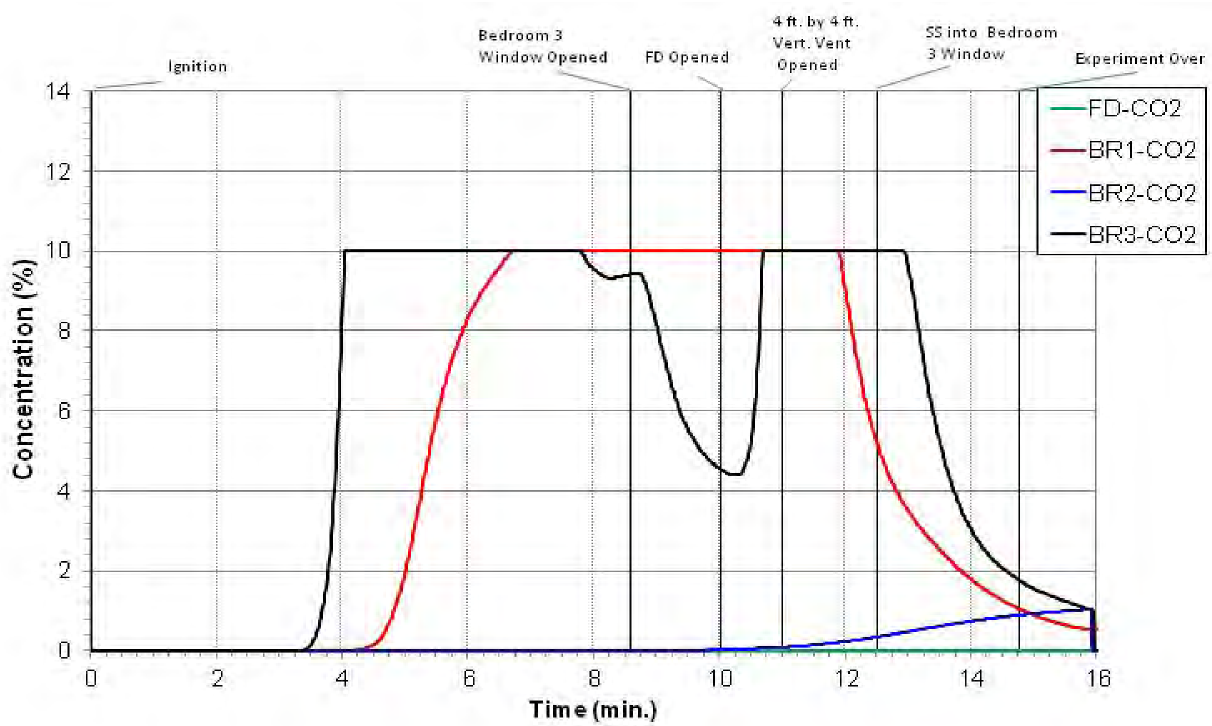


Figure 5.364: Experiment 14 - Carbon Dioxide Concentration

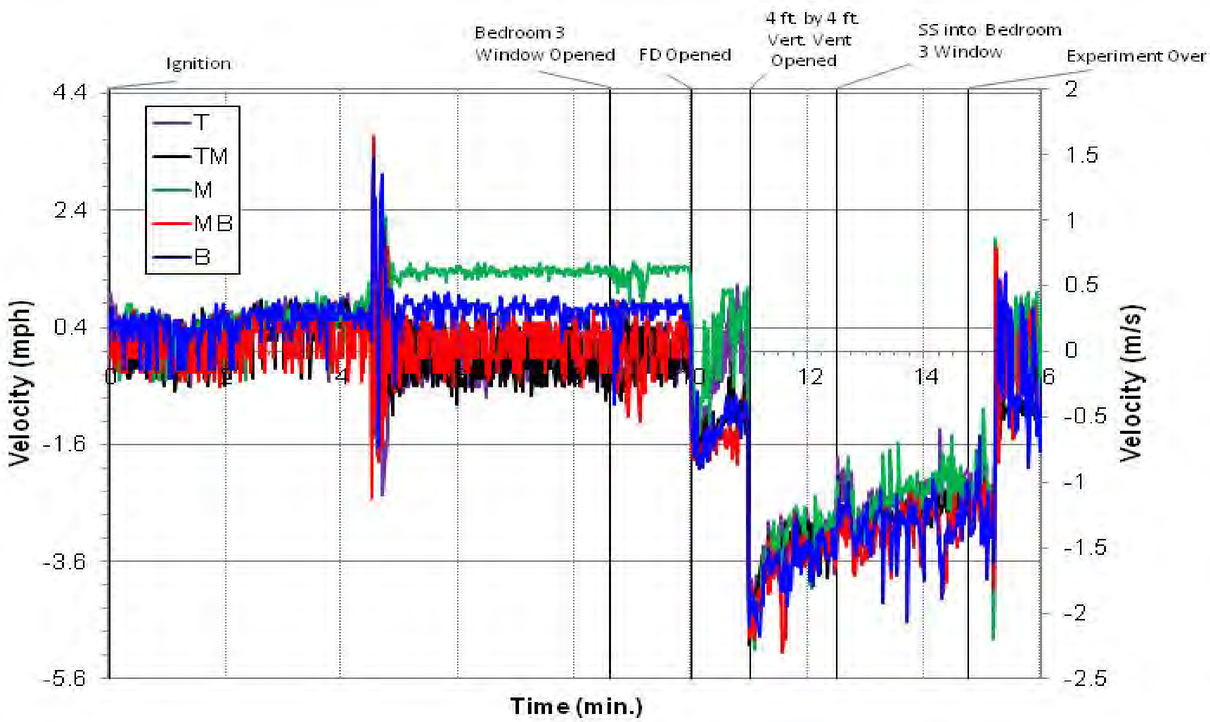


Figure 5.365: Experiment 14 - Front Door Velocity

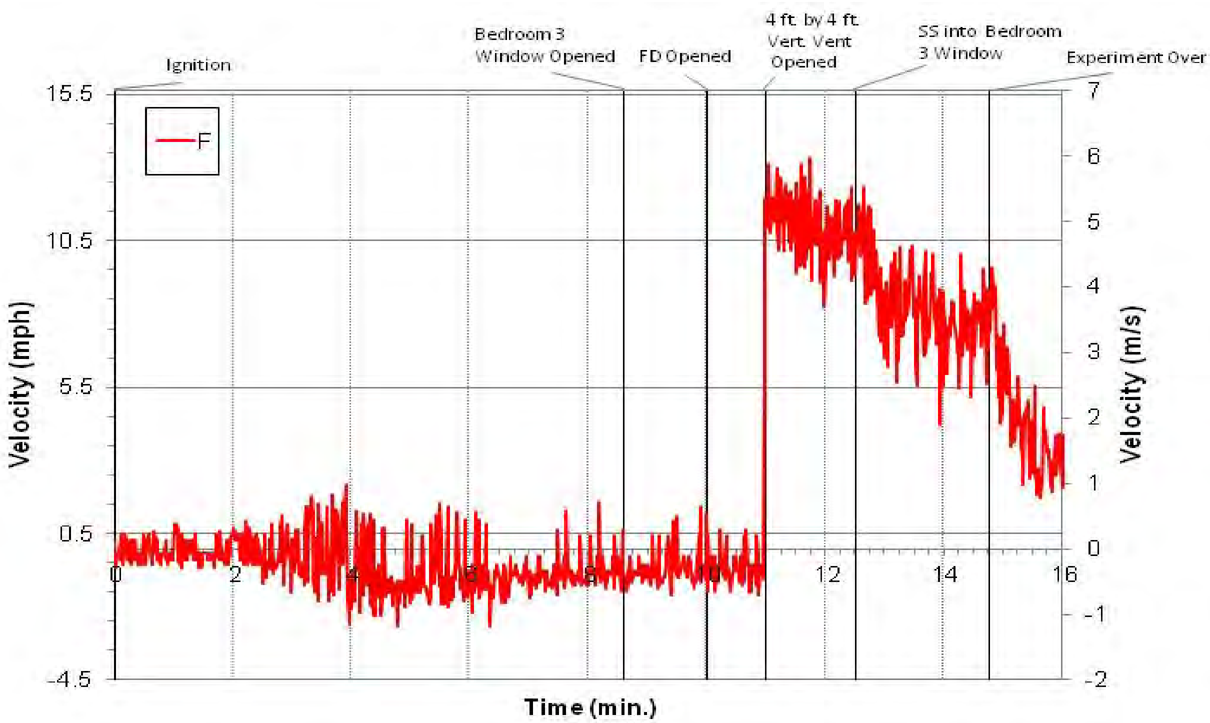


Figure 5.366: Experiment 14 - Roof Vent Velocity

5.7.8. Experiment 16

Experiment 16 was designed to simulate a two-story fire with ignition in the kitchen with fire spread to the family room. A simulated fire crew flowed water in from the outside on a well developed fire to examine the impact on potential occupants on the inside of the structure, especially in the flow path between the family room and the second floor bedroom. The fire was allowed to grow until 17:00, when the family room window was opened. At 21:25, there was an additional ignition in the family room. The fire was then allowed to continue to grow until 27:00, when the Bedroom 3 window was opened. Water was applied to the fire for 15 seconds with a combination nozzle in a straight stream pattern at 28:00. Water was then again applied to the fire for 15 and 14 seconds with a combination nozzle in a fog stream pattern at 29:30 and 31:05 respectively. At 33:30, 17 more seconds of water was applied to the fire with a combination nozzle in a straight stream pattern. The experiment ended at 35:50, and the crew extinguished the fire. Figure 5.368 through Figure 5.378 show images of the house during certain times of the experiment that highlight the events in the timeline. Figure 5.379 through Figure 5.388 detail the temperatures, pressures, gas concentrations, and gas velocities during the experiments.

Table 5.24: Experiment 16 Timeline

Time	Description
0:00	Ignition
17:00	Family Room Window Open
21:25	Additional Ignition in Family Room
27:00	Bedroom Window 3 Open
28:30	Straight Stream into Family Room Window toward Kitchen
29:30	Fog Stream into Family Room Window
31:05	Fog Stream into Family Room Window
33:30	Straight Stream into Family Room
35:50	Final Suppression (End of Experiment)

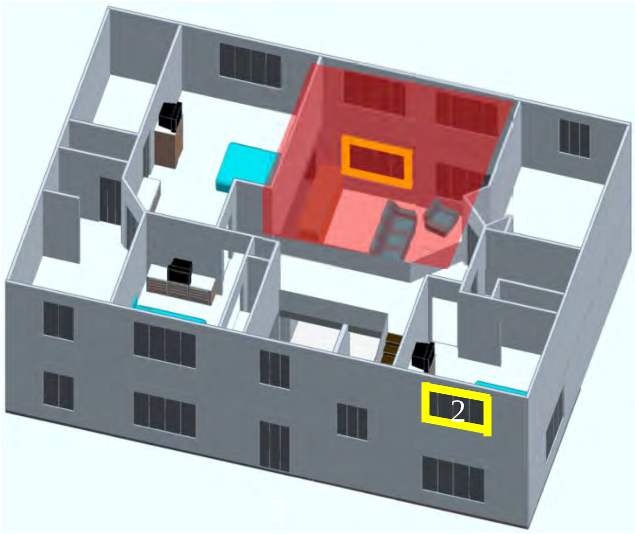


Figure 5.367: Experiment 16 Scenario

Figure 5.368: Experiment 16 - 0:00

Figure 5.369: Experiment 16 - 15:30

Figure 5.370: Experiment 16 - 17:05

Figure 5.371: Experiment 16 - 21:30

Figure 5.372: Experiment 16 - 27:05

Figure 5.373: Experiment 16 - 28:20

Figure 5.374: Experiment 16 - 28:35

Figure 5.375: Experiment 16 - 29:35

Figure 5.376: Experiment 16 - 31:10

Figure 5.377: Experiment 16 - 33:35

Figure 5.378: Experiment 16 - 34:00

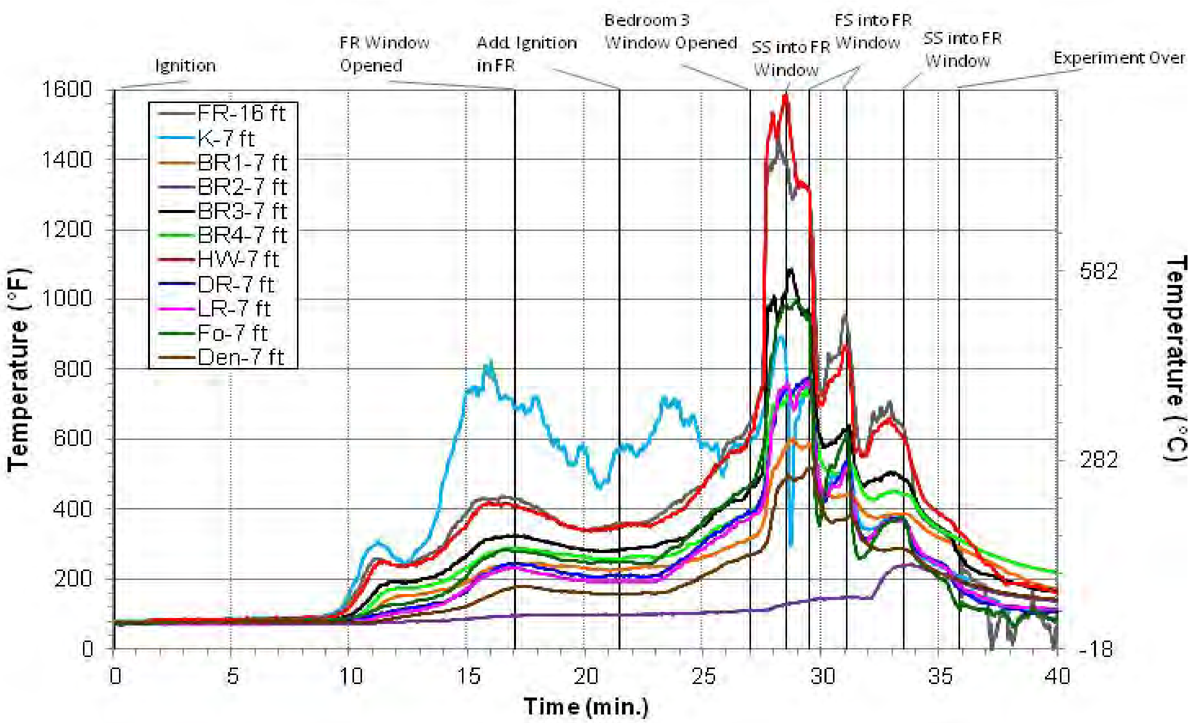


Figure 5.379: Experiment 16 - 7 ft. Temperatures

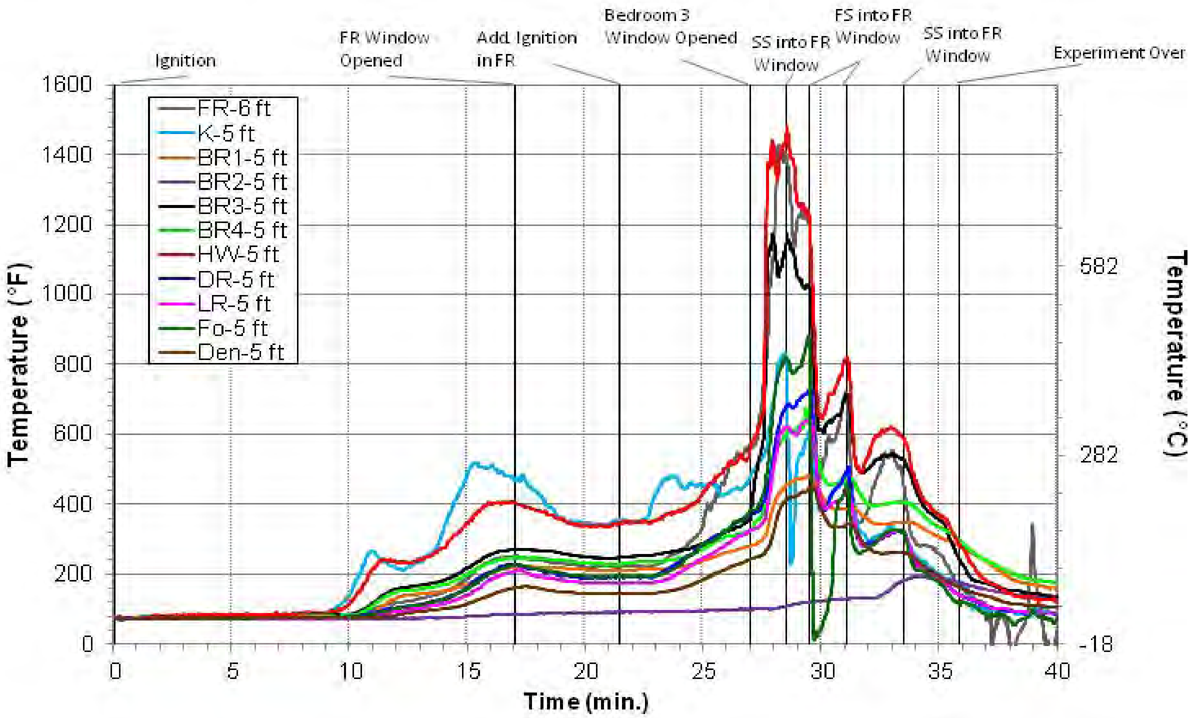


Figure 5.380: Experiment 16 - 5 ft. Temperatures

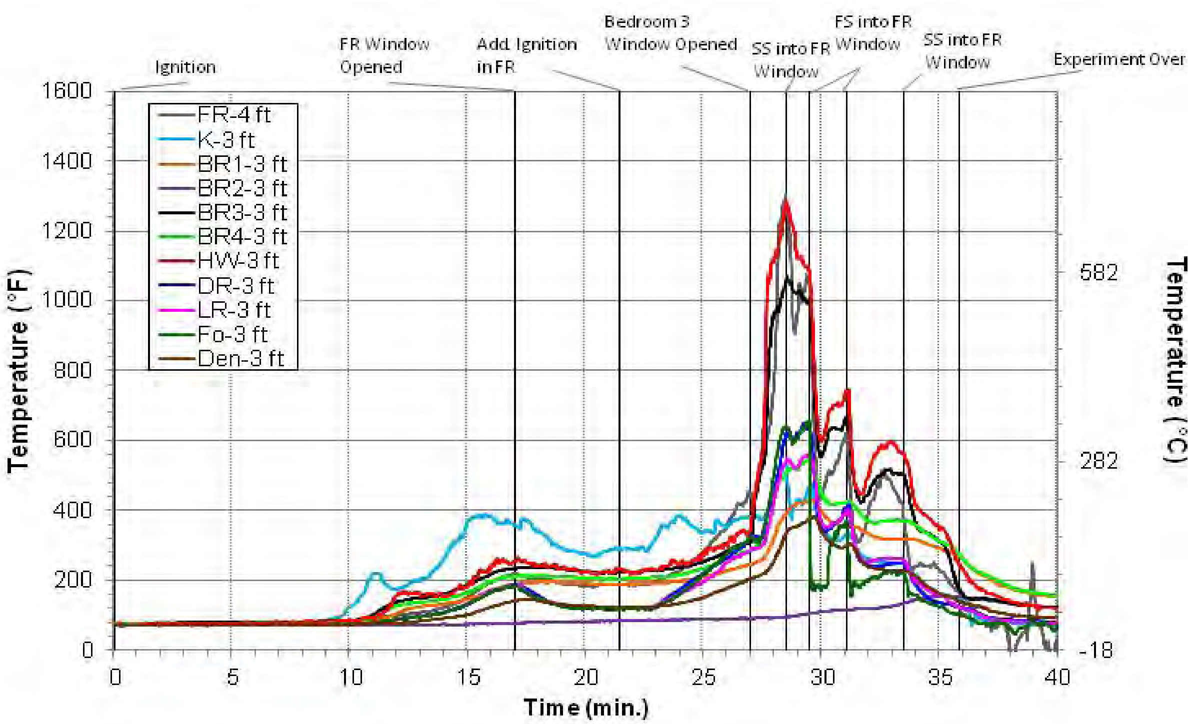


Figure 5.381: Experiment 16 - 3 ft. Temperatures

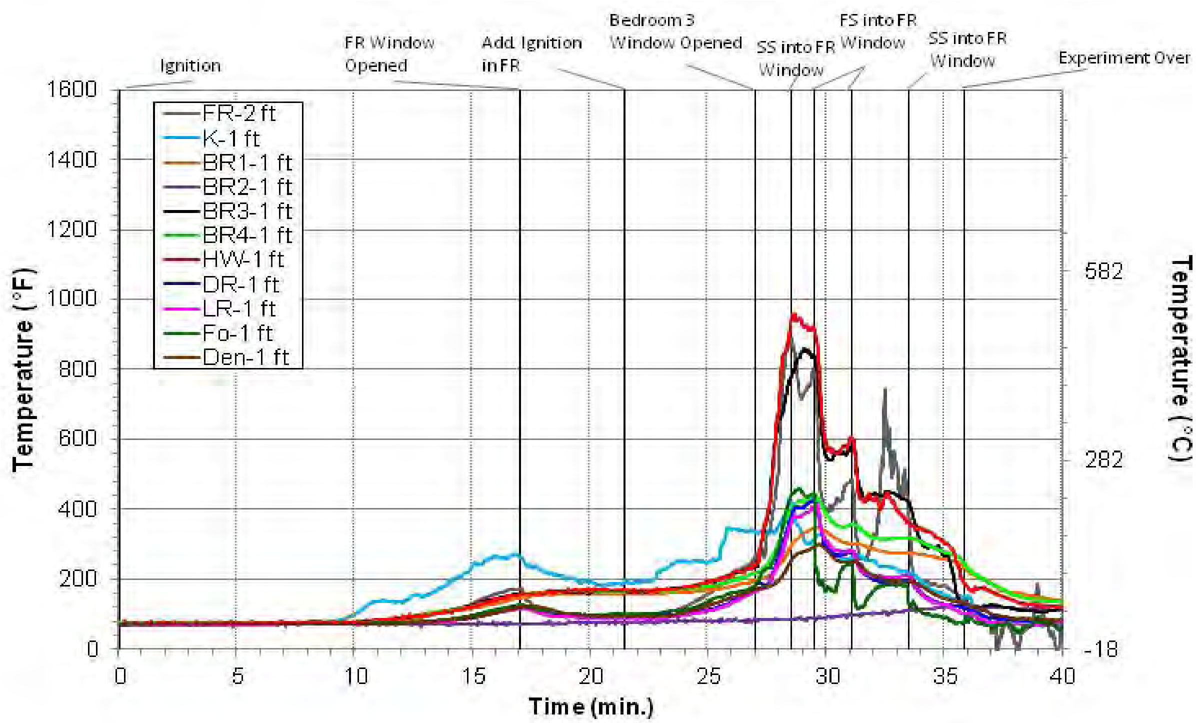


Figure 5.382: Experiment 16 - 1 ft. Temperatures

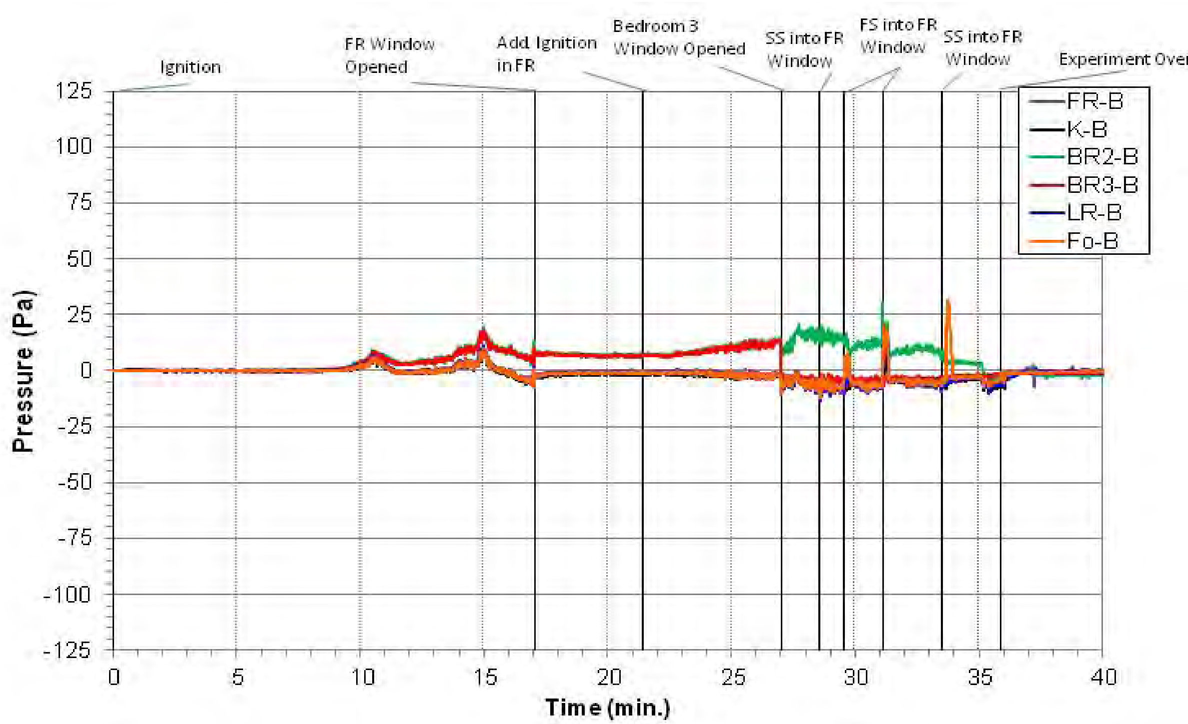


Figure 5.383: Experiment 16 - Bottom Pressure

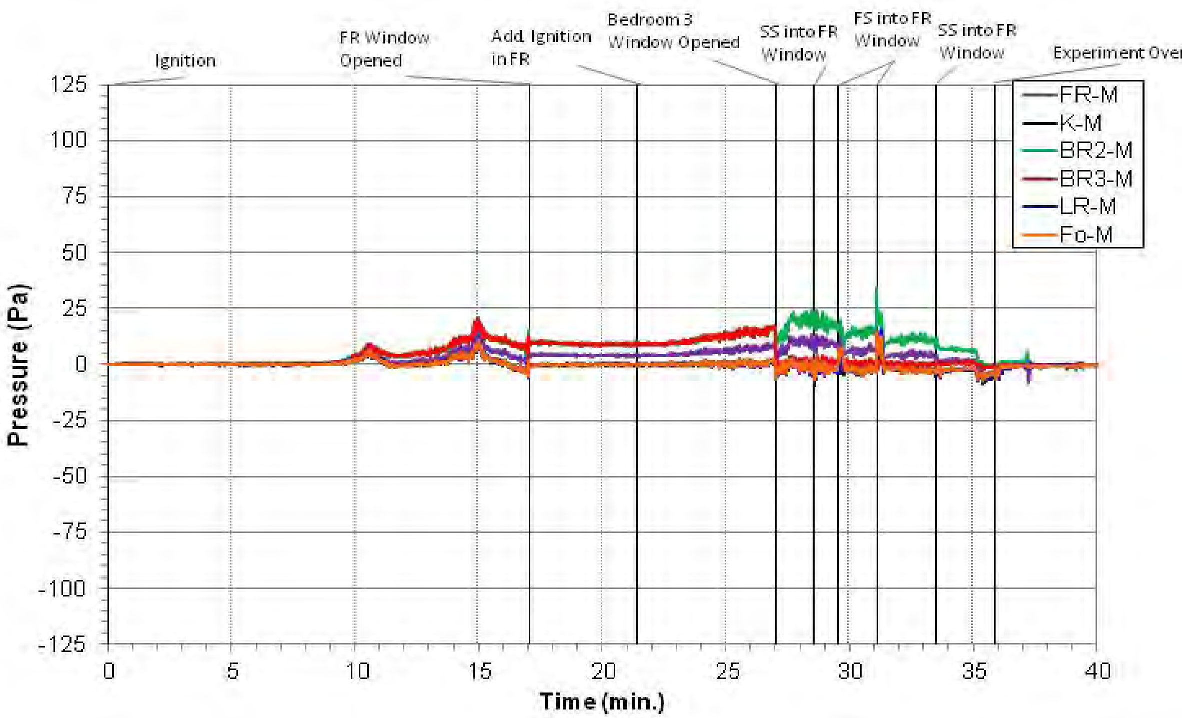


Figure 5.384: Experiment 16 - Middle Pressure

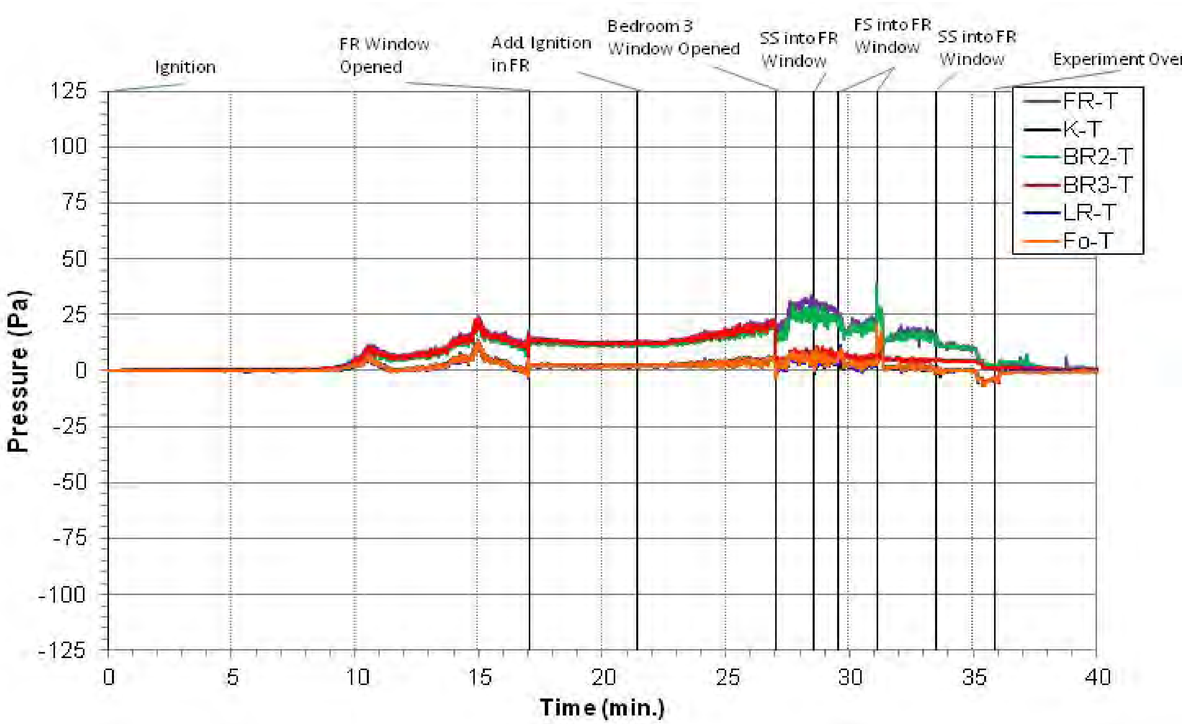


Figure 5.385: Experiment 16 - Top Pressure

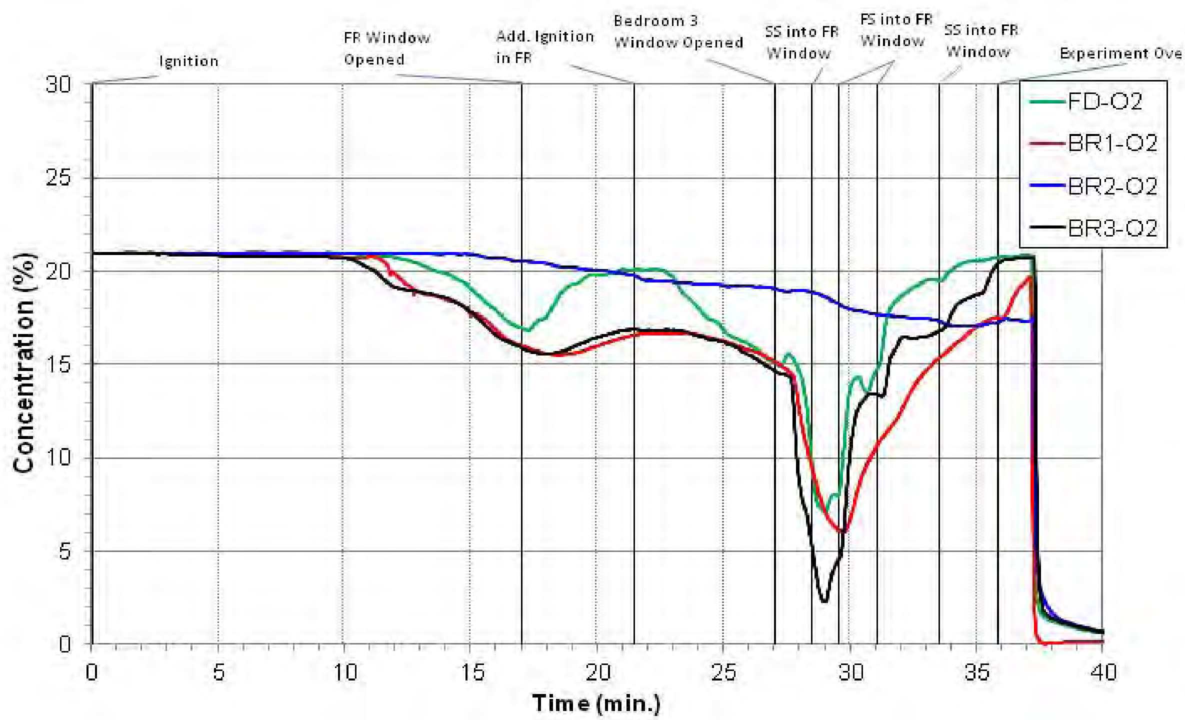


Figure 5.386: Experiment 16 - Oxygen Concentration

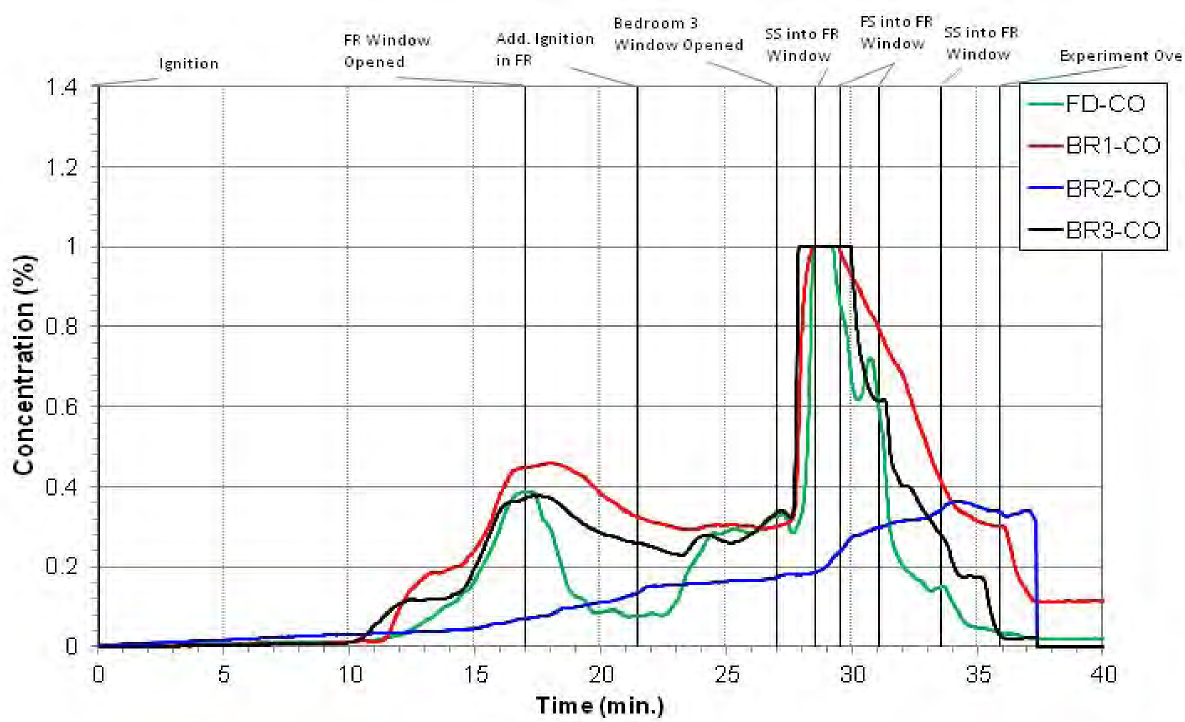


Figure 5.387: Experiment 16 - Carbon Monoxide Concentration

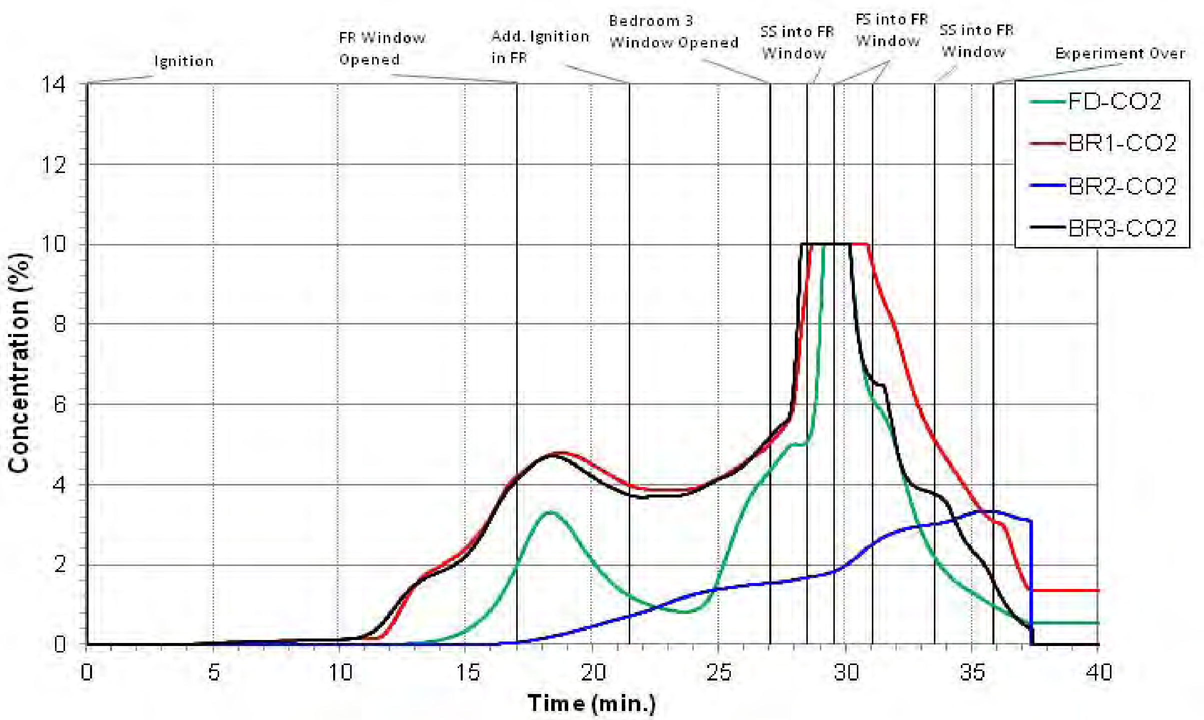


Figure 5.388: Experiment 16 - Carbon Dioxide Concentration

5.8. Discussion

In this section, the experiments' results are analyzed and discussed to develop tactical considerations for the firefighters. Results from the previous horizontal ventilation project titled, Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction (Kerber 2010) will also be used to complement the analysis.

5.8.1. Fuel Load and Repeatability Comparison between Experiment 1 to Experiment 9 (Horizontal Ventilation Project)

Experiment 1 was a replicate of Experiment 9 in the horizontal ventilation study [Now referred to as Experiment 9(H)]. The homes were rebuilt to the same specifications for both experiments, and the ignition sequence and timeline of ventilation openings was the same. The key difference in the experiments was that the fuel load that was purchased at different times and was not expected to be identical. Thus, comparison of the the conditions (e.g., temperature, oxygen concentration, etc.) in the test structure from the previous experiments to this investigation (Experiment 9(H) versus Experiment 1) was essential in establishing linkage between results of the previous horizontal and the current vertical ventilation experiments.

Figure 5.393 through Figure 5.395 compare the 7 ft. and 3 ft. temperatures as well as the oxygen concentrations from Experiment 1 and Experiment 9(H). From these figures it is evident that the temperatures and oxygen concentrations are similar between the two experiments. One difference is that, during flashover, Experiment 9(H) had a higher maximum temperature in the living room than Experiment 1. In both experiments the time to flashover after ventilation of the window is approximately 2 minutes. The temperatures in the non-fire rooms are still approximately equivalent, so the temperatures in the non-fire rooms were not changed much by the increased maximum temperature in the fire room during flashover. The oxygen concentrations also fluctuated similarly, however it is important that while they are measured at different elevations, the same trends can be noticed between the measurements. Through the first 4 minutes the oxygen concentration is unchanged from 21%. It is between 4 and 5 minutes that the oxygen concentration in the living room begins to quickly decrease. The oxygen concentration then recovers in both experiments until the living room reaches flashover, when the oxygen concentration in the living room drops to almost zero percent; and then, after water application, recovers to its previous level before flashover. Overall, this comparison shows that the fuel load from the 2008 and 2011 experiments results in similar behavior in the fire environment in the one-story structure.

Figure 5.389: Experiment 1 Fuel Load

Figure 5.390: Experiment 9H Fuel Load

Figure 5.391: Experiment 1 at 10:35 after ignition

Figure 5.392: Experiment 9H 10:00 after ignition

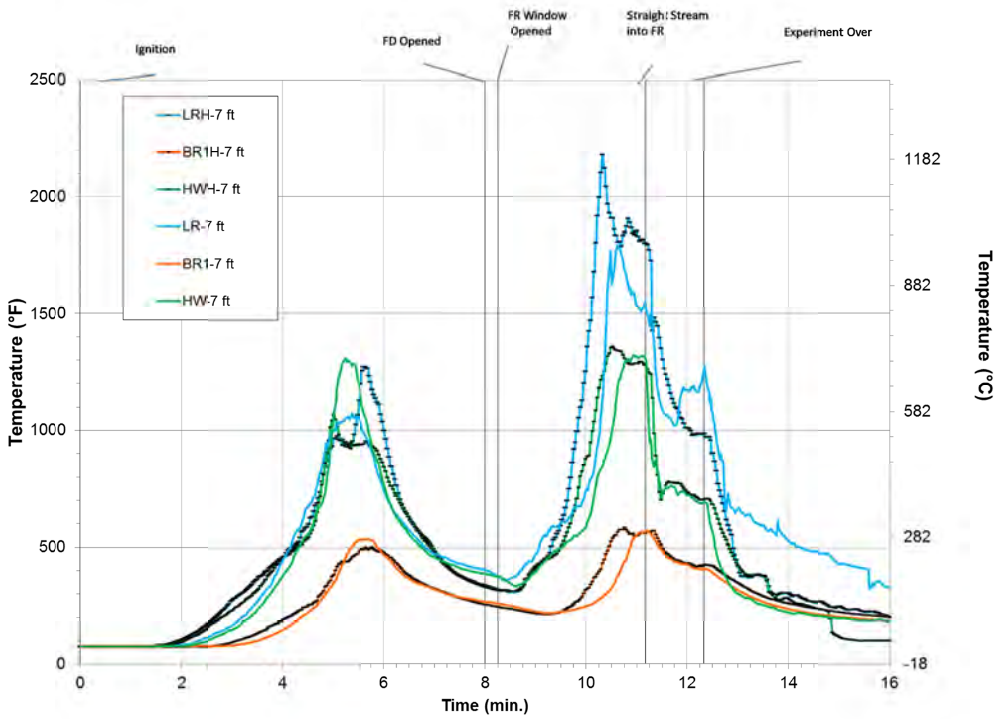


Figure 5.393: Comparison of 7 ft. Temperatures

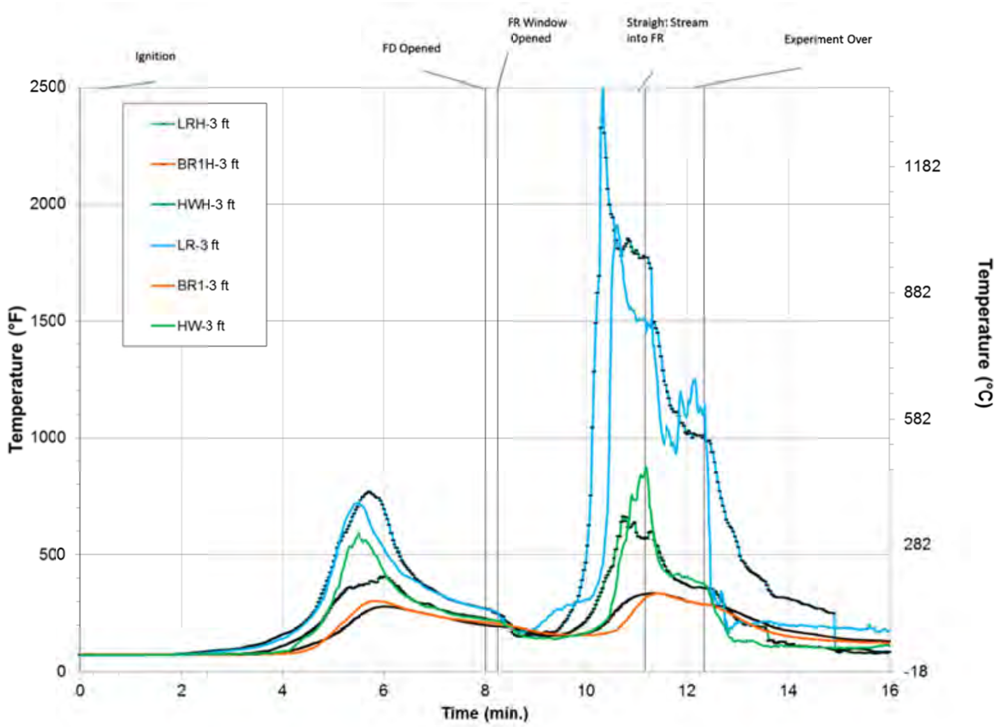


Figure 5.394: Comparison of 3 ft. Temperatures

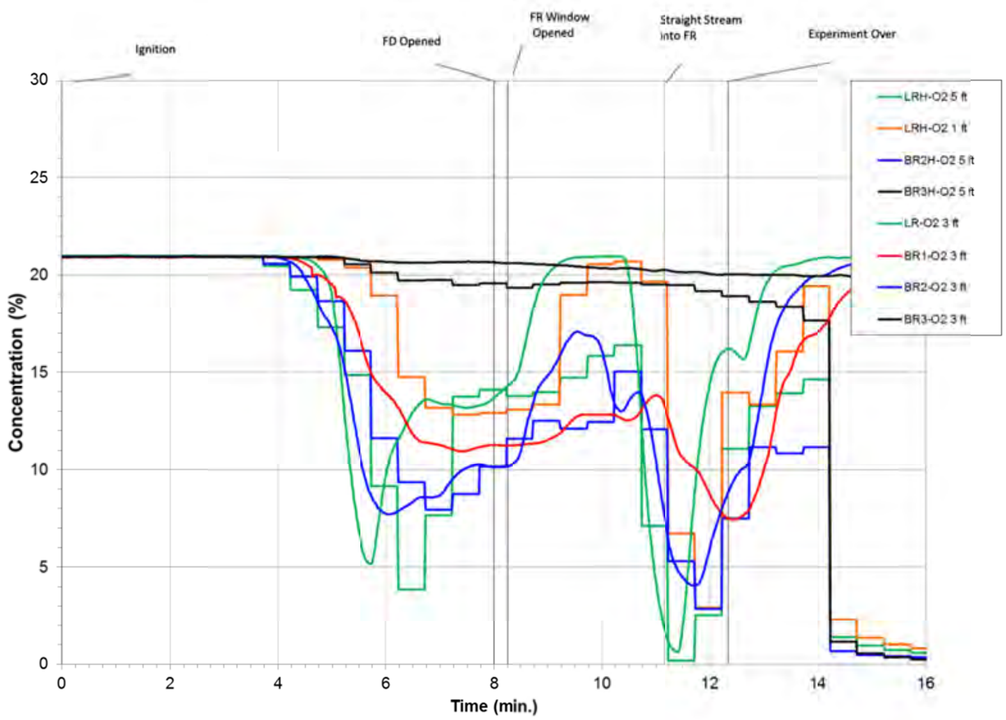


Figure 5.395. Comparison of Oxygen Concentrations

5.8.2. Fuel Load and Repeatability Comparison between Experiment 2 to Experiment 11 (Horizontal Ventilation Project)

A similar comparison of the fuel load was performed for the 2-story structure using Experiment 2 of the current study and Experiment 11 in the horizontal ventilation study (Now referred to as Experiment 11H). As with the single story structure, the 2-story structures were also built to identical specifications. The ignition sequence and timeline of ventilation openings was the same.

Figure 5.400 through Figure 5.402 compare the 16 ft. and 4 ft. family room temperatures, and the 7 ft. and 3 ft. Bedroom 3 and second floor hallway temperatures, as well as the oxygen concentrations from Experiment 2 and Experiment 11H. The temperatures reached before ventilation are similar, with Experiment 2 peaking and becoming ventilation-limited slightly faster than Experiment 11H. The time from ventilation to flashover was within 1 minute between the experiments, and the peak temperatures reached after ventilation were within 25%. The largest difference was at the 4 ft. elevation in the family room, but the shapes of the curves are consistent, indicating similar fire behavior in both experiments. The oxygen concentrations were not measured in the same locations between the experiments but they also follow the same trend lines, indicating similar fire behavior.

Figure 5.396: Experiment 2 Fuel Load

Figure 5.397: Experiment 11H Fuel Load

Figure 5.398: Experiment 2 14:21 after Ignition

Figure 5.399: Experiment 2 14:25 after Ignition

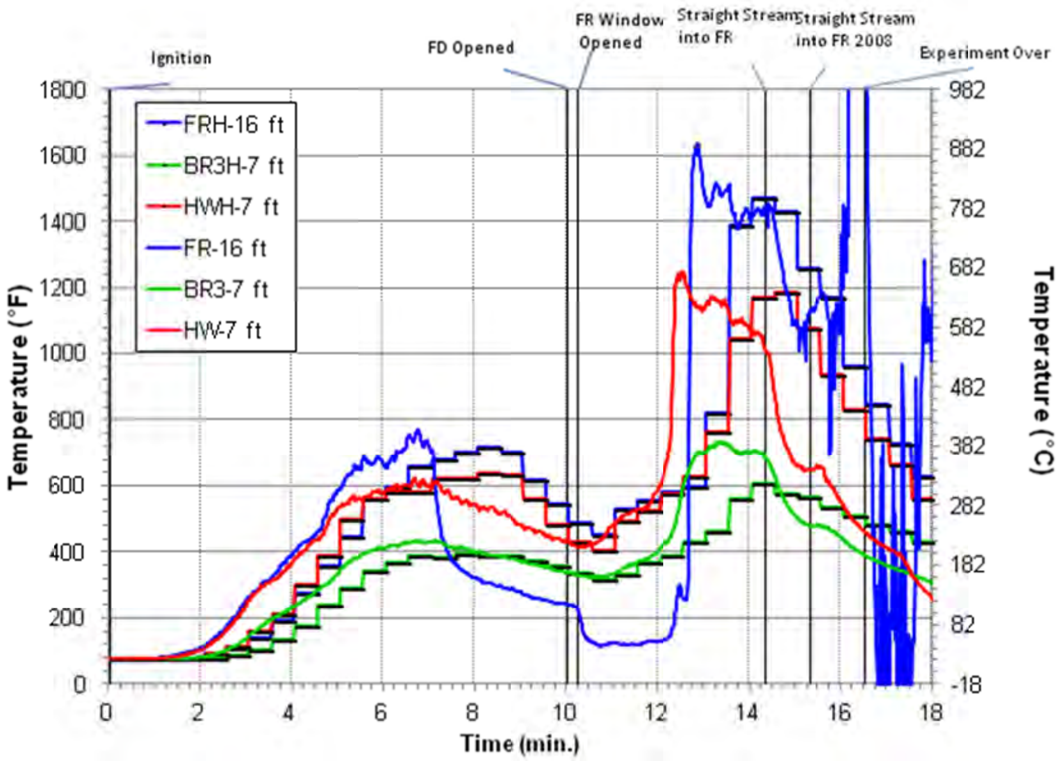


Figure 5.400: Comparison of 16 and 7 ft. temperatures

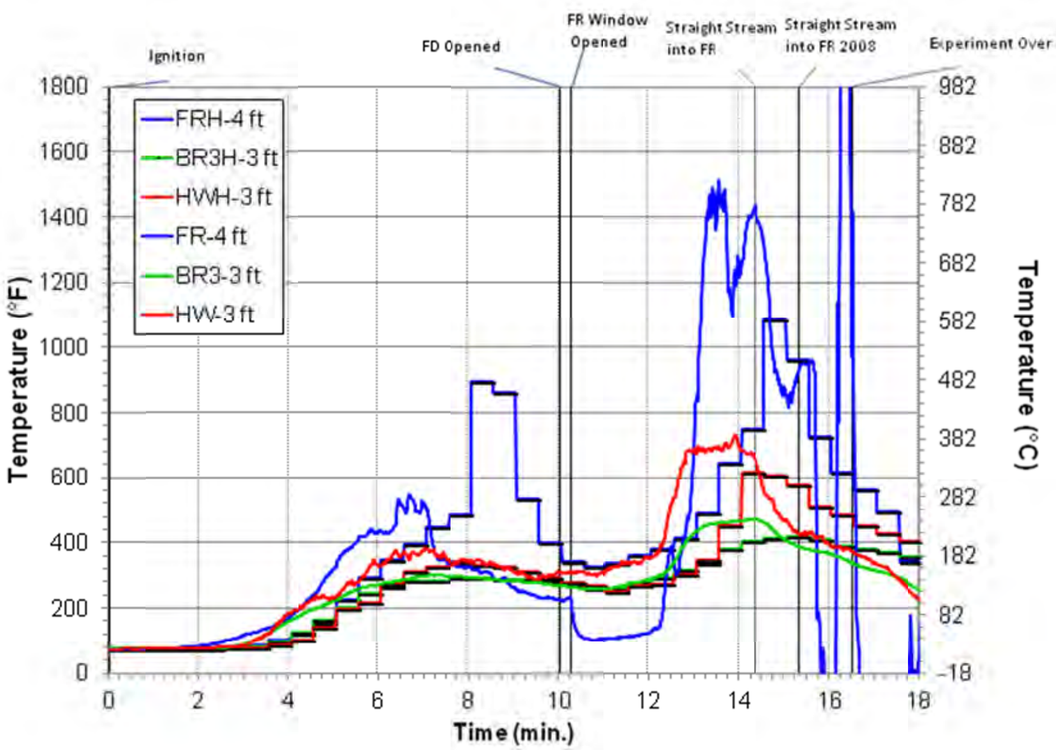


Figure 5.401: Comparison of 3 ft. temperatures

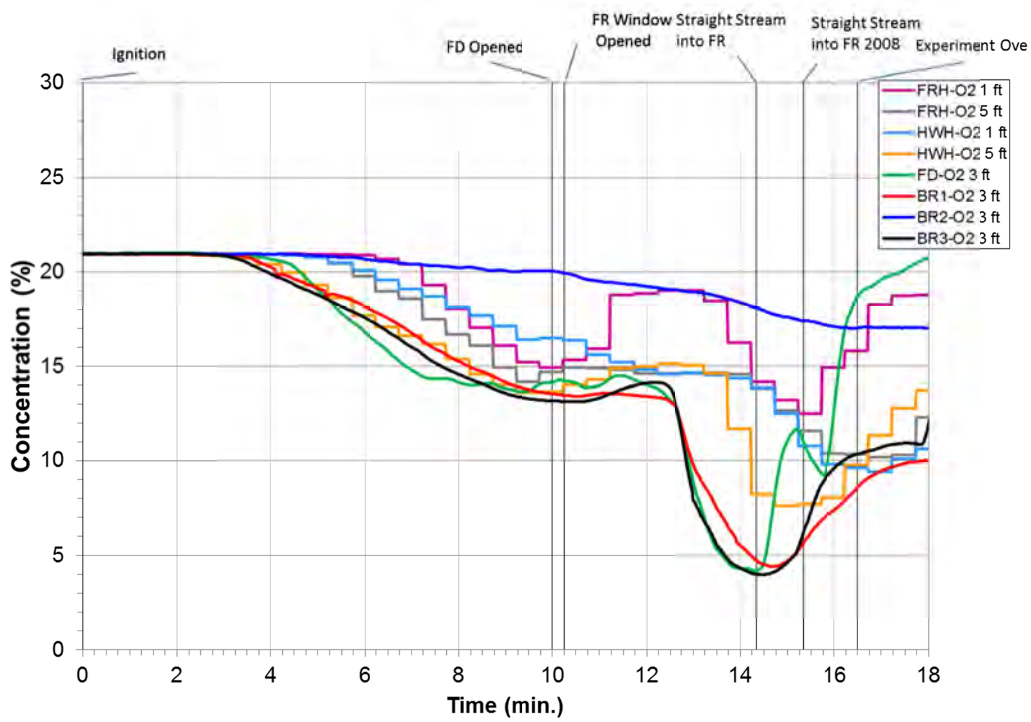


Figure 5.402: Comparison of oxygen concentrations

5.8.3. Door Control Comparison between Experiments 3 and 5 in the One-Story House

The main difference between Experiment 3 and Experiment 5 was the position of the front door once it was opened at 8 minutes after ignition. In Experiment 3, it was opened all the way to simulate a crew entering, and then it was closed to approximately 4 inches to allow sufficient space for their hoseline to be in the doorway. In Experiment 5, the door was opened completely at 8 minutes and then locked open for the duration of the Experiment. Once the living room temperature reached 400 °F at 3 ft. above the floor, the roof was ventilated. The comparison between the two tests are made up to the time of roof ventilation point and does not take into account the changes induced by the roof vent being opened.

Figure 5.403 shows the temperatures in the living room at 7 ft and 3 ft for Experiment 3 and Experiment 5. The temperatures are similar before affecting ventilation through the door, indicating that the fuel loads are similar in the two structures. The main difference is the growth of the 3 ft and 7 ft temperatures. In Experiment 5, the 3 ft and 7 ft temperatures begins to rapidly increase, while in Experiment 3, they remain relatively constant. This difference is explained by Figure 5.404, which shows the air and gas velocities through the front door for the two experiments. The bottom velocity is negative (incoming air) and approximately the same in Experiment 5 and in Experiment 3. The higher area of ventilation in Experiment 5 means that although the incoming velocities are the same in the two experiments, the incoming mass of oxygen is much larger in Experiment 5. The large amount of incoming oxygen results in the fire growth, and explains the temperature growth observed in Experiment 5.

Figure 5.405 shows conditions at the front of the house during both experiments and a thermal imaging view from Bedroom 2 looking back toward the living room fire. These images show the faster deterioration of conditions with the front door fully open versus controlled to be open the width of a hoseline. The thermal imaging views show conditions that are worse in the bedroom 2 minutes after a simulated crew entered the house, 10:00 in Experiment 5, versus 4 minutes after the simulated crew entered the house in Experiment 3.

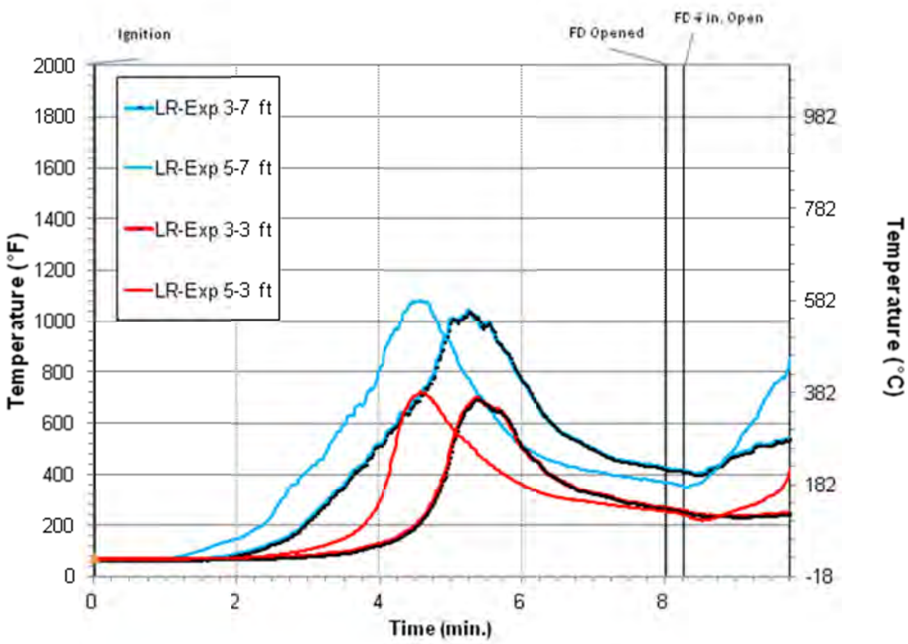


Figure 5.403: Comparison of 7 and 3 ft. Living Room Temperatures

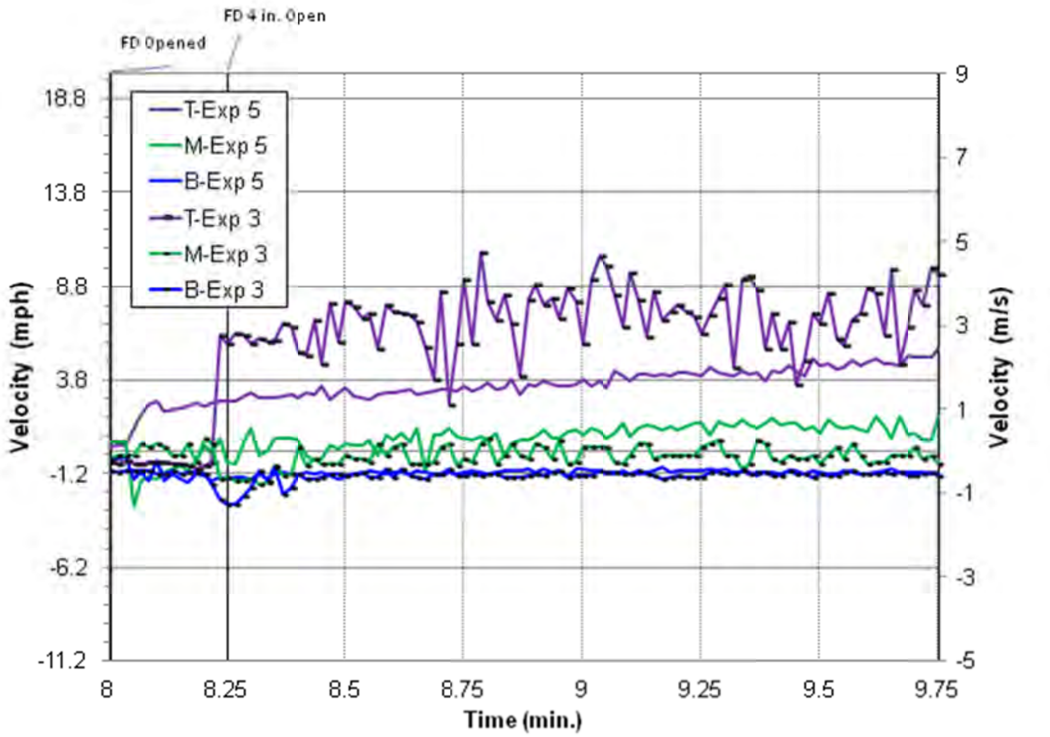


Figure 5.404: Comparison of Front Door Velocities

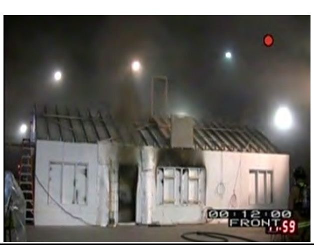
Experiment 3 – Door Control		Experiment 5 – Door Open	
9 Minutes			
			
10 Minutes			
			
12 minutes			
		Temperature exceeded and roof vent was finished being opened at 10:00 so no comparison pictures at 12:00	

Figure 5.405: Comparison of one-story door control experiments

5.8.4. Door Control Comparison between Experiments 4 and 6 in the Two-Story House

A similar comparison of the influence of the door control was performed for the two-story structure using data from Experiment 4 and Experiment 6. The main difference between these experiments was the position of the front door once it was opened, which was at 10 minutes after ignition. In Experiment 4, it was opened all the way to simulate a crew entering, and then it was closed to approximately 4 inches to allow sufficient space for their hoseline to be in the doorway. In Experiment 6 the door was opened completely at 10 minutes and locked open for the duration of the Experiment. The comparison between the two tests is made up to the time of roof ventilation point and does not take into account the changes induced by the roof vent being opened.

Figure 5.406 shows the temperatures in the family room at 16 ft and 4 ft for Experiment 4 and Experiment 6. The temperatures are similar before affecting ventilation through the door, suggesting the fuel loads are similar in the two structures. The key difference is the growth of the 4 ft temperature. In Experiment 6, the 4 ft temperature begins to rapidly increase, while in Experiment 4 it remains relatively constant. This difference is explained by Figure 5.407, which shows the front door velocities for the two experiments. The bottom velocity is more negative (incoming air) in Experiment 6 than in Experiment 4. The higher velocity of incoming air in Experiment 6 and the higher area of ventilation in Experiment 6 means that the family room is being supplied with more oxygen in Experiment 6 than in Experiment 4, which explains the temperature growth observed in Experiment 6.

Additionally, from the calculated CO tenability times (Table 5.25 and Table 5.26), it can be seen that Experiment 4 has longer times to untenability than Experiment 6. So, reducing the ventilation area at the door in the two-story structure reduces the danger of temperature and carbon monoxide poisoning within the two-story structure. This can be seen as counterintuitive because the conventional thinking is that ventilation allows the smoke to leave and therefore should reduce the CO concentrations. However, the additional combustion that takes place due to the oxygen allowed in by the ventilation opening outweighs the reduction due to smoke exiting the structure.

Figure 5.408 shows conditions at the front of the house during both experiments and an internal view of the family room. These images show the faster deterioration of conditions with the front door fully open versus controlled to be open the width of a hoseline. The interior views show conditions that are worse 1 minute after a simulated crew entered the house, 11:00 in Experiment 6, versus 3 minutes after the simulated crew entered the house in Experiment 4.

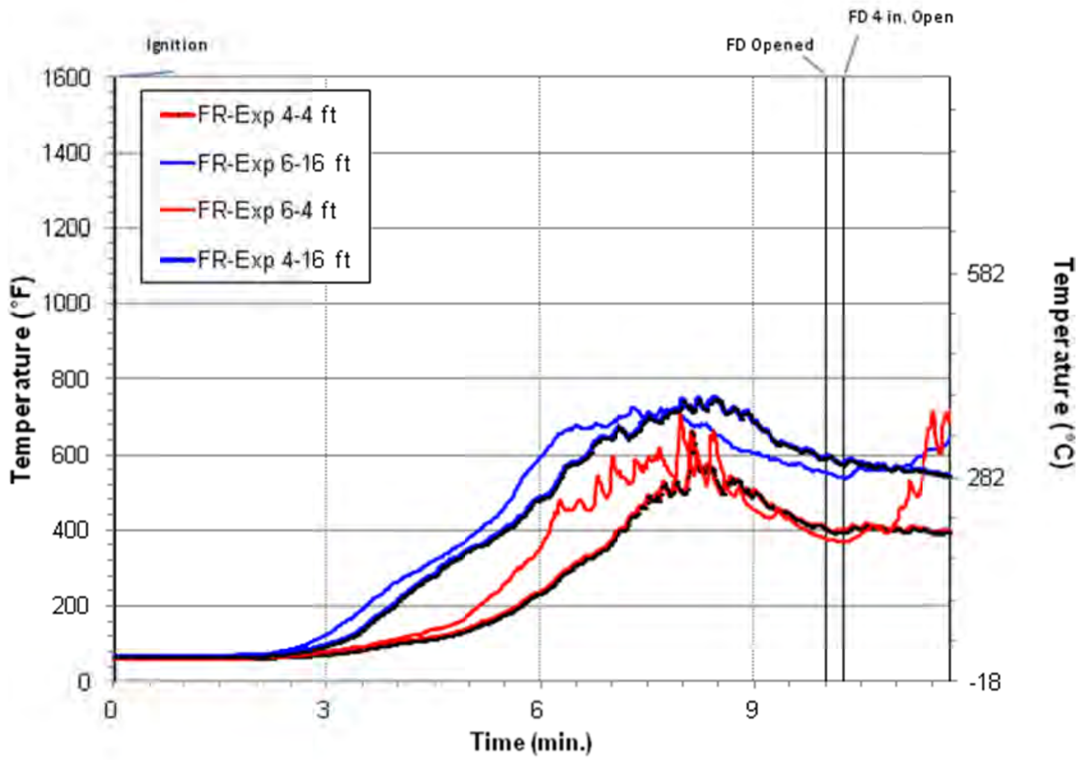


Figure 5.406: Comparison of 16 ft. and 4 ft. Temperatures

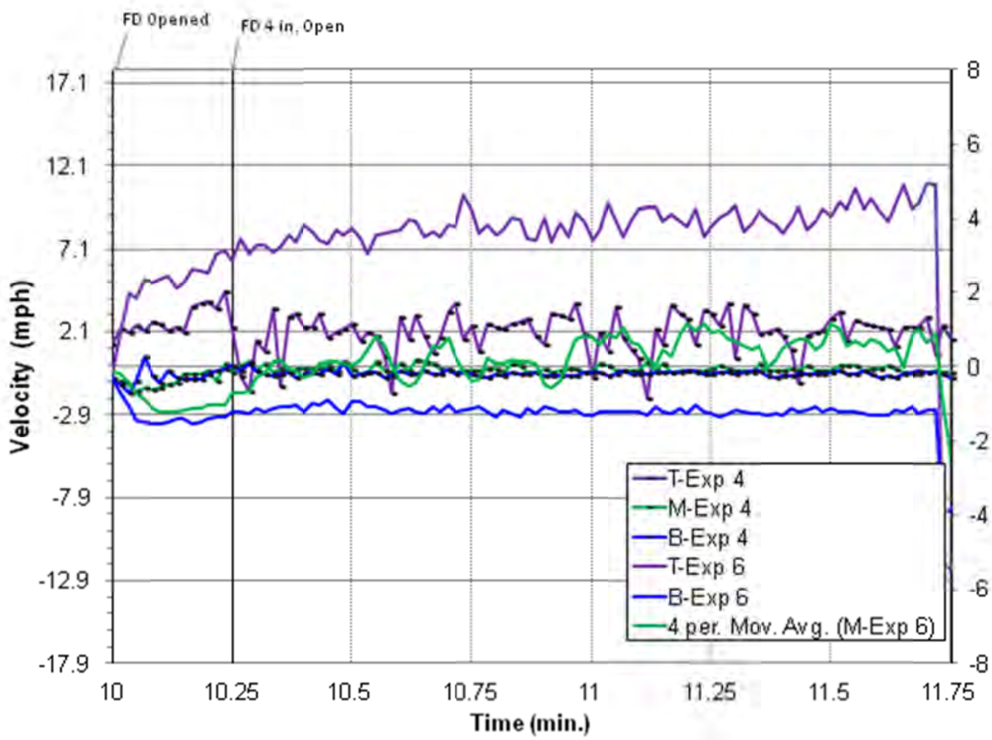


Figure 5.407: Comparison of Front Door Velocities

Table 5.25: Time to Untenability in Two-Story Experiments for FEC = 0.3

	FD @ 3 ft. (mm:ss)	BR1 @ 3 ft. (mm:ss)	BR2 @ 3 ft. (mm:ss)	BR3@ 3 ft. (mm:ss)
Experiment 4	09:28	10:43	N/A	10:25
Experiment 6	08:49	10:08	N/A	10:00

Table 5.26: Time to Untenability in Two-Story Experiments for FEC = 1.0

	FD @ 3 ft. (mm:ss)	BR1 @ 3 ft. (mm:ss)	BR2 @ 3 ft. (mm:ss)	BR3@ 3 ft. (mm:ss)
Experiment 4	12:55	13:32	N/A	13:22
Experiment 6	11:54	12:40	N/A	12:42

Experiment 4 – Door Control	Experiment 6 – Door Open
11 Minutes	
 	 
12 Minutes	**11 Minutes 45 Seconds**
 	 
13 Minutes	Temperature exceeded and roof vent was finished being opened at 11:45 so no comparison pictures at 12:00 or 13:00
 	

Figure 5.408: Comparison of two-story door control experiments

5.8.5. Impact of Vertical Ventilation Hole Size comparing Experiments 5 and 7 in the one-story house

Firefighter training publications have suggested ventilation hole size in homes be a minimum of 4 ft. by 4 ft but the reasons for this recommendation are not well-documented. Two experiments were conducted with vertical ventilation holes located above the fire; Experiment 5 had a 4 ft. by

4 ft. hole, and Experiment 7 had a 4 ft. by 8 ft. hole. In order to perform the vertical ventilation in a way that could be comparable between experiments, the vertical ventilation was opened using exterior crew1 min and 45 s after the front door was opened and followed by the interior crew entering the home. Prior to ventilation both experiments had similar temperatures that grew and decreased as conditions became ventilation-limited. At 8 minutes after ignition in both experiments the front door was opened and by 9:45 the roof vent was opened. Shortly after the roof vent was opened, the ceiling was opened (simulating a crew pushing down the interior ceiling with a tool) to the same size as the ventilation hole on the roof. In both experiments the additional air from the front door began to increase burning, subsequently increasing the temperatures throughout the house. Once the roof vent was opened the living rooms transitioned to flashover, at approximately 10:15 in both experiments, and temperatures throughout the house increased (Figure 5.409 and Figure 5.410).

In Experiment 7, smaller non-fire room temperatures were observed and may be explained by the larger vertical ventilation area. This is expected to result in more of the hot gases exiting through the vertical vent rather than spread to the non-fire rooms. On average this difference is less than 100 °F. There was no increase in visibility in either experiment after the roof vents were opened. There was only 15 seconds between roof ventilation and flashover in both experiments, where flames not only exited the roof vent but also the front doorway.

Figure 5.411 and Figure 5.412 show a comparison of front door velocities and roof vent velocities. Just after roof ventilation in both experiments, the flow at the front door moves completely inward, and hot gases flow out through the roof. This quickly changes as burning increases, and air flows in through the bottom two thirds of the doorway and the top third of the doorway. The flow inward with the 4 ft by 4 ft hole was approximately 2 mph and was approximately 6 mph with the 4 ft by 8 ft hole. This additional inward flow with the larger hole resulted in a 30 mph average flow out of the roof vent as compared to an average flow of 25 mph out of the smaller roof vent.

Figure 5.413 shows the comparison between oxygen and carbon monoxide concentrations in Bedroom 1, remote from the room of fire origin. There is a very small improvement in these conditions (i.e., higher oxygen and lower carbon dioxide concentrations) after roof ventilation, but not enough to affect any survivability within the structure. It isn't until after suppression that you are able to see that the larger vent hole may allow for conditions to improve faster. Ventilation alone, regardless of the sizes investigated, did not provide significant improvements with respect to the gas concentrations to indicate that the larger hole was more effective.

Figure 5.414 through Figure 5.423 show the photographs of the fire event just before roof ventilation and until 1 minute after ventilation. Flames can be seen beginning to exit the roof vent at 10:15 and by 10:30, they fill the vent. While the roof vent is full of flames, smoke and flames are still exiting the front door. This shows that while the larger vent hole exhausts more combustion products vertically, the house is still ventilation-limited in both experiments.

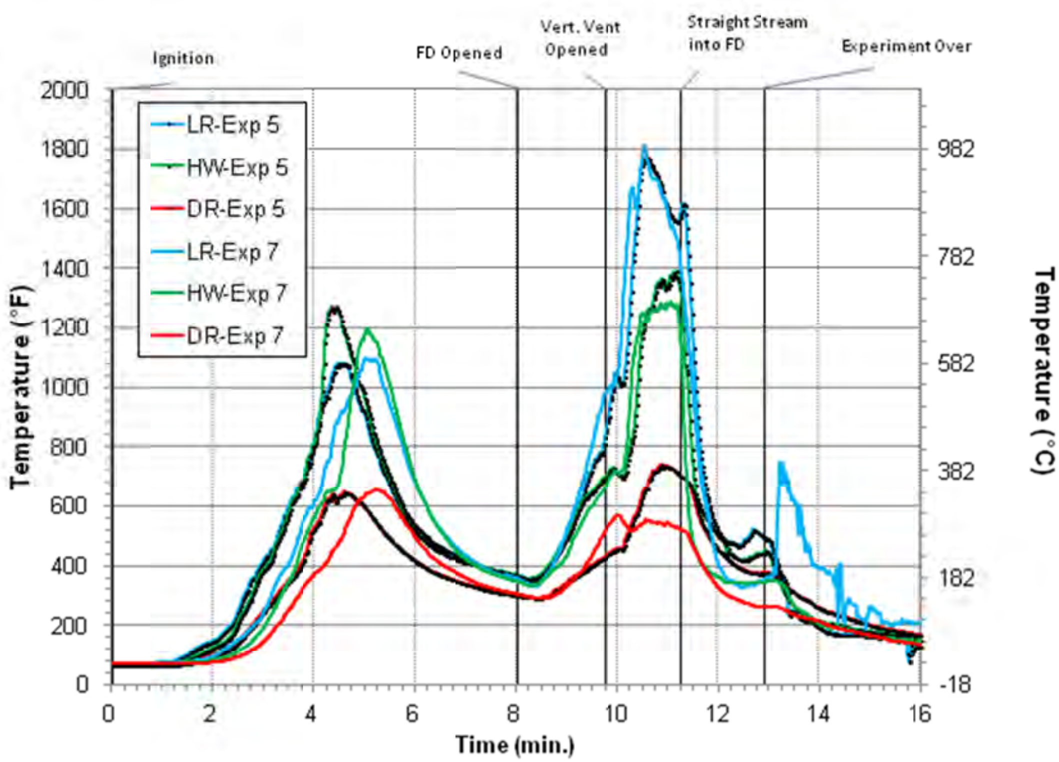


Figure 5.409: Comparison of 7 ft. Temperatures

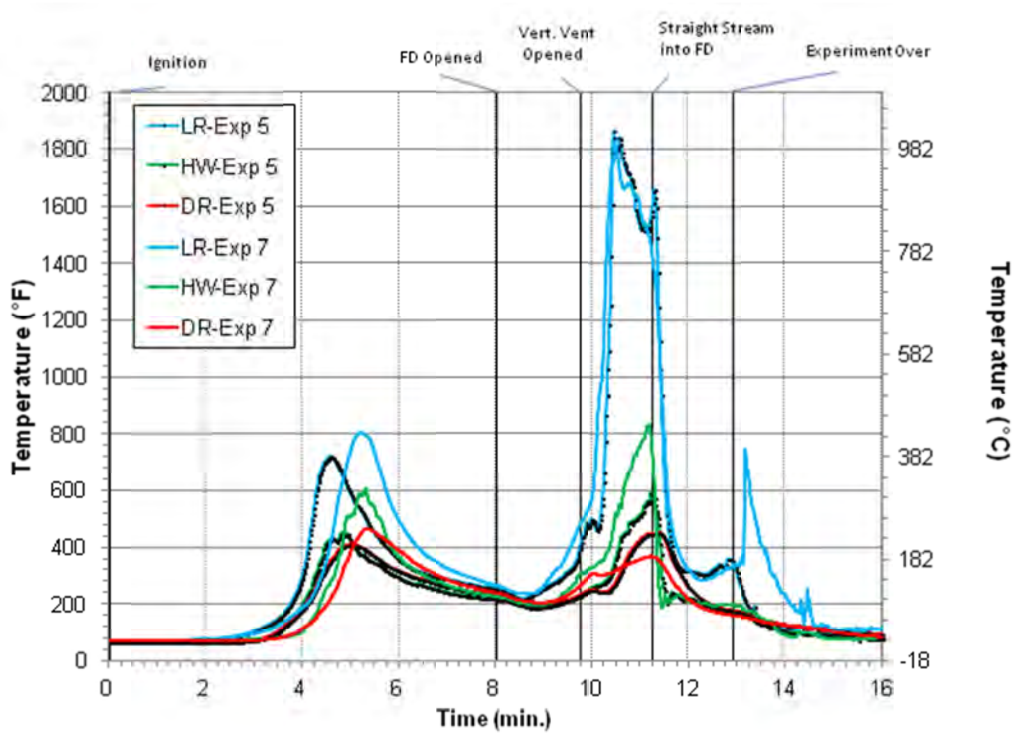


Figure 5.410: Comparison of 3 ft. Temperatures

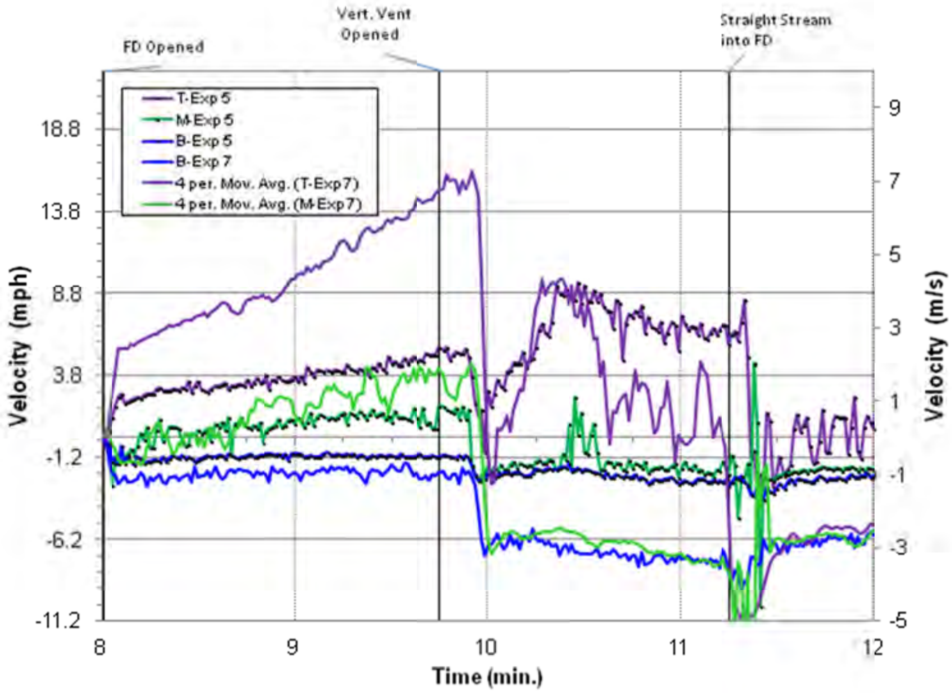


Figure 5.411: Comparison of Front Door Velocities

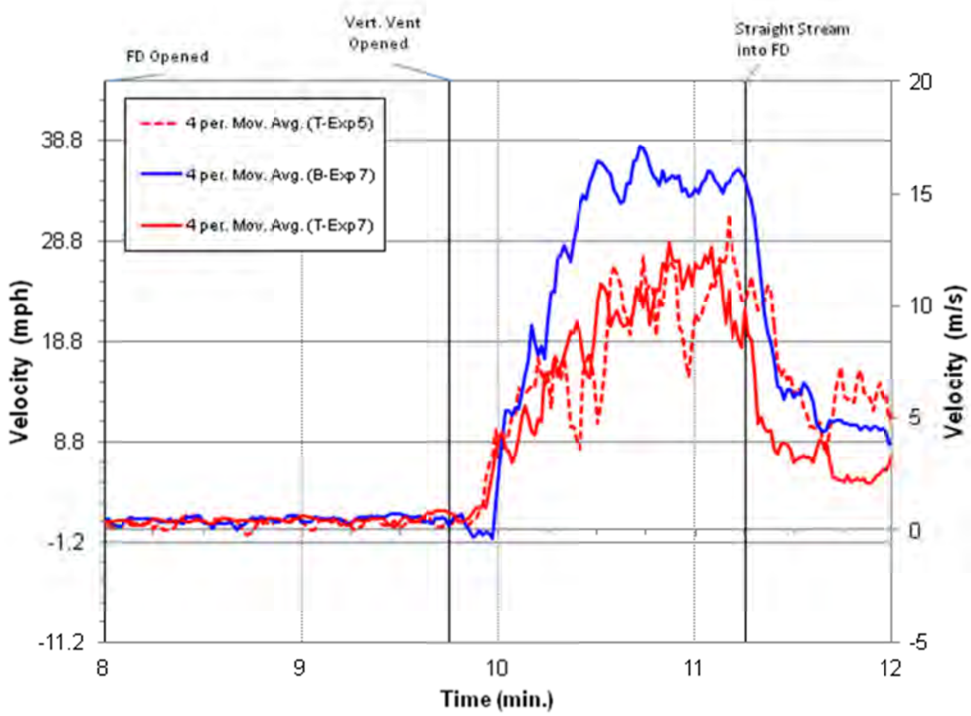


Figure 5.412: Comparison of Roof Vent Velocities

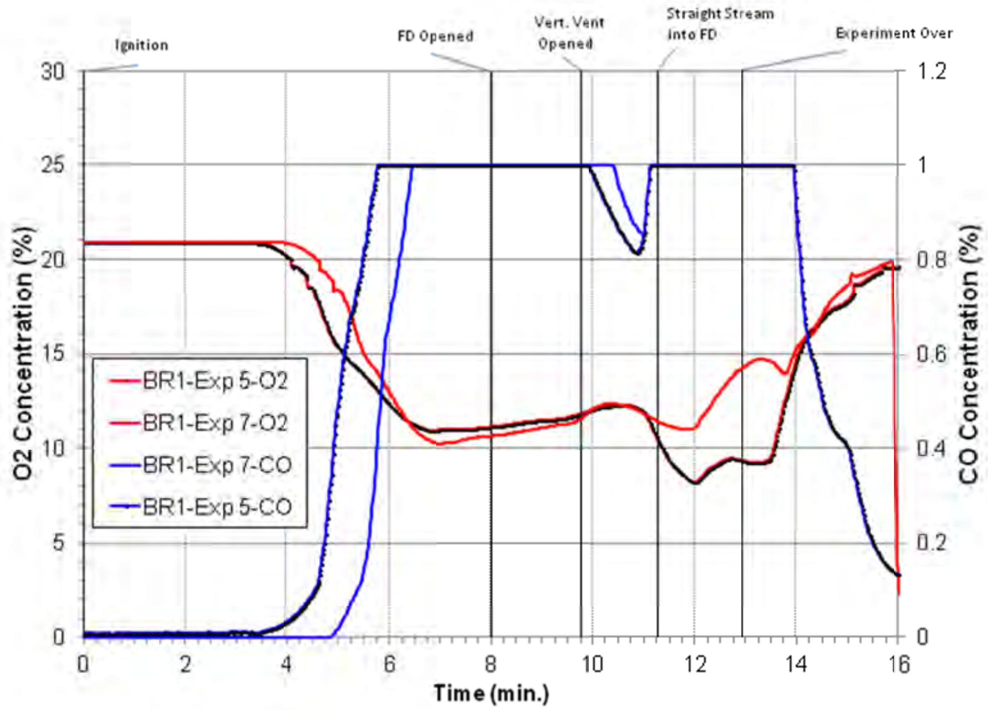


Figure 5.413: Comparison of CO and O2 Concentrations

Experiment 5 – 4 ft. by 4 ft. Vent Hole

Figure 5.414: Experiment 5, 9:45

Experiment 7 – 4 ft. by 8 ft. Vent Hole

Figure 5.415: Experiment 7, 9:45

Figure 5.416: Experiment 5, 10:00

Figure 5.417: Experiment 7, 10:00

Figure 5.418: Experiment 5, 10:15

Figure 5.419: Experiment 7, 10:15

Figure 5.420: Experiment 5, 10:30

Figure 5.421: Experiment 7, 10:30

Figure 5.422: Experiment 5, 10:45

Figure 5.423: Experiment 7, 10:45

5.8.6. Impact of Vertical Ventilation Hole Size comparing Experiments 6 and 8 in the two-story house

In the two-story house, the vertical ventilation openings were made over the two-story family room where the fire originated. Experiment 6 had a 4 ft. by 4 ft. vertical ventilation, while Experiment 8 had a 4 ft. by 8 ft. vertical ventilation. In both experiments, flashover occurred quickly after vertical ventilation. The temperatures after the vertical vent was opened show that the larger vertical ventilation area leads to slightly lower non-fire room temperatures during and after flashover (Figure 5.424 and Figure 5.425). This can again be explained by the higher exhaust of hot gases out of the structure due to the larger ventilation area, which then reduces the amount of flow of hot gases into the non-fire rooms.

The front door flow is compared in Figure 5.426. It shows that the average flow inward with the larger hole was approximately 8 mph while the flow with the smaller hole was fully inward at approximately 3 mph but transitioned to a bidirectional flow that was mainly outward at approximately 2 mph. The flows out of the roof vent are compared in Figure 5.427. Shortly after ventilation there is an average flow out of the vent of approximately 20 to 25 mph that increases to 30 to 40 mph once the Family Room transitioned to flashover. The flow out of the larger vent hole was approximately 3 to 5 mph faster post flashover.

The oxygen concentrations for both size vent holes were approximately the same in Bedroom 1, which was on the second floor but remote from the seat of the fire (Figure 5.428). The CO concentrations increased for both ventilation hole sizes. However, the increase was greater with the smaller vent hole. In both experiments, the addition of vertical ventilation caused gas concentrations to become more lethal until suppression took place.

Figure 5.429 through Figure 5.440 show the visual conditions from the front of the two-story house from moments before roof ventilation until 1 minute and 15 seconds later. In Experiment 6, the flow at the front door reverses inward after the 4 ft. by 4 ft. hole is made and then once the family room transitions to flashover, smoke and hot gases flow out of the front door again. In

Experiment 8, the flow at the front door reverses to completely inward after the 4 ft. by 8 ft. ventilation hole was created.

Figure 5.441 through Figure 5.444 show the video view right inside the front door at the ground level. This simulates what would be seen by someone looking into the house at the lowest level possible through the front door. The figures were captured at the moment just prior to roof ventilation and 30 seconds later. They show that the smoke layer does not lift significantly and that the smoke mixing at the front door does not greatly improve visibility for firefighters entering the front door.

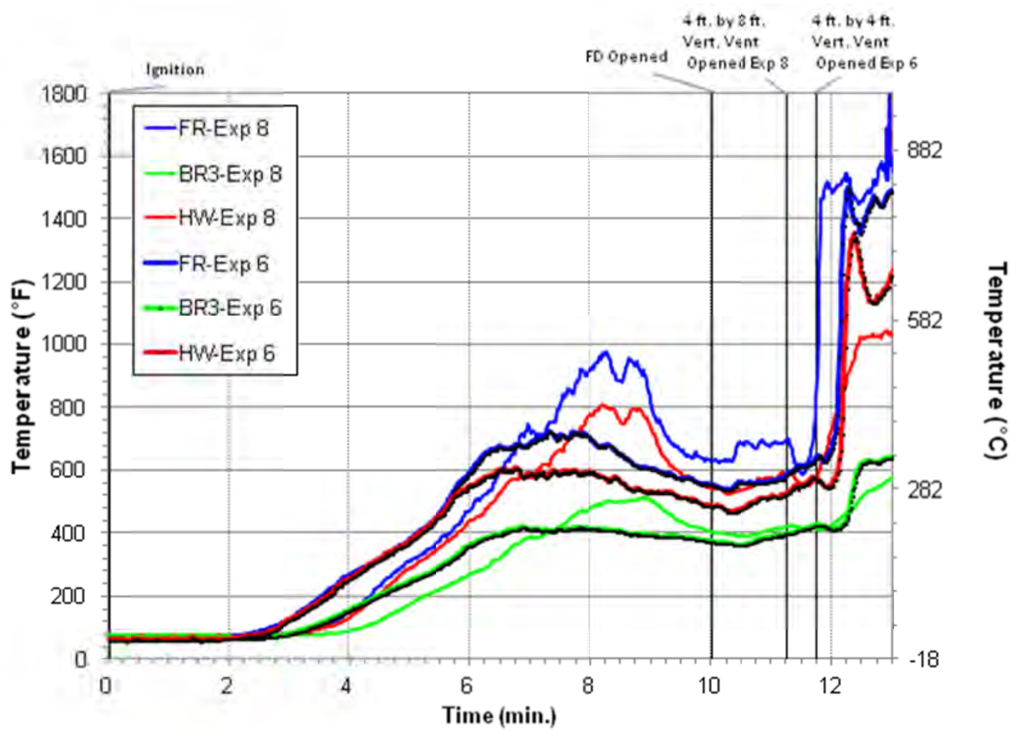


Figure 5.424: Comparison of 7 ft. (16 ft. for FR) Temperatures

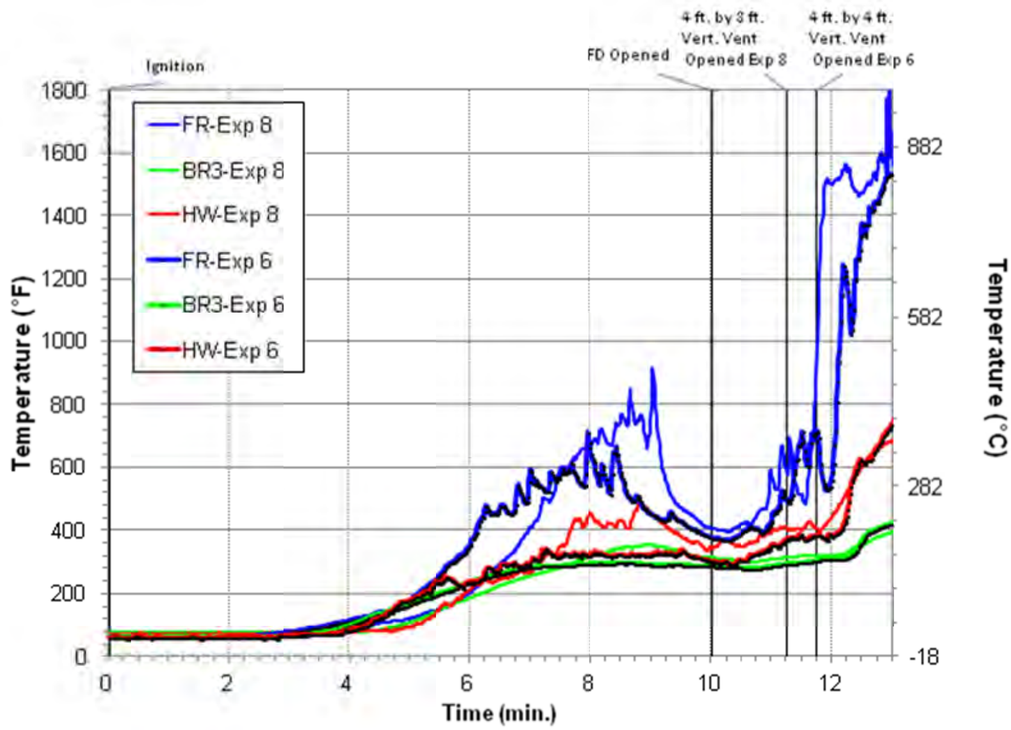


Figure 5.425: Comparison of 3 ft. (4 ft. for FR) Temperatures

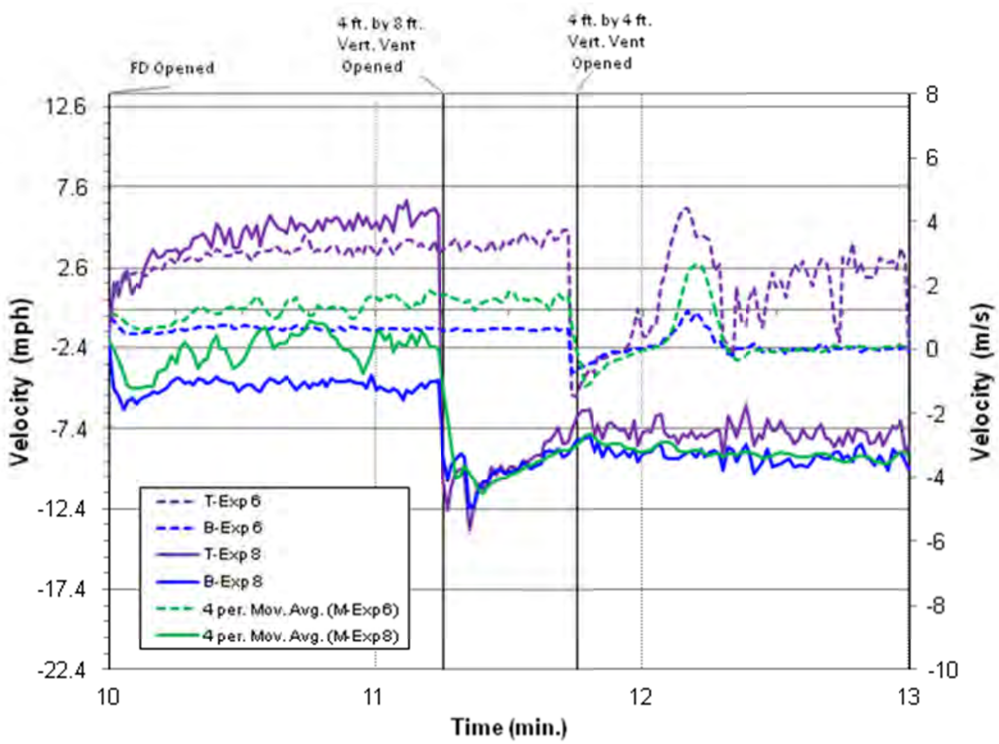


Figure 5.426: Comparison of Front Door Velocities

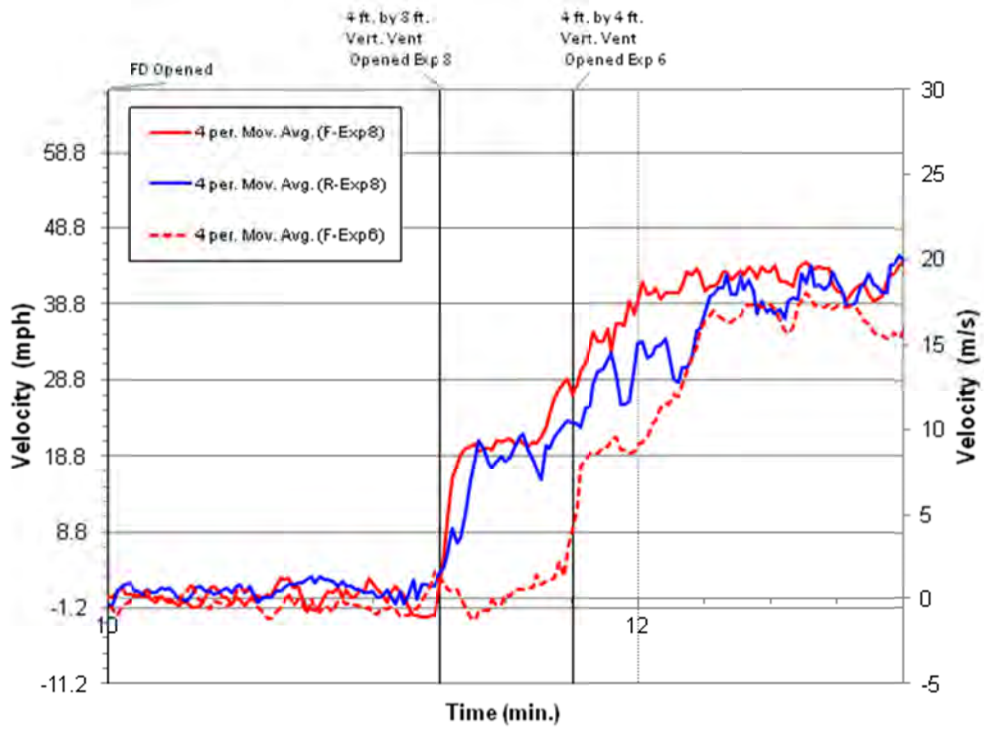


Figure 5.427: Comparison of Roof Vent Velocities

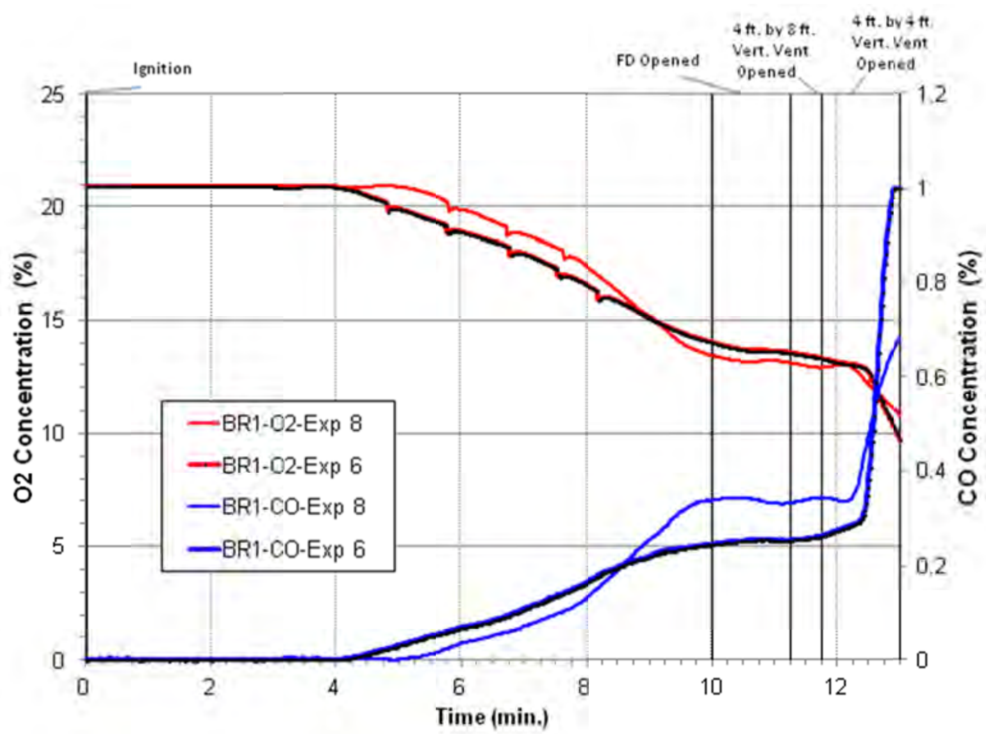


Figure 5.428: Comparison of Oxygen and CO Concentrations

Experiment 6 – 4 ft. by 4 ft. Vent Hole

Experiment 8 – 4 ft. by 8 ft. Vent Hole

Figure 5.429: Experiment 6, 11:45

Figure 5.430: Experiment 8, 11:15

Figure 5.431: Experiment 6, 12:00

Figure 5.432: Experiment 8, 11:30

Figure 5.433: Experiment 6, 12:15

Figure 5.434: Experiment 8, 11:45

Figure 5.435: Experiment 6, 12:30

Figure 5.436: Experiment 8, 12:00

Figure 5.437: Experiment 6, 12:45

Figure 5.438: Experiment 8, 12:15

Figure 5.439: Experiment 6, 13:00

Figure 5.440: Experiment 8, 12:30

Experiment 6 – 4 ft. by 4 ft. Vent Hole

Experiment 8 – 4 ft. by 8 ft. Vent Hole

Figure 5.441: Experiment 6, 11:45

Figure 5.442: Experiment 8, 11:15

Figure 5.443: Experiment 6, 12:15

Figure 5.444: Experiment 8, 11:45

5.8.7. Effect of Ventilation Location Relative to the Seat of the Fire by Comparing Experiments 5 and 9 in the One-Story House

In this section the influence of the location of vertical ventilation relative to the seat of the fire is explored. The discussion also addresses a common fire service concern that a vertical vent created outside of the room of origin will the pull the fire toward the vent location. In Experiment 5, vertical ventilation was over the fire in the living room (Figure 5.445), while in Experiment 9 vertical ventilation was created in the living room, remote from the fire in Bedroom 1 (Figure 5.446).

The source fire for each experiment was different but both produced ventilation-limited fire conditions. Each experiment can be examined in terms of conditions for potential victims and for firefighter operations inside the house. In Experiment 5, with the front door open and a 4 ft. by 4 ft. ventilation hole over the fire, temperatures increase throughout the house. The front door was opened at 8 minutes after ignition and the fire began to increase as air was entrained through the lower portion of the front door and hot gases flowed out the top of the doorway. As soon as the temperature in the living room at 3 ft. above the floor reached 400 °F the roof vent was opened. This enables the hot gases to flow out of the roof vent but also entrained more air through the front door. This additional air transitioned the living room to flashover and significantly increased the heat release rate. The additional burning could only occur at the roof vent and front door because the fire remained ventilation-limited. After the roof vent was opened the temperatures in the house increased as shown in Figure 5.447, Figure 5.448 and Table 5.27.

In Experiment 9, the front door was opened and then a 4 ft. by 4 ft. ventilation hole remotely located from the fire was opened. The front door was opened at 8 minutes after ignition and the fire began to increase as air was entrained through the lower portion of the front door, through the living room, hallway, and to Bedroom 1. As soon as the temperature in Bedroom 1 at 3 ft. above the floor reached 400 °F, the roof vent was opened. Once more hot gases were able to flow out of the roof vent; more air could be entrained through the front door. This additional air transitioned Bedroom 1 to flashover and significantly increased the burning rate. The temperatures increased in the fire room and between the fire room and the vent; but it was cooler in the remainder of the house. The additional burning was directed toward the roof vent and front door because the fire remained ventilation-limited. One difference in this scenario is that the smoke and hot gases directed away from Bedroom 1 mixed with the fresh air flowing in from the front door which limited the heat released by the fire in Bedroom 1. After the roof vent was opened, the temperatures in the house changed as shown in Figure 5.447, Figure 5.448, and Table 5.28. During this experiment, hot gases flowed to the roof vent, but ignition did not occur outside of Bedroom 1. Conditions and visibility at the crawling height of a firefighter improved in the flow path between the front door and the bedroom in this scenario (Figure 5.449 through Figure 5.452).

Figure 5.445: Experiment 5 Scenario

Figure 5.446: Experiment 9 Scenario

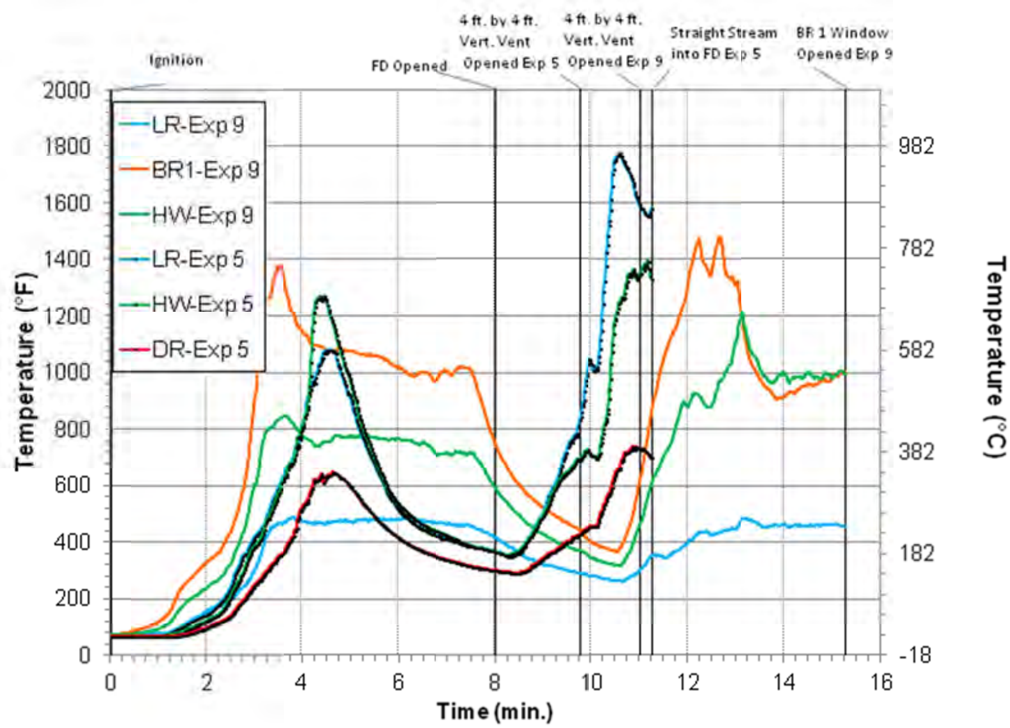


Figure 5.447: Comparison of 7 ft. Temperatures

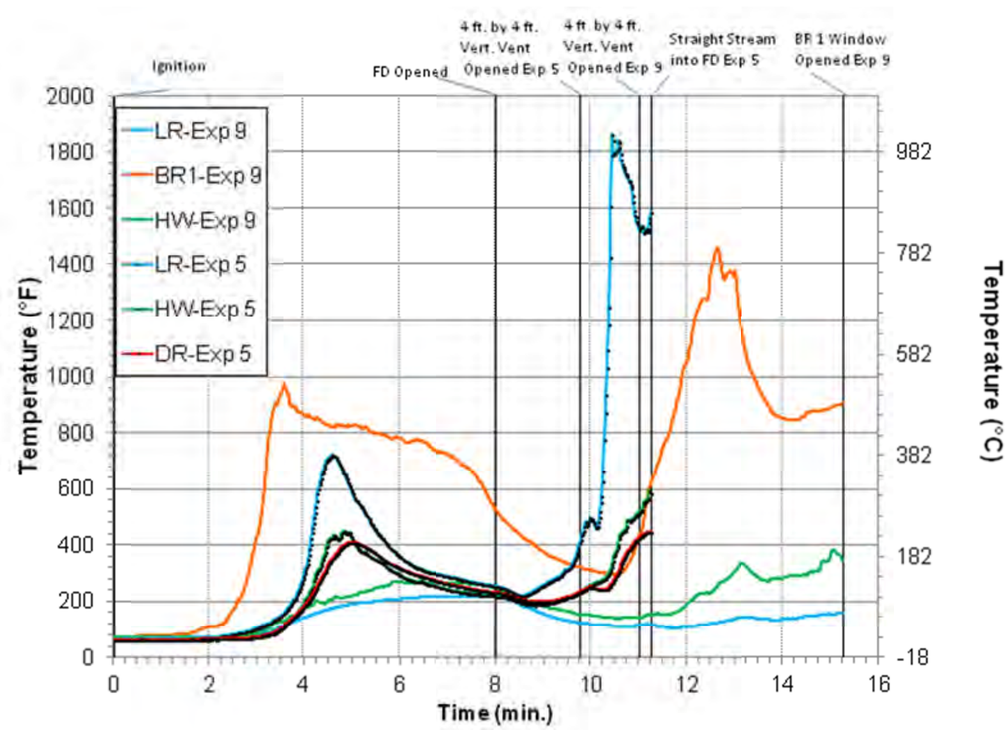


Figure 5.448: Comparison of 3 ft. Temperatures

Table 5.27: Experiment 5 Temperature Changes From Ventilation at 3 ft. above Floor

Room	Temperature at Door Open, 8:00	Temperature at Roof Vent Open, 9:45	Temperature 1:30 Later, 11:15 (total % increase)
Living Room	260	400	1653 (+536%)
Bedroom 1	204	196	316 (+55%)
Bedroom 2	218	224	380 (+74%)
Bedroom 3 (Closed)	77	78	80 (+4%)
Hallway	222	225	590 (+166%)
Dining Room	222	221	436 (+96%)
Kitchen	228	236	426 (+87%)

Table 5.28: Experiment 9 Temperature Changes From Ventilation at 3 ft. above Floor

Room	Temperature at Door Open, 8:00	Temperature at Roof Vent Open, 11:00	Temperature 1:30 Later, 12:30 (total % increase)
Living Room	217	113	141 (-35%)
Bedroom 1	554	417	1375 (+148%)
Bedroom 2	249	137	239 (+4%)
Bedroom 3 (Closed)	91	93	94 (+3%)
Hallway	256	141	331 (+29%)
Dining Room	204	105	87 (-57%)
Kitchen	201	110	89 (-56%)

Figure 5.449: Experiment 9 visibility at time of front door opening

Figure 5.450: Experiment 9 visibility just before roof vent

Figure 5.451: Experiment 9 visibility 1 minute after roof vent

Figure 5.452: Experiment 9 visibility 4 min after roof vent

5.8.8. Effect of Ventilation Location Relative to the Seat of the Fire by Comparing Experiments 6 and 10 in the Two-Story House

This comparison examines the influence of vertical ventilation location in relation to the seat of the fire for the two-story house. In Experiment 6, vertical ventilation was over the fire in the family room (Figure 5.453), while in Experiment 10 vertical ventilation was created in the family room, remote from the fire in Bedroom 3 (Figure 5.454). Figure 5.455 and Figure 5.456 show the 7 ft and 3 ft temperatures for Experiment 6 and Experiment 10. The temperature data shows that after vertical ventilation, Experiment 6 quickly transitioned to flashover in less than 30 seconds. In contrast, after vertical ventilation in Experiment 10, the fire environment took more than 3 minutes to transition to flashover. This long transition to flashover after vertical ventilation does not only depend on the vertical ventilation being far from the seat of the fire, but also on the path from incoming air (front door) and exiting gases (vertical vent) not passing through the seat of the fire, which results in much less oxygen supply to the fire room and slower fire growth. The temperature in the closest adjacent fire room is similar for both experiments (hallway temperature for both experiments), suggesting that in this scenario, venting directly over the fire or far from the fire resulted in little difference in the non-fire room temperatures.

Figure 5.457 through Figure 5.462 show the visual conditions on the second floor hallway looking at the top of the stairs toward the fire room, Bedroom 3. Opening the front door had little impact on visibility. There is no visibility on the second floor but clear visibility on the first floor. The flow path from the front door to the fire room was minimal because the hot gases and smoke were not able to flow down and out of the second floor. Once the roof vent is opened the hot gases and smoke were able to flow out of the family room and the fresh air from the front door and first floor is able to flow up to the fire room and out through the roof vent. This change in flow path increased the visibility on the second floor and slowly provided fresh air to the bedroom fire. By 4 minutes after roof ventilation the bedroom transitioned to flashover and flames flowed out of Bedroom 3 and over the hallway to the roof vent. Ignition did not take place outside of the bedroom but the visibility on the second floor worsened and temperatures greatly increased.

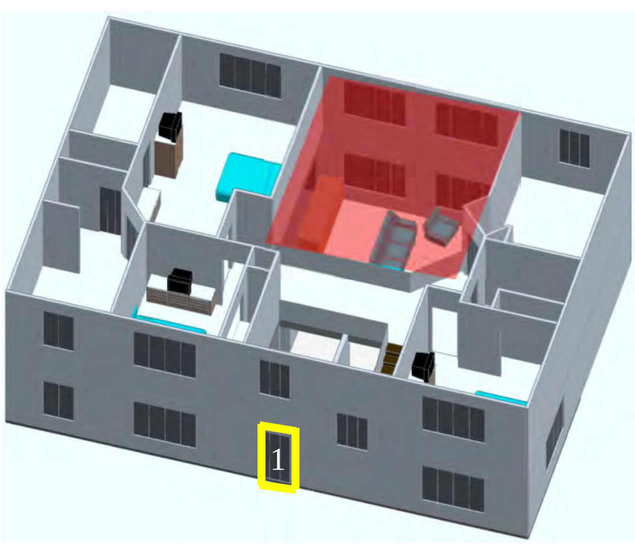


Figure 5.453: Experiment 6 Scenario

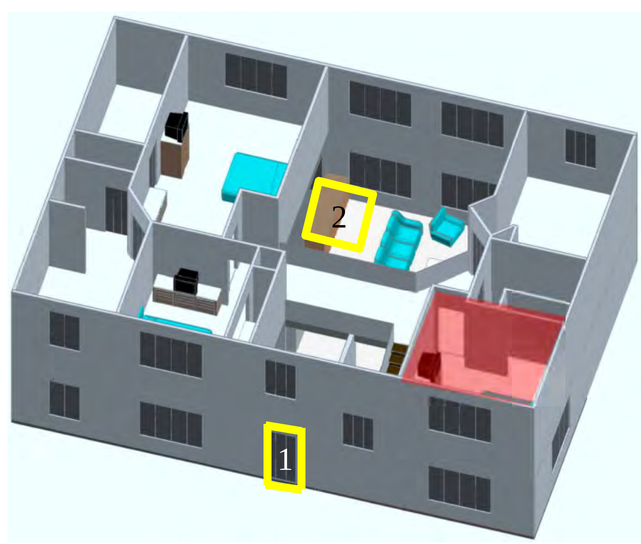


Figure 5.454: Experiment 10 Scenario

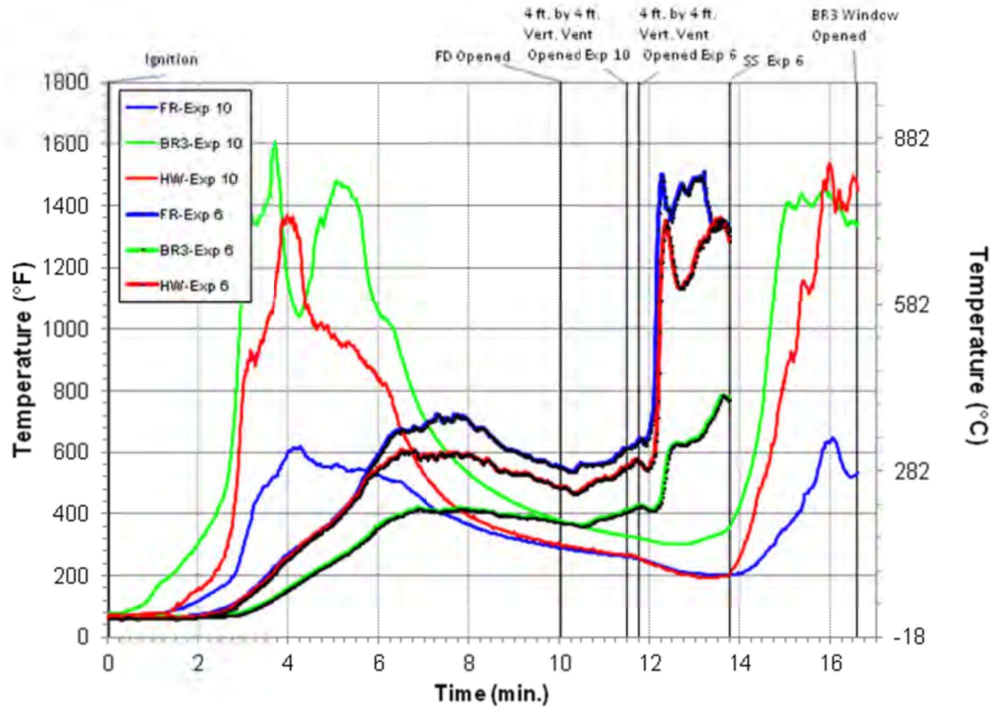


Figure 5.455: Comparison of 7 ft. (16 ft. for FR) Temperatures

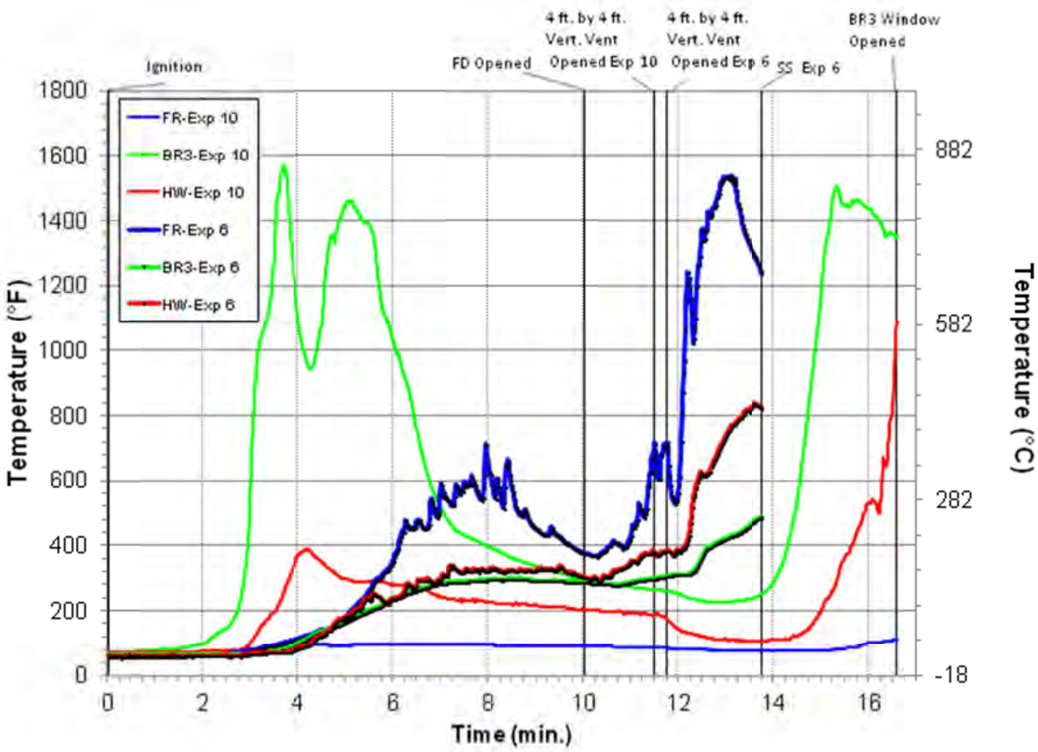


Figure 5.456: Comparison of 3 ft. (4 ft. for FR) Temperatures

Figure 5.457: Exp. 10 Hallway view @ 10:00 (Just before front door open)

Figure 5.458: Exp. 10 Hallway view @ 11:30 (Just before roof vent)

Figure 5.459: Exp. 10 Hallway view @ 12:30 min (1 min after roof vent)

Figure 5.460: Exp. 10 Hallway view @ 14:30 min (3 min after roof vent)

Figure 5.461: Exp. 10 Hallway view @ 15:30 min (4 min after roof vent)

Figure 5.462: Exp. 10 Hallway view @ 15:30 min (5 min after roof vent)

5.8.9. Examing vertical ventilation alone or after horizontal ventilation by comparing Experiments 9 and 11 in the One-Story House

In Experiment 11 the window to Bedroom 1 was opened prior to simulated fire department arrival. Therefore fire is showing upon arrival and Bedroom 1 is post-flashover prior to vertical ventilation. The fire in the bedroom consumes the oxygen in the house, and temperatures begin to decrease. Once the window was opened at 6 minutes, temperatures in the bedroom increased from 1000 °F to above 1500 °F. The temperatures in the hallway also increased to above 1200 °F. Once the front door was opened, the fresh air was also entrained into the bedroom fire from the hallway, which increased the burning at the bedroom doorway, as well as the window. The temperatures in the bedroom, hallway and living room also increased. Once the roof vent was opened, the hot gases exhausted between the roof and the front door. This cooled the living room from 650 °F to approximately 500 °F. Opening the roof vent in the living room lifted the neutral plane in the doorway, allowing more air to be entrained through the front door, which provided some cooling and increased visibility, while also increasing the burning, and amount of gases exhausting out of the top of the bedroom doorway toward the roof vent.

In Experiment 9, the window was kept closed and the Bedroom 1 fire became ventilation-limited prior to simulated fire department arrival. Once the front door was opened, air was able to flow through the living room and into the bedroom, and smoke escaped out of the top of the front door. The air that was entrained into the bedroom fire had an oxygen content less than 21% because it mixed with the smoke that was in the flowpath to the bedroom. Because the entrained air had a reduced oxygen concentration, the fire took longer to grow when compared to Experiment 11, where the air was allowed directly into the bedroom fire from the open bedroom window. This kept the fire ventilation-limited, and the temperature continued to decrease, since burning was slow to recover. At 11 minutes after ignition, the roof vent was opened. This enabled more smoke to escape through the roof vent, and more air to enter the through front door and to the bedroom fire. The increased air is led to burning to increase quickly and temperatures in the bedroom to increase from 400 °F to 1500 °F in approximately 1 minute. The hallway temperatures also increased quickly from 400 °F to 1200 °F in less than 2 minutes. Living room temperatures also increased 200 °F even though more fresh air was entrained through the living room.

The results from these experiments highlight the importance of understanding flow paths. The closer the air is provided to the seat of the fire, the faster it will intensify. The experiments also demonstrate that fire showing does not mean that the fire is vented; it means that it is venting and still remains ventilation-limited. The fire is burning outside of the window because there is no air available inside to burn.

Figure 5.463: Experiment 9 Scenario

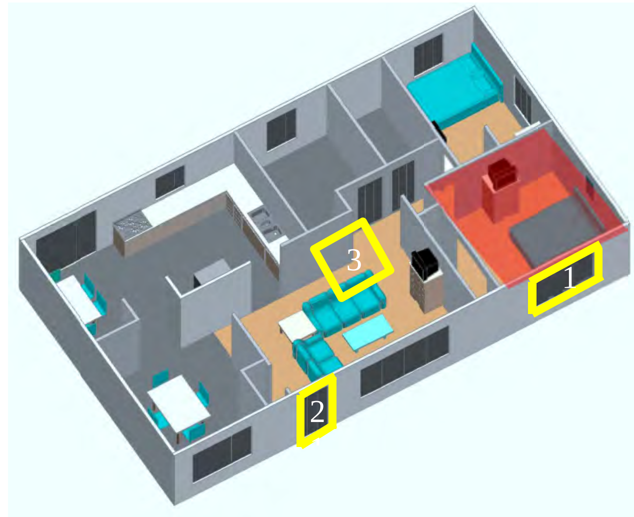


Figure 5.464: Experiment 11 Scenario

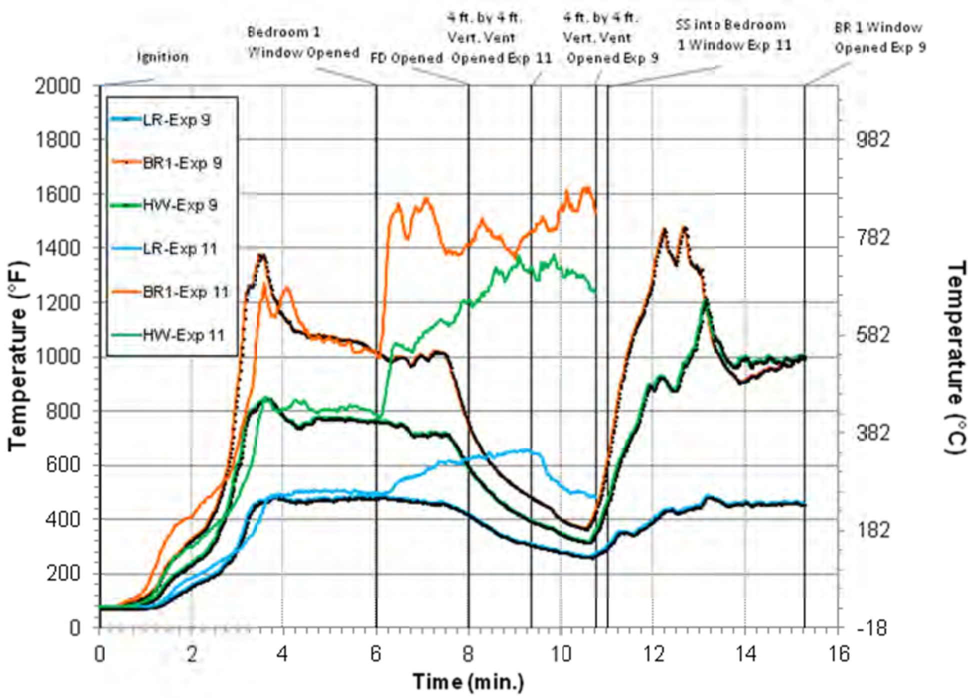


Figure 5.465: Comparison of 7 ft. Temperatures

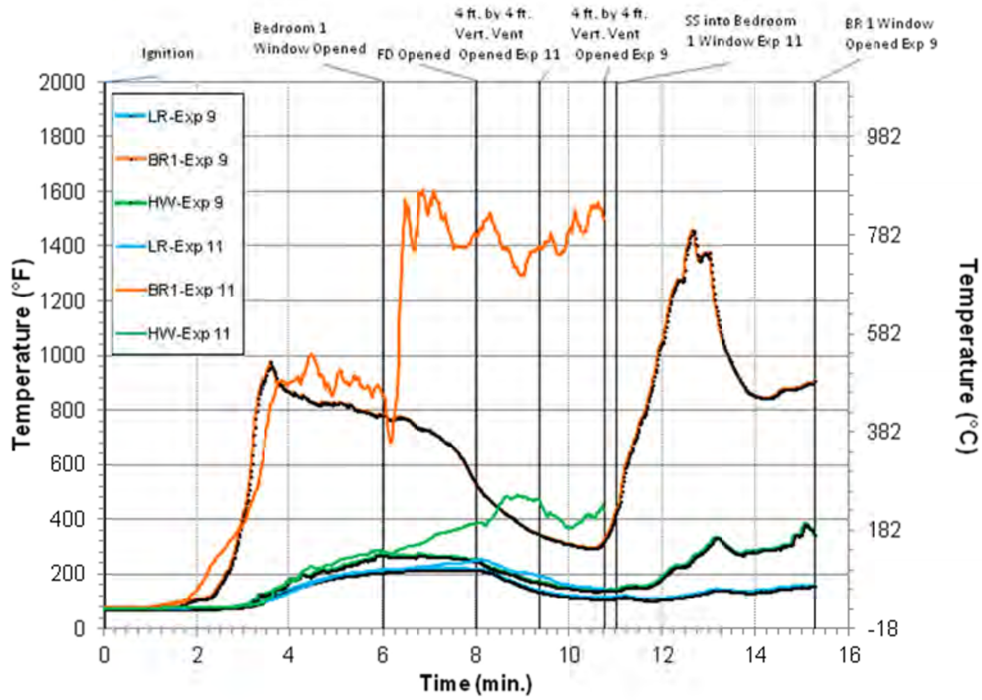


Figure 5.466: Comparison of 3 ft. Temperatures

5.8.10. Examining vertical ventilation alone or after horizontal ventilation by comparing Experiments 6 and 12 in the Two-Story House

Figure 5.469 and Figure 5.470 depict temperatures at 7 ft. and 3 ft. for Experiment 6 and Experiment 12 in the two-story structure. Experiments 6 and 12 are similar experiments, except for one key difference. In Experiment 12, the family room window was broken, with fire visible from the window at the time fire service arrived at the scene; while in Experiment 6, the family room window was kept intact. The temperature plots show that after the family room window is ventilated, the temperatures in Experiment 12 are higher than the temperatures in Experiment 6. However, the temperatures in Experiment 6 begin to decline at 8:00. This time was used in Experiment 12 to ventilate the family room window. In Experiment 12, the broken window does not increase the temperatures in the fire environment, and maintains them relatively unchanged. The temperatures in Experiment 12 do not begin to increase until about a minute after the front door is opened. In both experiments, the fire environment transitions quickly to flashover after vertical ventilation is implemented. It may be observed that Experiment 12 has lower non-fire room temperatures during flashover due to the additional exhaust of hot gases from the fire environment from the horizontal ventilation of the family room window.

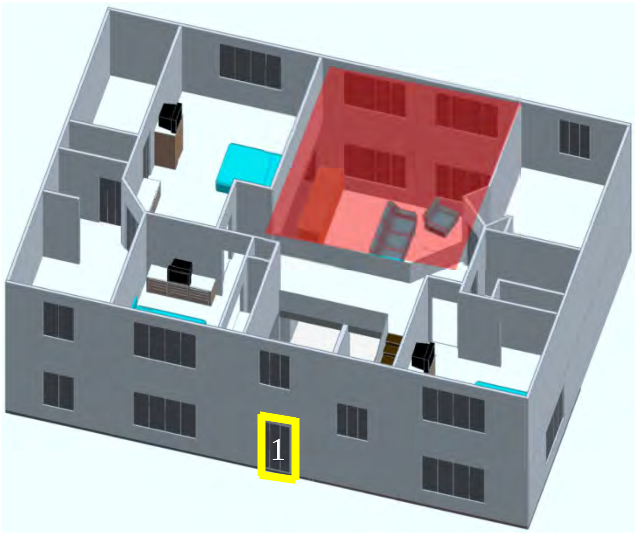


Figure 5.467: Experiment 6 Scenario

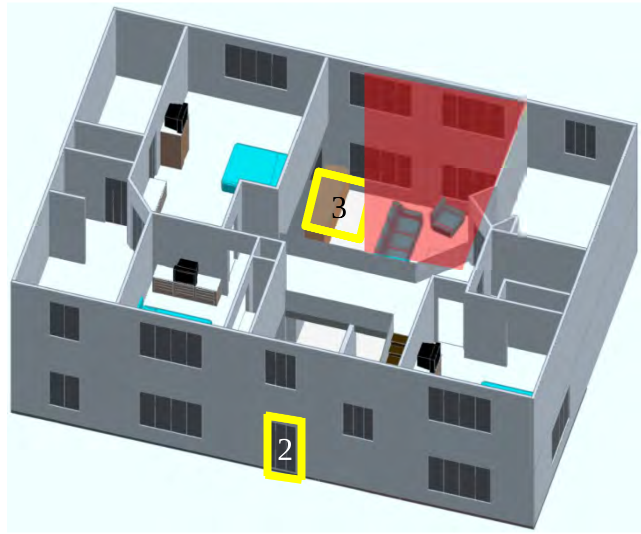


Figure 5.468: Experiment 12 Scenario

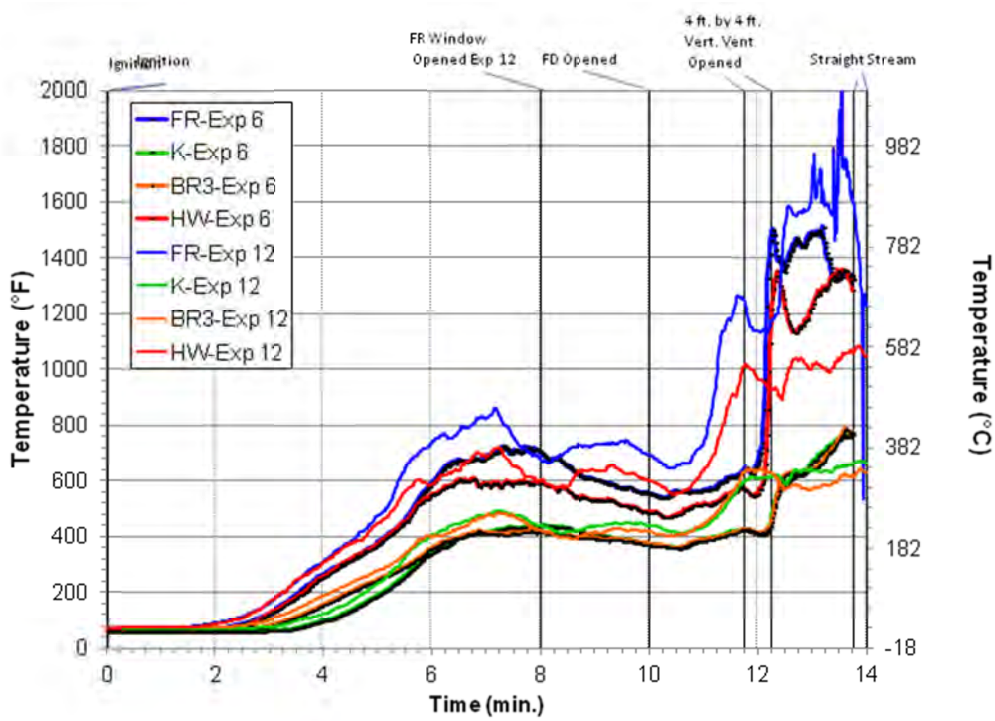


Figure 5.469: Comparison of 7 ft. (16 ft. for FR) Temperatures

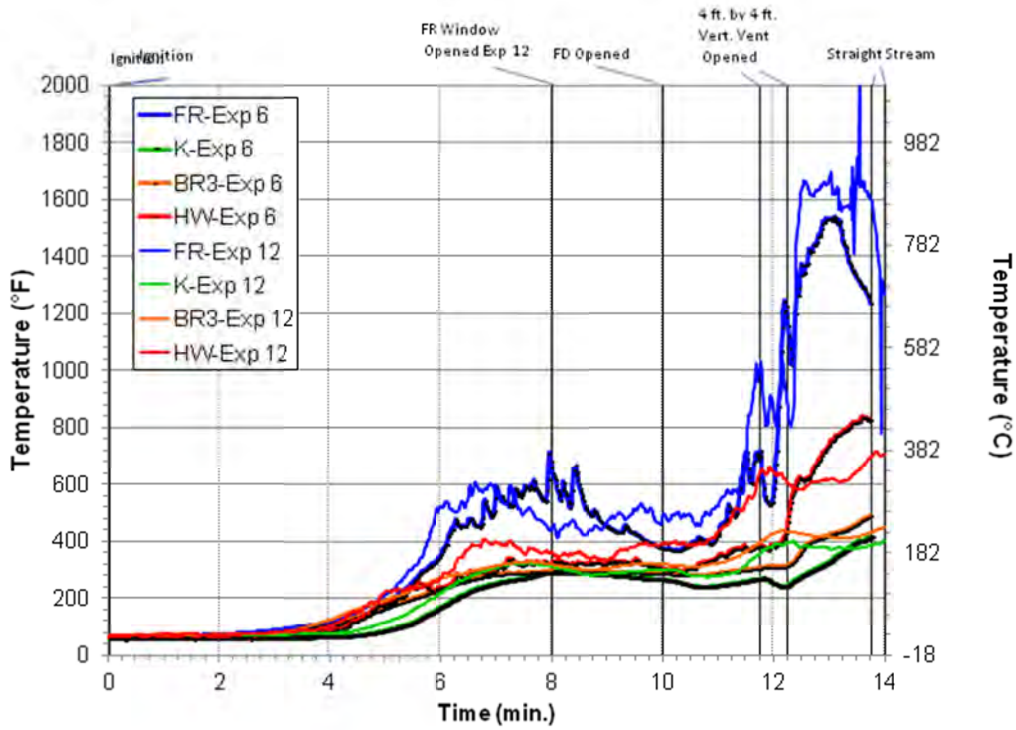


Figure 5.470: Comparison of 3 ft. (4 ft. for FR) Temperatures

5.8.11. Examining the impact of order of ventilation by comparing Experiments 10 and 14 in the Two-Story House

In Figure 5.473 and Figure 5.474 the temperatures at 7 ft. and 3 ft. are presented for experiment 10 and 14. In Experiment 10, the ventilation was implemented first with front door, followed by opening the vertical vent, and then the bedroom 1 window. In Experiment 14 ventilation was implemented first with bedroom 1 window, followed by front door, and then opening the vertical vent. In both these experiments, the fire was initiated in the second floor bedroom.

In Experiment 10, the bedroom fire filled the second floor of the house with smoke and lowered the oxygen concentration on the second floor, while the visibility was nearly 100% on the first floor. Since there were was no ventilation at or above the fire to allow products of combustion out of the house, air was not able to be entrained from the first floor to the fire. Opening the front door had no impact on the fire. Once the roof vent was opened, hot gases were able to exhaust and fresh air was able to be entrained into the bedroom, leading to flashover of the bedroom, in approximately 3 minutes, and elevated temperatures throughout the second floor of the house.

In Experiment 14 the bedroom fire lowered the oxygen concentration on the second floor and filled the floor with smoke. Temperatures decreased as the fire became ventilation-limited. Upon ventilation of the fire room window, the temperature in the fire room immediately started to increase as air was entrained right into the seat of the fire. Once the front door was opened additional air was entrained from the front door and into the fire room, increasing the burning intensity and temperatures. After the roof vent was opened, the bedroom temperatures increased and the temperatures in the hallway decreased but remained around 1000 °F.

Visibility improved with roof ventilation in both of these experiments. Figure 5.475 and Figure 5.476 show the smoke layer lift approximately 4 ft. after the roof ventilation was implemented in Experiment 10. Figure 5.477 and Figure 5.478 show the smoke layer lift approximately 2 ft. after roof ventilation took place in Experiment 14. The improvement was not as high in in this experiment versus Experiment 10, because the window to the room was already open and the bedroom transitioned to flashover, increasing the smoke production, whereas in Experiment 10, the window was opened after roof ventilation.

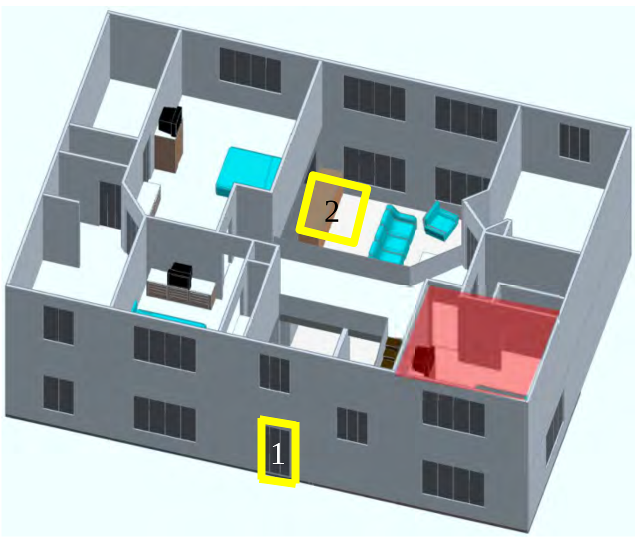


Figure 5.471: Experiment 10 Scenario

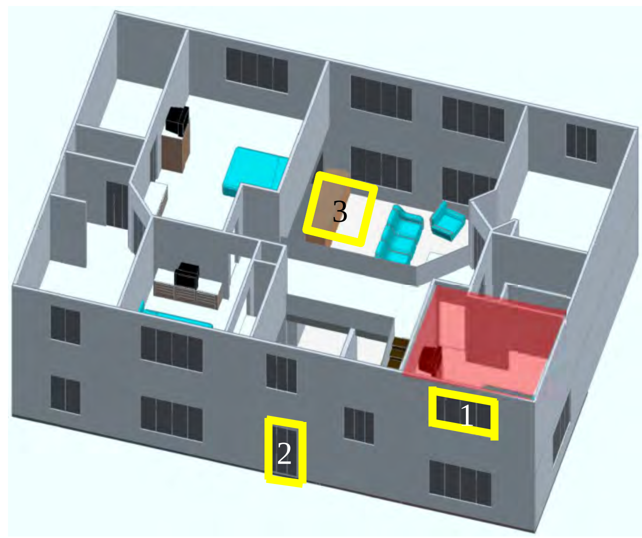


Figure 5.472: Experiment 14 Scenario

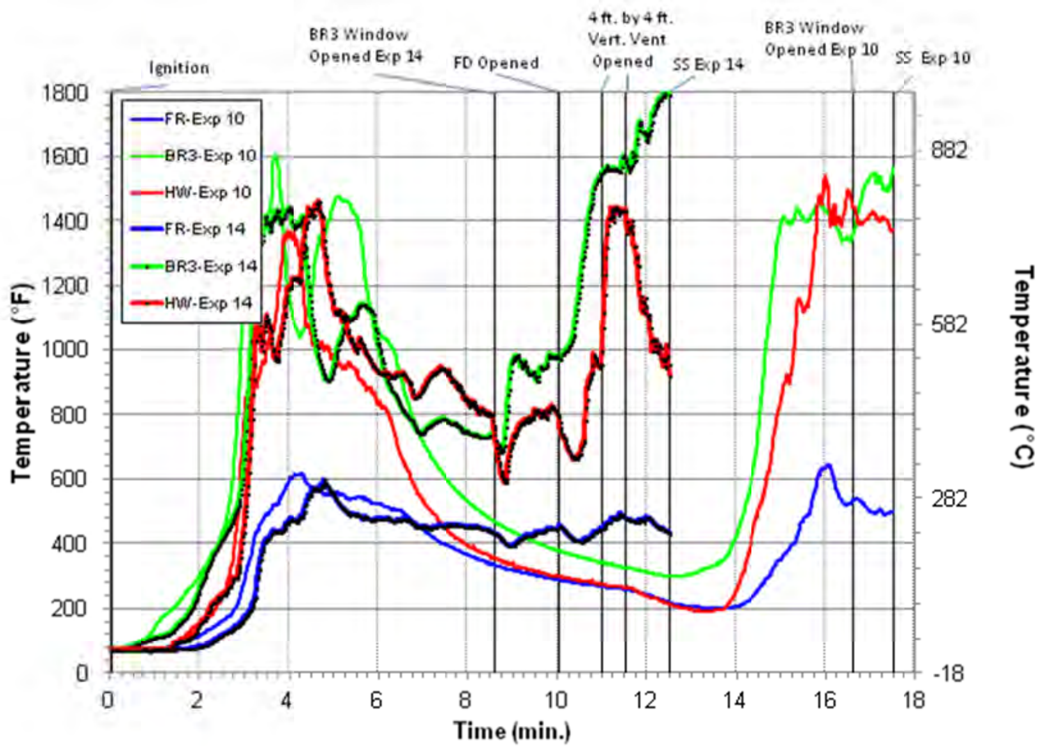


Figure 5.473: Comparison of 7 ft. (16 ft. for FR) Temperatures

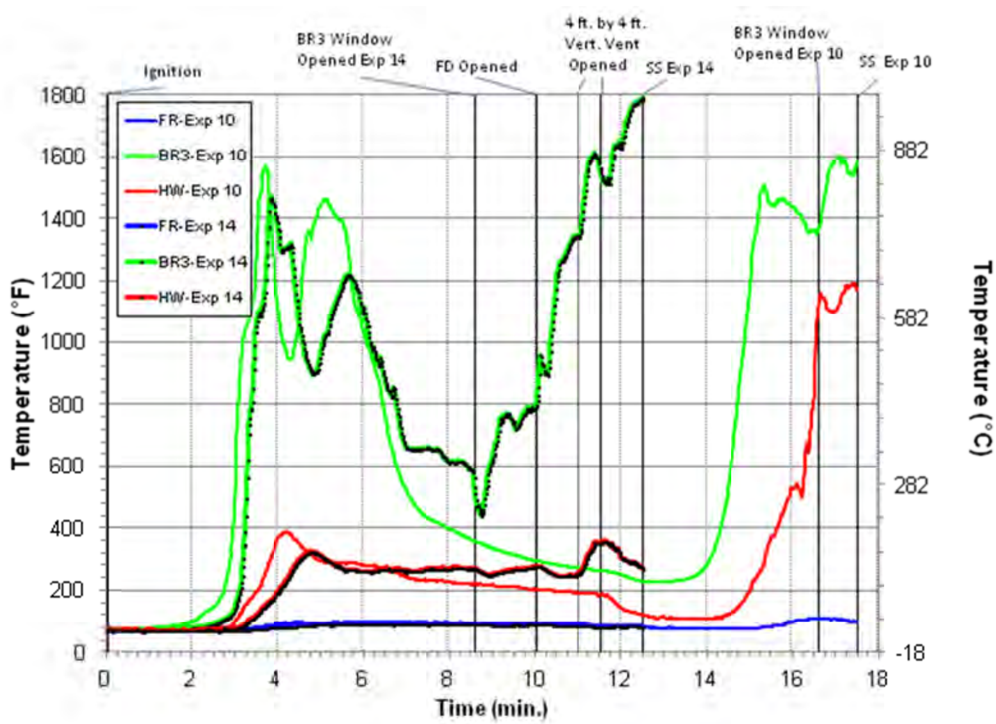


Figure 5.474: Comparison of 3 ft. (4 ft. for FR) Temperatures

Figure 5.475: Exp. 10 just before roof ventilation looking up to Bedroom fire

Figure 5.476: Exp. 10 thirty seconds after roof ventilation looking up to Bedroom fire

Figure 5.477: Exp. 14 just before roof ventilation looking up to Bedroom fire

Figure 5.478: Exp. 14 thirty seconds after roof ventilation looking up to Bedroom fire

5.8.12. Modern Versus Legacy (Experiments 1 and 17)

As part of the previous study on horizontal ventilation, UL conducted two room scale tests examining the difference between modern fuel loads and legacy fuel loads. This comparison showed a large difference in flashover times, 3:40 as compared to 29:30, and led to further exploration of the influence of fuel load by placing modern and legacy furnishings in a house. Experiment 1 was conducted with modern furniture, and Experiment 17 was conducted with legacy furniture. Both experiments were conducted in the one-story house. The only difference between the fuel loads was the sofas and the upholstered chair. The modern experiment had 2 sofas that were constructed with polyurethane foam. The legacy experiment had 2 slightly different sofas: the blue sofa, which had a goose feather seat and cotton sides and back, and the white sofa, which was constructed with cotton batting. The modern upholstered chair and ottoman were constructed with polyurethane foam, while the legacy experiment had 2 chairs constructed with cotton batting (Figure 5.481 through Figure 5.486). All other combustible products in the house, such as the carpeting and padding, the coffee table, the end table, the curtains, the TV stand, and the TV were identical.

Figure 5.479 and Figure 5.480 show temperatures at 7 ft. for experiments 1 and 17, respectively. The ventilation in the two experiments is similar. In Experiment 1, the fast fire growth leads to the fire quickly becoming ventilation-limited. The fire then begins to produce large amounts of carbon monoxide, and, in Experiment 1, this leads to a fire scenario where the tenability limit for carbon monoxide is attained in all rooms (except the room with the door shut) in less than 7 minutes. In Experiment 17, the shortest time to CO untenability is more than 23 minutes after ignition. Additionally, the temperatures in the structure are significantly lower prior to ventilation in Experiment 17, and after ventilation, flashover takes around 9 minutes compared with less than 3 minutes in Experiment 1. Once flashover does occur, the maximum temperatures in the fire room for both experiments reach approximately 1800 ^{o}F. The non-fire room temperatures (excluding the hallway, since it is so close to the fire room) after flashover are higher in Experiment 1 than in Experiment 17. The results of these two experiments, comparing fire growth with modern and legacy furniture, show that residential fires with modern furniture have the potential to create greater hazards to firefighters due to quicker fire growth, larger carbon monoxide production, and higher temperatures in the structure.

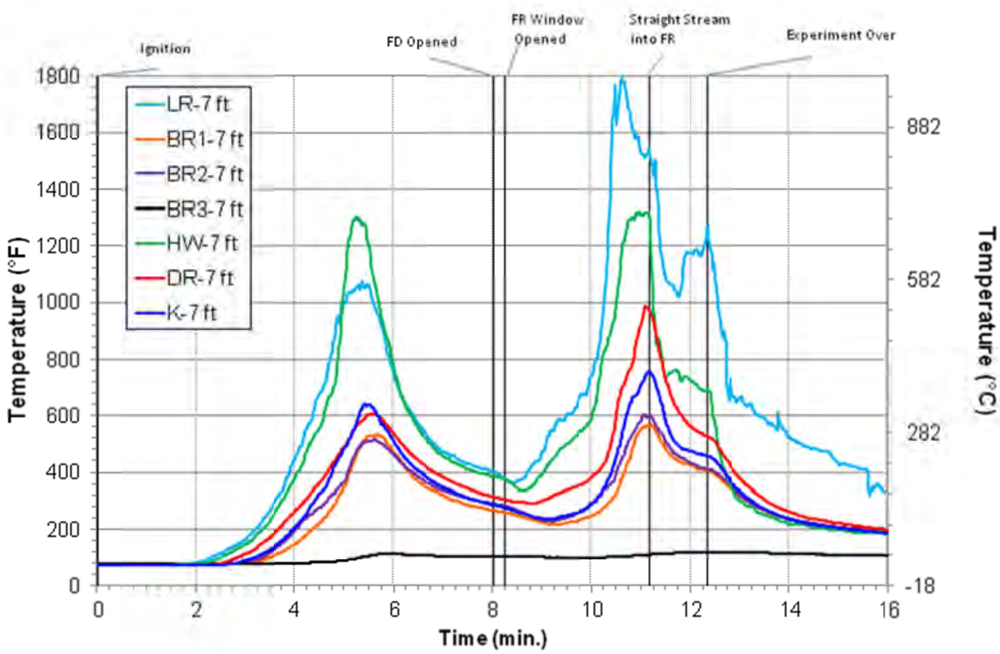


Figure 5.479: Experiment 1, 7 ft. Temperatures

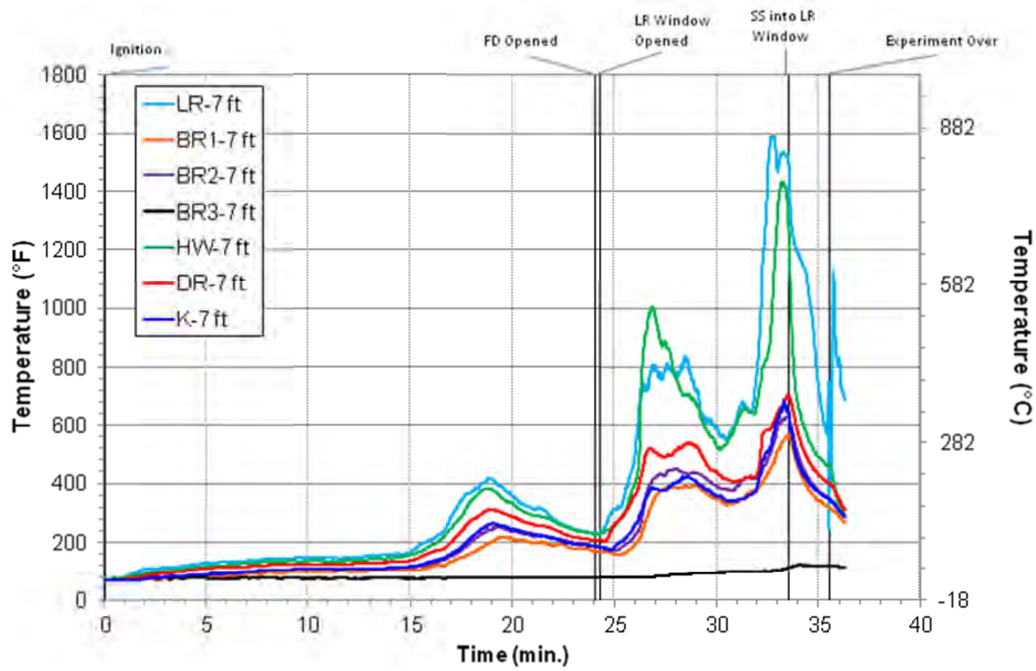


Figure 5.480: Experiment 17, 7 ft. Temperatures

Figure 5.481: Legacy Fuel Load

Figure 5.482: Modern Fuel Load

Figure 5.483: Goose Feather Cushion

Figure 5.484: Cotton Batting Sides and Back

Figure 5.485: Cotton Batting in White Sofa

Figure 5.486: Polyester Wrap over Polyurethane Foam Padding

Experiment 17 - Legacy Furnishings

IGNITION

VENTILATION

FLASHOVER

Experiment 1 – Modern Furnishings

IGNITION

VENTILATION

5.8.13. Tenability in Fire

Tenability, which is the survivability of occupants and firefighters in the fire environment, is the primary concern for any firefighting operation. It is helpful to understand the circumstances that can lead to untenable conditions in fires. In this section, the time to untenability, which is the time available for a person to escape the fire environment before incapacitation or death occurs, will be calculated based on the collected experimental data for both occupants and firefighters. For occupants, the influence of elevated temperature and carbon monoxide concentration on tenability will be examined. For firefighters, the influence of elevated temperature and the threat of flashover on tenability will be examined.

There are a number of variables beyond the 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 variables have additive effects. For example, an oxygen deficient environment could cause an individual to breathe faster, which would increase the intake of CO and hot gases (Gann, 2008).

5.8.13.1. CO Tenability

In residential fires, smoke and CO inhalation is a major cause of fatalities, primarily due to carbon monoxide poisoning (Hall 2011). According to the NFPA, in 2007 there were 3,290 deaths in home fires. Based on the autopsy data, 1,610 (49%) were due to smoke inhalation, 750 (23%) were due to both burns and smoke inhalation, and 870 (26%) were due to burns.

The standard ISO 13571 – 2007 (ISO 13571, 2012) was used to determine the when conditions in the experiments became untenable. This standard calculates the cumulative effect of carbon monoxide concentration in a fire environment. This is done in terms of the fractional effective concentration (FEC), which corresponds to percentage of occupants expected to have become incapacitated due to cumulative carbon monoxide inhalation. In this analysis, values of FEC = 0.3 and FEC = 1.0. These values correspond to 11.4 % and 50 % of occupants becoming incapactitated, respectively. The equations used to calculate the FEC values at each time are given by Eq. 1 and Eq. 2.

$$\upsilon_{CO_2} = exp\left(\frac{\varphi_{CO_2}}{5}\right) \qquad (1)$$

$$FEC = \sum\left[\frac{\varphi_{CO}}{3.5} * \upsilon_{CO_2} * \Delta t\right] \tag{2}$$

Where υ_{CO_2} is a frequency factor to account for the increased rate of breathing due to carbon dioxide, φ_{CO_2} and $\varphi_{CO}$are the mole fractions (%) of carbon dioxide and carbon monoxide, and Δt is the time increment of the measurements made in the experiments in minutes (1/60 in the experiments). According to ISO 13571, the uncertainty in Eq. 1 is $\pm$ 20 % and the uncertainty in Eq. 2 is $\pm$ 35 %. Examples of CO and CO_2 concentrations from the one-story structure can be found in Figure 5.487 and Figure 5.488, and for the two-story structure in Figure 5.489 and Figure 5.490. The times to untenability for every room in every experiment where the gas concentrations were measured for both FEC = 0.3 and FEC = 1.0 can be found in Table 5.29 through Table 5.32.

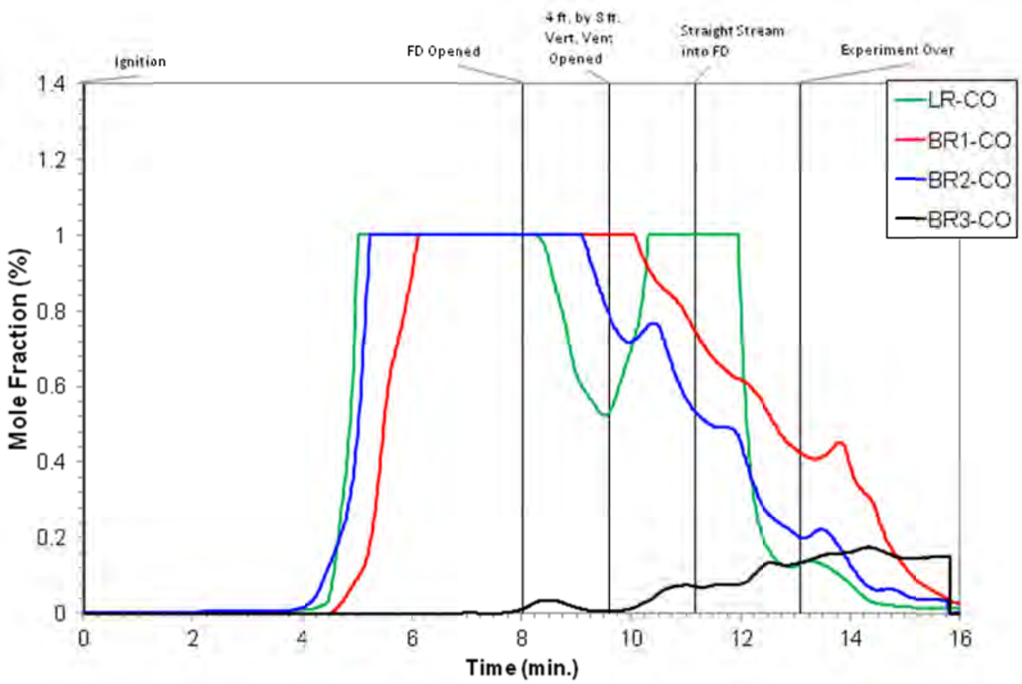


Figure 5.487: CO Measurements in One-Story Structure from Experiment 7

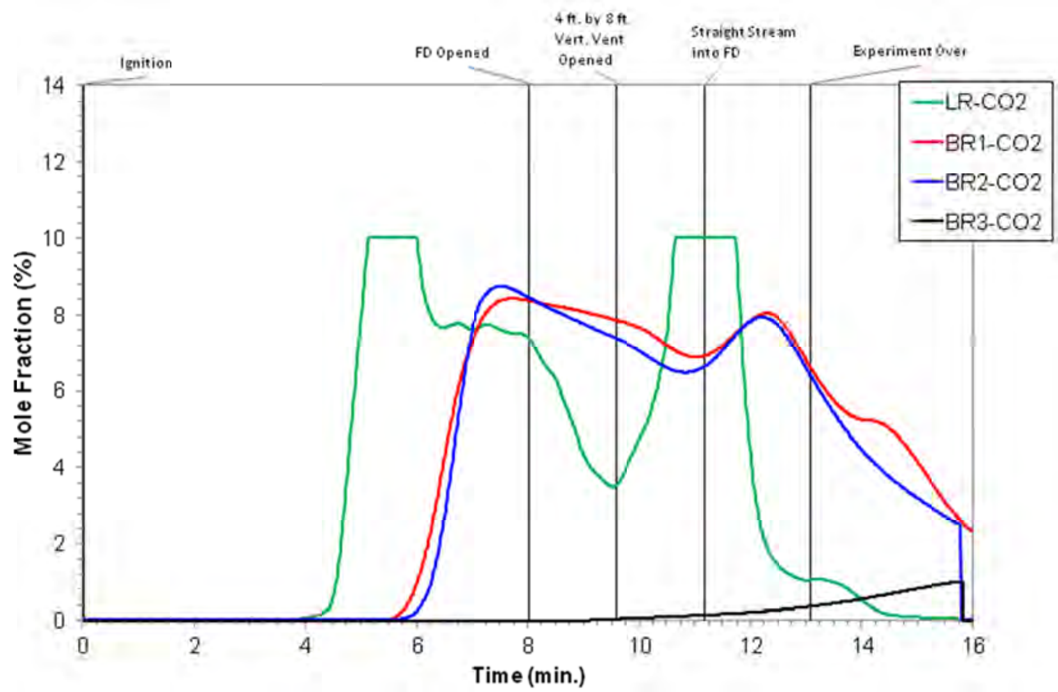


Figure 5.488: CO_2 Measurements in the One-Story Structure from Experiment 7

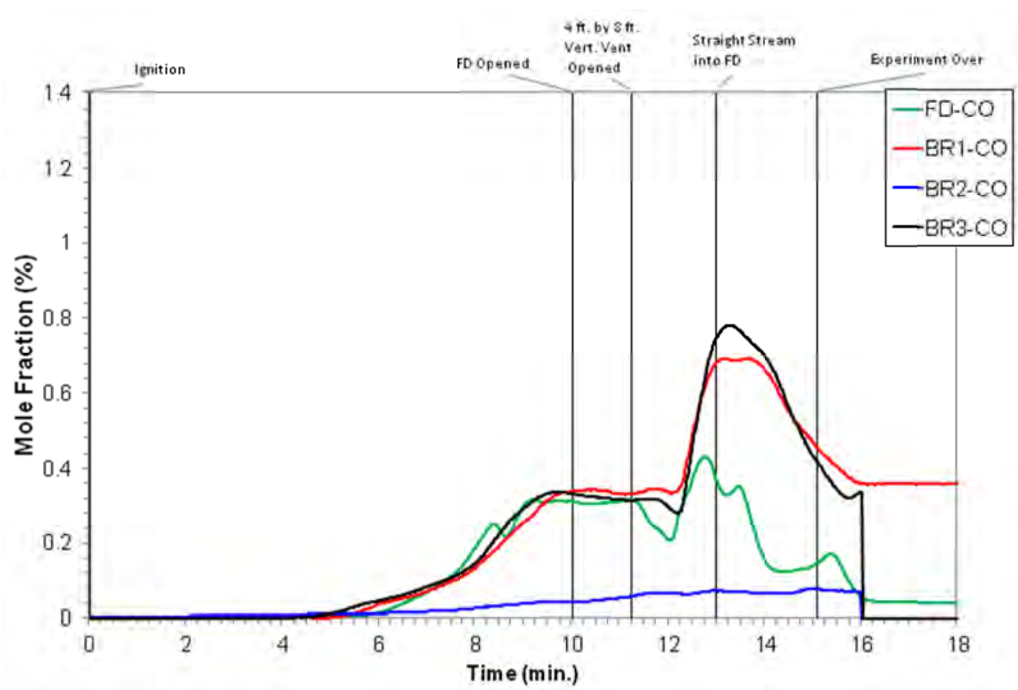


Figure 5.489: CO Measurements in Two-Story Structure from Experiment 8

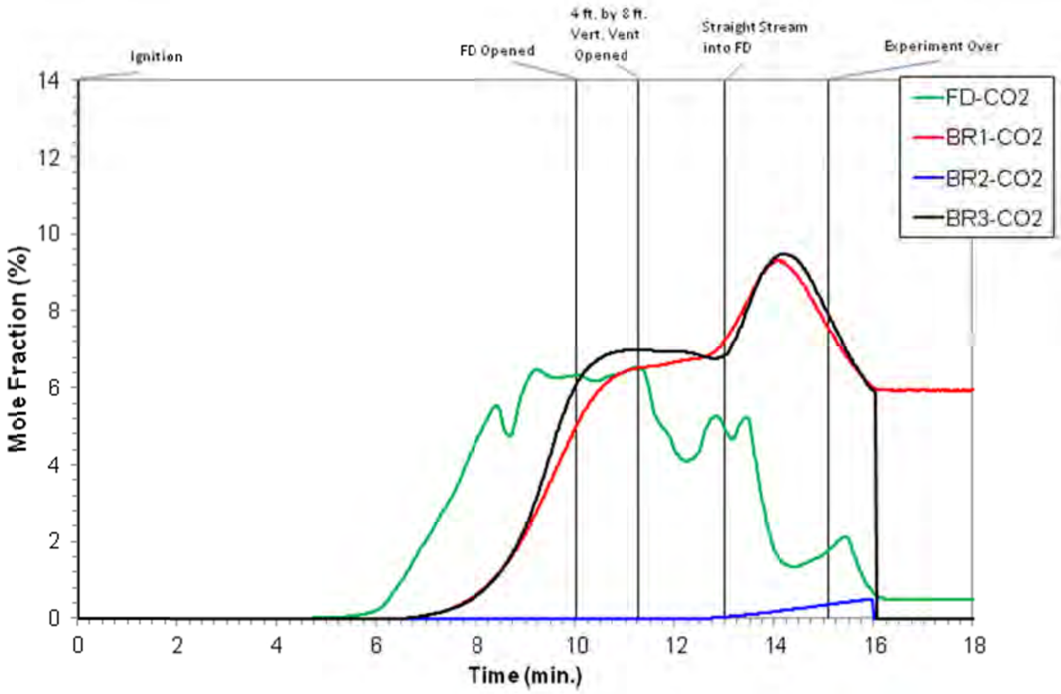


Figure 5.490: CO_2 Measurements in Two-Story Structure from Experiment 8

Table 5.29: Time to Untenability in One-Story Experiments for FEC = 0.3
(N/A means untenability was not reached)

	LR @ 3 ft. (mm:ss)	BR1 @ 3 ft. (mm:ss)	BR2 @ 3 ft. (mm:ss)	BR3@ 3 ft. (mm:ss)
Experiment 1	05:29	06:14	05:32	N/A
Experiment 3	05:30	06:44	05:29	N/A
Experiment 5	04:40	06:02	Equipment Malfunction	N/A
Experiment 7	05:06	06:24	05:57	N/A
Experiment 9	05:37	04:01	04:40	11:16
Experiment 11	06:06	Equipment Malfunction	05:09	N/A
Experiment 13	12:38	10:37	09:48	19:06
Experiment 15	05:39	05:32	05:24	13:41
Experiment 17	27:10	23:14	23:06	N/A

Table 5.30: Time to Untenability in One-Story Experiments for FEC = 1.0

	LR @ 3 ft. (mm:ss)	BR1 @ 3 ft. (mm:ss)	BR2 @ 3 ft. (mm:ss)	BR3@ 3 ft. (mm:ss)
Experiment 1	05:49	06:50	05:54	N/A
Experiment 3	05:50	08:03	05:53	N/A
Experiment 5	05:00	07:06	Equipment Malfunction	N/A
Experiment 7	05:26	07:08	07:04	N/A
Experiment 9	07:16	04:21	06:06	N/A
Experiment 11	07:26	Equipment Malfunction	06:11	N/A
Experiment 13	14:51	11:54	11:54	N/A
Experiment 15	06:09	06:03	05:51	19:33
Experiment 17	33:53	29:09	29:04	N/A

Table 5.31: Time to Untenability in Two-Story Experiments for FEC = 0.3

	FD @ 3 ft. (mm:ss)	BR1 @ 3 ft. (mm:ss)	BR2 @ 3 ft. (mm:ss)	BR3@ 3 ft. (mm:ss)
Experiment 2	07:55	09:43	N/A	09:06
Experiment 4	09:28	10:43	N/A	10:25
Experiment 6	08:49	10:08	N/A	10:00
Experiment 8	09:51	10:48	N/A	10:36
Experiment 10	N/A	05:07	17:31	03:56
Experiment 12	09:29	08:42	N/A	08:21
Experiment 14	N/A	05:14	12:37	04:00
Experiment 16	17:08	15:39	22:19	16:02

Table 5.32: Time to Untenability in Two-Story Experiments for FEC = 1.0

	FD @ 3 ft. (mm:ss)	BR1 @ 3 ft. (mm:ss)	BR2 @ 3 ft. (mm:ss)	BR3@ 3 ft. (mm:ss)
Experiment 2	11:10	12:36	N/A	11:46
Experiment 4	12:55	13:32	N/A	13:22
Experiment 6	11:54	12:40	N/A	12:42
Experiment 8	12:04	12:52	N/A	12:35
Experiment 10	N/A	05:55	N/A	04:18
Experiment 12	12:11	11:23	N/A	10:50
Experiment 14	N/A	05:56	N/A	04:20
Experiment 16	26:22	18:11	32:14	18:54

The calculated time to attain untenable conditions in the one-story structure, presented in Table 5.29 and Table 5.30 are longer than the actual times. This is because CO and CO_2 gas concentration exceeded the measurement limits (1% and 10% respectively) of the instruments used. This is also evident in Figure 5.487 and Figure 5.488, which show the data flat-line at the limits of the equipment. Thus, attainment of untenable conditions in the one-story structure is expected to be sooner than the calculations indicate.

In the two-story structure, the CO and CO_2 concentrations were below the equipment measurement limits. This may be observed in Figure 5.489 and Figure 5.490, which show the CO and CO_2 measurements respectively for the two-story structure (Experiment 8). The largest recorded value of CO in Experiment 8 was less than 0.8%, which is below the measurement limit of 1%. Similarly, the largest recorded value of CO_2 in Experiment 8 was also below the measurement limit of 10%.

The data in Table 5.29 through Table 5.32 shows that carbon monoxide poisoning is a very serious concern in regards to tenability during fires. In the one-story structure, for experiments where ignition occurred in the bedroom or living room, untenability was reached in every room at 3 ft. above the floor, other than the room with the door closed before the ventilation of the front door. The average time to untenability in the living room, bedroom 1, and bedroom 2 was 5:32 and 6:17 for the FEC criteria of 0.3 and 1.0, respectively. This implies that before firefighters are even able to enter the structure for search and rescue, the occupants inside the structure will have experienced untenable conditions. In the two-story structure, experiments with ignition initially in the family room (2, 4, 6, 8, 12), had average times to untenability of 9: 36 and 12:18 for FEC criteria of 0.3 and 1.0, respectively, in bedroom 3, bedroom 1, and at the front door. This shows that the time to untenability in the two-story structure is longer than in the one-story structure for similar fuel loads. This is mainly due to two reasons. The first reason is that for the same amount of CO generation in the two fires, the two-story structure will have a smaller CO volume % because of the larger volume of the compartment. The second reason is that, because of the larger volume in the two-story structure, there is more oxygen available to the fire. Figure 5.491 and Figure 5.492 show the oxygen concentration in the Experiments 7 and 8, respectively. Comparing these figures with Figure 5.487 and Figure 5.489 shows that CO generation coincides with the reduction of oxygen in the structure. As the fire becomes more oxygen-limited, the amount of CO generated in the combustion process begins to increase. Figure 5.491 shows a rapid decrease of oxygen in the living room around 4 min. 30s of Experiment 7, which is the same time that a sharp increase is seen in CO concentration in Figure 5.487. Figure 5.489 and Figure 5.492 show the same trend with the oxygen reduction and CO increase occurring at approximately 6 min. into Experiment 8. Figure 5.491 and Figure 5.492 not only explain the time at which CO begins to be generated in the structure, but also the rate of CO generation. Experiment 7 has a much larger and faster decrease in oxygen in the compartment then does Experiment 8, which explains the faster and larger rise in CO observed in the one-story structure compared with the two-story structure. This correlation between CO generation and oxygen depletion in the fire environment is expected, since as the oxygen supply is reduced, the combustion process and the resulting products begin to change within the structure, leading to an increase in CO and other toxins within the fire environment.

The data in Table 5.31 and Table 5.32 also show that fires in two-story structures with ignition in the upper floor behave similarly to one-story structure fires, with regards to CO untenability. This can be explained by the buoyant nature of the combustion products, which results in the smoke from fires beginning on the second floor to remain near the second floor creating a fire environment where the smoke is only in the top floor of the two story structure. The average times to untenability in bedroom 3 and bedroom 1 for Experiments 10 and 14 were 4:34 and 5:07 for FEC criteria of 0.3 and 1.0, respectively. These times are very similar to the times found in the one-story structure. It is interesting that for fires in the upper level of a two-story structure, untenability due to CO generation is not a concern on the lower level, since untenability was never reached at the front door in either Experiment 10 or Experiment 14. This can also be attributed to the buoyant motion of the combustion products.

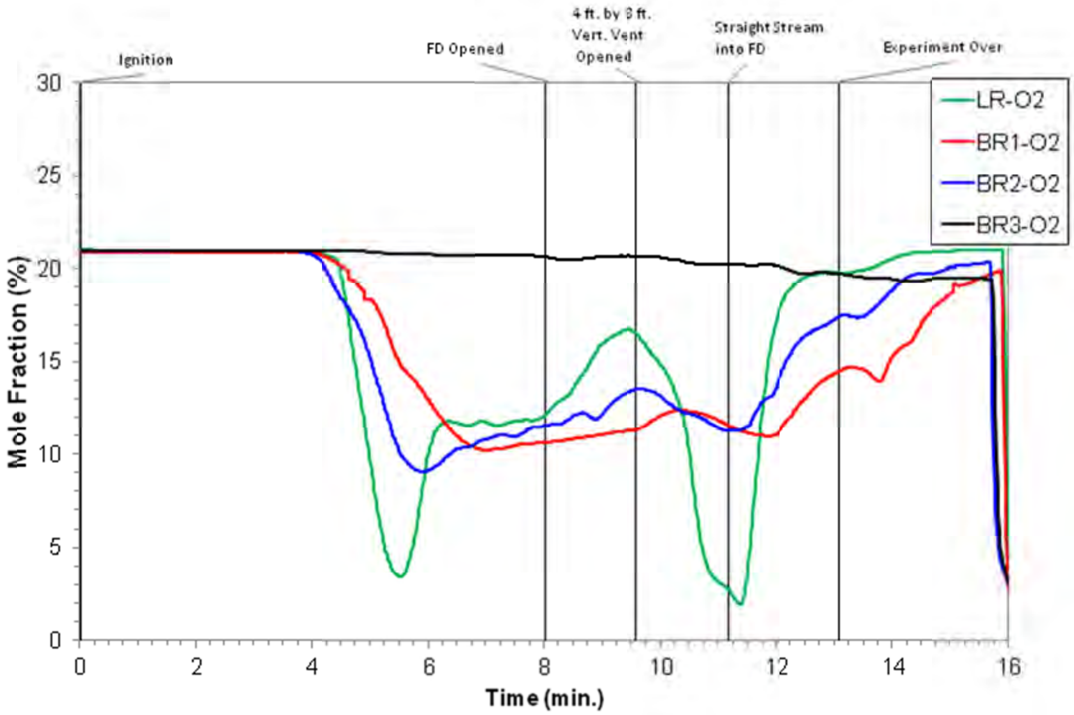


Figure 5.491: Oxygen Measurements in One-Story Structure from Experiment 7

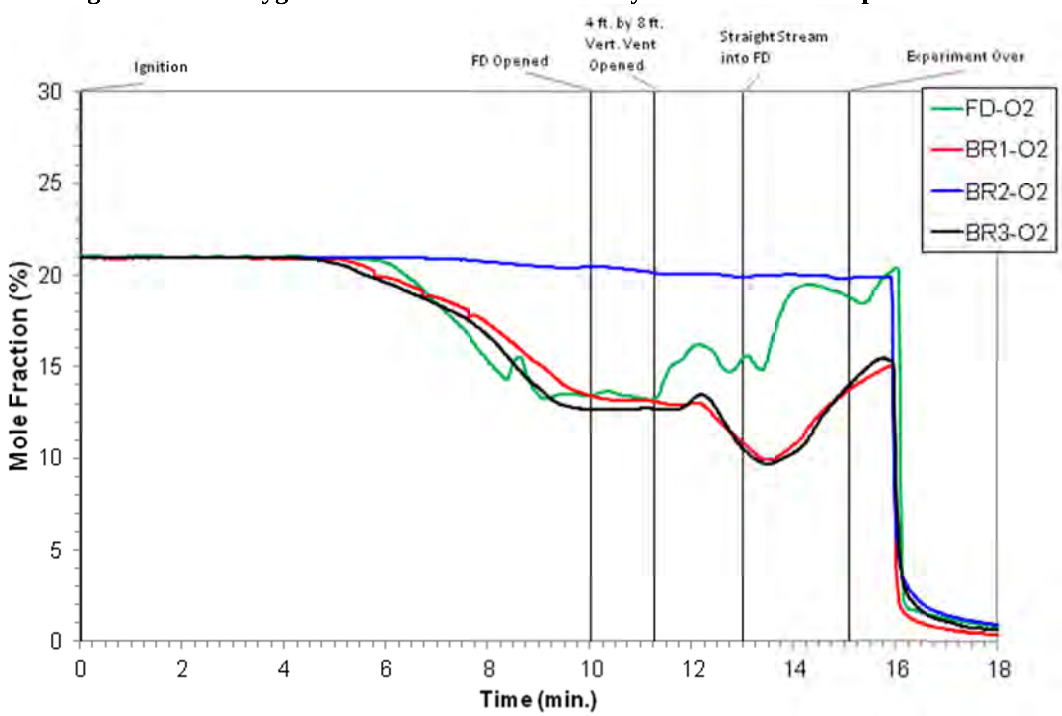


Figure 5.492: Oxygen Measurements in Two-Story Structure from Experiment 8

The times to untenability found in Table 5.29 through Table 5.32 also show prolonged periods of tenable conditions for occupants in compartments with closed doors. Bedroom 3 of the one-story structure and bedroom 2 of the two-story structure both had the bedroom doors closed for the duration of the experiments. This led to longer times to attain untenable conditions and, in most cases; especially for the FEC criteria of 1.0, untenable conditions were not reached. This shows that if occupants are trapped within a structure, it is very important that they attempt to isolate themselves (e.g., by remaining in a closed room) away from the fire room and its combustion products.

The final conclusion from the data in Table 5.29 and Table 5.30 is the increasing toxic potency of modern furniture as compared to the legacy furniture used in this study. Experiment 17 was the only experiment to use the legacy furniture. The average times to attain untenable conditions for Experiment 17 were 24:30 and 30:42 for FEC criteria of 0.3 and 1.0, respectively. This is an increase of approximately 20 minutes compared to the experiments with modern furnishings in the living room of the one-story structure.

5.8.13.2. Temperature Tenability

The temperatures in a residential fire also present hazards to occupants and firefighters. Determining the times to untenable conditions for occupants requires considering the effects of convection and radiation. The international standard (ISO-13571-2007) provides methodology to calculate influence of elevated temperature on occupants in the fire environment as shown in Equation (3). This calculation takes into account both influence of thermal radiation and convection on the occupancy as a fractional effective concentration.

$$FEC = \sum\left[\left(\frac{T^{3.61}}{4.1*10^{8}} + \frac{{q_{rad}}^{1.56}}{6.9}\right) * \Delta t\right] \tag{3}$$

In the equation, T is temperature near the occupant in degrees Celsius; and q_{rad} is the radiative heat flux in kW/m^2 based on the upper layer gas temperature. Equation 3 only applies for temperatures greater than 120°C and heat flux higher than 2.5 kW/m^2.

The times to untenability in each room at heights 1 ft., 3 ft., and 5 ft., above the floor for occupants in the one-story structure were calculated at threshold FEC values of 0.3 and 1.0. The heights were chosen to match an occupant lying on the floor (1 ft.), crawling on the floor (3 ft.), and standing in the room (5 ft.). The calculated data is presented in Table 5.33 through Table 5.38.

Table 5.33: One-Story, 1 ft. Occupant Times to Untenability, FEC = 0.3

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen	Firefighter Arrival
Exp 1	05:08	N/A	N/A	N/A	05:11	11:11	12:18	8:00
Exp 3	05:12	N/A	N/A	N/A	05:14	14:43	14:37	8:00
Exp 5	04:23	09:59	N/A	N/A	04:22	N/A	N/A	8:00
Exp 7	04:45	N/A	N/A	N/A	05:04	N/A	N/A	8:00
Exp 9	N/A	03:15	N/A	N/A	12:58	N/A	N/A	6:00
Exp 11	N/A	03:35	N/A	N/A	06:37	N/A	N/A	6:00
Exp 13	N/A	N/A	N/A	N/A	N/A	N/A	10:48	10:00
Exp 15	04:32	N/A	N/A	N/A	04:29	09:09	09:07	6:00
Exp 17	32:08	N/A	N/A	N/A	27:02	N/A	33:55	24:00

Table 5.34: One-Story, 3 ft. Occupant Times to Untenability, FEC = 0.3

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen	Firefighter Arrival
Exp 1	04:40	11:29	07:00	N/A	04:54	05:32	05:29	8:00
Exp 3	04:36	14:27	07:17	N/A	04:44	05:28	05:36	8:00
Exp 5	03:51	05:05	05:57	N/A	03:55	04:33	04:38	8:00
Exp 7	04:15	10:55	06:18	N/A	04:35	05:03	05:08	8:00
Exp 9	N/A	02:59	16:16	N/A	03:18	N/A	N/A	6:00
Exp 11	07:34	03:04	07:29	N/A	03:34	N/A	N/A	6:00
Exp 13	12:00	N/A	N/A	N/A	12:20	12:04	07:32	10:00
Exp 15	04:09	09:40	04:58	N/A	04:18	04:41	04:47	6:00
Exp 17	26:28	33:17	29:13	N/A	26:28	30:58	31:28	24:00

Table 5.35: One-Story, 5 ft. Occupant Times to Untenability, FEC = 0.3

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen	Firefighter Arrival
Exp 1	04:13	05:26	05:20	N/A	04:26	04:55	05:04	8:00
Exp 3	04:01	05:32	05:26	N/A	04:11	04:53	05:06	8:00
Exp 5	03:20	04:29	04:28	N/A	03:27	04:01	04:11	8:00
Exp 7	03:49	05:09	05:04	N/A	03:59	04:31	04:41	8:00
Exp 9	03:38	02:37	05:16	N/A	03:01	N/A	N/A	6:00
Exp 11	03:51	02:14	05:16	N/A	03:06	07:28	N/A	6:00
Exp 13	11:35	N/A	13:51	N/A	11:47	10:05	07:13	10:00
Exp 15	03:27	04:47	04:38	N/A	03:42	04:19	04:29	6:00
Exp 17	19:50	29:12	27:17	N/A	26:16	26:25	27:59	24:00

Table 5.36: One-Story, 1 ft. Occupant Times to Untenability, FEC = 1.0

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen	Firefighter Arrival
Exp 1	05:29	N/A	N/A	N/A	05:31	N/A	N/A	8:00
Exp 3	05:40	N/A	N/A	N/A	05:52	15:42	N/A	8:00
Exp 5	04:45	10:15	N/A	N/A	04:49	N/A	N/A	8:00
Exp 7	05:07	N/A	N/A	N/A	10:30	N/A	N/A	8:00
Exp 9	N/A	03:32	N/A	N/A	13:34	N/A	N/A	6:00
Exp 11	N/A	03:58	N/A	N/A	07:19	N/A	N/A	6:00
Exp 13	N/A	N/A	N/A	N/A	N/A	N/A	11:13	10:00
Exp 15	04:40	N/A	N/A	N/A	04:42	09:41	09:52	6:00
Exp 17	32:15	N/A	N/A	N/A	32:58	N/A	N/A	24:00

Table 5.37: One-Story, 3 ft. Occupant Times to Untenability, FEC = 1.0

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen	Firefighter Arrival
Exp 1	04:56	N/A	11:52	N/A	05:04	06:19	06:35	8:00
Exp 3	04:57	N/A	14:31	N/A	05:04	06:00	11:41	8:00
Exp 5	04:10	09:33	11:18	N/A	04:13	05:04	05:12	8:00
Exp 7	04:33	N/A	11:02	N/A	04:50	05:26	05:35	8:00
Exp 9	N/A	03:08	N/A	N/A	03:43	N/A	N/A	6:00
Exp 11	08:29	03:19	N/A	N/A	04:00	N/A	N/A	6:00
Exp 13	12:24	N/A	N/A	N/A	13:16	12:22	08:02	10:00
Exp 15	04:25	10:36	08:50	N/A	04:25	04:56	05:05	6:00
Exp 17	26:59	N/A	32:53	N/A	26:44	32:38	33:03	24:00

Table 5.38: One-Story, 5 ft. Occupant Times to Untenability, FEC = 1.0

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen	Firefighter Arrival
Exp 1	04:29	05:53	05:45	N/A	04:44	05:15	05:23	8:00
Exp 3	04:20	06:08	05:54	N/A	04:29	05:13	05:28	8:00
Exp 5	03:37	04:53	04:50	N/A	03:45	04:18	04:31	8:00
Exp 7	04:06	05:38	05:28	N/A	04:18	04:50	05:02	8:00
Exp 9	04:18	02:52	08:23	N/A	03:12	N/A	N/A	6:00
Exp 11	04:26	02:40	06:39	N/A	03:24	N/A	N/A	6:00
Exp 13	11:51	N/A	N/A	N/A	12:04	10:57	07:28	10:00
Exp 15	03:50	05:11	04:54	N/A	04:03	04:35	04:44	6:00
Exp 17	26:09	32:38	27:57	N/A	26:25	26:56	29:56	24:00

The times to reach untenable temperature conditions at 1 ft. show that only the fire room and hallway (next to the fire room) that had temperatures higher than the fire room temperatures during the experiments, reach untenable conditions in most experiments. In other rooms, the tenability limit (i.e., FEC=0.3 or FEC 0.1) is reached after firefighter arrival. In comparison, untenable conditions with respect to CO are reached prior to firefighter arrival in all rooms except bedroom 3 for almost each one-story experiment. This indicates that there is a higher potential for CO toxicity and an incapcitated occupant in a non-fire room within a one-story structure. However, the times to attain untenable conditions in the fire room due to elevated temperature, typically around 4 min., are significantly lower than the for the effect of CO. Thus, in the fire room, elevated temperatures are a greater hazard to an occupant than is CO poisoning. The above tables also show the rapid deterioration in tenability with height above the floor and are due to the vertical temperature gradient observed in all the rooms.

At the 5 ft. level, untenable conditions are reached in most rooms before firefighter arrival. At the 3 ft. level, most of the non-fire rooms eventually reach untenable conditions, sometimes before firefighter arrival and sometimes after fire fighter arrival. These calculations show that the hazard from heat exposure in the one-story structure is not as significant as the hazard from elevated CO concentration. However, in absence of elevated CO concentration, elevated temperatures still present a significant hazard to occupants. Often, untenable conditions with respect to elevated temperatures are reached within the fire environment, even in the non-fire rooms, prior to firefighter arrival.

The times to reach untenable conditions in every room at 1 ft., 3 ft., and 5 ft., for occupants in the two-story structure, using FEC values of 0.3 and 1.0, can be found in Table 5.39 through Table 5.50.

Table 5.39: Two-Story, First Floor, 1 ft. Occupant Times to Untenability, FEC = 0.3

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room	Firefighter Arrival
Exp 2	06:20	N/A	N/A	N/A	N/A	14:10	10:00
Exp 4	07:42	N/A	N/A	N/A	17:46	17:55	10:00
Exp 6	07:01	N/A	N/A	N/A	13:22	N/A	10:00
Exp 8	07:27	N/A	N/A	N/A	N/A	N/A	10:00
Exp 10	N/A	N/A	N/A	N/A	N/A	N/A	10:00
Exp 12	06:13	N/A	N/A	N/A	N/A	12:59	8:00
Exp 14	N/A	N/A	N/A	N/A	N/A	N/A	8:35
Exp 16	27:40	25:26	N/A	28:37	28:11	28:39	27:00

Table 5.40: Two-Story, First Floor 3 ft. Occupant Times to Untenability, FEC = 0.3

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room	Firefighter Arrival
Exp 2	05:09	08:43	14:16	06:40	07:05	07:47	10:00
Exp 4	06:38	10:07	17:59	08:21	08:27	09:09	10:00
Exp 6	06:04	09:17	14:09	07:40	07:44	08:15	10:00
Exp 8	06:43	09:00	N/A	08:01	08:06	08:33	10:00
Exp 10	16:03	N/A	N/A	N/A	N/A	N/A	10:00
Exp 12	05:36	07:55	13:23	06:57	07:08	07:26	8:00
Exp 14	N/A	N/A	N/A	N/A	N/A	N/A	8:35
Exp 16	25:56	14:39	29:11	27:30	27:29	27:52	27:00

Table 5.41: Two-Story, First Floor, 5 ft. Occupant Times to Untenability, FEC = 0.3

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room	Firefighter Arrival
Exp 2	04:33	06:24	12:51	06:11	05:40	06:56	10:00
Exp 4	06:00	07:49	13:32	07:36	07:07	08:20	10:00
Exp 6	05:35	07:08	12:00	06:54	06:28	07:34	10:00
Exp 8	06:07	07:35	09:53	07:35	07:07	07:50	10:00
Exp 10	03:35	N/A	N/A	N/A	N/A	N/A	10:00
Exp 12	05:07	06:20	09:16	06:25	05:59	06:37	8:00
Exp 14	03:59	N/A	N/A	N/A	N/A	N/A	8:35
Exp 16	15:45	14:01	28:15	26:09	26:04	27:06	27:00

Table 5.42: Two-Story, First Floor, 1 ft. Occupant Times to Untenability, FEC = 1.0

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room	Firefighter Arrival
Exp 2	06:53	N/A	N/A	N/A	N/A	N/A	10:00
Exp 4	08:17	N/A	N/A	N/A	N/A	N/A	10:00
Exp 6	07:33	N/A	N/A	N/A	N/A	N/A	10:00
Exp 8	07:47	N/A	N/A	N/A	N/A	N/A	10:00
Exp 10	N/A	N/A	N/A	N/A	N/A	N/A	10:00
Exp 12	06:42	N/A	N/A	N/A	N/A	14:48	8:00
Exp 14	N/A	N/A	N/A	N/A	N/A	N/A	8:35
Exp 16	27:50	27:57	N/A	29:09	28:33	29:24	27:00

Table 5.43: Two-Story, First Floor, 3 ft. Occupant Times to Untenability, FEC = 1.0

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room	Firefighter Arrival
Exp 2	05:37	12:52	N/A	09:34	12:10	12:49	10:00
Exp 4	07:08	16:51	N/A	11:40	12:24	14:06	10:00
Exp 6	06:26	13:00	N/A	10:56	11:27	12:29	10:00
Exp 8	07:07	12:57	N/A	09:09	08:44	11:20	10:00
Exp 10	N/A	N/A	N/A	N/A	N/A	N/A	10:00
Exp 12	05:57	11:45	N/A	08:25	09:52	10:56	8:00
Exp 14	N/A	N/A	N/A	N/A	N/A	N/A	8:35
Exp 16	26:31	15:08	N/A	28:09	27:55	28:14	27:00

Table 5.44: Two-Story, First Floor, 5 ft. Occupant Times to Untenability, FEC = 1.0

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room	Firefighter Arrival
Exp 2	04:58	07:08	13:33	07:10	06:16	09:25	10:00
Exp 4	06:27	08:29	17:34	08:58	07:44	10:57	10:00
Exp 6	05:54	07:49	13:25	07:57	07:03	08:39	10:00
Exp 8	06:33	08:06	13:19	08:05	07:37	08:20	10:00
Exp 10	04:05	N/A	N/A	N/A	N/A	N/A	10:00
Exp 12	05:29	06:54	12:49	06:57	06:29	07:11	8:00
Exp 14	04:38	N/A	N/A	N/A	N/A	N/A	8:35
Exp 16	16:47	14:26	28:42	27:35	26:45	27:54	27:00

Table 5.45: Two-Story, Second Floor, 1 ft. Occupant Times to Untenability, FEC = 0.3

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3	Firefighter Arrival
Exp 2	15:41	13:54	12:27	N/A	13:40	10:00
Exp 4	19:29	17:46	15:44	N/A	16:58	10:00
Exp 6	15:00	13:36	12:19	N/A	13:32	10:00
Exp 8	N/A	13:15	09:58	N/A	13:47	10:00
Exp 10	N/A	N/A	03:44	N/A	03:04	10:00
Exp 12	14:21	12:16	10:52	N/A	09:47	8:00
Exp 14	N/A	N/A	03:34	N/A	03:17	8:35
Exp 16	29:34	28:31	27:37	N/A	27:43	27:00

Table 5.46: Two-Story, Second Floor, 3 ft. Occupant Times to Untenability, FEC = 0.3

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3	Firefighter Arrival
Exp 2	13:52	08:27	05:59	N/A	07:34	10:00
Exp 4	17:21	09:56	07:30	N/A	09:04	10:00
Exp 6	13:07	09:00	06:39	N/A	08:23	10:00
Exp 8	11:55	09:00	07:13	N/A	08:34	10:00
Exp 10	N/A	N/A	03:06	N/A	02:55	10:00
Exp 12	10:54	07:54	06:05	N/A	07:31	8:00
Exp 14	N/A	N/A	03:15	N/A	03:08	8:35
Exp 16	28:22	27:41	25:34	N/A	27:05	27:00

Table 5.47: Two-Story, Second Floor, 5 ft. Occupant Times to Untenability, FEC = 0.3

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3	Firefighter Arrival
Exp 2	11:43	06:46	04:17	N/A	06:11	10:00
Exp 4	11:16	08:08	05:38	N/A	07:49	10:00
Exp 6	Malfunction	07:26	05:10	N/A	06:54	10:00
Exp 8	09:43	08:01	05:57	N/A	07:35	10:00
Exp 10	N/A	07:07	02:58	N/A	02:38	10:00
Exp 12	08:39	06:49	04:54	N/A	06:28	8:00
Exp 14	N/A	07:45	03:08	N/A	02:42	8:35
Exp 16	27:44	26:24	15:05	N/A	18:36	27:00

Table 5.48: Two-Story, Second Floor, 1 ft. Occupant Times to Untenability, FEC = 1.0

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3	Firefighter Arrival
Exp 2	N/A	N/A	12:42	N/A	15:47	10:00
Exp 4	N/A	N/A	16:14	N/A	18:46	10:00
Exp 6	N/A	N/A	12:31	N/A	14:19	10:00
Exp 8	N/A	N/A	12:27	N/A	N/A	10:00
Exp 10	N/A	N/A	04:04	N/A	03:17	10:00
Exp 12	N/A	14:30	11:50	N/A	13:12	8:00
Exp 14	N/A	N/A	04:12	N/A	03:32	8:35
Exp 16	33:37	29:01	27:46	N/A	27:53	27:00

Table 5.49: Two-Story, Second Floor, 3 ft. Occupant Times to Untenability, FEC = 1.0

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3	Firefighter Arrival
Exp 2	16:05	12:47	06:38	N/A	12:32	10:00
Exp 4	19:24	15:45	08:15	N/A	13:30	10:00
Exp 6	13:44	12:34	07:26	N/A	12:26	10:00
Exp 8	13:47	12:20	07:44	N/A	11:35	10:00
Exp 10	N/A	N/A	03:24	N/A	03:01	10:00
Exp 12	13:49	11:09	06:41	N/A	10:55	8:00
Exp 14	N/A	N/A	03:24	N/A	03:14	8:35
Exp 16	28:53	28:06	26:47	N/A	27:37	27:00

Table 5.50: Two-Story, Second Floor, 5 ft. Occupant Times to Untenability, FEC = 1.0

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3	Firefighter Arrival
Exp 2	13:02	10:17	04:48	N/A	06:56	10:00
Exp 4	16:13	11:06	06:12	N/A	08:38	10:00
Exp 6	Malfunction	10:17	05:42	N/A	08:06	10:00
Exp 8	12:29	08:44	06:24	N/A	08:09	10:00
Exp 10	N/A	N/A	03:05	N/A	02:51	10:00
Exp 12	11:59	08:04	05:21	N/A	07:05	8:00
Exp 14	N/A	N/A	03:14	N/A	03:00	8:35
Exp 16	28:12	27:43	16:30	N/A	26:04	27:00

The times for untenable conditions in the two-story structure follow similar trends to the one-story structure. Elevated temperatures lead to untenable conditions at 1 ft., 3 ft. and 5 ft. above the floor in the fire room prior to firefighter arrival. Additionally, tenability deteriorates at higher locations above the floor, similarly to the one-story structure. An important observation in the two-story structure is that on the second floor untenable conditions at 1 ft. above the floor are reached in most experiments in a majority of the upper floor rooms; and the times are long after the simulated firefighter arrival. This indicates that in the two-story structure, based on elevated temperatures, there may be trapped occupants on the upper floors that need rescue. The same results were found with respect to CO in the two-story structure, although the times to achieve untenable conditions with respect to CO are lower than the heat exposure times. This again indicates that elevated CO is more of a hazard to occupants than heat exposure. The CO times to attain untenable conditions at the FEC value of 1.0 were around 2 minutes after firefighter arrival, while the times for elevated temperature at the lower FEC value of 0.3 were typically more than three minutes after firefighter arrival. On the first floor, the times to untenability at 1 ft. are all after the simulated firefighter arrival time in the non-fire rooms. At higher distances from the floor, the times to untenability decrease. At the 5 ft. level, the times to untenability are lower on the first floor than on the second floor for the family room fires. The times to untenability on the first floor at the 5 ft. level for FEC value of 0.3 is achieved before the simulated arrival of the firefighting crew for the family room fires, except in the den. The den is the only room with no visual access to the family room on the lower floor, which, since there is no radiation from the fire room to the den, consistently results in lower temperatures in the den and thus longer times to untenability. Similar to the upper floor, the danger of CO poisoning is greater than the danger of heat exposure for passed out occupants on the lower level of the two-story structure.

5.8.13.3. Firefighter Tenability

The time for reaching tenability threshold for firefighters was calculated based on the temperature threshold criteria of 500 °F (260^{o}C). Using temperature is a basic estimate of firefighter tenability because of how turnout gear protects a firefighter. Turnout gear absorbs energy to protect the firefighter inside. Once the gear becomes saturated it passes heat through to the firefighter which would lead to burn injuries. This is a complex series of events that depends on a number of variables such as type of materials that make the gear, air gaps in the gear, age of the gear, cleanliness of the gear, time of exposure, temperature, heat flux, etc. Due to this complexity a temperature of 500 °F was chosen as it represents a level at which the gear will begin to degrade, and is also the temperature the gear is tested to NFPA 1981 standard (NFPA, 2013). In practice, the firefighter in the gear could already be compromised prior to the 500 °F threshold or after it depending on all the variables described above.

This time was compared to the time to flashover to determine the egress time available for a firefighter in a quickly deteriorating fire environment. The times to untenability were determined for each experiment for each room at heights of 3 ft. and 7 ft. above the floor. These heights were chosen to simulate a crawling firefighter (3 ft.) and a worst-case scenario (7 ft.). The results for the one-story structure are presented in Table 5.51 and Table 5.52. The times presented are after the first ventilation event as firefighters can only enter the structure through the process of ventilation.

This analysis does not take radiative effects into consideration because heat flux was not measured. It is important to mention that exposure to high heat flux levels could reduce the times tabulated below significantly. This analysis is meant to be a reminder that ventilation actions by the fire service may contribute to developing conditions that are hazardous for the firefighters inside the structure.

Table 5.51: Firefighter Tenability in One-Story Structure at 3 ft.

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen
Exp 1	10:21*	N/A	N/A	N/A	10:42	10:59	11:11
Exp 3	12:59*	N/A	N/A	N/A	13:21	13:43	15:08
Exp 5	10:12*	N/A	N/A	N/A	10:55	N/A	N/A
Exp 7	09:49*	N/A	N/A	N/A	10:29	N/A	N/A
Exp 9	N/A	11:07*	N/A	N/A	15:43	N/A	N/A
Exp 11	N/A	06:00*	N/A	N/A	N/A	N/A	N/A
Exp 13	N/A	N/A	N/A	N/A	N/A	13:12	11:48*
Exp 15	08:27*	N/A	N/A	N/A	08:56	09:03	09:25
Exp 17	27:59*	N/A	N/A	N/A	32:27	32:57	N/A

*Room of Fire Origin

Table 5.52: Firefighter Tenability in One-Story Structure at 7 ft.

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Hallway	Dining Room	Kitchen
Exp 1	09:05*	10:52	10:45	N/A	09:31	10:24	10:36
Exp 3	09:14*	13:59	13:37	N/A	09:35	13:01	13:19
Exp 5	09:00*	08:24	10:39	N/A	09:01	10:12	10:25
Exp 7	08:58*	10:45	10:30	N/A	09:10	09:42	09:50
Exp 9	15:49	09:00*	N/A	N/A	11:05	N/A	N/A
Exp 11	06:17	06:00*	07:24	N/A	06:00	N/A	N/A
Exp 13	11:29	N/A	N/A	N/A	11:43	11:19	10:00*
Exp 15	07:04*	09:20	08:58	N/A	06:00	08:05	08:43
Exp 17	26:02*	32:57	32:38	N/A	26:15	26:34	32:24

*Room of Fire Origin

The data in Table 5.52 is anticipated to be a more conservative estimate for times to reach untenable conditions than data in Table 5.51, since firefighters are likely to be positioned closer to the floor. Table 5.51 shows that firefighter tenability in the residential fire environment is mainly a concern in the fire room, since the times to untenability in the non-fire rooms are significantly longer than in the fire room. In Experiment 11, it was the rare case where upon ventilation, firefighter tenability in the fire room had already been reached (6 minutes after ignition). Typically; however, firefighters have approximately 2 min. after initial ventilation before untenability in the fire room is reached. The low-end estimate based on the data in Table 5.52 suggests that firefighters have only 1 min. to search the fire environment. One important thing to note is that Experiment 3 has almost 3 min. longer of tenability than does Experiment 5 at the 3 ft. level. The main difference in those experiments was shutting the front door after ventilation of the front door in Experiment 3. This shows that this tactic reduces the risk to firefighters searching the fire environment. Another thing to consider is the danger of flashover to firefighters. When untenability is reached within the fire environment, firefighters may still have time to escape as they are expected to be equipped with PPE for search and rescue in the fire environment. However, flashover eliminates this possibility and can cause firefighter deaths. The time difference between untenability at 3 ft. in the fire room and flashover are presented in Table 5.53. The times in Table 5.53 are meant to show how quickly conditions can change. They assume the firefighter does not sense deteriorating conditions until the temperature at 3 ft. reaches 500 °F.

Table 5.53: Firefighter Escapability

Experiment	Time for firefighter escape (s)
1	14
3	19
5	14
7	39
9	79
11	29
13	No Flashover
15	28
17	267

Table 5.53 shows that firefighters have little time to escape once the fire environment begins to deteriorate. The time in Experiment 17 suggests that this was not always the case, since the time between untenability and flashover is more than 4 min. In modern fire environments, the data suggests that firefighters may have less than 15 seconds to escape the fire environment once untenability is reached.

The times to reach untenable conditions in the two-story structure were calculated similarly to the one-story structure. The results are presented in Table 5.54 through Table 5.57.

Table 5.54: Firefighter Tenability in Two-Story Structure at 3 ft., Lower Level

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room
Exp 2	12:55*	N/A	N/A	12:55	12:59	N/A
Exp 4	14:28*	N/A	N/A	N/A	16:53	N/A
Exp 6	11:10*	N/A	N/A	13:14	13:36	N/A
Exp 8	10:58*	N/A	N/A	N/A	N/A	N/A
Exp 10	N/A	N/A	N/A	N/A	N/A	N/A
Exp 12	09:13*	N/A	N/A	11:50	12:45	N/A
Exp 14	N/A	N/A	N/A	N/A	N/A	N/A
Exp 16	27:25	28:16*	N/A	28:11	28:01	28:18

*Room of Fire Origin

Table 5.55: Firefighter Tenability in Two-Story Structure at 7 ft., Lower Level

	Family Room	Kitchen	Den	Dining Room	Foyer	Living Room
Exp 2	12:42*	12:27	N/A	12:31	12:05	12:29
Exp 4	10:00*	15:51	N/A	16:02	15:20	15:49
Exp 6	10:00*	12:18	N/A	12:22	12:09	12:21
Exp 8	10:00*	12:22	N/A	12:13	11:48	12:21
Exp 10	15:30	N/A	N/A	N/A	N/A	N/A
Exp 12	08:00*	11:23	N/A	11:25	10:55	11:33
Exp 14	N/A	N/A	N/A	N/A	N/A	N/A
Exp 16	25:22	17:00*	29:18	27:43	27:17	27:45

*Room of Fire Origin

Table 5.56: Firefighter Tenability in Two-Story Structure at 3 ft., Upper Level

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3
Exp 2	N/A	N/A	12:29	N/A	N/A
Exp 4	N/A	N/A	15:35	N/A	N/A
Exp 6	N/A	N/A	12:18	N/A	N/A
Exp 8	N/A	N/A	12:12	N/A	N/A
Exp 10	N/A	N/A	15:55	N/A	14:28*
Exp 12	N/A	N/A	11:17	N/A	N/A
Exp 14	N/A	N/A	N/A	N/A	08:35*
Exp 16	N/A	28:26	27:21	N/A	27:26

*Room of Fire Origin

Table 5.57: Firefighter Tenability in Two-Story Structure at 7 ft., Upper Level

	Bedroom 1	Bedroom 4	Hallway	Bedroom 2	Bedroom 3
Exp 2	13:16	12:28	11:11	N/A	12:26
Exp 4	17:09	16:30	10:00	N/A	15:33
Exp 6	12:35	12:17	10:43	N/A	12:19
Exp 8	12:29	12:14	10:00	N/A	12:27
Exp 10	N/A	N/A	14:30	N/A	14:10*
Exp 12	13:22	11:42	08:00	N/A	11:18
Exp 14	N/A	N/A	08:35	N/A	08:35*
Exp 16	27:57	27:39	25:21	N/A	27:32

*Room of Fire Origin

The data in Table 5.54 suggests that firefighters typically have around 1 minute after ventilation before the fire room becomes untenable. However, in the situation where the door is closed behind entry, as in Experiment 4, the tenability time in the fire room increases by more than 3 min. compared with Experiment 6 and Experiment 8. Additionally, Table 5.56 shows that at 3 ft., the hallway is untenable approximately 2 min. after ventilation and entry. This gives firefighters a short amount of time to search the larger two-story structure. Table 5.56 and Table 5.57 show the low-end estimate of times to untenability. These times are low and in several experiments, the fire room and the hallway are untenable upon ventilation and entry. One more thing to note from Table 5.54 is that the foyer and dining room reach untenability at the 3 ft. level approximately 3 min. after ventilation and entry in some of the experiments. On the other hand, the other lower level non-fire rooms do not reach untenability in any of the experiments except Experiment 16, with ignition in the kitchen and family room. The times from 500 °F at 3 ft. above the floor until flashover are presented in Table 5.58.

Table 5.58: Firefighter Escapability

Experiment	Time for firefighter escape (s)
2	8
4	No Flashover
6	54
8	47
10	52
12	191
14	117
16	No Flashover

Table 5.58 shows that, except for Experiment 2, the times between untenability and flashover are longer in the two-story structure than in the one-story structure. Several experiments in the one-story structure transitioned to flashover in less than 20 s, but in the two-story structure only one experiment transitioned from tenable to flashover in less than 40 s.

5.8.14. Suppression Analysis

Many fire departments have had success with applying initial water to the fire from the outside, a tactic called by names such as transitional attack, softening the target, hitting it hard from the yard, quick water, etc. With the changes that have occurred in the fire environment and the speed at which fires grow, there have been questions about the concept of “pushing the fire” with a hose stream. Pushing fire is thought to occur as a result of three potential mechanisms that start with a hose stream directed into an opening with fire or hot gases exiting. The pressure from the stream, the airflow created by the stream, or steam expansion could create conditions in the house that are worse downstream.

The efficacy of this tactic was investigated in every experiment conducted by incorporating a stream of water directed into a ventilation opening for approximately 15 seconds. Experiments 13, 15, and 16 were specifically designed to examine the impact of exterior water flow with and without a flow path. These experiments will be examined in detail. The hose line used was a 1 ¾ inch with a combination nozzle with approximately 100 psi nozzle pressure, creating a flow of 100 gpm. 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 into the structure. The nozzleman was directed to put water on what they saw was burning, so the nozzle was not held stationary. During the fog stream application the nozzle was adjusted to create an approximate 30 degree fog pattern and also directed into the structure with the intent to extinguish the visible fire while not holding the nozzle stationary.

With the flow rate of the nozzle of 100 gpm, 25 gallons of water were delivered through the opening into the house during the 15 second flow. The purpose of this flow was not to move into the structure and extinguish the fire but to suppress as much fire as possible and to observe the impact to the temperatures in the surrounding rooms. The experiment was terminated at least one minute after the hose stream, and suppression was completed by the firefighting crew.

There were 23 instances of water application throughout the 17 experiments where the water was applied directly to the fire room. Of these 23 water applications, 13 were in the one-story experiments and the other ten were in the two-story experiments. Eighteen of the 23 water applications used a straight stream nozzle, while the other five water applications used a fog stream nozzle. Information for all of the instances of water application can be found in Table 5.59.

Table 5.59: Information on Water Application

Structure	Experiment #	Stream Type	Duration (s)	Water (gallons)
One-Story	1	Straight Stream	13	22
One-Story	3	Straight Stream	11	18
One-Story	5	Straight Stream	17	28
One-Story	7	Straight Stream	15	25
One-Story	11	Straight Stream	16	27
One-Story	13	Straight Stream	6	10
One-Story	13	Fog Stream	7	12
One-Story	13	Straight Stream	6	10
One-Story	13	Fog Stream	41	68
One-Story	13	Straight Stream	12	20
One-Story	15	Straight Stream	11	18
One-Story	15	Fog Stream	13	22
One-Story	17	Straight Stream	15	25
Two-Story	2	Straight Stream	12	20
Two-Story	4	Straight Stream	13	22
Two-Story	6	Straight Stream	15	25
Two-Story	8	Straight Stream	15	25
Two-Story	10	Straight Stream	12	20
Two-Story	12	Straight Stream	16	27
Two-Story	14	Straight Stream	15	25
Two-Story	16	Fog Stream	15	25
Two-Story	16	Fog Stream	14	23
Two-Story	16	Straight Stream	17	28

To measure the effect of water application on the fire environment, the temperature at a height of 3 ft. in each room within the structure was measured and recorded the second before water application, directly after water application, 10 s after water application, 30 s after water application, and 60 s after water application. The height of 3 ft. was chosen because it is near the height of a crawling firefighter and near the height of an incapacitated occupant. The temperatures in each room before water application, 10 s after, 30 s after, and 60 s after water application for each application of water in the experiments can be found in the Section 5.8.14.1 and 5.8.14.2.

5.8.14.1. Water Application (One-Story)

KEY
Temperature (3 ft. above floor) just prior to water application
Temperature (3 ft. above floor) 10 seconds after water application
Temperature (3 ft. above floor) 30 seconds after water application
Temperature (3 ft. above floor) 60 seconds after water application
Change in Temperature after 60 seconds (Percent change)

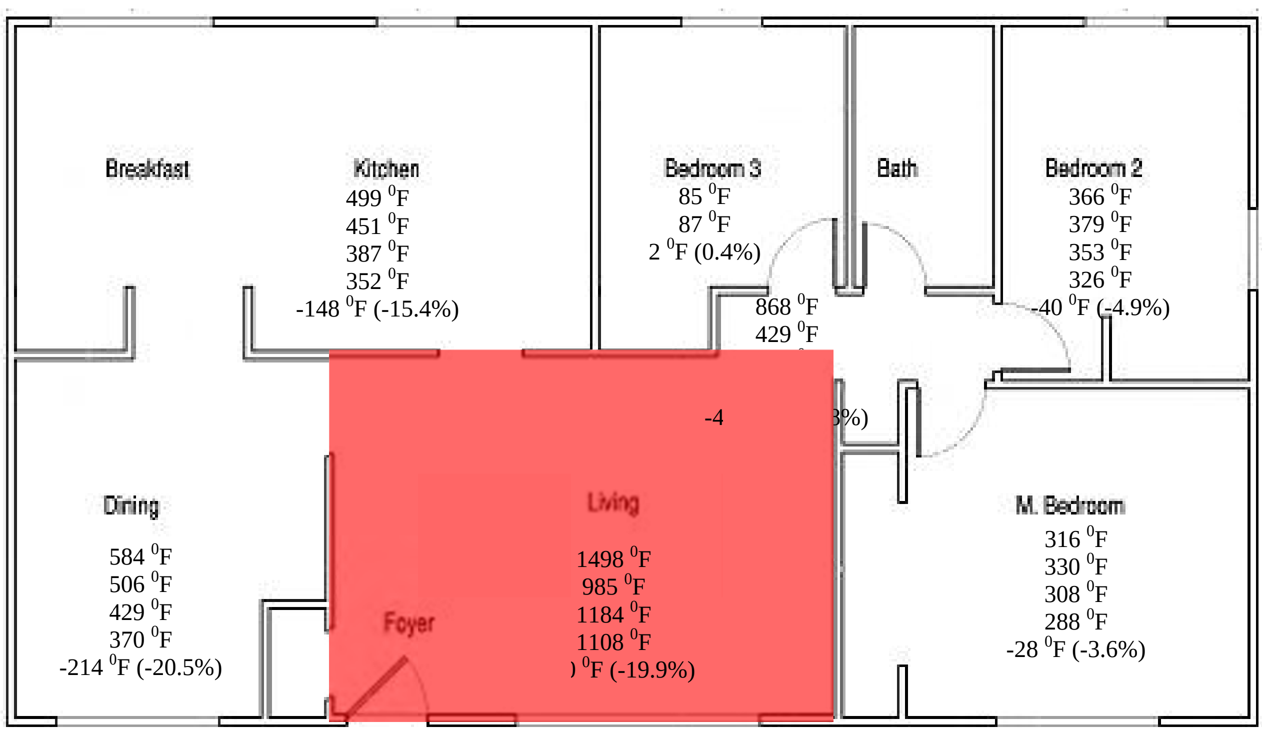


Figure 5.493: Experiment 1, Straight Stream,

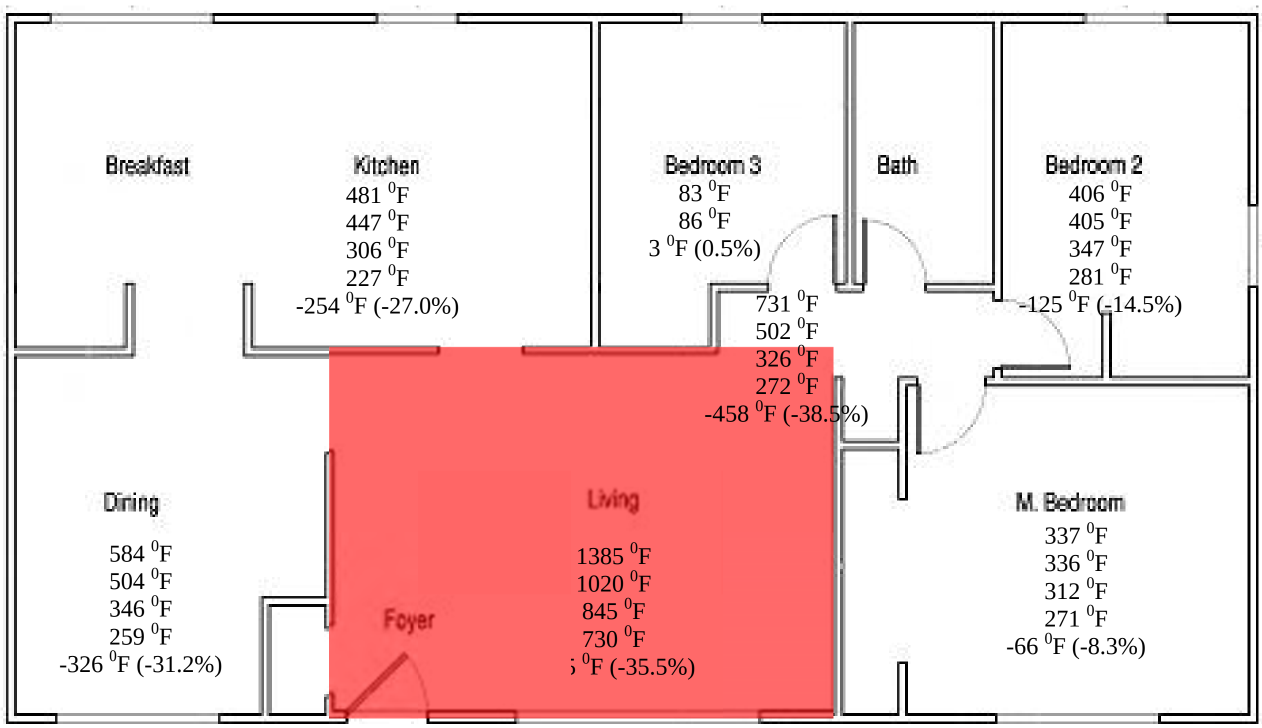


Figure 5.494: Experiment 3, Straight Stream

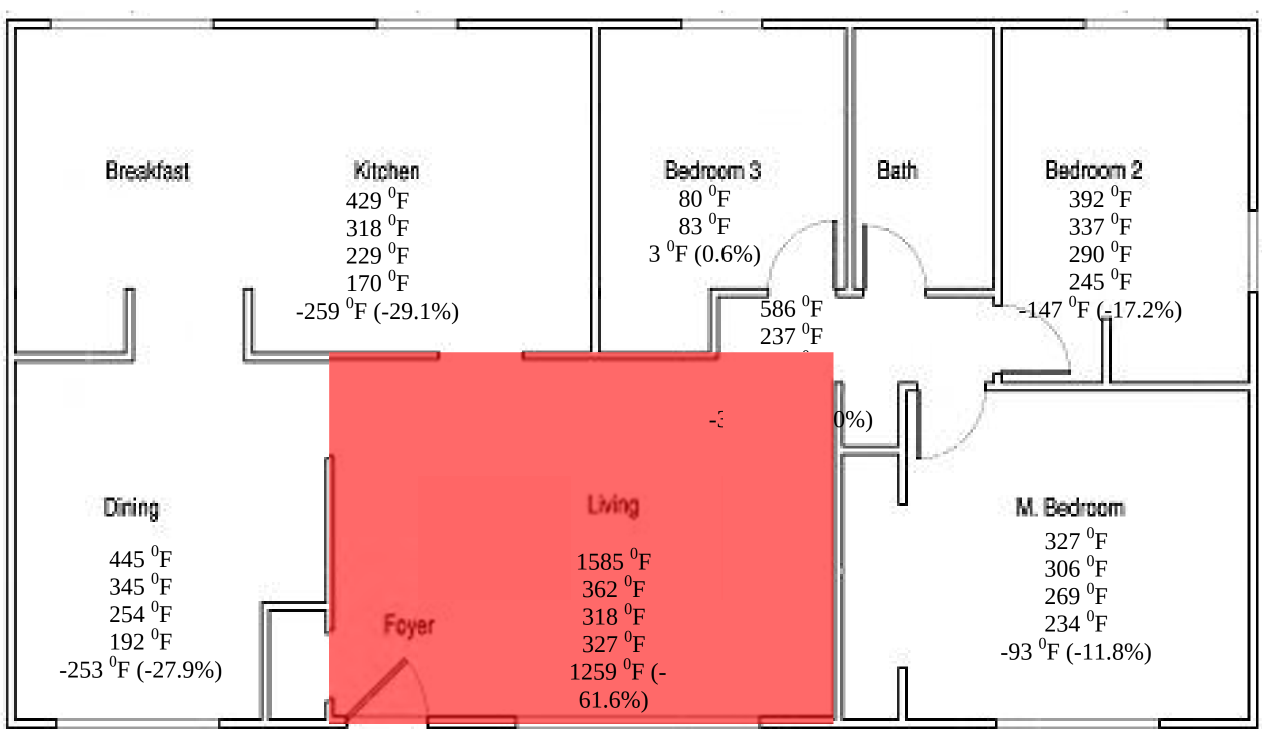


Figure 5.495: Experiment 5, Straight Stream

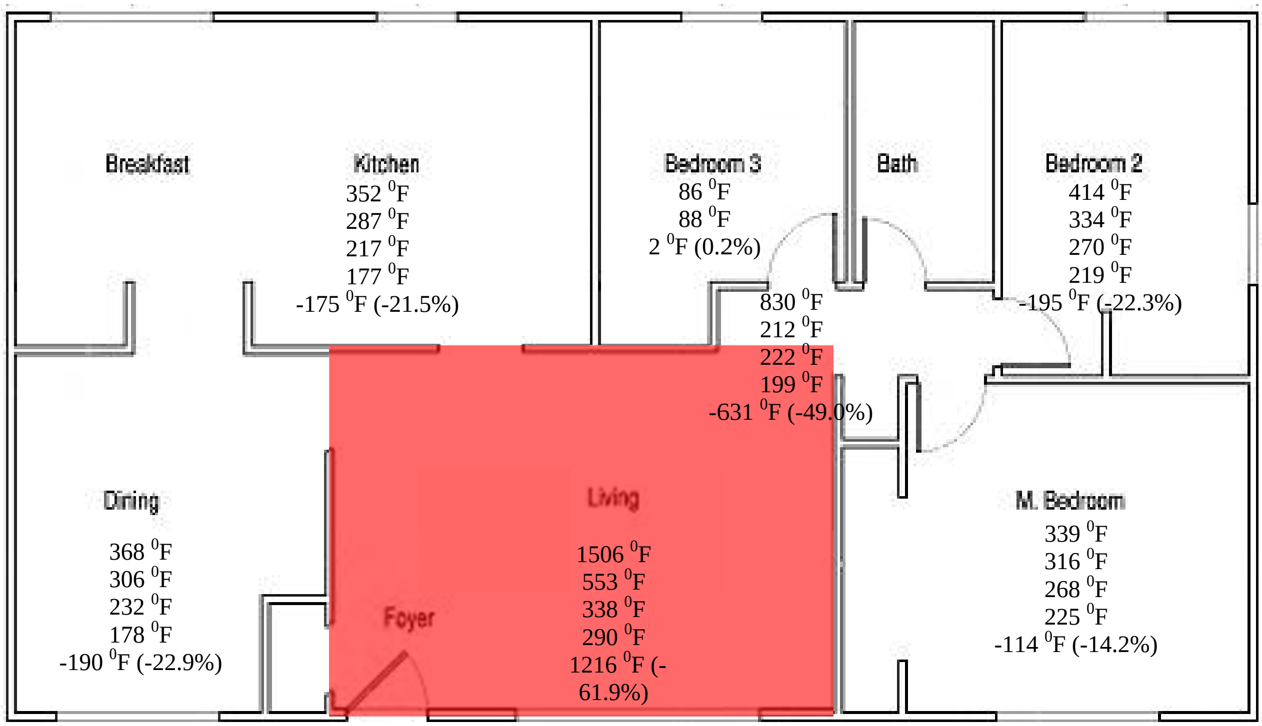


Figure 5.496: Experiment 7, Straight Stream

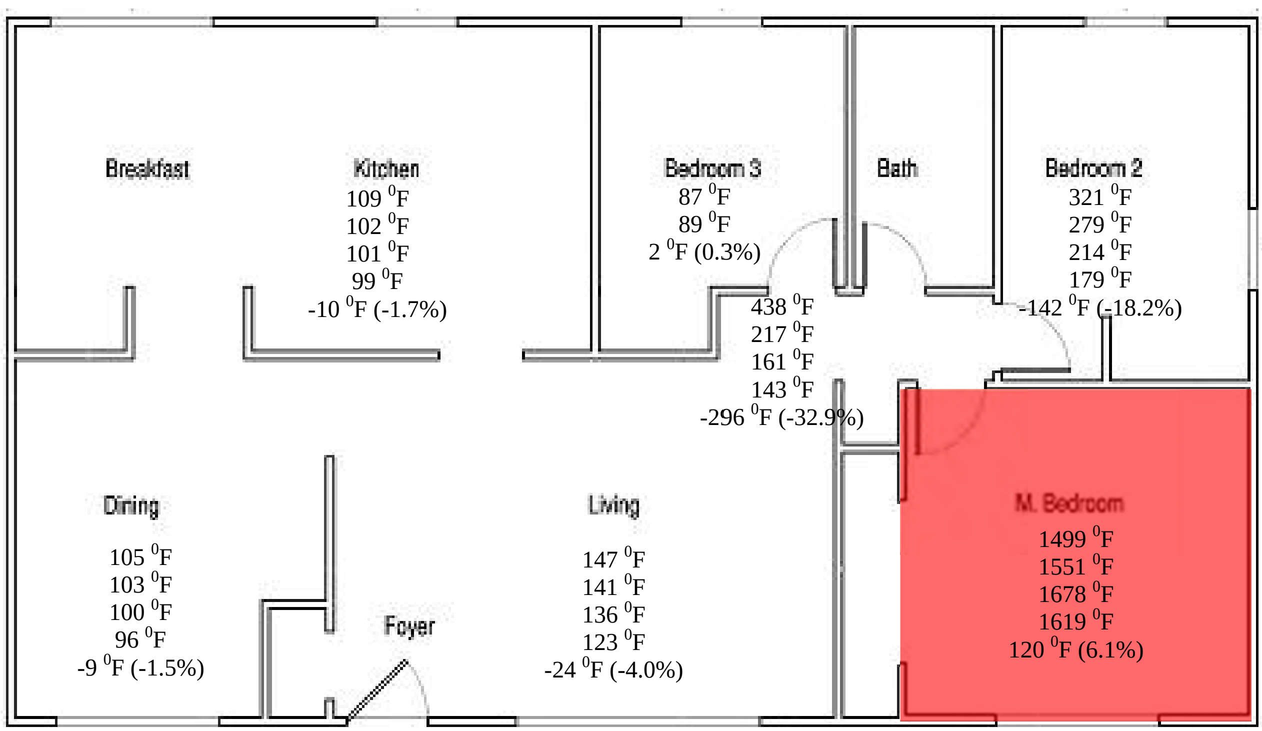


Figure 5.497: Experiment 11, Straight Stream

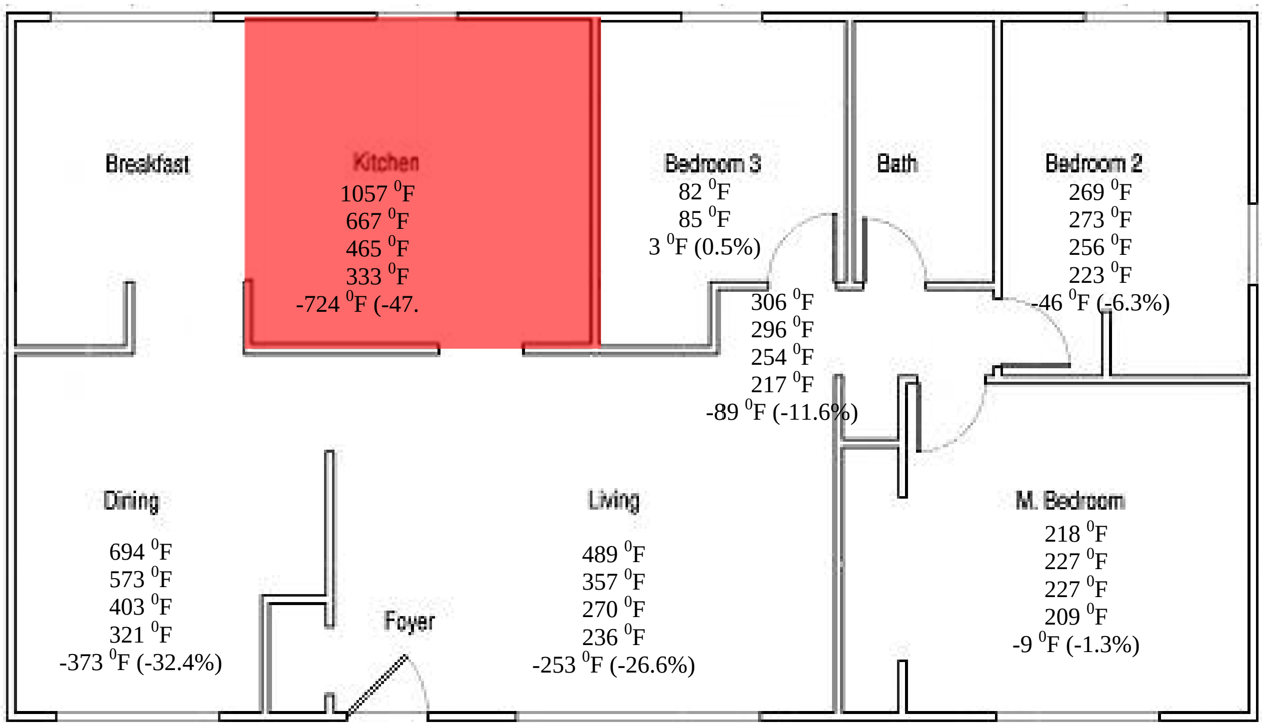


Figure 5.498: Experiment 13, Straight Stream #1

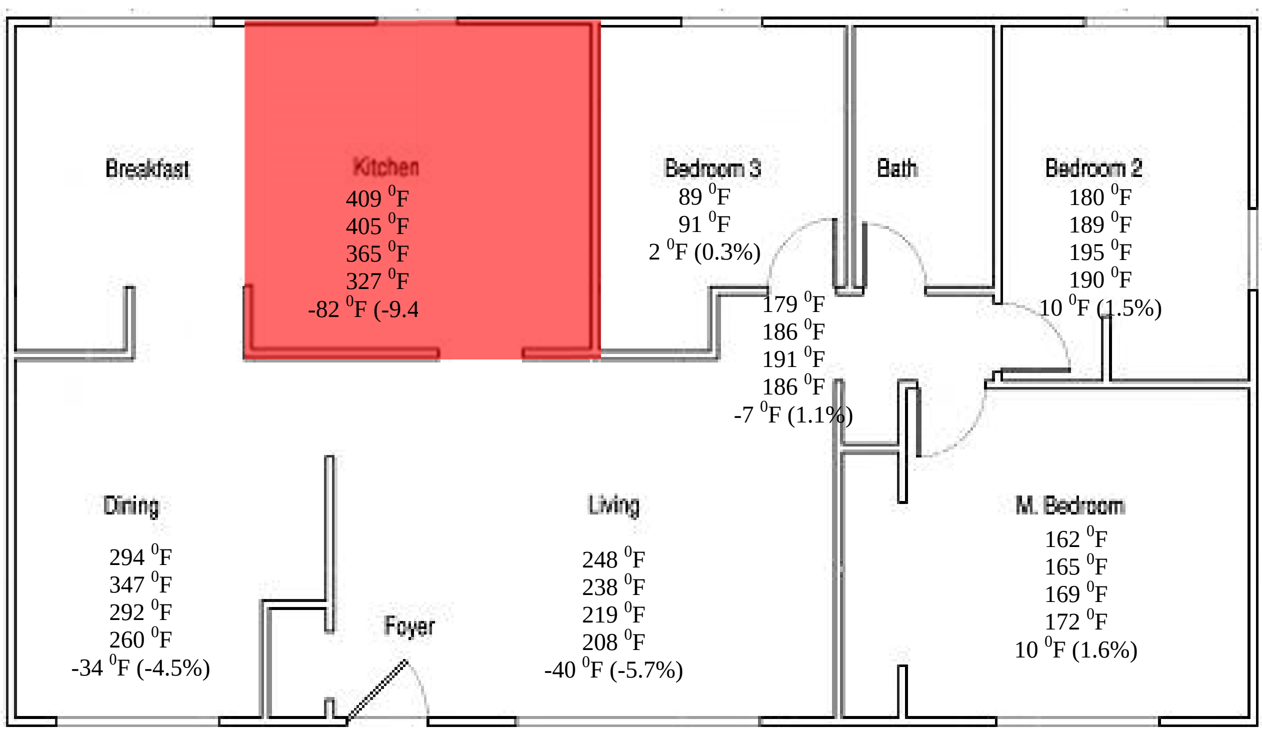


Figure 5.499: Experiment 13, Fog Stream #1

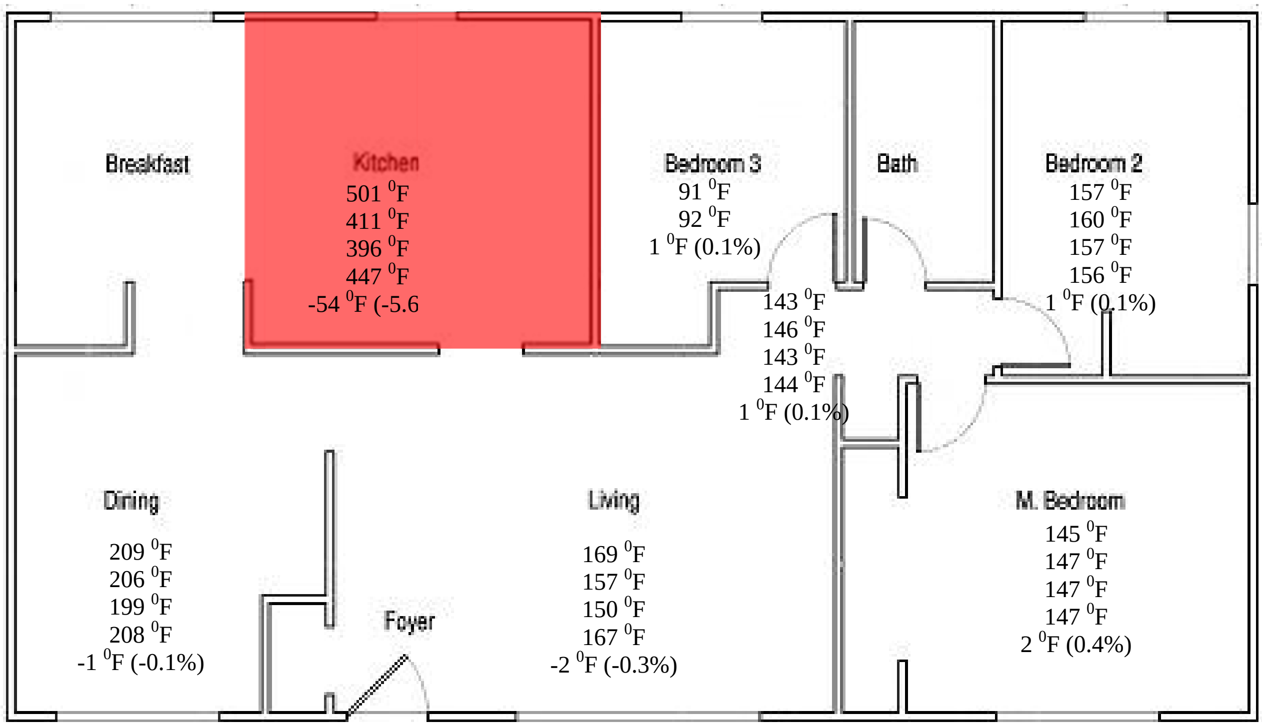


Figure 5.500: Experiment 13, Straight Stream #2

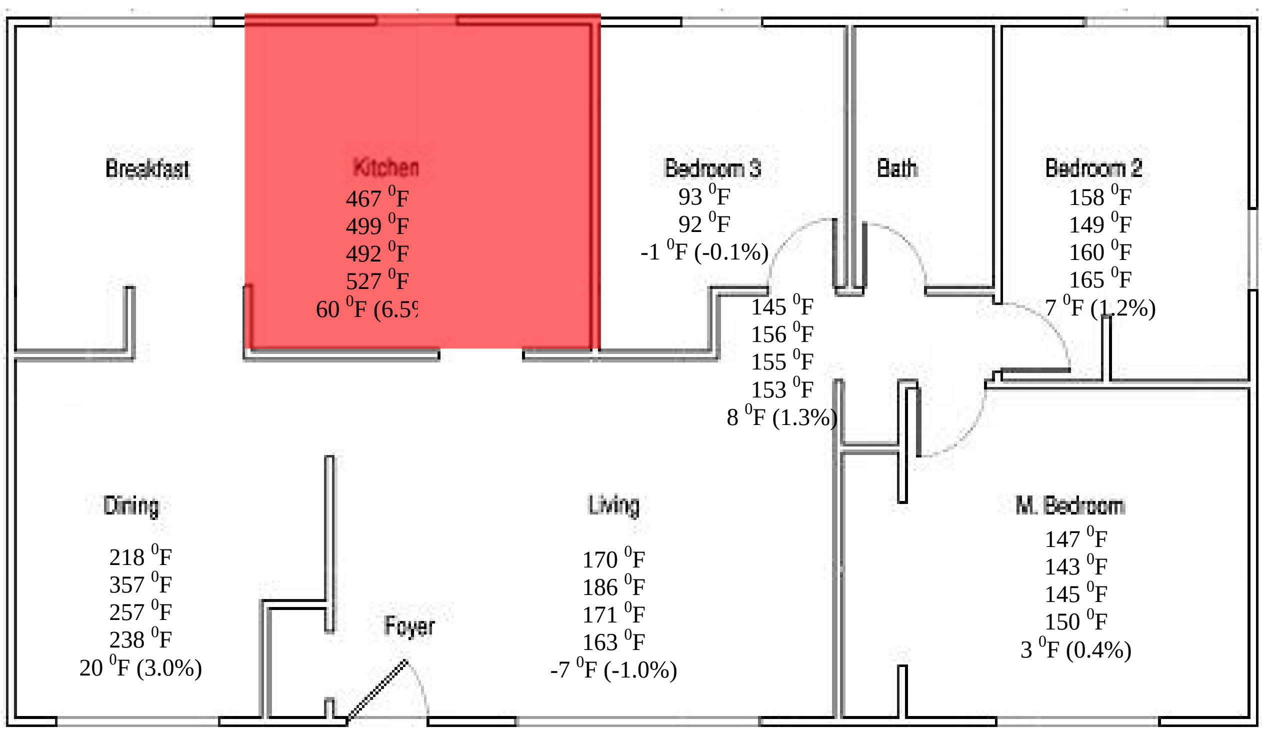


Figure 5.501: Experiment 13, Fog Stream #2

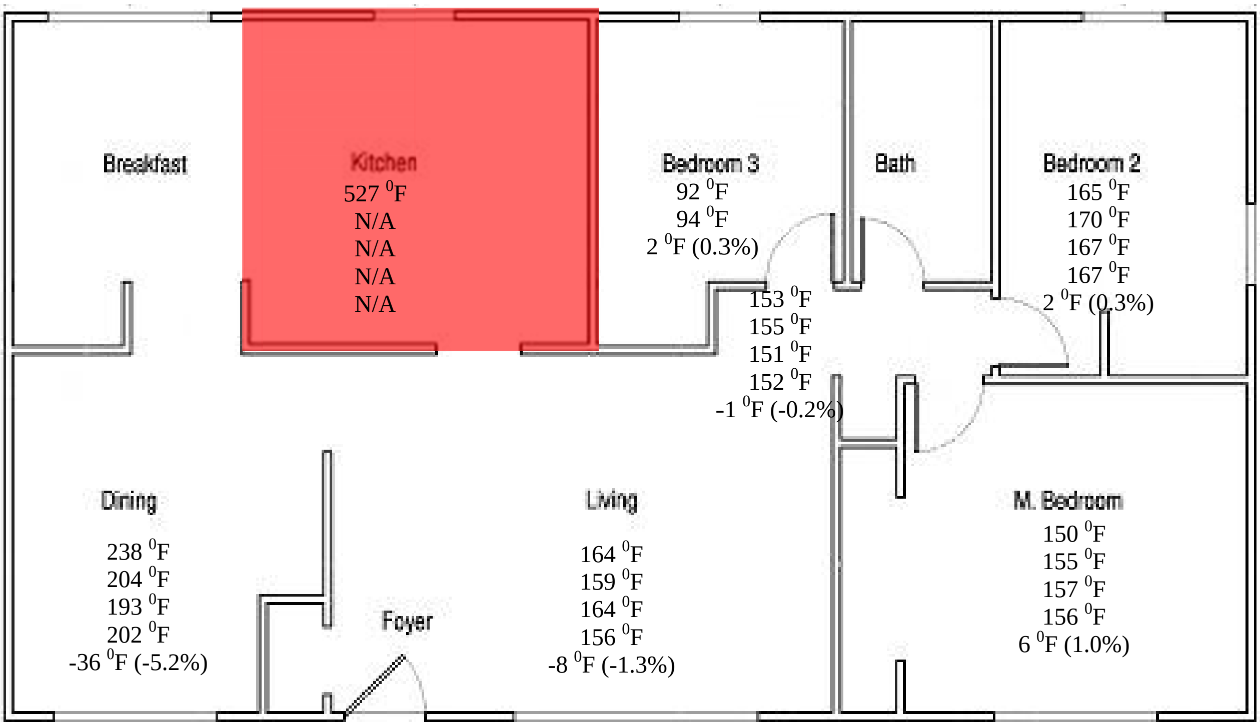


Figure 5.502: Experiment 13, Straight Stream #3

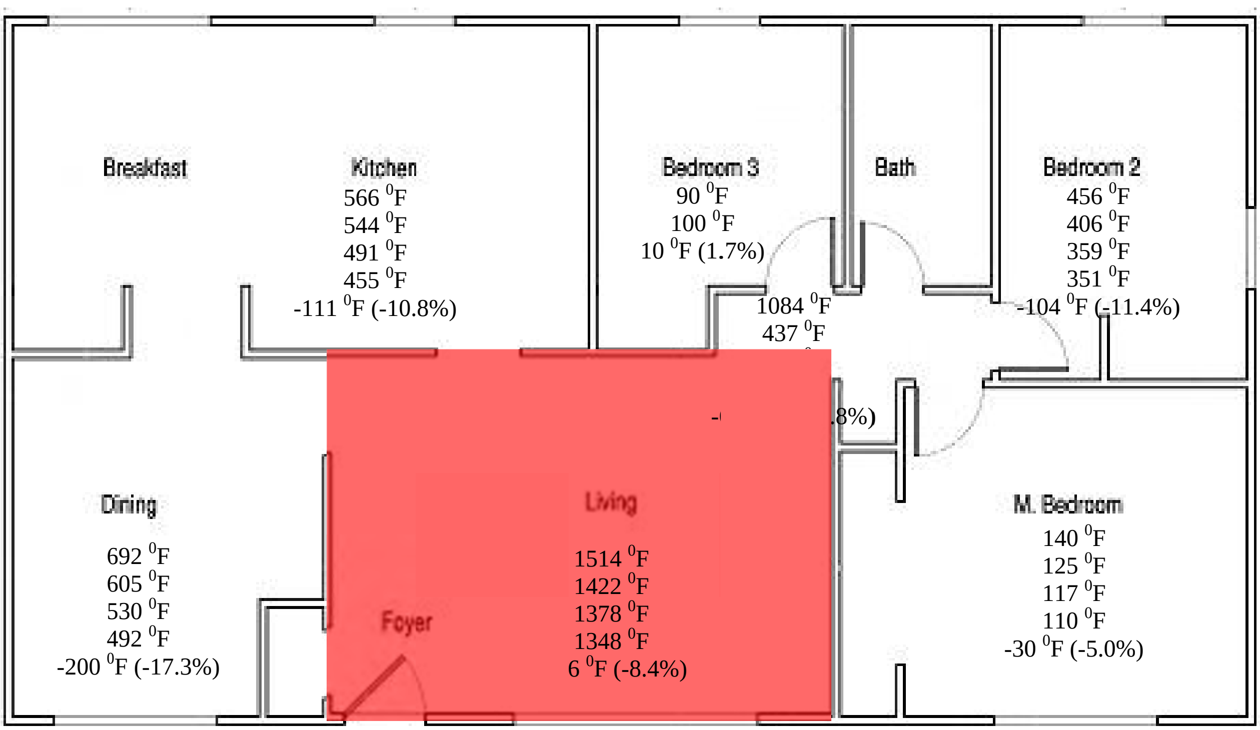


Figure 5.503: Experiment 15, Straight Stream

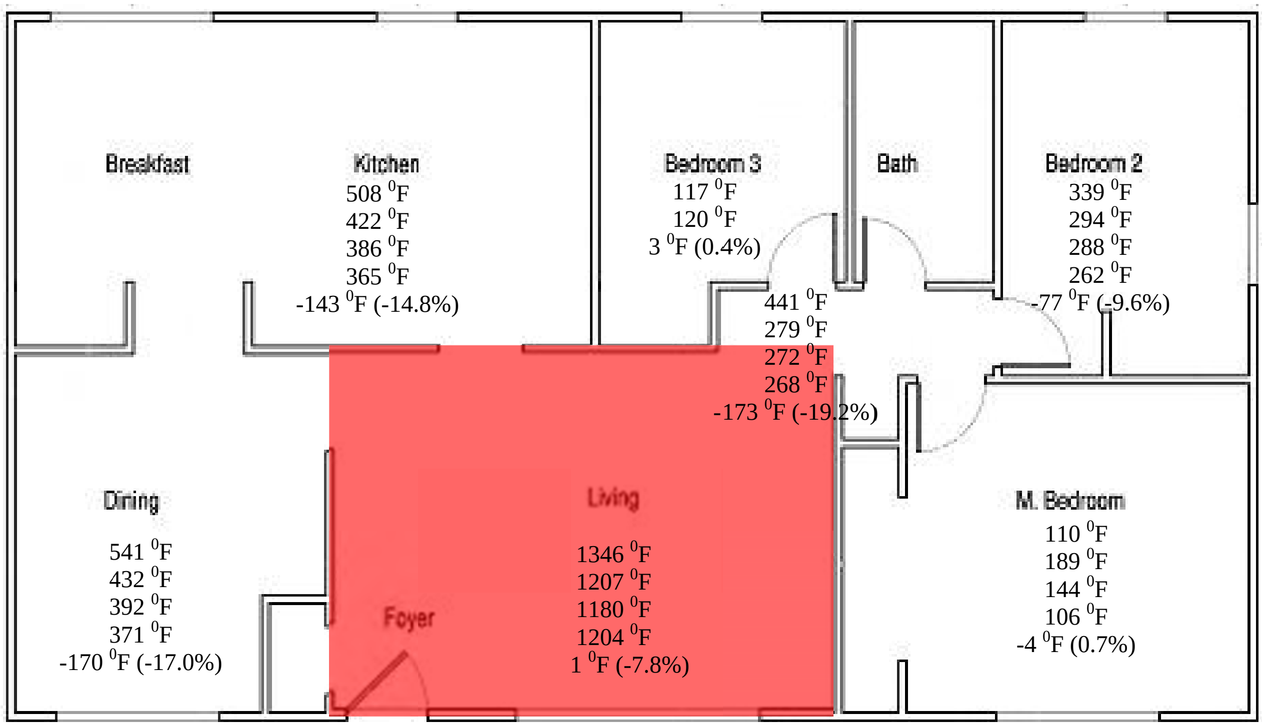


Figure 5.504: Experiment 15, Fog Stream

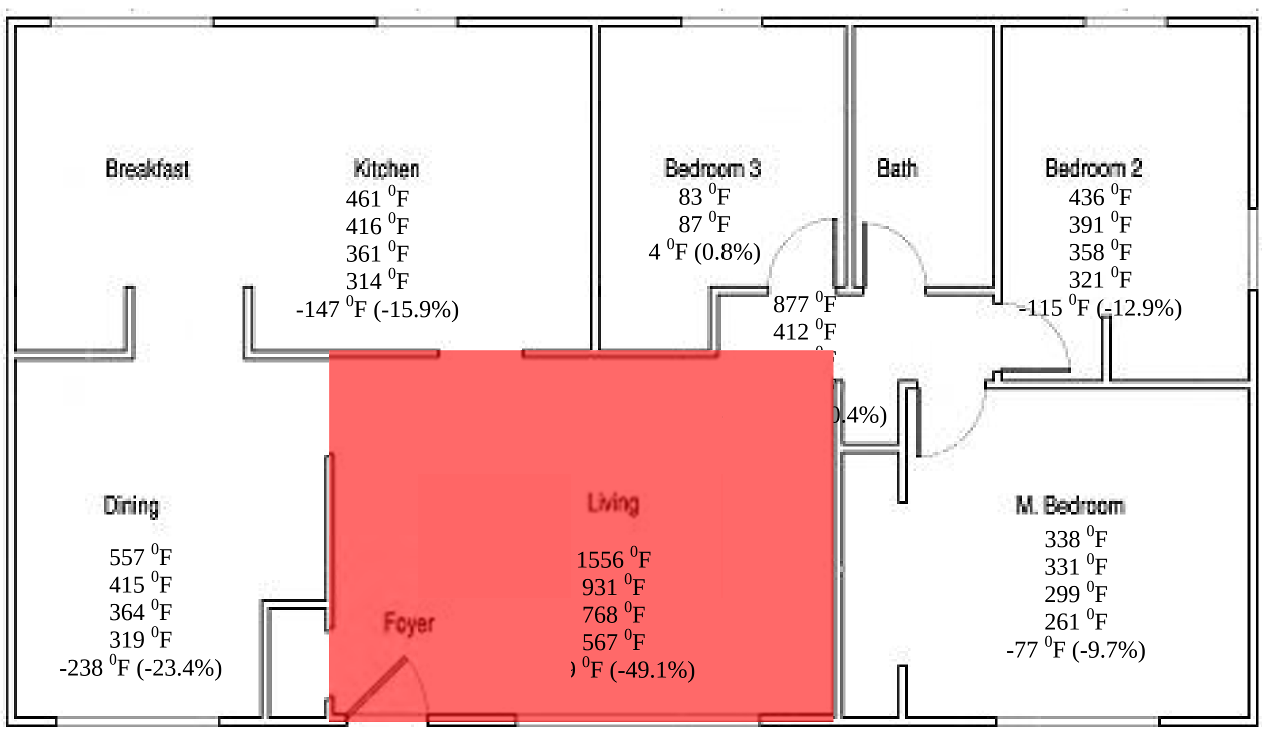


Figure 5.505: Experiment 17, Straight Stream

5.8.14.2. Water Application (Two-story)

<u>KEY</u>
Temperature (3 ft. above floor) just prior to water application
Temperature (3 ft. above floor) 10 seconds after water application
Temperature (3 ft. above floor) 30 seconds after water application
Temperature (3 ft. above floor) 60 seconds after water application
Change in Temperature after 60 seconds (Percent change)

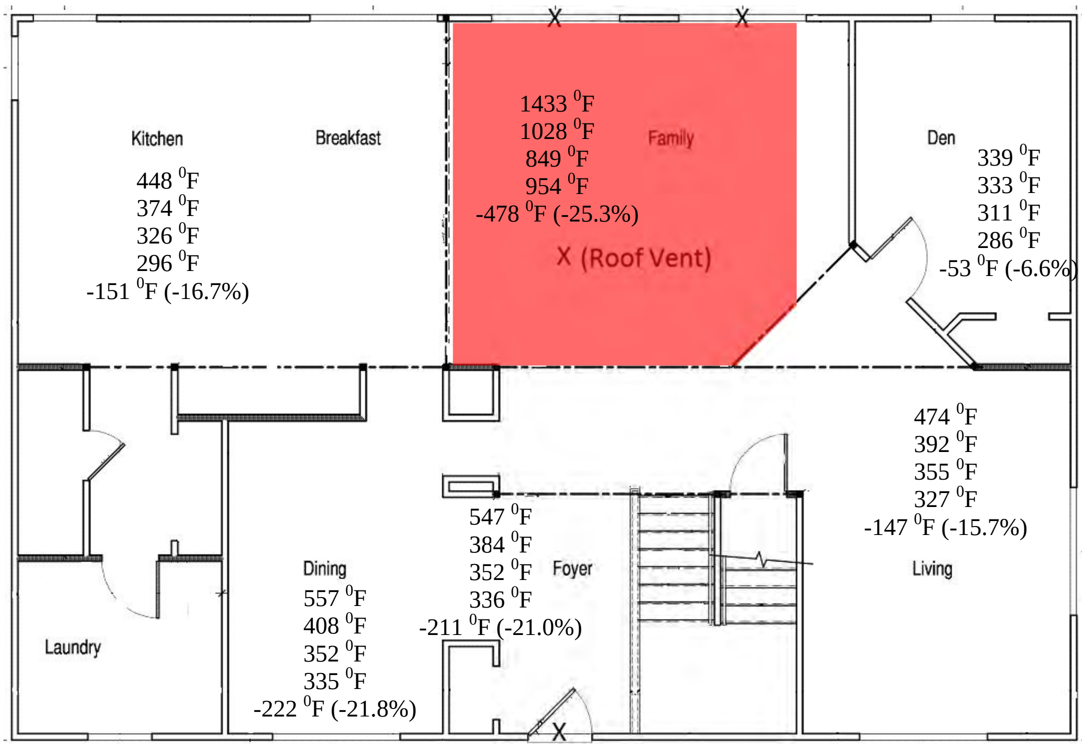


Figure 5.506: Experiment 2, First Floor, Straight Stream

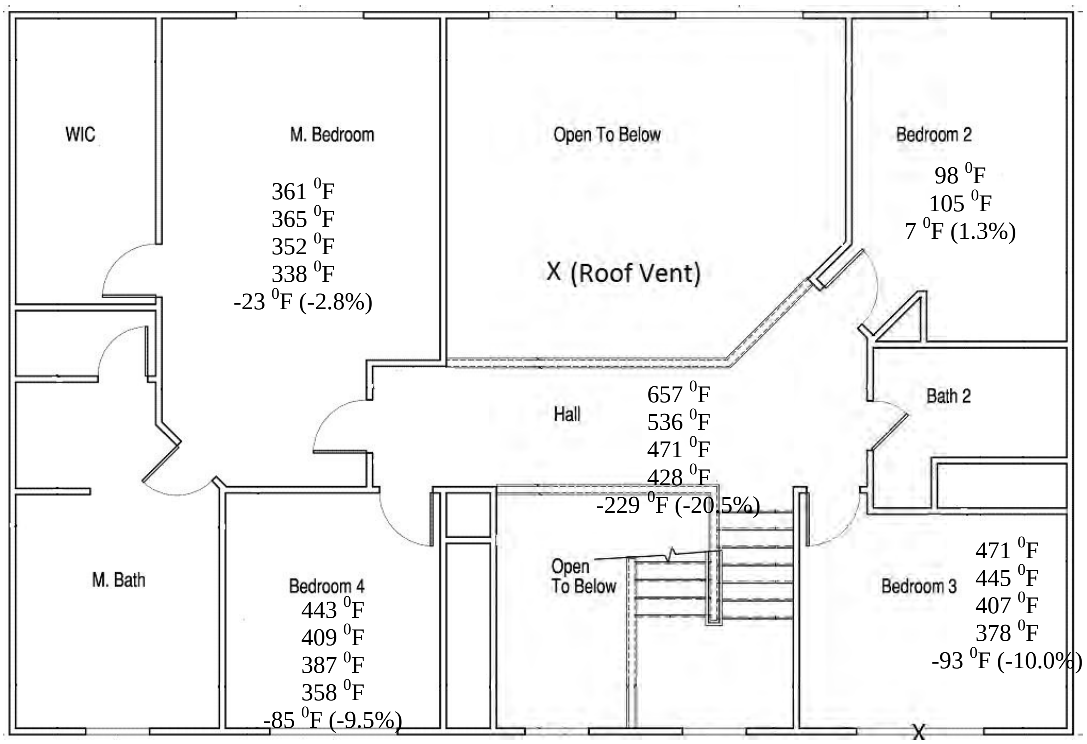


Figure 5.507: Experiment 2, Second Floor, Straight Stream

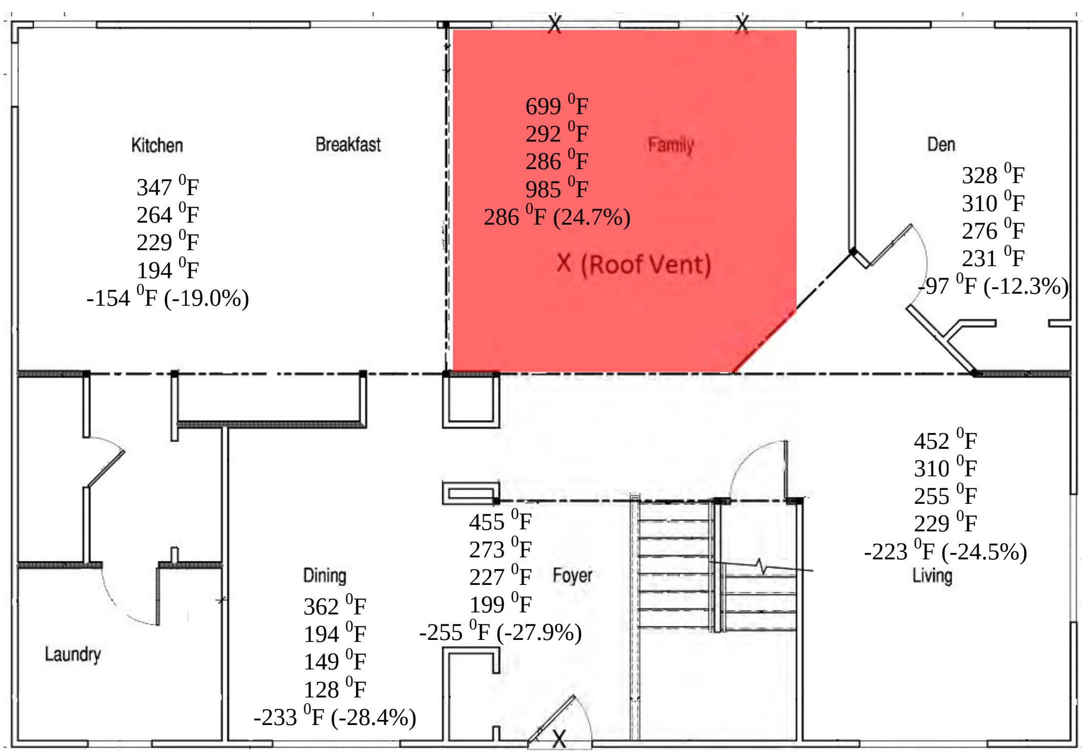


Figure 5.508: Experiment 4, First Floor, Straight Stream

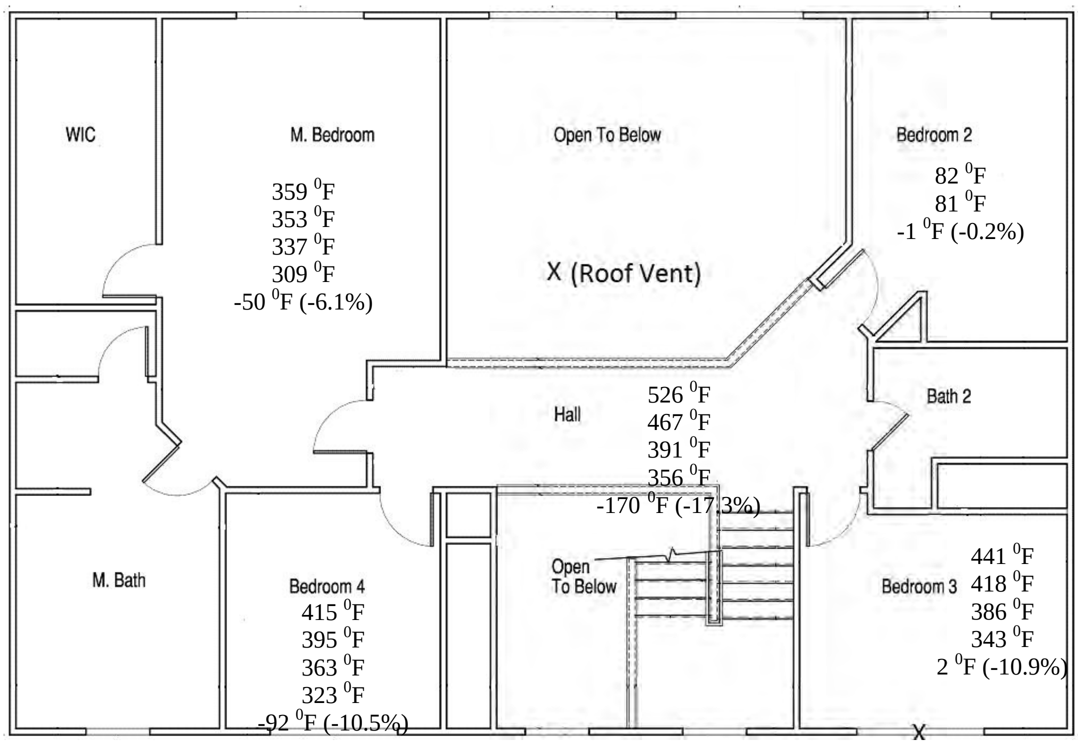


Figure 5.509: Experiment 4, Second Floor, Straight Stream

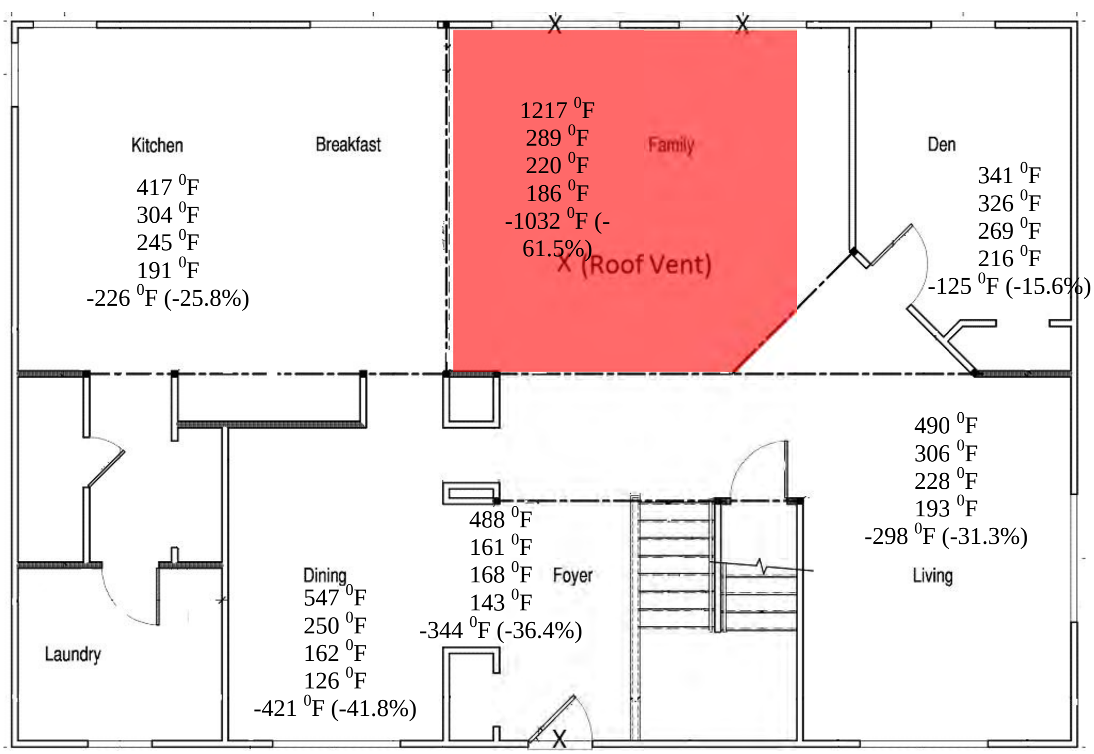


Figure 5.510: Experiment 6, First Floor, Straight Stream

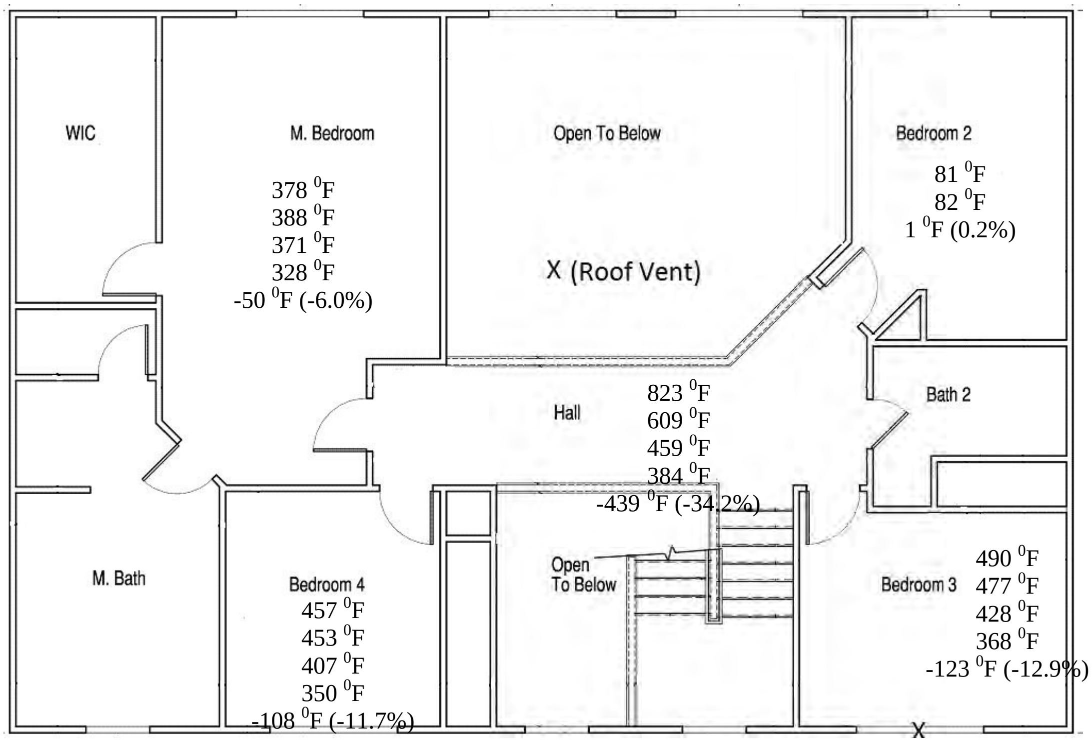


Figure 5.511: Experiment 6, Second Floor, Straight Stream

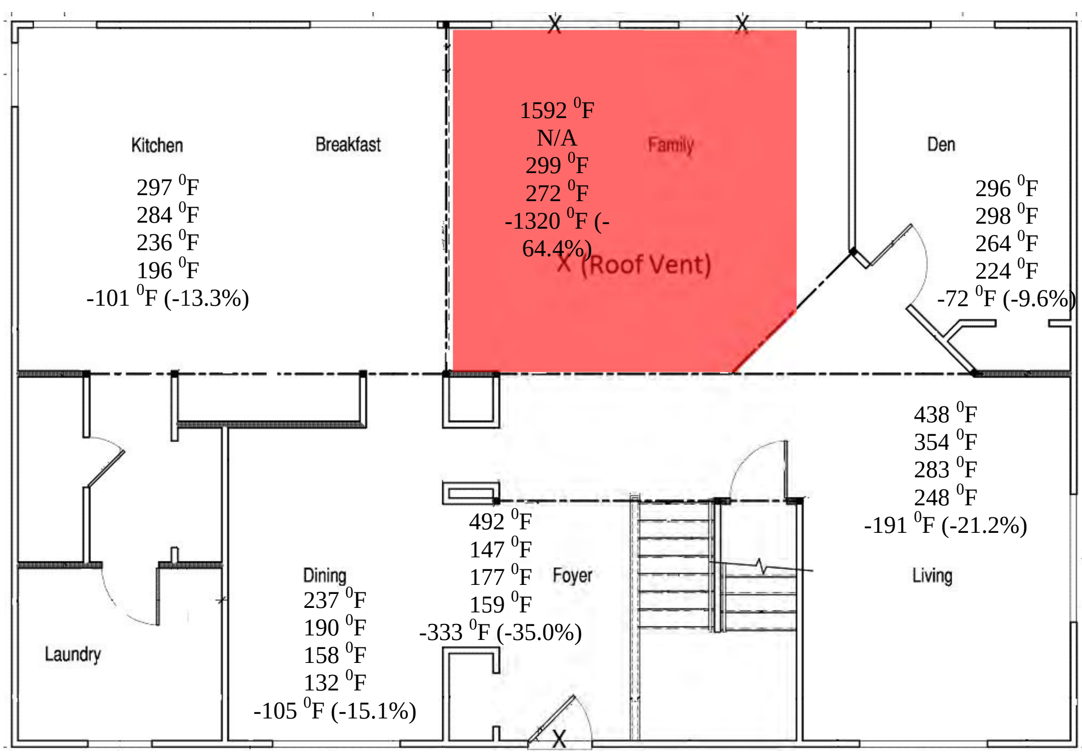


Figure 5.512: Experiment 8, First Floor, Straight Stream

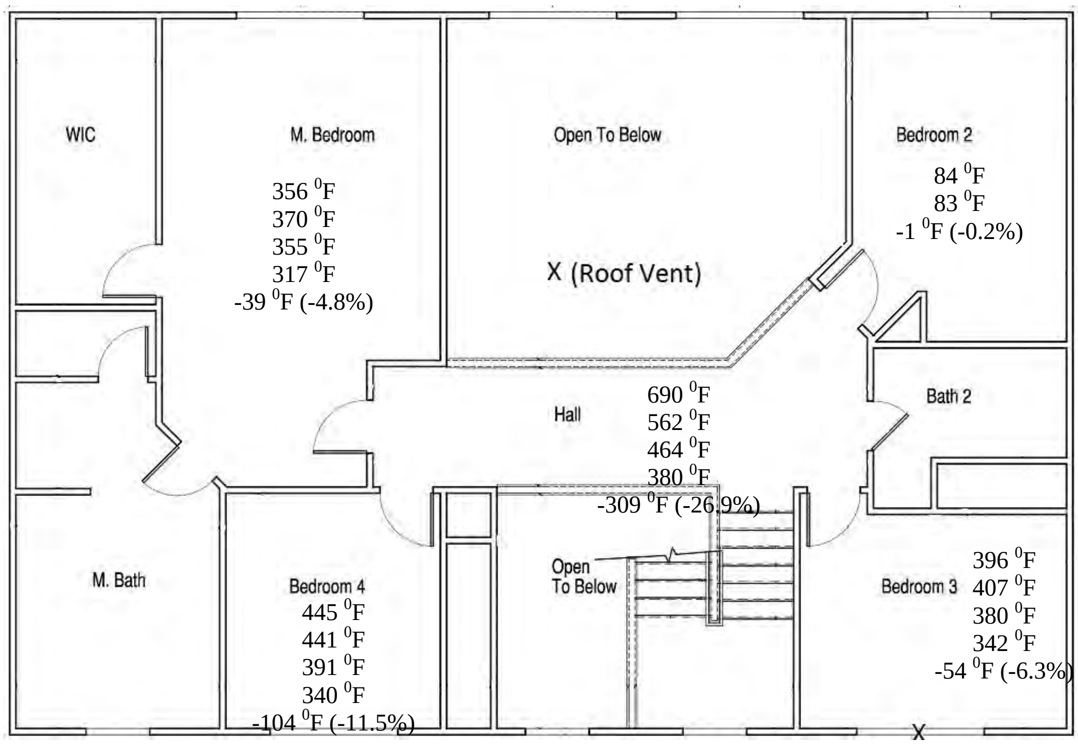


Figure 5.513: Experiment 8, Second Floor, Straight Stream

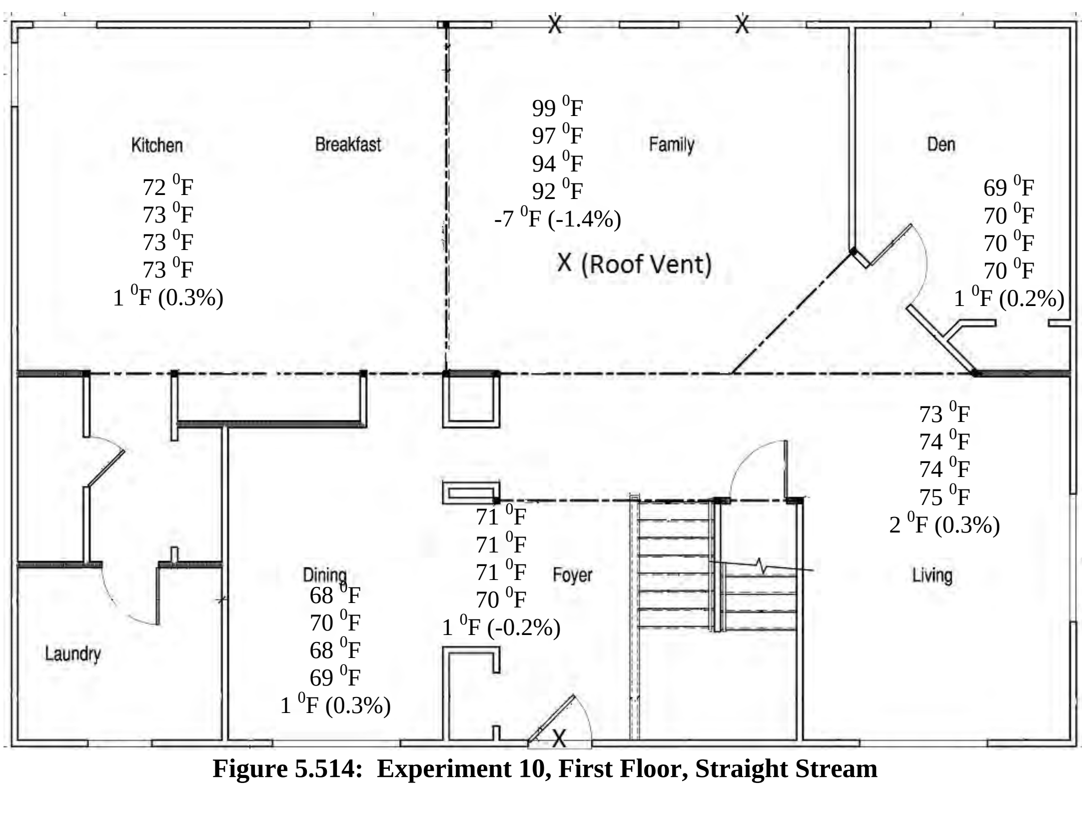


Figure 5.514: Experiment 10, First Floor, Straight Stream

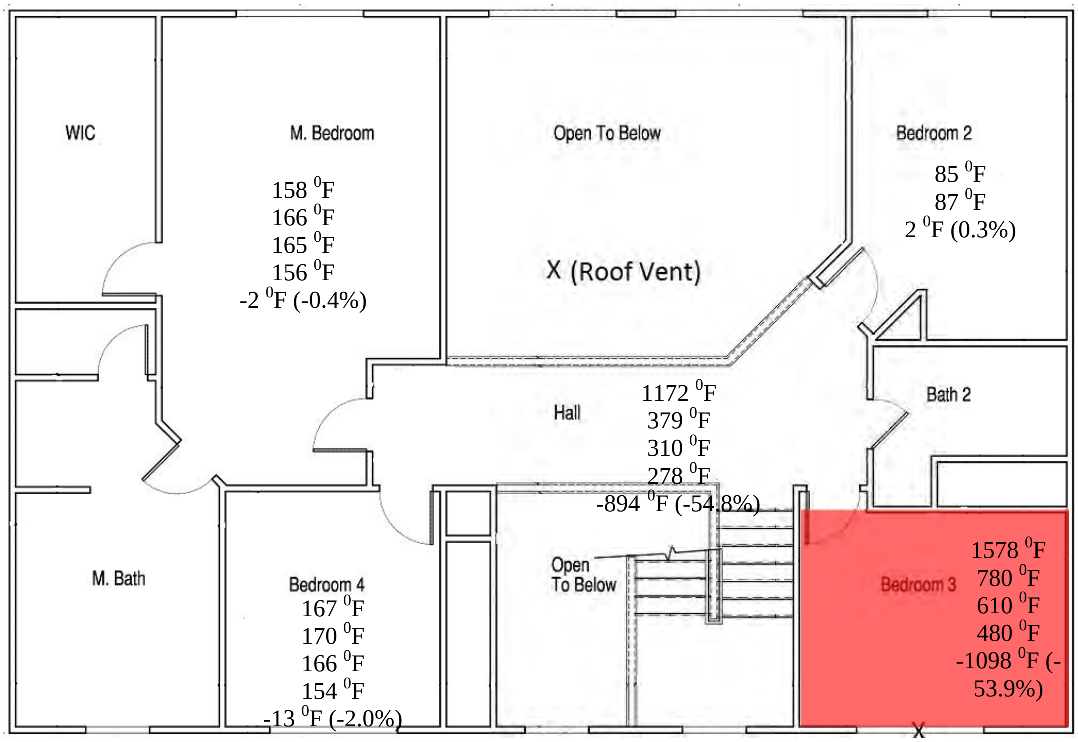


Figure 5.515: Experiment 10, Second Floor, Straight Stream

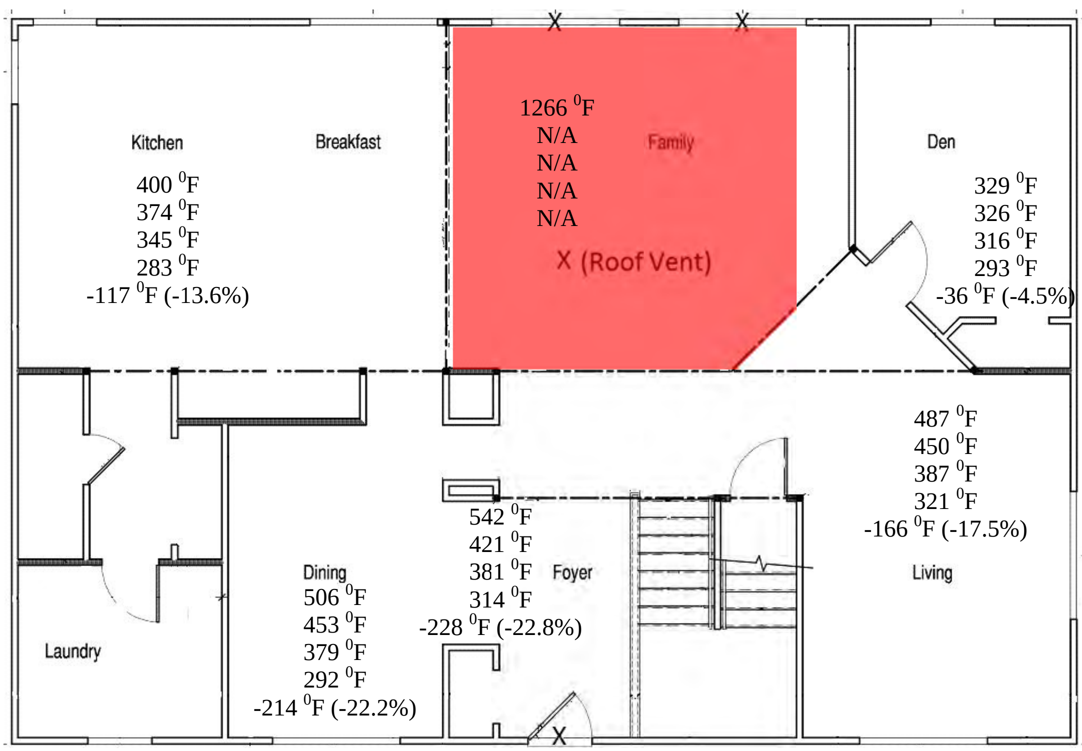


Figure 5.516: Experiment 12, First Floor, Straight Stream

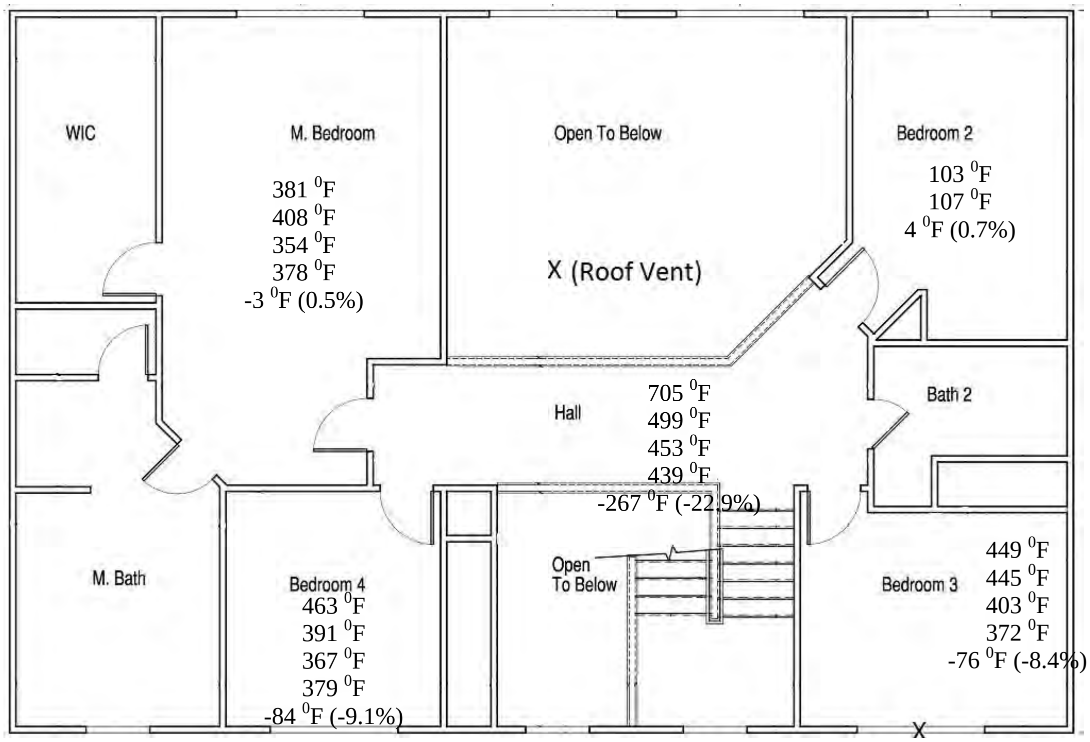


Figure 5.517: Experiment 12, Second Floor, Straight Stream

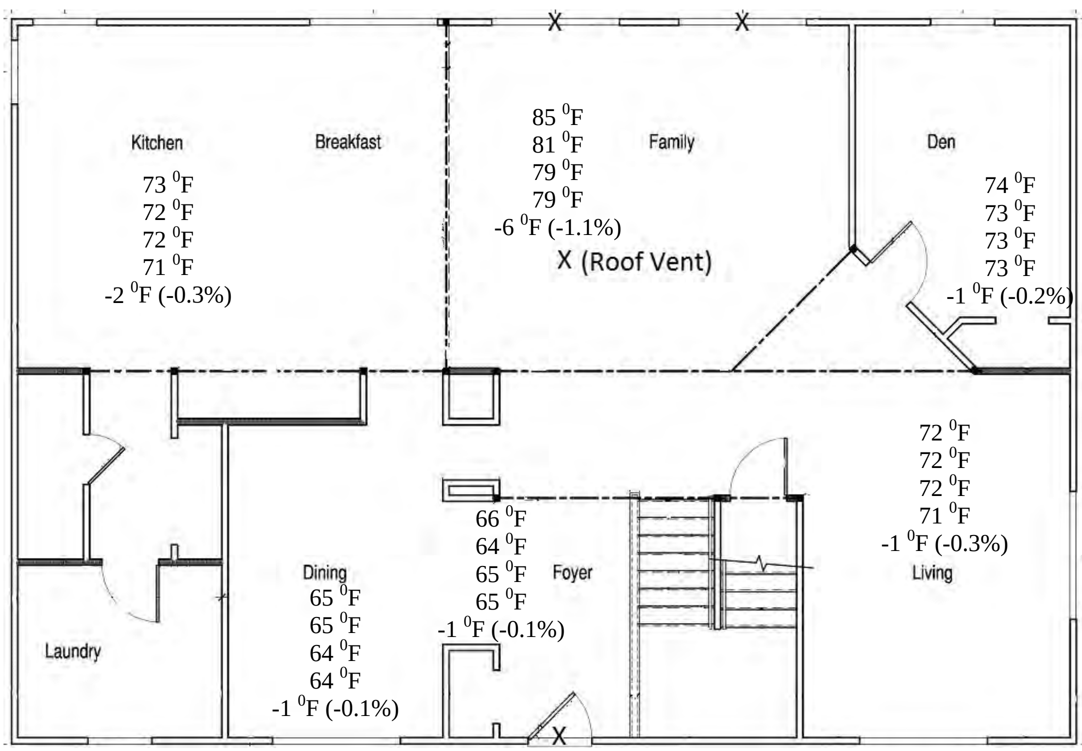


Figure 5.518: Experiment 14, First Floor, Straight Stream

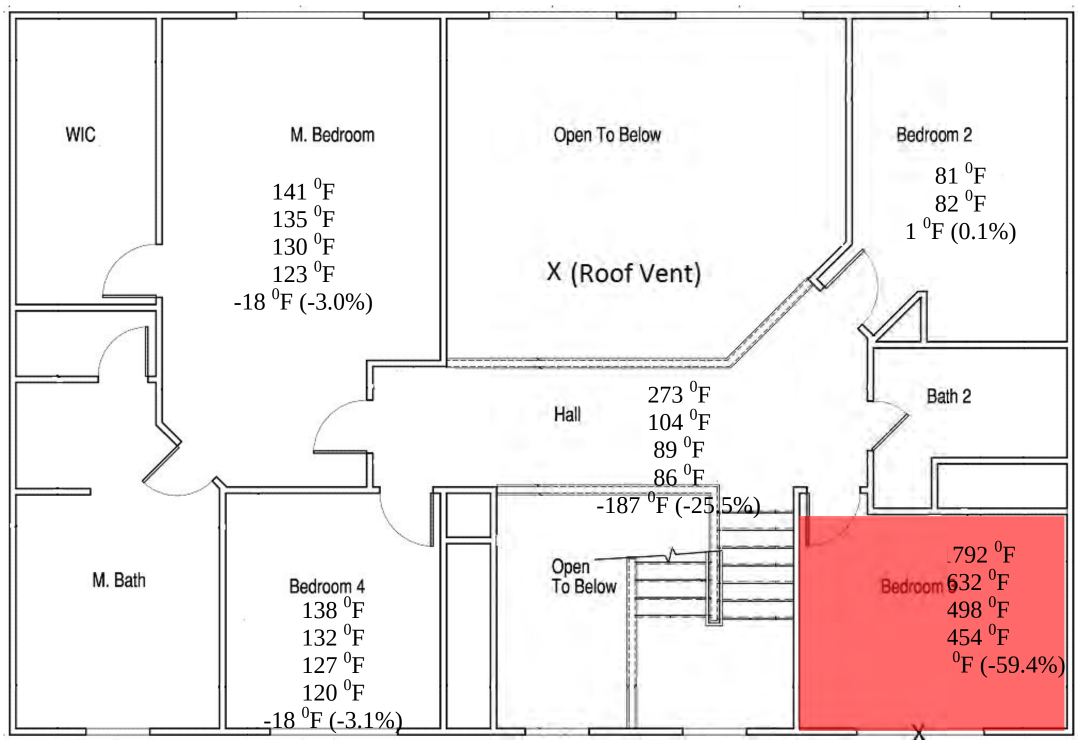


Figure 5.519: Experiment 14, Second Floor, Straight Stream

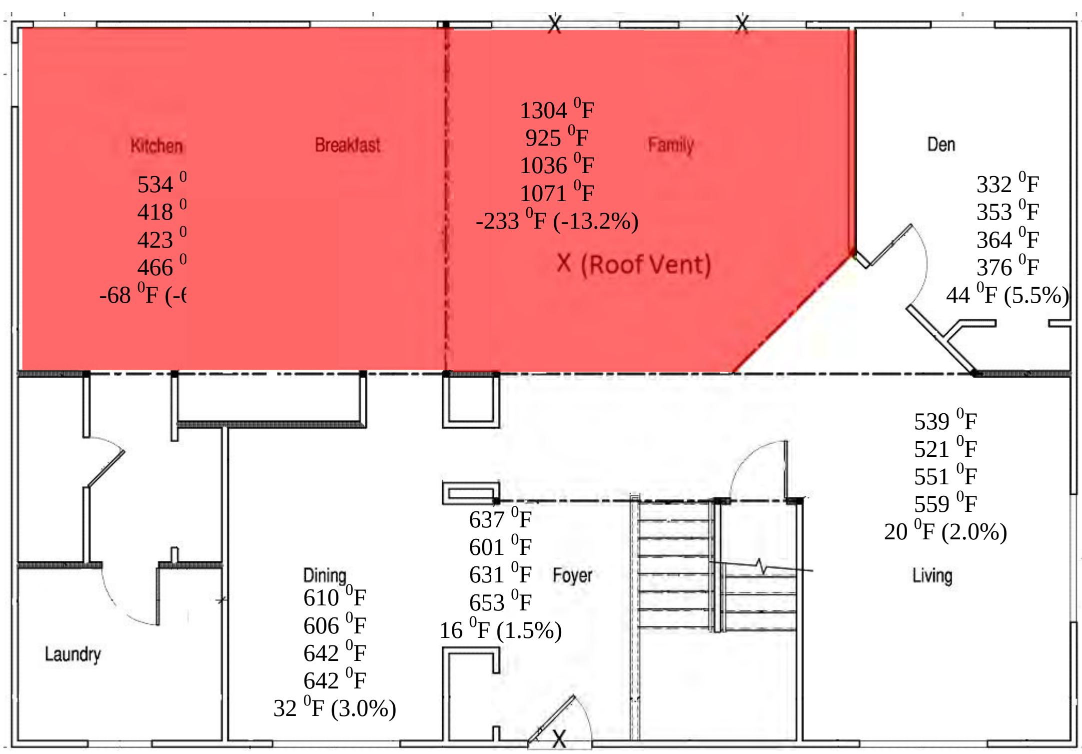


Figure 5.520: Experiment 16, First Floor, Straight Stream

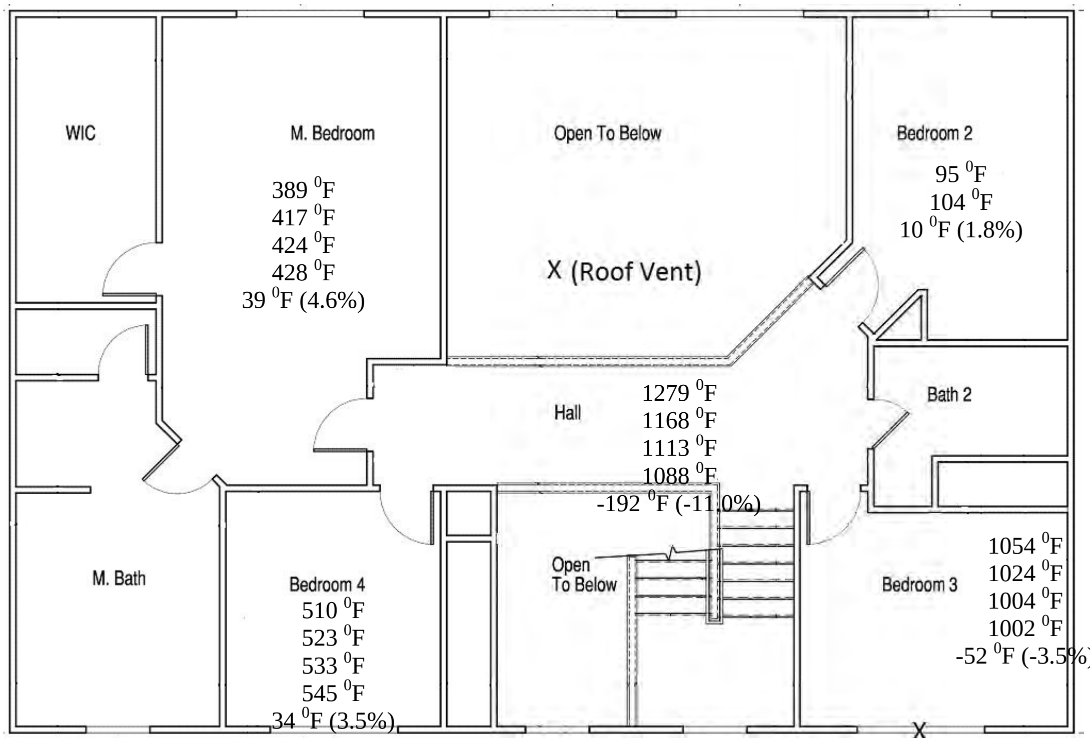


Figure 5.521: Experiment 16, Second Floor, Straight Stream

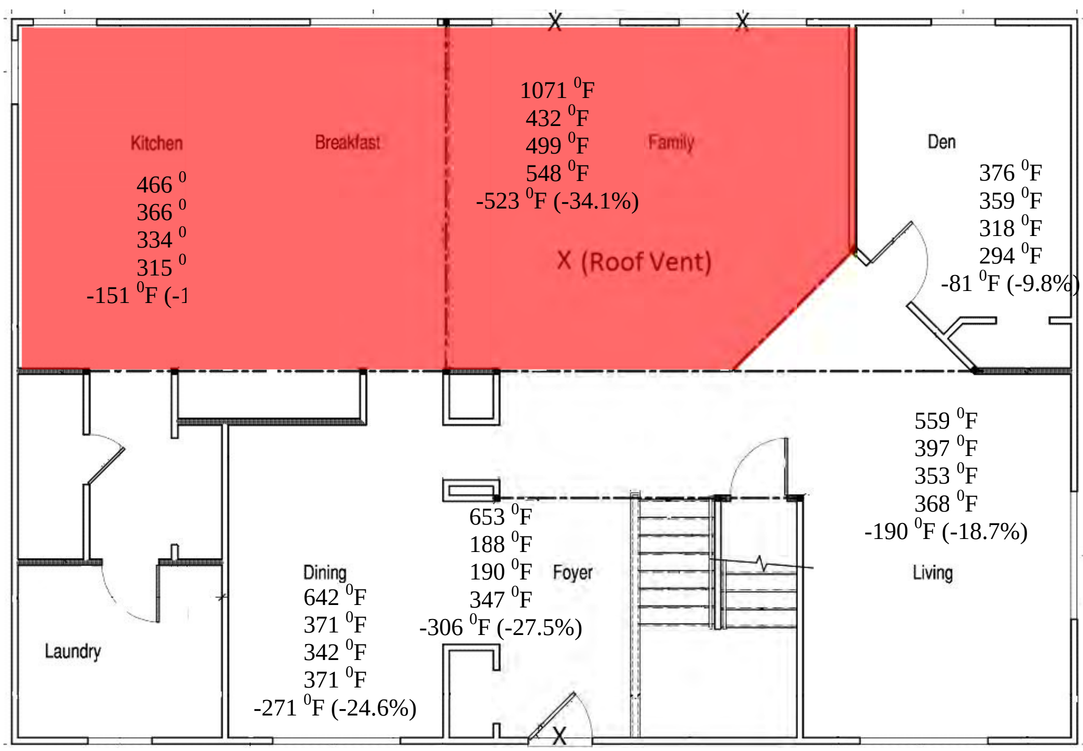


Figure 5.522: Experiment 16, First Floor, Fog Stream

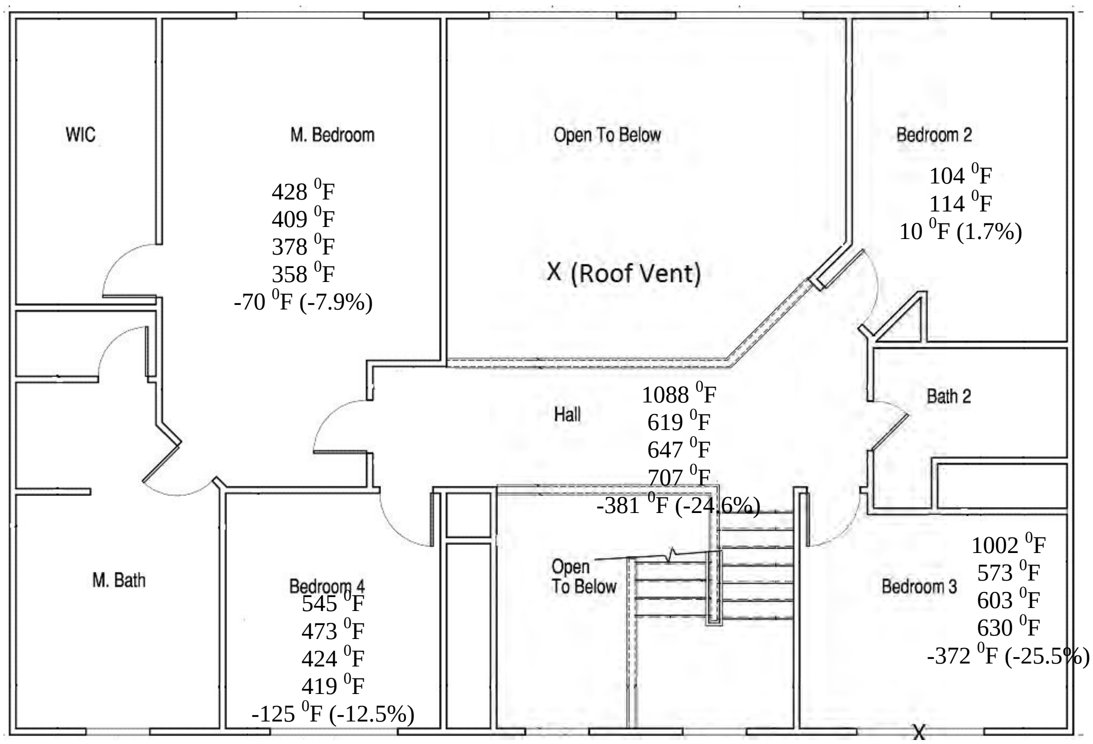


Figure 5.523: Experiment 16, Second Floor, Fog Stream

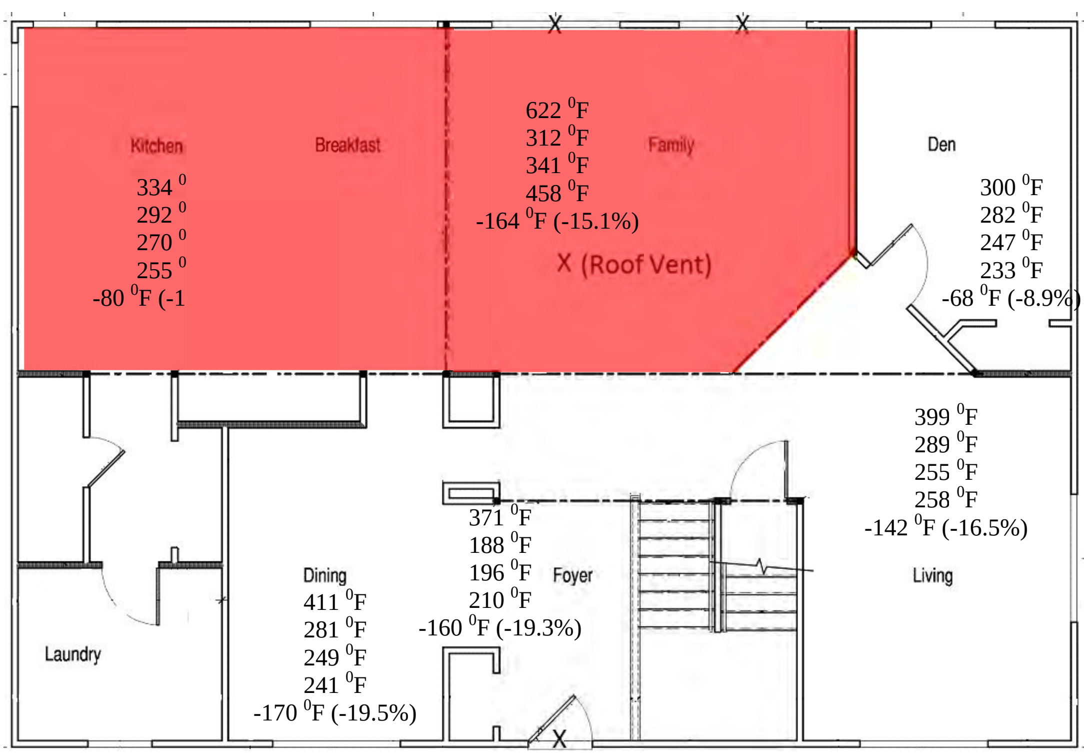


Figure 5.524: Experiment 16, First Floor, Fog Stream

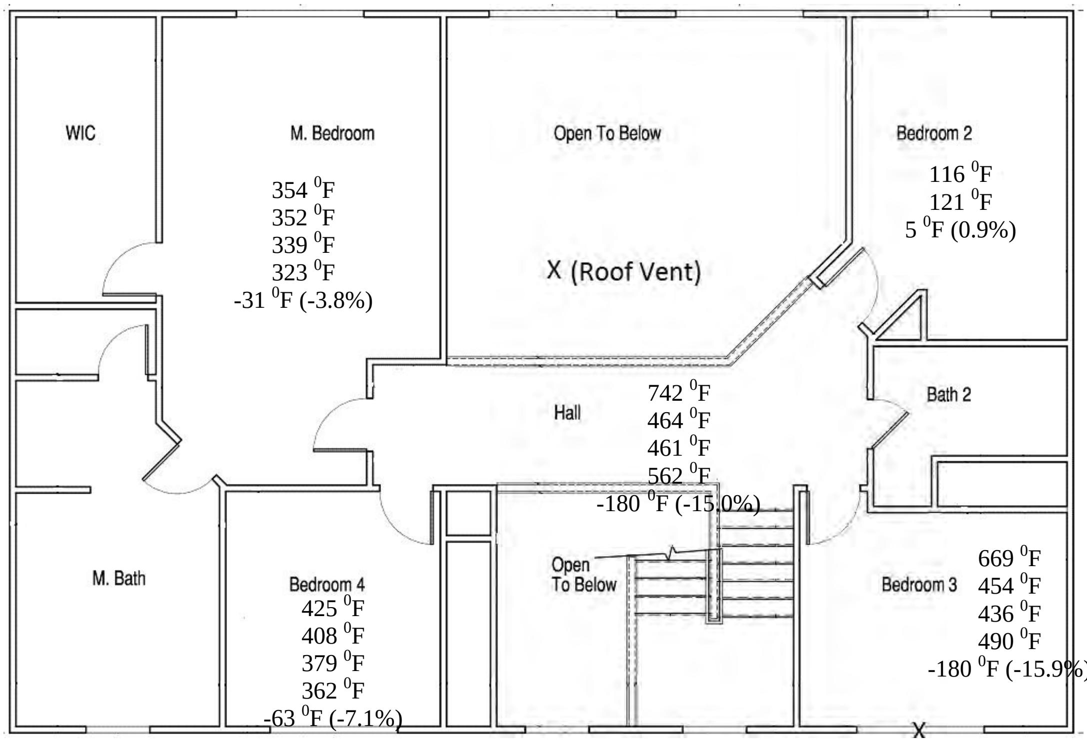


Figure 5.525: Experiment 16, Second Floor, Fog Stream

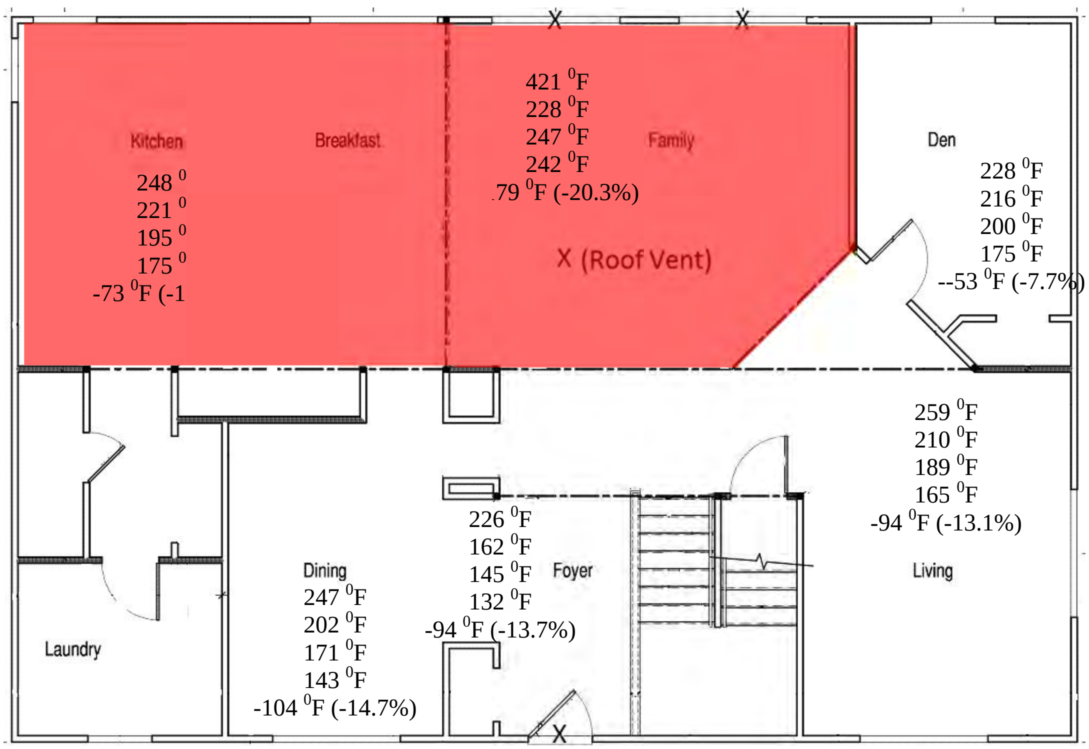


Figure 5.526: Experiment 16, First Floor, Straight Stream

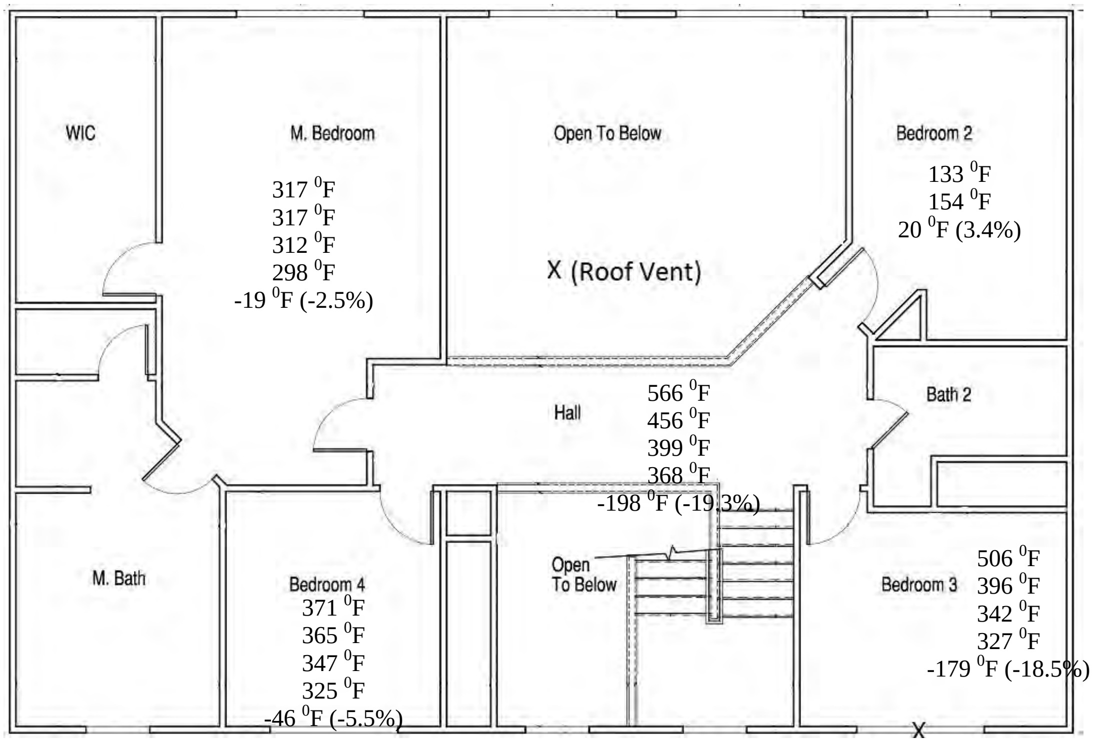


Figure 5.527: Experiment 16, Second Floor, Straight Stream

5.8.14.3. Detailed Analysis of Water Application Experiments

Experiments 13, 15 and 16 were specifically designed to examine the impact of exterior water flow with and without a flow path. During these experiments only horizontal ventilation was utilized and two types of streams were used, a straight stream and a narrow fog stream, both from the same nozzle documented previously in the report. The focus of these experiments was to assess the conditions created for the simulated advancing crew and potential victims in the house particularly in the flow path downstream of the nozzle flow.

During Experiment 13 the kitchen fire grew until 10:00, and then the front door was opened. At 13:45, 6 seconds of water was applied through the front door with a combination nozzle positioned in a straight stream pattern (Figure 5.528 and Figure 5.530). At 19:00, 7 seconds of water was applied through the front door with a combination nozzle positioned in a fog stream pattern (Figure 5.531). The dining room window was opened at 20:00. Water was again applied to the fire at 22:40 for 6 seconds with a combination nozzle positioned in a straight stream pattern (Figure 5.529 and Figure 5.532). At 24:00, 41 seconds of water was applied to the fire with a combination nozzle positioned in a fog stream pattern (Figure 5.533). Water was applied to the fire for a fifth time at 25:35 for 12 seconds with a combination nozzle positioned in a straight stream pattern, this time through the dining room window rather than the front door (Figure 5.534).

Figure 5.535 shows the temperatures during the experiment at 3 ft. above the floor for the kitchen (fire room) and two surrounding rooms (living room and dining room). The main focus was on the dining room temperature to see if hot gases are forced into the dining room once water was applied to the kitchen fire through the living room. After 7 seconds of straight stream into the kitchen, the dining room temperature decreased from approximately 700 °F to 250 °F before the temperatures began to recover. The kitchen temperature decreased from 1100 °F to 250 °F and the living room temperature decreased from 500 °F to 200 °F.

Figure 5.536 shows the temperatures during the experiment at 7 ft. above the floor for the kitchen (fire room) and two surrounding rooms (living room and dining room). After 7 seconds of straight stream into the kitchen, the dining room temperature decreased from approximately 850 °F to 450 °F before the temperatures began to recover. The kitchen temperature decreased from 1700 °F to 650 °F and the living room temperature decreased from 900 °F to 350 °F.

The fire did not recover to the original magnitude but additional water was applied in a fog stream twice and a straight stream one additional time. The fog stream applied for 7 seconds caused an approximate 50 °F increase in dining room temperature at 3 ft. above the floor and a 50 °F decrease in 7 ft. dining room temperature. The dining room window was then removed to make a flow path completely through the dining room. There was a shielded fire in the kitchen that was not accessible from the doorway water flow. The straight stream application of 6 seconds caused the dining room temperature to decrease slightly. The fog stream application of 41 seconds created a 300 °F increase in temperature at the 3 ft. elevation in the dining room as the thermal layering was mixed. This was due to the air flow forced in through the front door to the kitchen fire with no cooling, as water was not applied to the seat of the fire. Figure 5.537 shows the sustained pressure increase in the kitchen as the fog stream was flowing and forcing air into the kitchen.

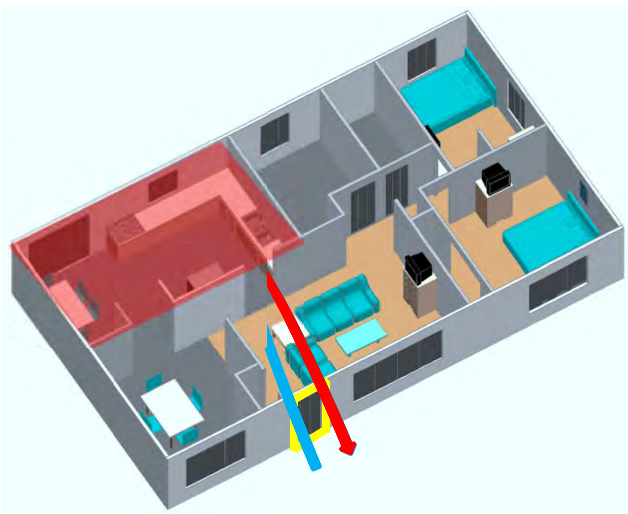


Figure 5.528: Flow Path with Water Flow through Front Door

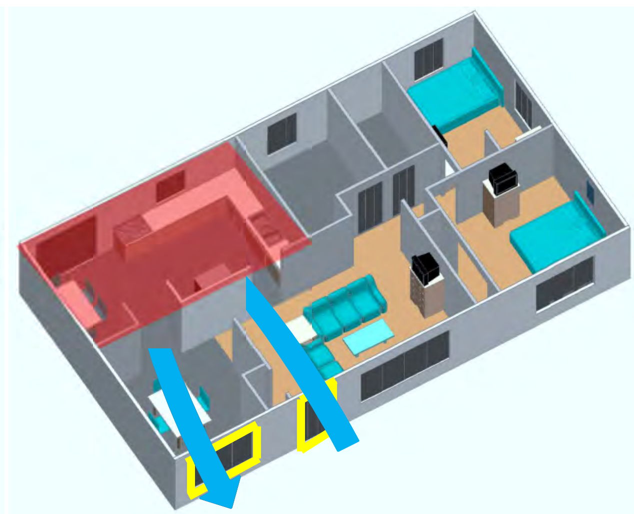


Figure 5.529: Flow Path with Water Flow through Front Door with Dining Room Window Open


Figure 5.530: Straight Stream #1


Figure 5.531: Fog Stream #1


Figure 5.532: Straight Stream #2 with Flow Path


Figure 5.533: Fog Stream #2


Figure 5.534: Straight Stream #3

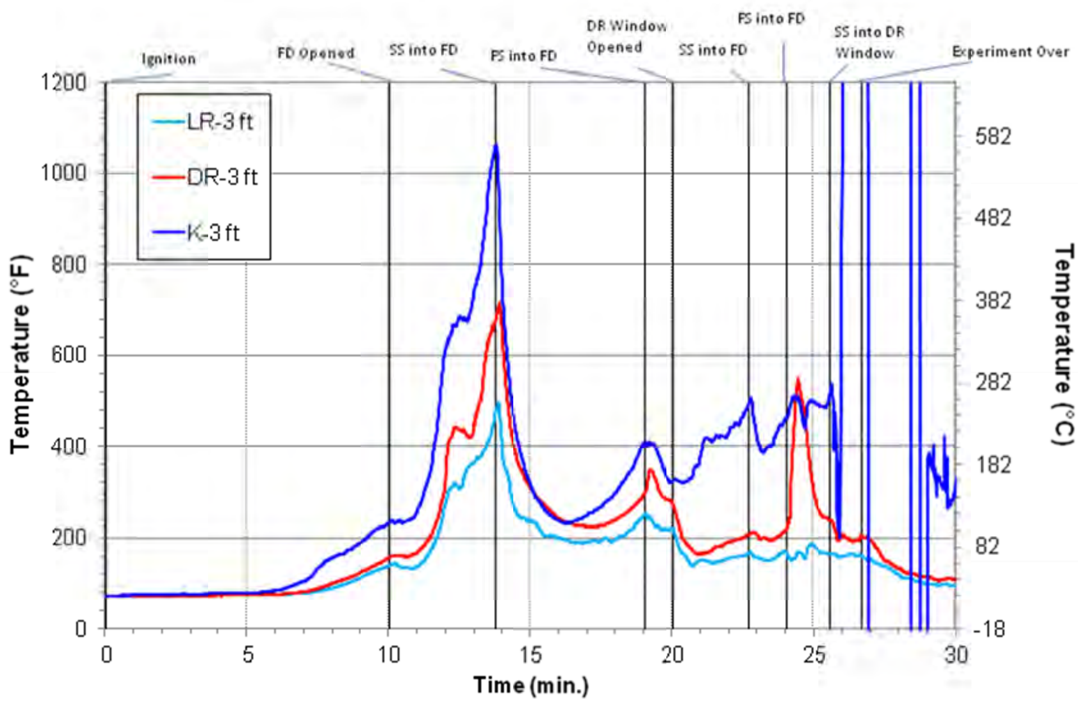


Figure 5.535: 3 ft. Temperatures in the rooms affected by water application

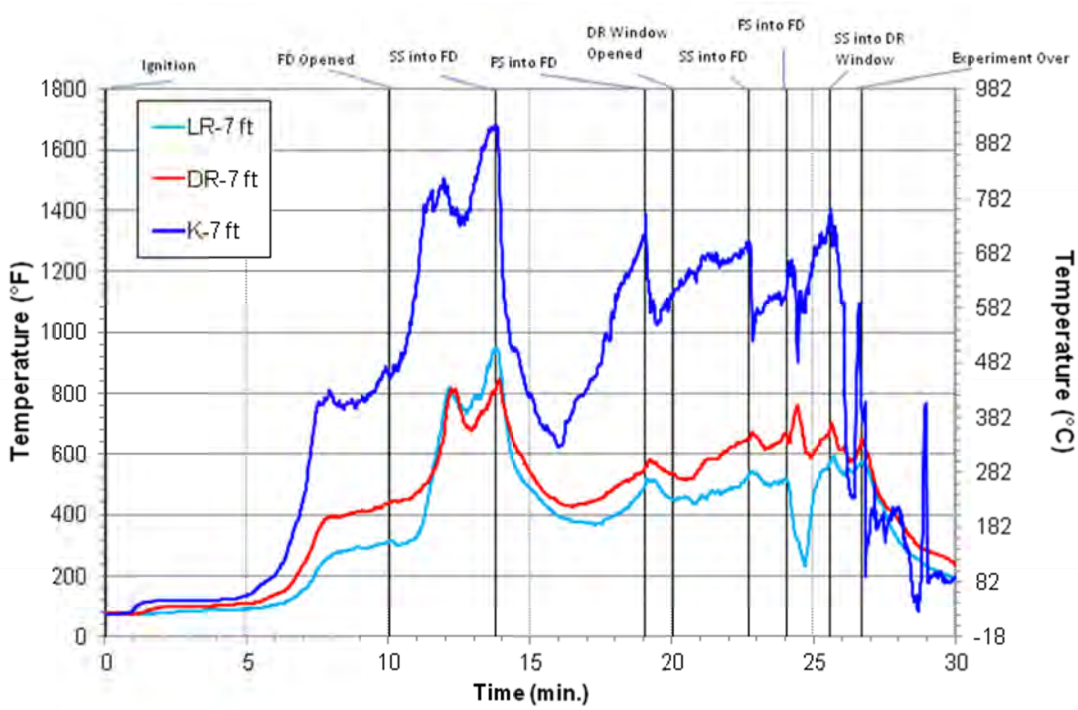


Figure 5.536: 7 ft. Temperatures in the rooms affected by water application

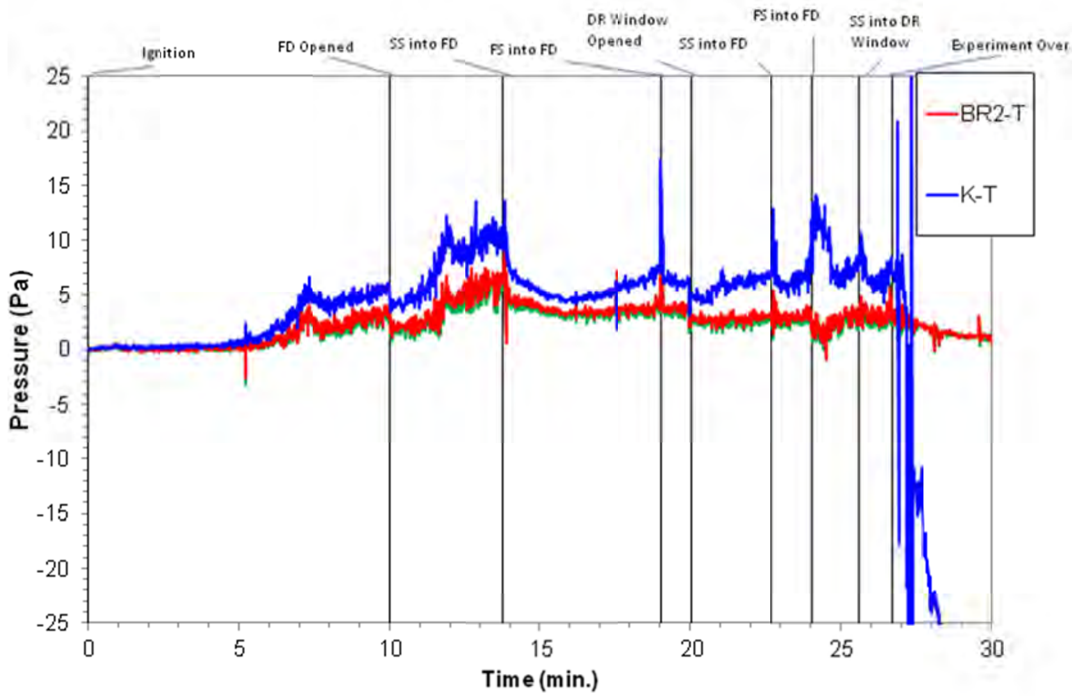


Figure 5.537 : Increase in Pressure in the Top Layer with Fog Stream Application

Experiment 15

In Experiment 15, ignition occurred in the living room. The fire was allowed to grow until 6:00, when the living room window was opened. The fire then continued to grow to post-flashover conditions, and at 9:30 the Bedroom 1 window was opened. Once the bedroom was opened, fire continued to burn out of the living room window and air was entrained through the bedroom window to the hallway. The air that entered the hallway increased the burning in the area of the hallway. Hot gases and smoke flowed out of the top two-thirds of the window as upper layer temperatures increased. At 10:30, 11 seconds of water was applied to the fire with a combination nozzle positioned in a straight stream pattern (Figure 5.538, Figure 5.539 and Figure 5.540). The fire was allowed to regrow and at 18:00, 13 seconds of water was applied to the fire with a combination nozzle positioned in a fog stream pattern to see if it had the effect of pushing the fire (Figure 5.541).

Figure 5.542 shows the influence on temperatures in the house near the ceiling. After the 11 second flow of water into the post-flashover fire in the living room, all the room temperatures decreased. The living room temperature decreased from 1600 °F to 1200 °F, the hallway reduced from 1700 °F to 800 °F, Bedroom 1 decreased from 700 °F to 500 °F. Figure 5.543 shows the influence of temperatures at crawling height (3 ft. level). The living room temperature decreased from 1500 °F to 1200 °F, and the hallway temperature reduced from 1100 °F to 400 °F. The Bedroom 1 temperature decreased from 300 °F to 100 °F.

During the use of the fog stream all temperatures except for the 3 ft. level decreased. The Bedroom 1 temperature was increased from 120 °F to 200 °F for 30 seconds before decreasing to below 100 °F. This is due to the air entrainment into the living room by the fog nozzle and mixing downstream in the flow path. This same phenomenon was not witnessed during the straight stream water application, due to the limited air entrainment.

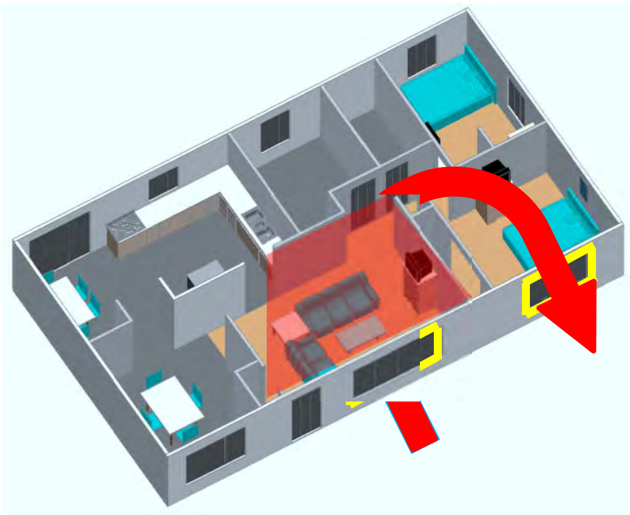


Figure 5.538: Flow Path with Water Flow through the Living Room Window with Bedroom 1 Window Open

Figure 5.539: Start of Straight Stream Application

Figure 5.540: Just after Straight Stream Application

Figure 5.541: Fog Stream Application

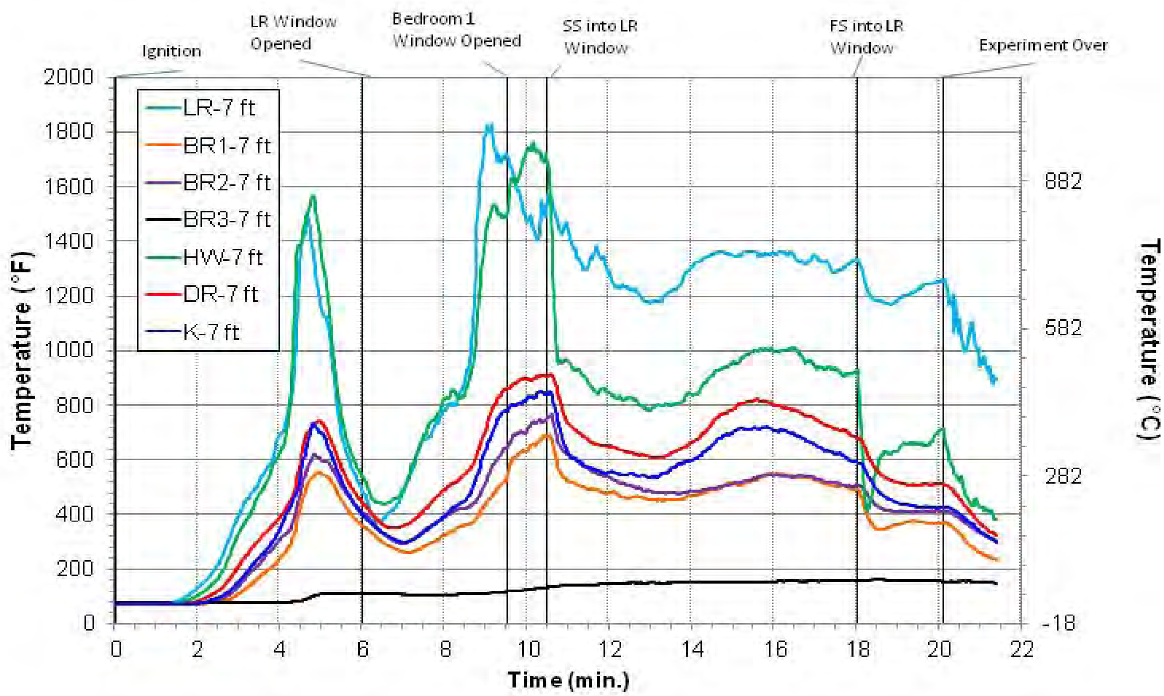


Figure 5.542: 7 ft. Temperatures showing Impact of Water Flow

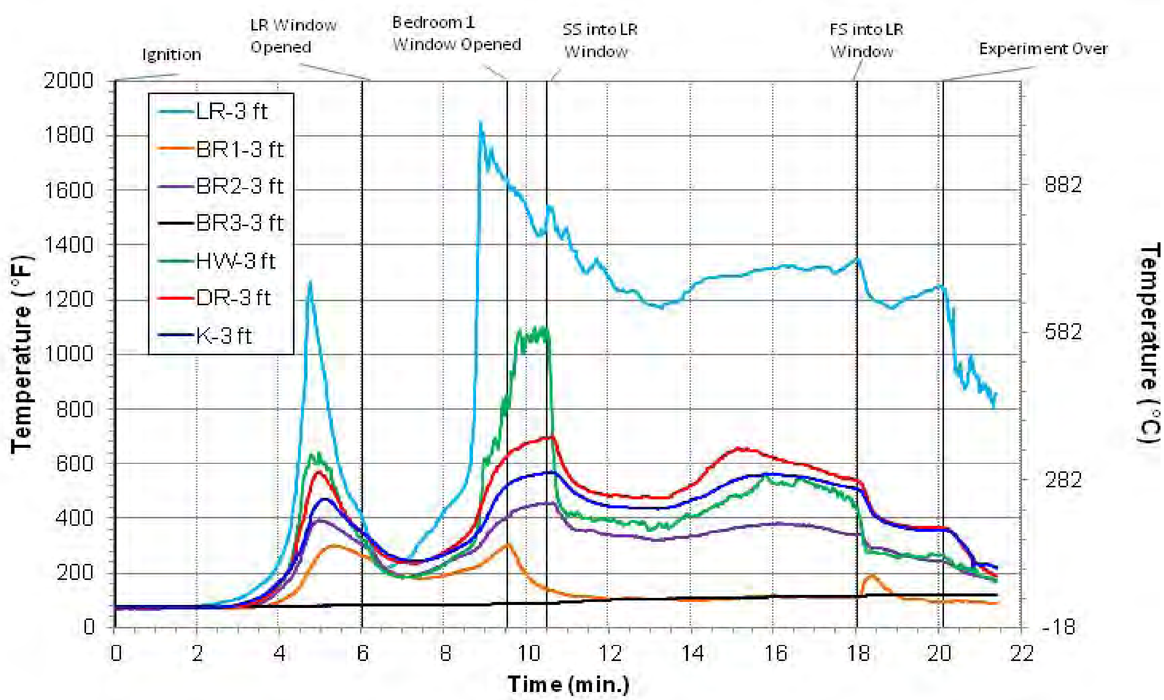


Figure 5.543: 3 ft. Temperatures showing Impact of Water Flow

Experiment 16

In Experiment 16, the fire was allowed to grow until 17:00, when the family room window was opened. This fire took longer to develop, because the fire was ignited in the kitchen cabinets and not in a piece of upholstered furniture. At 21:25, there was an additional ignition in the family room. The purpose of this was to have two rooms involved in fire before the application of water. The fire was then allowed to continue to grow until 27:00, and then the Bedroom 3 window was opened. After the flow path was established through the second floor bedroom, the bedroom temperatures 3 ft. above the floor increased from 300 °F to 1100 °F in 90 seconds. Water was applied to the fire for 15 seconds with a combination nozzle in a straight stream pattern at 28:00. The water was directed through the family room window in the kitchen (Figure 5.545). Water was then again applied to the fire for 15 and 14 seconds with a combination nozzle in a fog stream pattern at 29:30 and 31:05 respectively (Figure 5.546). At 33:30, 17 more seconds of water was applied to the fire with a combination nozzle in a straight stream pattern.

Figure 5.547 and Figure 5.548 show the temperature impact at 3 ft and 7 ft above the floor for every room in the two-story house after the Bedroom 3 window was opened and during water applications. The first 15 seconds of water application used a straight stream pattern directed to the kitchen area as the fire grew in the kitchen and family room. This had little impact on temperatures because water was not being applied to the burning surfaces of the fuel in the family room and much of the kitchen. Water was able to reach some of the kitchen cabinets, but no water was being applied to the furniture burning in the family room. However, temperatures that were on the increase, especially in the flow path to the second floor were held steady for 60 seconds after water application. Next, a fog stream was directed into the family room window and was rotated in a circular pattern for 15 seconds. During this flow, water was applied to the burning sofas in the family room, and temperatures decreased in every room. Most significantly, the temperatures downstream in the flow path through Bedroom 3 decreased from 1000 °F to 550 °F in seconds at the 3 ft elevation, and from 950 °F to 550 °F at the ceiling. The second fog stream application had a similar impact by reducing temperatures, and the second straight stream application reduced all temperatures as well. It was observed that temperature conditions did not deteriorate anywhere in the home from the introduction of water, even if water was not applied directly to the seat of the fire.

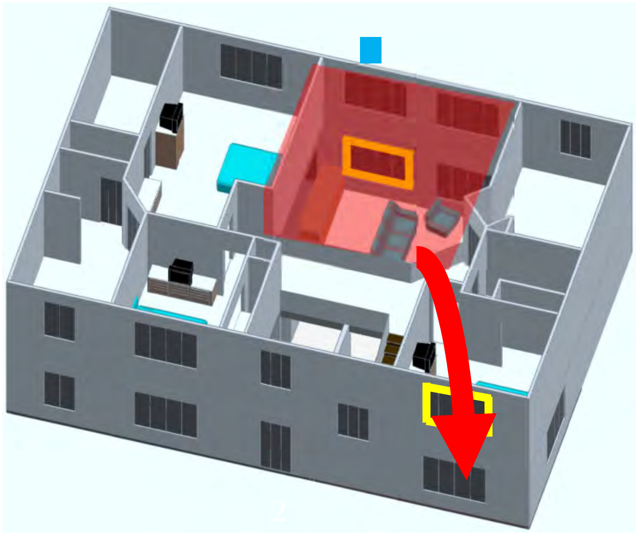


Figure 5.544: Experiment 16 Scenario

Figure 5.545: Straight Stream Application Toward Kitchen

Figure 5.546: Fog Stream Application

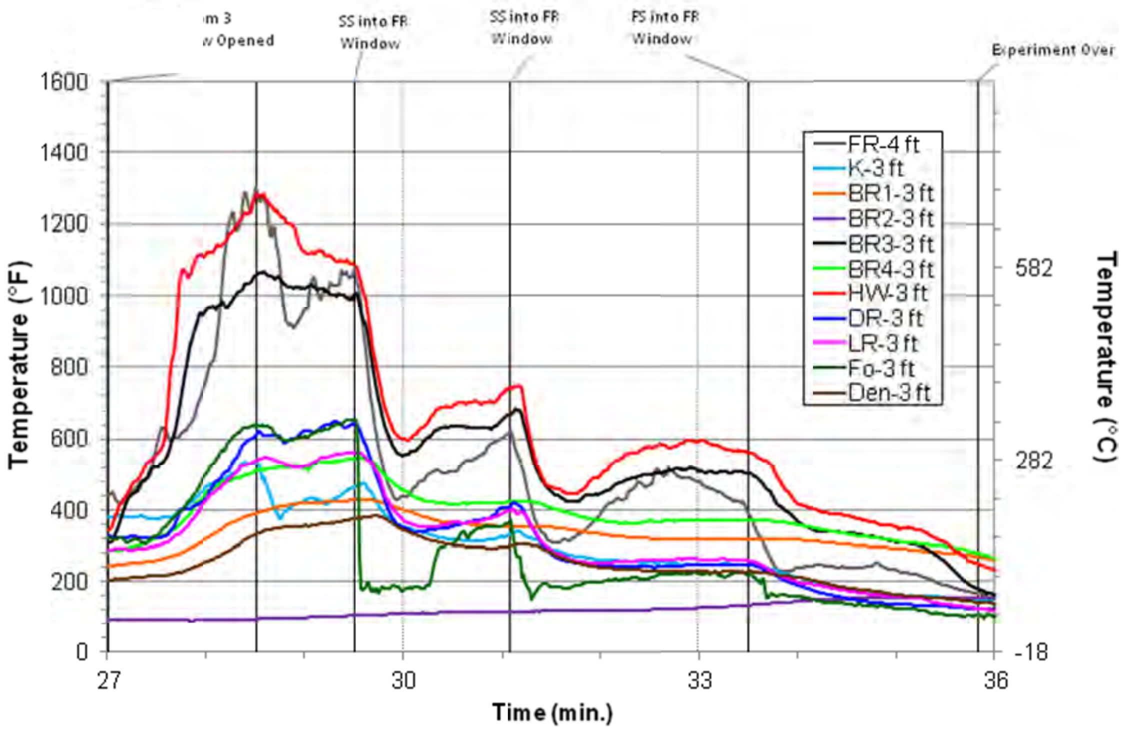


Figure 5.547: 3 ft. Temperatures showing Impact of Water Flow

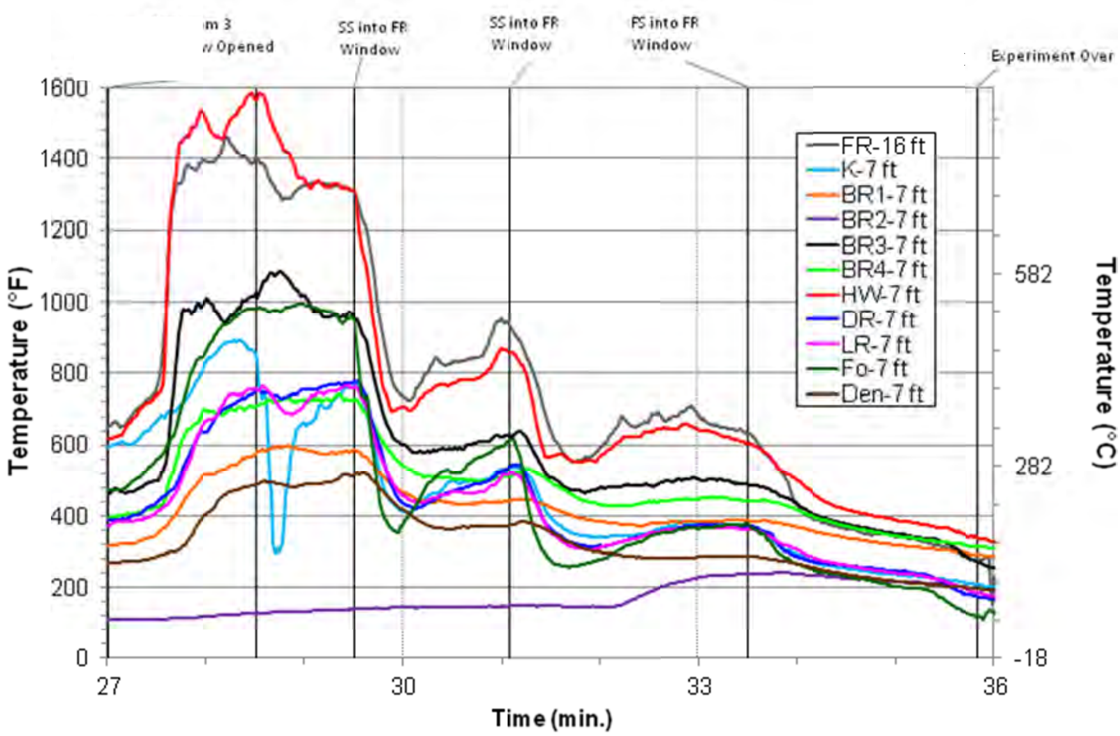


Figure 5.548: 7 ft. Temperatures showing Impact of Water Flow

5.8.14.4. Water Application Summary

The results of applying water to the fire on the temperatures in the home structure are presented in Table 5.60 and Table 5.61. These tables show that temperatures decrease throughout the house in almost all cases. There were two exceptions. In Experiment 11, the bedroom fire recovered in 60 seconds for a modest increase in temperature of 6%; however the remainder of the house temperatures decreased an average of 26%. In Experiment 13, a fog stream was directed into the front door of the one-story house toward the kitchen fire. The dining room window was opened to create an additional flow path from the kitchen through the dining room to the outside. The air entrainment from the stream caused the temperatures to increase a small amount of 7% in the fire room and 3% in the adjacent rooms. Neither of these temperature increases would be noticeable without thermocouple measurements.

Table 5.60: Percent Change of Temperature in Fire Rooms and Non-Fire Room for Straight Stream Water Application

Experiment #	House	Location of Fire	Duration (s)	Fire Room Temp Change (%)	Average Non-Fire Room Temp Change (%)
1	1	Living Room	13	-20	-16
3	1	Living Room	11	-36	-24
5	1	Living Room	17	-62	-25
7	1	Living Room	15	-62	-26
11	1	Bedroom 1	16	6	-26
13	1	Kitchen	6	-48	-16
13	1	Kitchen	6	-6	N/A
13	1	Kitchen	12	N/A	N/A
15	1	Living Room	11	-8	-21
17	1	Living Room	15	-49	-20
2	2	Family Room	12	-25	-14
4	2	Family Room	13	N/A	-17
6	2	Family Room	15	-62	-24
8	2	Family Room	15	-64	-16
10	2	Bedroom 3	12	-54	-55
12	2	Family Room	16	N/A	-14
14	2	Bedroom 3	15	-59	-26
16	2	Family Room/Kitchen	17	-15	-12

Table 5.61: Percent Change of Temperature in Fire Rooms and Non-Fire Room for Fog Stream Water Application

Exp #	House	Location of Fire	Duration (s)	Fire Room Temp Change (%)	Average Non-Fire Room Temp Change (%)
13	1	Kitchen	7	-9	-5
13	1	Kitchen	41	7	3
15	1	Living Room	13	-8	-15
16	2	Family Room/Kitchen	15	-25	-19
16	2	Family Room/Kitchen	14	-13	-13

6. Tactical Considerations

In this section, the results of all the experiments are discussed to develop relationship to tactics on the fire ground as it may impact the safety of the fire service. The topics examined in this section were identified by the project's technical panel.

The application of the findings discussed in this section to the fire scene depend upon many factors such as (i) building structure; (ii) capabilities and resources available to the first responding fire department; and (iii) availability of mutual aid. In addition, the tactical considerations provided should be viewed as concepts for the responding fire service personnel to consider at the fire scene.

6.1. Modern versus Legacy Fire Development

As more and more home furnishings are made of synthetic materials, the heat release rate generated by furniture has increased significantly. This change speeds up the stages of fire development, creating an increased potential for ventilation-limited fire conditions prior to fire department arrival.

The fire service’s workplace has changed and one of several significant factors is home furnishings. As home furnishings have evolved over decades to be made of synthetic materials, the heat release rates generated by home furnishings have increased significantly. This change speeds up the stages of fire development creating an increased potential for ventilation-limited fire conditions prior to fire department arrival. Earlier ventilation-limited conditions make the ventilation tactics of the fire service of utmost importance. Figure 6.1 details many differences of how fires develop today versus decades ago. Peak temperatures prior to becoming ventilation-limited are very different: 1100 °F in the modern fire, compared to 450 °F in the legacy fire. The minimum oxygen concentration prior to fire service ventilation was 5% in the modern fire, compared to 18% in the legacy fire. Most importantly, the time between ventilation and flashover are 2 minutes for the modern fire and over 8 minutes in the legacy fire. The legacy fire could be described as forgiving as it pertains to ventilation. Poorly timed ventilation or an uncoordinated attack can be made up for prior to flashover because there is 8 minutes to adapt.

The time to recover in the modern fire was only 2 minutes, or 25% of the legacy time. This supports the adage, "You are not fighting your grandfather's fire anymore."

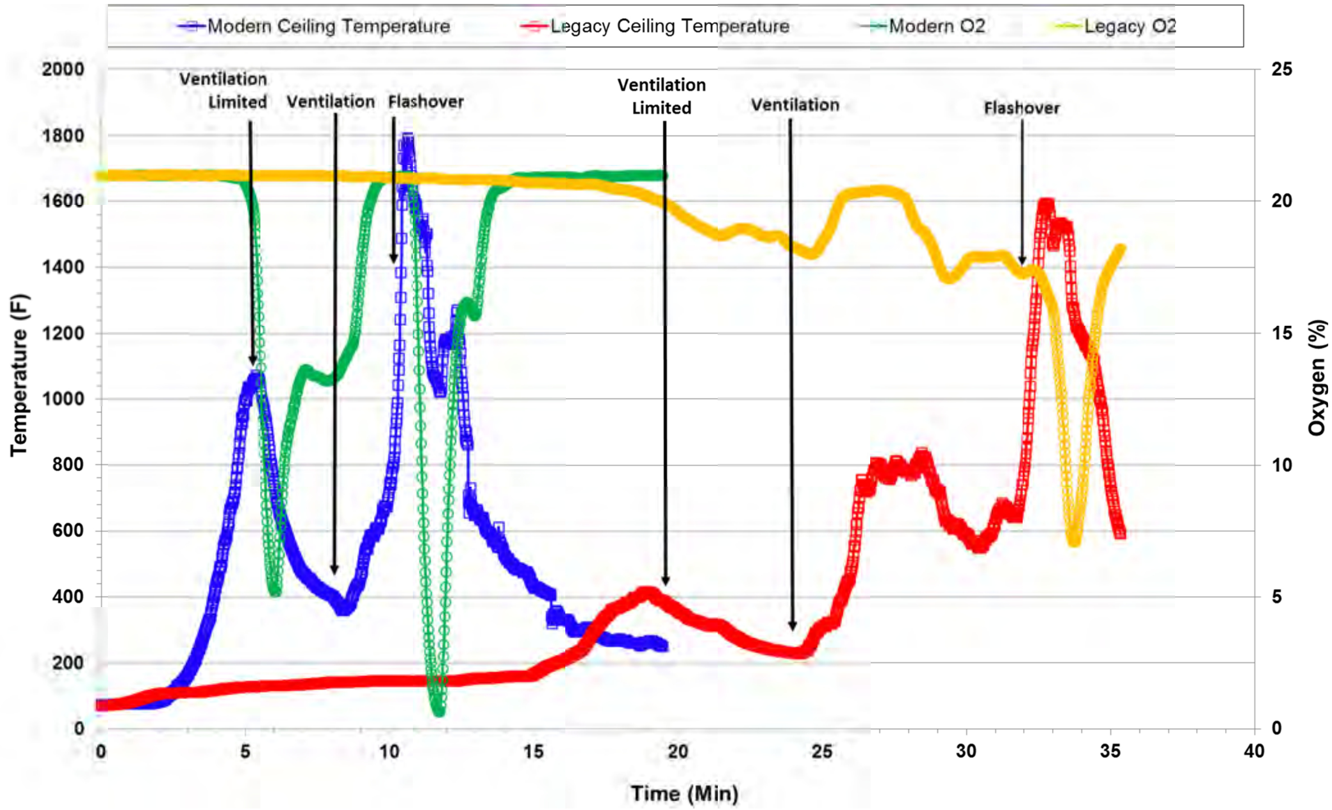


Figure 6.1: Modern vs. Legacy Temperatures and Oxygen Concentration Comparison

6.2. Control the Access Door

While opening a door is a necessity for gaining access, if you limit the amount of air entering, you limit the fire's ability to grow. The experiments in the previous UL horizontal ventilation study demonstrated that opening the front door needs to be thought of as ventilation, as well as making an access point. This necessary tactic also needs to be coordinated with the rest of the operations on the fire ground. A simple action of pulling the front door closed after forcing entry will limit the air to the fire and slow the potential rapid fire progression until access is ready to be made as part of the coordinated attack. The same results were observed in these experiments, and two of the experiments were designed to take it a step further.

One experiment in each house simulated door control. First, the front door was opened fully to allow simulated crew access and then the door was controlled by pulling it closed to the width of a hoseline traveling straight through the doorway (Figure 6.2). This simulated having a control man at the door, feeding hose and holding the door as closed as possible to not impede the advancement of the line. The fire room temperatures at firefighter crawling height from both houses are shown in Figure 6.3 and Figure 6.4. These graphs show that controlling the door keeps temperatures lower than completely opening the door. Temperatures are shown from time of door opening until just before the roof vent was opened so the only effect on temperature was from the front door.

The fire dynamics of door control are fairly simple. If you have a ventilation-limited fire and you limit the air, then you limit the heat able to be released. While this does not completely cut off the oxygen supply, it slows it, which slows fire growth. The more the door is closed, the less the fire can grow. The less the fire grows, the less water required to bring it under control and extinguish it. Doors are also the most efficient air inlet because they go all the way to the ground, as opposed to a window. The air gets entrained low in the doorway, while products of combustion can flow out the top of the doorway, creating a complete flow path through the same opening.

Tactically, there are several considerations for door control. Most importantly, it is a temporary action. The door should be controlled until water is applied to the fire. Once water goes on the fire and the attack crew has the upper hand, meaning more energy is being absorbed by the water than is being created by the fire, the door can be opened. At that point, it is no longer a ventilation-limited fire, so all ventilation will allow more hot gases and smoke out than are being created by the fire. If you are able to apply water to the fire quickly, then this tactic is not needed. Door control does not only have to be done with the front door or with a hoseline. During a search, interior doors can be controlled as crews are trying to find and control the fire or find victims. Any door that has the potential to feed air to the fire should be controlled until water is on the fire or the fire is contained to a known room. If there is concern that a door will lock and trap a crew, a tool can be placed in the doorway to prevent the door from closing and locking.

If there are concerns that an access door will not be able to be reopened after the crew enters, then it should not be controlled, but the potential impact of the added air should be factored in to the operation. One of the most dangerous places for a firefighter to be is between where the fire is and where it wants to go. If the door behind you is the only outlet, then the fire wants to go over or through you to the door.

Figure 6.2: Door Control with a 1 3/4 inch Hoseline

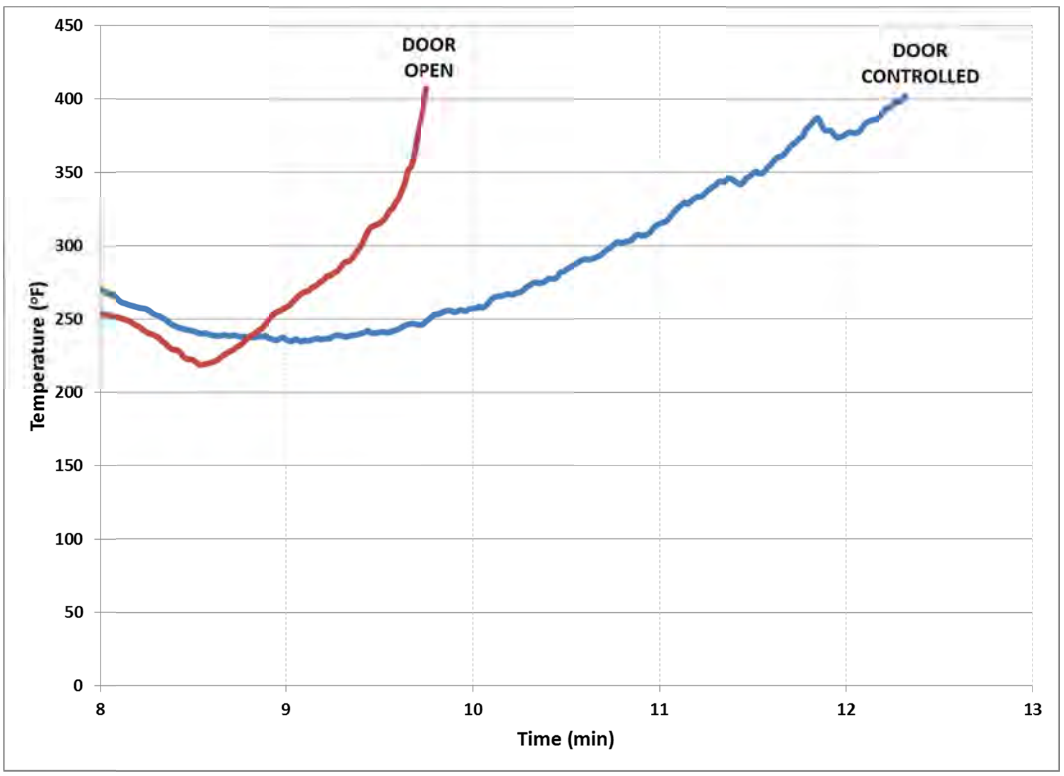


Figure 6.3: One-Story Living Room Temperatures after Front Door Open and Before Roof Open

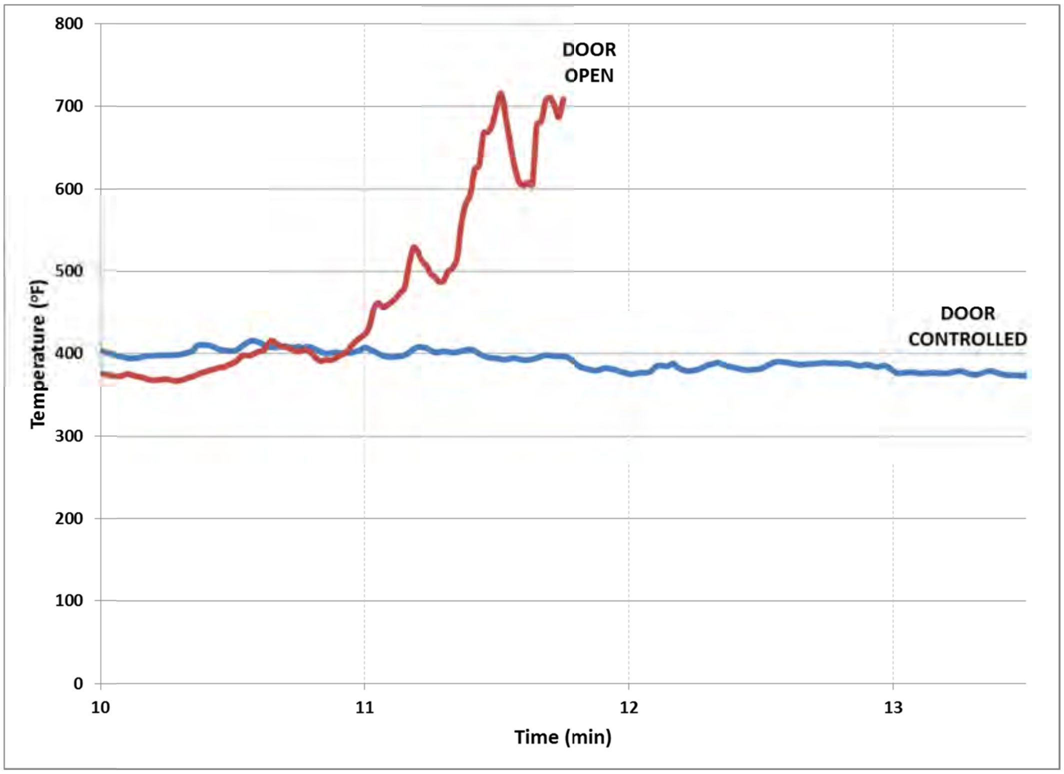


Figure 6.4: Two-Story Family Room Temperatures after Front Door Open and Before Roof Open

6.3. Coordinated Attack Includes Vertical Ventilation

"Taking the lid off" does not guarantee positive results. Most firefighters will tell you that the roof needs to be opened to accomplish two main things: 1) quickly slow down the horizontal fire spread of fire by channeling it where it wants to go, upward; and 2) improve the atmosphere inside the structure so other operations can take place in a safer environment. Most fire training publications describe the benefits of vertical ventilation in this way. There is a significant caveat to this description, and it has to do with the air allowed in to the compartment that is being vertically ventilated.

Vertical ventilation is the most efficient type of natural ventilation. It allows the hottest gases to exit the structure quickly. However, it also allows the most air to be entrained into the structure through a horizontal entry vent, such as a door. If the fire is ventilation-limited, the air entrained can produce an increased burning rate than can be exhausted out of the vertical ventilation hole. When this occurs, conditions can deteriorate within the structure very quickly, which is not the intent of the ventilation operation.

The answer is coordination of vertical ventilation with fire attack, just like one would expect with horizontal ventilation. To make sure the fire does not get larger and that ventilation works as intended, take the fire from ventilation-limited (where it needs air to grow) to fuel limited by applying water. As soon as the water has the upper hand and more energy is being absorbed by the water than is being created by the fire, ventilation will begin to work as intended. With vertical ventilation, this will happen faster than with horizontal ventilation, assuming similar vent sizes.

Opening the roof of any structure is not a fast operation, when compared to ventilating a window. Even if there are skylights, it takes additional time to get to the roof. Because of the time this tactic takes, it is commonly done after a charged hoseline is in place and having an impact, or has already suppressed the fire. That said, there is the potential that the roof vent could be opened before the engine company has a charged hoseline in position to begin fire control. In such cases, the roof could be cut, but pulling or louvering the cut could be held until the incident commander or interior crews indicate that roof ventilation is needed. Once coordinated, the result has a much better chance of having a safe and effective outcome.

Take Experiment 5 in the one-story house as an example. There is a narrow window of opportunity before temperatures in the entire house rise because of added oxygen (Figure 6.5, Figure 6.6 and Figure 6.7). Opening the front door started the process of providing oxygen to the ventilation-limited fire. The fire would have transitioned to flashover without the roof vent, but creating an opening above the fire speeds the process. Many would think that opening that hole would slow the process down by allowing hot gases out, but the air allowed in generates more heat and smoke than can escape through the 4 ft. by 4 ft. hole.

Figure 6.5: 5 seconds after roof vent

Figure 6.6: 60 seconds after roof vent

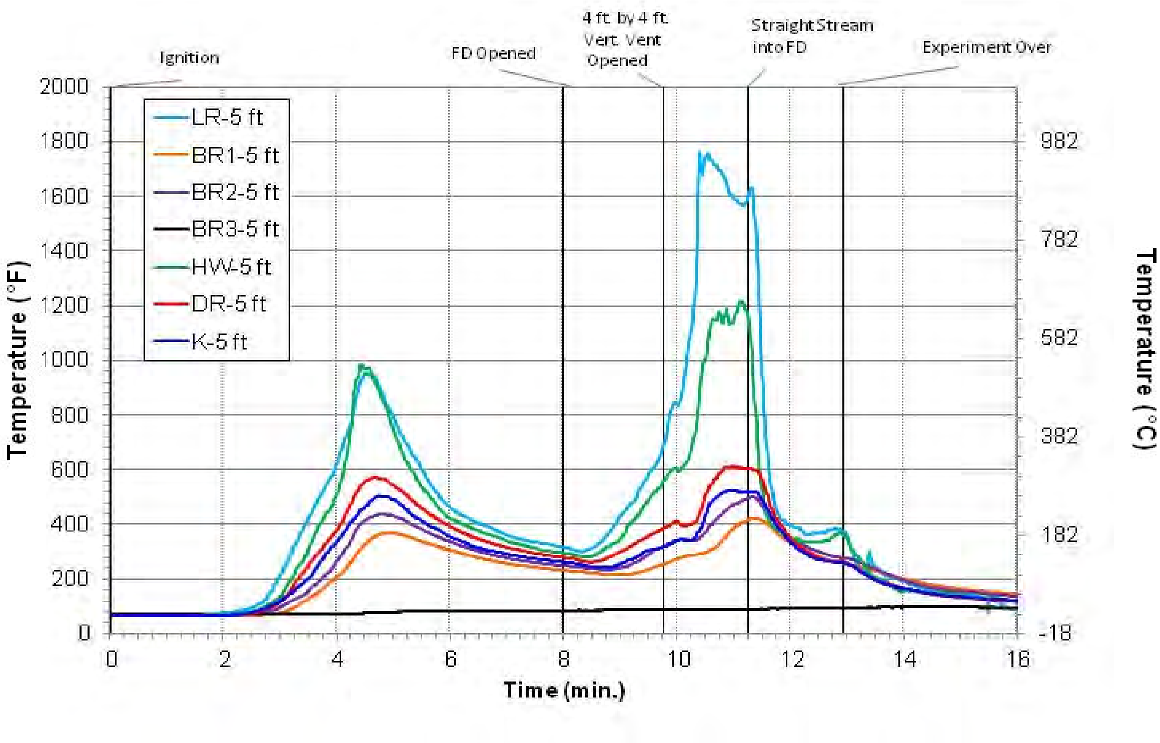


Figure 6.7: 5 ft. temperatures in the one-story house showing coordination window

6.4. How big of a hole?

A 4 ft. by 8 ft. hole over a ventilation-limited fire does not get rid of more smoke and hot gases than are created by the flow of oxygen through the front door. Fire training often refers to a 4 ft. by 4 ft. hole as the vertical ventilation hole size required for a single family house, but there is no reason provided for this estimation. Alternative ventilation hole size guidance found in fire service literature recommends 10% of the container size beneath the hole. The one-story house has a living room that is approximately 230 ft^2, which equates to a 4 ft. by 6 ft. hole. The two story house has a family room that is approximately the same size but it also has an open floor plan, so there is no defined container size.

For each structure, two ventilation holes were created - one 4 ft. by 4 ft. and one 4 ft. by 8 ft. The holes were created over the living room fire in the one story and over the family room fire in the two-story. The front door was open in each house simulating crew entry, and assuming the fire department would not wait for vertical ventilation to be the only task completed during a fire attack (Figure 6.8 through Figure 6.11). These graphs show the conditions after ventilation in each case and a graph of the temperatures in every room from the time of vertical ventilation until water was applied. The only impact on these temperatures is the ventilation taking place, and the graphs show that ventilation alone did not localize fire growth or reduce temperatures as compared to not performing vertical ventilation.

The data from these experiments show that a 4 ft. by 8 ft. hole above the fire in each of the houses alone did not improve conditions or make ventilation-limited fire conditions into fuel-limited conditions. When water was applied to the fire to reduce the heat release, the fire transitioned to a fuel-controlled fire. At that point, the larger the hole, the better conditions became for any potential victims or firefighters operating inside the structure.

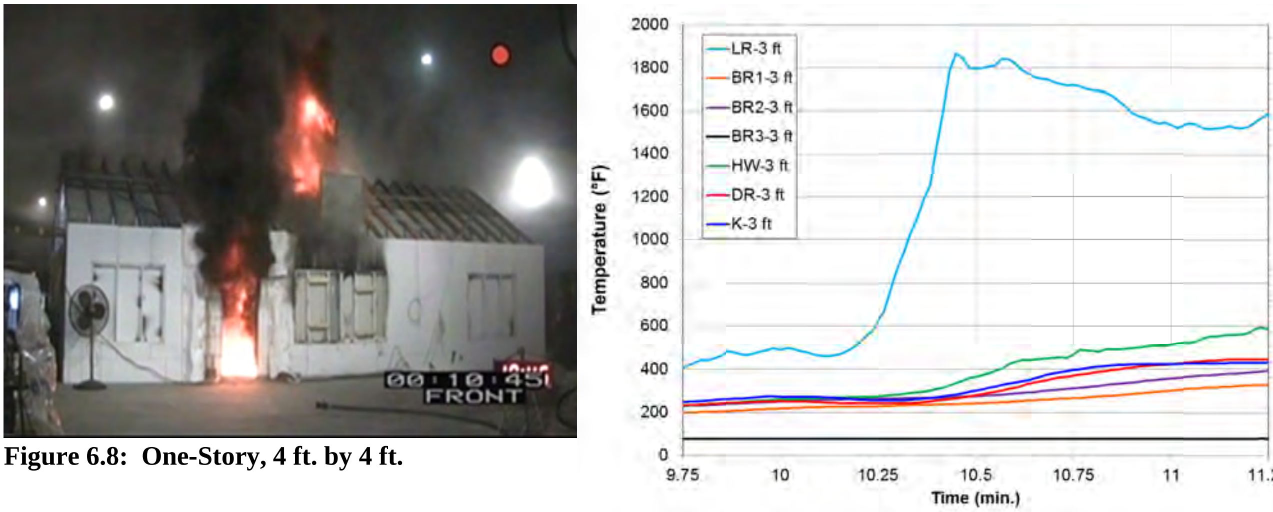


Figure 6.8: One-Story, 4 ft. by 4 ft.

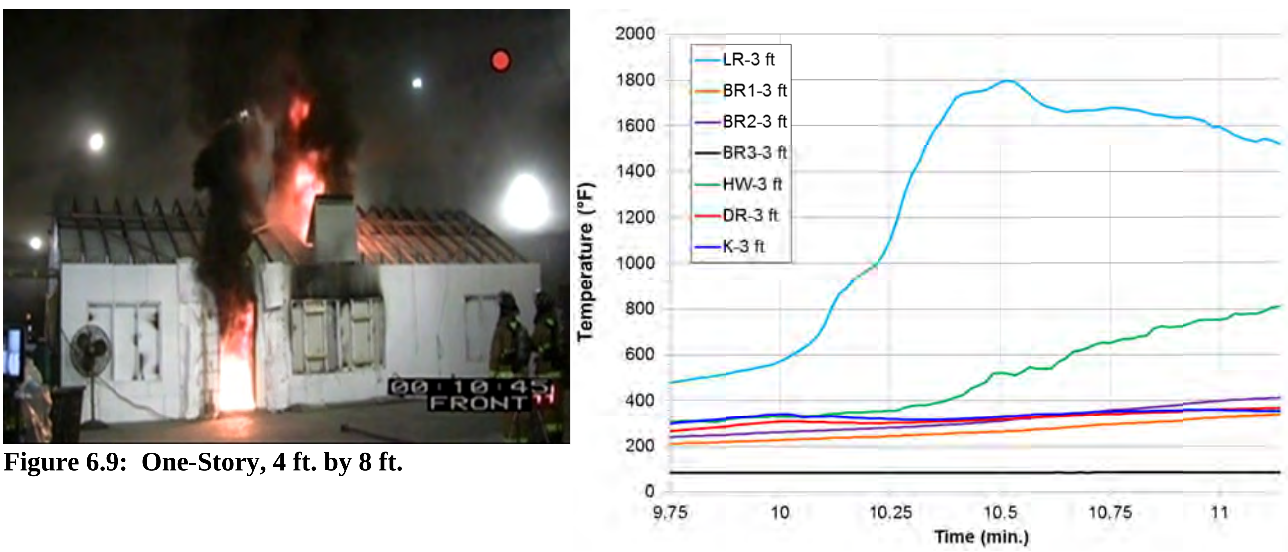


Figure 6.9: One-Story, 4 ft. by 8 ft.

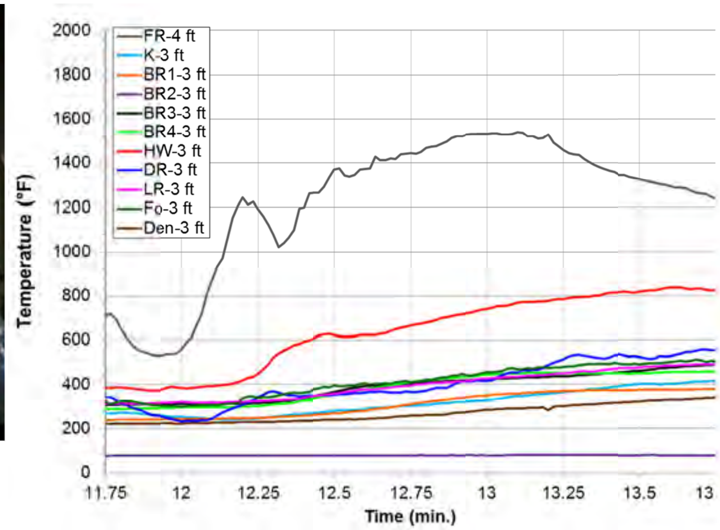


Figure 6.10: Two-Story, 4 ft. by 4 ft.

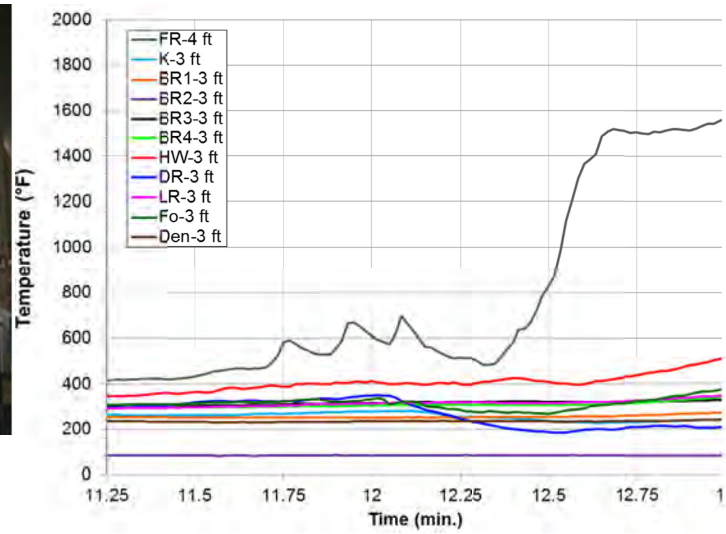


Figure 6.11: Two-Story, 4 ft. by 8 ft.

6.5. Where do you vent?

Ventilating over the fire is the best choice if your fire attack is coordinated. The coordinated attack tactical consideration established that a ventilation-limited fire would increase in size if it receives air. Additionally, the closer the source of the air to the seat of the fire, the quicker it will increase in size (the heat release rate will increase and temperatures will increase). Placement of vertical ventilation can be a complex situation, especially if you do not know where the fire is in the house. Optimally, you plan your vertical ventilation based on the room geometry, door locations, air inlet location, and subsequent flow paths. If you ventilate in coordination with fire attack, the hose stream is removing more energy than is being created, so it does not matter where you ventilate. But the closer it is to the seat of the fire, the more efficient the vent will be in removing heat and smoke, which will improve conditions for the remainder of the operations taking place on the fire ground. If you vertically ventilate and fire attack is delayed, then ventilating in general is bad, and vertically ventilating in close proximity to the seat of the fire will result in the worst conditions the fastest. With today's fuel loads and heat release rates, there is a good chance that the fire will generate enough energy quickly enough to overwhelm any vent that is created. Simply put, the fire is producing more than can be let out, so conditions get worse in the absence of water application.

Ventilating remote from the fire can be effective under some circumstances. If the fire is in a room that is connected to the rest of the house by a doorway, ventilating the roof outside of that room could allow smoke to clear from the rest of the house. However, while visibility may improve in the flow path leading from the air inlet to the fire room, the fire will increase in size as the air is entrained. The doorway becomes the limiting factor in keeping the fire contained. Once fuel outside of that doorway ignites, such as a bedroom fire extending to living room furniture, the heat release rate can increase quickly and overcome the temporary benefit of the remote vertical ventilation hole. This is an example of a situation where the vertical vent can provide a temporary visibility benefit, but the fire and temperatures in the area of the fire are continuing to increase.

6.6. Stages of Fire Growth and Flow Paths

The stage that the fire is in, ventilation- or fuel-limited, the distance from the inlet (door or window) air to the fire, the distance from the fire to the outlet (door, window, roof vent), the shape of the inlet and outlet and the type and shape of items (furniture or walls), or openings (interior doors) in the flow paths, all play key roles in how quickly a fire will respond to oxygen and ultimately firefighter safety.

Flow paths can be defined as the movement of heat and smoke from the higher air pressure within the fire area to all other lower air pressure areas both inside and outside of a fire building. As the heated fire gases are moving towards the low pressure areas, the energy of the fire is entraining oxygen towards the fire, as the fire is rapidly consuming the available oxygen in the area. Based on varying building design and the available ventilation openings (doors, windows, etc.), there may be several flow paths within a structure. Operations conducted in the flow path can place firefighters at significant risk due to the increased flow of fire, heat, and smoke toward their position.

The following series of images and text shows a one-story house fire that begins in the living room.

Figure 6.12 shows the heat release rate of the fire as the fire progresses. The following series of images illustrates the relative temperatures in the house and the flow path(s) indicated with blue and red arrows. After an object ignites in the living room, the **growth stage** of the fire begins. During this stage, the fire is **fuel-limited/controlled** (not because fuel is absent but rather because it is not involved in the fire yet) and air feeds the fire from all directions and smoke and hot gases are spread along the ceiling to all of the open rooms in the house.

As the fire grows in the compartment, the smoke layer reaches the location where burning is taking place. This is still the **growth stage** but the fire becomes **ventilation- limited/controlled**. The fire is still growing but this growth slows down because the fire does not have all the air it needs to burn freely as if it were not in a compartment. The oxygen concentration begins at 21%, but, as the oxygen is consumed, the fresh air entrained to the fire begins to mix with smoke, lowering the oxygen concentration and slowing fire growth. Also during this stage, the fire has most likely spread beyond the first object ignited and can be considered a compartment fire or room fire. Once the oxygen concentration drops below approximately 16%, the fire begins its **initial decay stage**. The oxygen level at which this occurs varies, but depends mainly on the temperature in the room. Higher temperatures before the oxygen concentration decreases will support longer fire growth before the decay stage. As the fire decays, temperatures in the fire room remain high, but temperatures throughout the rest of the house decrease as heat release rate decreases. During this stage there is no significant flow path. The fire is trying to entrain air from any void or crack in the house, which may look like pulsing smoke from the outside.

A decaying fire must entrain more oxygen, or it will self-extinguish. Ventilation, which provides the fire the access to oxygen that it needs, can be caused a number of ways, by the fire failing a window or glass door, by a neighbor or a police officer trying to help, or by the fire department venting a window or forcing open a door. Once an opening is made, a **second growth stage** begins. The speed at which the fire responds and the speed at which the heat release rate increases depends on the extent to which the fire decayed and the distance between the air supply and the burning room. Awareness of the flow path during this stage is critical, because firefighters will interact with the ventilation-limited fire at this time. They have the potential to be in the flow path when the fire changes rapidly. In this scenario, the front door enters right into the fire room. The resulting flow path consists of fresh air flowing in through the bottom half of the front door, or low pressure, and hot gases and smoke flowing out through the top of the door under a higher pressure. Controlling the front door or applying water is the only ways to slow the second growth stage of the fire.

During the second growth stage, if the door is not controlled or water is not applied, the fire will transition to flashover. **Flashover** is a momentary event that occurs during the second growth stage. After flashover the fire grows to the point where there is more burning (heat release rate) than can be supported by the air coming in through the front door. Fuel rich smoke and hot gases flow out of the front door and meet the oxygen outside of the house and burn outside the house. This is what the fire service would refer to as “fire showing.” At this stage, the fire is ventilation-limited and temperatures in the house will remain high. The fire is not vented, but it is venting, and if no additional windows fail, doors are opened, or holes are cut in the roof, the fire enters the **fully developed stage**. The fire will burn at the same heat release rate unless additional oxygen is made available to the fire, or if fuel is consumed to the point the fire pulls back into the house and becomes fuel limited or if water is applied to the fire returning it to a fuel limited fire.

In this scenario a vertical ventilation hole is made into the fire room. This transitions the fire into a third **growth stage**. The heat release rate increases as additional smoke and hot gases are ventilated out of the roof, which allows more oxygen to be entrained into the front door. The flow path inward increases in size and speed while the outward flow path splits. The majority of the outflow is through the roof while some remains out of the front door. With fuel remaining, there is now fire out of the roof and front door and the fire is still ventilation-limited. Since it is ventilation-limited, it enters a **second fully developed stage.** The fire will remain at this stage until additional oxygen is made available to the fire (opening a window, opening a door, or making a larger roof hole); fuel is consumed to the point that the fire pulls back into the house and becomes fuel limited; or water is applied to the fire, returning it to a fuel limited fire. In this scenario, **suppression** is commenced. This marks the start of the **decay stage**. The heat release rate is reduced, controlling the fire and returning it to a **fuel-limited fire**. During this stage more hot gases and smoke are being ventilated than are being created, so the house temperatures will cool and the visibility will improve, allowing for searches, extinguishment, salvage, overhaul, etc.

Experiment 5 followed a similar timeline to this example. Figure 6.13 shows an overlay of stages of fire growth over the actual temperatures in the house during the experiment. The only difference is the timing between the front door being opened and the roof vent being opened. In the example, flashover occurred prior to roof ventilation, and in the experiment, the roof was opened sooner, and flashover occurred after roof ventilation. This figure provides an approximation of what non-fire room temperatures would be in the example as the ventilation occurs and the stages of fire development take place.

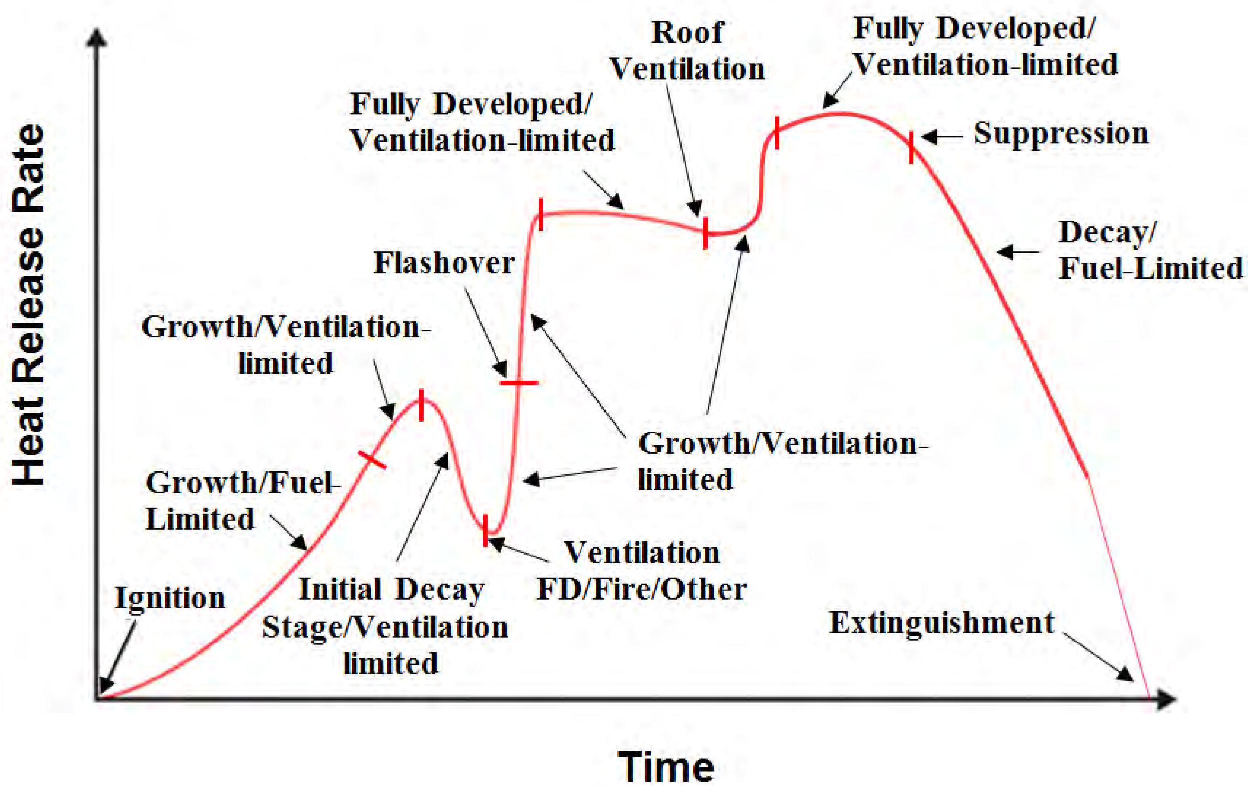
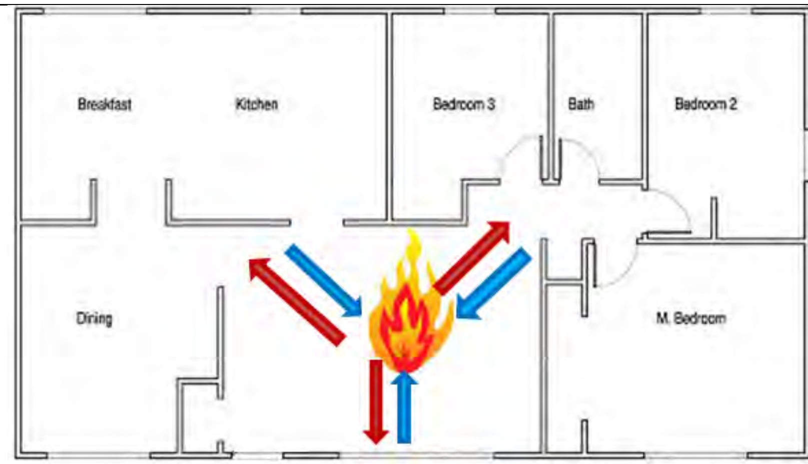
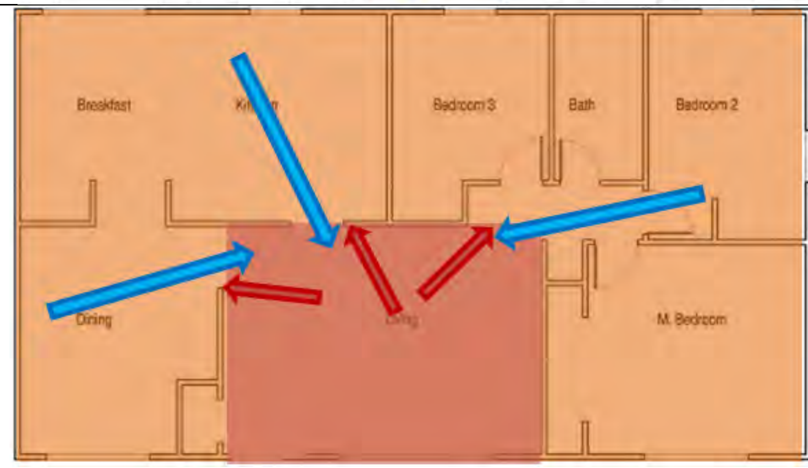
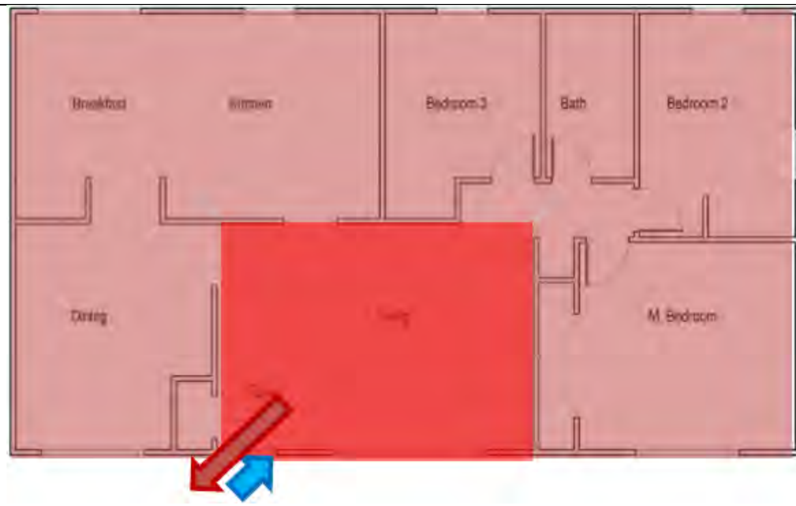
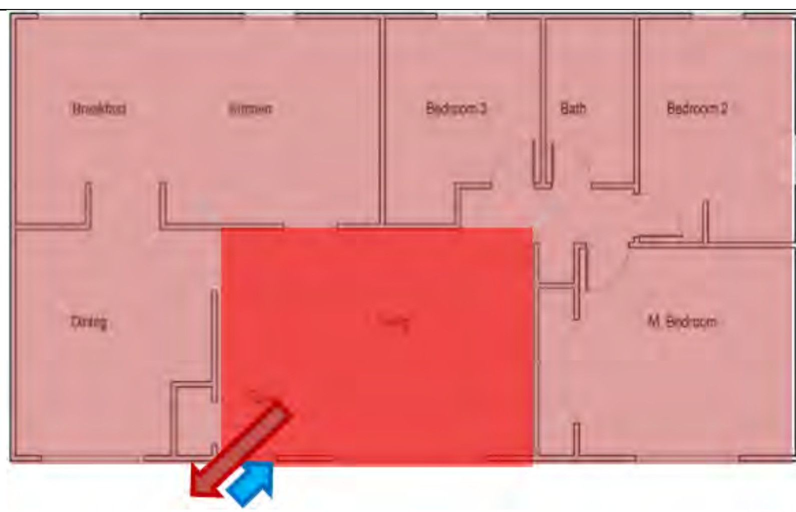
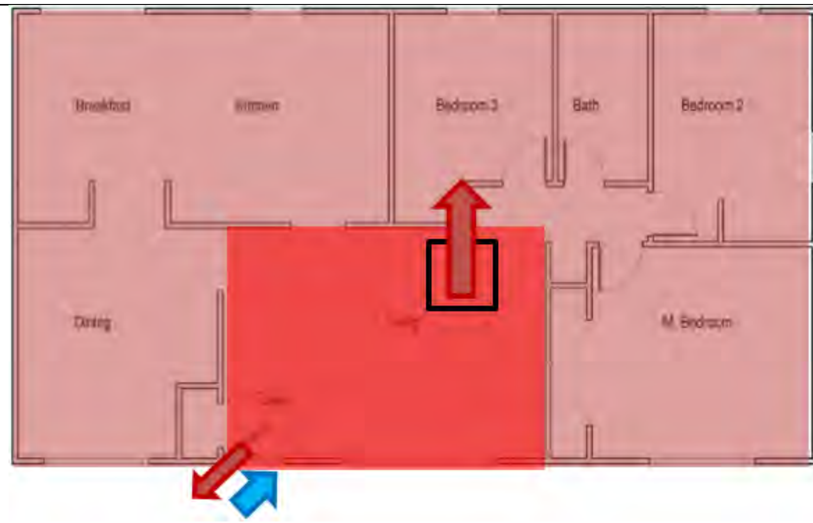
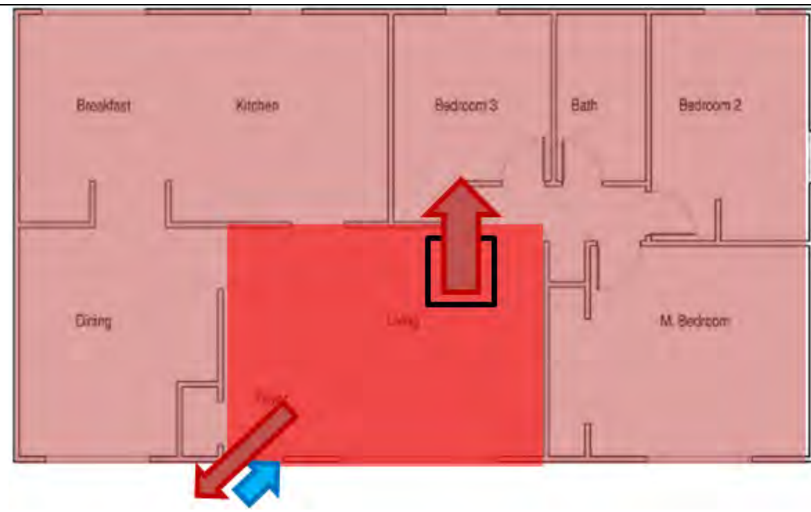


Figure 6.12: Fire growth curve for this fire example

Growth Stage: Fuel Limited Fire. Object on fire. Flow Path – Oxygen flows to fire from all directions (BLUE Arrows) and hot gases flow away from fire at ceiling level (RED Arrows).	
Growth Stage: Ventilation-limited Fire. Room on fire, oxygen is decreasing Flow Path – Oxygen flows to fire room from all directions (BLUE Arrows) and hot gases flow away from fire at all levels (RED Arrows).	
Initial decay stage: Ventilation-limited Fire. Room on fire, oxygen is running out and temperatures are dropping Flow Path – Oxygen flows to fire room through cracks or leakage from all directions and hot gases also attempt to push through cracks, There can be some pulsing of smoke visualized.	

Ventilation Takes Place: Door is Opened, Growth Stage 2: Ventilation-limited Fire. Room on fire, oxygen is pulled in and temperatures are increasing Flow Path – Oxygen flows to fire room through bottom of open front door (BLUE Arrow) and hot gases push out of the top of the doorway (RED Arrow)	
Flashover: Ventilation-limited Fire. Flames extend out of doorway, inside house is too fuel rich to burn Flow Path – Oxygen meets fuel at doorway (BLUE Arrow) and flames push out of the top of the doorway (RED Arrow)	
Fully Developed Stage: Ventilation-limited Fire. Flames extend out of doorway, inside house is too fuel rich to burn but continues to increase in temperature Flow Path – Oxygen meets fuel at doorway (BLUE Arrow) and flames push out of the top of the doorway (RED Arrow)	

Additional Ventilation is made, Roof Ventilation. Growth Stage 3: Ventilation-limited Fire. Flames extend out of doorway and roof vent, inside house is too fuel rich to burn but continues to increase in temperature Flow Path – Oxygen meets fuel at doorway (BLUE Arrow) and flames push out of the top of the doorway and roof (RED Arrows)	
Fully Developed Stage 2: Ventilation-limited Fire. Flames continue to extend out of doorway and roof vent, inside house is too fuel rich to burn but temperatures remain high Flow Path – Oxygen meets fuel at doorway (BLUE Arrow) and flames push out of the top of the doorway and roof (RED Arrows)	
Water Application: Fuel Limited Fire. Temperatures are cooled. Flow Path – Oxygen enters front door (BLUE Arrow) and hot gases exit mainly through roof and through the front door, cooling temperatures in the entire house (RED Arrows)	

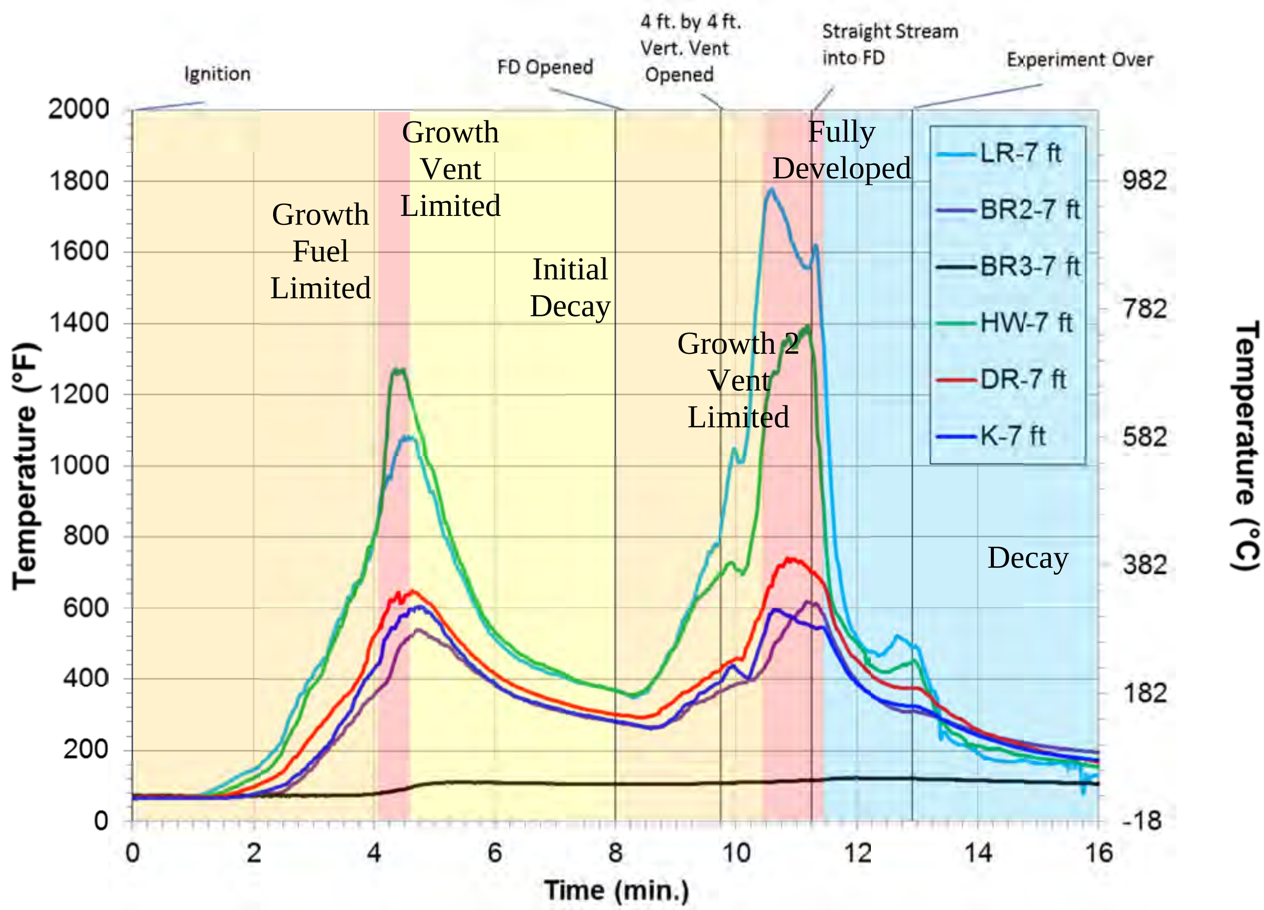


Figure 6.13: Experiment 5 Stages of Fire Development

In the one-story experiments we opened the front door to the house and ventilated over the living room fire or we opened the front door and ventilated remotely from the bedroom fire (over the living room). The location of the fresh air was the same but the air had to travel different paths to grow the fire and the hot gases had to travel different paths to exit the structure. These fire dynamics are key to understanding how the fire will react to ventilation. Opening the roof over the fire (the pre-heated room full of unburned fuel) and allowing air in right to the base of what is burning is the most efficient way to allow the fire to increase in magnitude (heat release rate) (Figure 6.14).

Opening the front door and the roof outside of the fire room and entraining the air from outside the room places a doorway in the flow path, which significantly impact the fire dynamics (Figure 6.15). Once the vents are opened, the neutral plane lifts, allowing hot gases to exit the top of the fire room doorway and for fresh air to be entrained into the bottom of the doorway. Since the hot gases need to flow from the ceiling of the fire room (the high pressure area) and downward to go through the door, this slows down the flow as the gases make their way to the low pressure, which is the roof vent and front door. The low pressure side of the flow path is from the front door to the bottom portion of the fire room door.

While the fresh air travels this path, it mixes with smoke and unburned gases, which make it less than 21% oxygen and therefore less efficient to grow the fire. With the doorway as a choke point, the fire grows slower when it is remote from the vent points. Once the fire entrains enough air, however, it will transition to flashover, and flames and hot gases will exit the room and spread toward the vents. If other fuels are in this path, they will ignite and increase the HRR rapidly because they are in a preheated environment with additional unburned fuel from the initial fire room (Figure 6.16). This fire will then spread until it becomes ventilation-limited, with the new flow path directly into the living room. There are now 2 fire rooms, but the original fire room (bedroom) will have burning decrease and temperatures reduce because oxygen is being consumed by the living room fire, so oxygen never makes it back to the bedroom (Figure 6.17).

Figure 6.18 shows the flow paths after the front bedroom window was ventilated. The front bedroom (original fire room) was full of unburned fuel and was heated due to the combustion in the room. Once the window was opened, air was able to mix with the fuel and heat to ignite and burn. The bedroom would transition to flashover and become fully developed with fire coming from the front door, bedroom window and roof vent.

The home continues to burn in the fully developed stage until the rear bedroom window was ventilated. This creates a flow path through the rear bedroom and into the hallway, supplying air to the high heat condition in the hallway. The open window allows hot gases to flow to the low pressure and out through the top of the window (Figure 6.19). As these gases flow out of the bedroom, they heat this room, and once an object in the room ignites it increases the HRR rapidly. Figure 6.20 shows the flow paths after the rear bedroom transitions to flashover.

The fire is fully developed, and the flow paths exist at the ventilation openings because the interior of the house is ventilation-limited and the air to burn is on the outside of the home. The dining room and kitchen area are elevated in temperature, but are not burning. This is due to the lack of oxygen in the house. If the windows to those rooms were ventilated or fail due to the heat, then they would transition to flashover as well. This example shows a house burning with only ventilation added. If water was applied to this fire at any point, the heat release rate and temperatures would decrease and the ventilation would begin to assist in letting more combustion products out than are being created by the fire. In other words, the fire would transition from a ventilation-limited fire to a fuel-limited fire. Limiting flow paths until water is ready to be applied is important to limiting heat release and temperatures in the house.

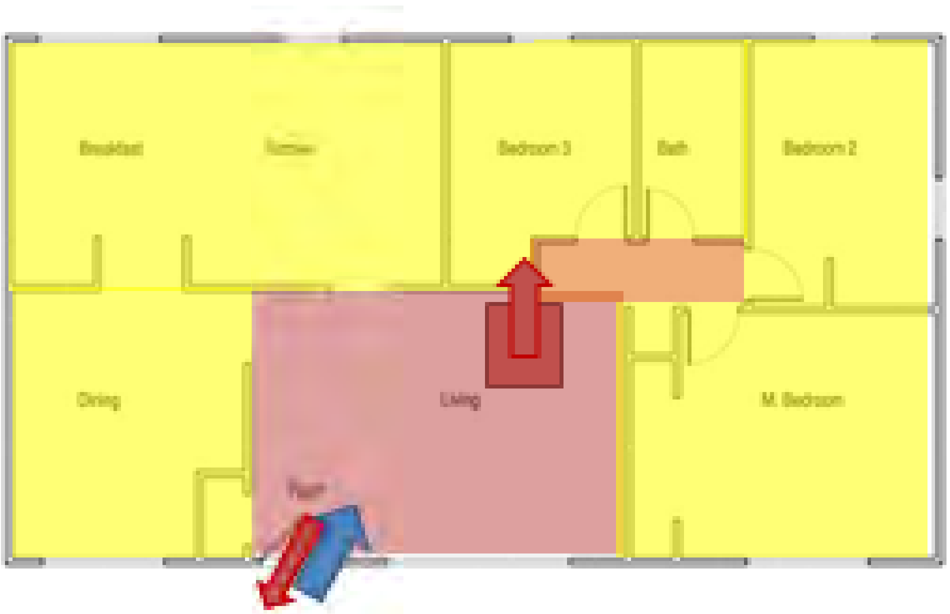


Figure 6.14: Flow path directly into and out of the fire room

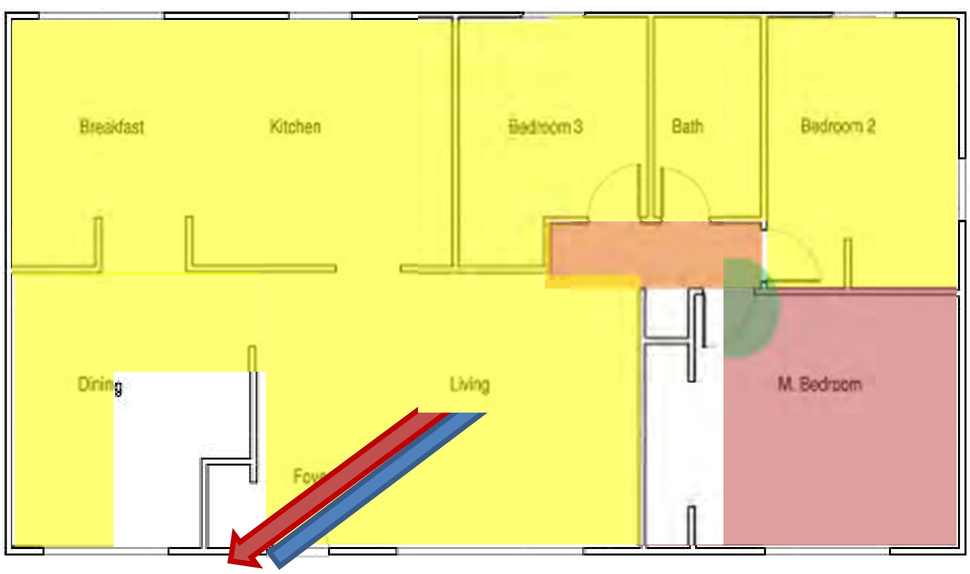


Figure 6.15: Flow path through another room to the seat of the fire

Figure 6.16: Flow path as furnishings are ignited in the living room

Figure 6.17: Flow path after the living room reaches flashover

Figure 6.18: Flow paths after front bedroom window is opened

Figure 6.19: Flow paths after rear bedroom is opened

Figure 6.20: Flow paths as fire becomes fully developed

6.7. Timing is vital

Firefighters performing effective ventilation are thinking about timing. It is not possible to make statements about the effectiveness of ventilation unless you include timing. In previous tactical considerations, we examined coordination, where to vent, and flow paths. All of these discussions hinge on proper timing. Every firefighter that has performed ventilation on a fire ground has seen the outcome of their actions, but do they know why? In some cases, the conditions inside may have been improved and in others, the fire may have transitioned to flashover. It is essential that every firefighter know why the fire responded the way it did by having an understanding of fire dynamics. Otherwise, that experience may be wasted or be wrong and misapplied in the future.

Venting does not always equal cooling, but well timed and placed ventilation equals improved conditions. These improved conditions are cooling, increased visibility, useful flow paths opposite a hose line to release steam expansion, and other benefits. That same ventilation action 30 seconds earlier or later could have a dramatically different outcome. This is especially true for vertical ventilation. Vertical ventilation is the most efficient, and therefore causes the most rapid changes. A good example of this is when a content fire is vertically ventilated into a wood framed attic space. When the vent is opened and the ceiling is pushed, the fire will extend into the attic space. Since the attic is designed to be ventilated even before the vent hole is cut, there is often plenty of air and fuel to burn. If water is not going to be applied to the interior fire and followed with overhaul in the area of the vertical vent hole, then the roof could burn out of control.

As we discuss timing there are several useful considerations:

- The fire does not react to additional oxygen instantaneously. A ventilation action may appear to be positive at first, as air is entrained into the ventilation-limited fire; however, 2 minutes later, conditions could become deadly without water application.

- The higher the interior temperatures, the faster the fire reacts. If fire is showing on arrival, the interior temperatures are higher than if the house is closed. This means that additional ventilation openings are going to create more burning in a shorter period of time.

- The closer the air is to the fire, the faster the fire reacts. Venting the fire room will increase burning faster, but it will also let the hot gases out faster after water is applied.

- The higher the ventilation, the faster the fire reacts. Faster and more efficient ventilation means faster air entrainment, which means more burning and higher temperatures. It also means better ventilation after water is applied.

- The more air, the faster the fire reacts. Also, the more exhaust, the more air that can be entrained into the fire. A bigger ventilation hole in the roof means that more air will be entrained into the fire. If the fire is fuel limited, this is good, but if the fire is ventilation-limited, this could be bad.

6.8. Reading Smoke

Observing smoke conditions is a very important component of size-up. Don't get complacent if there is nothing showing on arrival. Figure 6.21 shows conditions on side alpha during an experiment in the one-story house. The top two pictures are 10 seconds prior to the interior temperatures reaching their peak, the smoke coming out of the cracks of the structure transitions from black and under pressure to grey with less pressure. Ten seconds later, there is no visible smoke showing at all. The fire has run out of oxygen and is decaying. The picture on the bottom right shows the conditions once the front door was opened.

Figure 6.22 shows the pressures decreasing rapidly to negative values as smoke flow stops and the oxygen concentration falling rapidly as the fire reaches its peak temperature and begins to decay. Comparing the temperature data with the pressure data shows that the pressure in the house goes negative while the living room is still 800 °F. No or little smoke showing could mean a fuel-limited fire that is producing little smoke or, as in this case, it could mean a ventilation-limited fire that is in the initial decay stage and is starved for air. In order to increase firefighter safety, consider treating every fire like a ventilation-limited fire until proven otherwise.

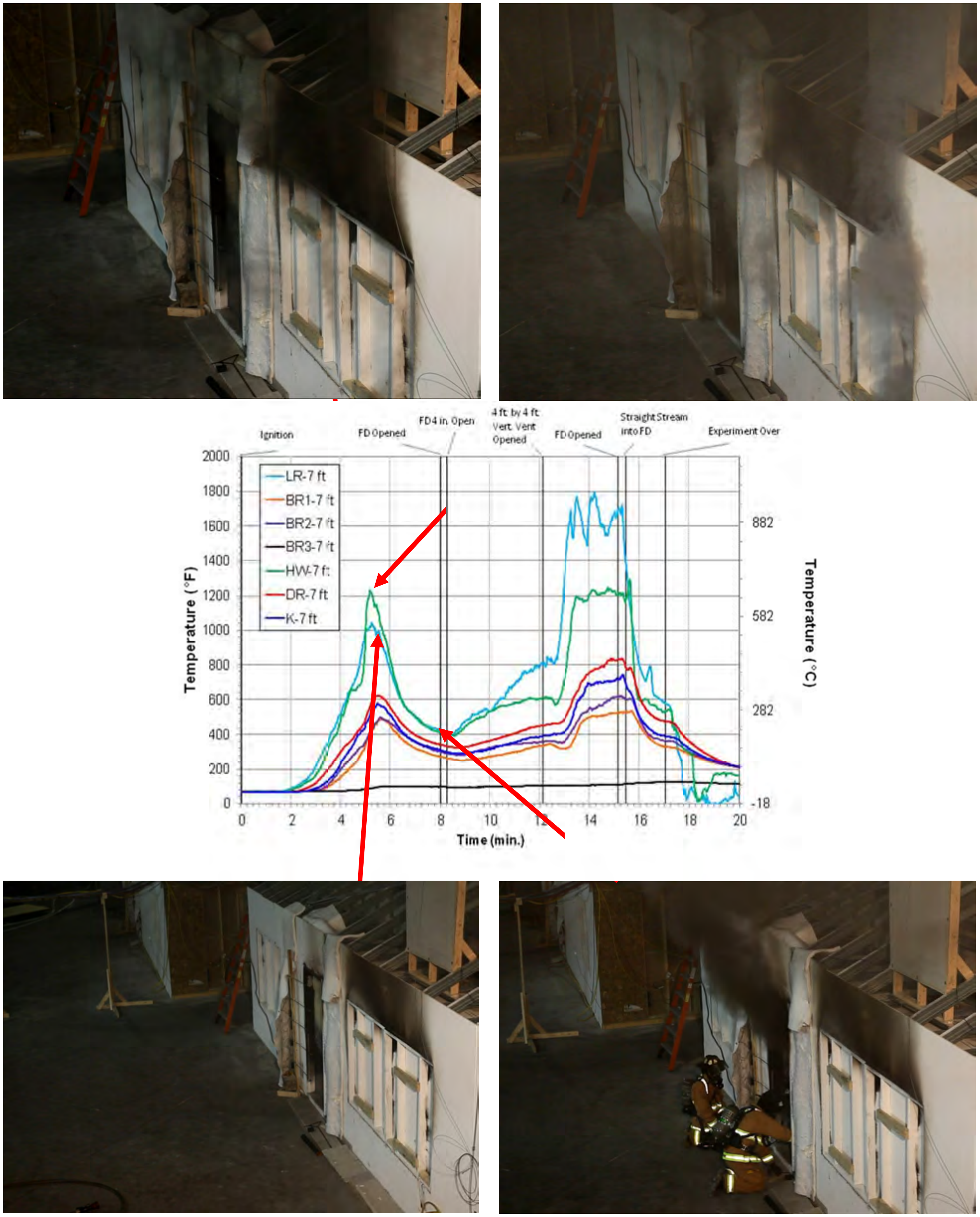


Figure 6.21: Changing smoke conditions

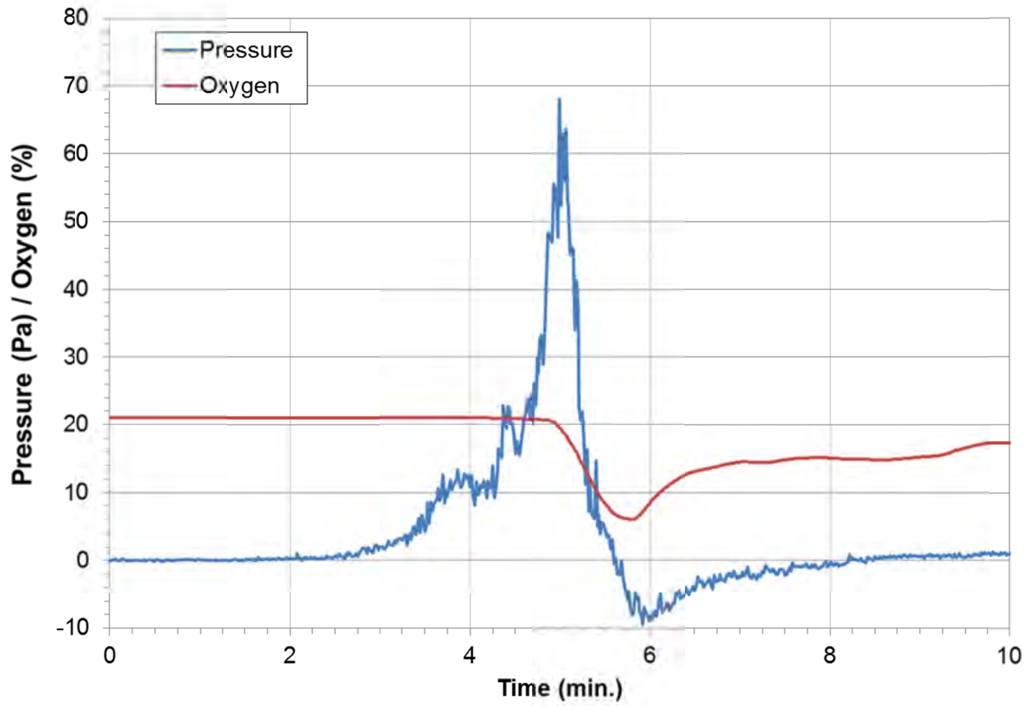


Figure 6.22: Pressure and Oxygen Concentrations that Impact Smoke Showing

6.9. Impact of Shut Door on Victim Tenability and Firefighter Tenability

The most likely place to find a victim that can be rescued is behind a closed door. In every experiment, a victim in the closed bedroom would be tenable and able to function through the length of the experiment and well after fire department arrival. In the open bedroom, this would be a very different story.

When it comes to rescuing occupants, the fire service makes risk-based decisions on the tenability of victims. They assume personal risk if it may save someone in the house. Each of the experiments included one closed bedroom next to an open bedroom. This allowed for the comparison of tenability of two side-by-side bedrooms; one with an open door and another with the door closed. The assumption here is that the occupant already had a closed door, or they closed it when the fire was discovered.

Table 6.1 and Table 6.2 show the times to carbon monoxide and temperature untenability for occupants in the open and closed bedrooms at 3 ft. above the floor in both houses. In every experiment, a victim in the closed bedroom would have been tenable and able to function throughout the experiment and well after fire department arrival. In the open bedroom, there would be a very different story; most victims would be unconscious, if not deceased, prior to fire department arrival or as a result of fire ventilation actions.

Table 6.1: One-Story CO and Temperature Tenability at 3 ft. above the Floor in the Open and Closed Bedrooms

Experiment	Open Bedroom CO (mm:ss)	Closed Bedroom CO (mm:ss)	Open Bedroom Temp (mm:ss)	Closed Bedroom Temp (mm:ss)	Firefighter Arrival
1	05:54	N/A	07:00	N/A	8:00
3	05:53	N/A	07:17	N/A	8:00
5	Equipment Malfunction	N/A	05:57	N/A	8:00
7	07:04	N/A	06:18	N/A	8:00
9	06:06	N/A	16:16	N/A	6:00
11	06:11	N/A	07:29	N/A	6:00
13	11:54	N/A	N/A	N/A	10:00
15	05:51	19:33	04:58	N/A	6:00
17	29:04	N/A	29:13	N/A	24:00

Table 6.2: Two-Story CO and Temperature Tenability at 3 ft. above the Floor in the Open and Closed Bedrooms

Experiment	Open Bedroom CO (mm:ss)	Closed Bedroom CO (mm:ss)	Open Bedroom Temp (mm:ss)	Closed Bedroom Temp (mm:ss)	Firefighter Arrival
2	11:46	N/A	07:34	N/A	10:00
4	13:22	N/A	09:04	N/A	10:00
6	12:42	N/A	08:23	N/A	10:00
8	12:35	N/A	08:34	N/A	10:00
12	10:50	N/A	07:31	N/A	8:00
16	18:54	32:14	27:05	N/A	27:00

NOTE: Experiments 10 and 14 were removed because the open bedroom was the fire room.

6.10. Softening the Target

Applying water to the fire as quickly as possible, regardless of where it is from, can make conditions in the entire structure better. Even a small amount of water has a positive impact on conditions within the house, increasing the potential for victim survivability and firefighter safety.

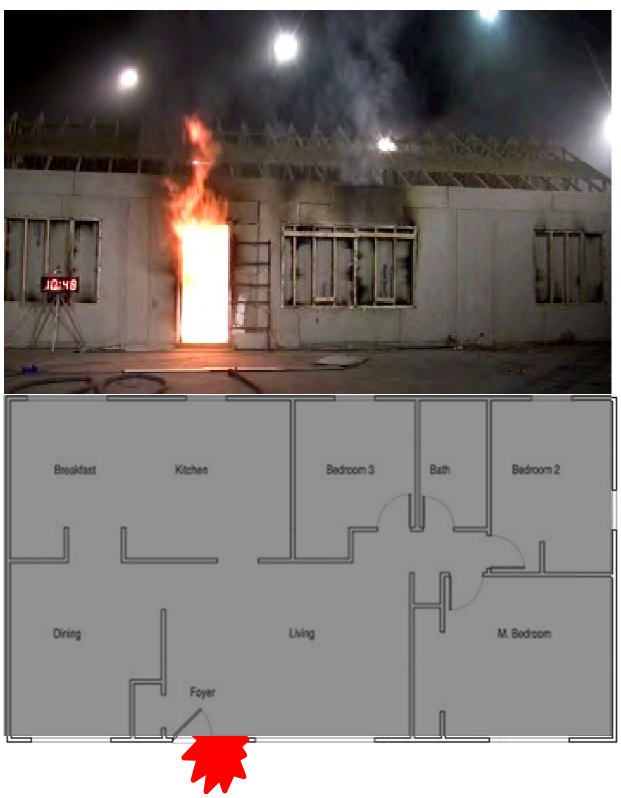
During these experiments, water was applied into a door or window with fire coming from it or with access to the fire from the exterior for approximately 15 seconds. This included stopping water flow for 60 seconds while conditions were monitored. This small amount of water had a positive impact on conditions within the houses, increasing the potential for victim survivability and firefighter safety. If a firefighter crew moved in and continued to suppress the fire, conditions would have improved that much faster.

During size-up, firefighter crews should assess the fastest and safest way to apply water to the fire. This may include applying water through a window, through a door, from the exterior, or from the interior. Using the ranch house as an example, the first line can be positioned in a variety of places based on the location of the fire, what is determined from the size-up, staffing, and many other considerations. If getting water on the fire is a top priority, then the discussion becomes narrowed. Assuming the hoseline approaches from side A or the bottom of each figure, then this first example with fire showing from the front door would have water applied through the front door. While this is not the traditional approach of fighting the fire from the unburned to the burned, it will make conditions better faster for victims and firefighters alike.

Example 2, with fire showing from the living room window, would have water applied through the front window before entering the doorway. While the front door and living room fire are attached in this floor plan, which is most likely not known upon arrival. The front door may not necessarily directly access this room. There could be an entranceway that would require the crew to make it down a hallway to get to the fire, placing the crew in the flow path once they open the door.

Example 3 has fire showing from a bedroom on side A. Applying water through the bedroom window would occur more quickly than navigating the interior of the home, regardless of interior layout or conditions.

Example 4 has smoke showing from the front door and fire showing from a kitchen window on side C. If it can be done quickly, it may be more efficient to apply water from the front door or interior than to stretch a hoseline to the back of the house. If the fire cannot be seen through the open front door and the path to the fire is unknown, then the better choice may be to stretch to the back and put water on the fire through the window, where it can be seen, to reach the seat of the fire.



Experiment 14 in the 2-story house is a good example of softening the target in a situation that is not commonly done in the fire service. Here, fire is showing from the second floor of Side A. (Figure 6.27 and Figure 6.28). The hoseline is typically charged in the front of the house prior to entry, but water is usually not flowed onto the fire prior to entry. However, even if the interior path to the fire is known, flowing water directly onto the fire is faster from the outside than it is from the inside. The visible flames were extinguished in less than 5 seconds; steam did not reduce smoke layer height; and by 15 seconds after water application, the smoke was beginning to lift and conditions were improved.

A common argument against flowing water onto the fire prior to entry is the belief that conditions beyond the fire would be made worse. Data from this experiment showed otherwise. Temperatures were measured in the hallway just outside the room and in the other bedrooms on the second floor, (Figure 6.29). As shown in Figure 6.29, 25 gallons of water directed off of the ceiling of the fire room decreased fire room temperatures from 1792 °F to 632 °F in 10 seconds and the hallway temperature decreased from 273 °F to 104 °F in 10 seconds. Figure 6.30 through Figure 6.33 show the interior conditions as water was applied from the outside.

Figure 6.27: Conditions prior to arrival

Figure 6.28: Water being applied from outside the house

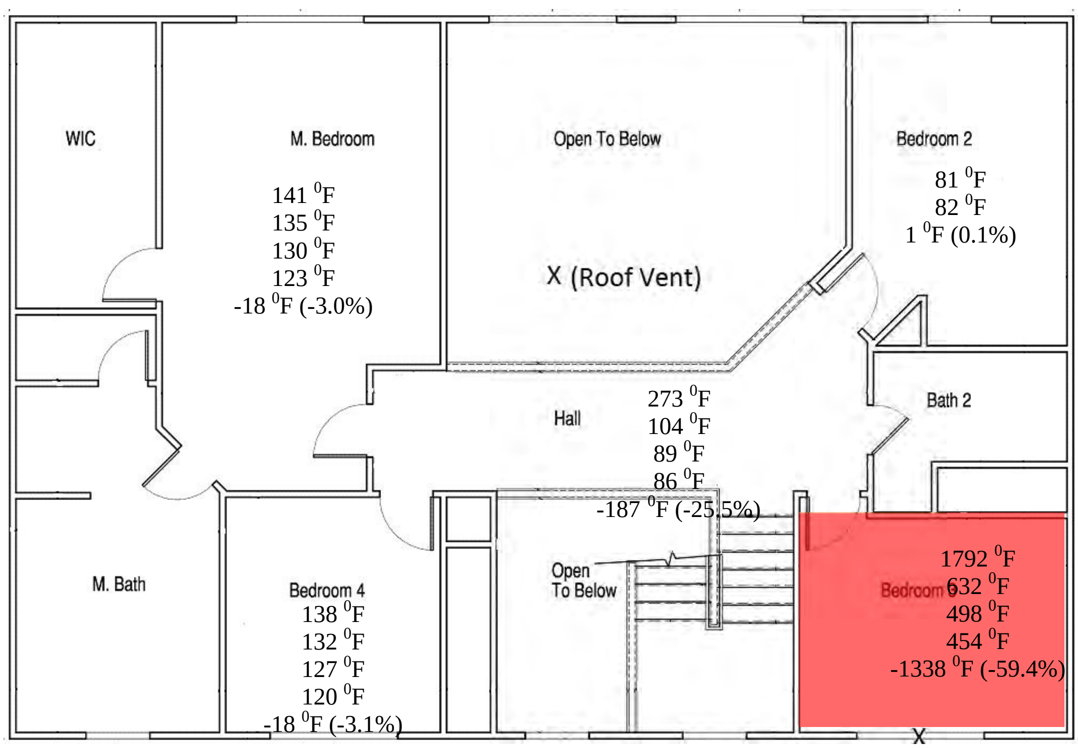


Figure 6.29: Experiment 14, Second Floor, Straight Stream

Figure 6.30. Just before water application

Figure 6.31: Five seconds into water application, visible flame out

Figure 6.32: At end of water application, steam moving to roof vent

Figure 6.33: Fifteen seconds after water, smoke layer lifting

6.11. You Can't Push Fire

You cannot push fire with water. The previous UL ventilation study included the concept of pushing fire in the data analysis. That study generated a lot of discussion, and stories surfaced from well-respected fire service members who had experienced the phenomenon of pushing fire, or had perceived that it had happened. The specific fires recalled by the firefighters were discussed in detail. In many of these situations, the firefighters were in the structure and in the flow path opposite the hoseline. In most cases, the event described occurred while fire attack crews were advancing on the inside, and not while applying water from the outside into a fully developed fire. All of the experiments in this study were designed to examine the operations and the impact of the initial arriving fire service units. It is not suggested that firefighters position themselves in a flow path opposite the hoseline. However, there are times when this may happen so the experience of these firefighters should not be discounted. Also, the experiments did not simulate water being applied from inside the structure by an advancing hoseline. It is understood that this happens on most fires.

During the discussions, four events were identified that could have been witnessed, and have had the appearance of pushing fire:

1) A flow path is changed with ventilation and not water application. When the firefighters are opposite the hoseline, in many cases they entered from a different point than the hoseline and left the door or window open behind them. This flow path is entraining air low, where they are crawling, and hot gases are exiting over their heads. As the fire reacts to the added air, the burning moving over their heads increases and conditions could deteriorate quickly. If an attack crew is preparing to move in or is inside, the experience of the firefighters opposite the hoseline could be blamed on the hoseline. However, the fire was just responding to the air and the added flow path and not to water flow. Often this occurs in close timing of water application and occurs without coordination (Figure 6.34).

Figure 6.34: Heat experienced by search crew because of ventilation no water application

2) A flow path is changed with water. Opening a wide fog changes the flow path or plugs a flow path (Figure 6.35 and Figure 6.36); this can also be accomplished with a straight stream when whipped in a circular pattern (Figure 6.37 through Figure 6.39). This can disrupt the thermal layer and move steam ahead of the line, which is why firefighters do it. If a firefighter is downstream, they may get the impression of pushing fire or elevated heat, especially if they are in the cool inflow of another vent location.

Figure 6.35: Flow path before Water Application

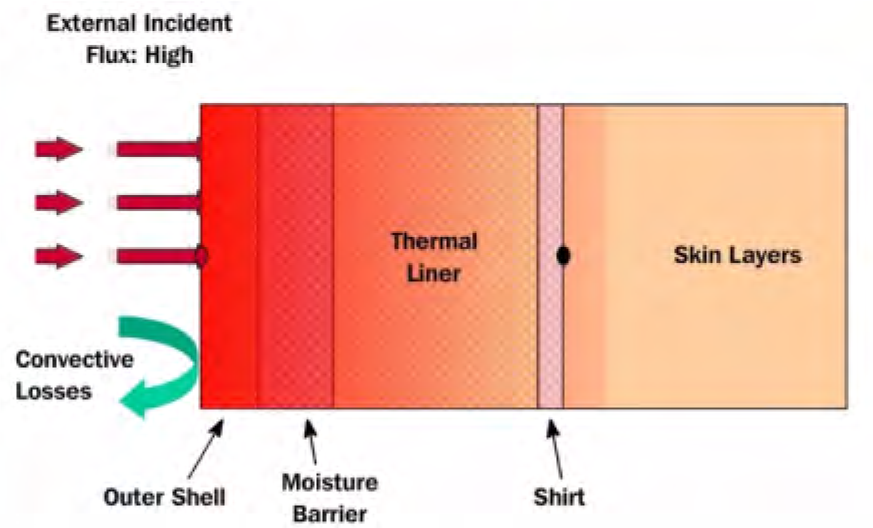
Figure 6.36: Fog Stream Sealing Flow Path

Figure 6.37: Prior to Water

Figure 6.38: Smooth bore being Whipped in a circular pattern blocking flow path out of Fire room

Figure 6.39: Flow path out re-established after Stream was Shut Down

3) Turnout gear becomes saturated with energy and passes through to firefighter. It is important for firefighters to know how their gear protects them. Gear absorbs energy to keep if from getting to the firefighter inside. After the gear has already absorbed what it can, any additional energy can pass through to the low temperature firefighter inside the encapsulation. In some cases, firefighters inside a structure have been absorbing energy for some time. When a hoseline is opened in close proximity to this saturation time, then it may be interpreted that the hoseline caused a rapid heat build-up when, in fact, it could be that their gear was saturated and heat began to pass through.



4) One room is extinguished, which allows air to entrain into another room, causing it to ignite or increase in burning. Certain types of buildings have a layout where rooms are attached in a linear fashion. These are commonly referred to as railroad or shot gun layouts. In these structures, it is possible for multiple rooms to be on fire. Once one room gets suppressed, the ventilation-limited room behind it now has access to oxygen to increase burning. Usually, the hoseline cools several of these rooms at the same time. There may be a case, however, where doorways are offset, and water does not make it to the second room.

Figure 6.40 shows a fire that started in the middle room of a railroad flat structure and spread to the right room because of the air supplied by the open doorway. The left room and the middle room have decreased in temperature due to the lack of oxygen making it back to these rooms. The right room has flashed over and fire is showing out of the doorway.

Figure 6.41shows how conditions change after water is flowed into the right room. The water decreases the burning and allows air to be entrained into the ventilation-limited middle room, allowing it to flashover. This could be interpreted as the hoseline pushing the fire to the middle room. However, it is flow paths that explain the fire dynamics, and not the water flow that caused the middle room to flashover.

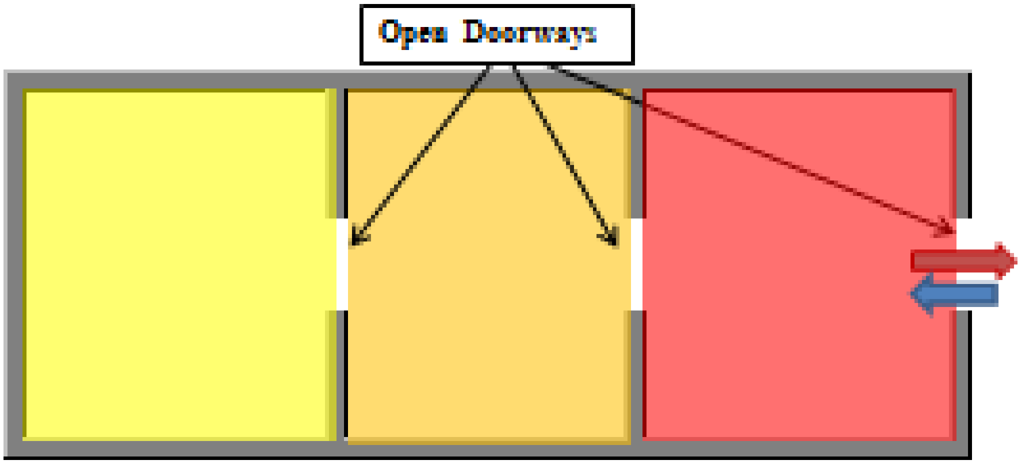


Figure 6.40: Rail Road Flat Fire before Water Application

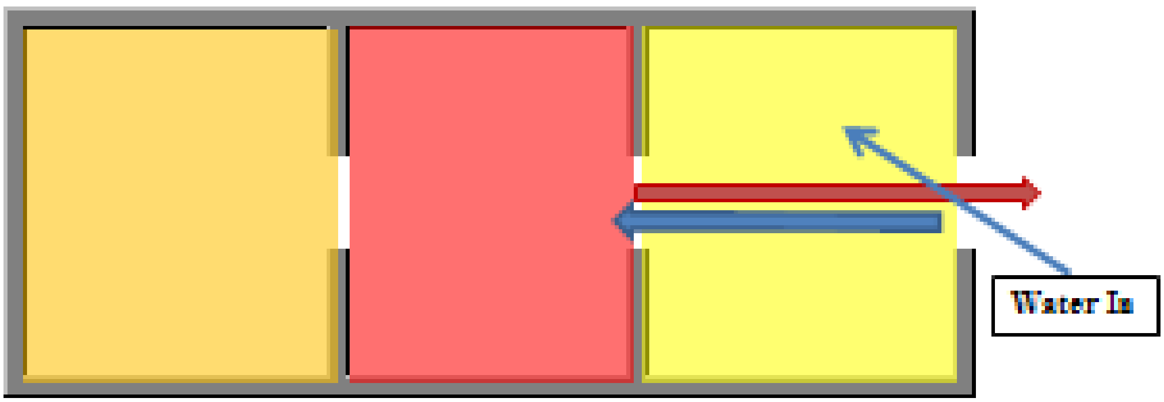


Figure 6.41: Rail Road Flat Fire after Water Application

6.12. Big volume, apply water to what is burning

In larger volume spaces, such as the family room/great room in the 2-story house, it is important to put water on what is burning. In modern floor plans with high ceilings and great rooms, there is a very large volume. Water application in these structures is not the same as a legacy home with smaller rooms and eight foot ceilings. Much of the water applied to a flashover condition in a small room will knock down a burning surface and the gases will cool as the water is converted to steam. In modern floor plans, a stream of water can end up several rooms away from the room that has flashed over. In order to have the biggest impact, water should be directed onto burning objects if possible.

The same open floor plan that can allow water to flow beyond the fire room can also allow for suppression of a fire that is several rooms away. In open floor plan houses, the reach of a hose stream can be beneficial, whereas in an older, divided home, it may not be as useful. In the 2-story floor plan, water can be applied into any room from more than 20 ft. away with some open lines of sight longer than 35 ft. (Figure 6.42). This allows the fire to be knocked down from a safer distance, without needing to be in the room or right next to the room to begin suppression. In addition, every bedroom on the second floor could have water flowed into it from the first floor before proceeding up the stairs.

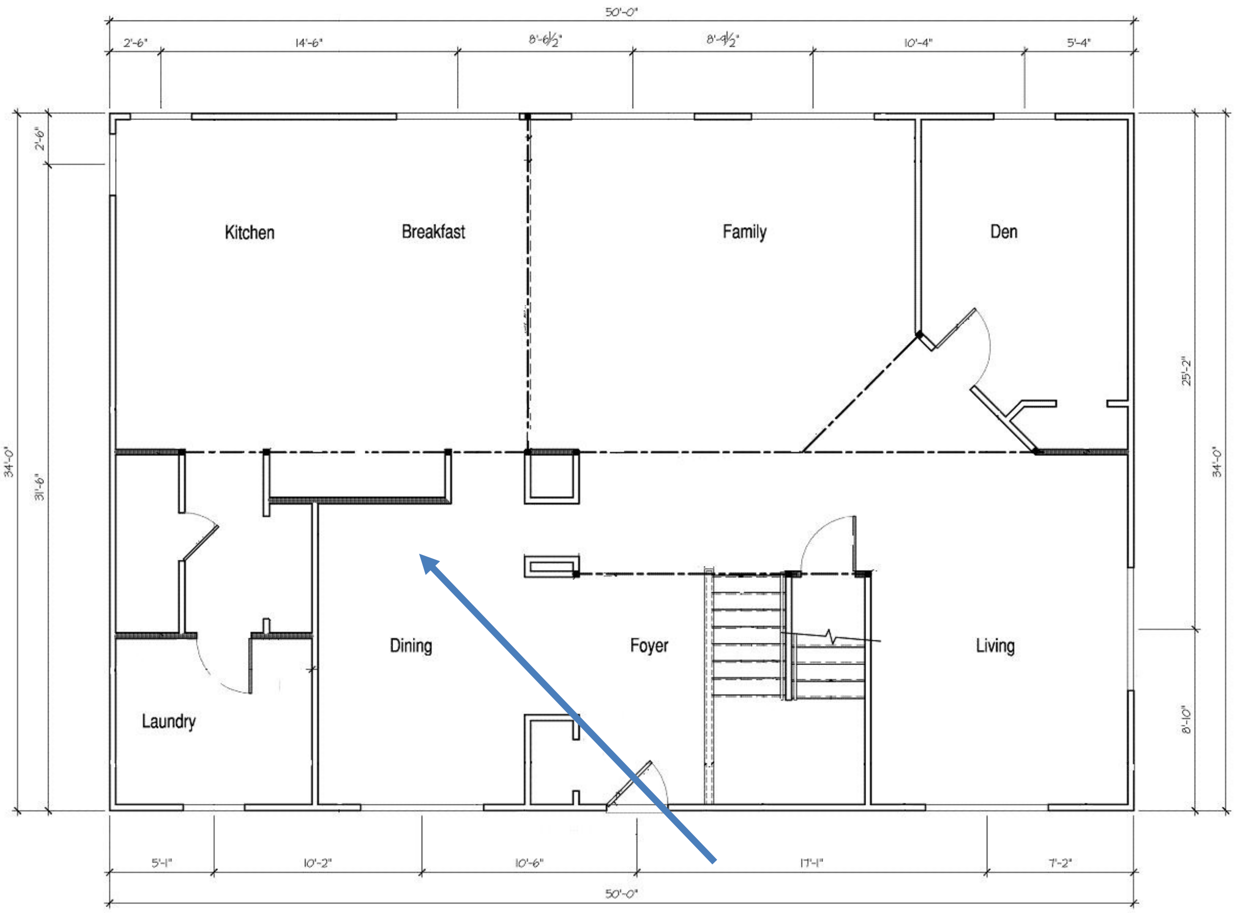


Figure 6.42: 2-story open floor plan with hose stream reaches

In Experiment 16, two rooms (Kitchen and Family Room) were involved in fire when water was applied. As flames were venting from the family room window, water was intentionally directed toward the kitchen fire for 15 seconds. While this slightly cooled the kitchen area, the family room fire was still fully developed and maintaining high temperatures in the remainder of the house. Once the stream was directed into the family room, the temperatures in the whole house cooled significantly.

7. 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 17 full-scale residential structure fires to examine this change in fire behavior and the impact of firefighter ventilation and suppression tactics. This fire research project developed the experimental data that is needed to quantify the fire behavior associated with these scenarios, and result in the immediate development of the necessary firefighting ventilation practices to reduce firefighter death and injury.

The fuel loads acquired for these experiments produced approximately 9 MW to 10 MW, which was enough energy to create the necessary ventilation-limited conditions in both houses. The bedrooms and living rooms were loaded to between 2 lb/ft^2 and 4 lb/ft^2 and the kitchens were loaded to between 4 lb/ft^2 and 5 lb/ft^2. These could be considered low compared to actual homes, which have more clutter. Despite this, ventilation-limited conditions were created, and additional loading would just allow the fire to burn longer. Additionally, the heat release rate and total heat released from the living room fuel load is within 10% of that of the fuel load used in the previous study on horizontal ventilation, such that the experiments can be compared for various horizontal and vertical ventilation scenarios. Doubling the volume of the fire room by raising the ceiling height while maintaining the same amount of ventilation does not significantly slow down the time to flashover due to the rapid increase in heat release rate that occurs prior to flashover. Each room fire experiment transitioned to flashover in 5:00 to 5:30 after ignition.

Limiting the air supply to the fire was found to be an important consideration for the ventilation-limited fires in this series of experiments. The experiments where the door was opened to allow access and then closed the width of a hoseline slowed the growth of the fire, which maintained lower interior temperatures and better gas concentrations than if the door were opened completely. This allows for fire department intervention while keeping the fire at a lower heat release rate, which makes it easier to extinguish.

There was not a ventilation hole size used (4 ft. by 4 ft. or 4 ft. by 8 ft.) in these experiments that slowed the growth of the fire. All vertical ventilation holes created flashover and fully developed fire conditions more quickly. Once water was applied to the fire, however, the larger the hole was, and the closer it was to the fire, allowed more products of combustion to exhaust out of the structure, causing temperatures to decrease and visibility to improve.

Ventilating over the fire is the best choice if your fire attack is coordinated. If a ventilation-limited fire receives air, it will increase in size. Additionally, the closer the source of the air to the seat of the fire, the quicker it will increase in size. If you ventilate in coordination with fire attack (the hose stream is removing more energy than is being created), it does not matter where you ventilate, but the closer to the seat of the fire, the more efficient the vent will be in removing heat and smoke, which will improve conditions for the remainder of the operations taking place on the fire ground. Ventilating remote from the fire can be effective under some circumstances. If the fire is in a room that is connected to the rest of the house by a doorway, ventilating the roof outside of that room could allow for smoke to be cleared from the rest of the house. However, as air is entrained to the room, the fire will increase in size, while visibility may improve in the flow path leading from the air inlet to the fire room. The reason the fire does not grow uncontrolled is because the doorway becomes the limiting factor in keeping the fire contained. Once fuel outside of that doorway ignites, such as a bedroom fire extending to living room furniture, the heat release rate can increase quickly and overcome the temporary benefit of the remote vertical ventilation hole. Vertical ventilation remote from the fire can provide a visibility benefit but the fire and temperatures in the area of the fire are increasing.

Flow paths and timing are very important to understanding fire dynamics and the impact of firefighter tactics on the fire ground. The closer the air is provided to the seat of the fire, the faster it can intensify. Several experiments showed that fire showing does not mean that the fire is vented; it means it is venting and still remains ventilation-limited. In every experiment, the fire was burning outside of the window or roof ventilation hole because there is no air available inside to burn. It is not possible to make statements about the effectiveness of ventilation unless you include timing while understanding that the longer the fresh air has to travel, the slower the fire will react to it. However the larger the flow path to catch firefighters in between where the fire is receiving fresh air and where the fire is exhausting to the low pressure behind them the greater chance that a rapid change can result in a negative outcome.

The fire service's workplace has changed and one of several significant factors is home furnishings. As home furnishings have evolved over decades to be made of synthetic materials, the heat release rates generated by home furnishings have increased significantly. This change speeds up the stages of fire development, creating an increased potential for ventilation-limited fire conditions prior to fire department arrival. In these experiments, it took 5 minutes for the modern fuel to transition the one-story house to ventilation-limited conditions while the legacy fuel took approximately 18 minutes. Earlier ventilation-limited conditions make the ventilation tactics of the fire service of utmost importance. Most importantly, the time between ventilation and flashover are 2 minutes for the modern fire and over 8 minutes in the legacy fire. The legacy fire could be described as forgiving as it pertains to ventilation. Poorly timed ventilation or an uncoordinated attack can be made up for prior to flashover because there is 8 minutes to adapt. The time to recover in the modern fire was 2 minutes, or 25% of the legacy time.

Tenability was exceeded in the fire room of every experiment prior to fire department arrival except for the legacy experiment in the one-story house. Behind a closed door is the most likely place to find a victim that can be rescued. Every experiment included one closed bedroom next to an open bedroom. In every experiment, a victim in the closed bedroom was tenable and able to function throughout every experiment and well after fire department arrival. In the open bedroom, there would be a very different story. Most victims would be unconscious, if not deceased, prior to fire department arrival or as a result of fire ventilation actions. The average time to untenability in the open bedroom was 7:30 taking into account temperature and carbon monoxide concentrations, while the closed bedroom did not exceed either of these criteria until well after fire department intervention.

Water was applied to the fire from the exterior during every experiment, in some experiments through the doorway and some through the window. Water was flowed for approximately 15 seconds, delivering 25 gallons of water into the structures. Comparing temperatures just before water application to temperatures 60 seconds after flow was stopped resulted in an average of a 40% decrease in fire room temperatures and a 22% decrease in the temperatures of surrounding rooms. In almost all of the experiments, tenability was improved everywhere in both structures with the application of water into the structure, even in locations downstream of the fire in the flow path. The data demonstrated the potential benefits of softening the target prior to making entry into the structure; the inability to push fire, as fire was never close to being forced from one room to another with a hose stream; and the benefits of applying water to the seat of the fire in a large open volume.

The fire dynamics of home fires are complex and challenging for the fire service. Ventilation is paramount to understand for safe and effective execution of the mission of the fire service to protect life and property. Vertical ventilation is especially important because it requires being positioned above the fire and can have a fast impact on interior fire conditions. This research study developed experimental fire data to demonstrate fire behavior resulting from varied ignition locations and ventilation opening locations in legacy residential structures compared to modern residential structures. This data will be disseminated to provide education and guidance to the fire service in proper use of ventilation as a firefighting tactic that will result in reduction of the risk of firefighter injury and death associated with improper use of ventilation and to better understand the relationship between ventilation and suppression operations.

8. Future Research Needs:

This project built on the previous horizontal ventilation study and a future study on positive pressure ventilation in houses like these would be very beneficial to have the three main types of ventilation studied under similar conditions. Additional vertical ventilation experiments should be conducted where the fire has transitioned to a structure fire. Experiments where the fire is in the attic space prior to fire department arrival and the corresponding impact of vertical ventilation may be assessed under different conditions. Future experiments should examine different suppression flow rates, utilizing various suppression media.

9. Acknowledgements:

The author would like to acknowledge the financial support of the Department of Homeland Security's Assistance to Firefighters Grant Program's Fire Prevention and Safety Grants, in particular the staff members Dave Evans, Ellen Sogolow, Lillian Ricardo and Maggie Wilson for their guidance and expertise.

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:

- Josh Blum, Deputy Chief, Loveland – Symmes (OH) Fire Department
- John Ceriello, Lieutenant, Fire Department of New York
- James Dalton, Coordinator of Research, Chicago Fire Department
- Sean DeCrane, Battalion Chief, Cleveland Fire Department
- Harvey Eisner, Editor, Firehouse Magazine
- Ed Hadfield, Division Chief, City of Coronado (CA) Fire Department
- Bobby Halton, Editor, Fire Engineering Magazine
- Todd Harms, Assistant Chief, Phoenix Fire Department
- Ed Hartin, Fire Chief, Central Whidbey Island Fire Rescue Department

- George Healy, Battalion Chief, Fire Department of New York
- Otto Huber, Fire Chief, Loveland – Symmes (OH) Fire Department
- Dan Madrzykowski, Fire Protection Engineer, National Institute of Standards and Technology
- Mark Nolan, Fire Chief, City of Northbrook (IL)
- David Rhodes, Battalion Chief, Atlanta Fire Department
- David Rickert, Firefighter, Milwaukee Fire Department
- Andy Rick, Firefighter, Lake Forest (IL) Fire Department
- Tim Sendelbach, Editor, Fire Rescue Magazine
- Pete Van Dorpe, Chief of Training, Chicago Fire Department

The author would also like to acknowledge Nicholas Traina, a graduate student at the University of Illinois, for his assistance with the project.

10. Bibliography

Fahy, F., LeBlanc, P., & Molis, J. (2007). *What's Changed in the Past 30 Years.* Quincy: NFPA.

Gann, R. a. (2008). Combustion products and their effects on life safety. In: *The Fire Protection Handbook.* Quincy, MA: NFPA.

ISO 13571. (2012). *Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability in fires.* ISO.

Karter, M. (2012). *Fire Loss in the United States during 2011.* Quincy: NFPA.

Kerber, S. (2010). *Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction.* Northbrook: Underwriters Laboratories.

Kerber, S. (2012). Analysis of Changing Residential Fire Dynamics and its Implications on Firefighter Operational Timeframes. *Fire Technology*, 865-891.

Kerber, S. (2012). Analysis of One and Two-Story Single Family Home Fire Dynamics and the Impact of Firefighter Horizontal Ventilation. *Fire Technology*.

Michael J. Karter, J., & Molis, J. L. (2010). *U.S. Firefighter Injuries - 2009.* Quincy: NFPA.

National Fallen Firefighters Foundation. (2005). *National Fire Service Research Agenda Symposium.* Emmitsburg: NFFF.

National Firefighter Near Miss Reporting System. (2009). *Lightweight construction Reports.* Washington D.C.: IAFC.

NFPA. (2013). *NFPA 1981: Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting.* Quincy, MA: National Fire Protection Association.

NIOSH. (1998). *Commercial Structure Fire Claims the Life of One Fire Fighter—California.* Morgantown: NIOSH.

NIOSH. (2005). *Career Fire Fighter Dies and Two Career Captains are Injured While Fighting Night Club Arson Fire - Texas.* Morgantown: NIOSH.

NIOSH. (2008). *A Volunteer Mutual Aid Captain and Fire Fighter Die in a Remodeled.* Morgantown: NIOSH.

NIOSH. (2008). *Volunteer Fire Fighter and Trapped Resident Die and a Volunteer Lieutenant is Injured following a Duplex Fire - Pennsylvania.* Morgantown: NIOSH.

NIOSH. (2009). *Nine Career Fire Fighters Die in Rapid Fire Progression at Commercial Furniture Showroom – South Carolina.* Morgantown: NIOSH.

NIOSH. (2010). *NIOSH Alert: Preventing Deaths and Injuries of Fire Fighters using Risk Management Principles at Structure Fires.* Morgantown: NIOSH.

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 A. 1 provides a set of temperatures commonly experienced during firefighting operations and information on the human and equipment response. Table A. 2 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 A. 1: 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.

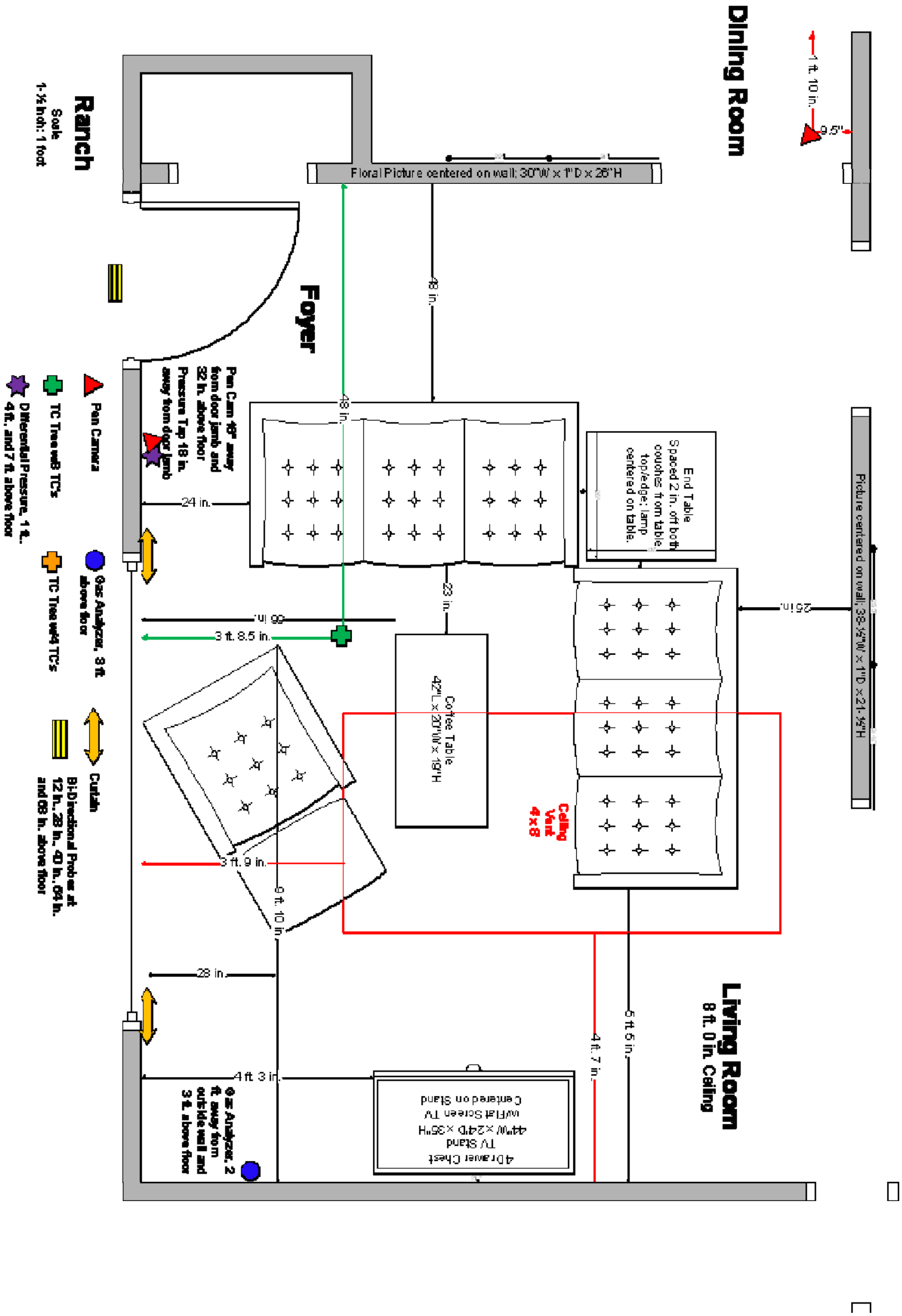
Table A. 2: Carbon Monoxide Firefighter Reference Table 1, 2, 3

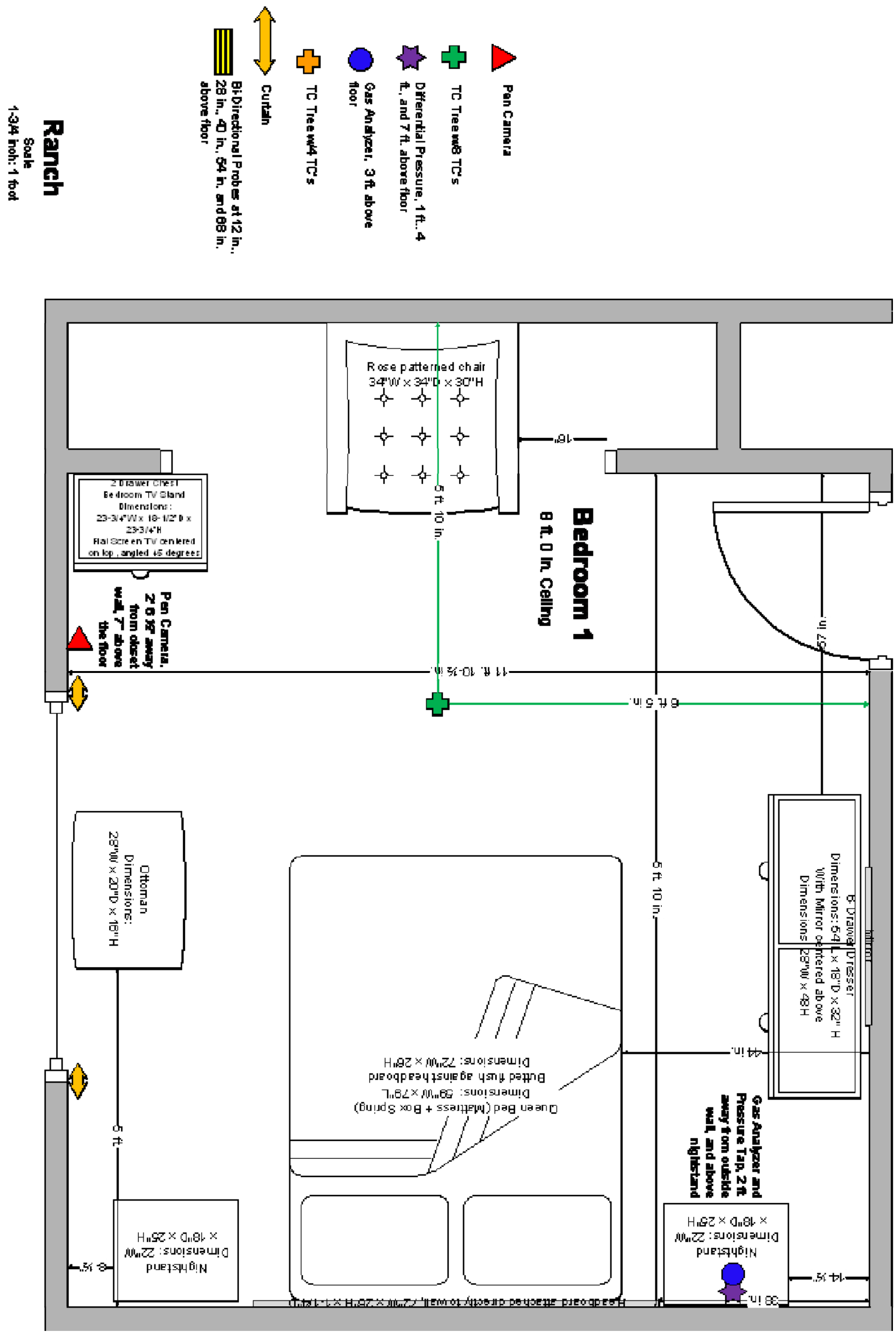
Concentration	Common Symptoms	Duration of Exposure
35 ppm (0.0035 %)	None	<= 8 hours
150 ppm (0.0150 %)	Mild headache	2 – 3 hours
400 ppm (0.04 %)	Headache/nausea	1 – 2 hours
800 ppm (0.08 %)	Headache/nausea/dizziness Progressing to unconsciousness	45 minutes 2 hours
6400 ppm (0.64 %)	Headache/nausea/dizziness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

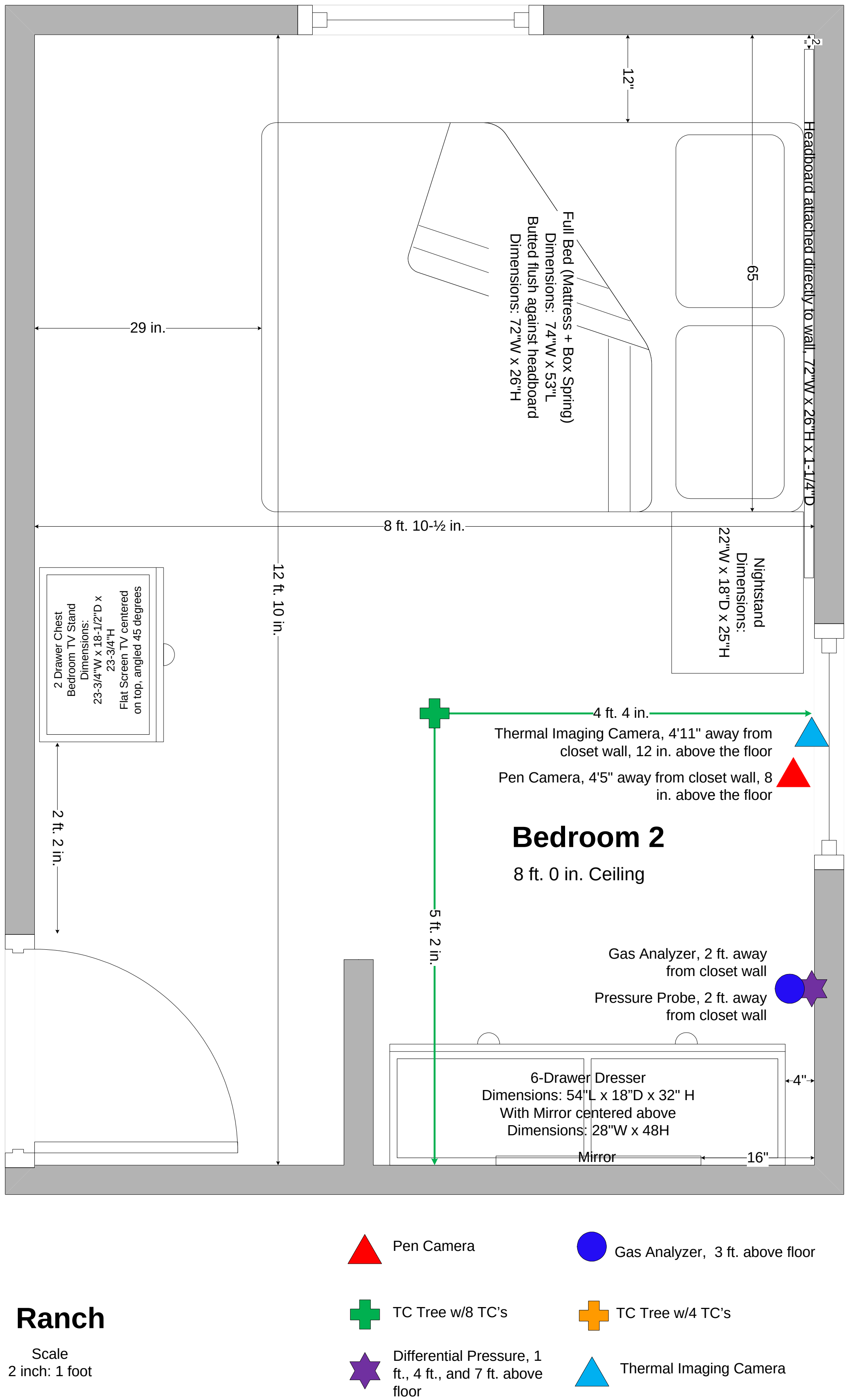
References:

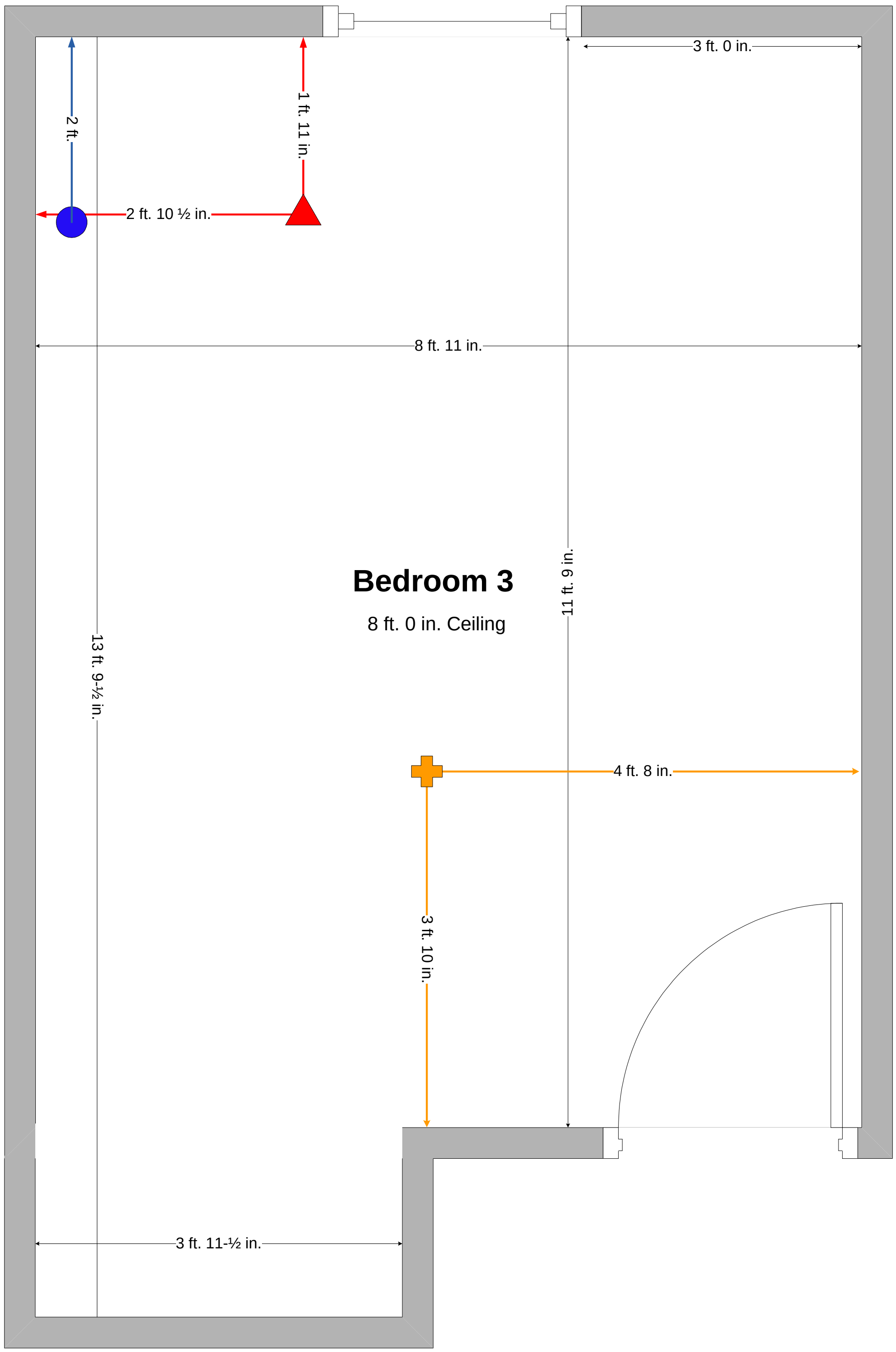
1. Delagi, Robert, “A CO Emergency: Whose Call Is It, Anyway?”, *Fire Engineering Magazine*, October 2007.
2. Henry CR, Satran D, Lindgren B, Adkinson C, Nicholson CI, Henry TD, MD (2006). "Myocardial Injury and Long-term Mortality Following Moderate to Severe Carbon Monoxide Poisoning". *JAMA* **295**: 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 Floor Plans




Pen Camera
TC Tree w/8 TCs
Differential Pressure, 1 ft., 4 ft., and 7 ft. above floor
Gas Analyzer, 3 ft. above floor
TC Tree w/4 TCs
Curtain
Bi-Directional Probes at 12 in., 28 in., 40 in., 54 in. and 68 in. above floor
Ranch
Scale
1-3/4 inch: 1 foot
Bedroom 1
8 ft. 0 in. Ceiling
Rose patterned chair
34"W x 34"D x 30"H
2 Drawer Chest
Bedroom TV Stand
Dimensions:
23-3/4"W x 18-1/2"D x 23-3/4"H
Flat Screen TV centered on top, angled 45 degrees
Pen Camera, 2' 6 1/2" away from closet wall, 7' above the floor
Ottoman
Dimensions:
28"W x 20"D x 18"H
Queen Bed (Mattress + Box Spring)
Dimensions: 59"W x 79"L
Butted flush against headboard
Dimensions: 72"W x 26"H
Headboard attached directly to wall, 72"W x 26"H x 1-1/4"D
6-Drawer Dresser
Dimensions: 64"L x 18"D x 32"H
With Mirror centered above
Dimensions 28"W x 48"H
Mirror
Gas Analyzer and Pressure Tap, 2 ft away from outside wall, and above nightstand
Nightstand
Dimensions: 22"W x 18"D x 25"H
11 ft. 10-½ in.
6 ft. 5 in.
5 ft. 10 in.
27 in.
44 in.
14-½"
38 in.
8-½"
5 ft.
18"


12"
Headboard attached directly to wall. 72"W x 26"H x 1-1/4"D
65
Full Bed (Mattress + Box Spring)
Dimensions: 74"W x 53"L
Butted flush against headboard
Dimensions: 72"W x 26"H
29 in.
8 ft. 10-½ in.
12 ft. 10 in.
2 Drawer Chest
Bedroom TV Stand
Dimensions:
23-3/4"W x 18-1/2"D x
23-3/4"H
Flat Screen TV centered
on top, angled 45 degrees
Nightstand
Dimensions:
22"W x 18"D x 25"H
4 ft. 4 in.
Thermal Imaging Camera, 4'11" away from
closet wall, 12 in. above the floor
Pen Camera, 4'5" away from closet wall, 8
in. above the floor
Bedroom 2
8 ft. 0 in. Ceiling
2 ft. 2 in.
5 ft. 2 in.
Gas Analyzer, 2 ft. away
from closet wall
Pressure Probe, 2 ft. away
from closet wall
6-Drawer Dresser
Dimensions: 54"L x 18"D x 32" H
With Mirror centered above
Dimensions: 28"W x 48H
4"
Mirror
16"
Pen Camera
Gas Analyzer, 3 ft. above floor
TC Tree w/8 TC's
TC Tree w/4 TC's
Differential Pressure, 1
ft., 4 ft., and 7 ft. above
floor
Thermal Imaging Camera
Ranch
Scale
2 inch: 1 foot



Pen Camera

Gas Analyzer, 3 ft. above floor

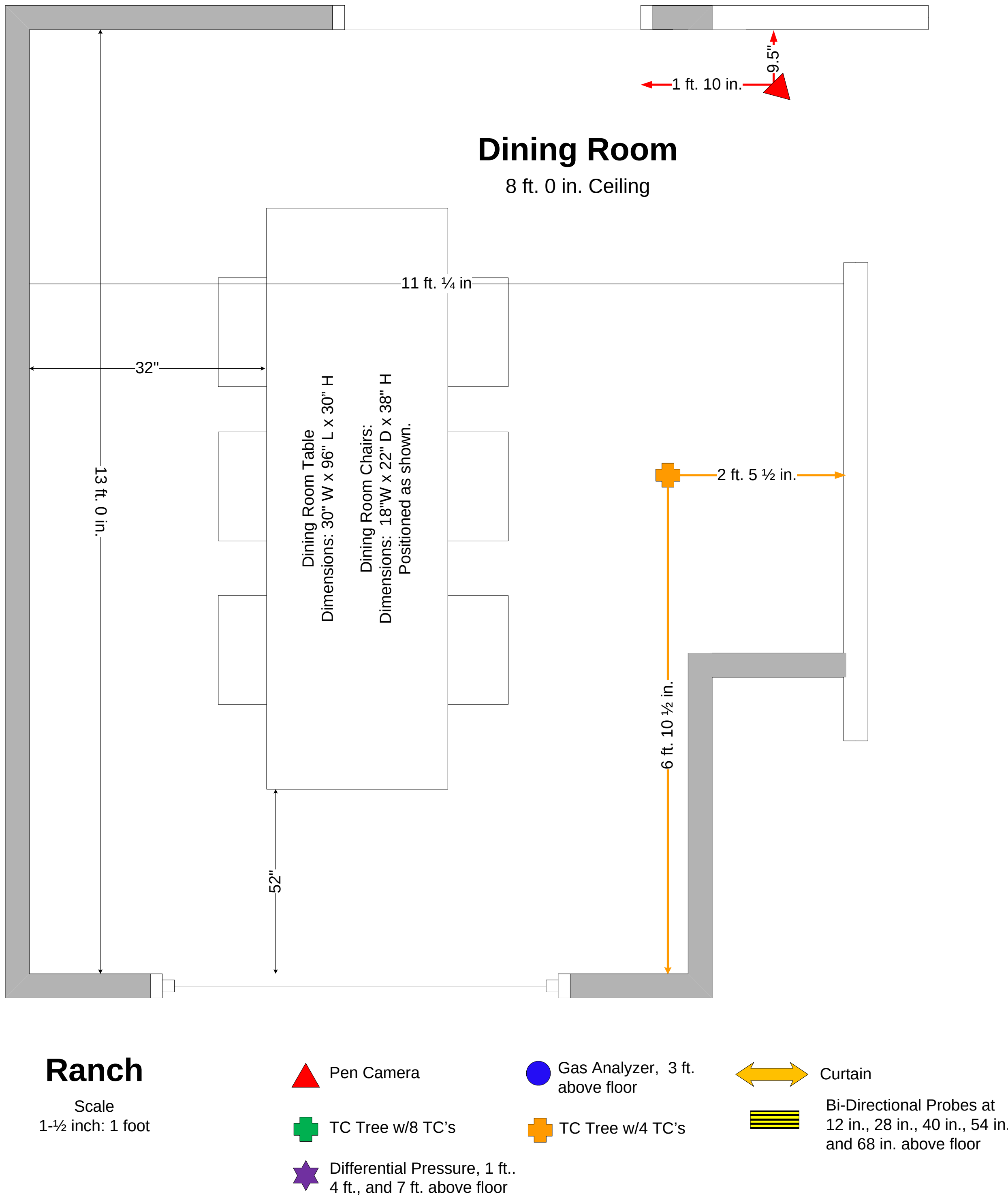
Ranch

Scale
2 inch: 1 foot

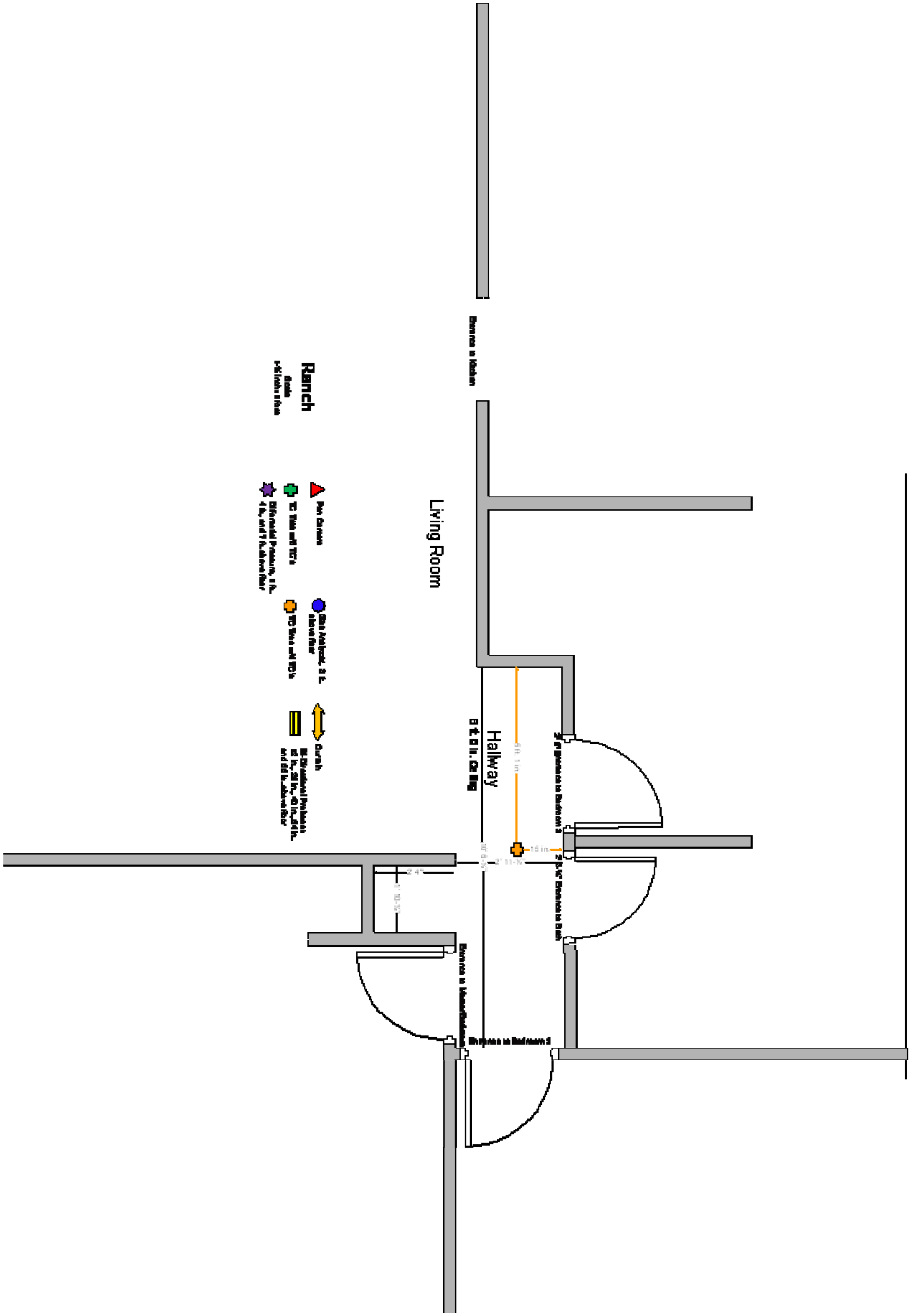
TC Tree w/8 TC's

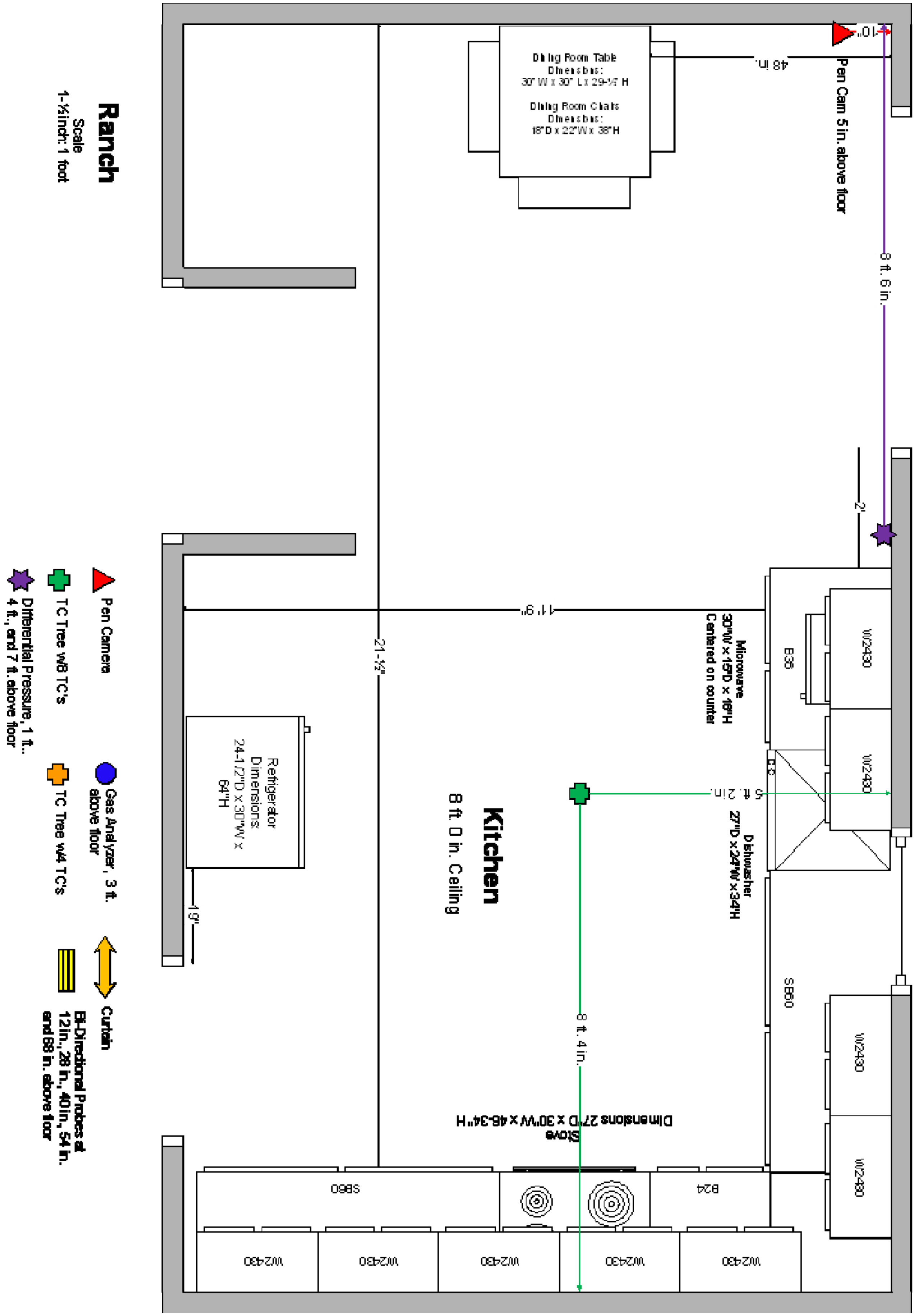
TC Tree w/4 TC's

Differential Pressure, 1 ft.. 4 ft., and 7 ft. above floor

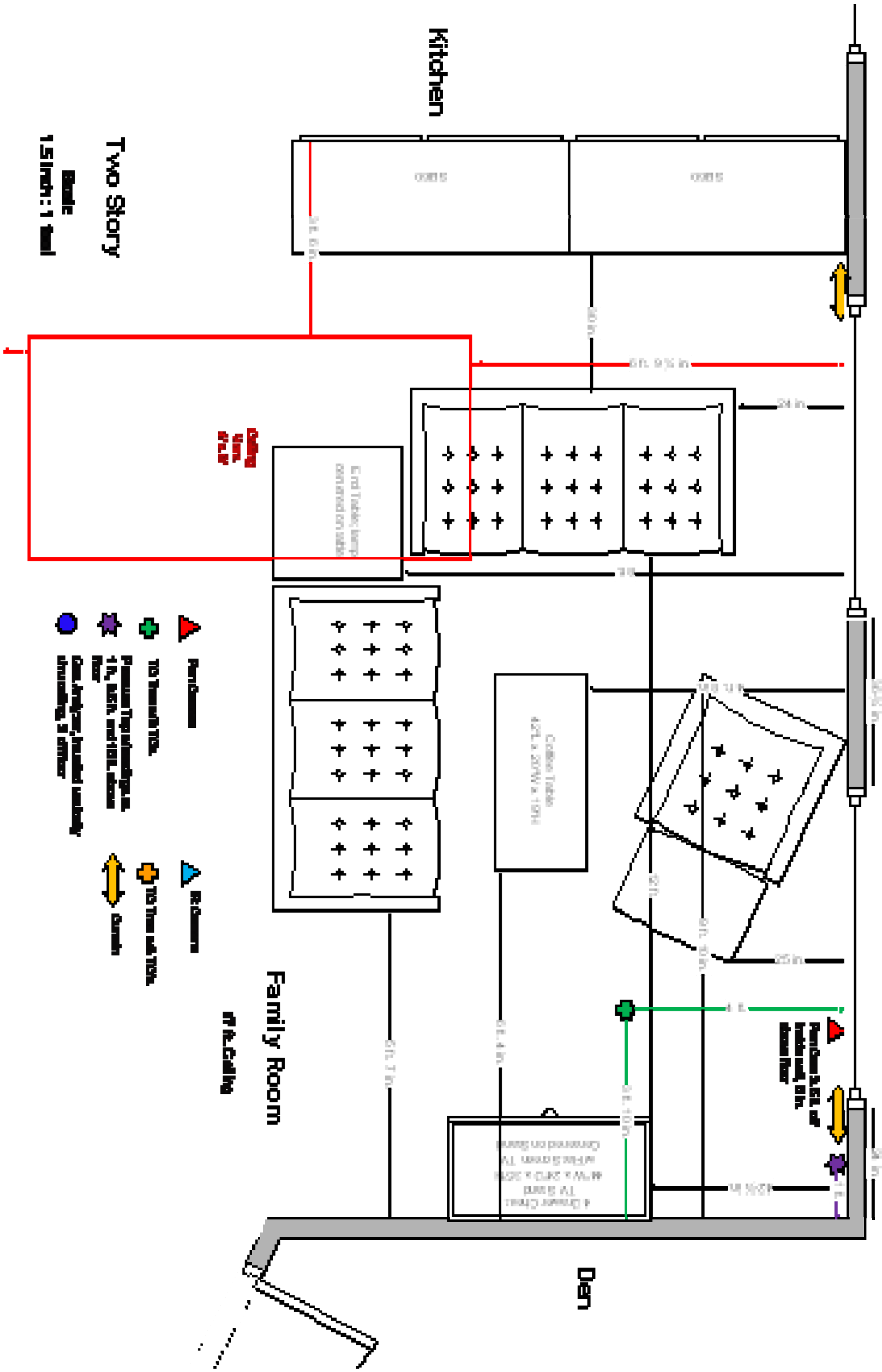


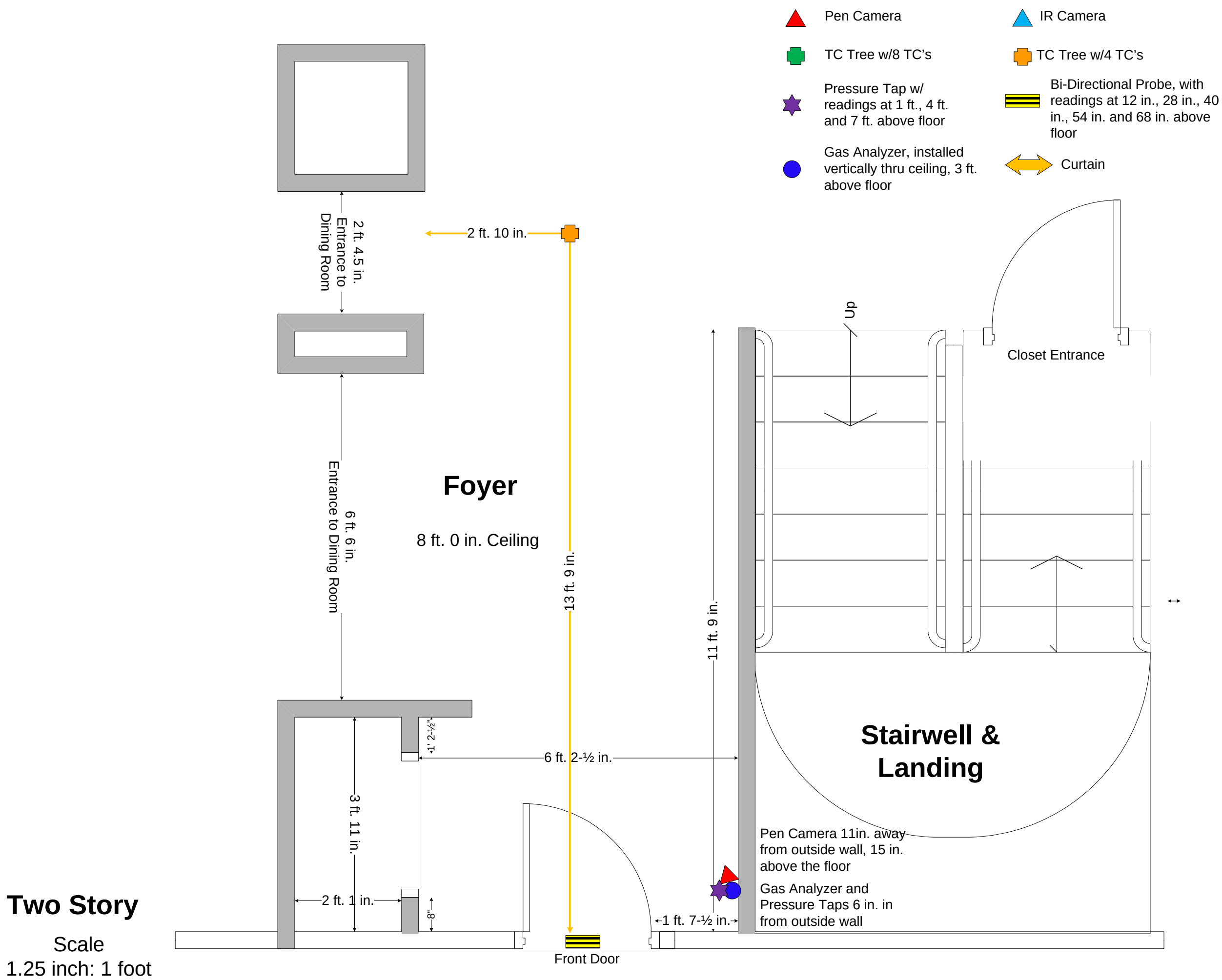
Dining Room
8 ft. 0 in. Ceiling
1 ft. 10 in.
9.5"
11 ft. ¼ in
32"
13 ft. 0 in.
Dining Room Table
Dimensions: 30" W x 96" L x 30" H
Dining Room Chairs:
Dimensions: 18"W x 22" D x 38" H
Positioned as shown.
2 ft. 5 ½ in.
6 ft. 10 ½ in.
52"
Ranch
Scale
1-½ inch: 1 foot
Pen Camera
Gas Analyzer, 3 ft. above floor
Curtain
TC Tree w/8 TC's
TC Tree w/4 TC's
Bi-Directional Probes at 12 in., 28 in., 40 in., 54 in. and 68 in. above floor
Differential Pressure, 1 ft.. 4 ft., and 7 ft. above floor

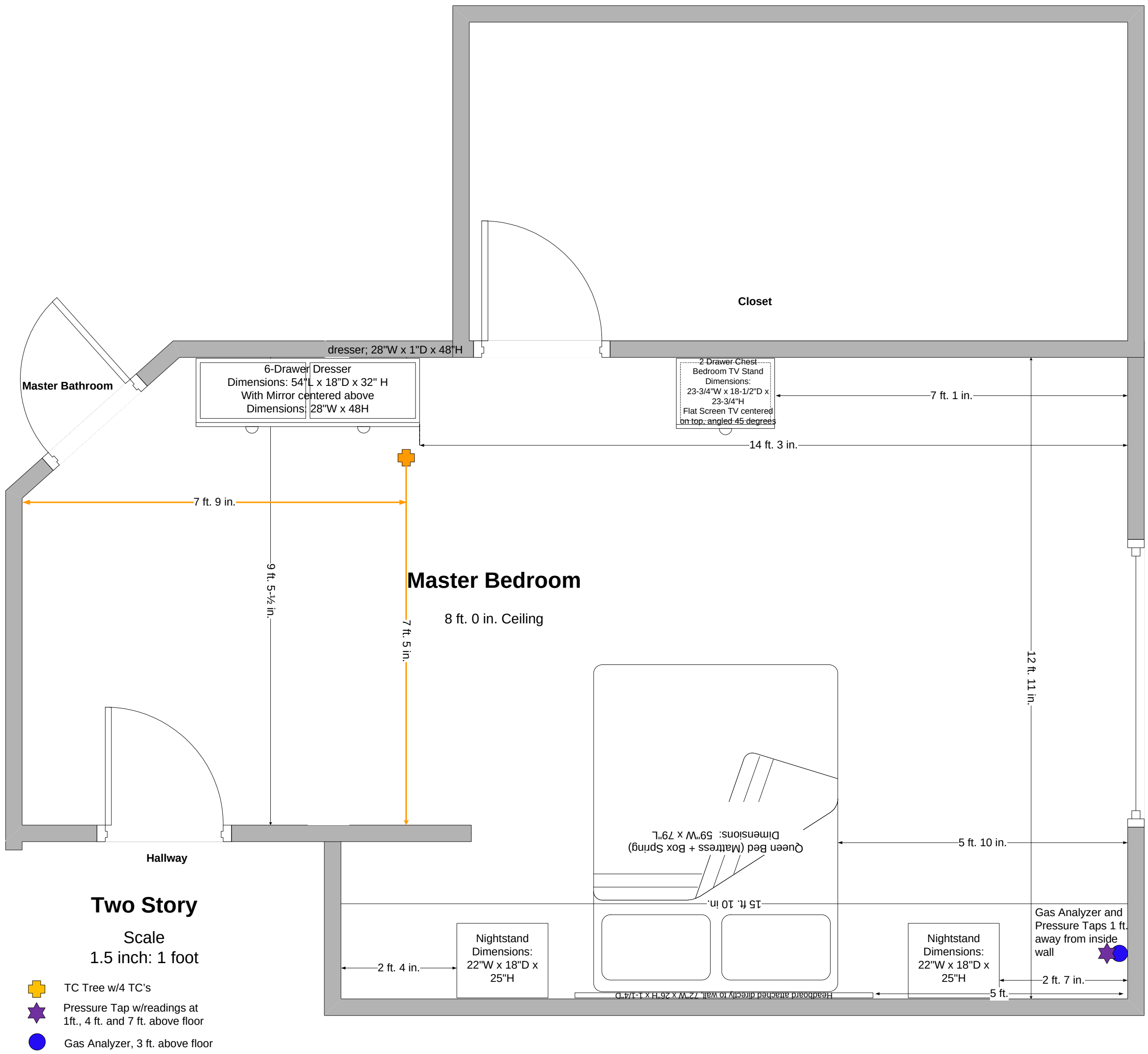

Ranch
Living Room
Hallway

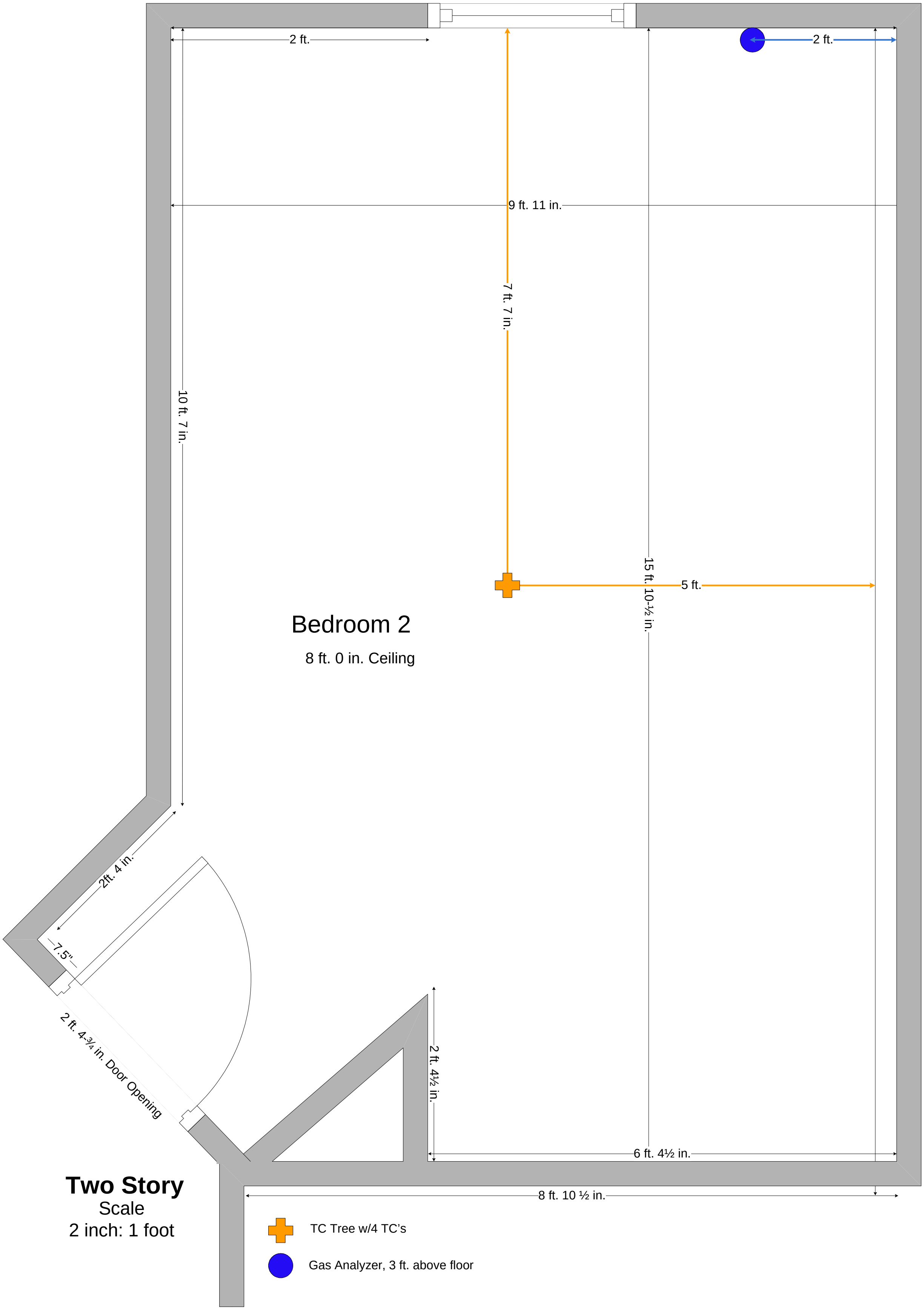

Ranch
Scale
1-½inch: 1 foot
Kitchen
8 ft. 0 in. Ceiling
Dining Room Table
Dimensions:
30" W x 30" L x 29-½" H
Dining Room Chairs
Dimensions:
18"D x 22"W x 38"H
Pen Cam 5 in. above floor
48 in.
10"
8 ft. 6 in.
2'
11'9"
21-½"
19"
Microwave
30"W x 15"D x 16"H
Centered on counter
Dishwasher
27"D x 24"W x 34"H
Refrigerator
Dimensions
24-1/2"D x 30"W x
64"H
Stove
Dimensions 27"D x 30"W x 48-34"H
8 ft. 4 in.
W2430
B36
SB60
B24
Pen Camera
TC Tree w/8 TC's
Differential Pressure, 1 ft.,
4 ft., and 7 ft. above floor
Gas Analyzer, 3 ft.
above floor
TC Tree w/4 TC's
Curtain
Bi-Directional Probes at
12in., 28 in., 40in., 54 in.
and 68 in. above floor

Appendix C: Detailed Two-Story Floor Plans

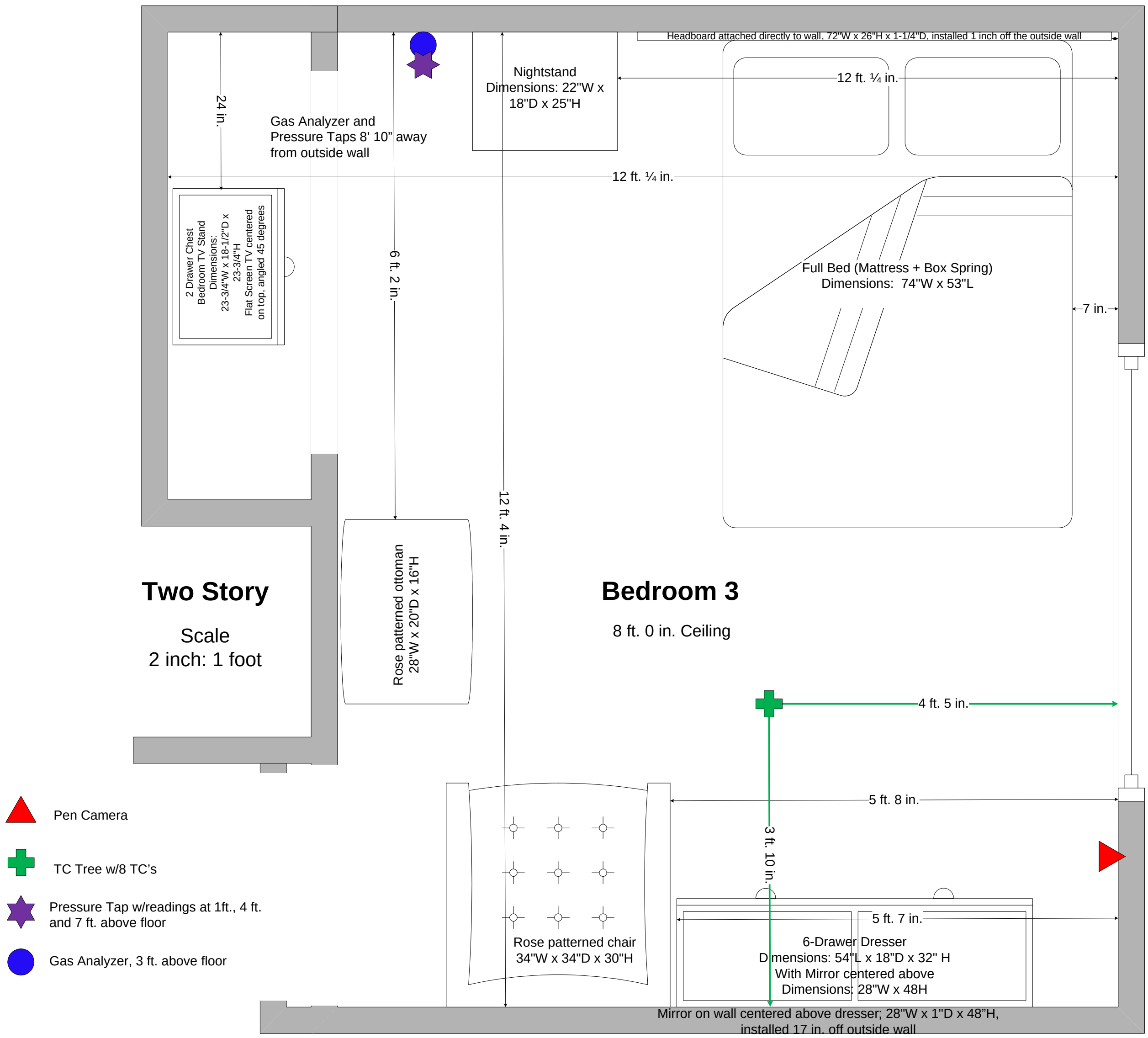


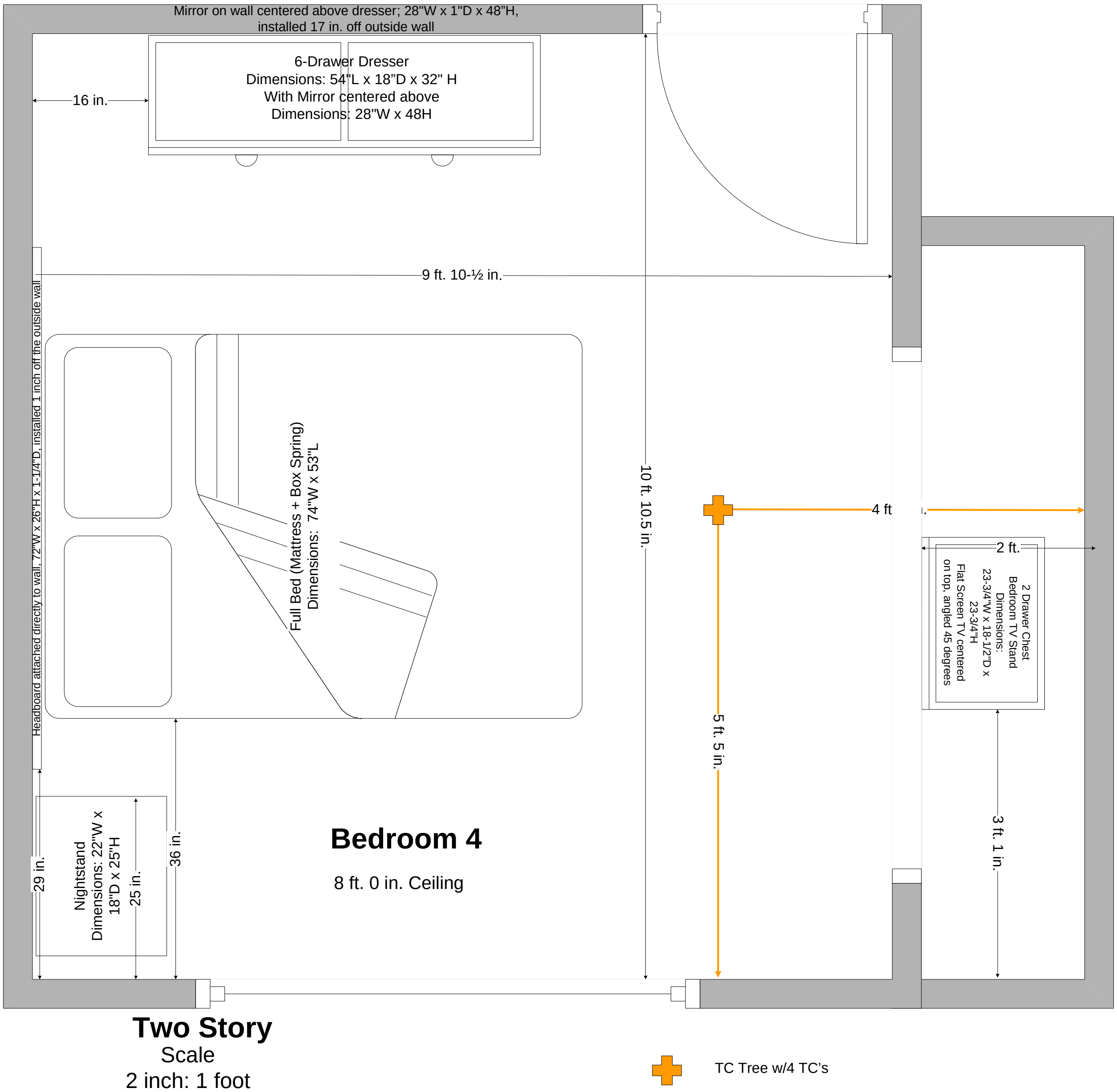

Pen Camera
IR Camera
TC Tree w/8 TC's
TC Tree w/4 TC's
Pressure Tap w/ readings at 1 ft., 4 ft. and 7 ft. above floor
Bi-Directional Probe, with readings at 12 in., 28 in., 40 in., 54 in. and 68 in. above floor
Gas Analyzer, installed vertically thru ceiling, 3 ft. above floor
Curtain
2 ft. 4.5 in. Entrance to Dining Room
2 ft. 10 in.
Up
Closet Entrance
Foyer
8 ft. 0 in. Ceiling
6 ft. 6 in. Entrance to Dining Room
13 ft. 9 in.
11 ft. 9 in.
Stairwell & Landing
1' 2-½"
6 ft. 2-½ in.
3 ft. 11 in.
Pen Camera 11in. away from outside wall, 15 in. above the floor
Gas Analyzer and Pressure Taps 6 in. in from outside wall
2 ft. 1 in.
8"
1 ft. 7-½ in.
Front Door
Two Story
Scale
1.25 inch: 1 foot

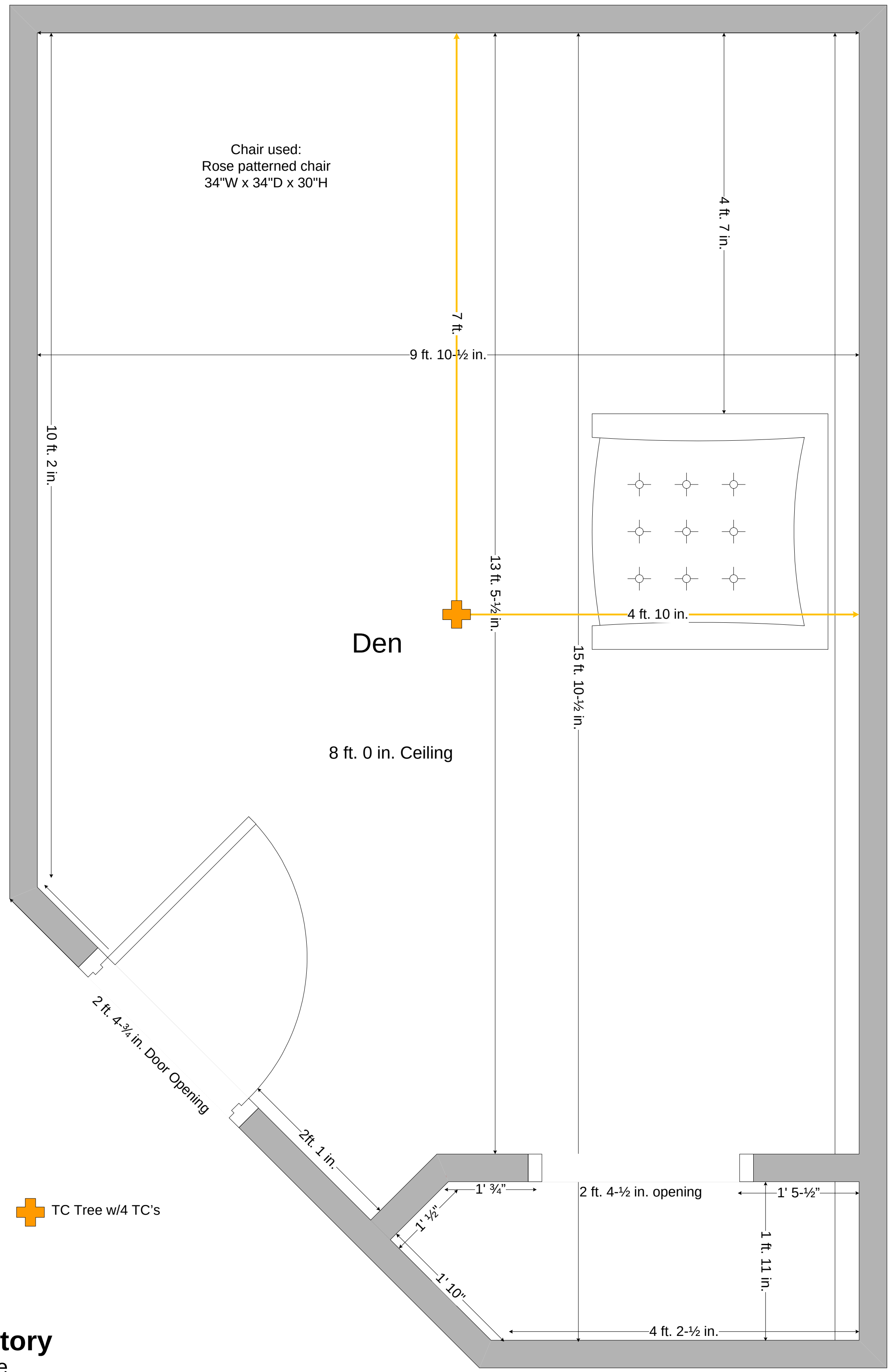

Closet
Master Bathroom
dresser; 28"W x 1"D x 48"H
6-Drawer Dresser
Dimensions: 54"L x 18"D x 32" H
With Mirror centered above
Dimensions: 28"W x 48H
2 Drawer Chest
Bedroom TV Stand
Dimensions:
23-3/4"W x 18-1/2"D x
23-3/4"H
Flat Screen TV centered
on top, angled 45 degrees
7 ft. 1 in.
14 ft. 3 in.
7 ft. 9 in.
9 ft. 5-½ in.
7 ft. 5 in.
Master Bedroom
8 ft. 0 in. Ceiling
12 ft. 11 in.
Queen Bed (Mattress + Box Spring)
Dimensions: 59"W x 79"L
5 ft. 10 in.
15 ft. 10 in.
Hallway
Two Story
Scale
1.5 inch: 1 foot
Nightstand
Dimensions:
22"W x 18"D x
25"H
2 ft. 4 in.
Nightstand
Dimensions:
22"W x 18"D x
25"H
Gas Analyzer and
Pressure Taps 1 ft.
away from inside
wall
2 ft. 7 in.
5 ft.
Headboard attached directly to wall, 72"W x 26"H x 1-1/4"D
TC Tree w/4 TC's
Pressure Tap w/readings at
1ft., 4 ft. and 7 ft. above floor
Gas Analyzer, 3 ft. above floor



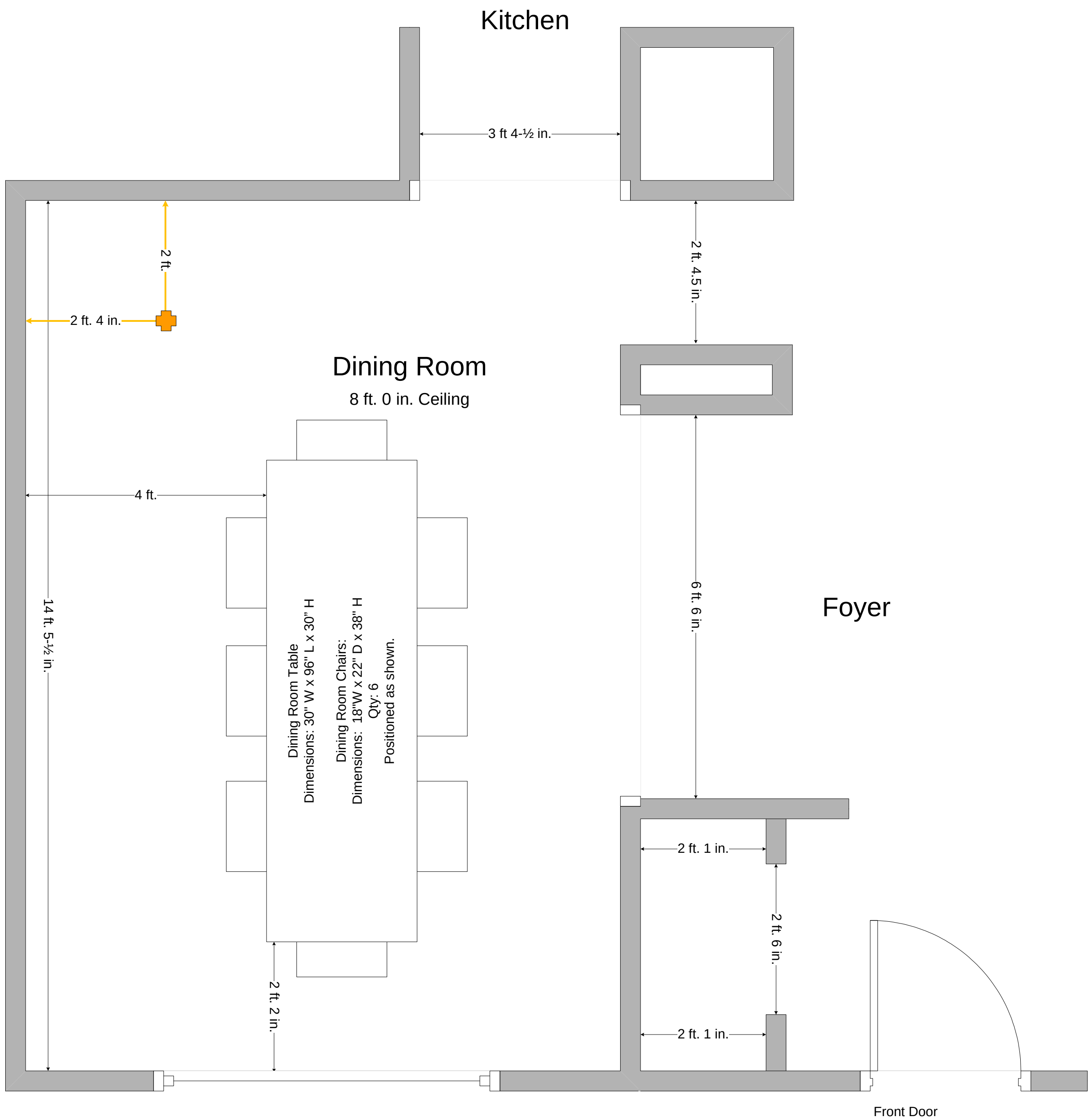
2 ft.
2 ft.
9 ft. 11 in.
7 ft. 7 in.
10 ft. 7 in.
15 ft. 10-½ in.
5 ft.
Bedroom 2
8 ft. 0 in. Ceiling
2ft. 4 in.
7.5"
2 ft. 4-¾ in. Door Opening
2 ft. 4½ in.
6 ft. 4½ in.
8 ft. 10 ½ in.
Two Story
Scale
2 inch: 1 foot
TC Tree w/4 TC's
Gas Analyzer, 3 ft. above floor


Headboard attached directly to wall, 72"W x 26"H x 1-1/4"D, installed 1 inch off the outside wall
24 in.
Gas Analyzer and
Pressure Taps 8' 10" away
from outside wall
Nightstand
Dimensions: 22"W x
18"D x 25"H
12 ft. ¼ in.
12 ft. ¼ in.
2 Drawer Chest
Bedroom TV Stand
Dimensions:
23-3/4"W x 18-1/2"D x
23-3/4"H
Flat Screen TV centered
on top, angled 45 degrees
6 ft. 2 in.
Full Bed (Mattress + Box Spring)
Dimensions: 74"W x 53"L
7 in.
12 ft. 4 in.
Rose patterned ottoman
28"W x 20"D x 16"H
Two Story
Scale
2 inch: 1 foot
Bedroom 3
8 ft. 0 in. Ceiling
4 ft. 5 in.
5 ft. 8 in.
3 ft. 10 in.
5 ft. 7 in.
Rose patterned chair
34"W x 34"D x 30"H
6-Drawer Dresser
Dimensions: 54"L x 18"D x 32" H
With Mirror centered above
Dimensions: 28"W x 48H
Mirror on wall centered above dresser; 28"W x 1"D x 48"H,
installed 17 in. off outside wall
Pen Camera
TC Tree w/8 TC's
Pressure Tap w/readings at 1ft., 4 ft.
and 7 ft. above floor
Gas Analyzer, 3 ft. above floor


Mirror on wall centered above dresser; 28"W x 1"D x 48"H, installed 17 in. off outside wall
6-Drawer Dresser
Dimensions: 54"L x 18"D x 32" H
With Mirror centered above
Dimensions: 28"W x 48H
16 in.
9 ft. 10-½ in.
Headboard attached directly to wall, 72"W x 26"H x 1-1/4"D, installed 1 inch off the outside wall
Full Bed (Mattress + Box Spring)
Dimensions: 74"W x 53"L
10 ft. 10.5 in.
4 ft
2 ft.
2 Drawer Chest
Bedroom TV Stand
Dimensions:
23-3/4"W x 18-1/2"D x
23-3/4"H
Flat Screen TV centered
on top, angled 45 degrees
5 ft. 5 in.
3 ft. 1 in.
Nightstand
Dimensions: 22"W x
18"D x 25"H
29 in.
25 in.
36 in.
Bedroom 4
8 ft. 0 in. Ceiling
Two Story
Scale
2 inch: 1 foot
TC Tree w/4 TC's



Two Story
Scale
2 inch: 1 foot



Pen Camera

IR Camera

TC Tree w/8 TC's

TC Tree w/4 TC's

Pressure Tap w/readings at 1 ft., 4 ft. and 7 ft. above floor

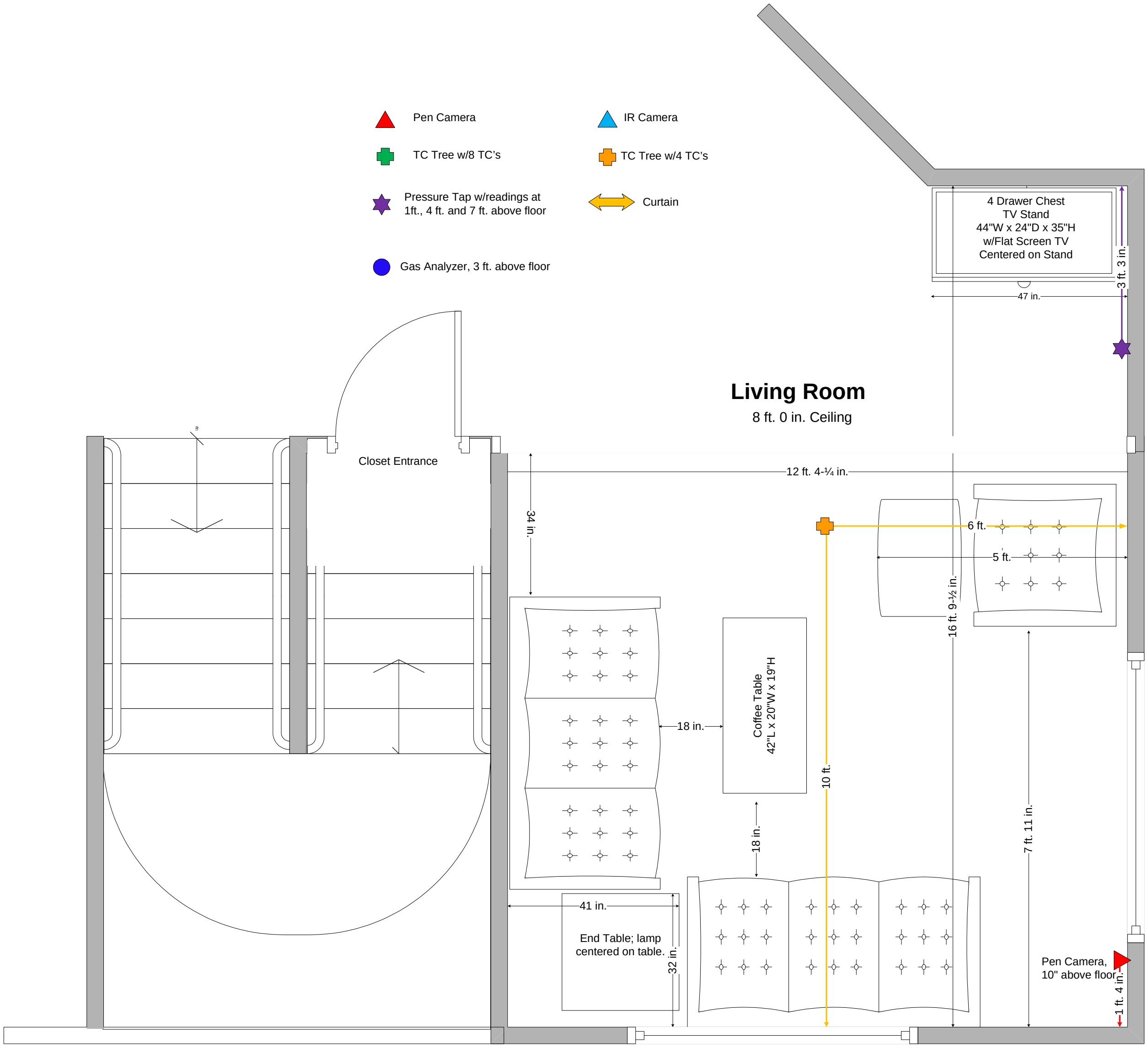
Bi-Directional Probe, with readings at 12 in., 28 in., 40 in., 54 in. and 68 in. above floor

Gas Analyzer, 3 ft. above floor

Curtain

Two Story

Scale
1-½ inch: 1 foot



Two Story

Scale

1-½ inch: 1 foot

Appendix D: Furniture Pictures

Figure D.1: 4 Drawer Chest

Figure D.2: Green Stripe Sofa

Figure D.3: Rose Chair

Figure D.4: Rose Ottoman

Figure D.5: Coffee Table

Figure D.6: Table Lamp w/ Shade

Figure D.7: TV Set

Figure D.8: End Table

Figure D.9: Picture

Figure D.10: Drapes

Figure D.11: Queen Mattress

Figure D.12: Queen Box Spring

Figure D.13: Full Mattress

Figure D.14: Full Box Spring

Figure D.15: Nightstand

Figure D.16: 2 Drawer Chest

Figure D.17: 6 Drawer Wood Dresser

Figure D.18: Mirror for Wood Dresser

Figure D.19: Headboard

Figure D.20: Pillow

Figure D.21: Sheets

Figure D.22: Mattress Pad

Figure D.23: Bed in a Bag

Figure D.24: Kitchen Table


Figure D.25: Dining Room Table Top


Figure D.26: Stack Chairs


Figure D.27: Dishwasher


Figure D.28: Refrigerator


Figure D.29: Stove


Figure D.30: Microwave

Figure D.31: Kitchen Cabinet-SB60

Figure D.32: Base Kitchen Cabinet-B36

Figure D.33: Base Kitchen Cabinet-B24

Figure D.34: Wall Kitchen Cabinet-W2430

Figure D.35: Wall Kitchen Cabinet-W3630

Figure D.36: Vintage – Tan Sofa


Figure D.37: Vintage – Blue Sofa


Figure D.38: Vintage – Tan Flower Chair


Figure D.39: Vintage – Blue Striped Chair

Appendix E: Detailed House Experiment Room Data Graphs

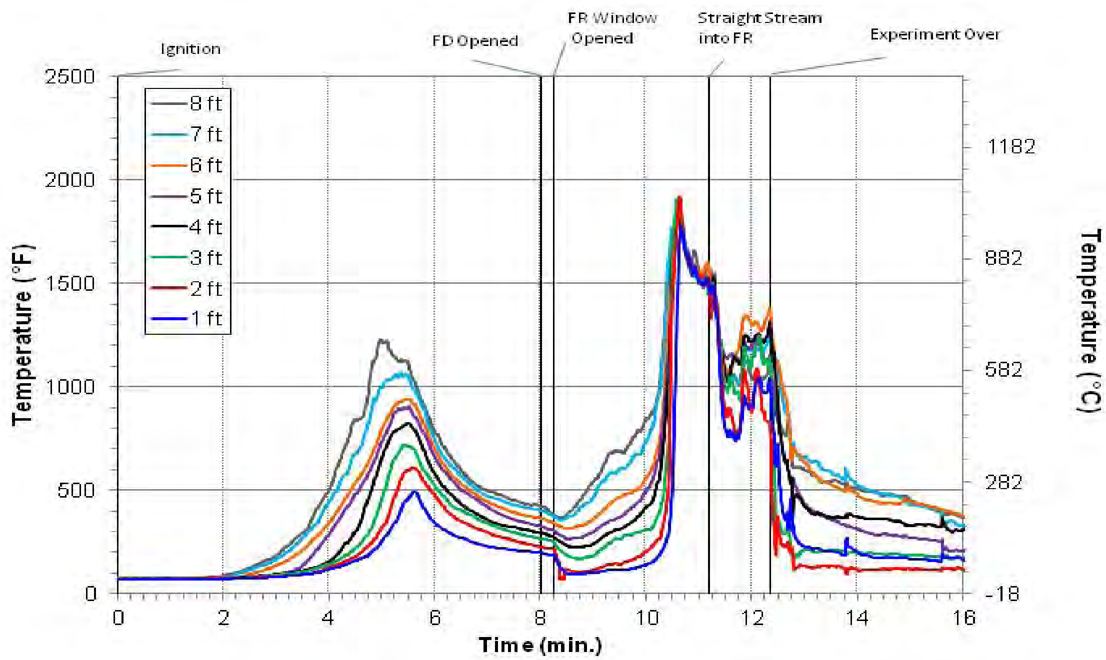


Figure E.1: Experiment 1 Living Room Temperature

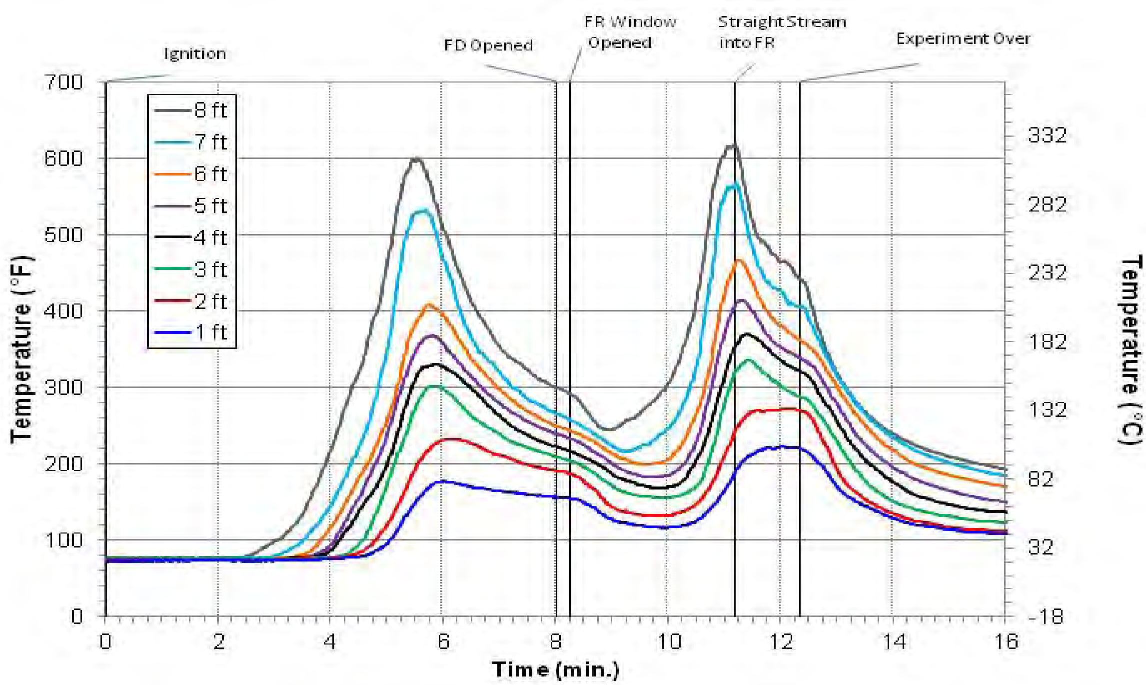


Figure E.2: Experiment 1 Bedroom 1 Temperature

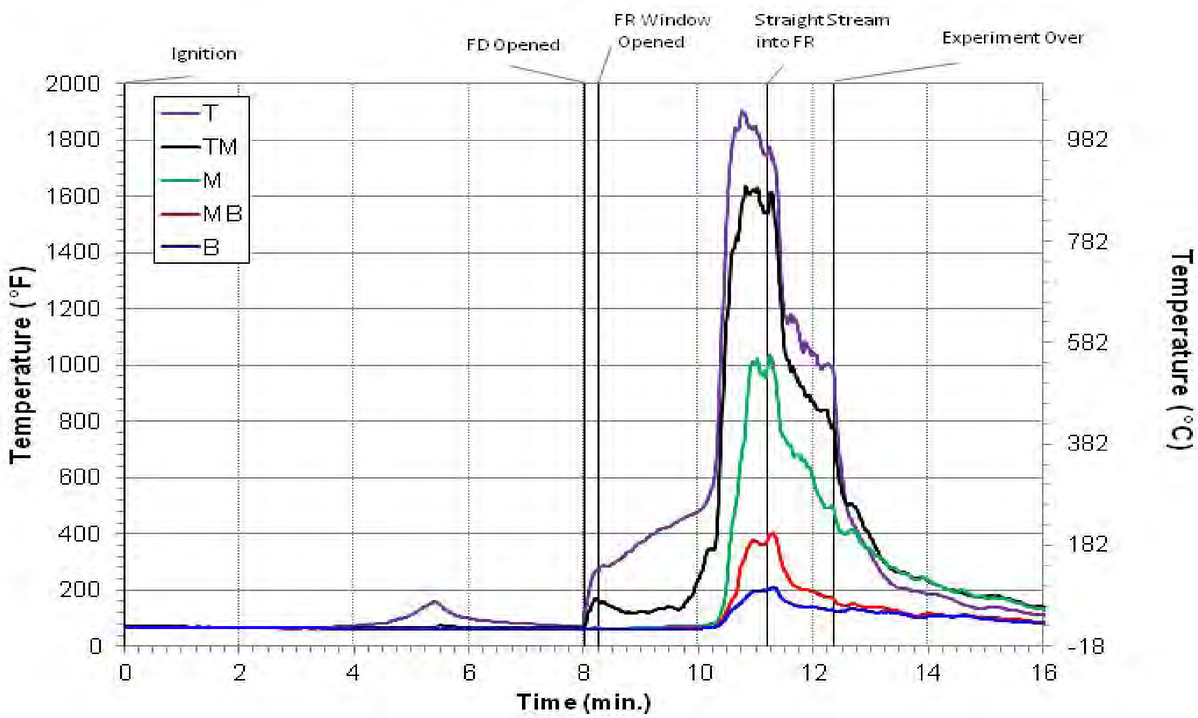


Figure E.3: Experiment 1 Front Door Temperature

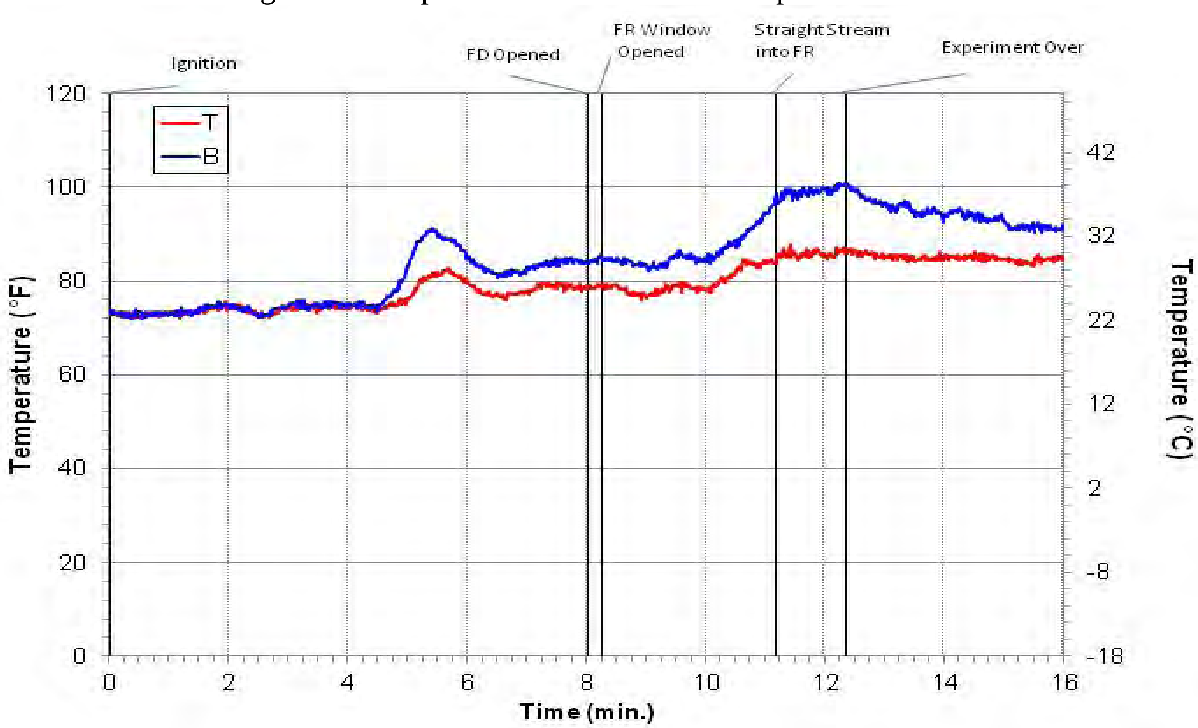


Figure E.4: Experiment 1 Vent Temperature

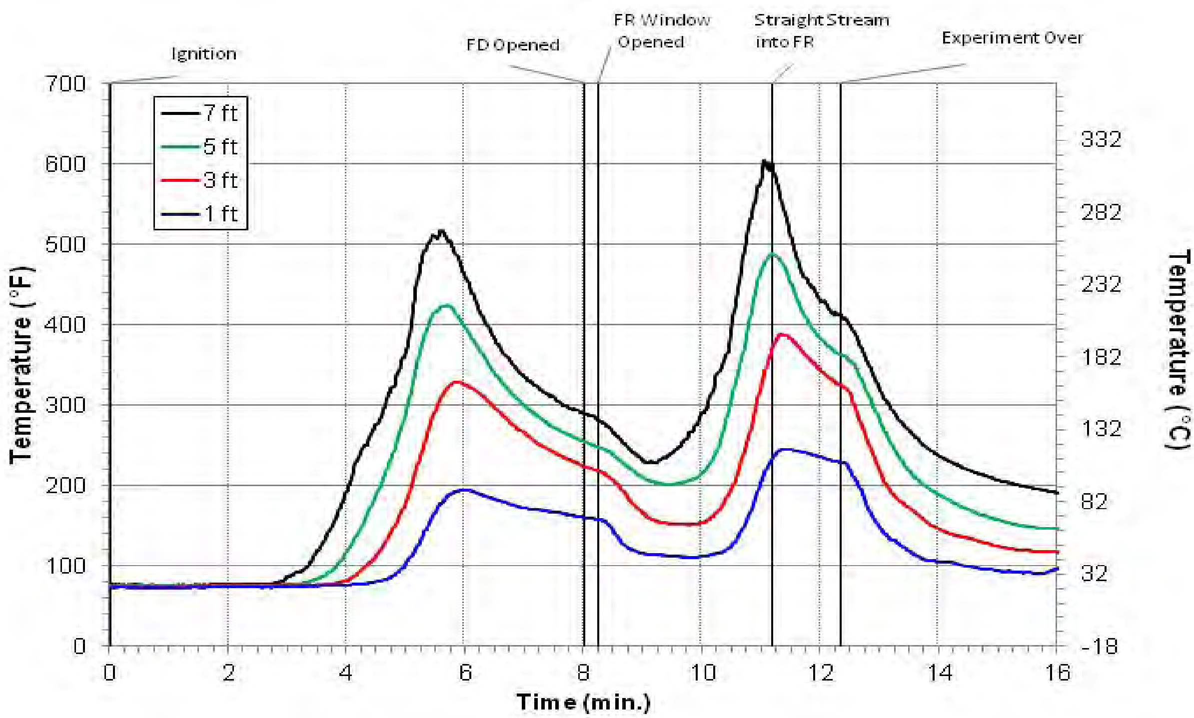


Figure E.5: Experiment 1 Bedroom 2 Temperature

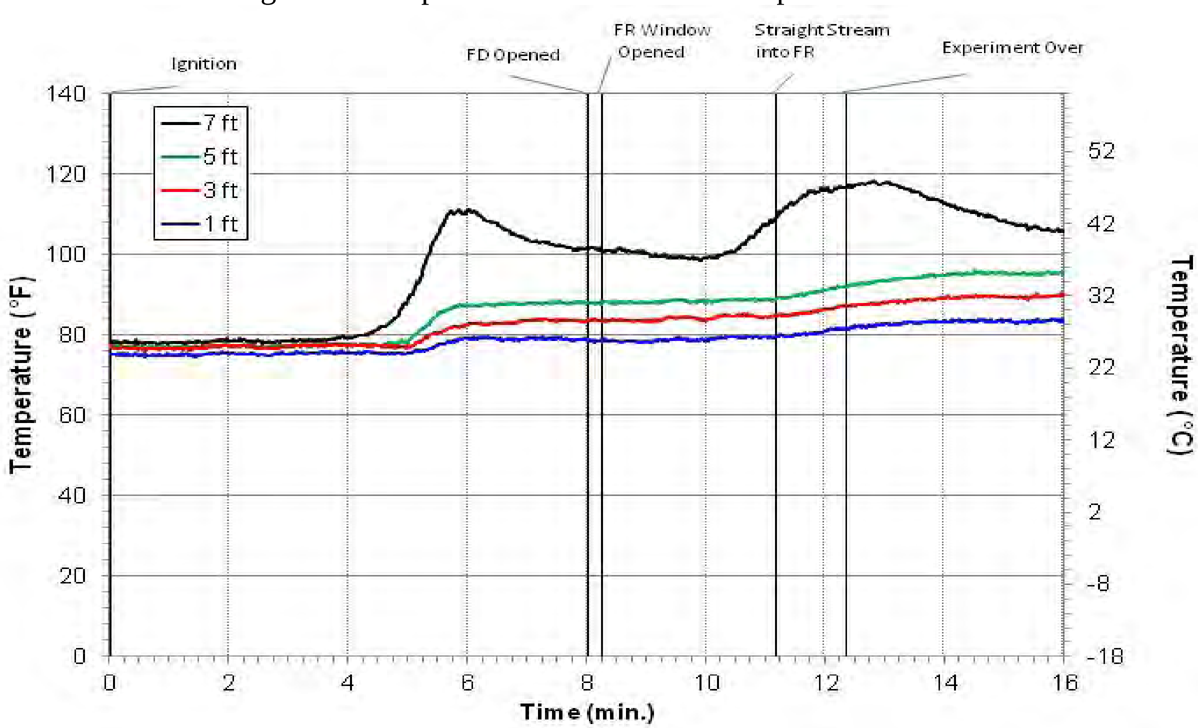


Figure E.6: Experiment 1 Bedroom 3 Temperature

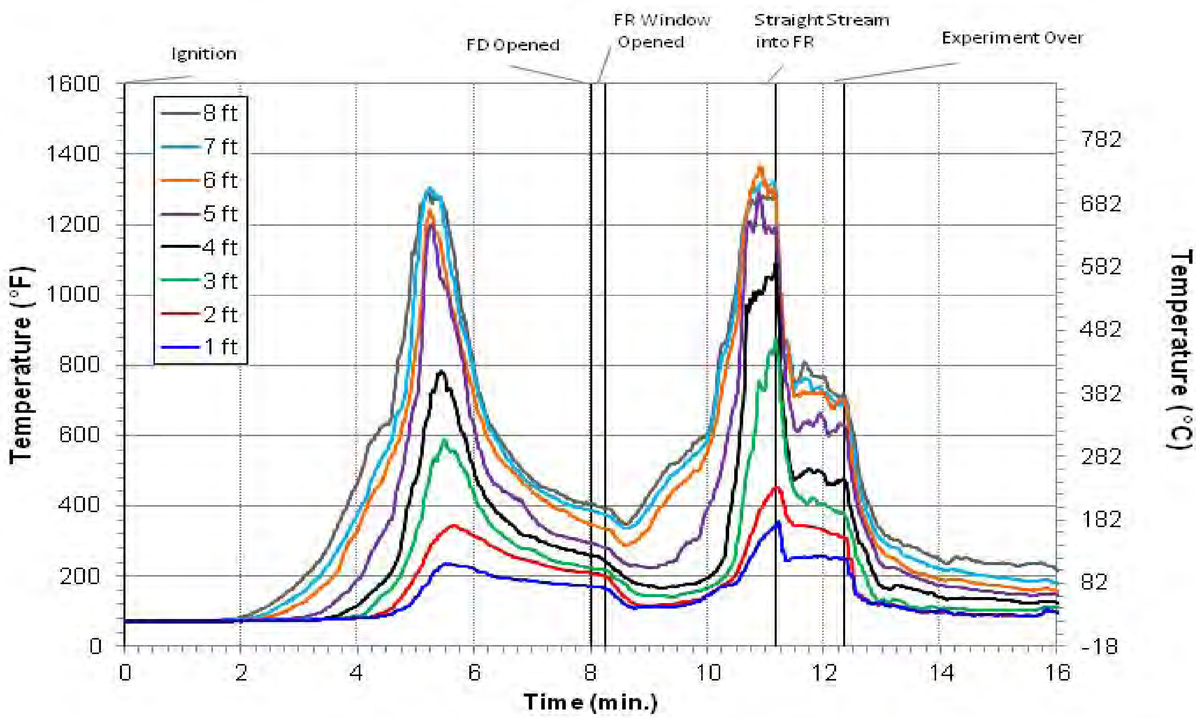


Figure E.7: Experiment 1 Hallway Temperature

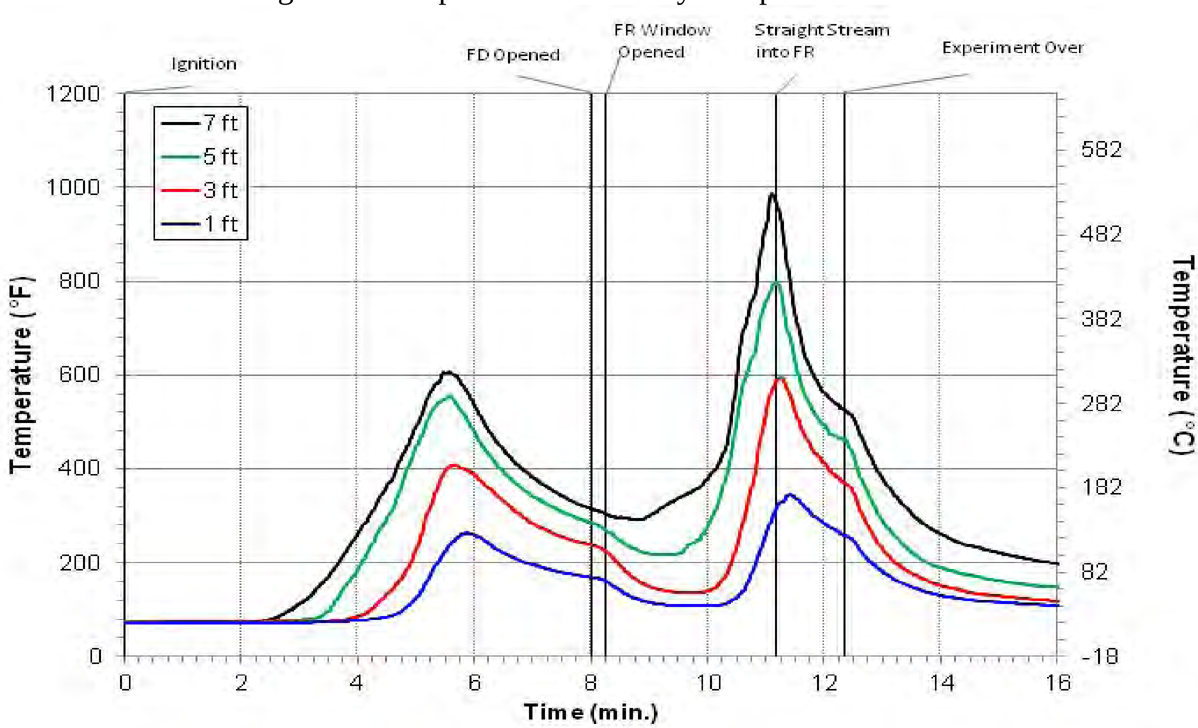


Figure E.8: Experiment 1 Dining Room Temperature

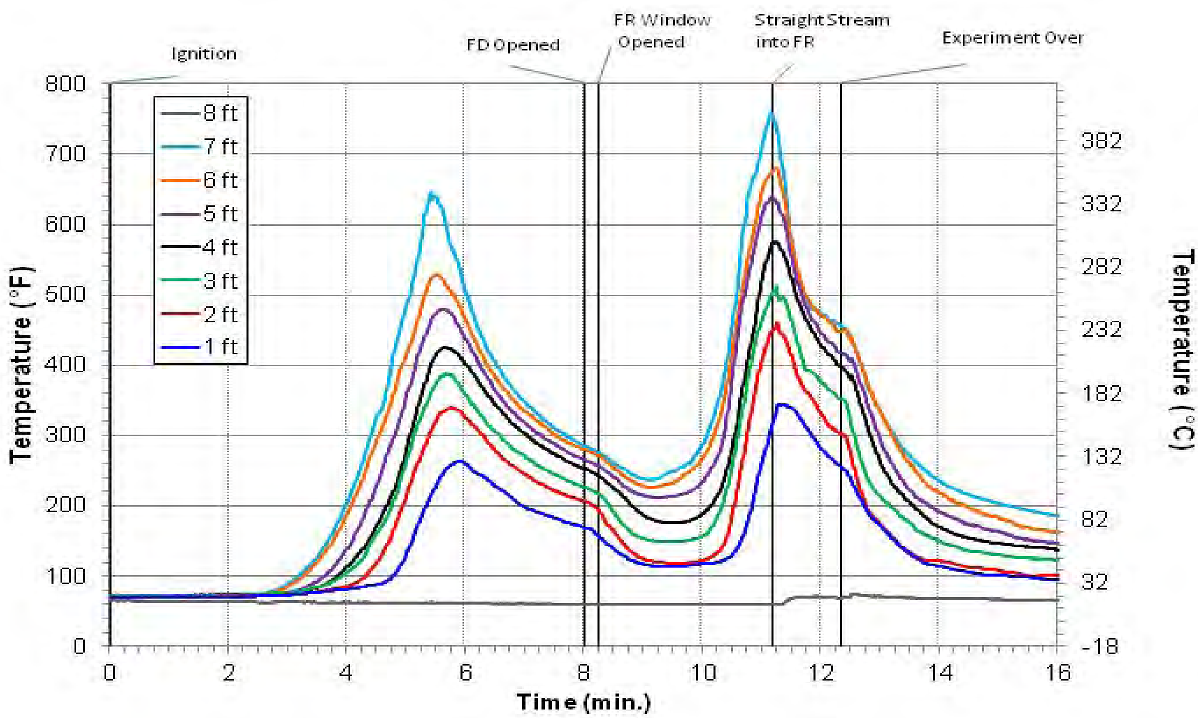


Figure E.9: Experiment 1 Kitchen Temperature

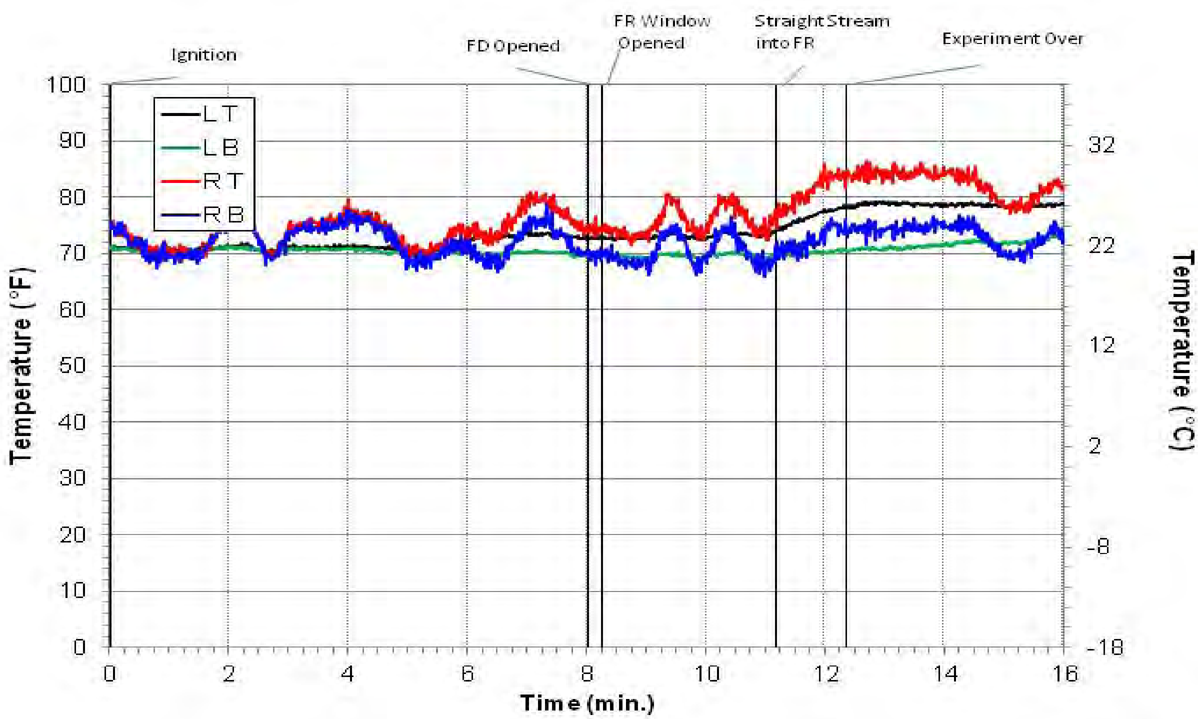


Figure E.10: Experiment 1 Attic Temperature

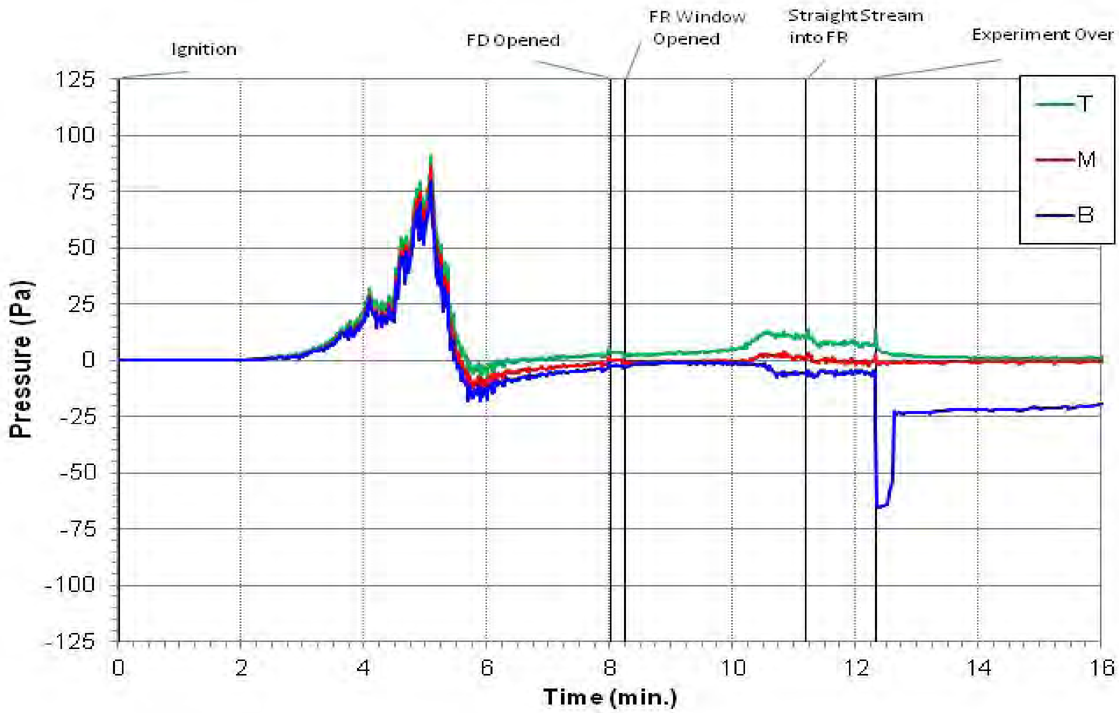


Figure E.11: Experiment 1 Living Room Pressure

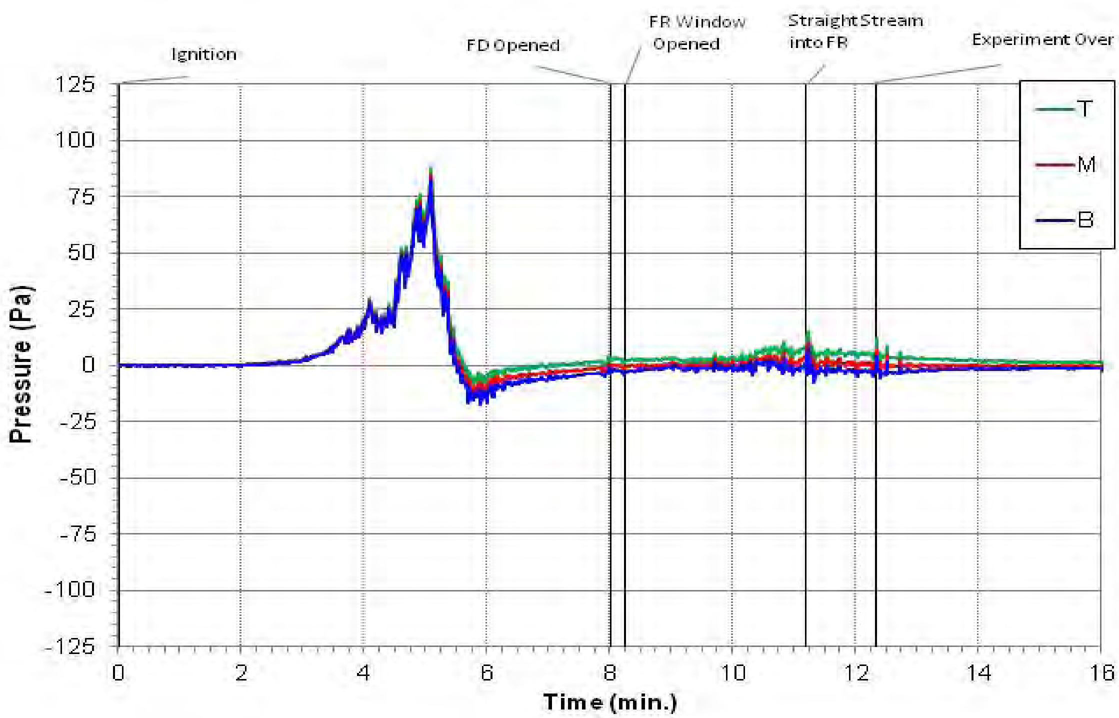


Figure E.12: Experiment 1 Bedroom 1 Pressure

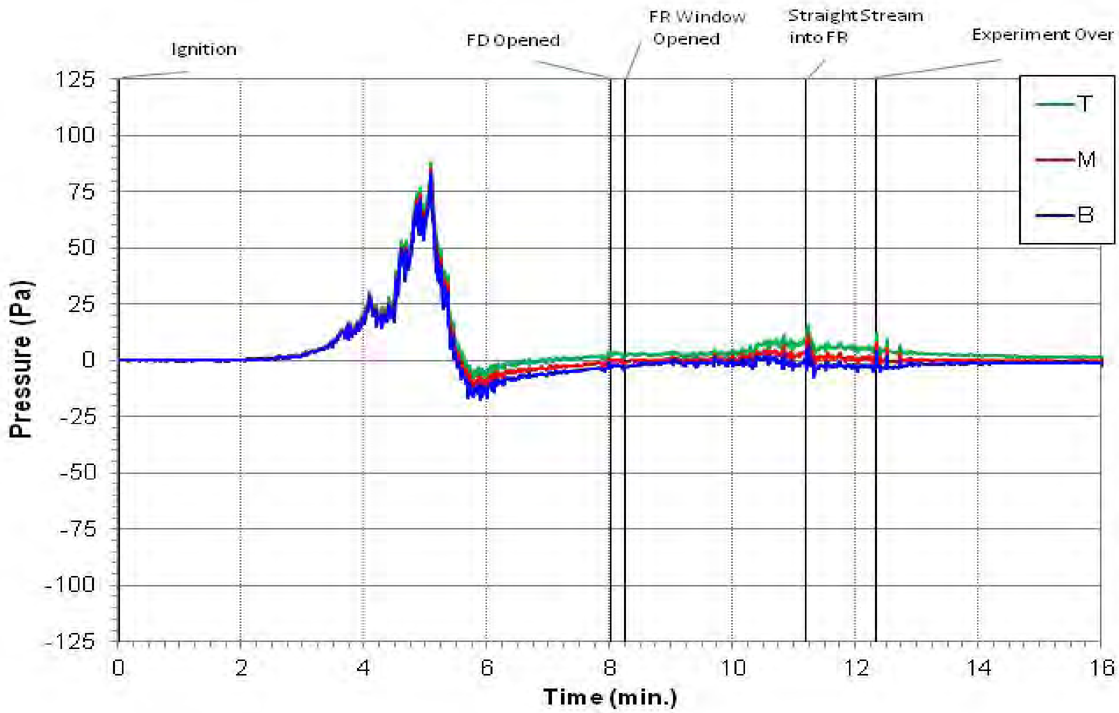


Figure E.13: Experiment 1 Bedroom 2 Pressure

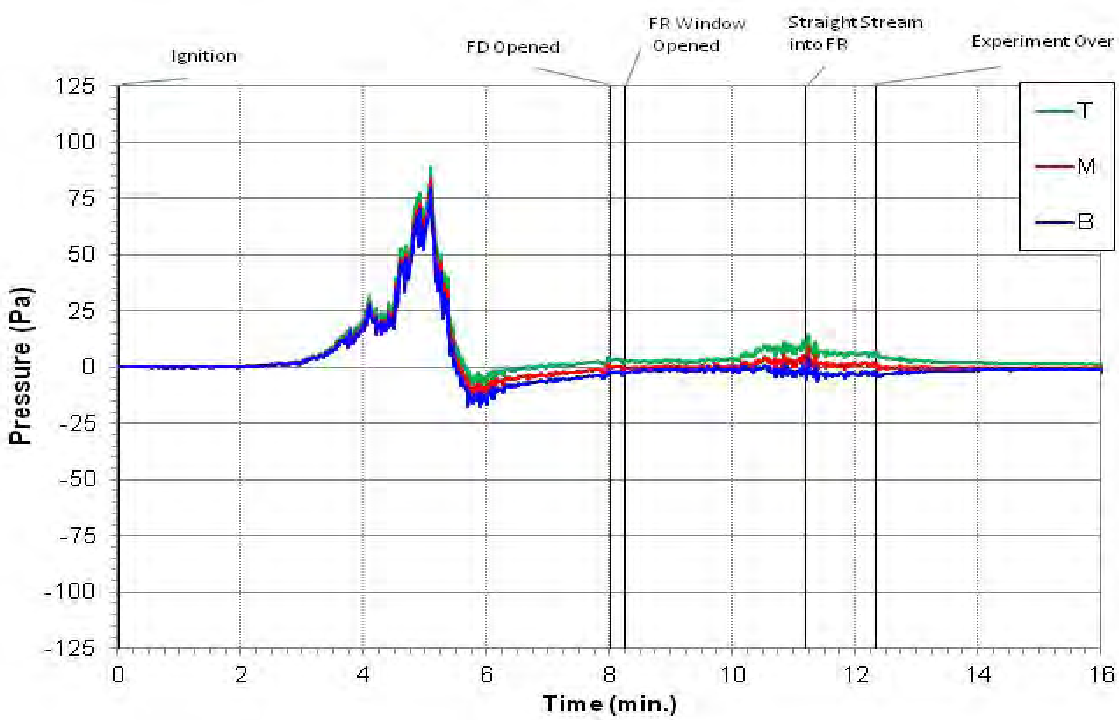


Figure E.14: Experiment 1 Kitchen Pressure

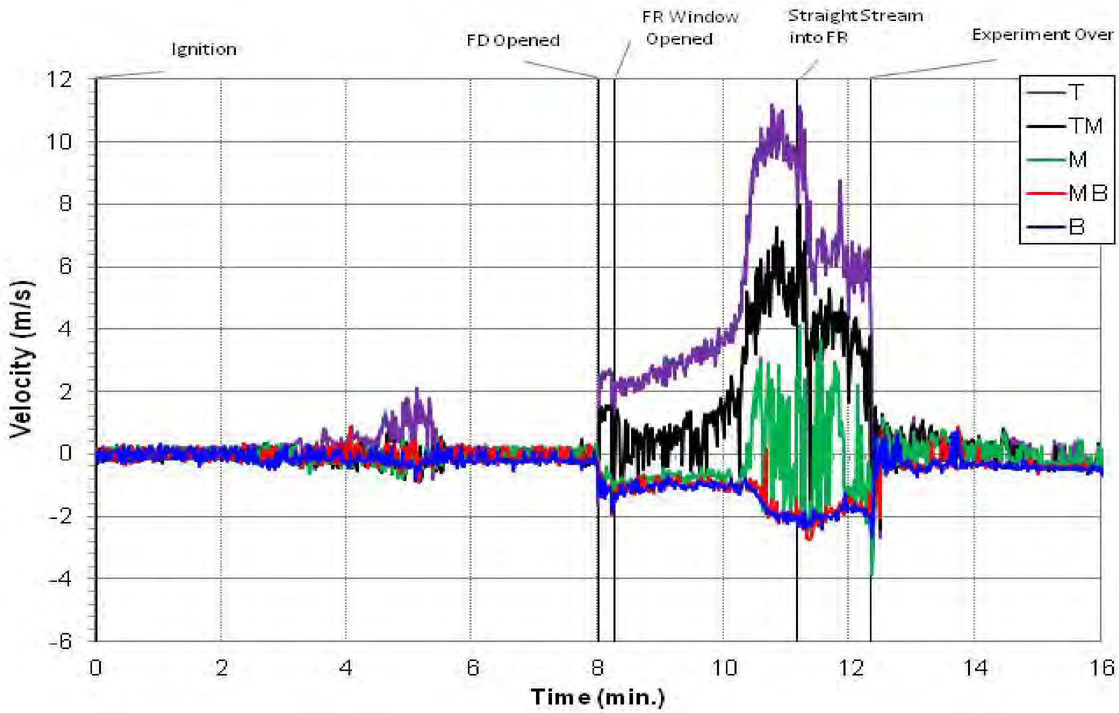


Figure E.15: Experiment 1 Front Door Velocity

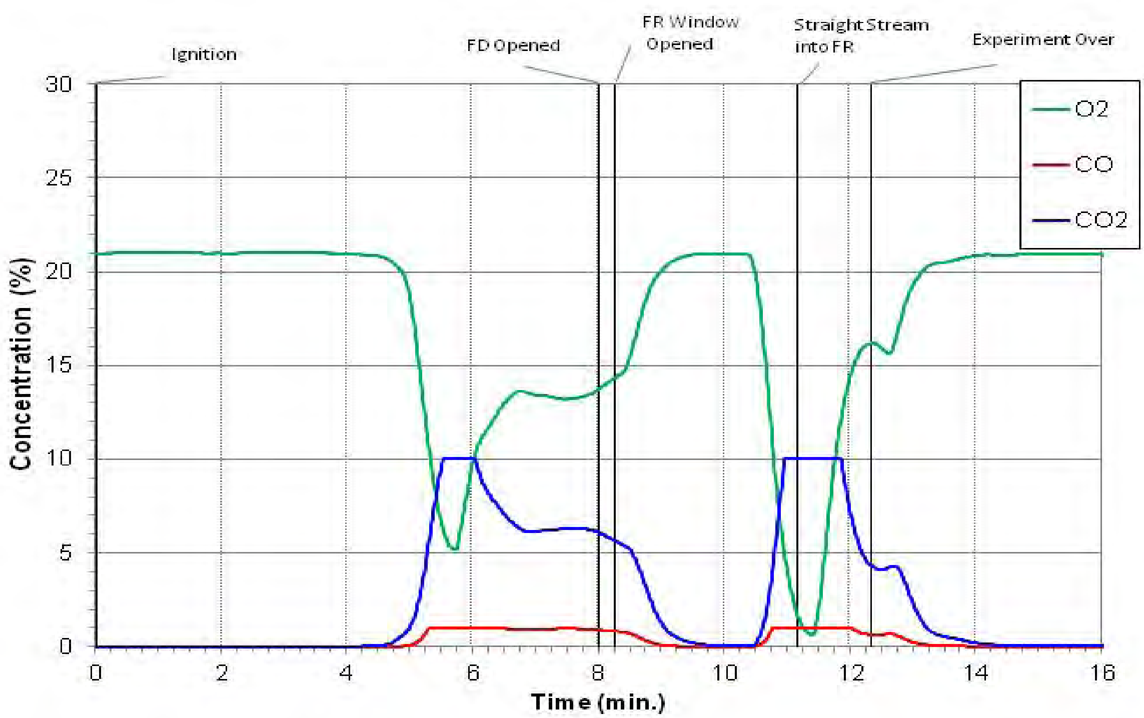


Figure E.16: Experiment 1 Living Room Gas

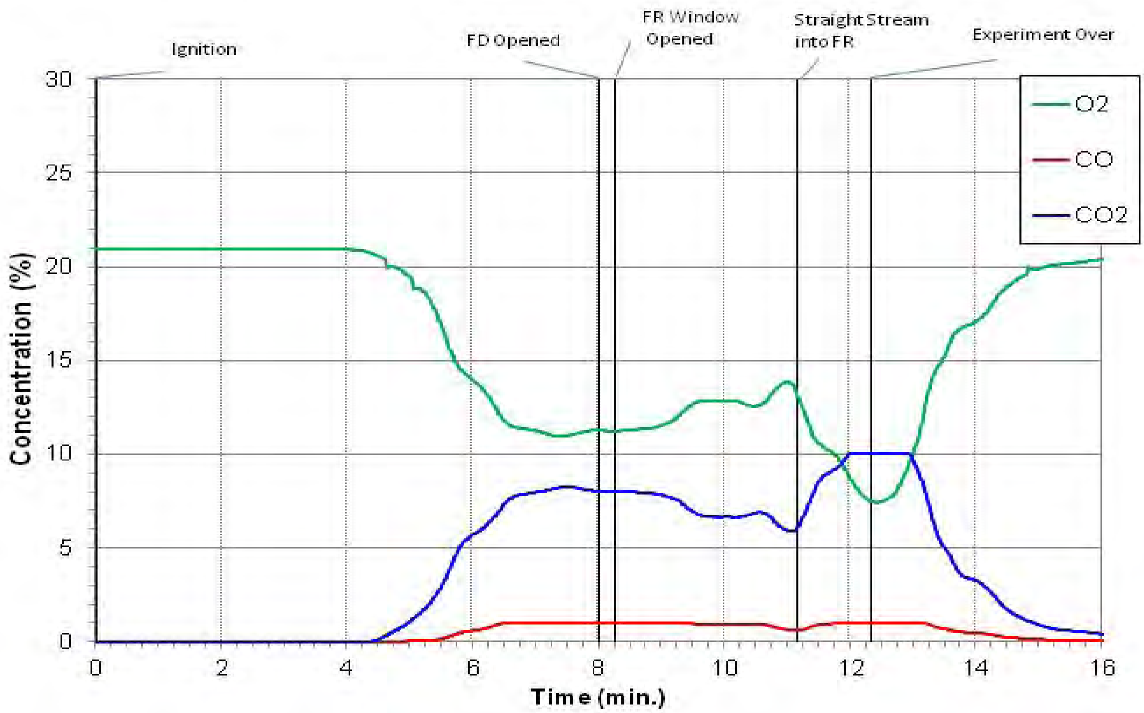


Figure E.17: Experiment 1 Bedroom 1 Gas

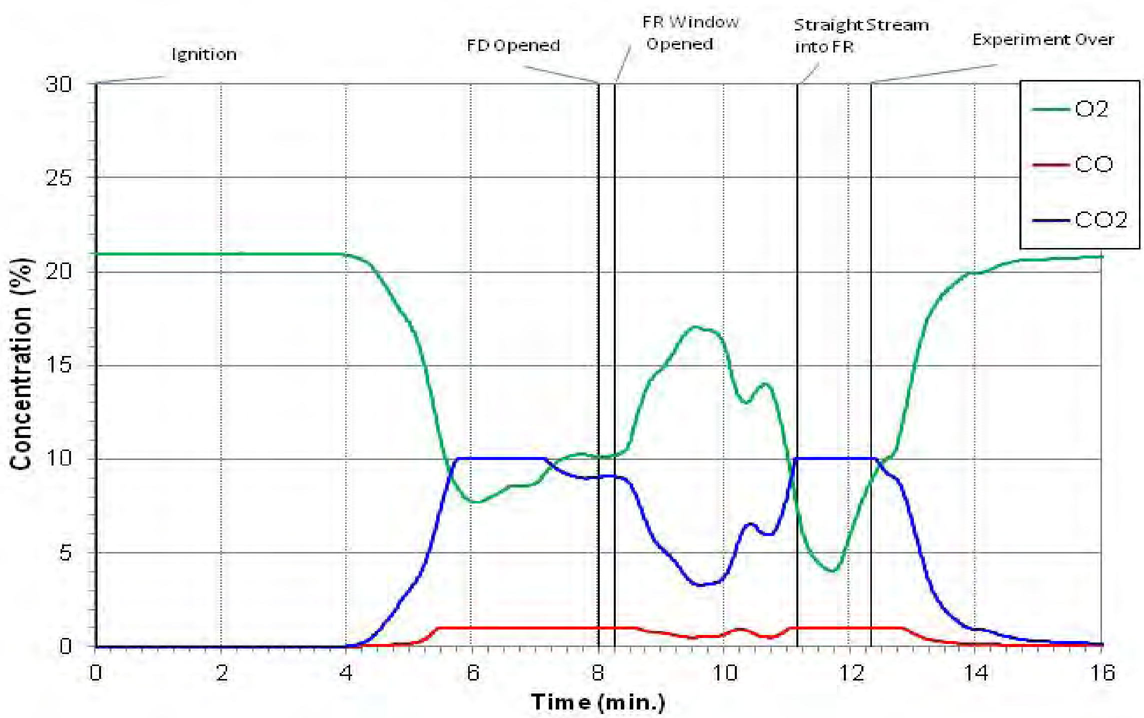


Figure E.18: Experiment 1 Bedroom 2 Gas

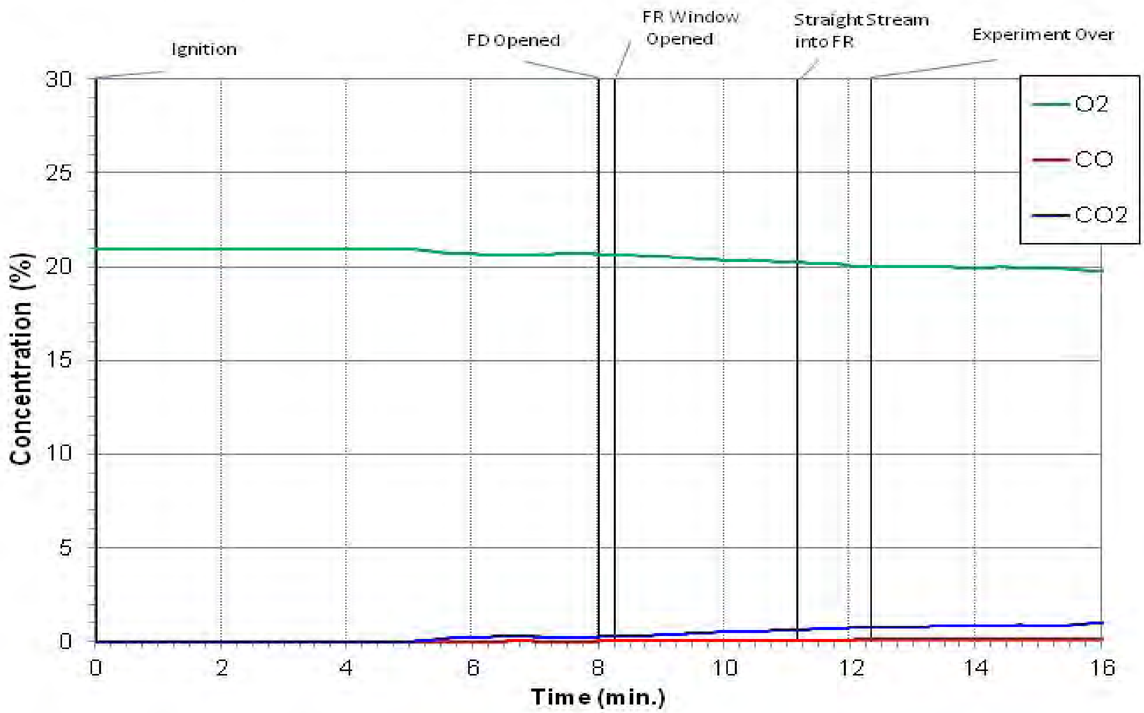


Figure E.19: Experiment 1 Bedroom 3 Gas

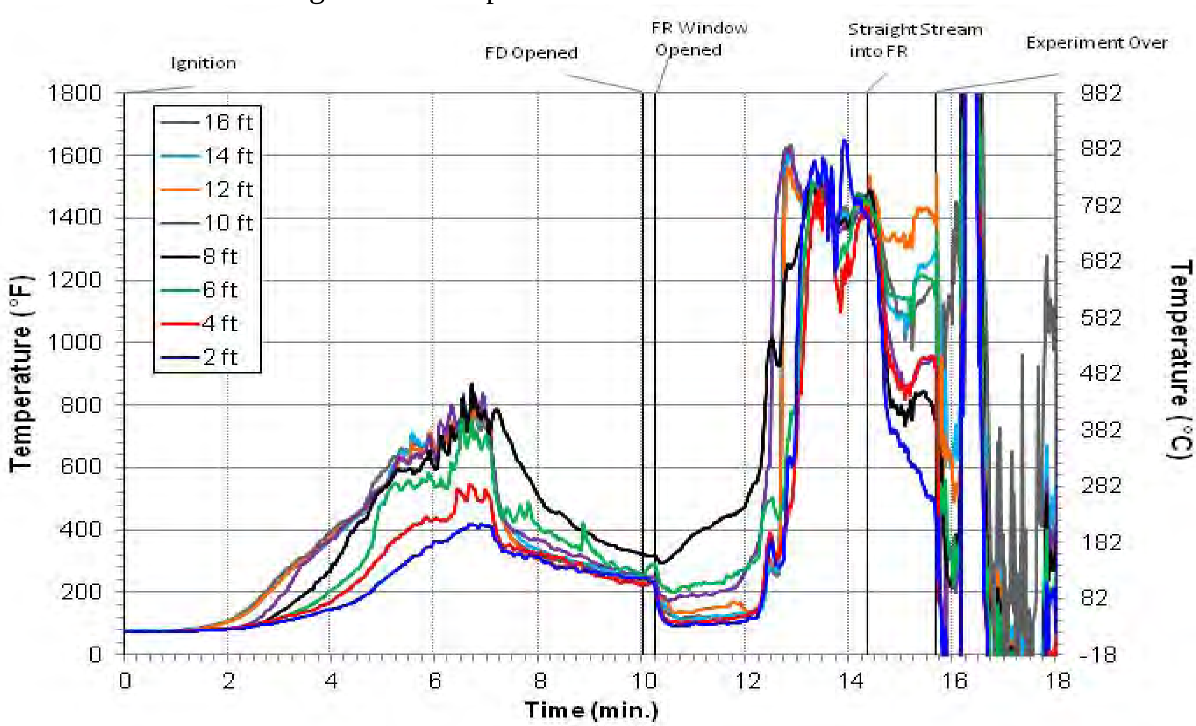


Figure E.20: Experiment 2 Family Room Temperature

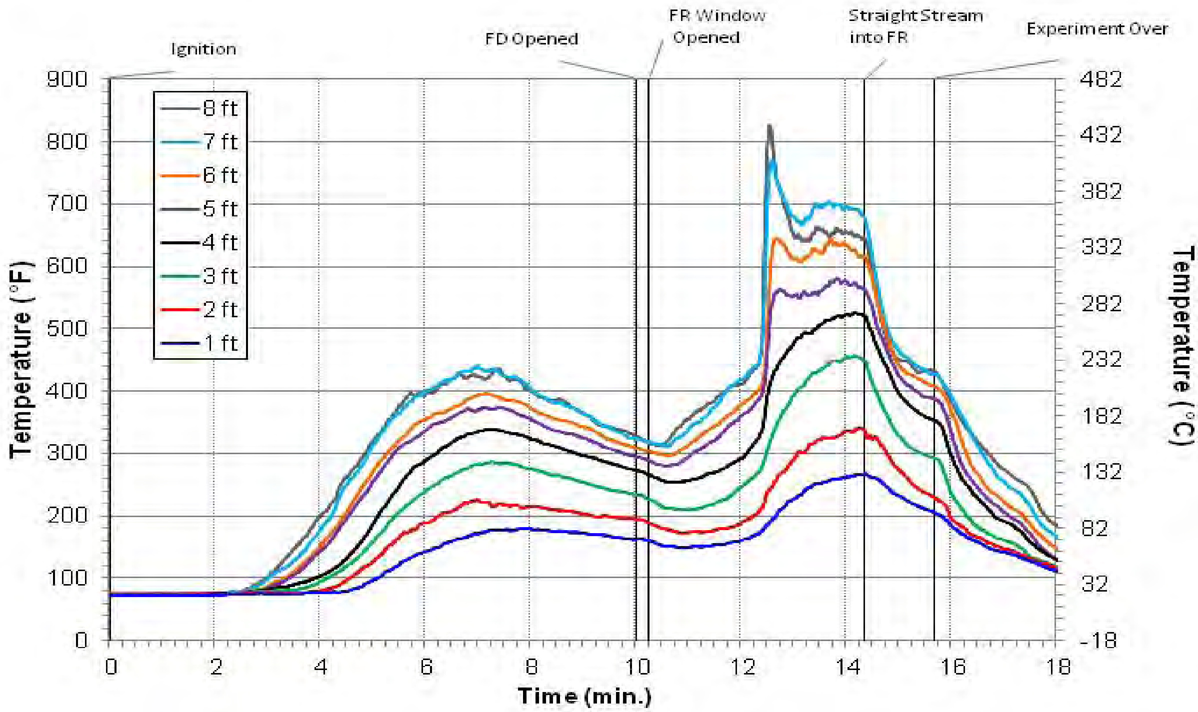


Figure E.21: Experiment 2 Kitchen Temperature

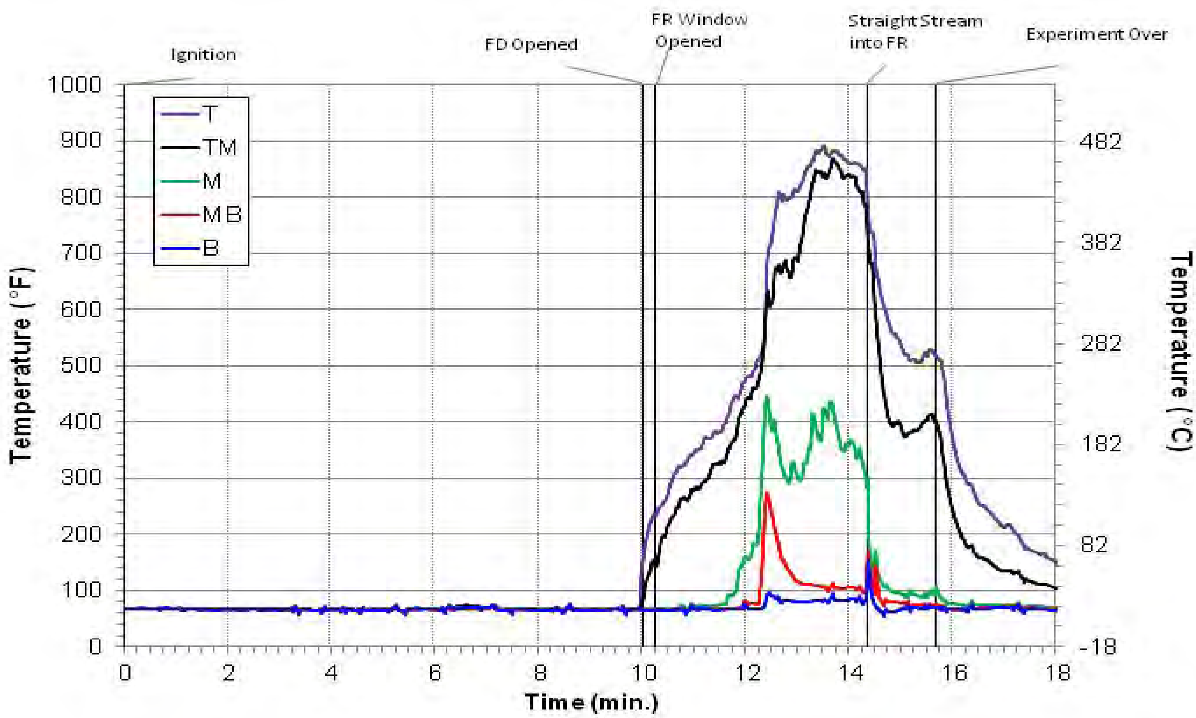


Figure E.22: Experiment 2 Front Door Temperature

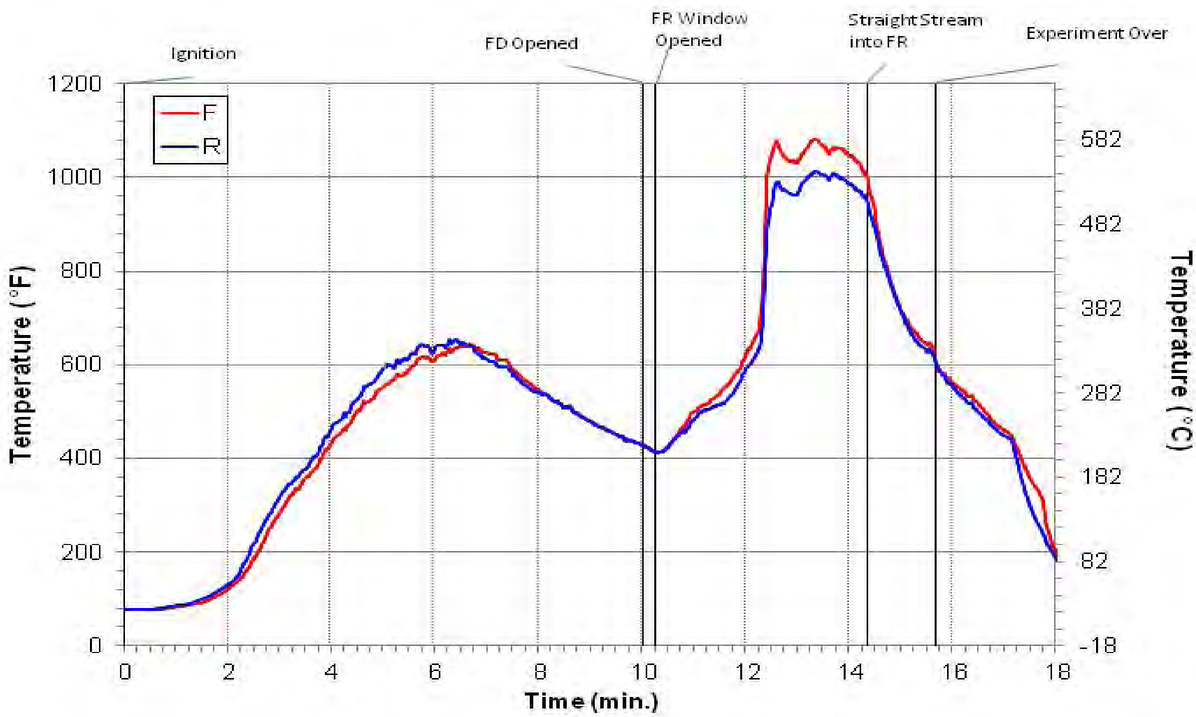


Figure E.23: Experiment 2 Vent Temperature

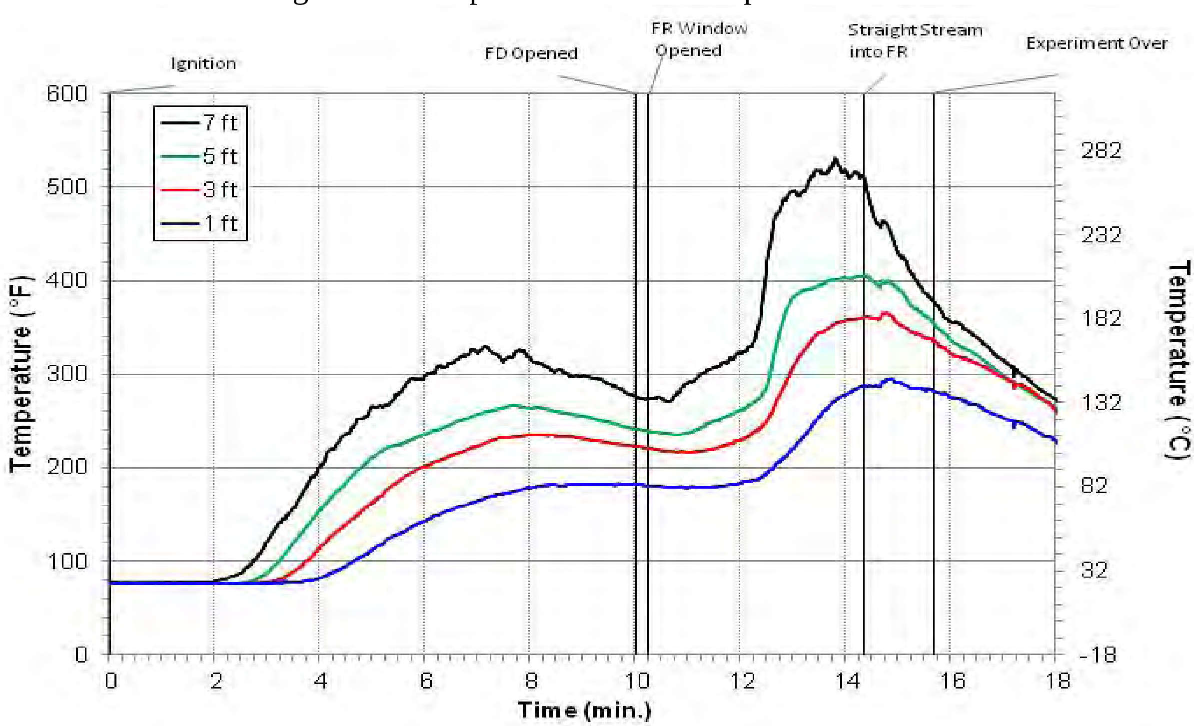


Figure E.24: Experiment 2 Bedroom 1 Temperature

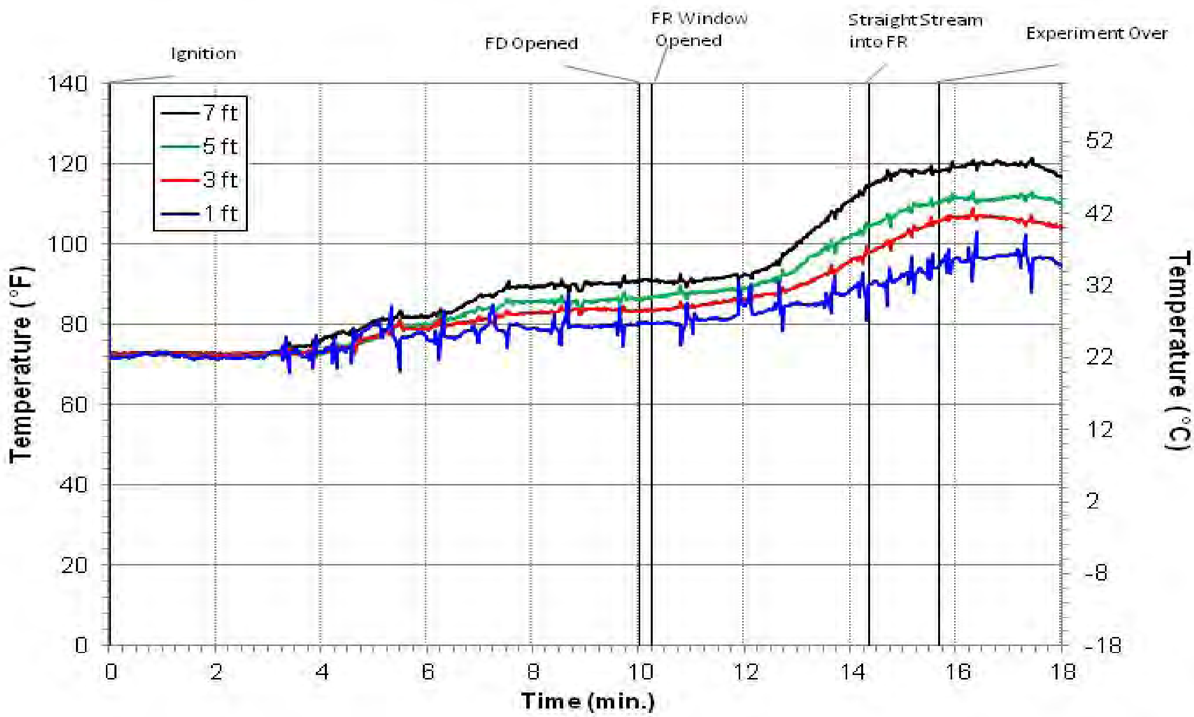


Figure E.25: Experiment 2 Bedroom 2 Temperature

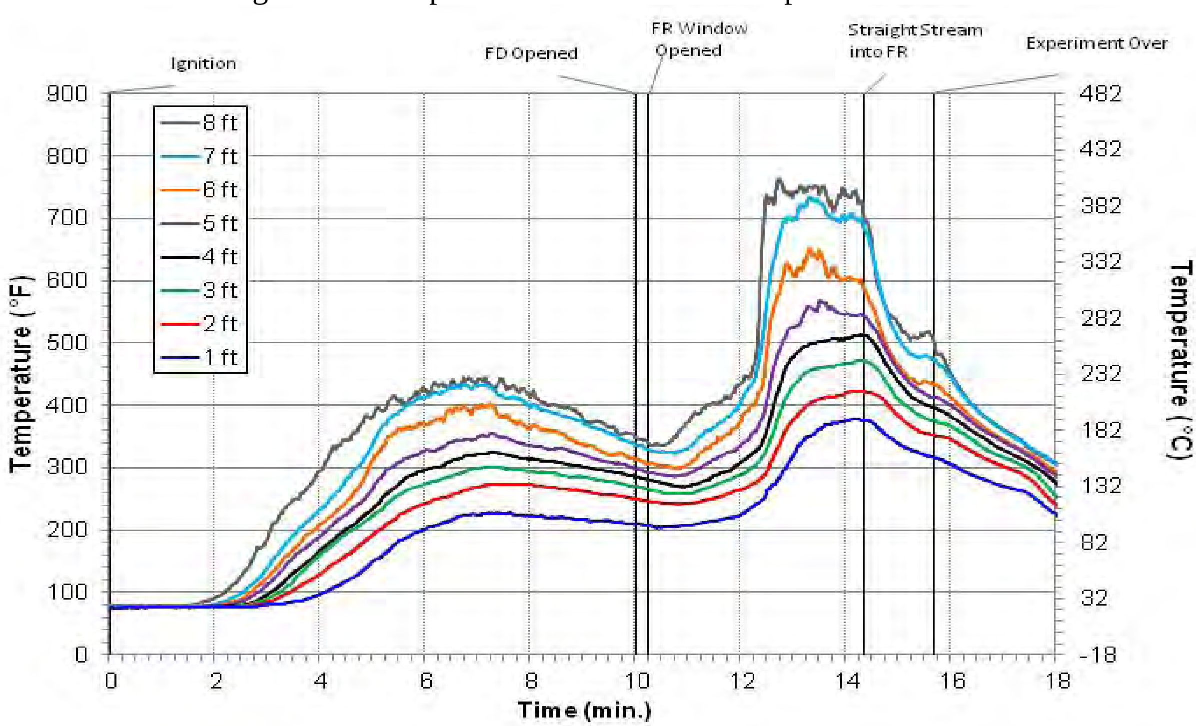


Figure E.26: Experiment 2 Bedroom 3 Temperature

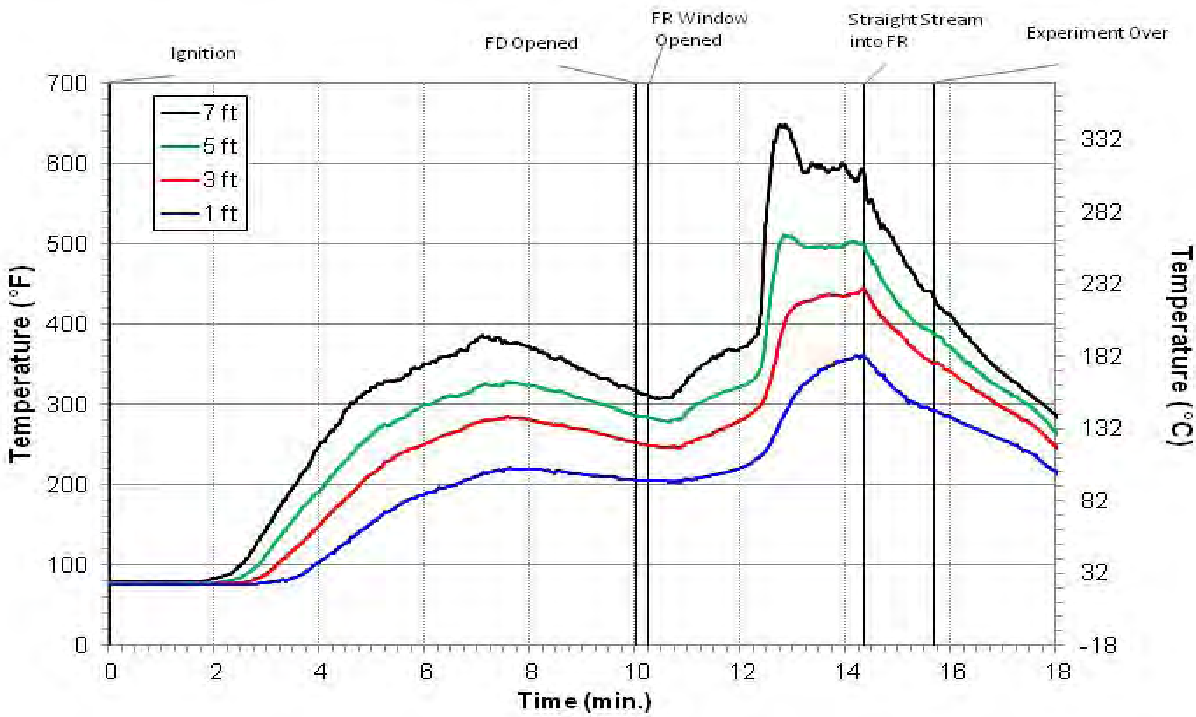


Figure E.27: Experiment 2 Bedroom 4 Temperature

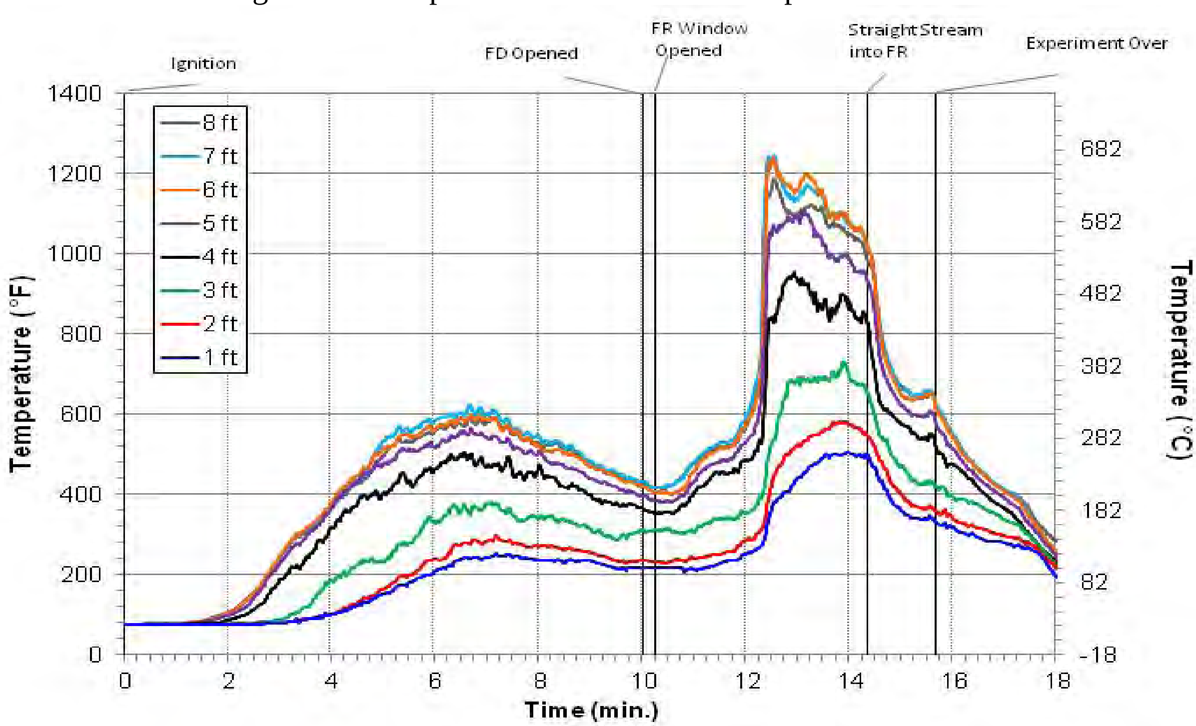


Figure E.28: Experiment 2 Hallway Temperature

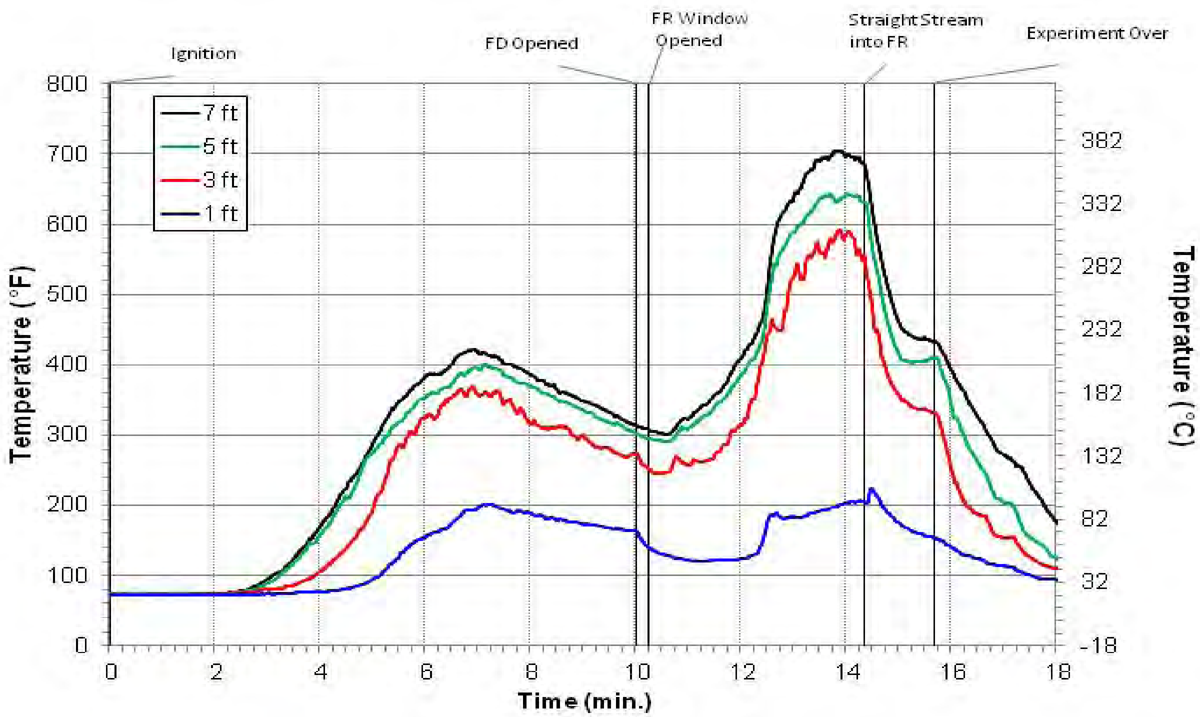


Figure E.29: Experiment 2 Dining Room Temperature

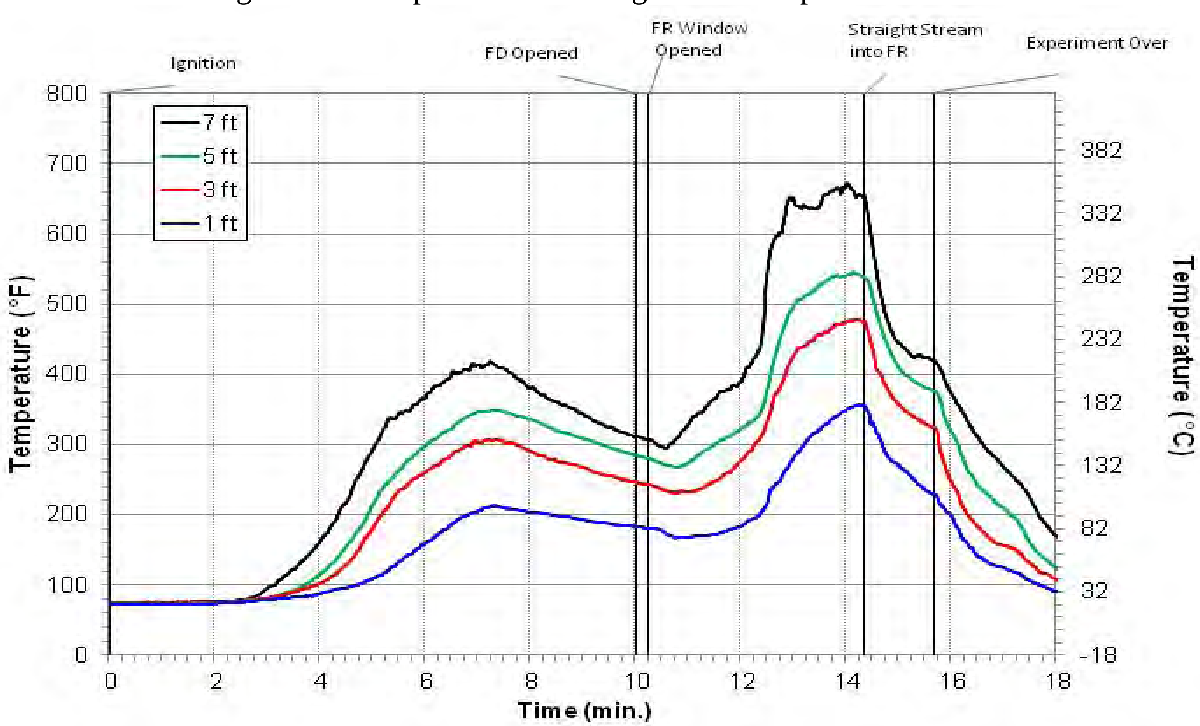


Figure E.30: Experiment 2 Living Room Temperature

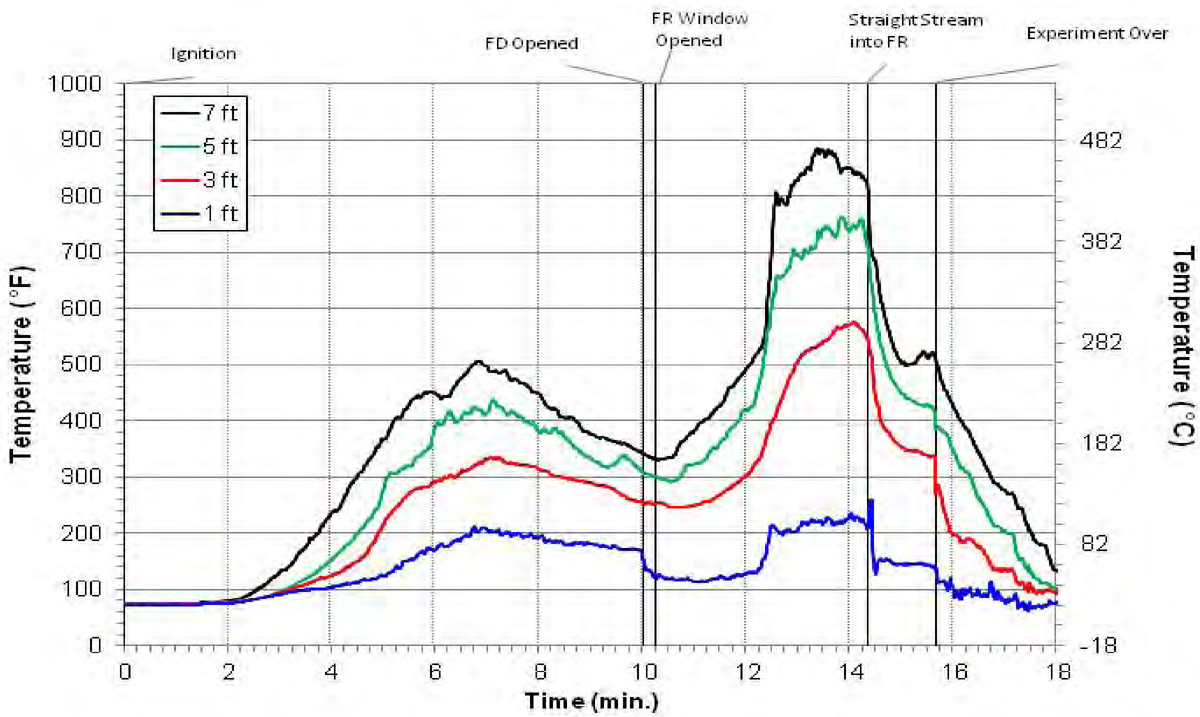


Figure E.31: Experiment 2 Foyer Temperature

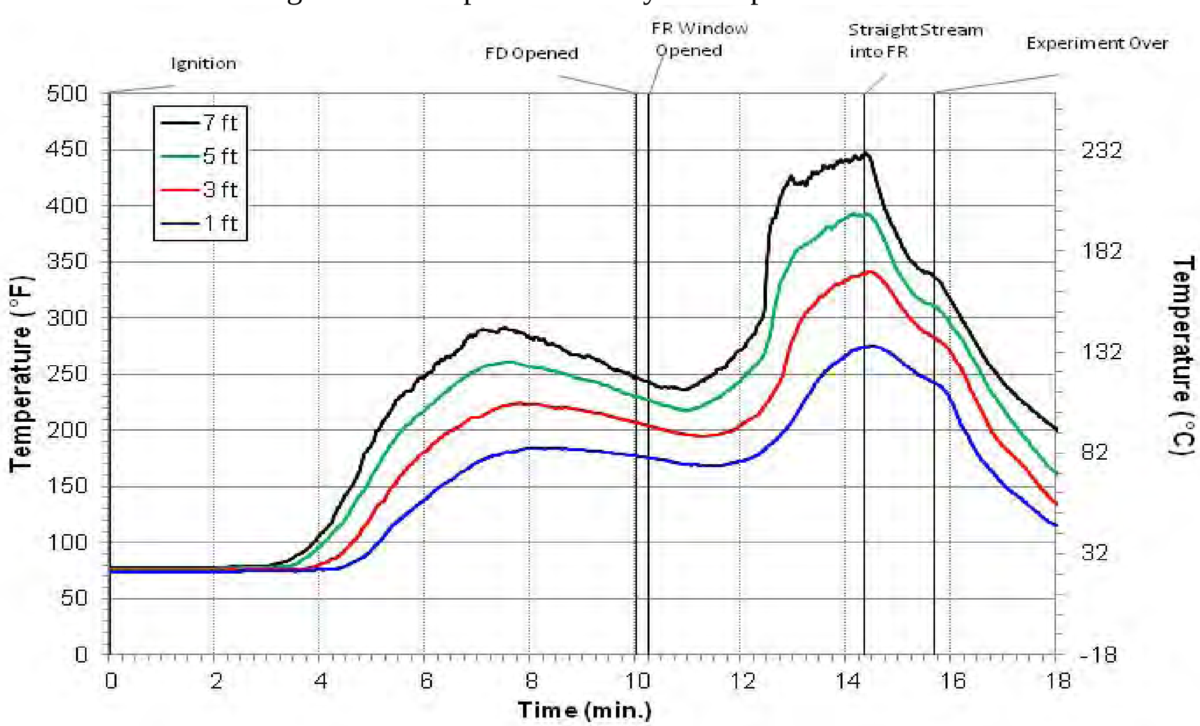


Figure E.32: Experiment 2 Den Temperature

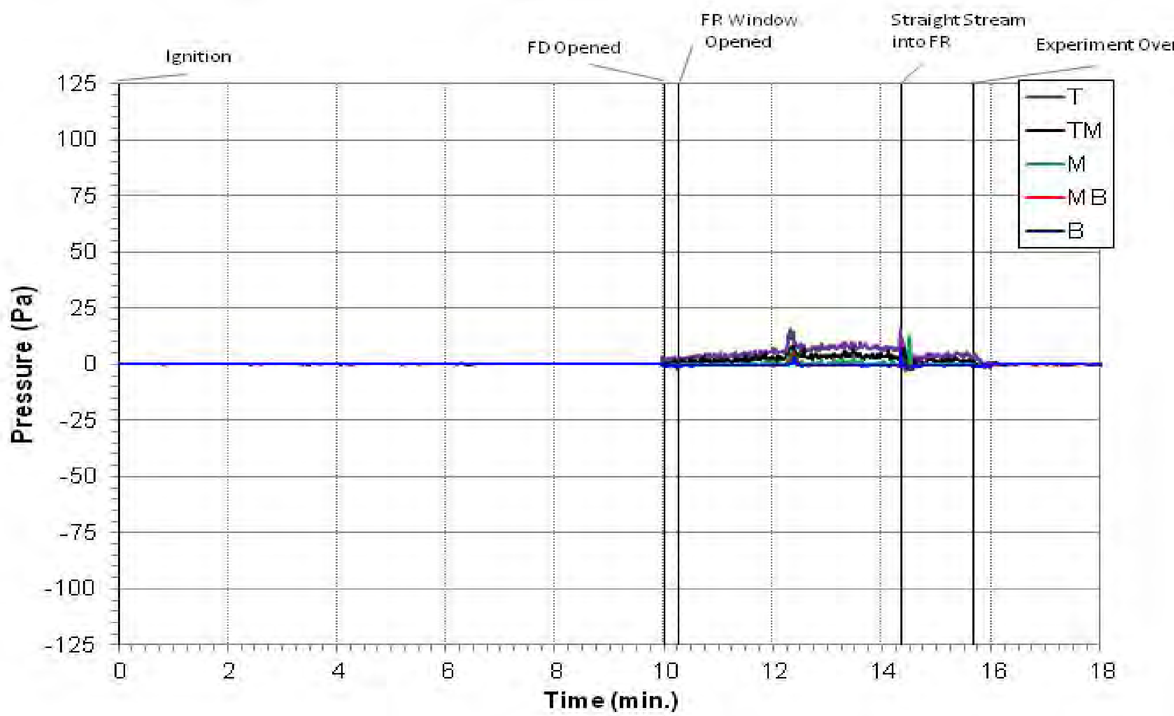


Figure E.33: Experiment 2 Front Door Pressure

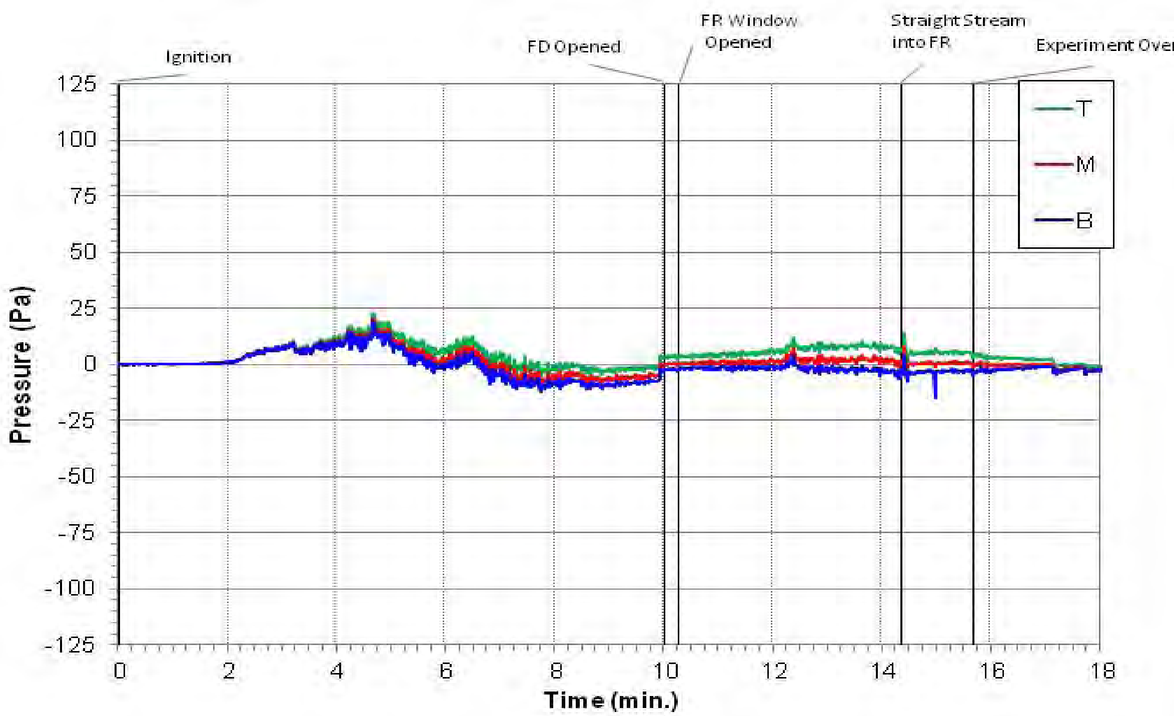


Figure E.34: Experiment 2 Living Room Pressure

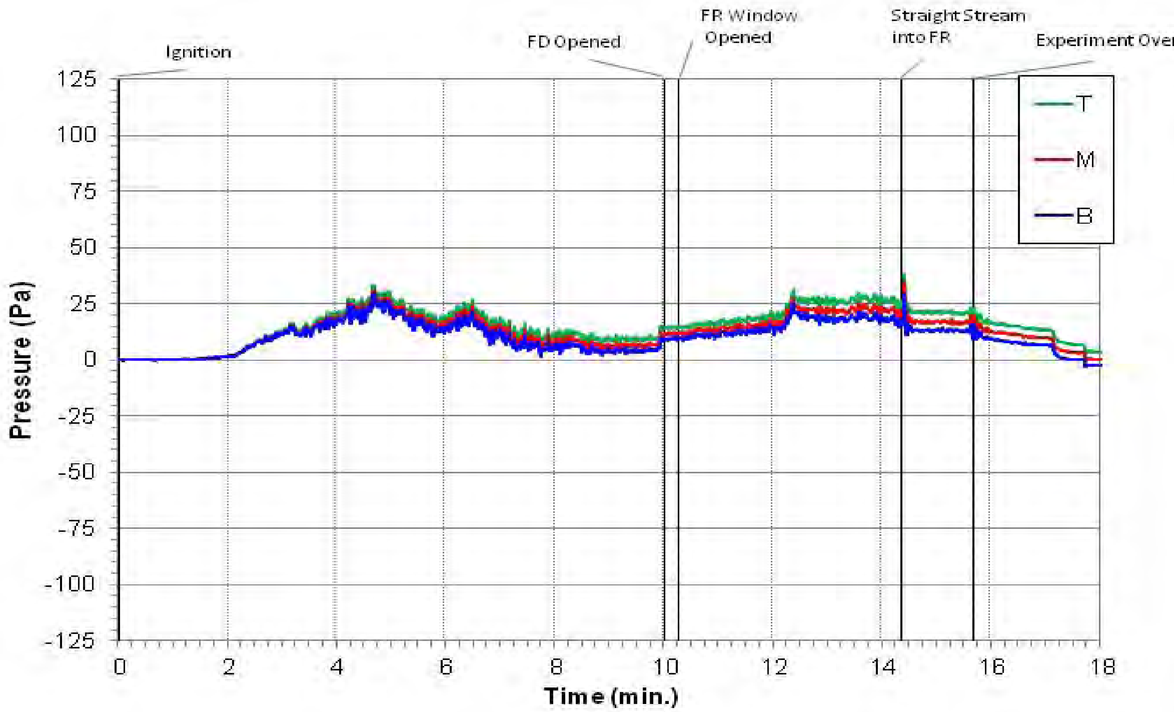


Figure E.35: Experiment 2 Bedroom 2 Pressure

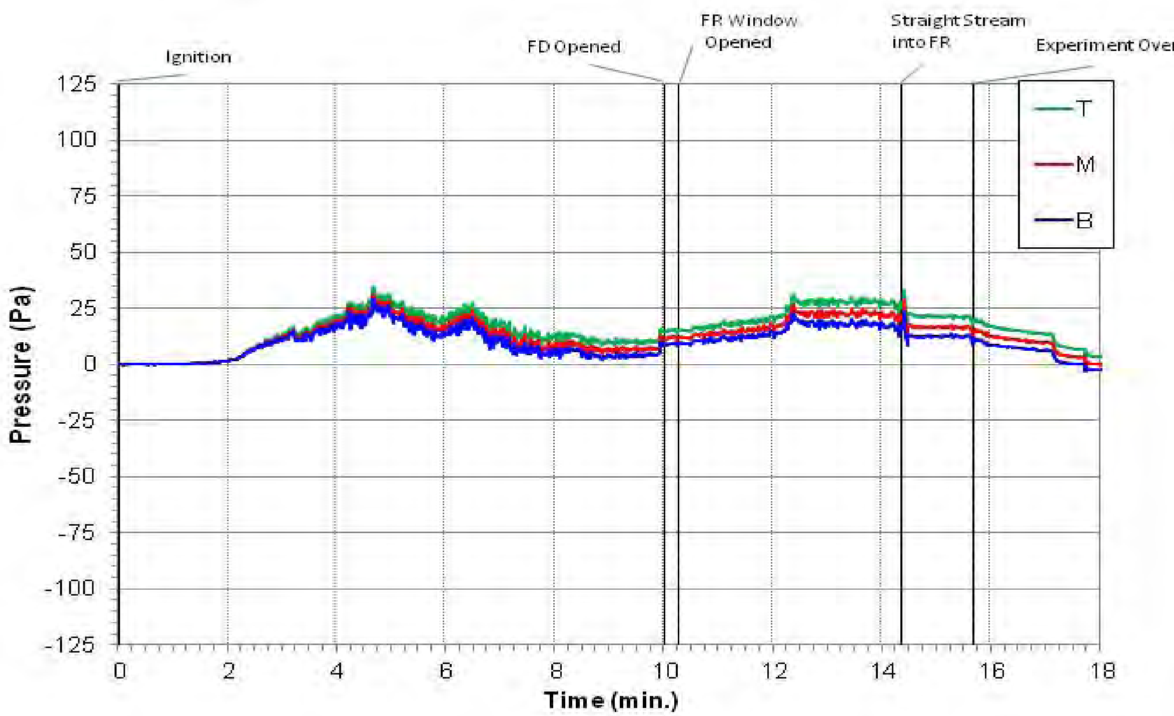


Figure E.36: Experiment 2 Bedroom 3 Pressure

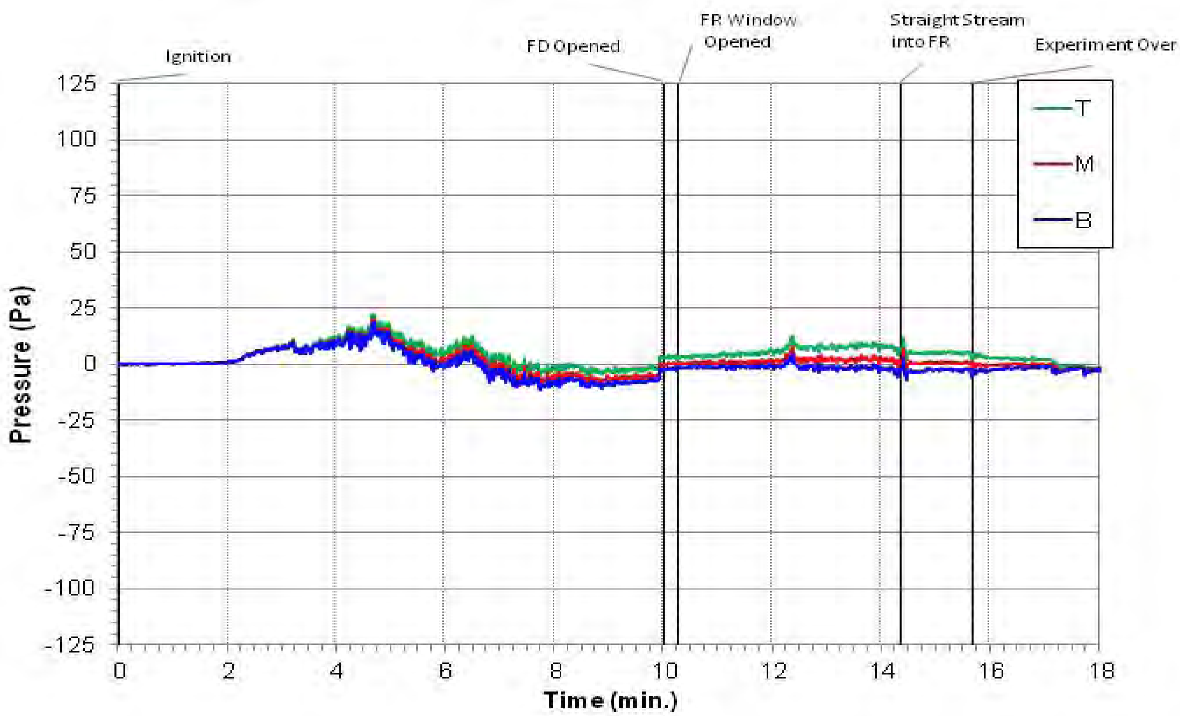


Figure E.37: Experiment 2 Kitchen Pressure

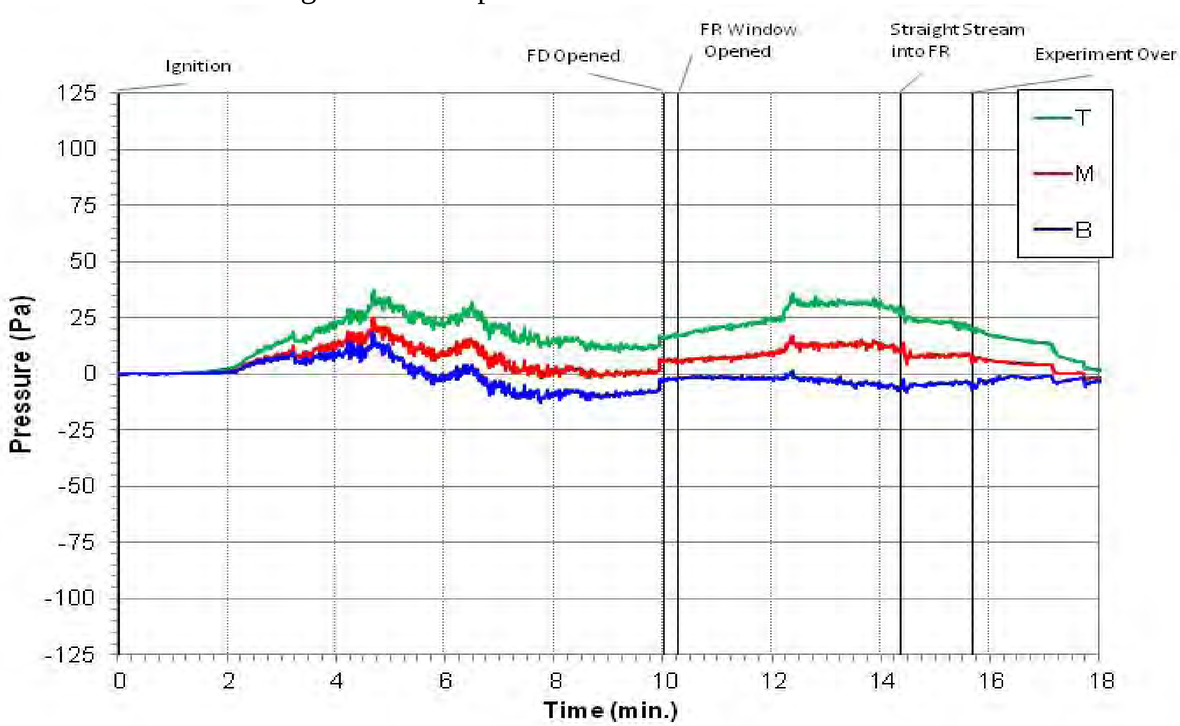


Figure E.38: Experiment 2 Family Room Pressure

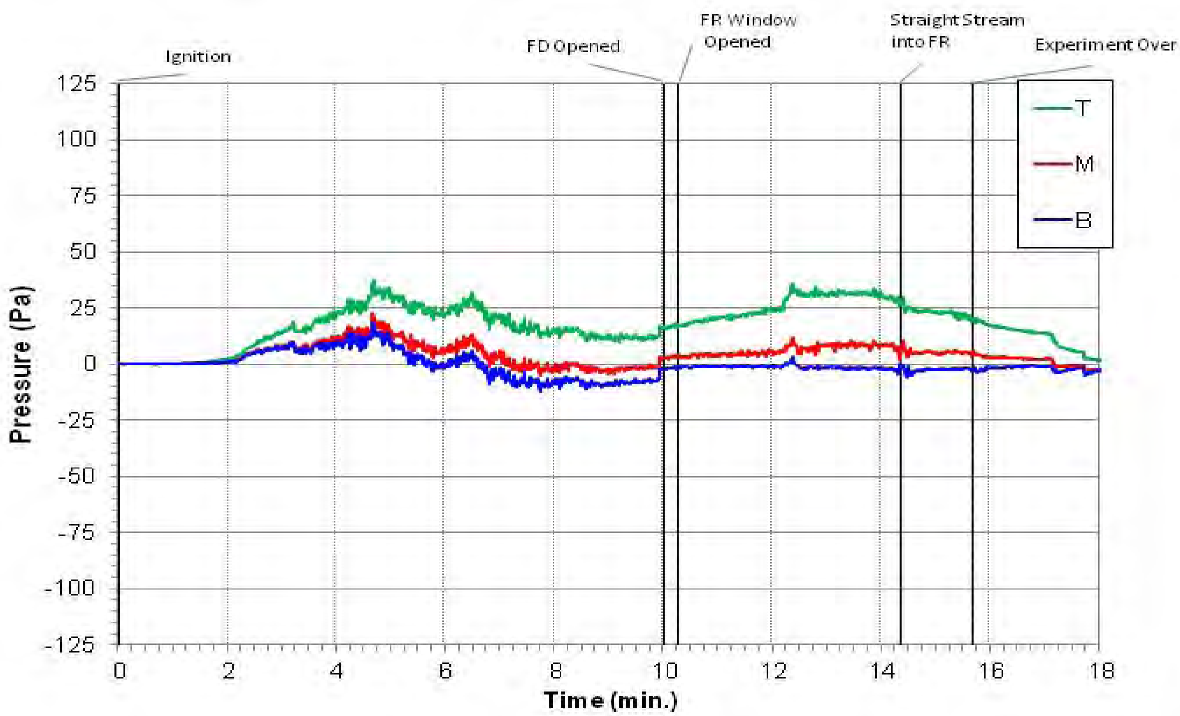


Figure E.39: Experiment 2 Foyer Pressure

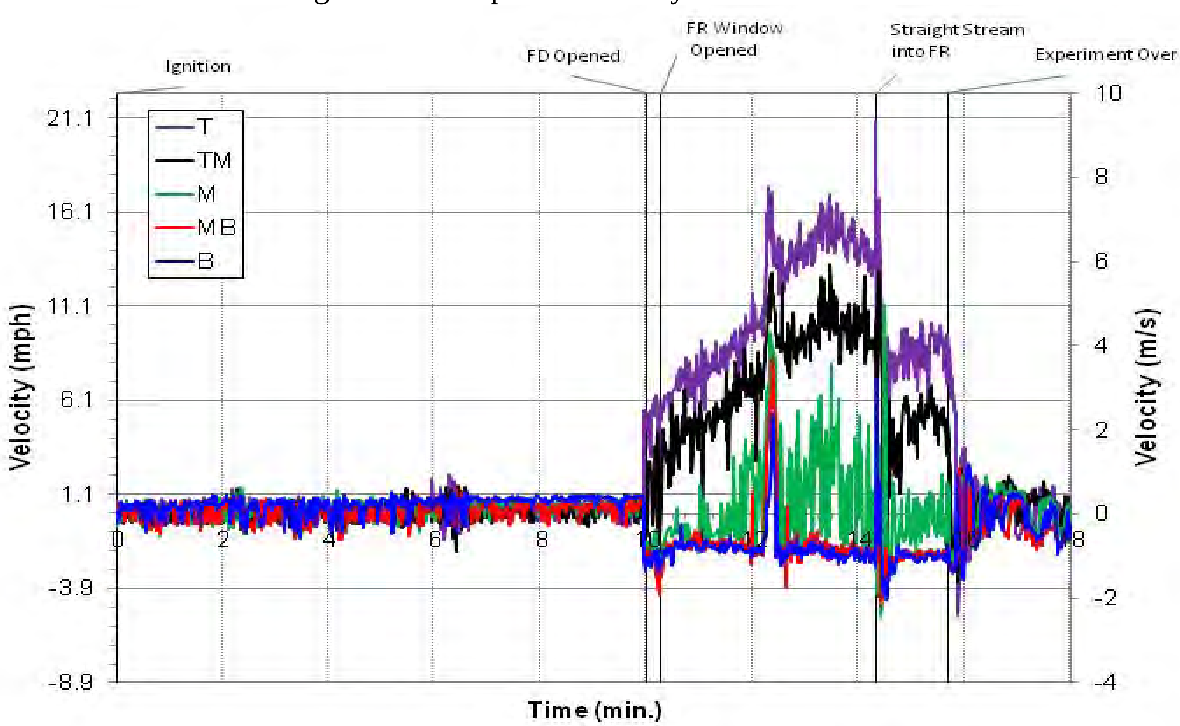


Figure E.40: Experiment 2 Front Door Velocity

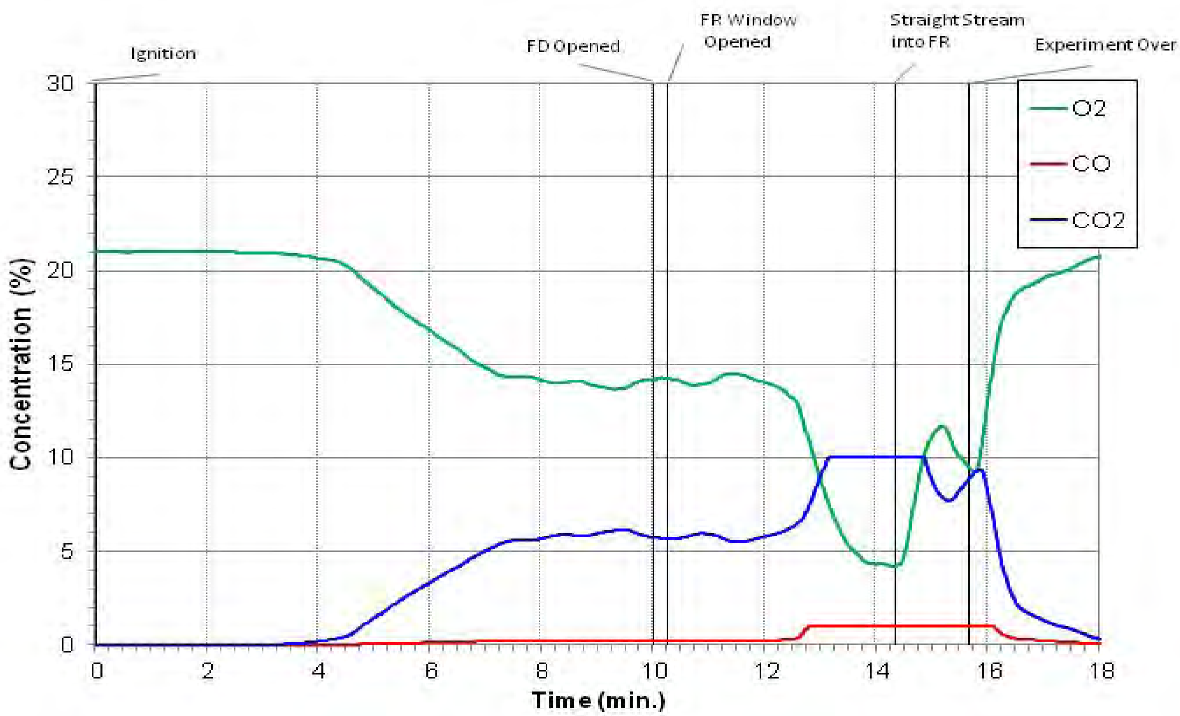


Figure E.41: Experiment 2 Front Door Gas

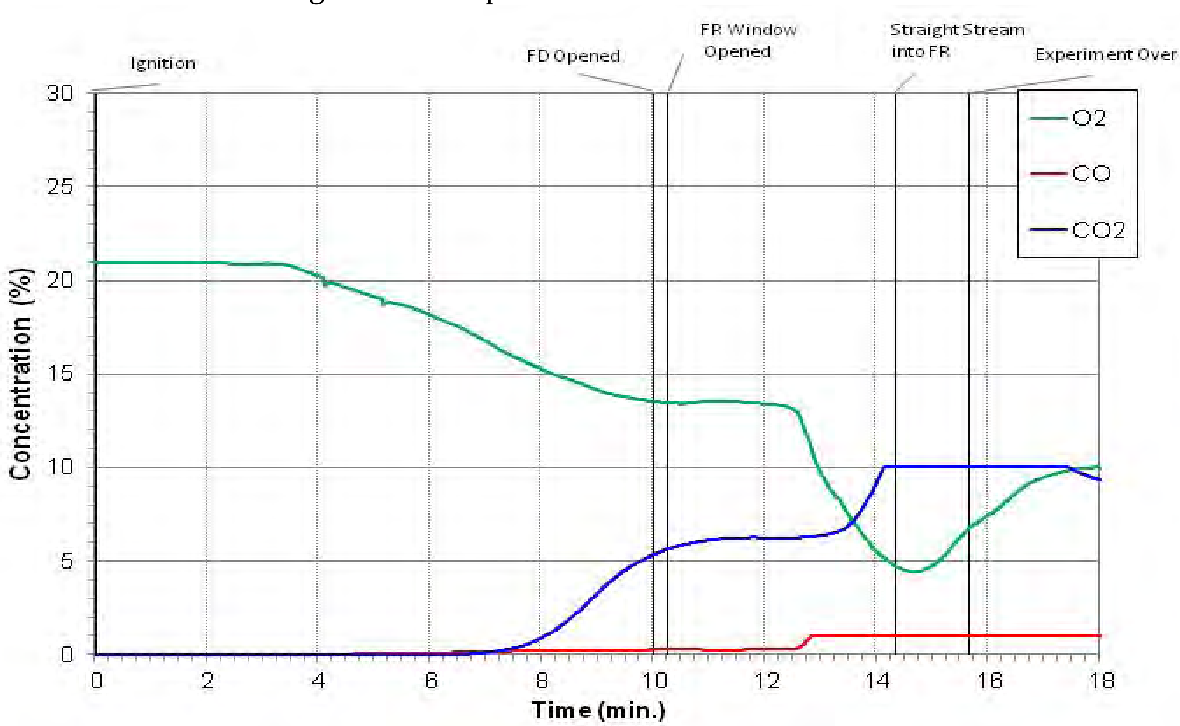


Figure E.42: Experiment 2 Bedroom 1 Gas

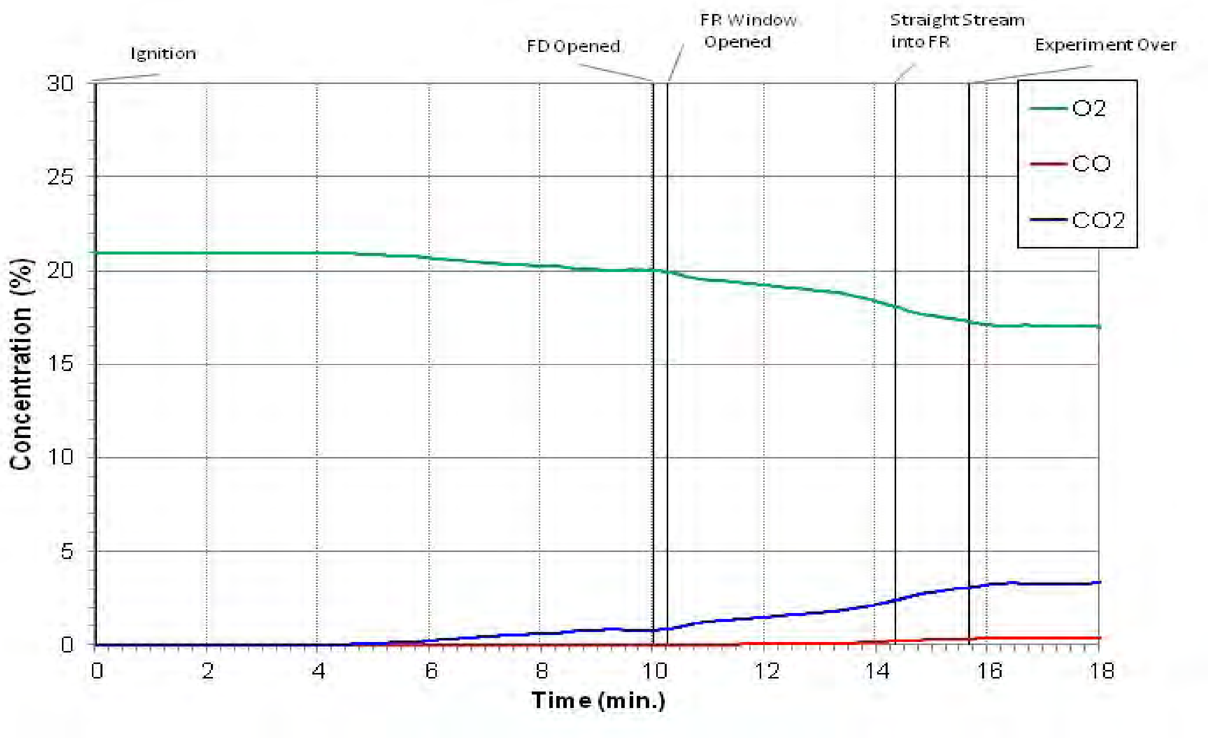


Figure E.43: Experiment 2 Bedroom 2 Gas

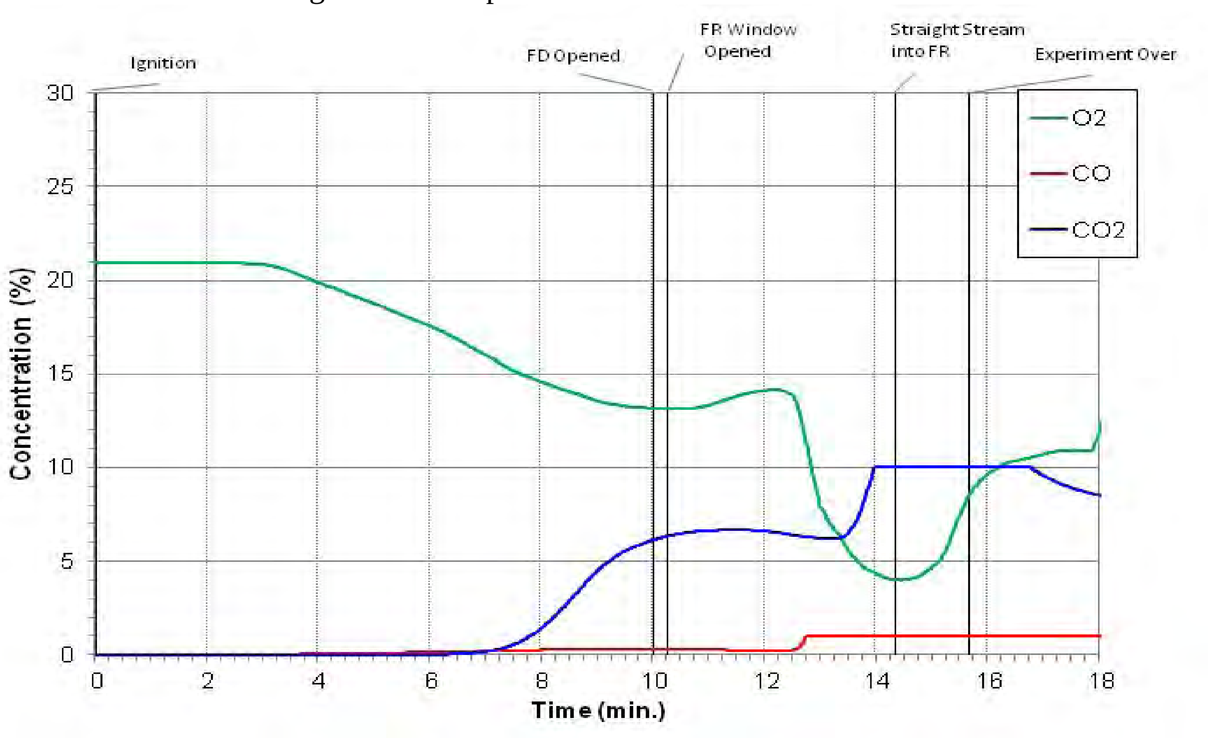


Figure E.44: Experiment 2 Bedroom 3 Gas

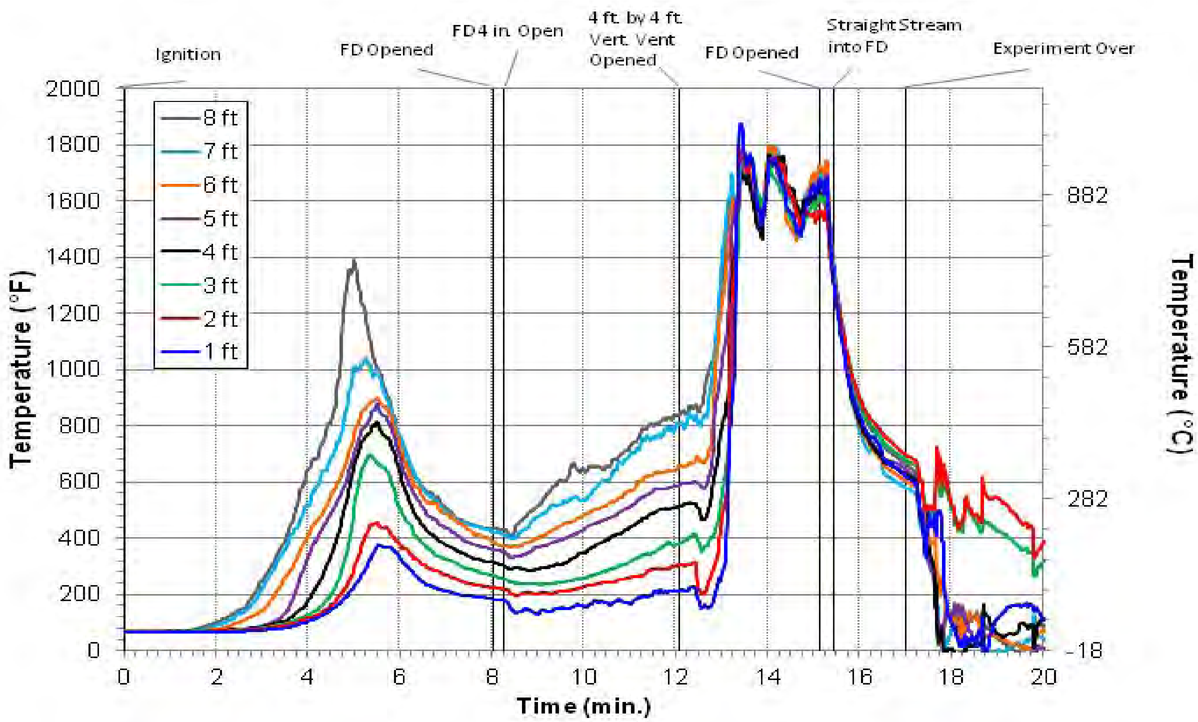


Figure E.45: Experiment 3 Living Room Temperature

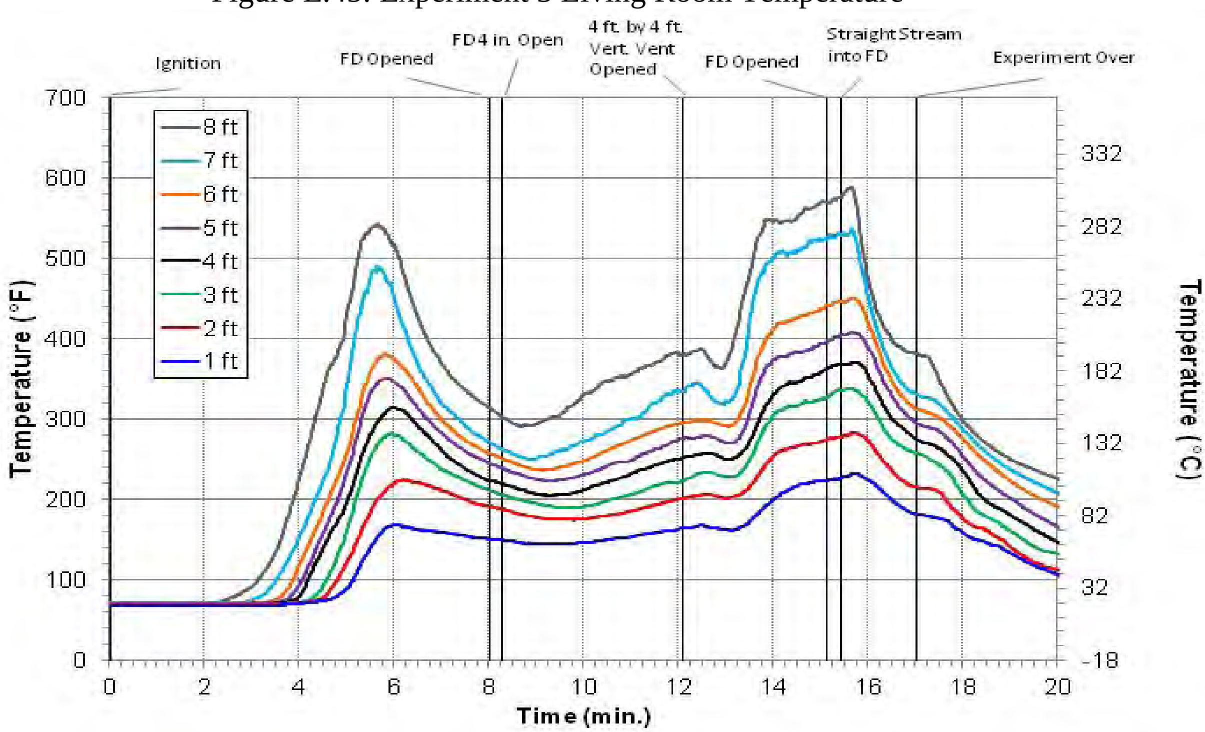


Figure E.46: Experiment 3 Bedroom 1 Temperature

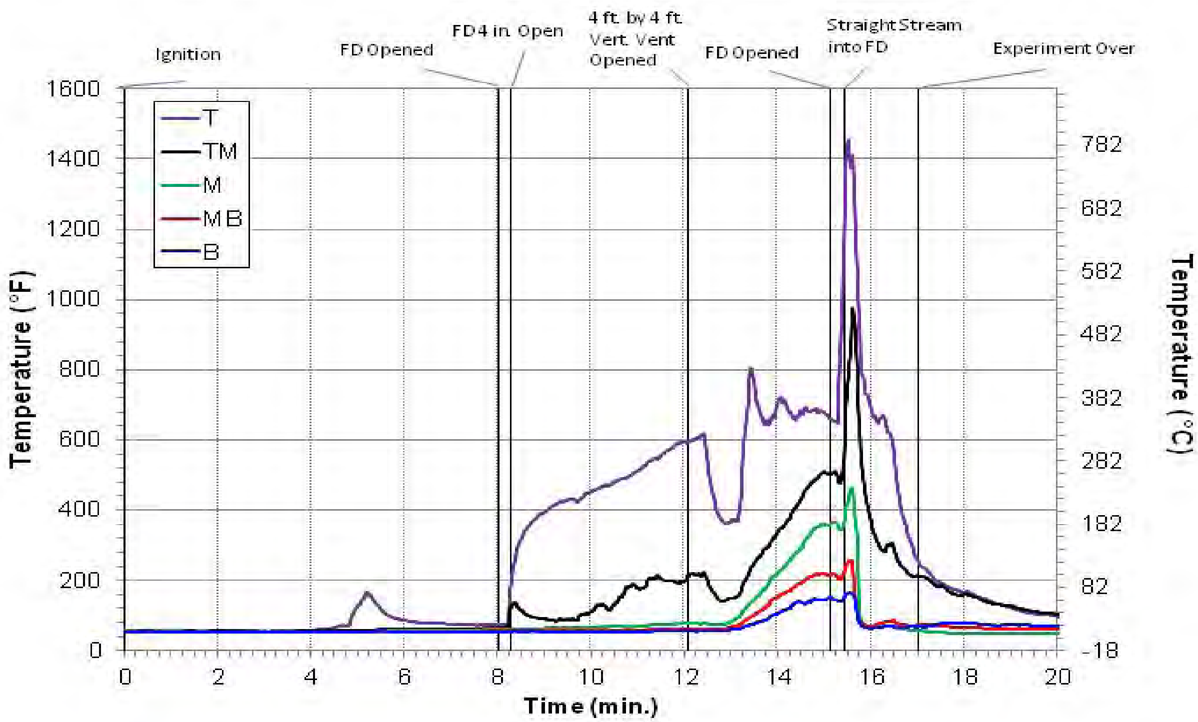


Figure E.47: Experiment 3 Front Door Temperature

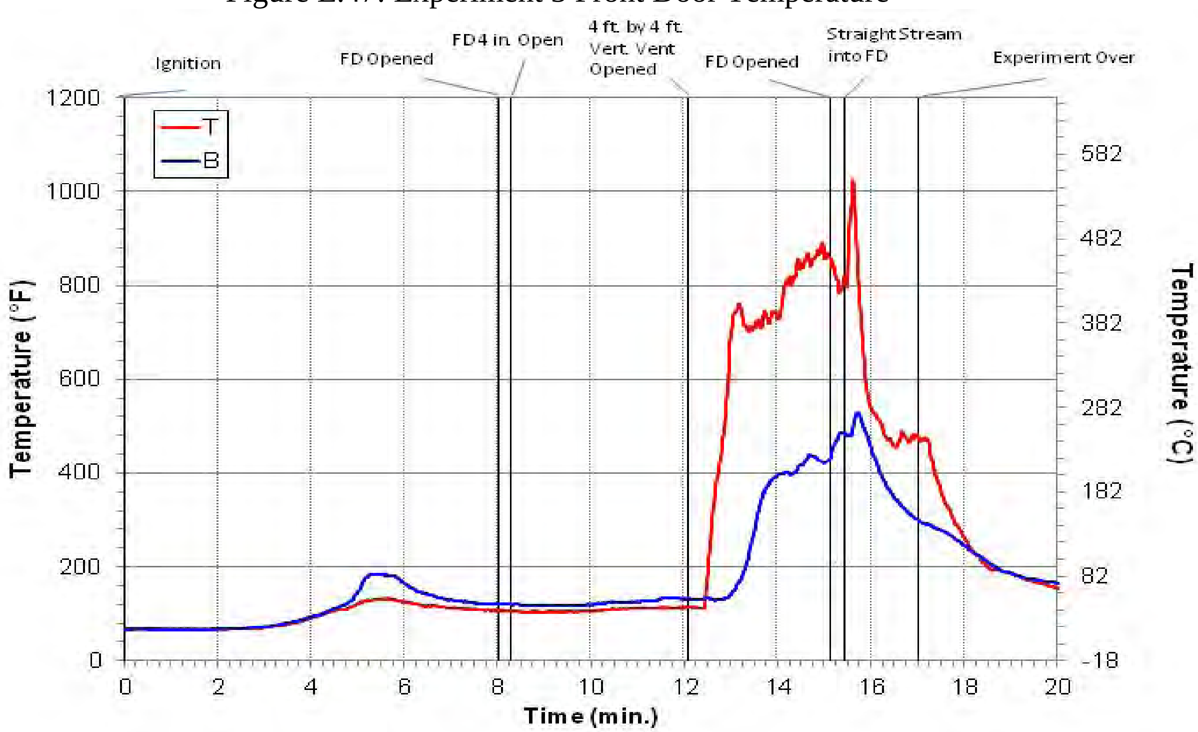


Figure E.48: Experiment 3 Vent Temperature

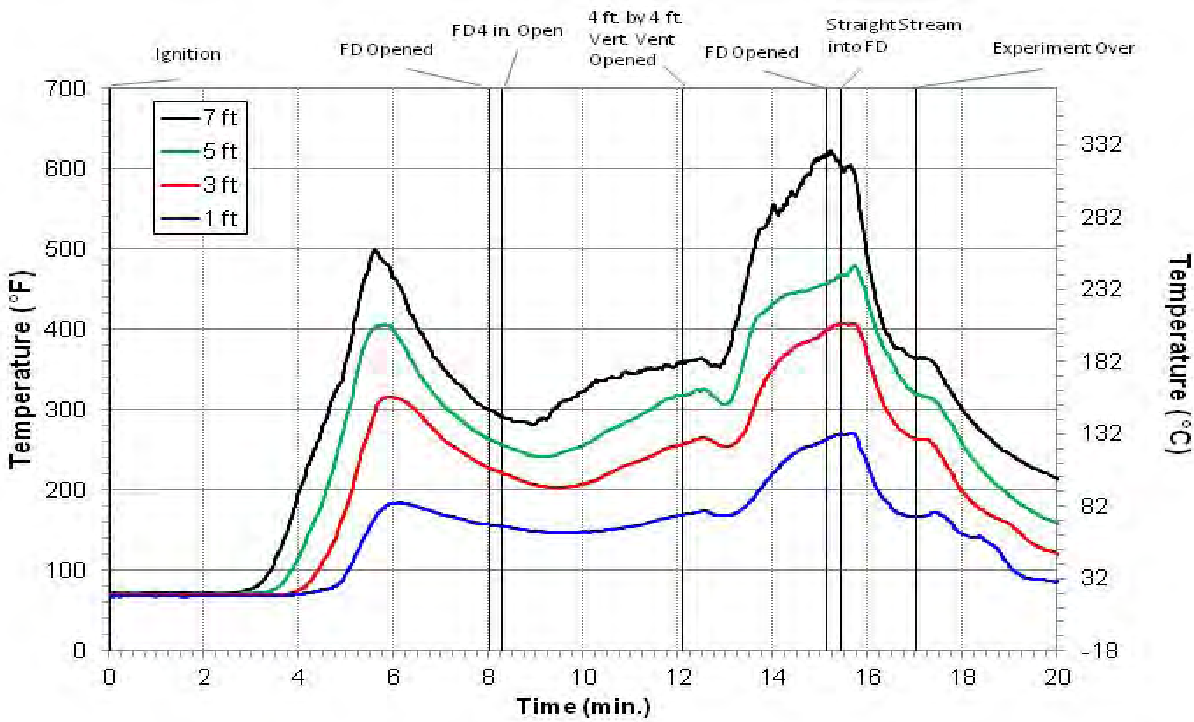


Figure E.49: Experiment 3 Bedroom 2 Temperature

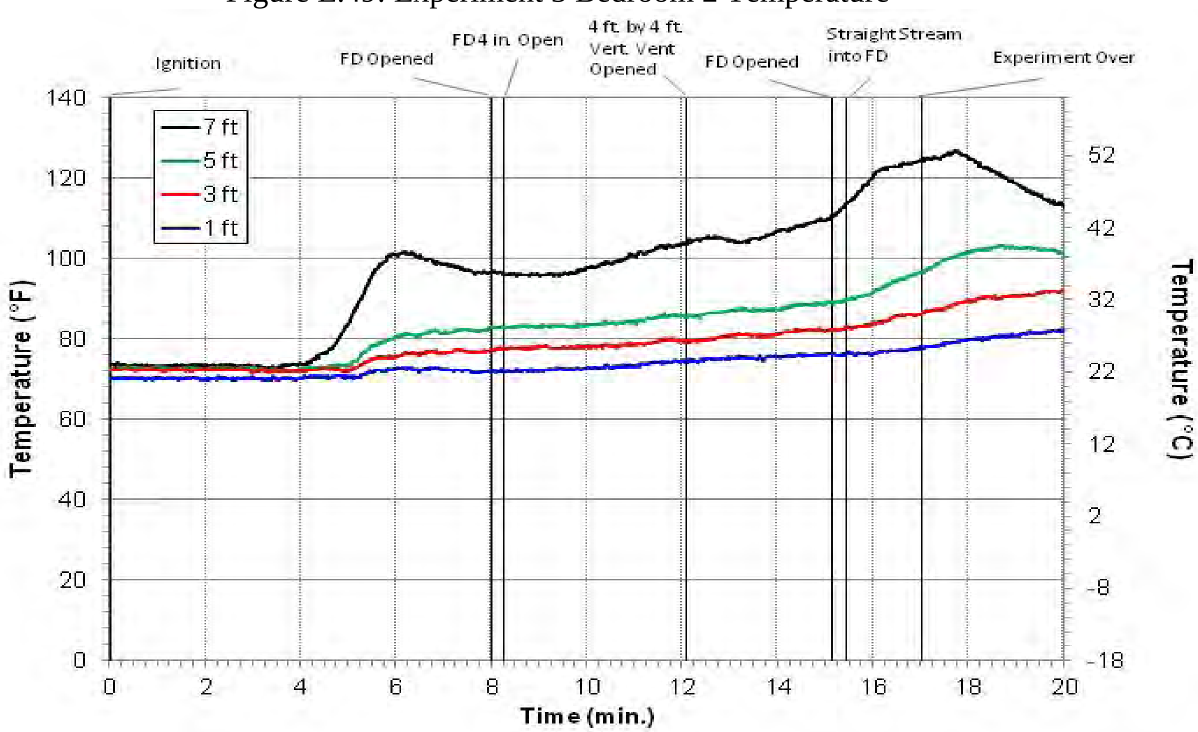


Figure E.50: Experiment 3 Bedroom 3 Temperature

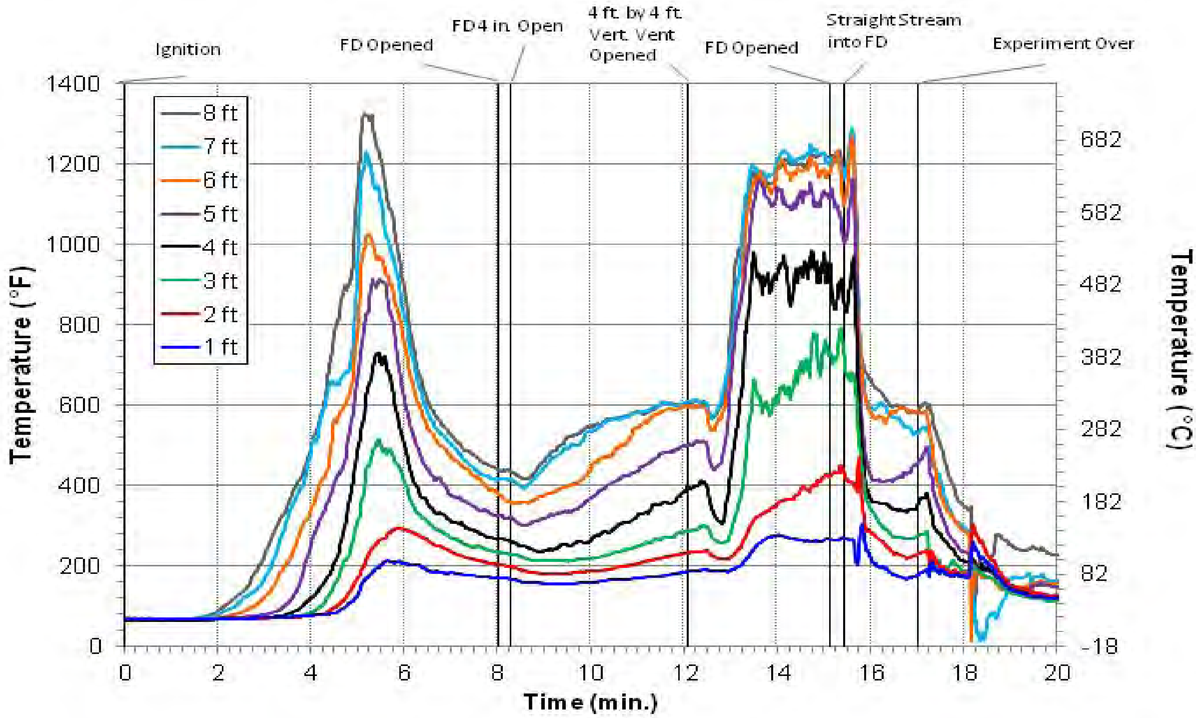


Figure E.51: Experiment 3 Hallway Temperature

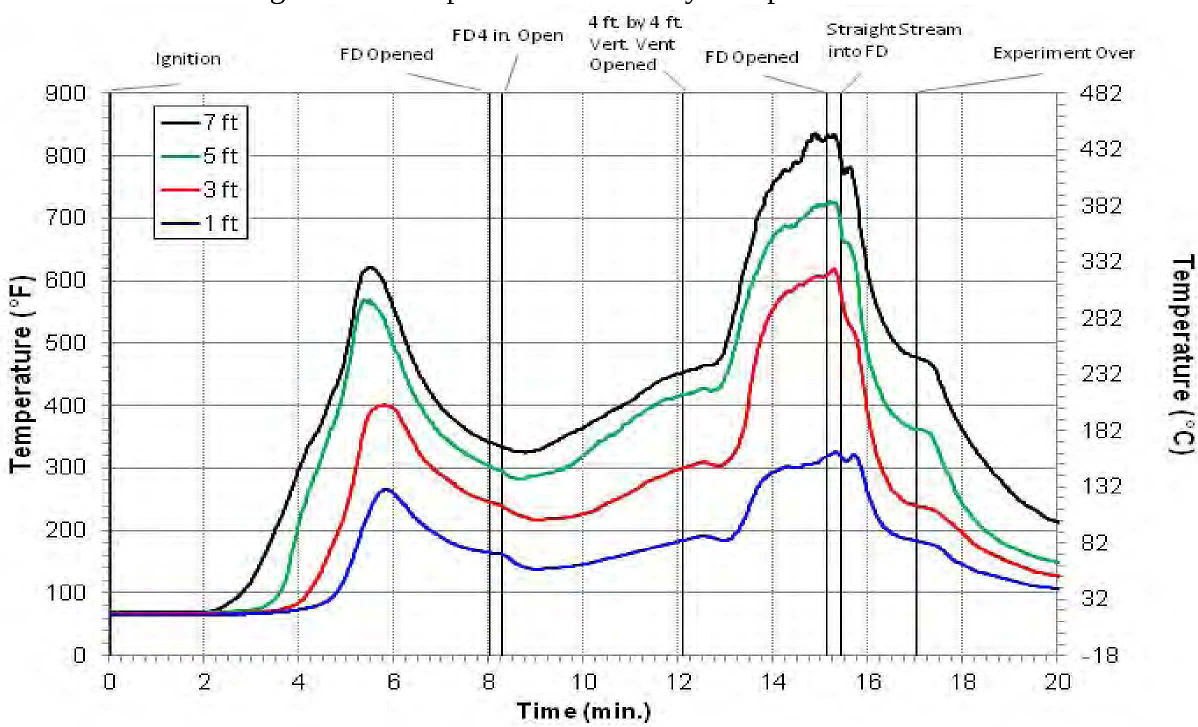


Figure E.52: Experiment 3 Dining Room Temperature

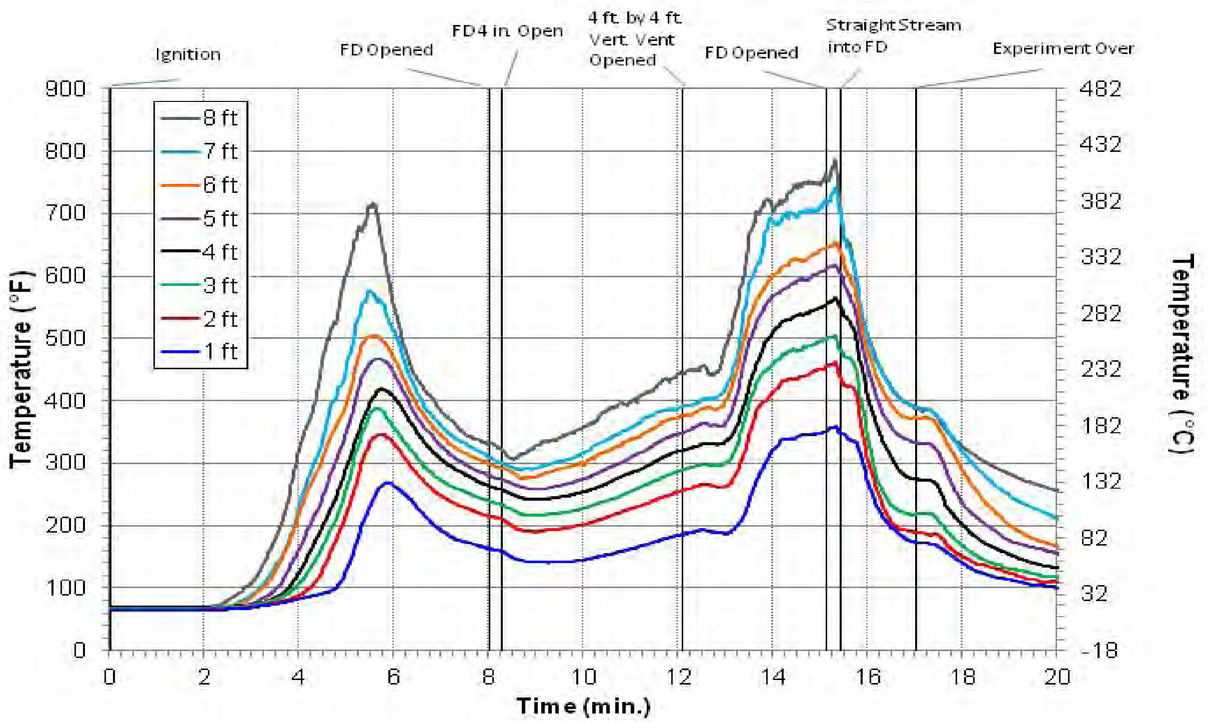


Figure E.53: Experiment 3 Kitchen Temperature

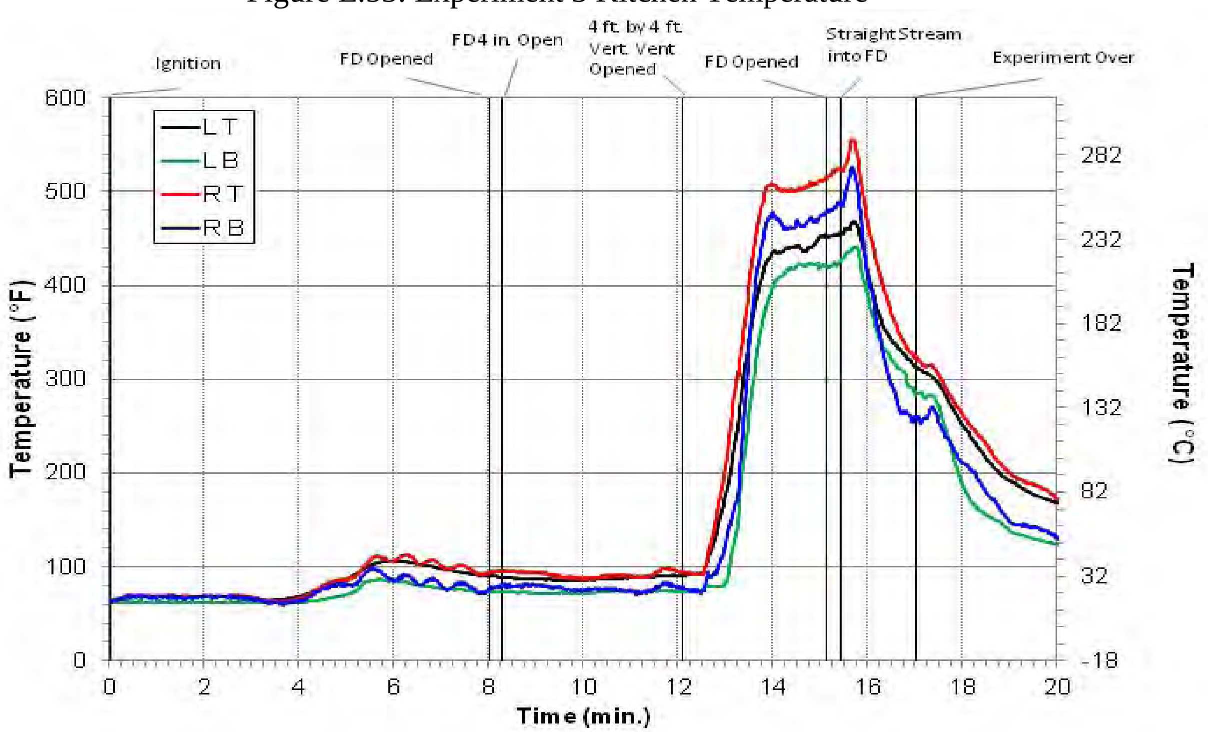


Figure E.54: Experiment 3 Attic Temperature

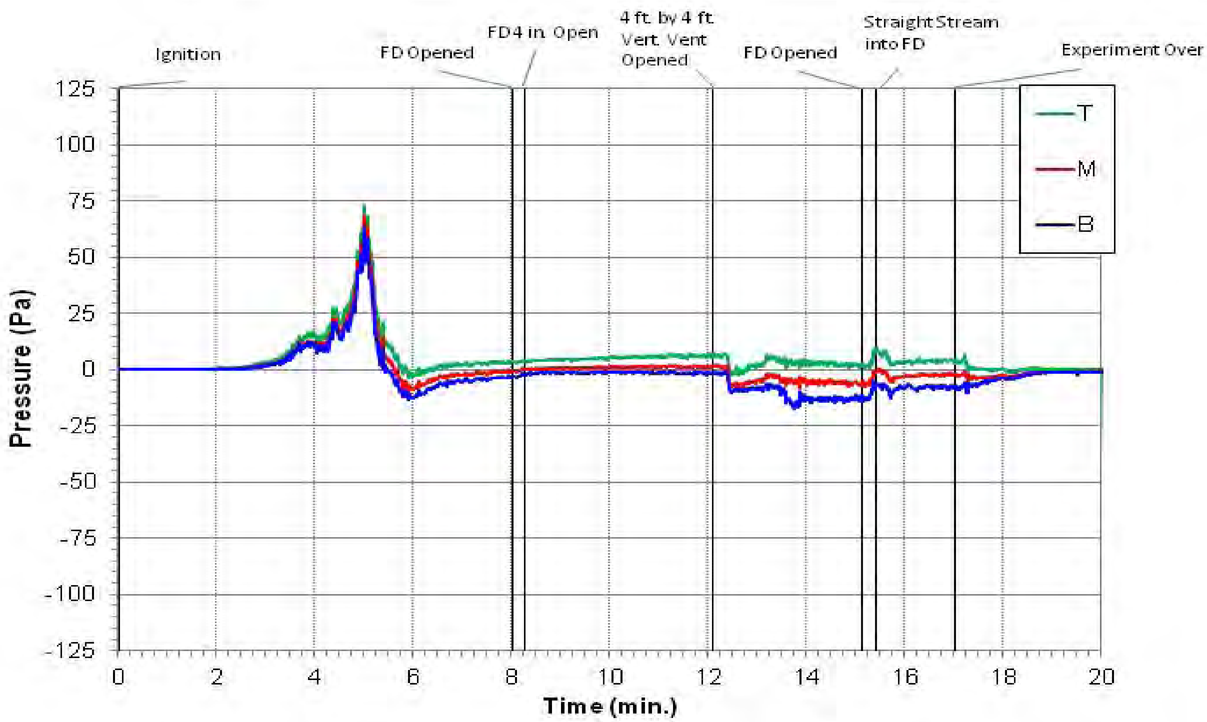


Figure E.55: Experiment 3 Living Room Pressure

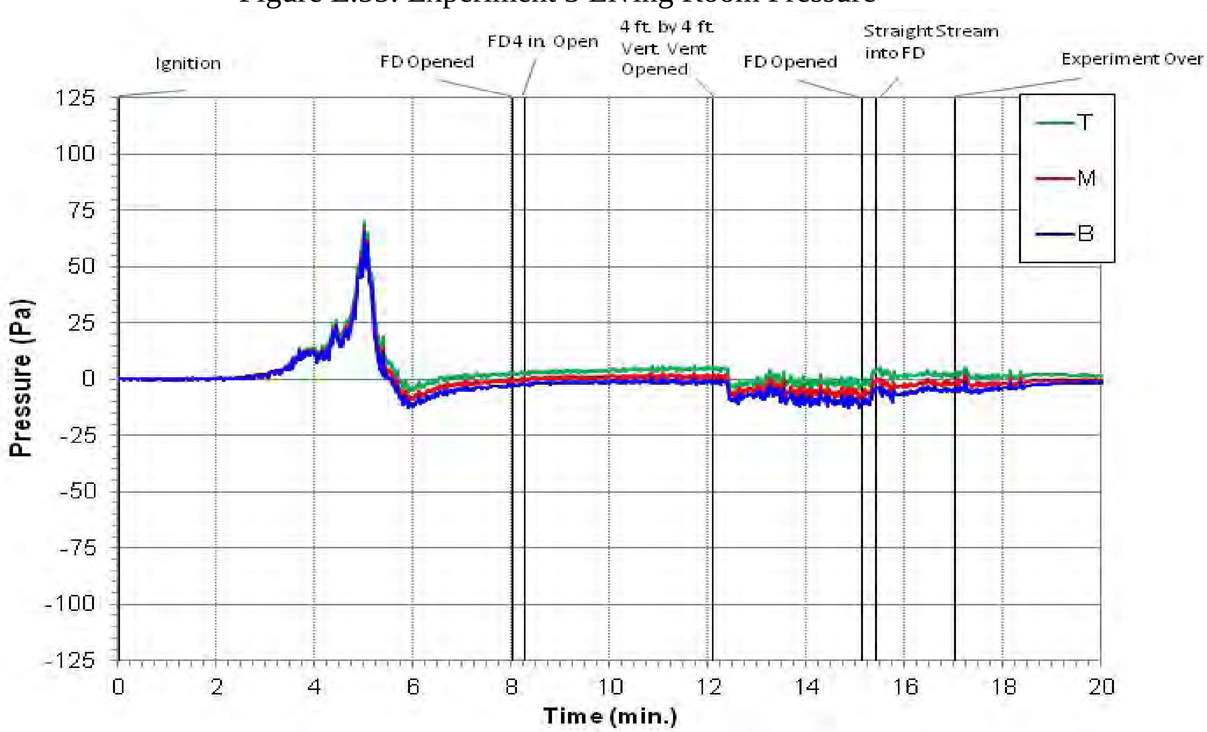


Figure E.56: Experiment 3 Bedroom 1 Pressure

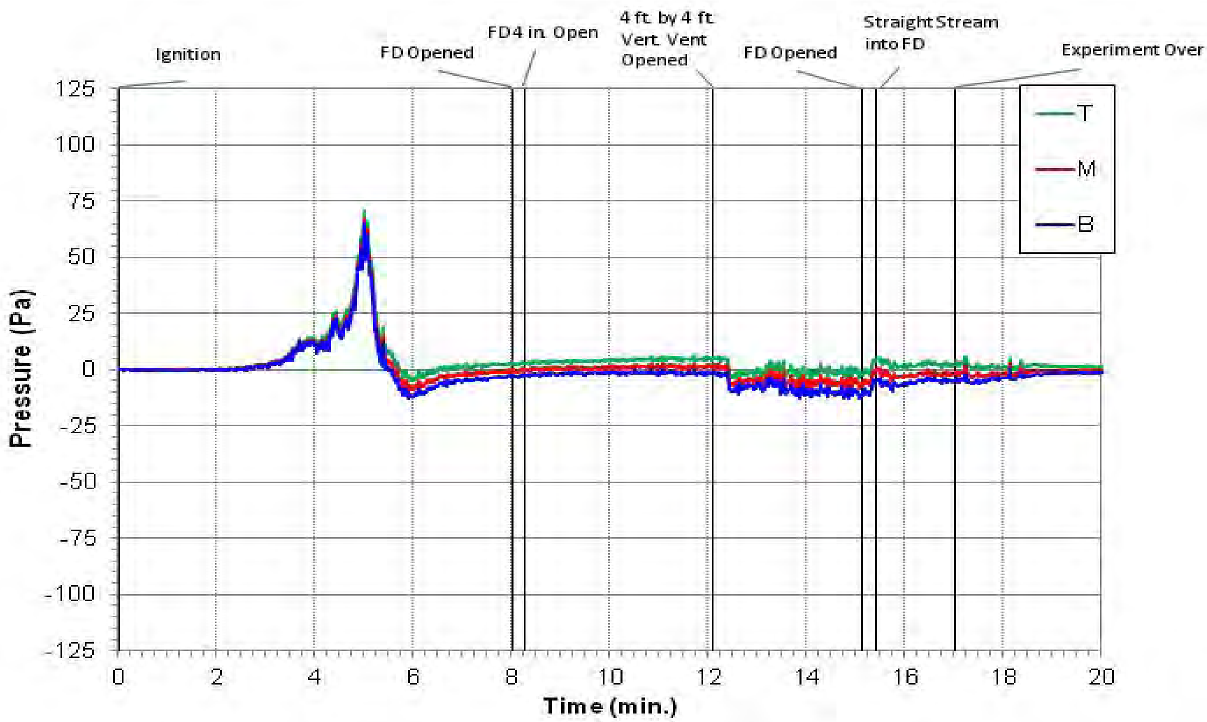


Figure E.57: Experiment 3 Bedroom 2 Pressure

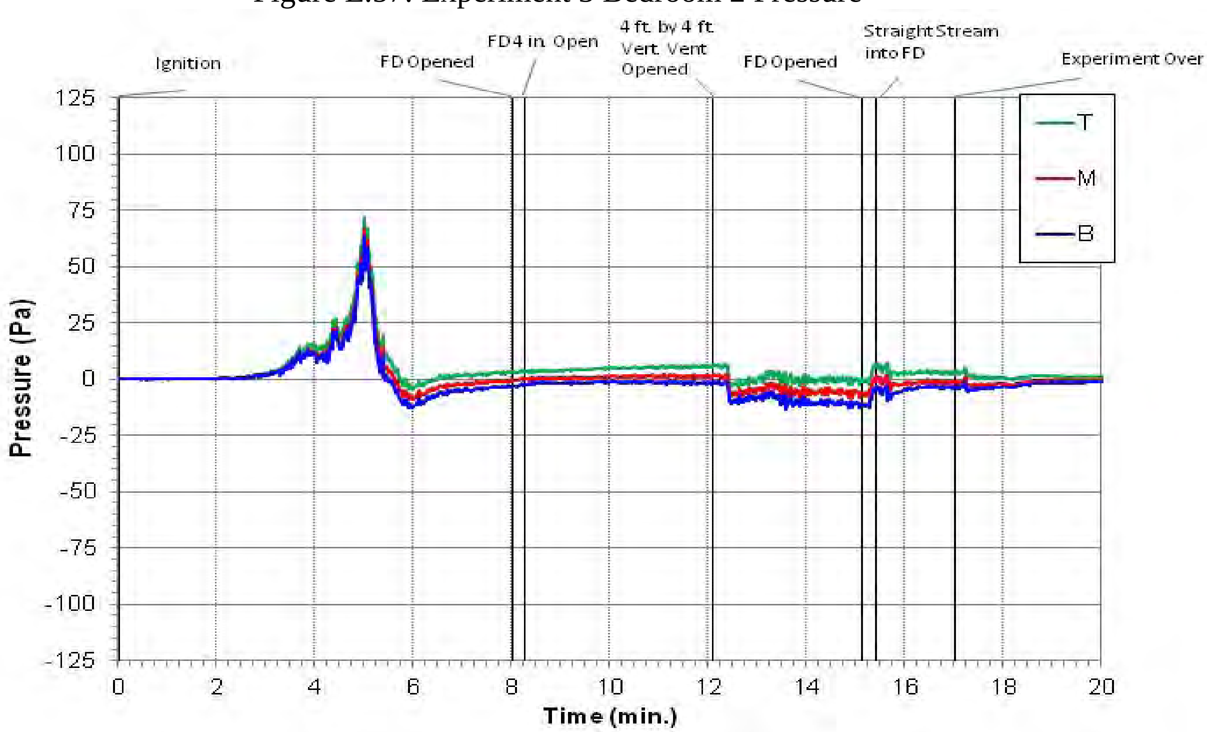


Figure E.58: Experiment 3 Kitchen Pressure

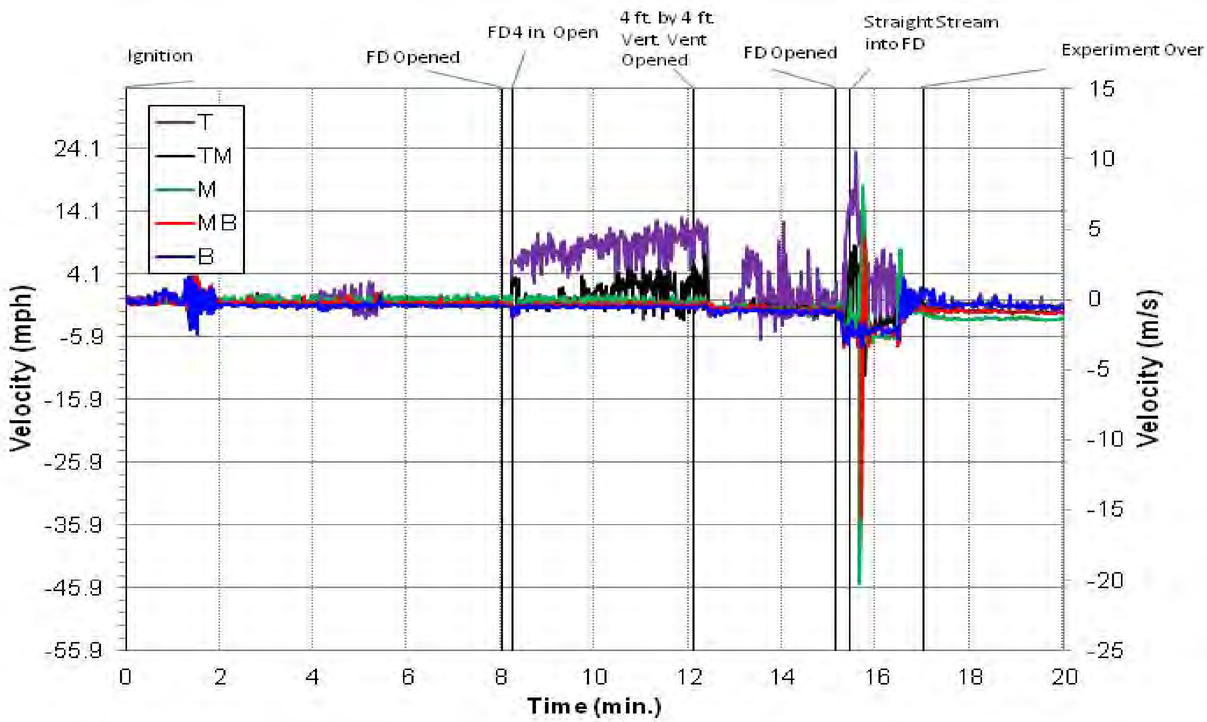


Figure E.59: Experiment 3 Front Door Velocity

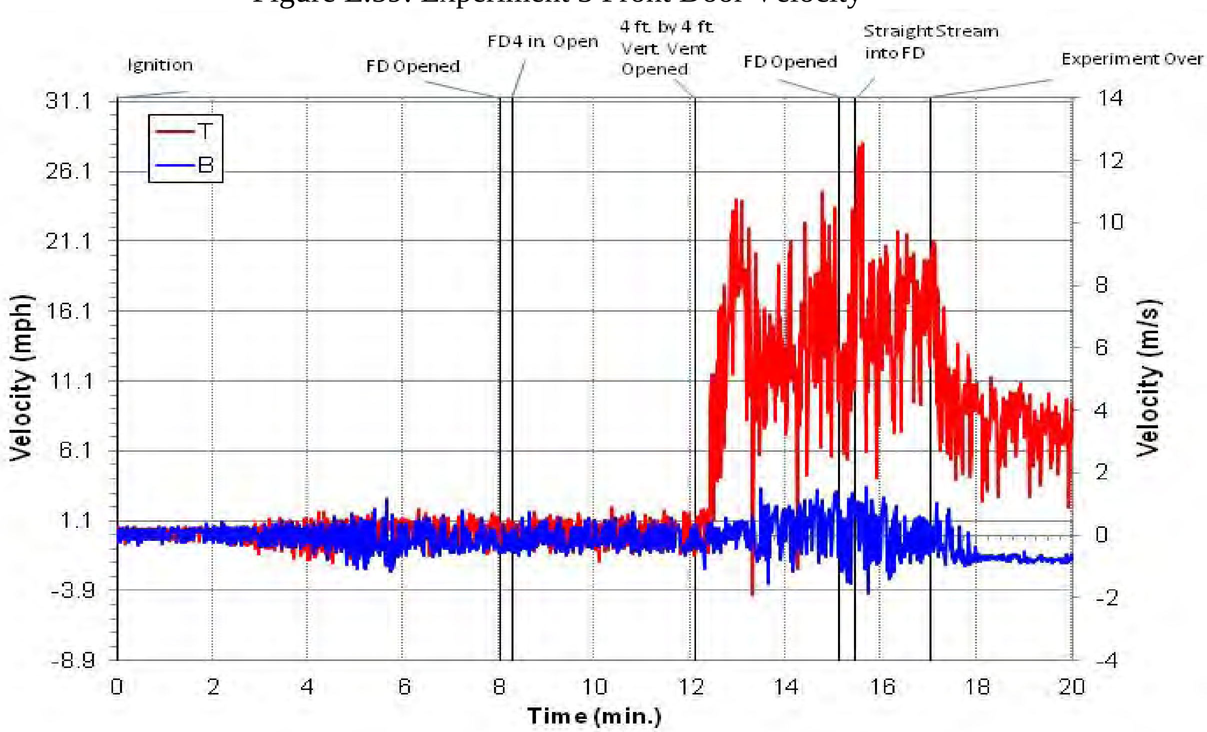


Figure E.60: Experiment 3 Vent Velocity

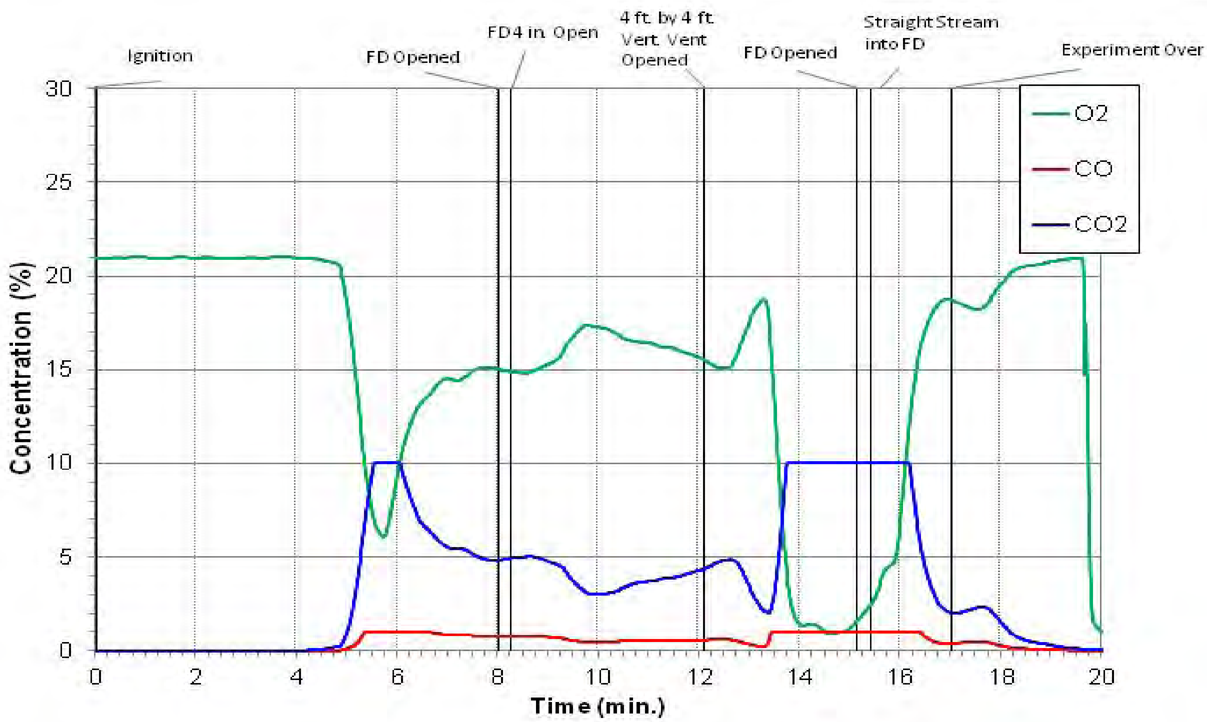


Figure E.61: Experiment 3 Living Room Gas

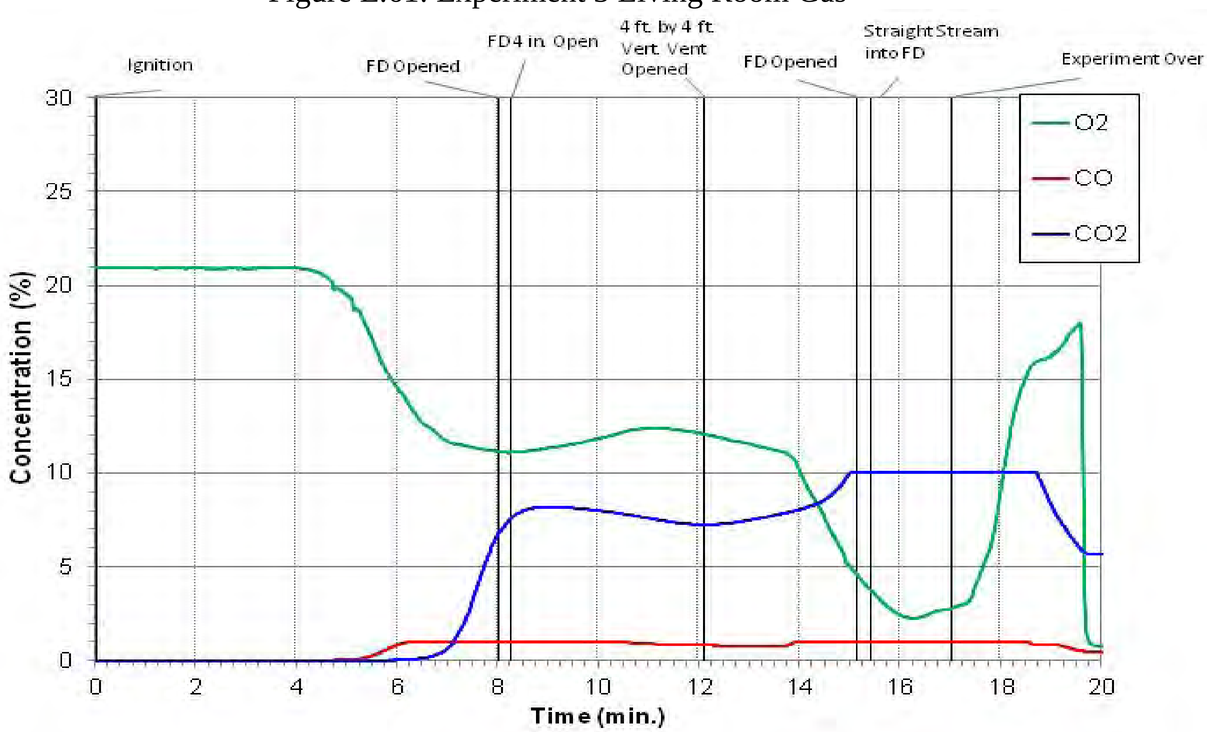


Figure E.62: Experiment 3 Bedroom 1 Gas

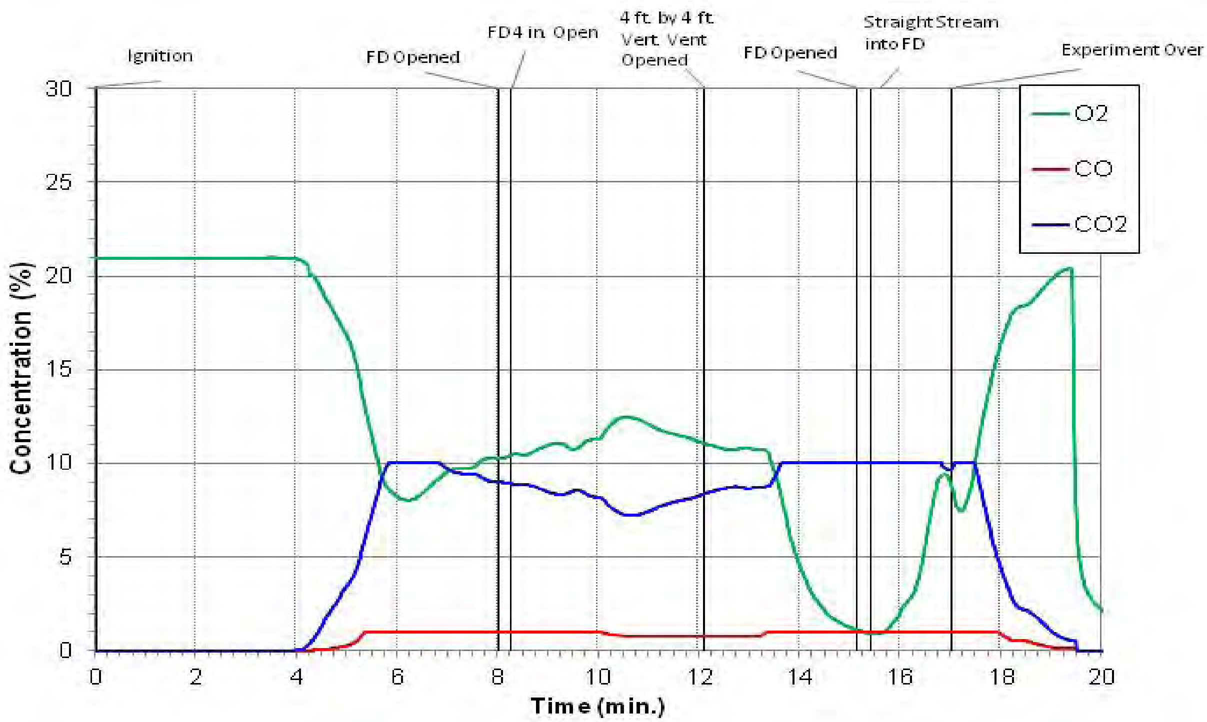


Figure E.63: Experiment 3 Bedroom 2 Gas

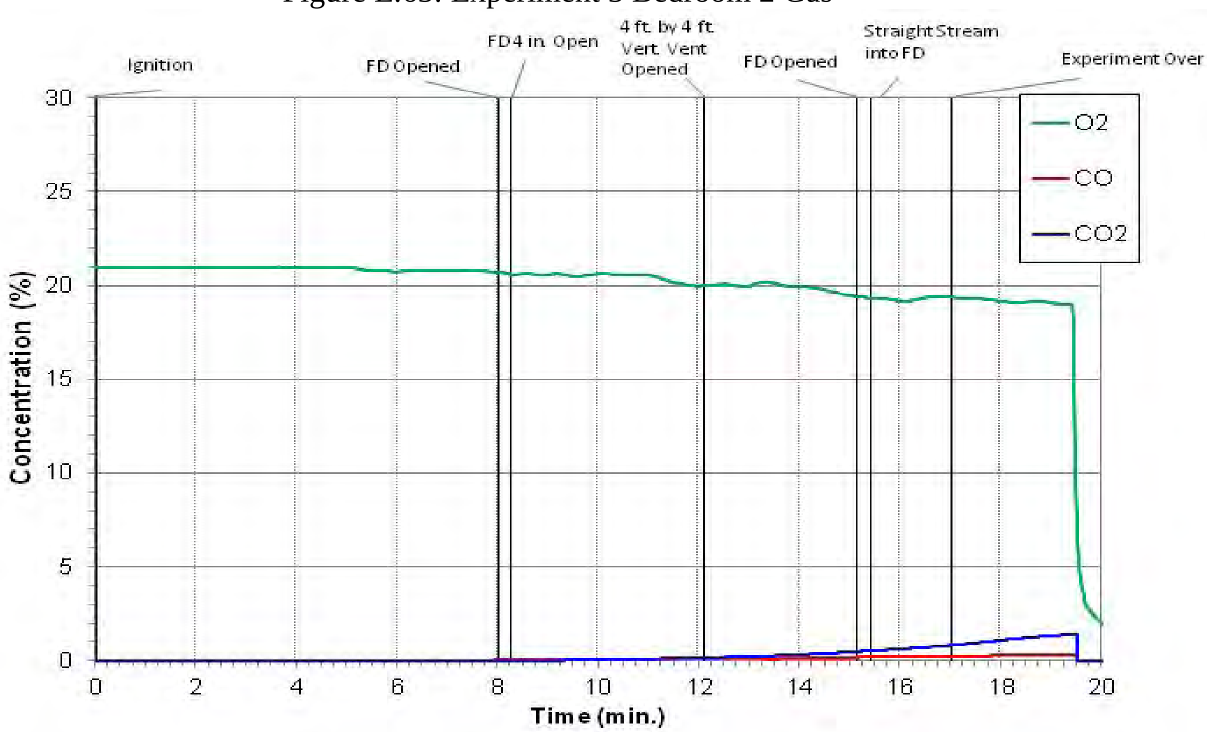


Figure E.64: Experiment 3 Bedroom 3 Gas

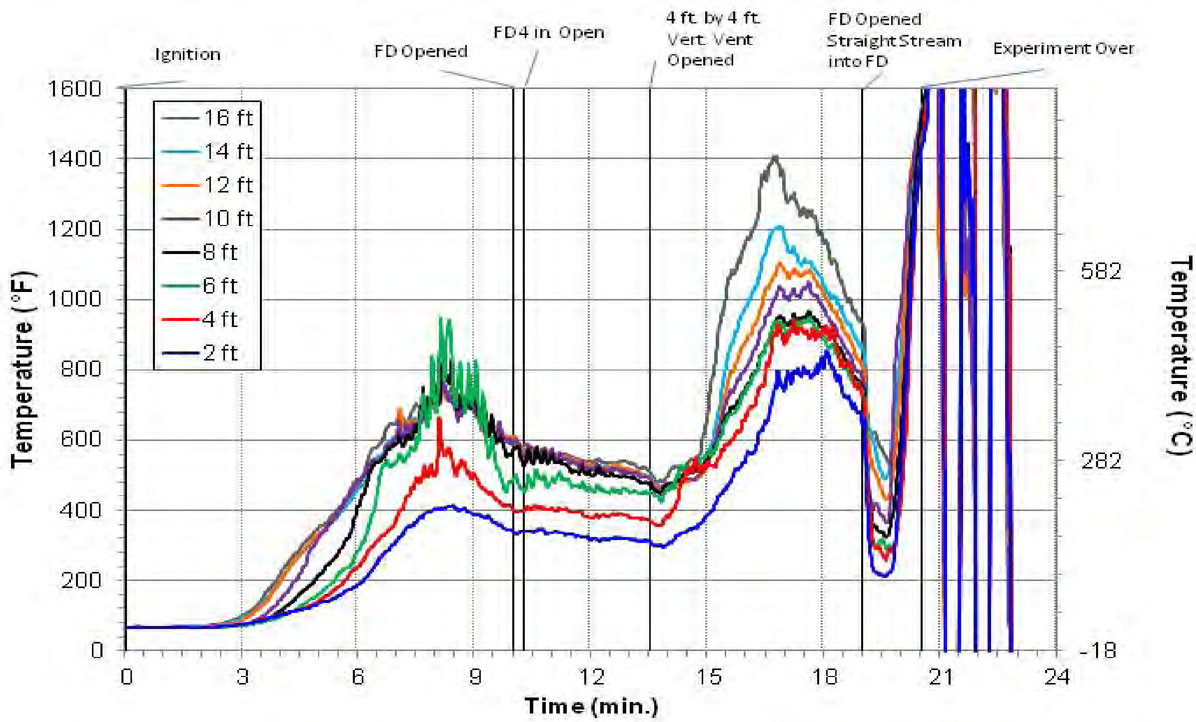


Figure E.65: Experiment 4 Family Room Temperature

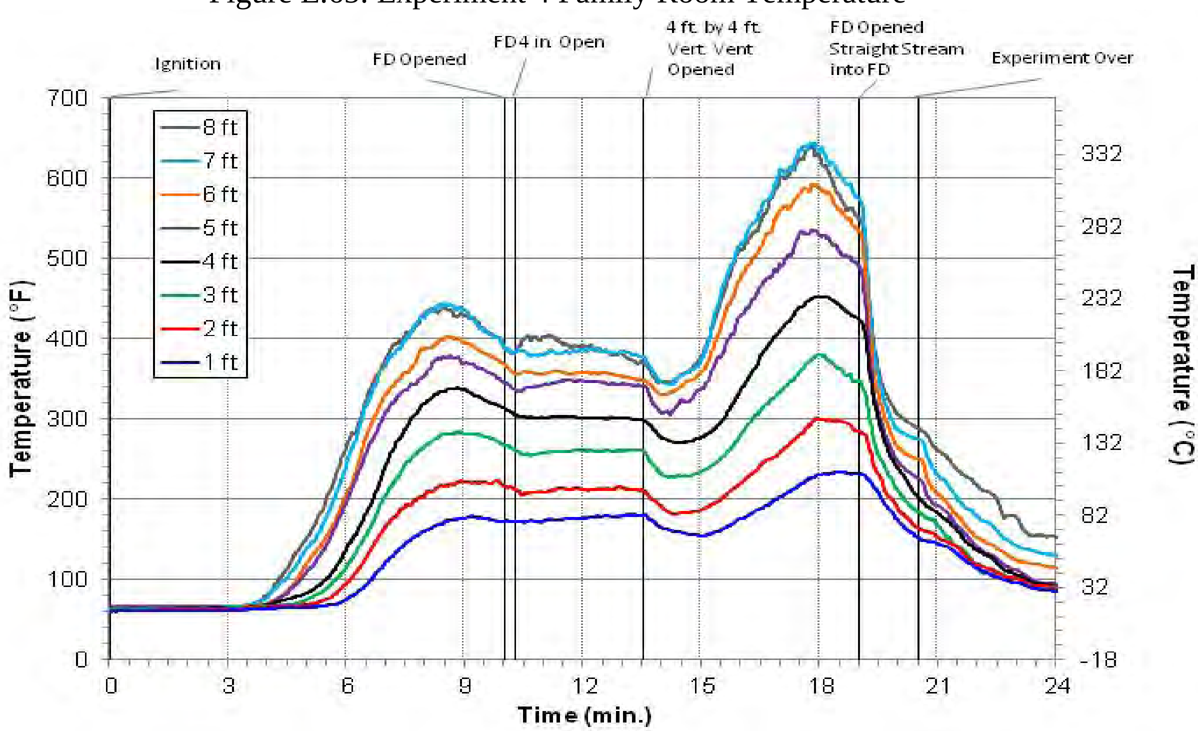


Figure E.66: Experiment 4 Kitchen Temperature

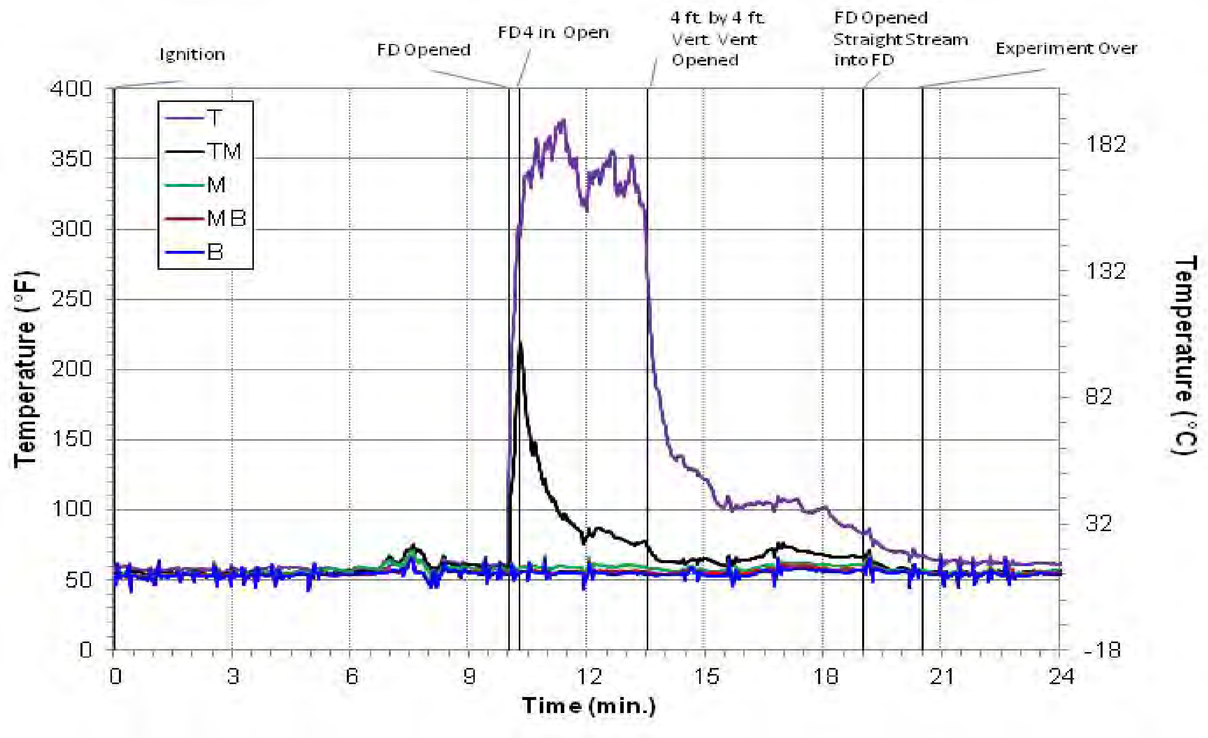


Figure E.67: Experiment 4 Front Door Temperature

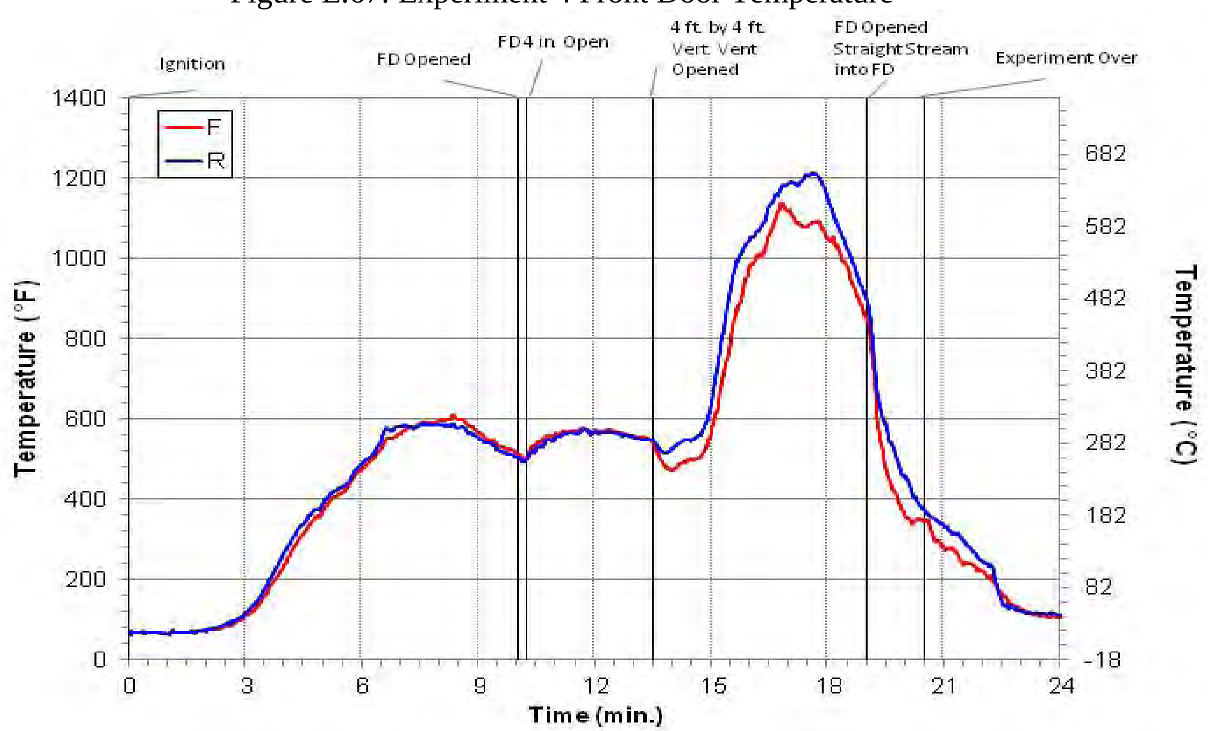


Figure E.68: Experiment 4 Vent Temperature

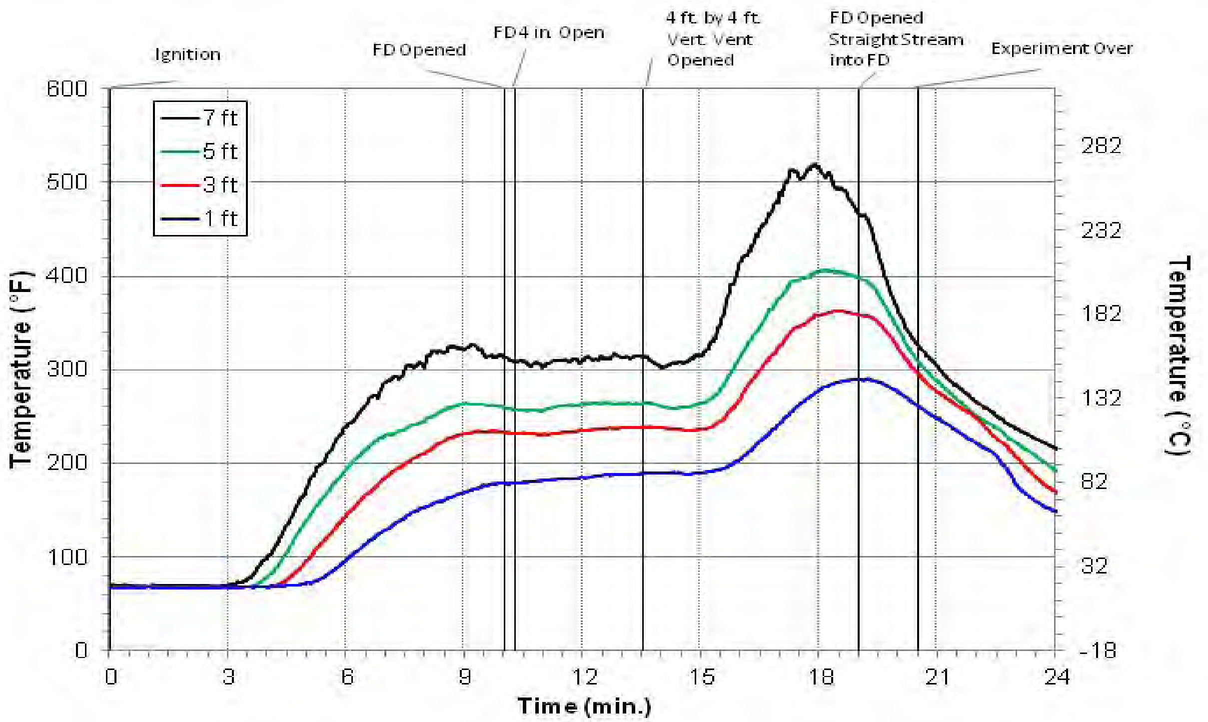


Figure E.69: Experiment 4 Bedroom 1 Temperature

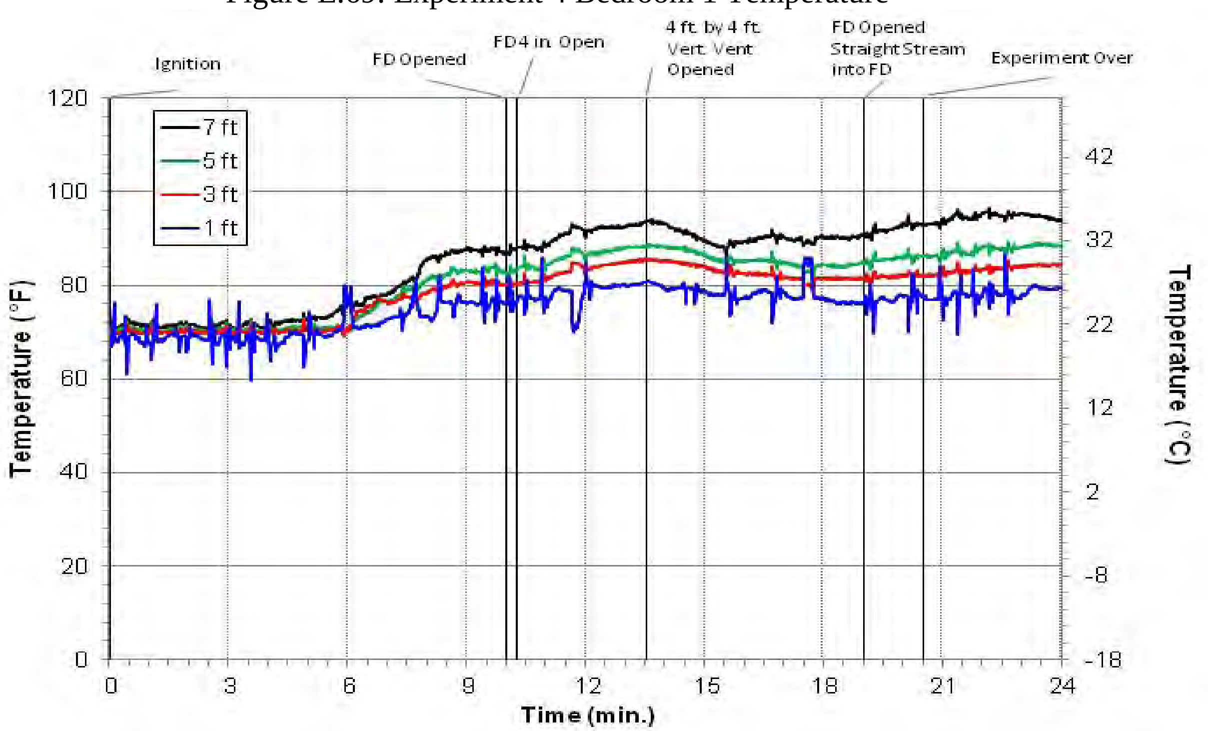


Figure E.70: Experiment 4 Bedroom 2 Temperature

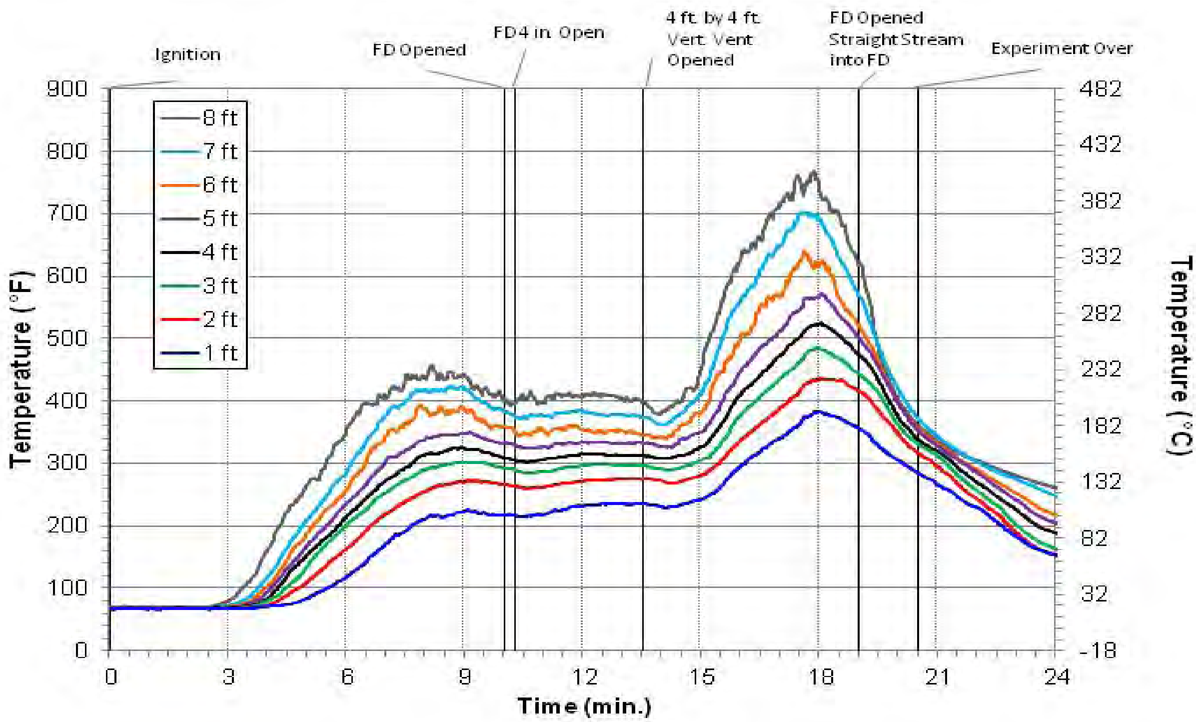


Figure E.71: Experiment 4 Bedroom 3 Temperature

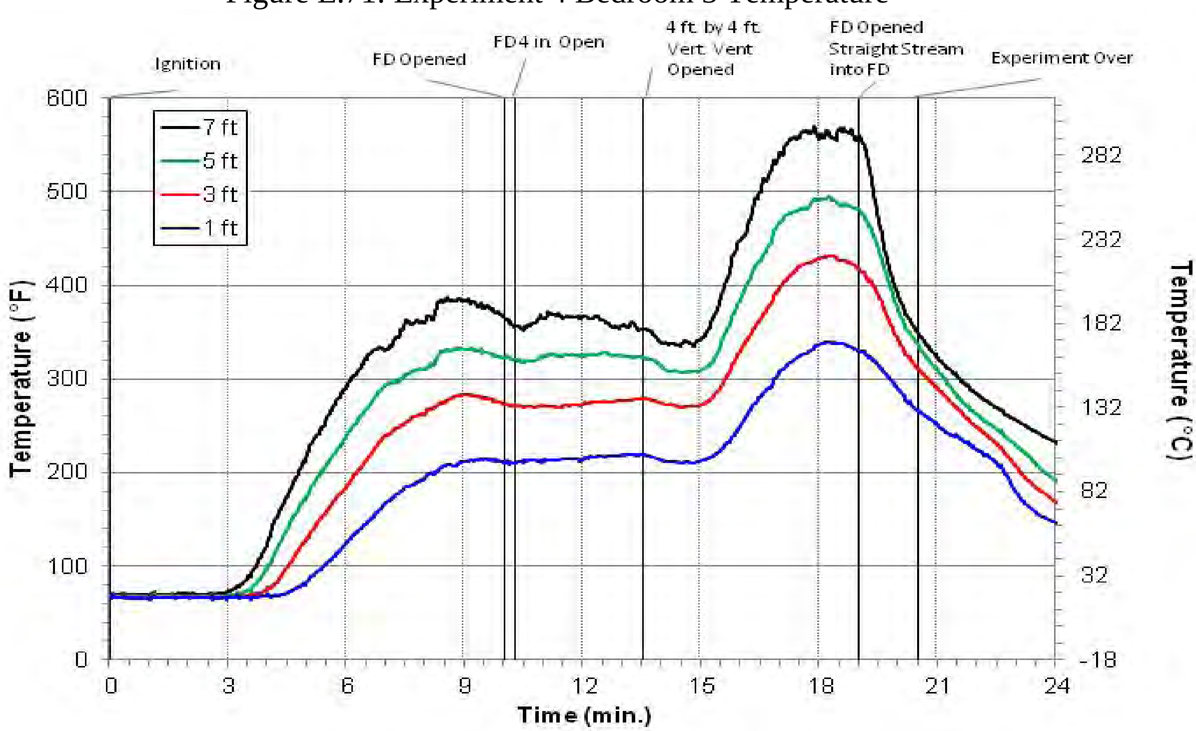


Figure E.72: Experiment 4 Bedroom 4 Temperature

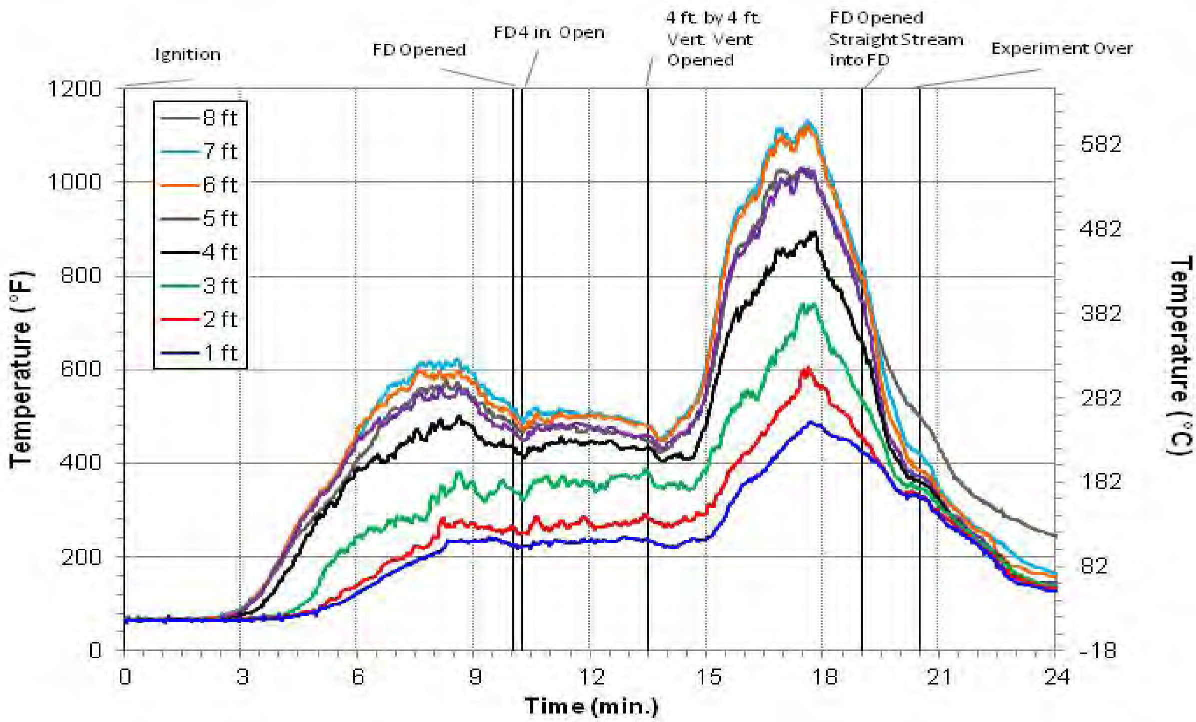


Figure E.73: Experiment 4 Hallway Temperature

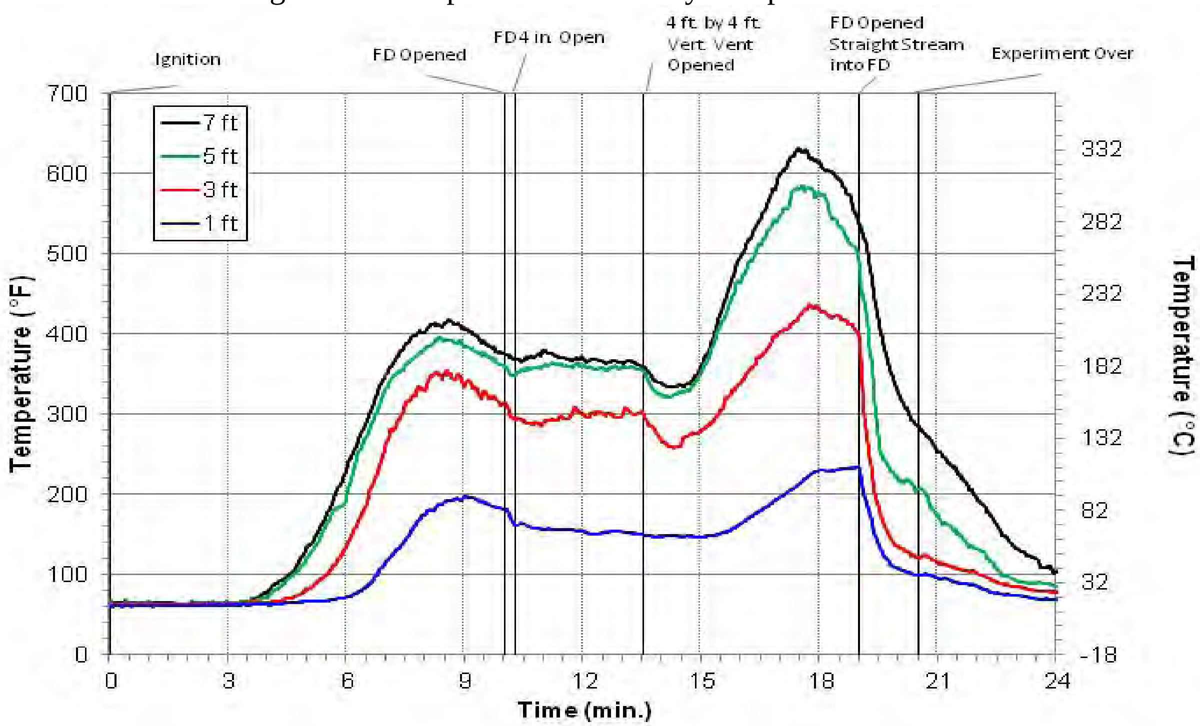


Figure E.74: Experiment 4 Dining Room Temperature

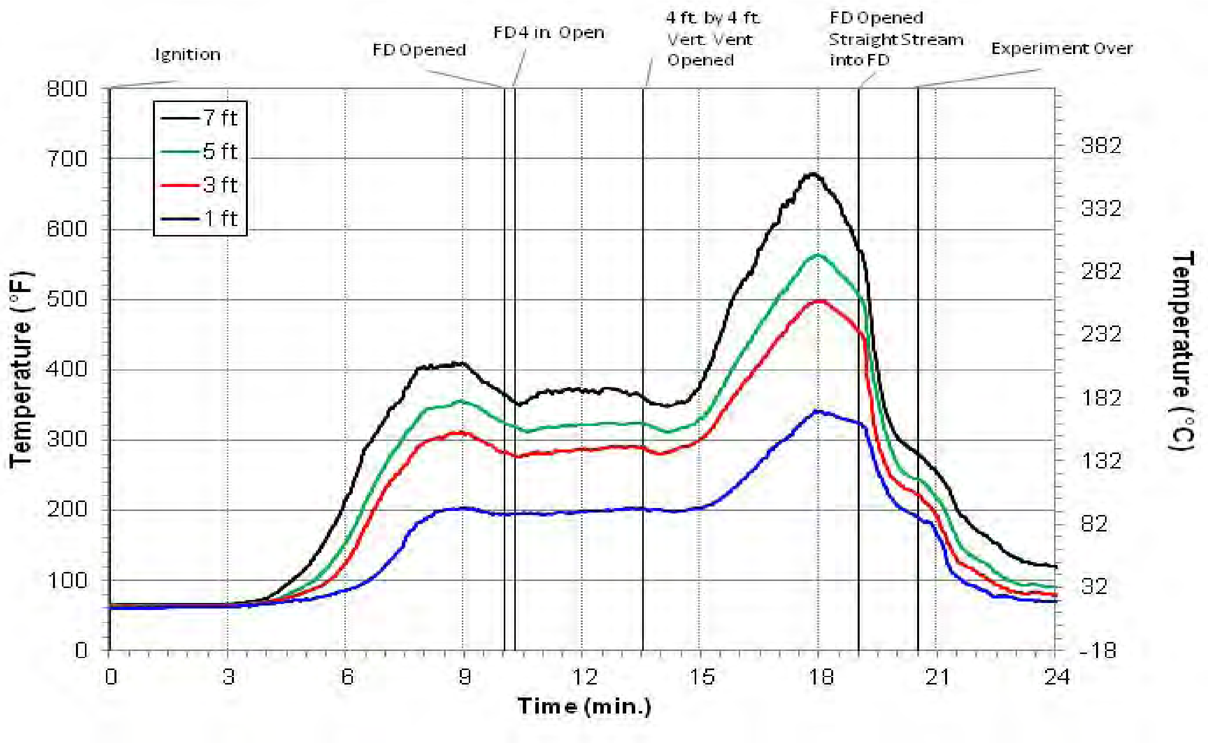


Figure E.75: Experiment 4 Living Room Temperature

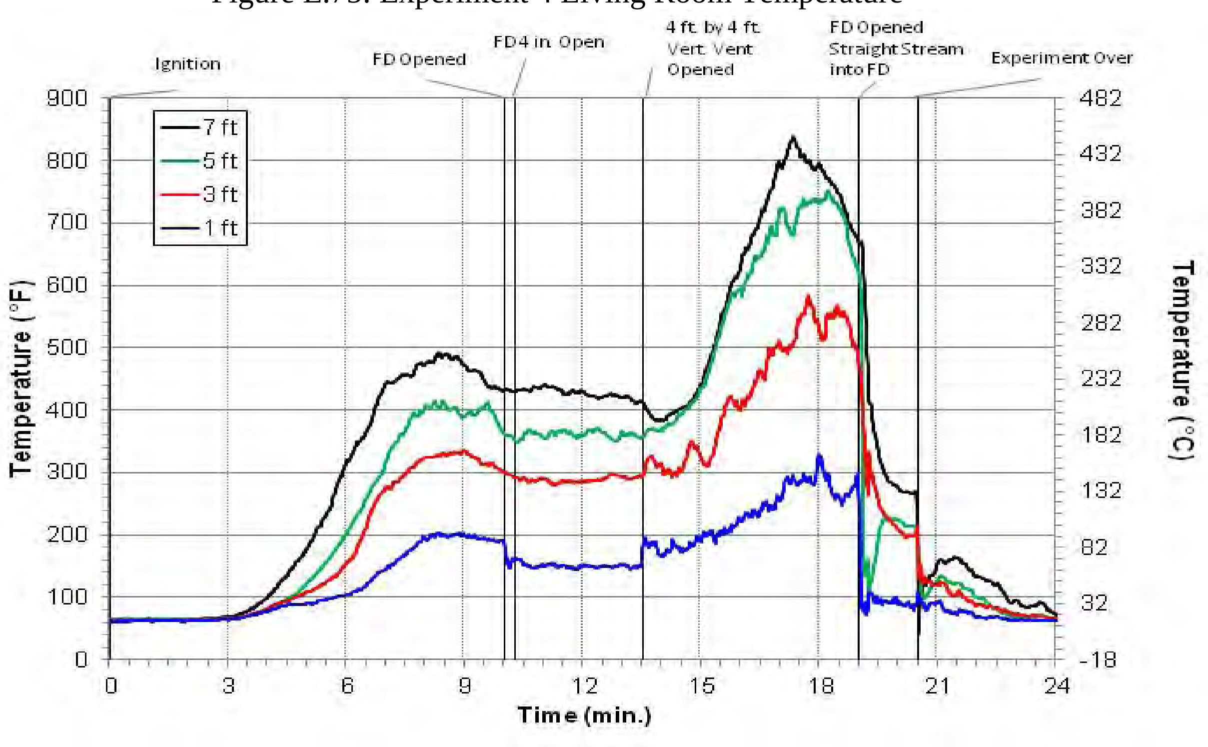


Figure E.76: Experiment 4 Foyer Temperature

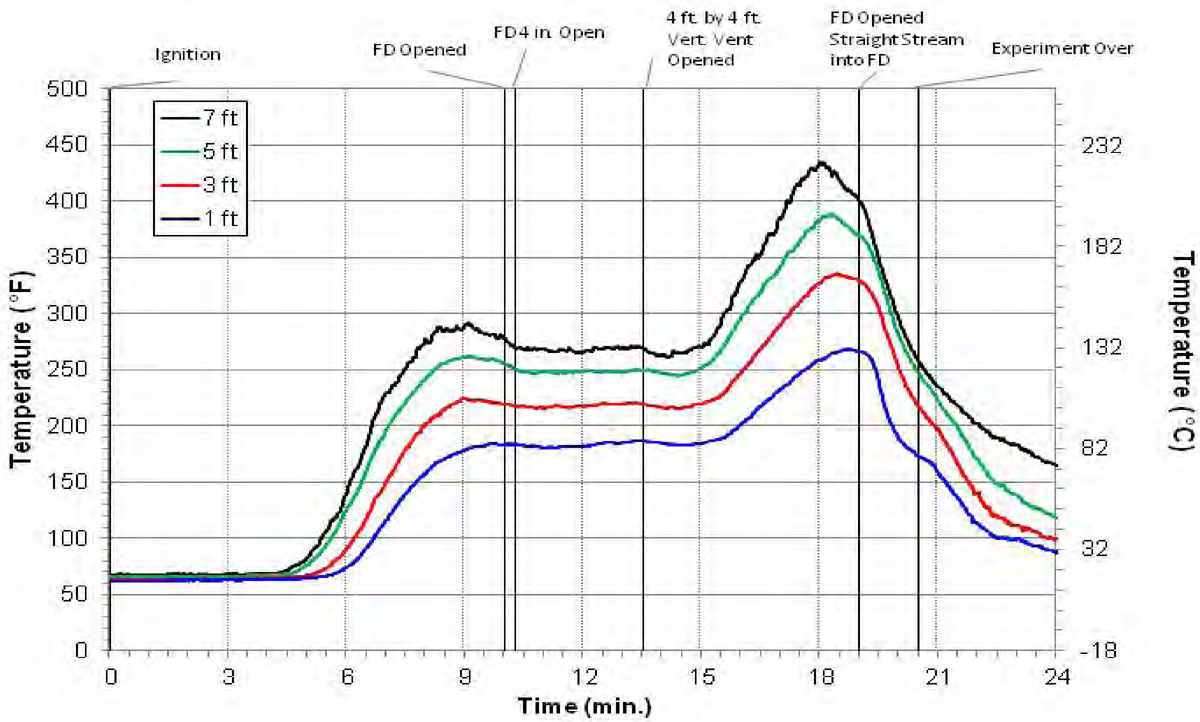


Figure E.77: Experiment 4 Den Temperature

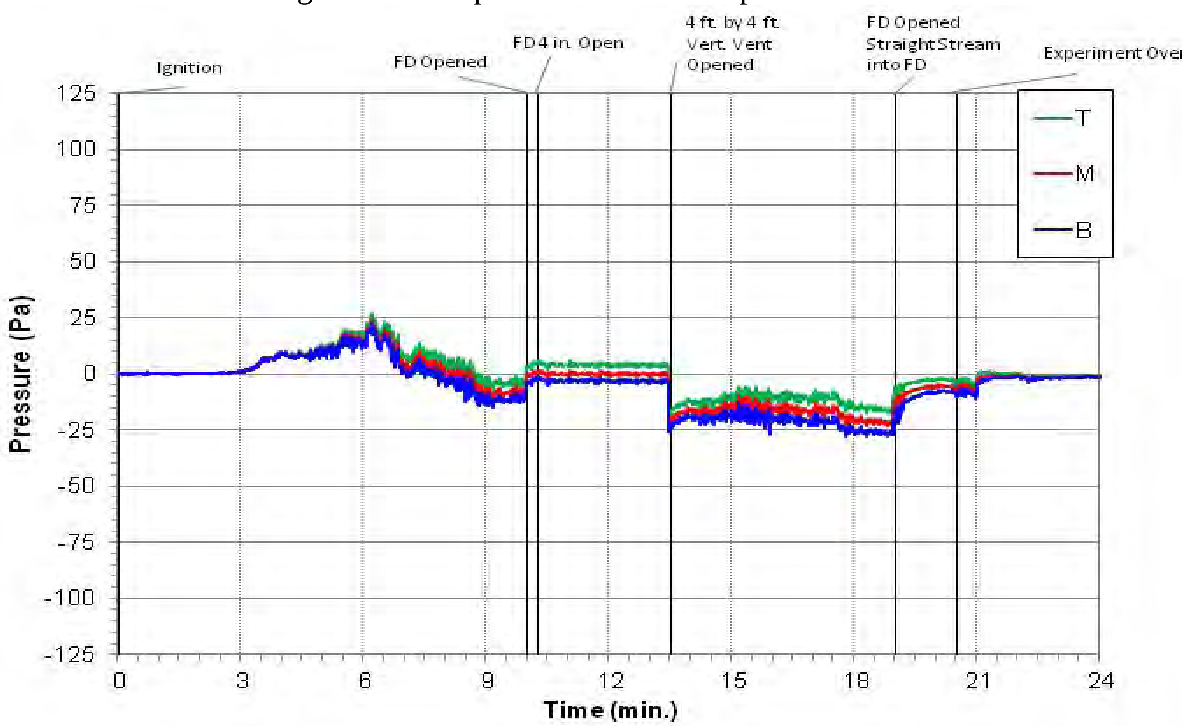


Figure E.78: Experiment 4 Living Room Pressure

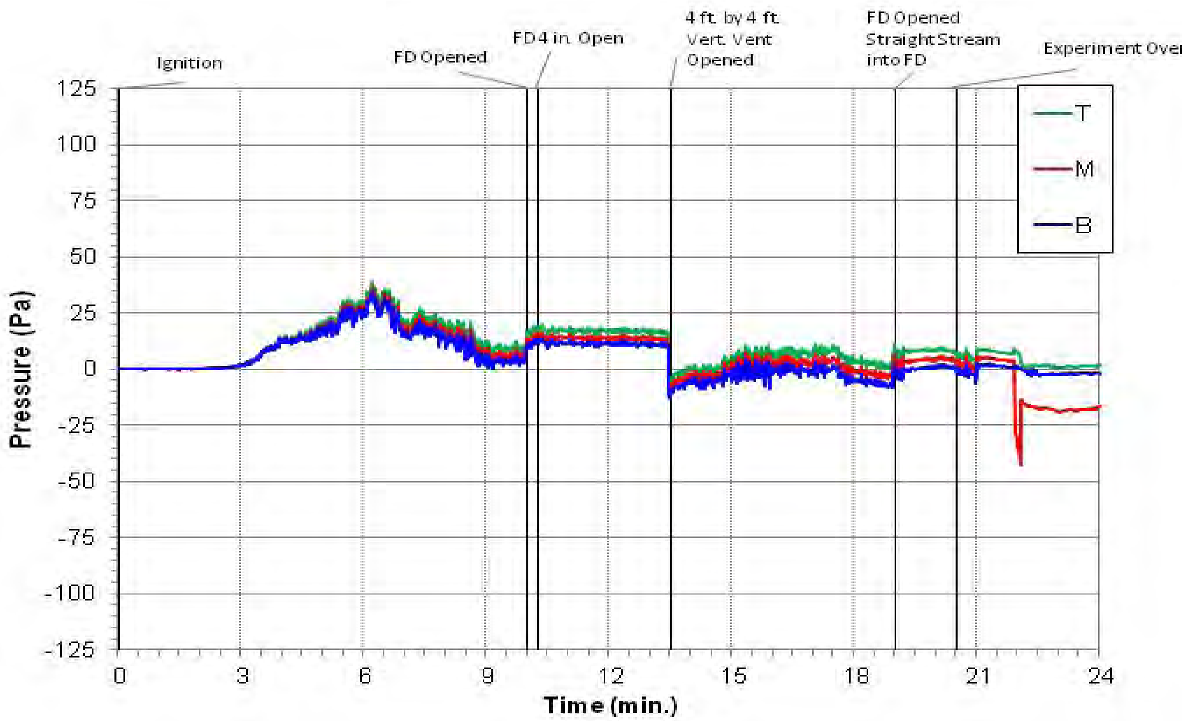


Figure E.79: Experiment 4 Bedroom 2 Pressure

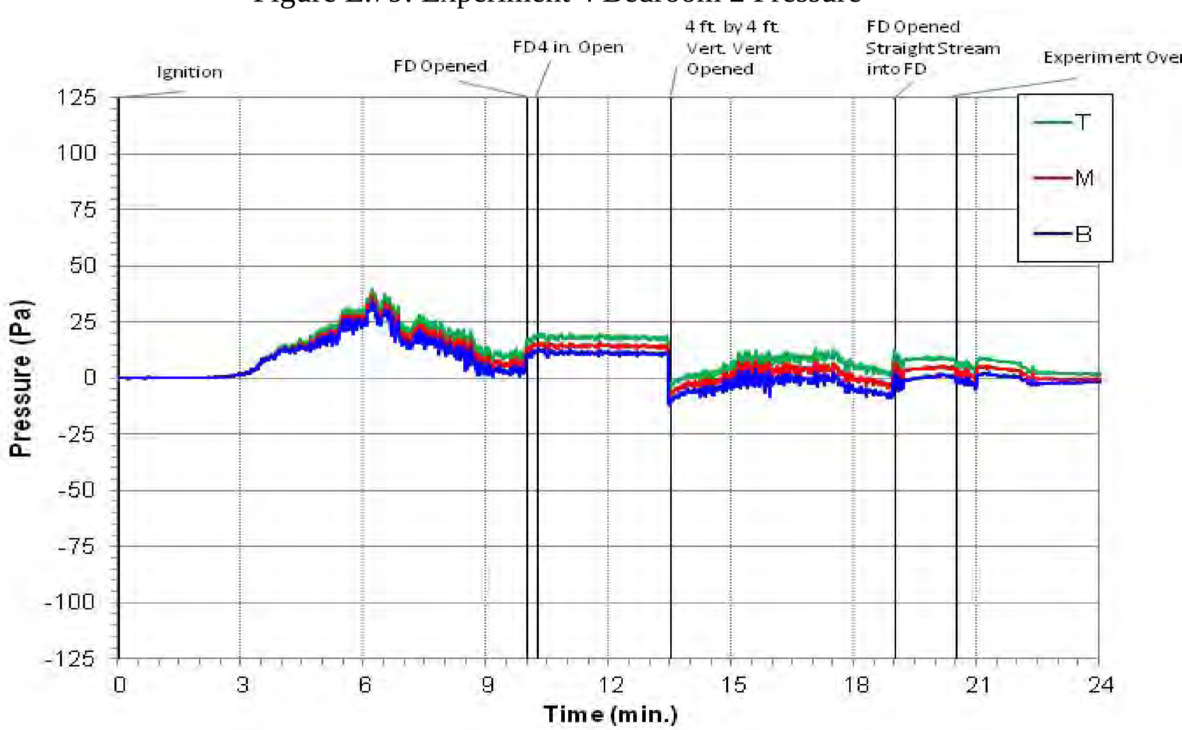


Figure E.80: Experiment 4 Bedroom 3 Pressure

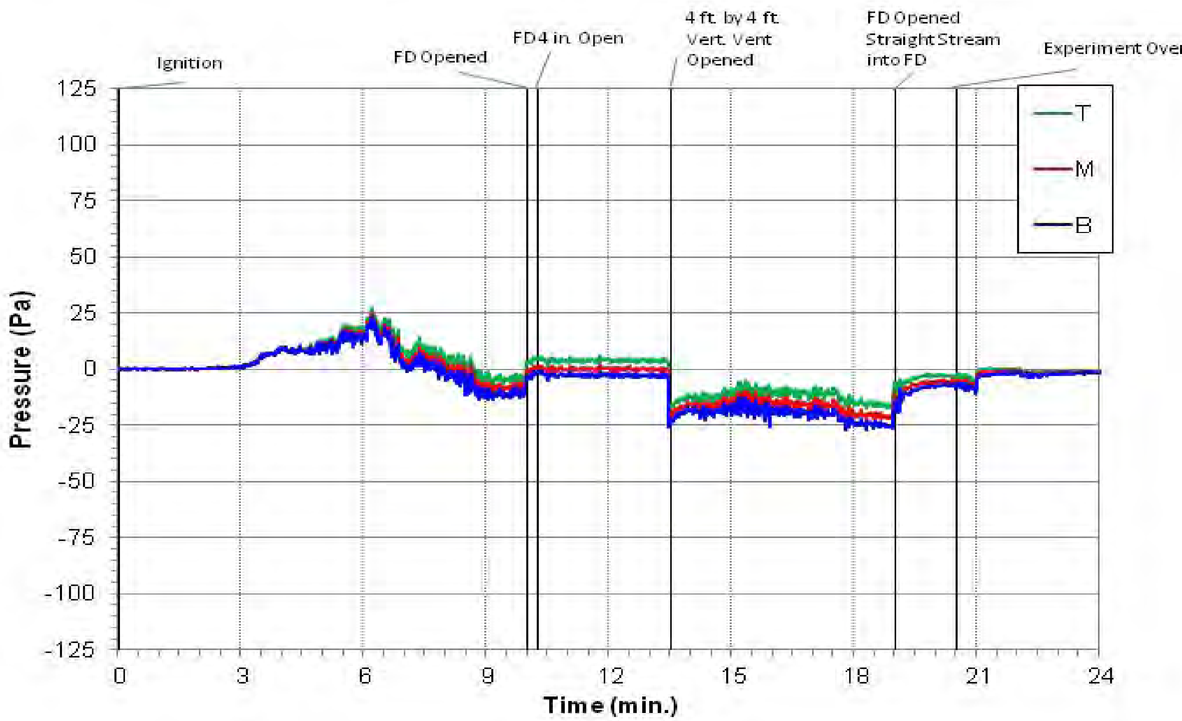


Figure E.81: Experiment 4 Kitchen Pressure

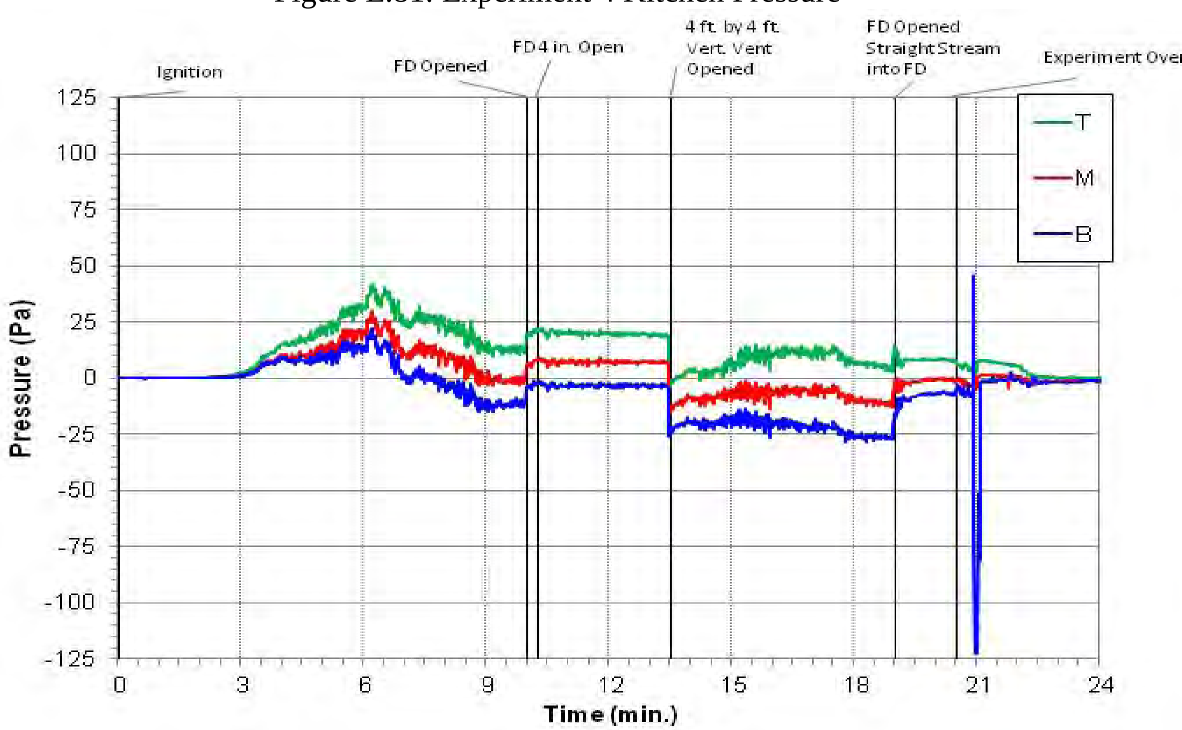


Figure E.82: Experiment 4 Family Room Pressure

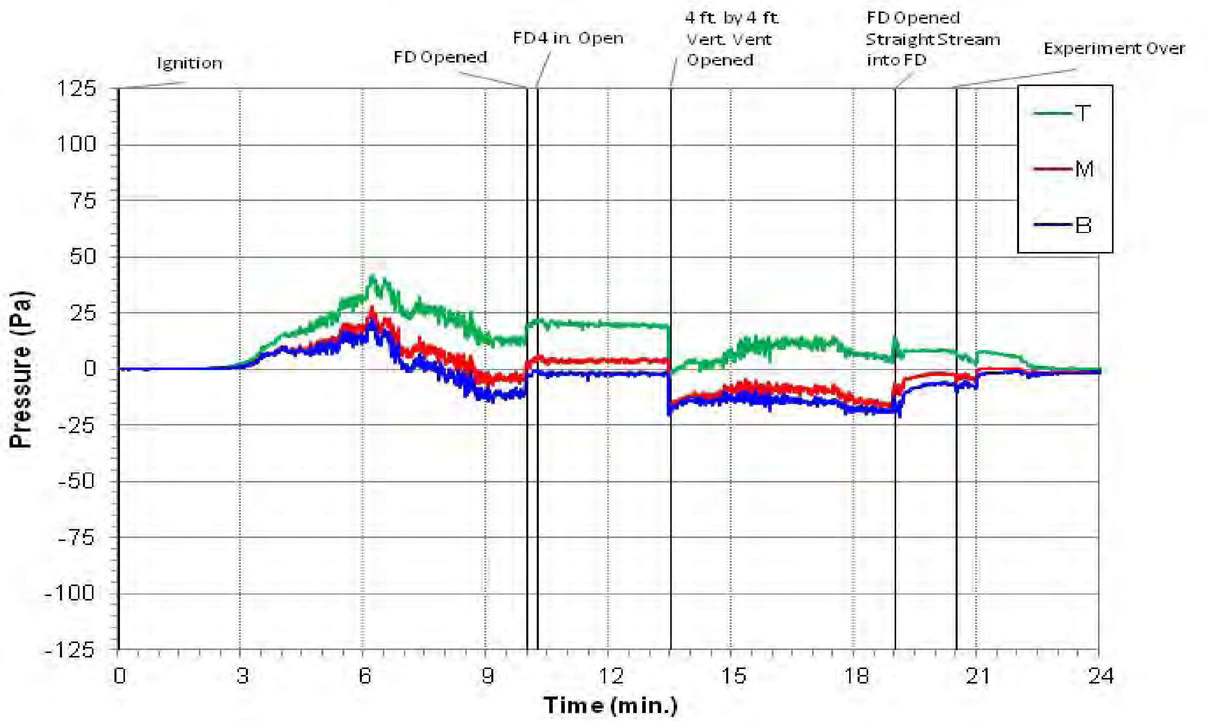


Figure E.83: Experiment 4 Foyer Pressure

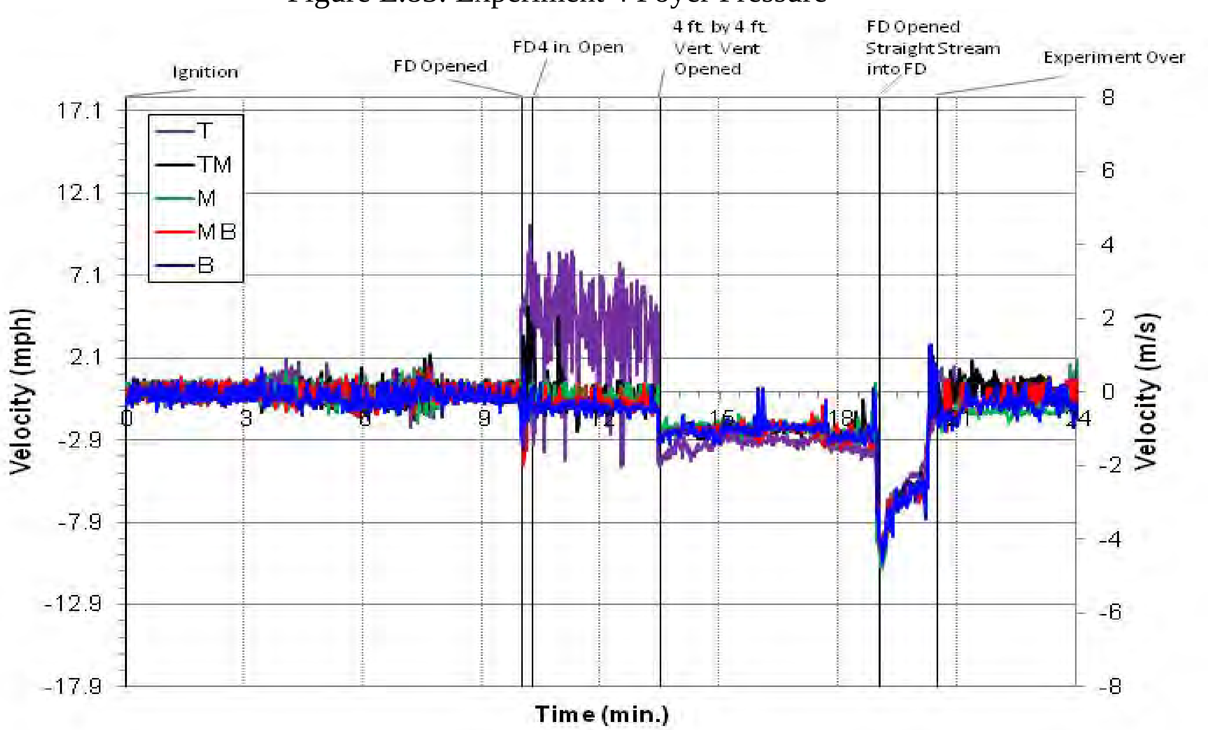


Figure E.84: Experiment 4 Front Door Velocity

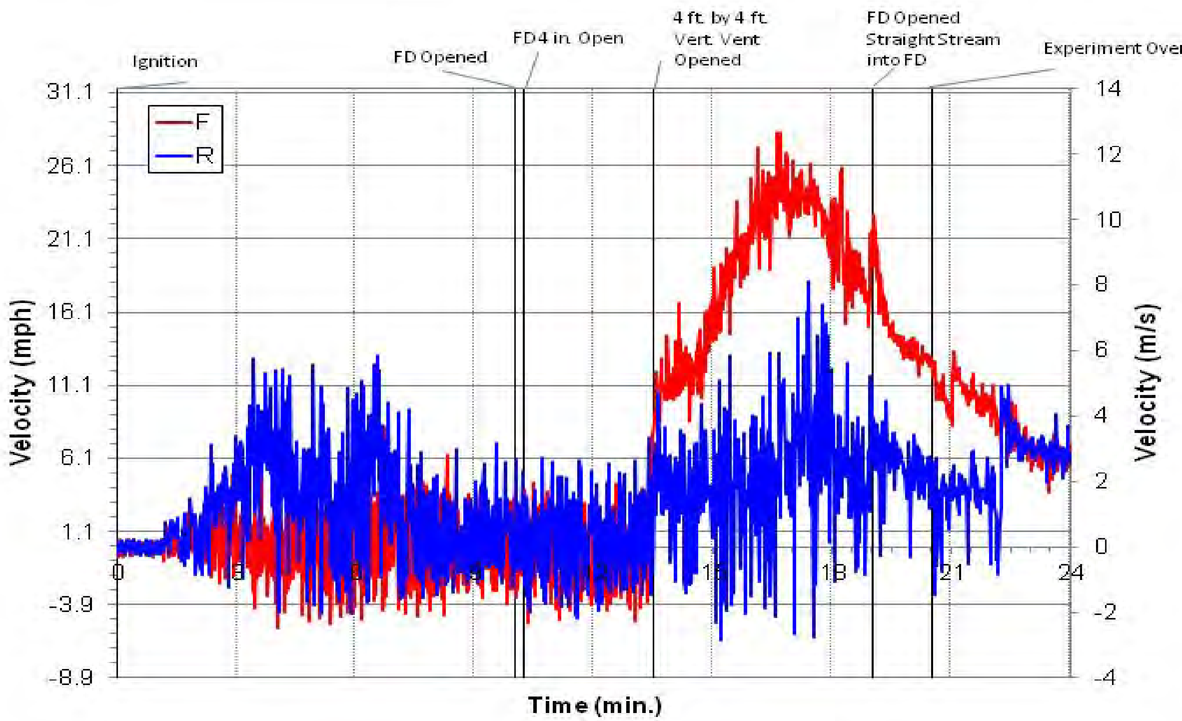


Figure E.85: Experiment 4 Vent Velocity

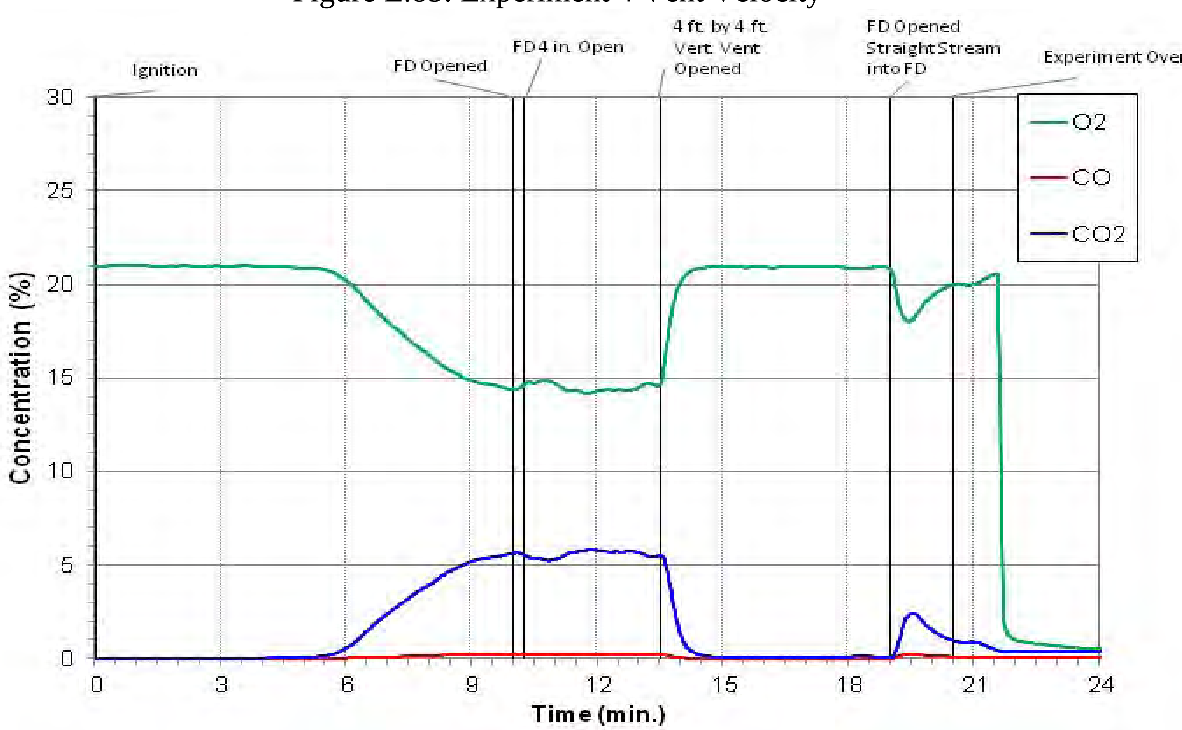


Figure E.86: Experiment 4 Front Door Gas

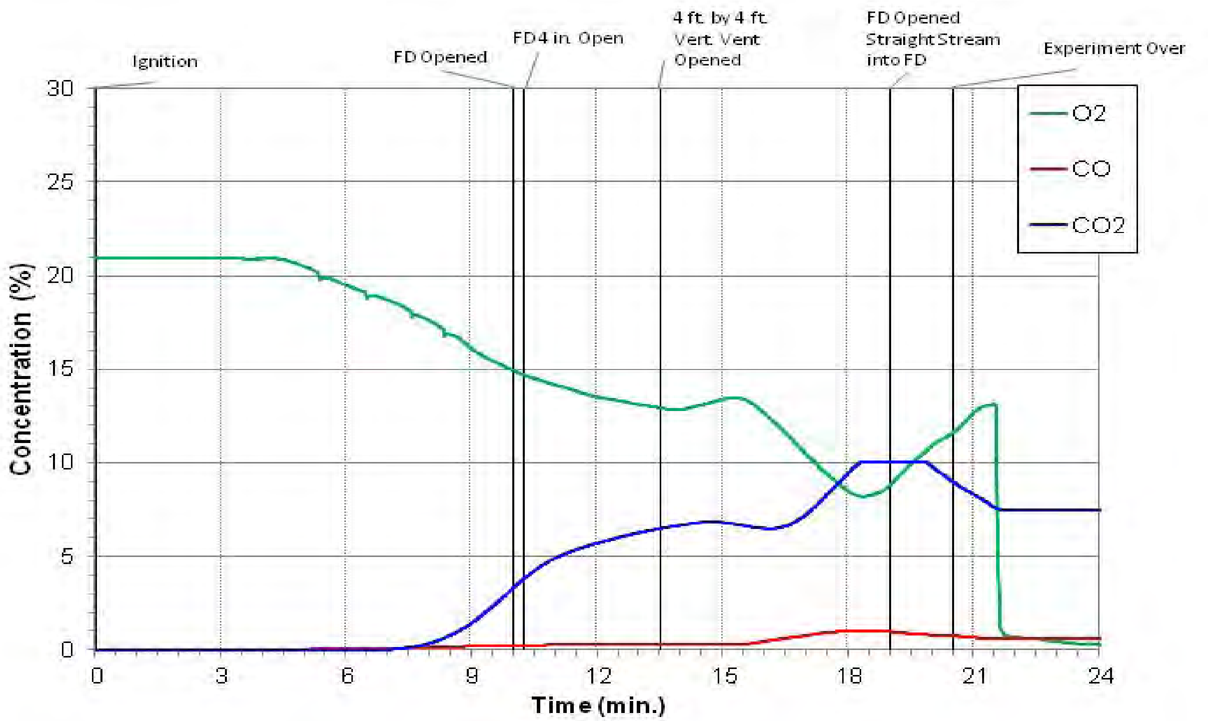


Figure E.87: Experiment 4 Bedroom 1 Gas

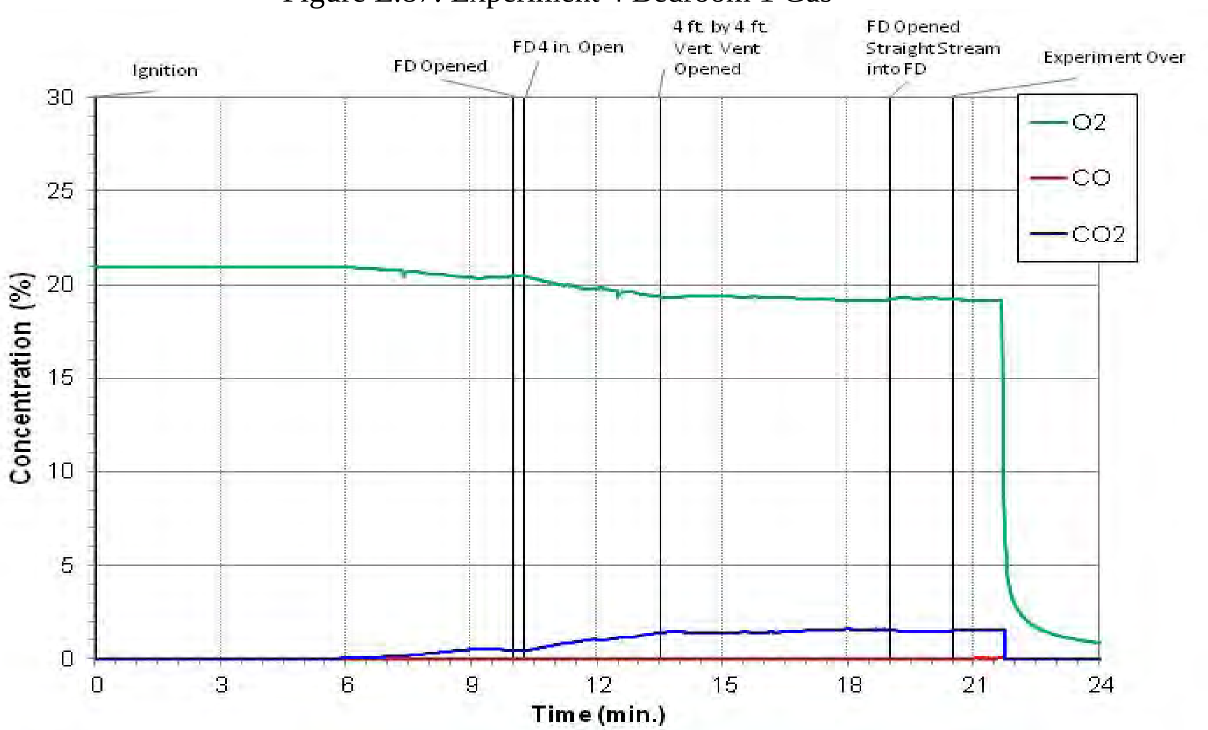


Figure E.88: Experiment 4 Bedroom 2 Gas

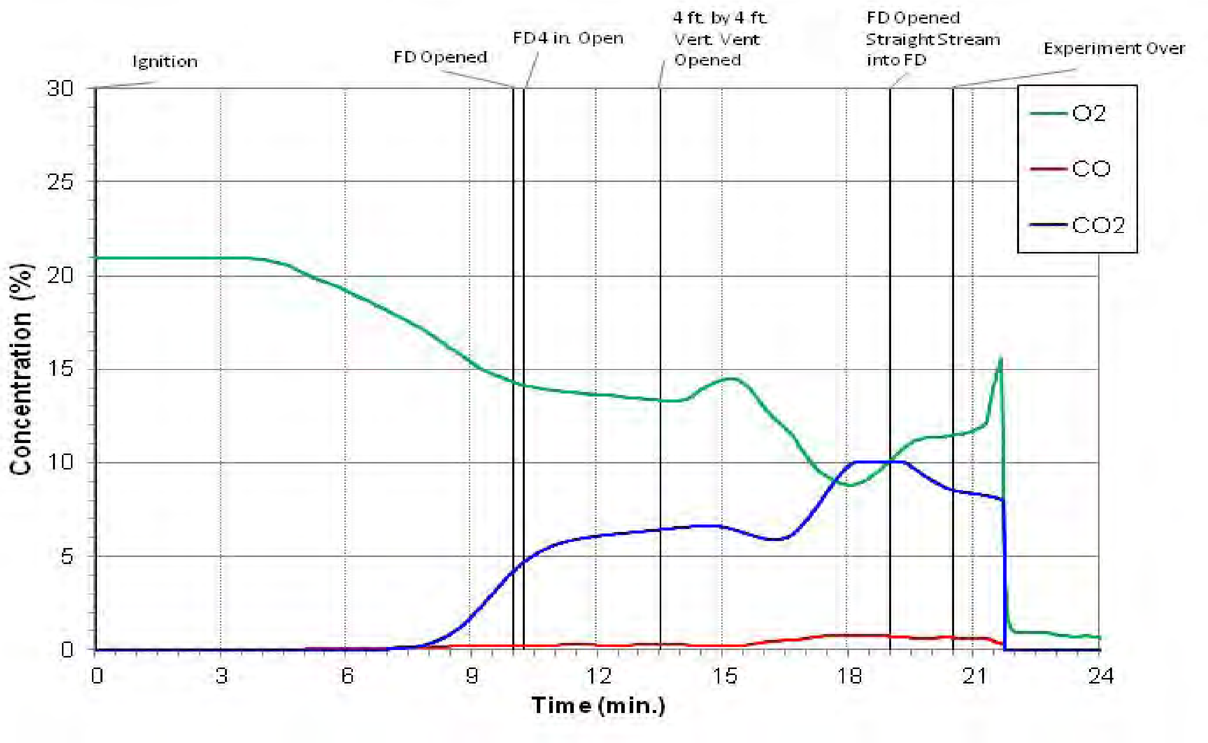


Figure E.89: Experiment 4 Bedroom 3 Gas

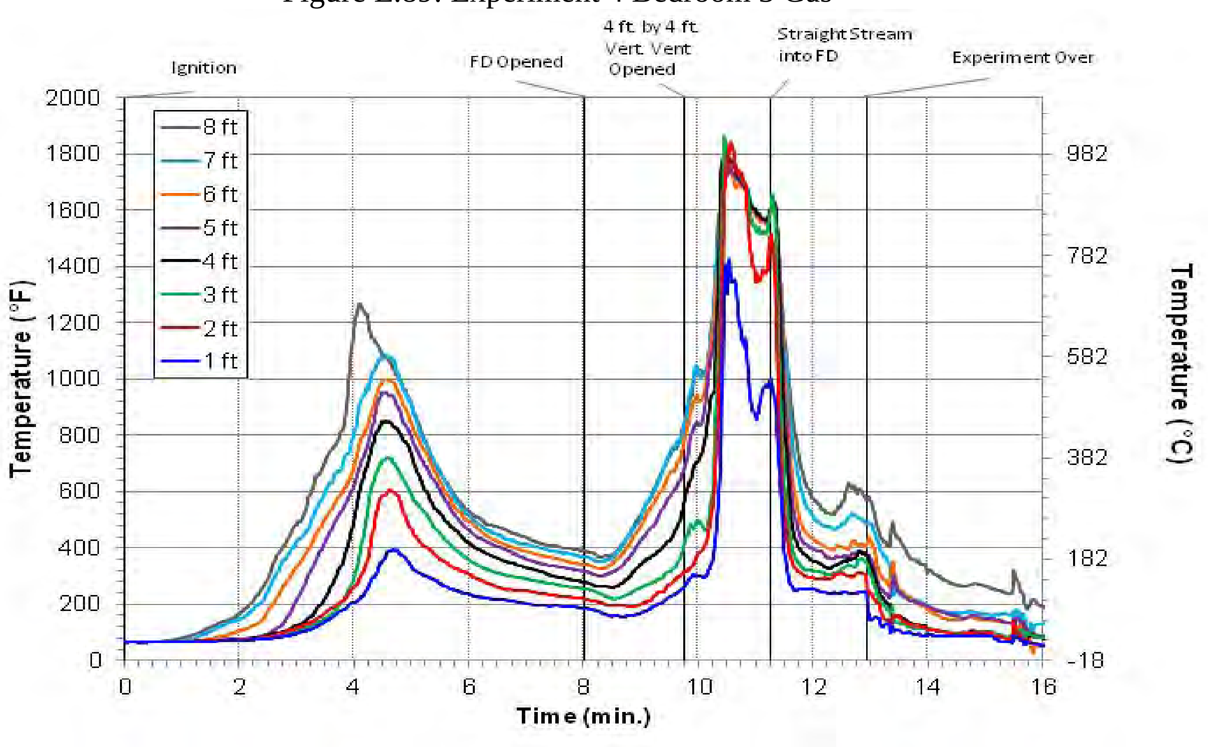


Figure E.90: Experiment 5 Living Room Temperature

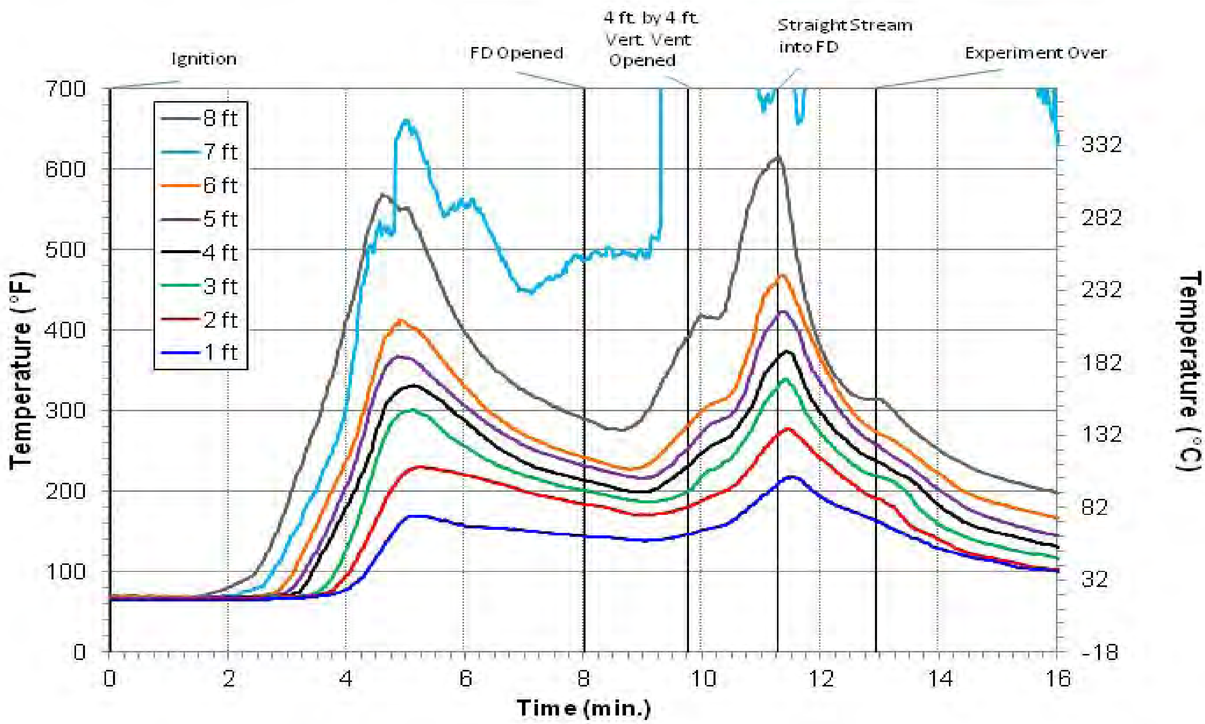


Figure E.91: Experiment 5 Bedroom 1 Temperature

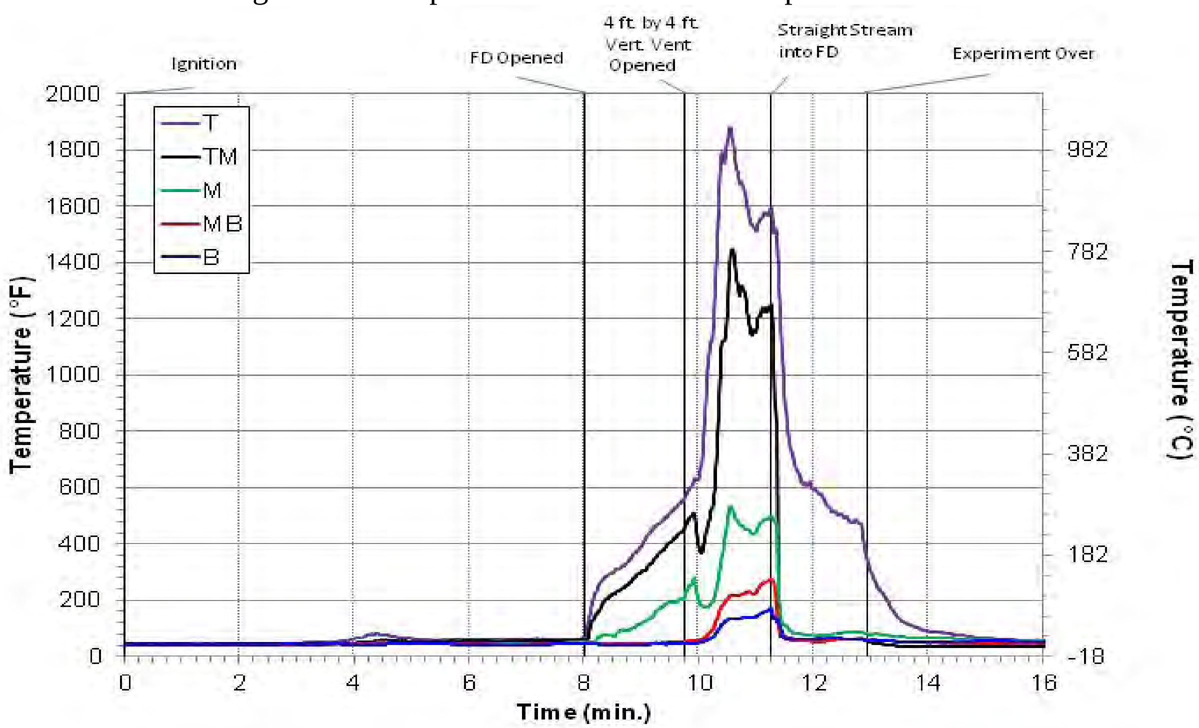


Figure E.92: Experiment 5 Front Door Temperature

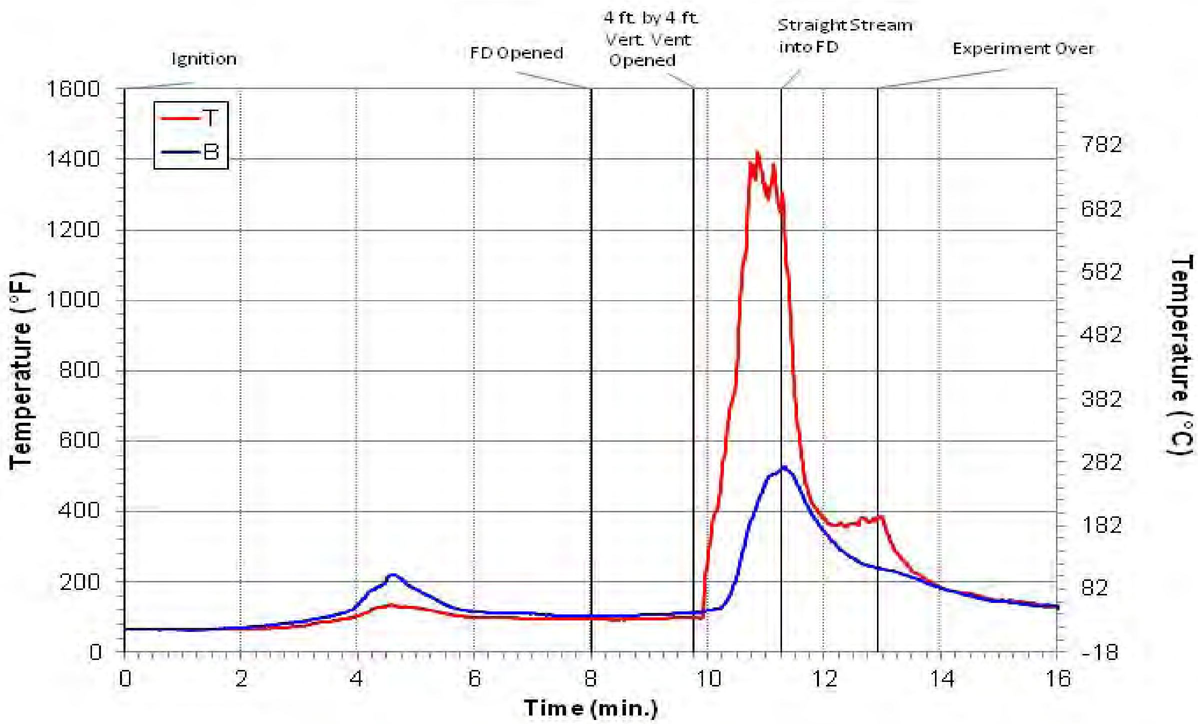


Figure E.93: Experiment 5 Vent Temperature

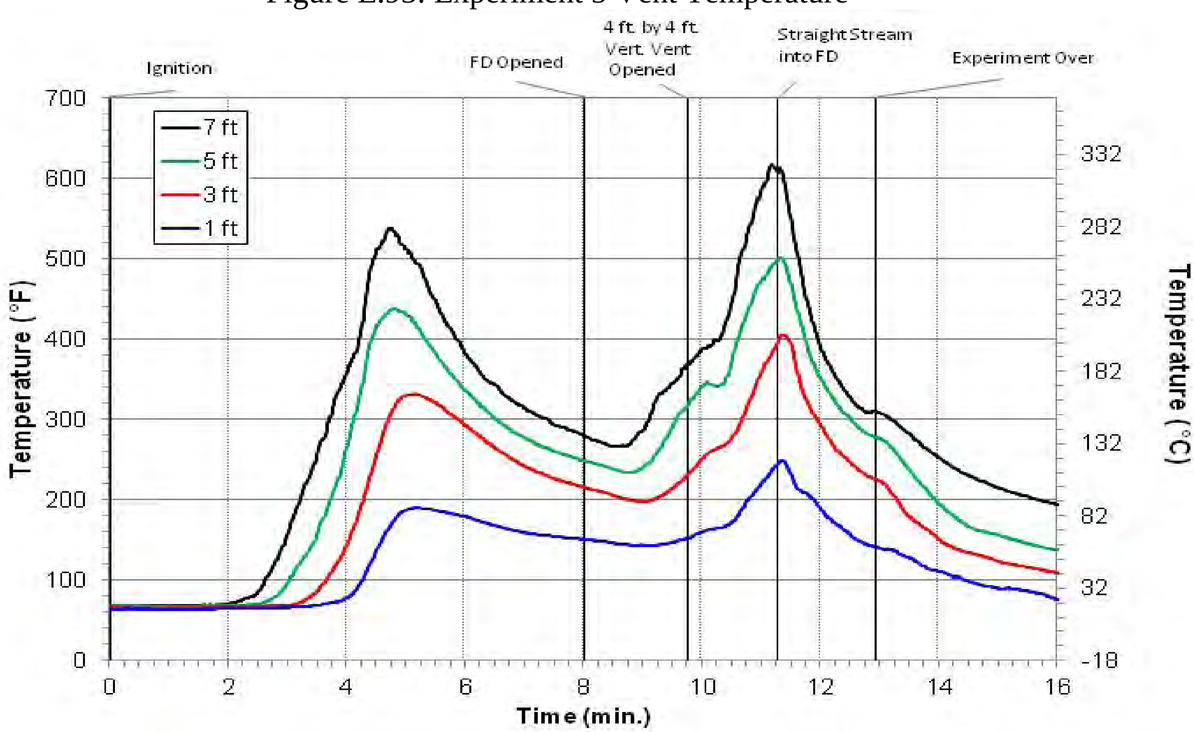


Figure E.94: Experiment 5 Bedroom 2 Temperature

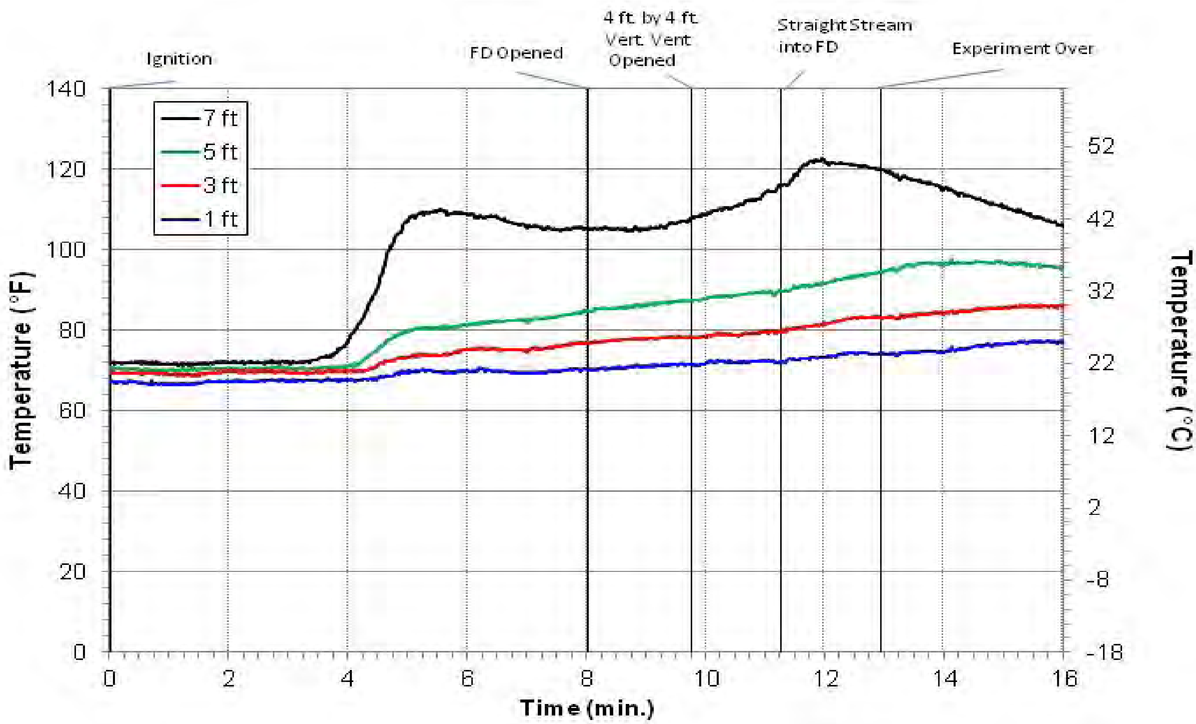


Figure E.95: Experiment 5 Bedroom 3 Temperature

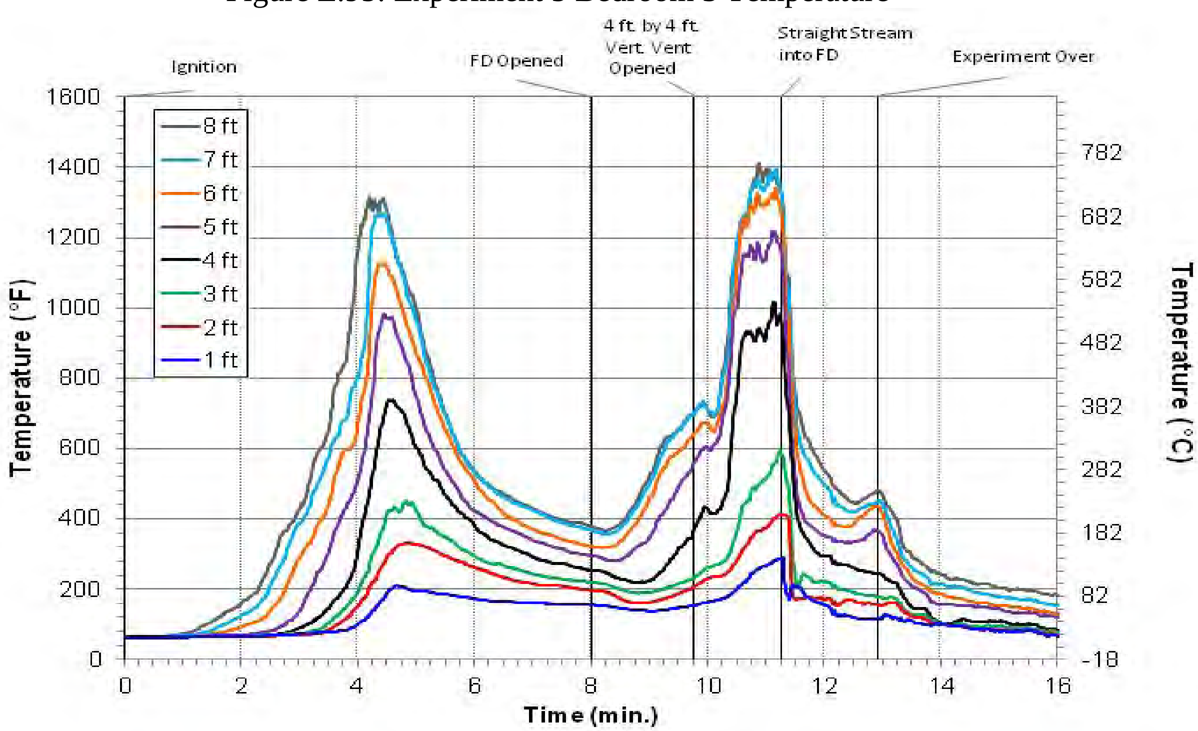


Figure E.96: Experiment 5 Hallway Temperature

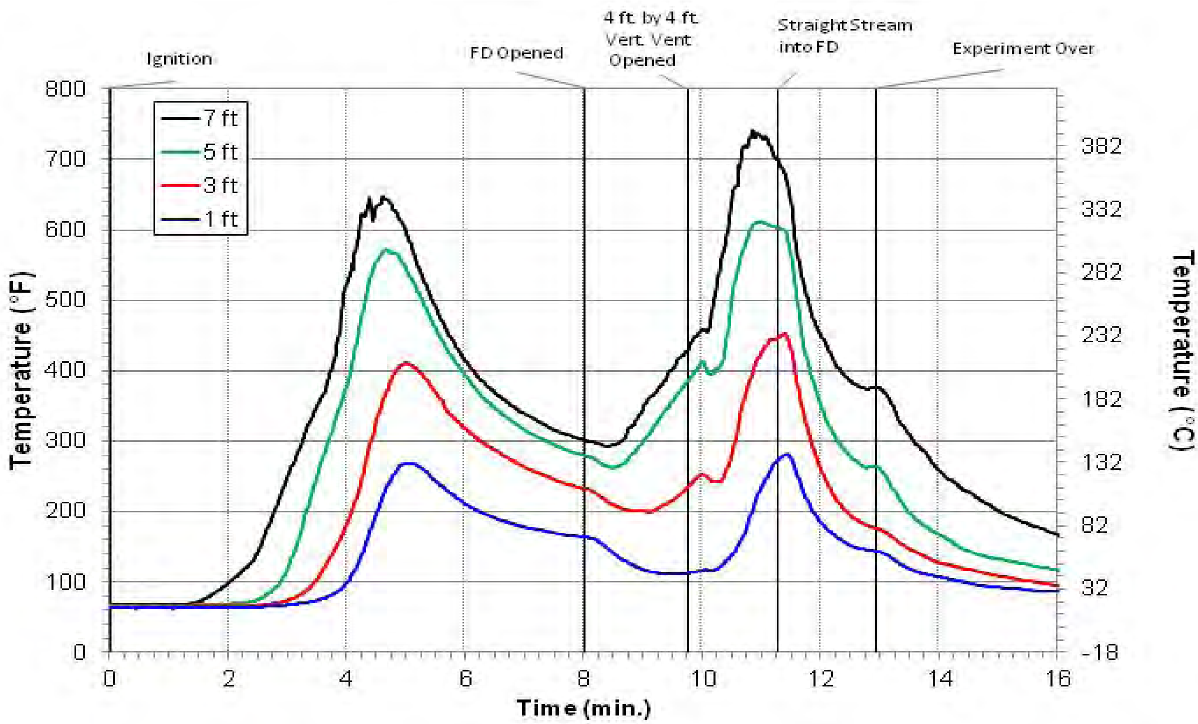


Figure E.97: Experiment 5 Dining Room Temperature

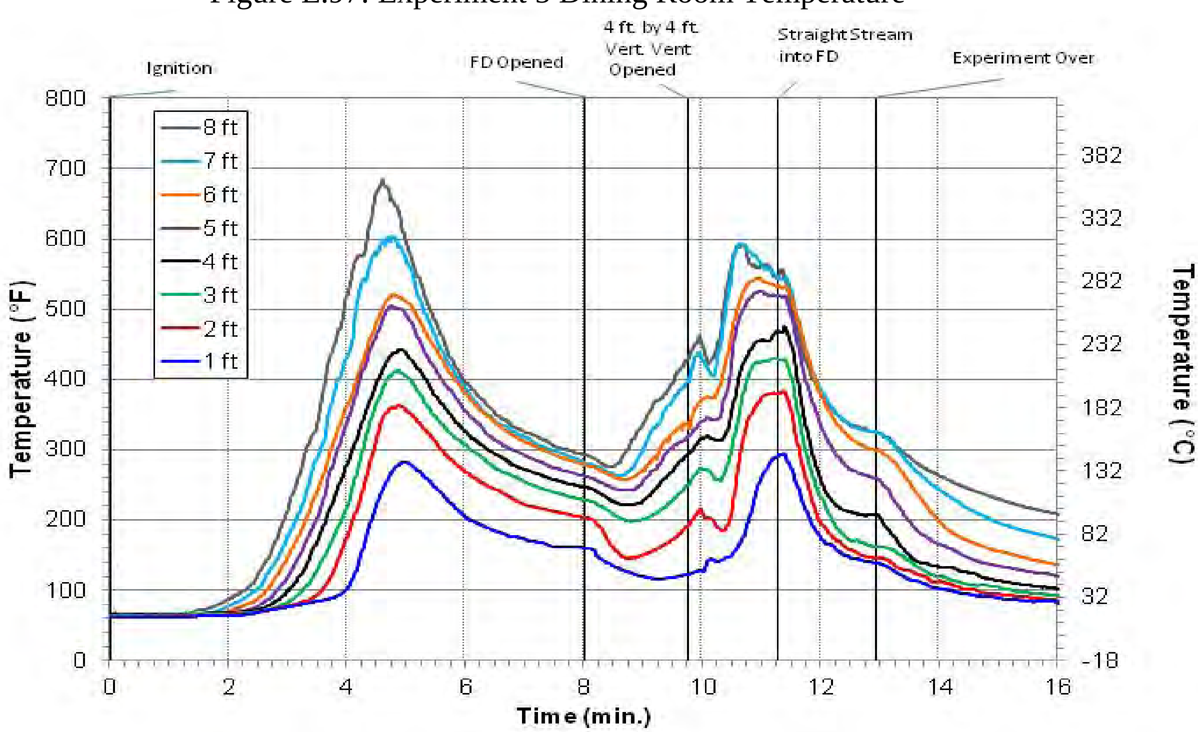


Figure E.98: Experiment 5 Kitchen Temperature

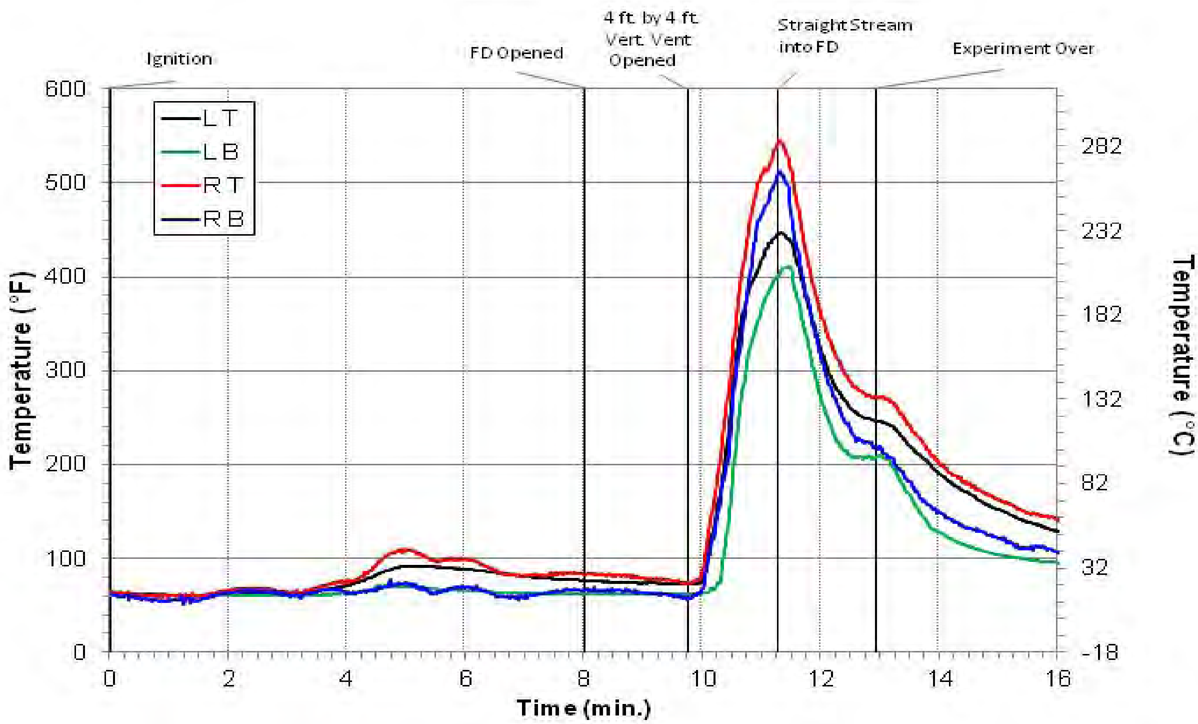


Figure E.99: Experiment 5 Attic Temperature

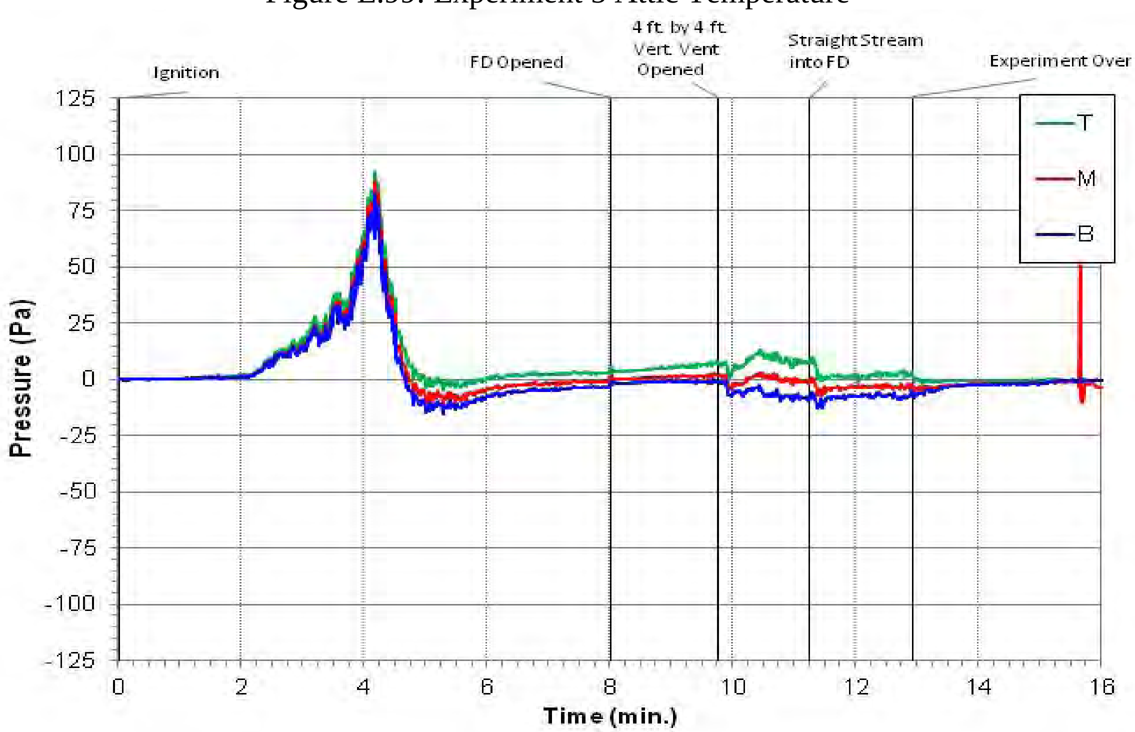


Figure E.100: Experiment 5 Living Room Pressure

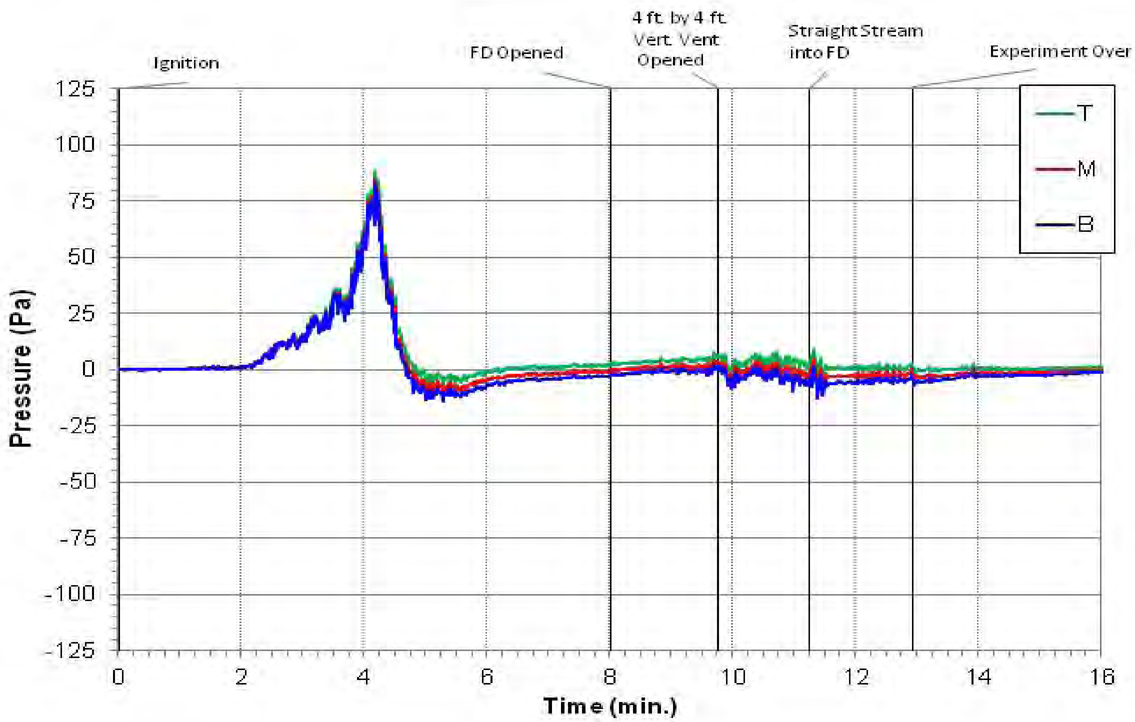


Figure E.101: Experiment 5 Bedroom 1 Pressure

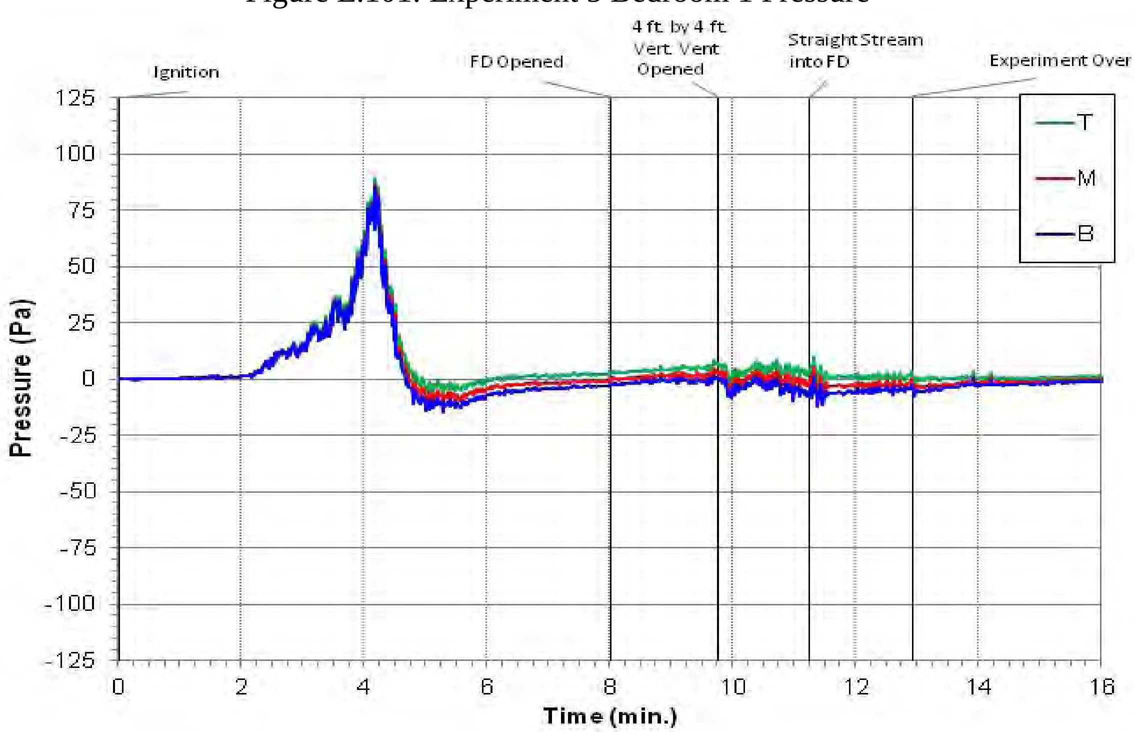


Figure E.102: Experiment 5 Bedroom 2 Pressure

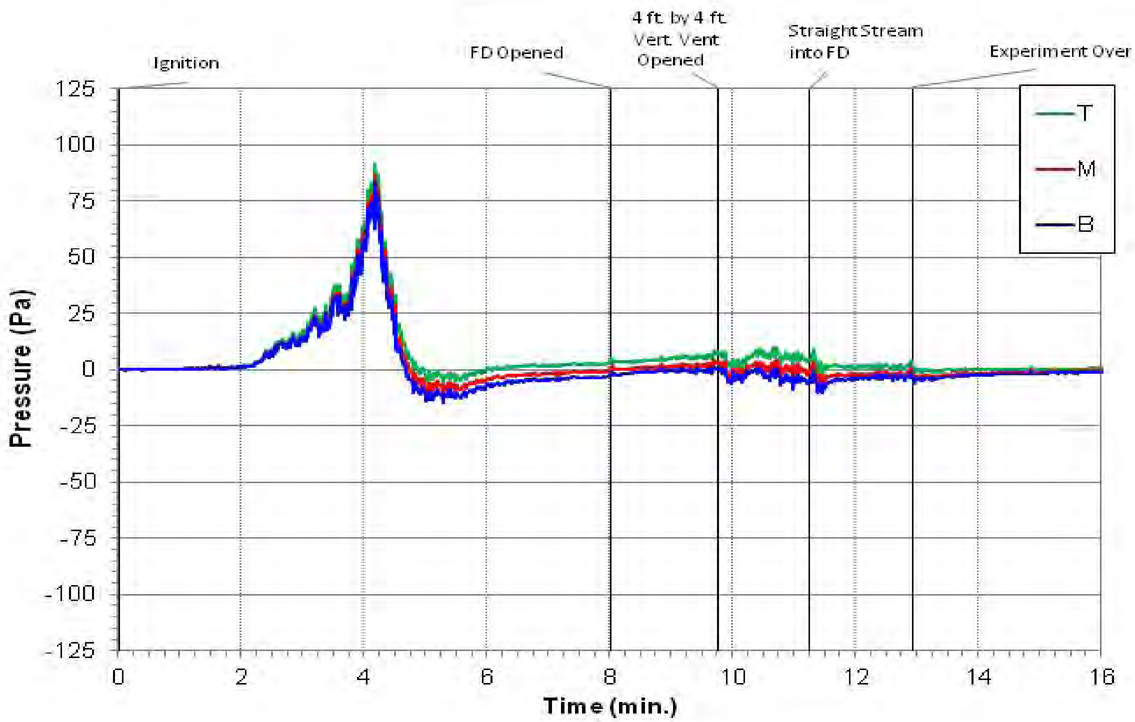


Figure E.103: Experiment 5 Kitchen Pressure

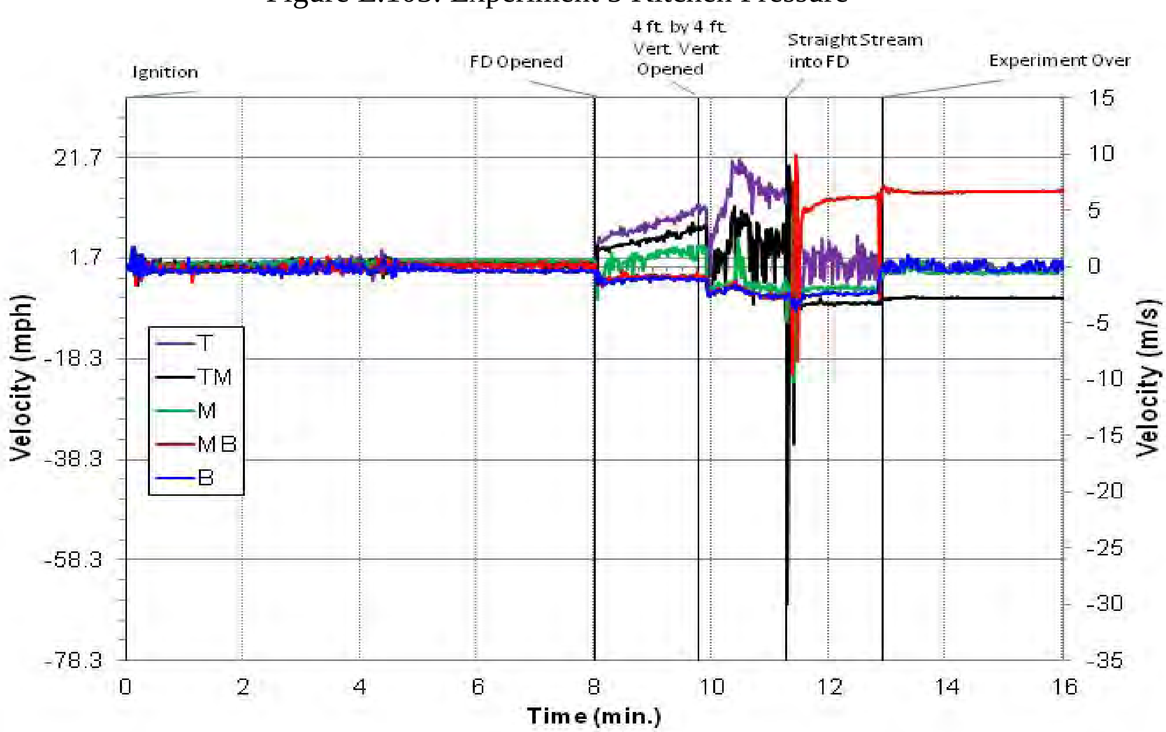


Figure E.104: Experiment 5 Front Door Velocity

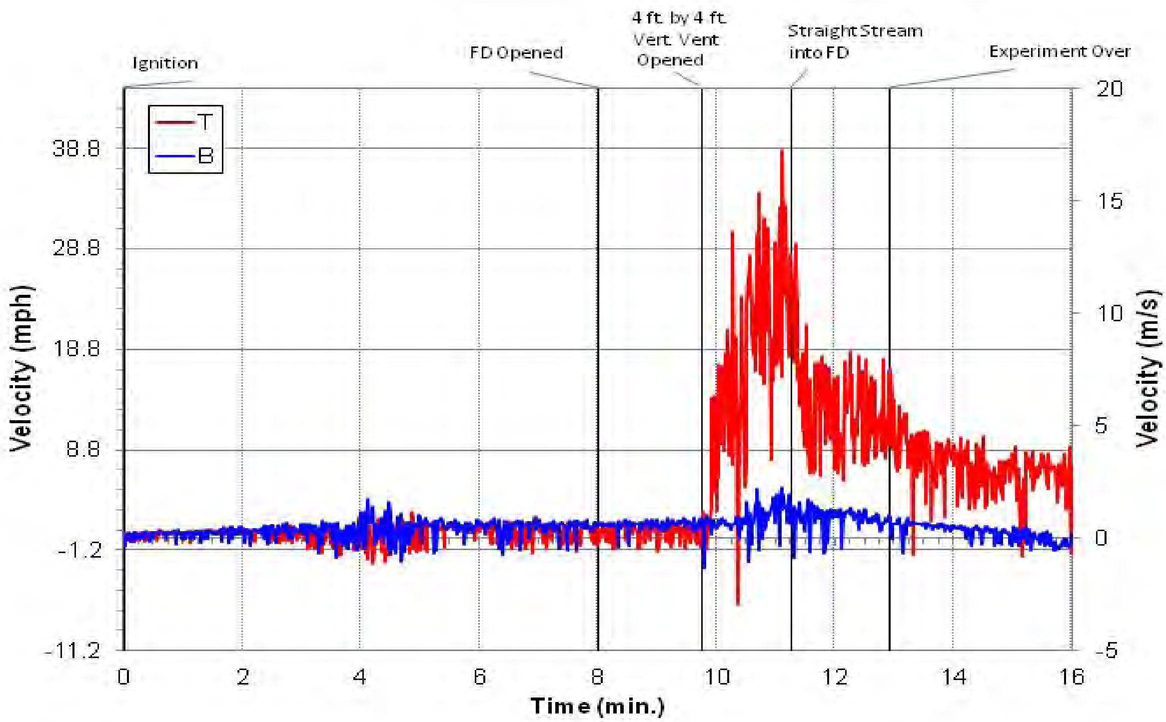


Figure E.105: Experiment 5 Vent Velocity

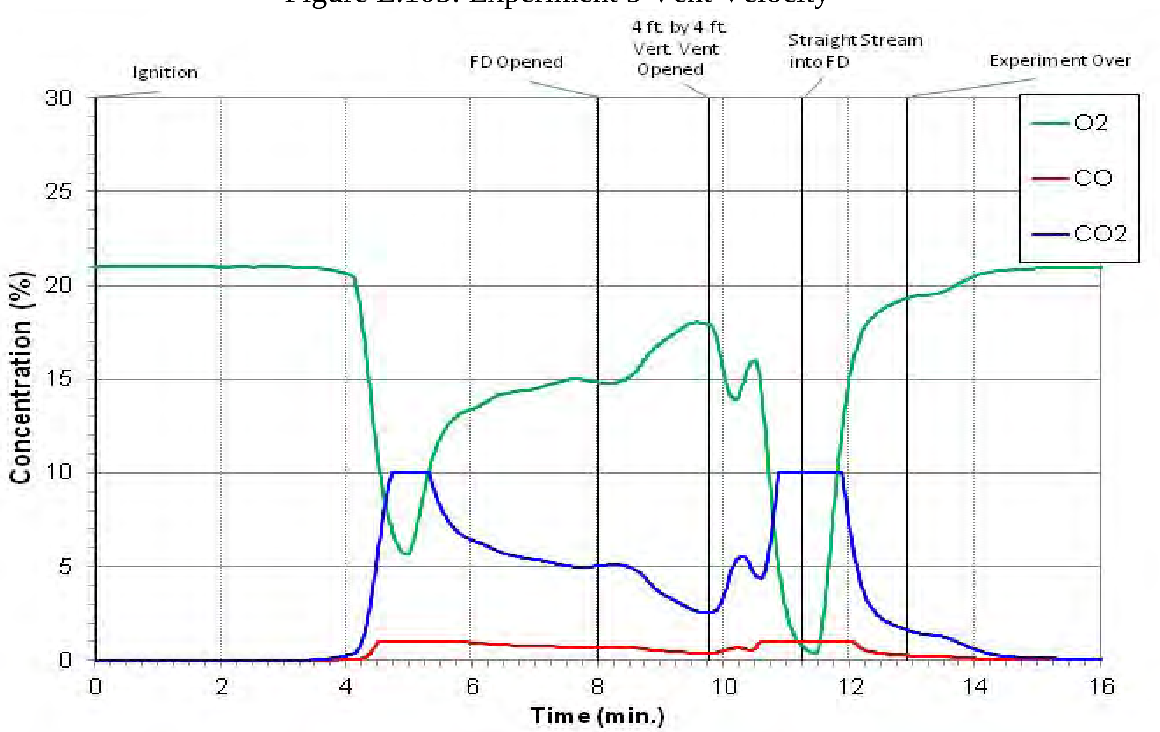


Figure E.106: Experiment 5 Living Room Gas

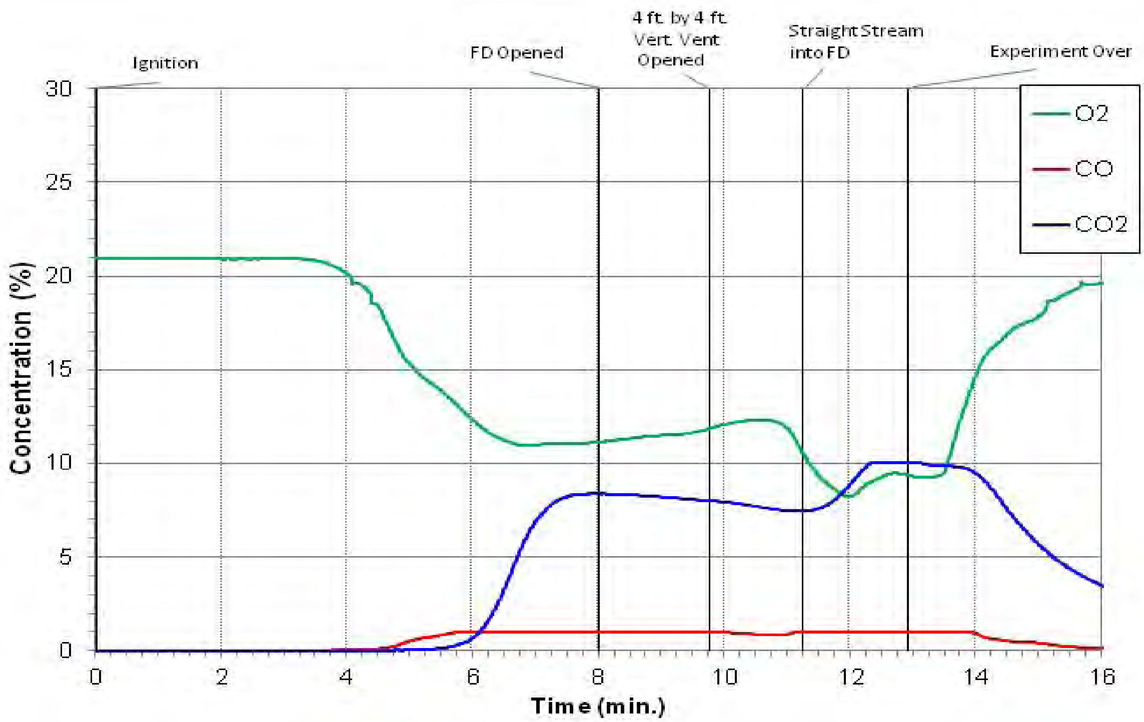


Figure E.107: Experiment 5 Bedroom 1 Gas

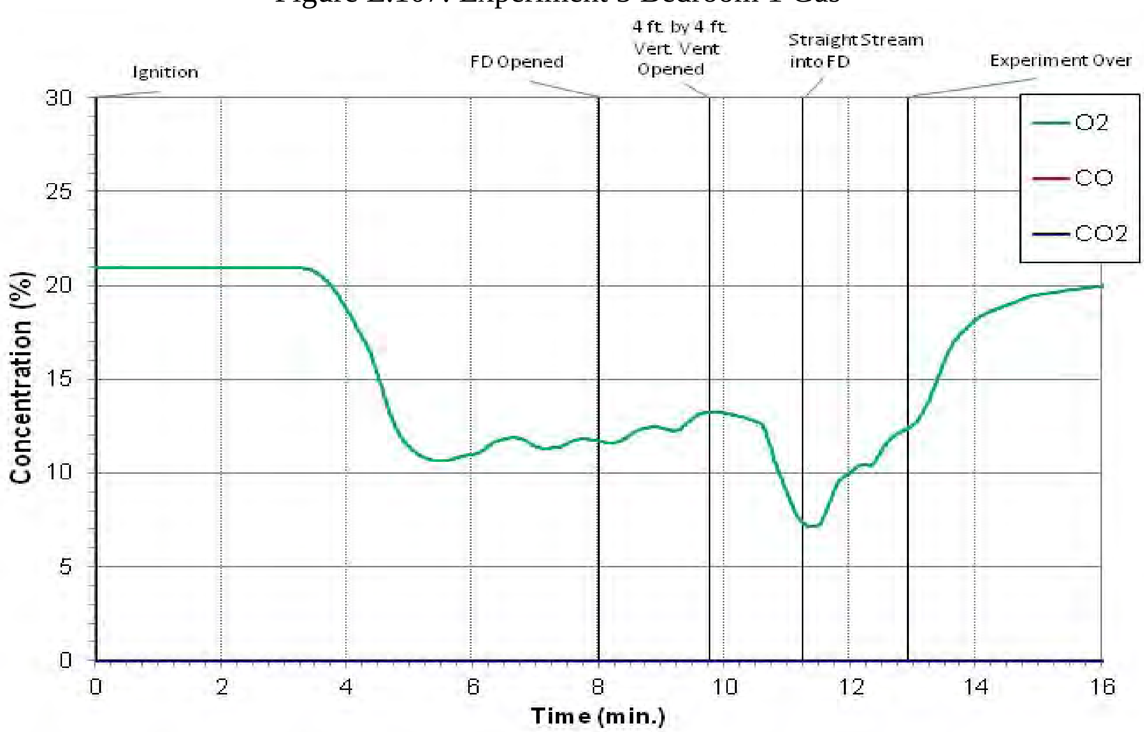


Figure E.108: Experiment 5 Bedroom 2 Gas

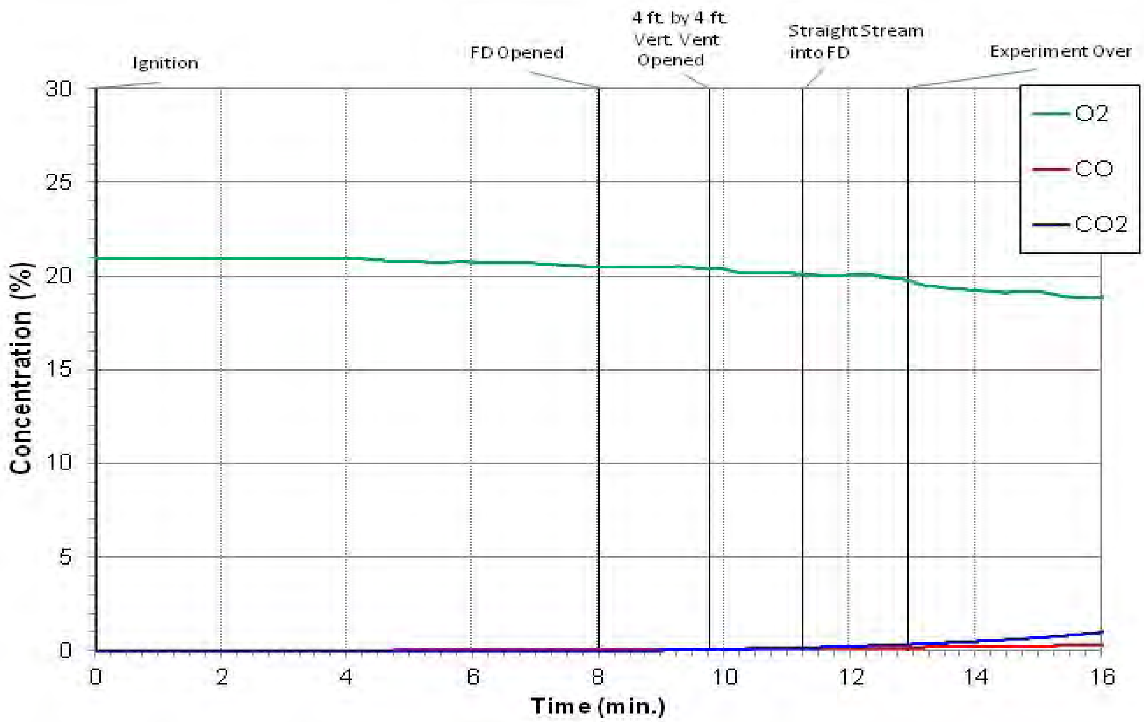


Figure E.109: Experiment 5 Bedroom 3 Gas

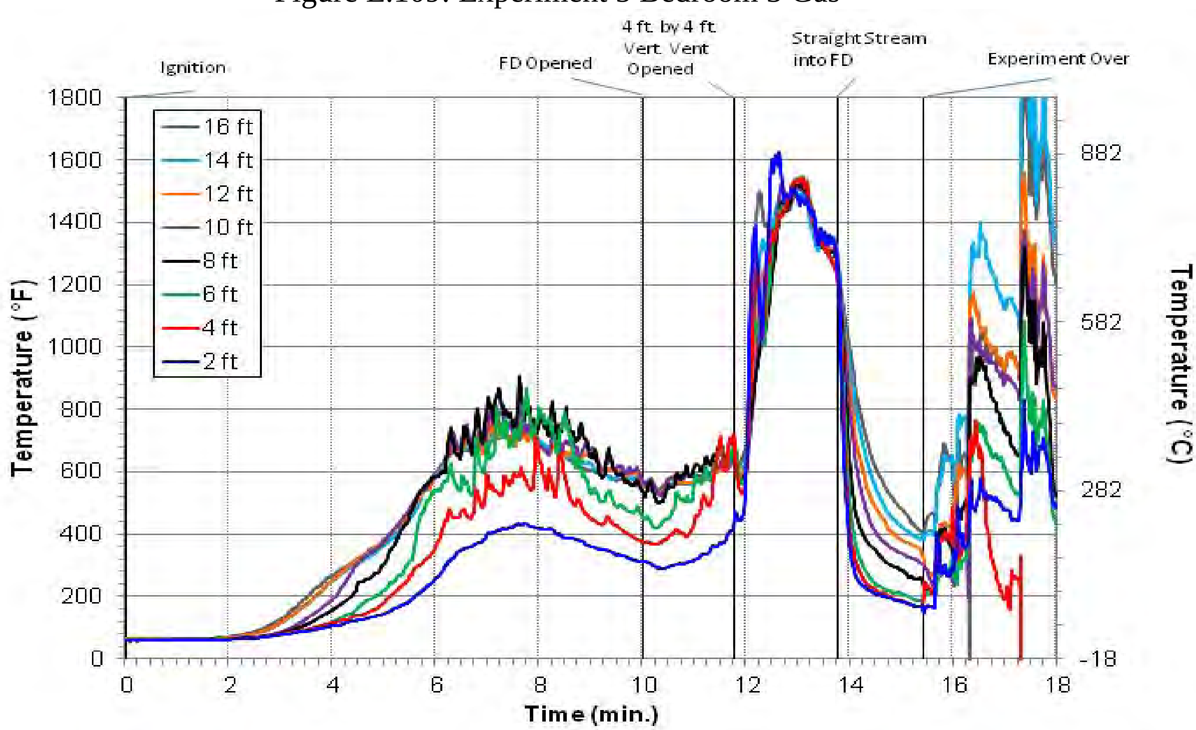


Figure E.110: Experiment 6 Family Room Temperature

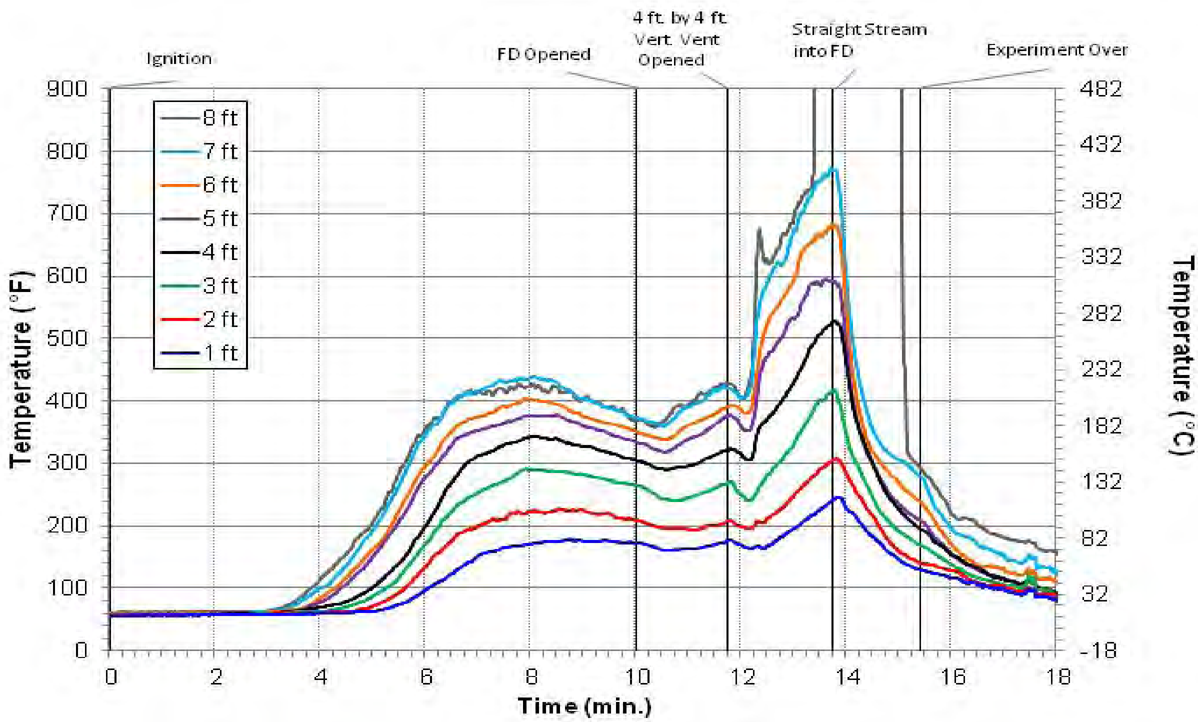


Figure E.111: Experiment 6 Kitchen Temperature

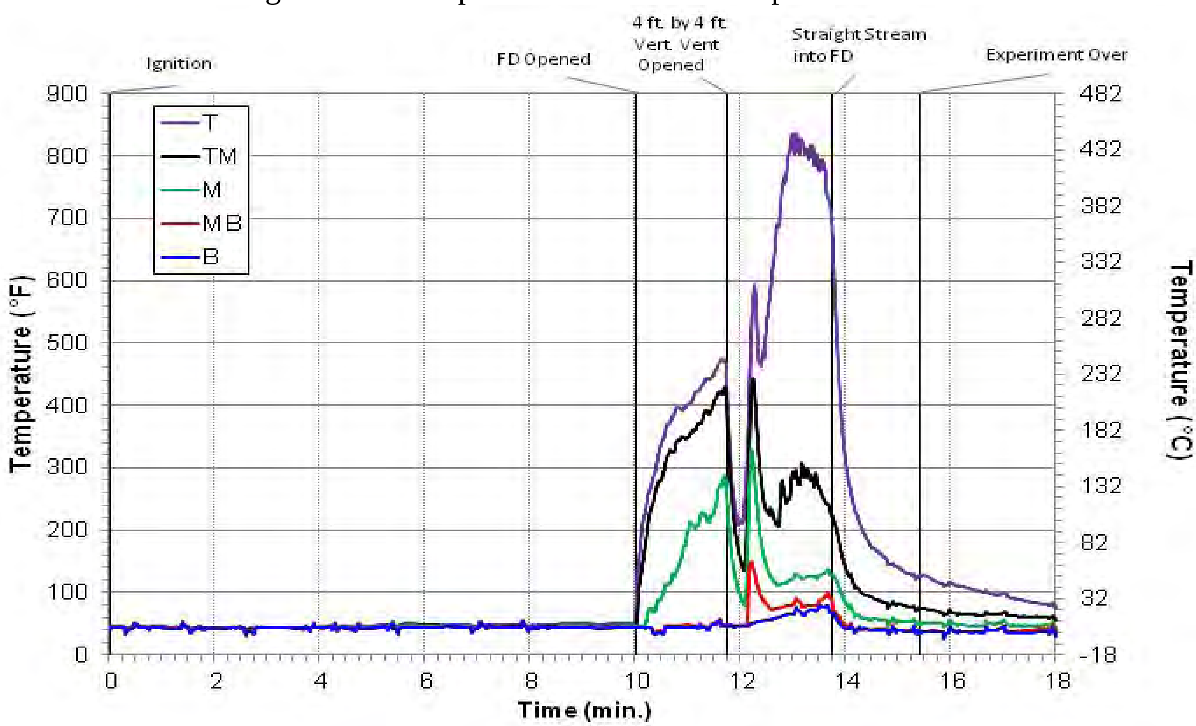


Figure E.112: Experiment 6 Front Door Temperature

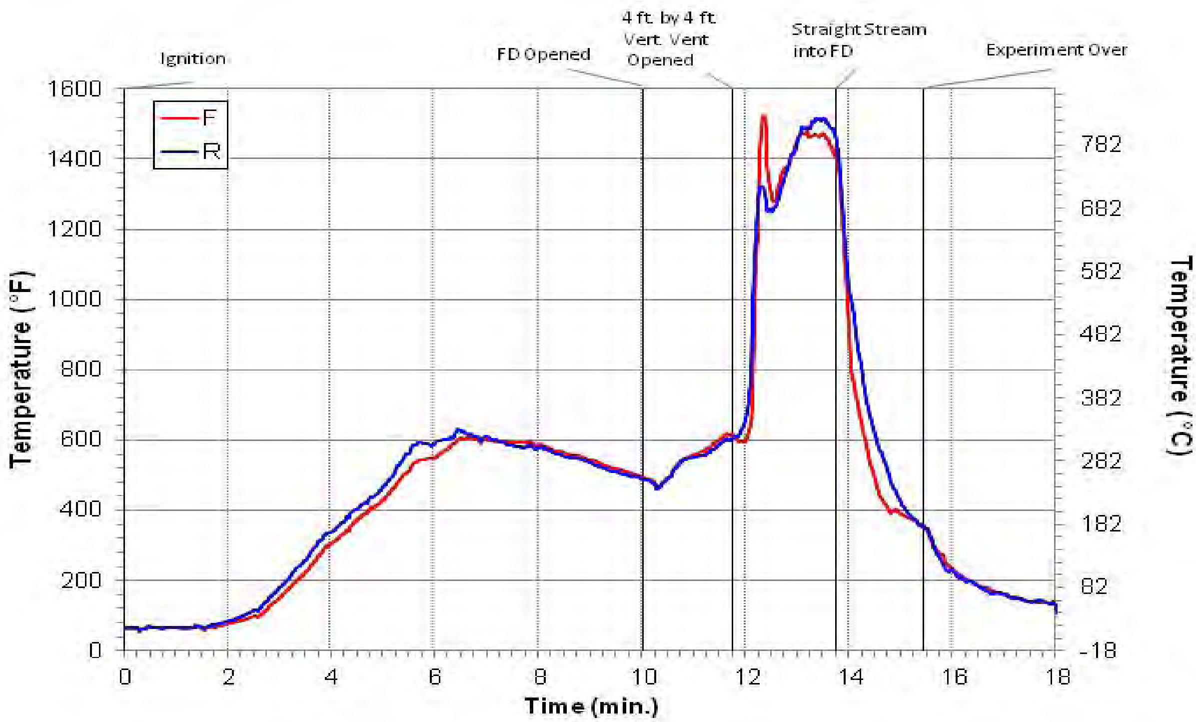


Figure E.113: Experiment 6 Vent Temperature

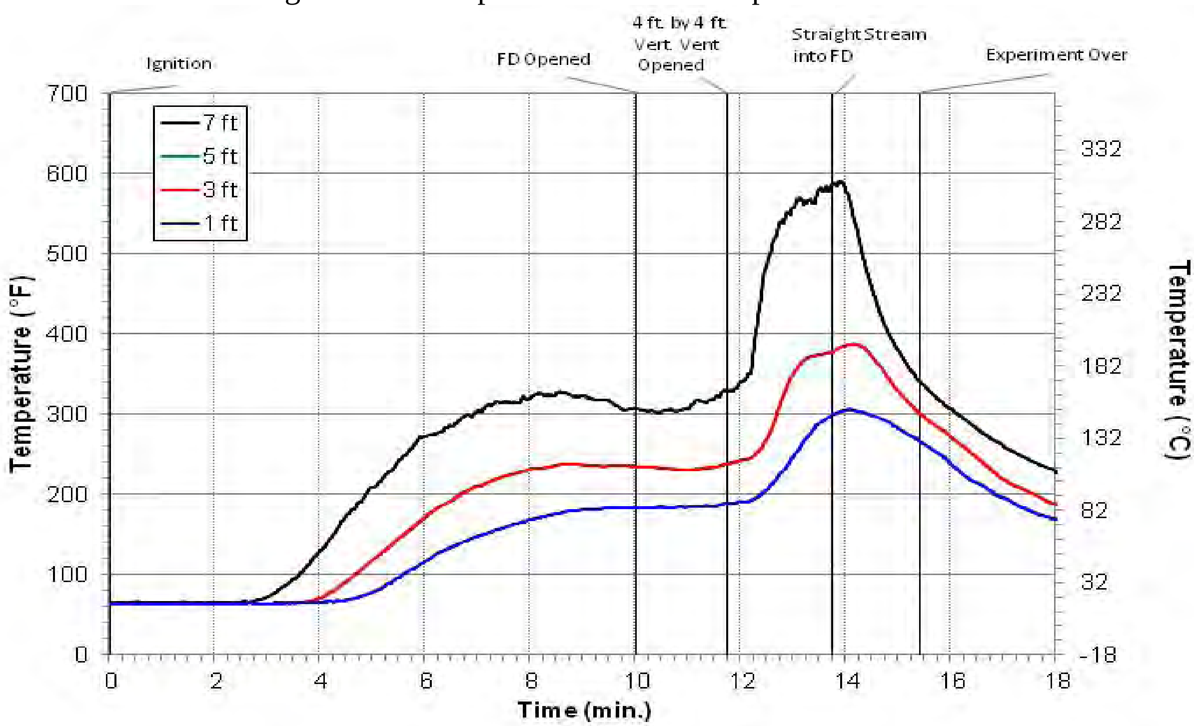


Figure E.114: Experiment 6 Bedroom 1 Temperature

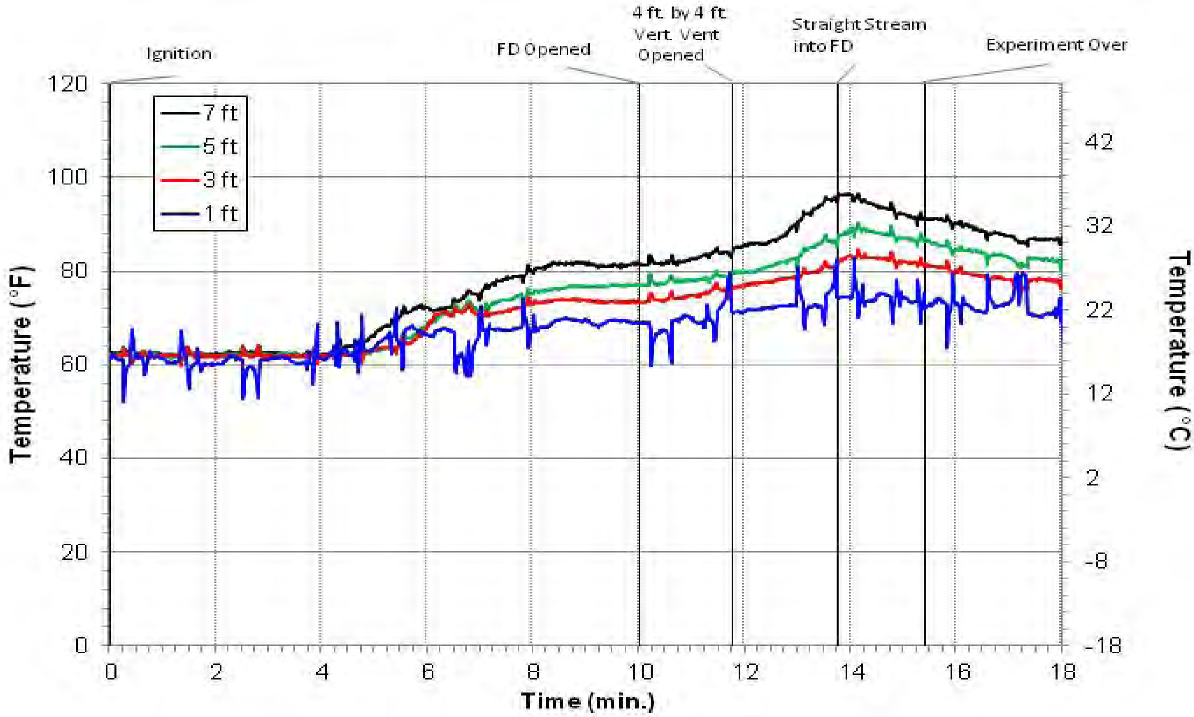


Figure E.115: Experiment 6 Bedroom 2 Temperature

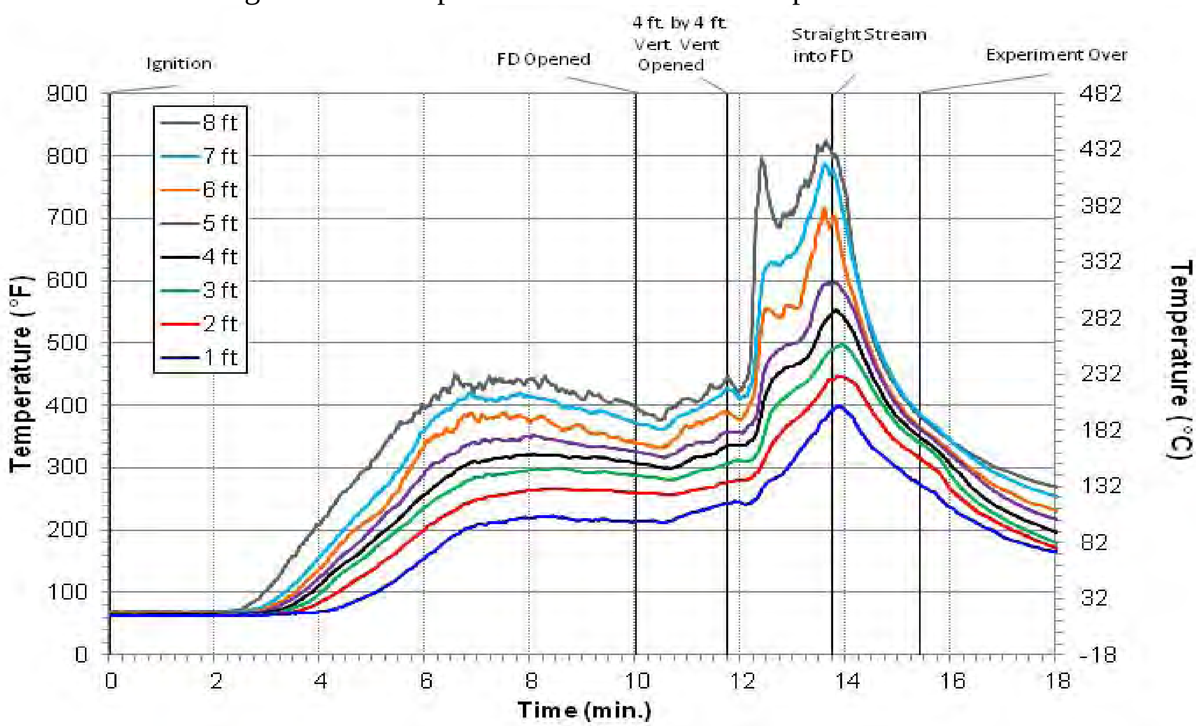


Figure E.116: Experiment 6 Bedroom 3 Temperature

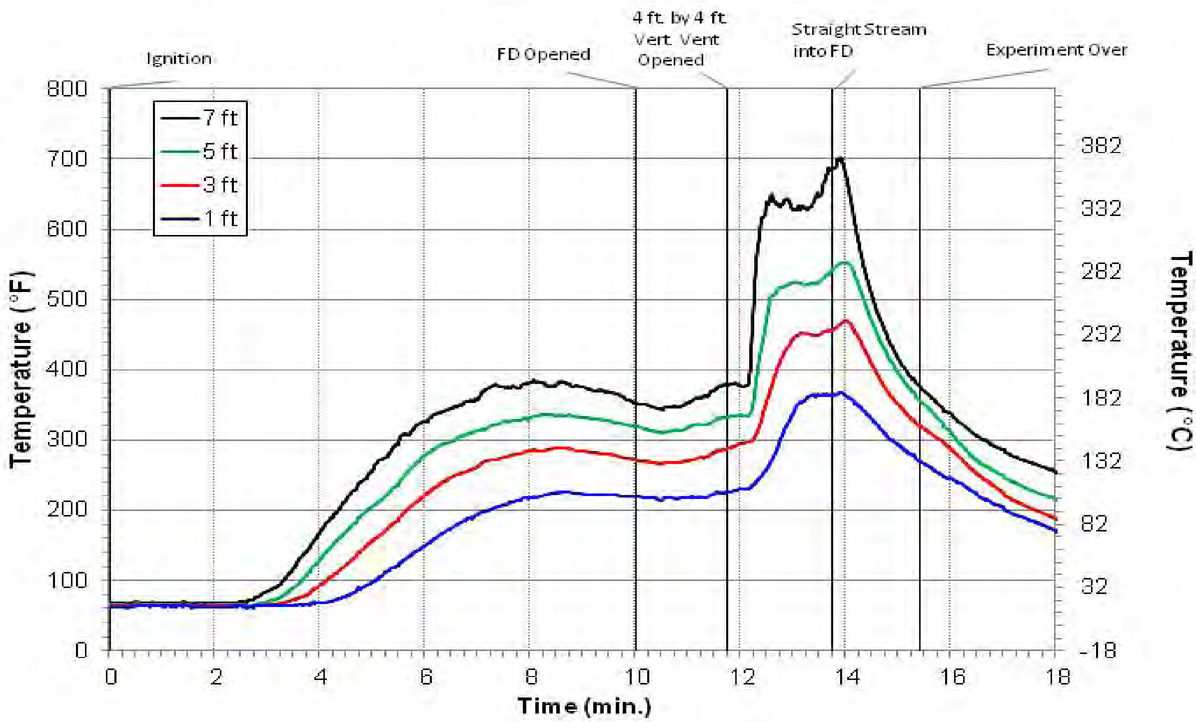


Figure E.117: Experiment 6 Bedroom 4 Temperature

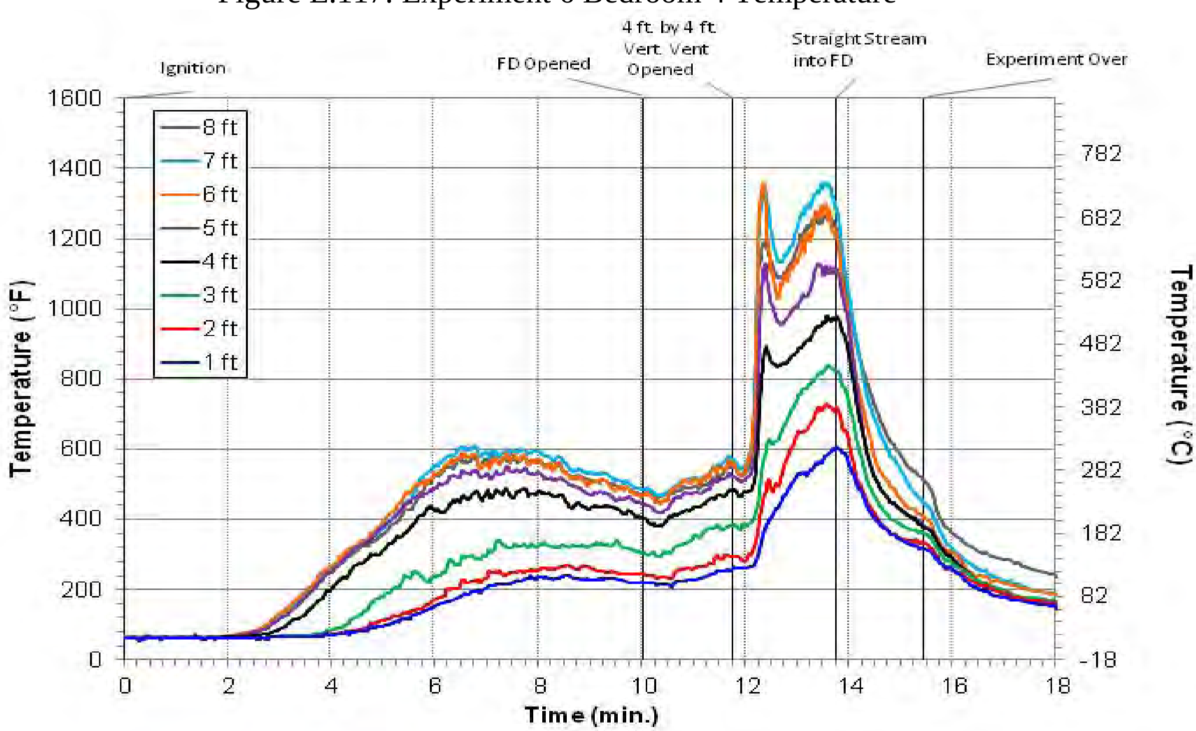


Figure E.118: Experiment 6 Hallway Temperature

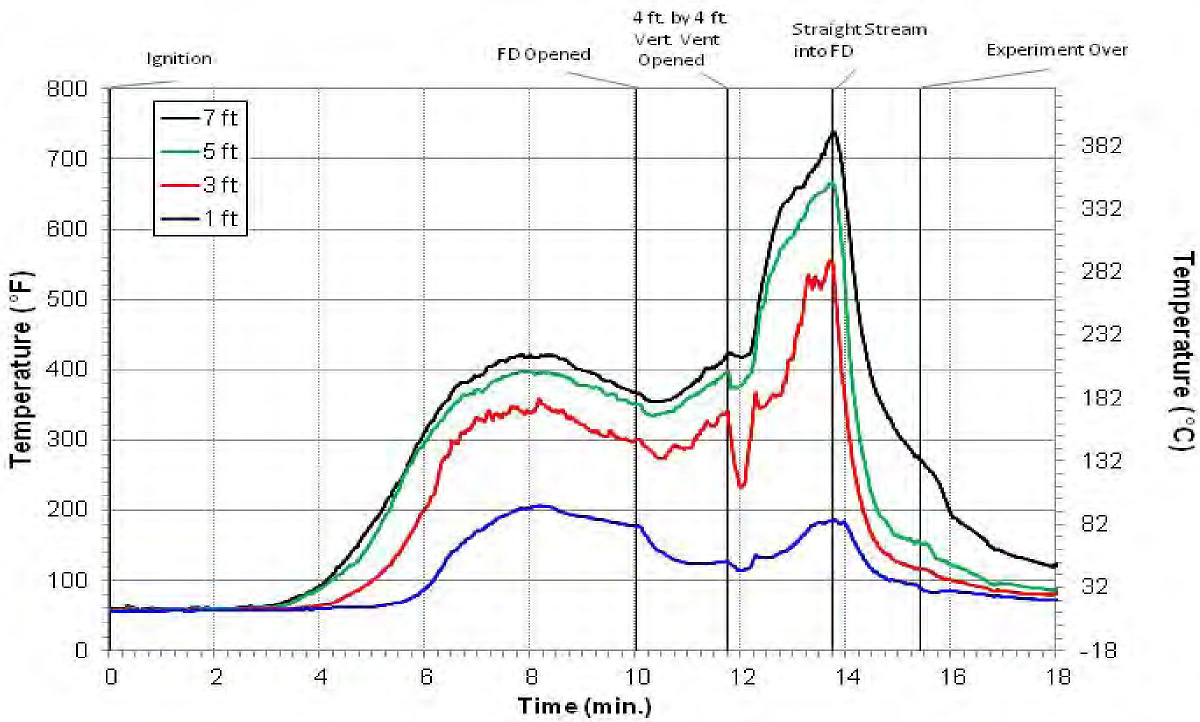


Figure E.119: Experiment 6 Dining Room Temperature

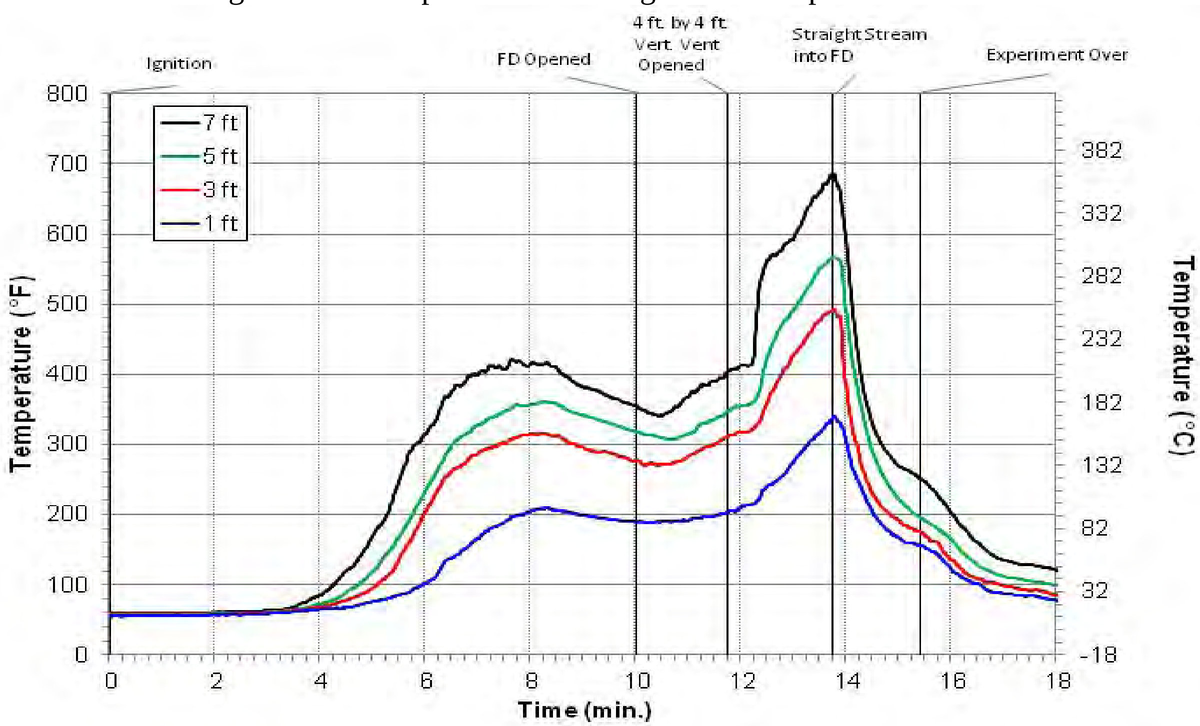


Figure E.120: Experiment 6 Living Room Temperature

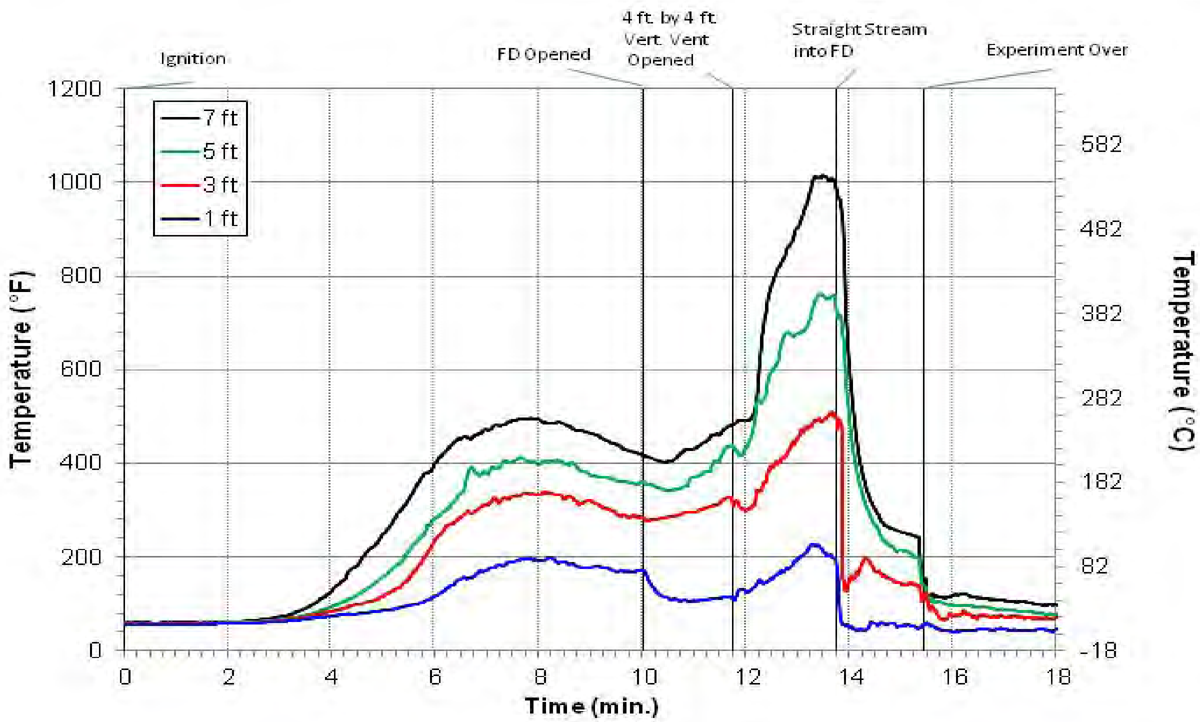


Figure E.121: Experiment 6 Foyer Temperature

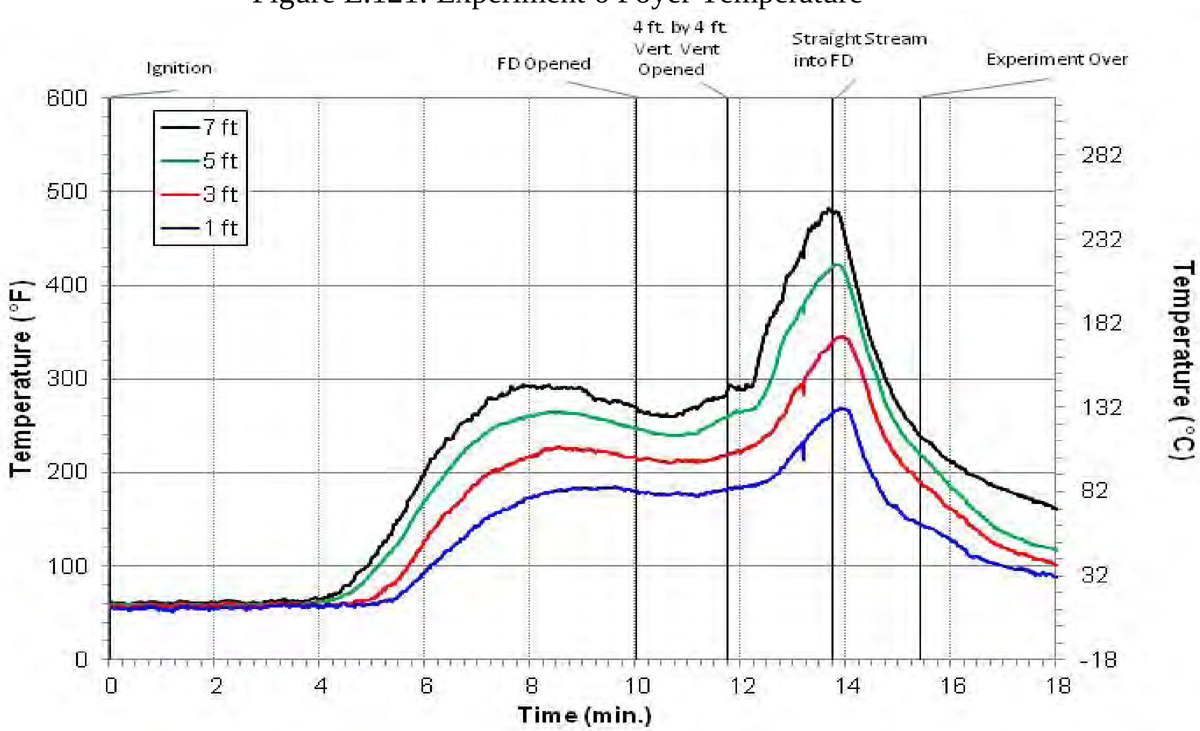


Figure E.122: Experiment 6 Den Temperature

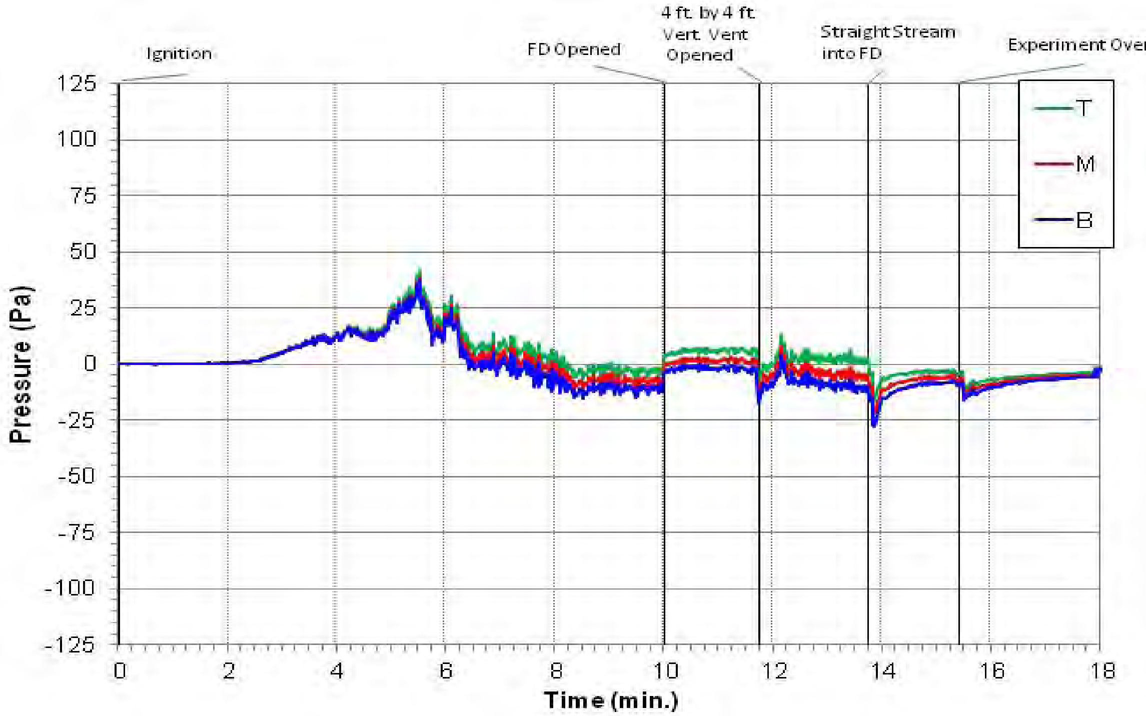


Figure E.123: Experiment 6 Living Room Pressure

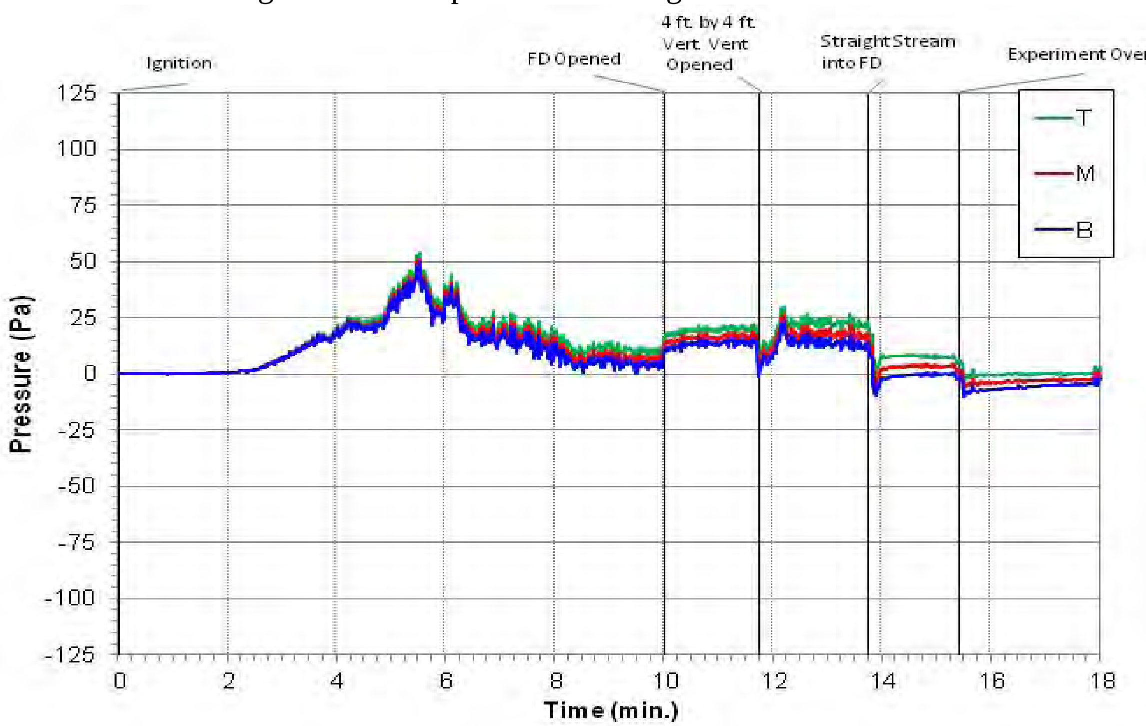


Figure E.124: Experiment 6 Bedroom 2 Pressure

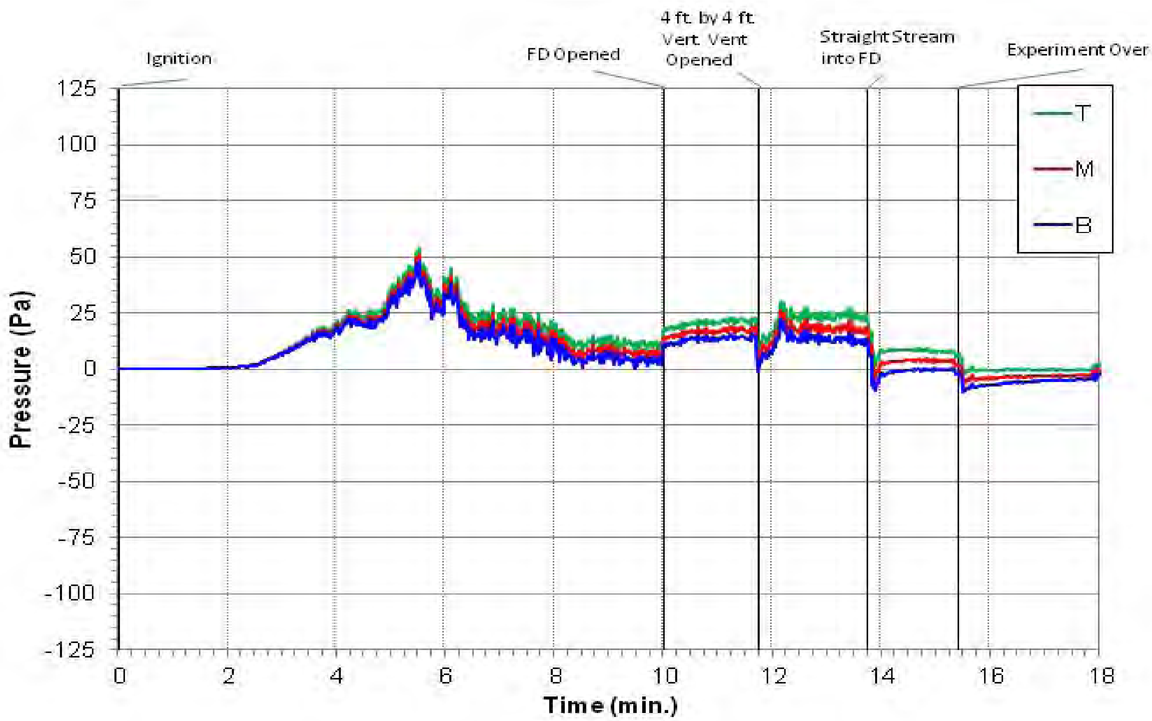


Figure E.125: Experiment 6 Bedroom 3 Pressure

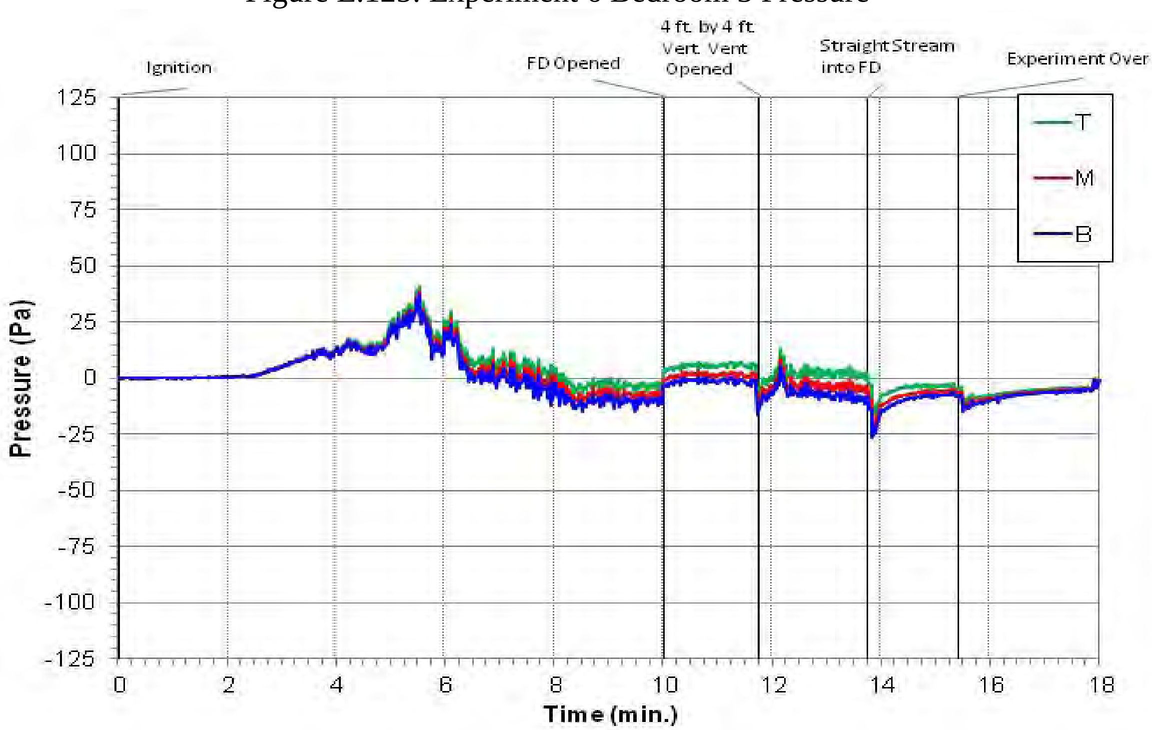


Figure E.126: Experiment 6 Kitchen Pressure

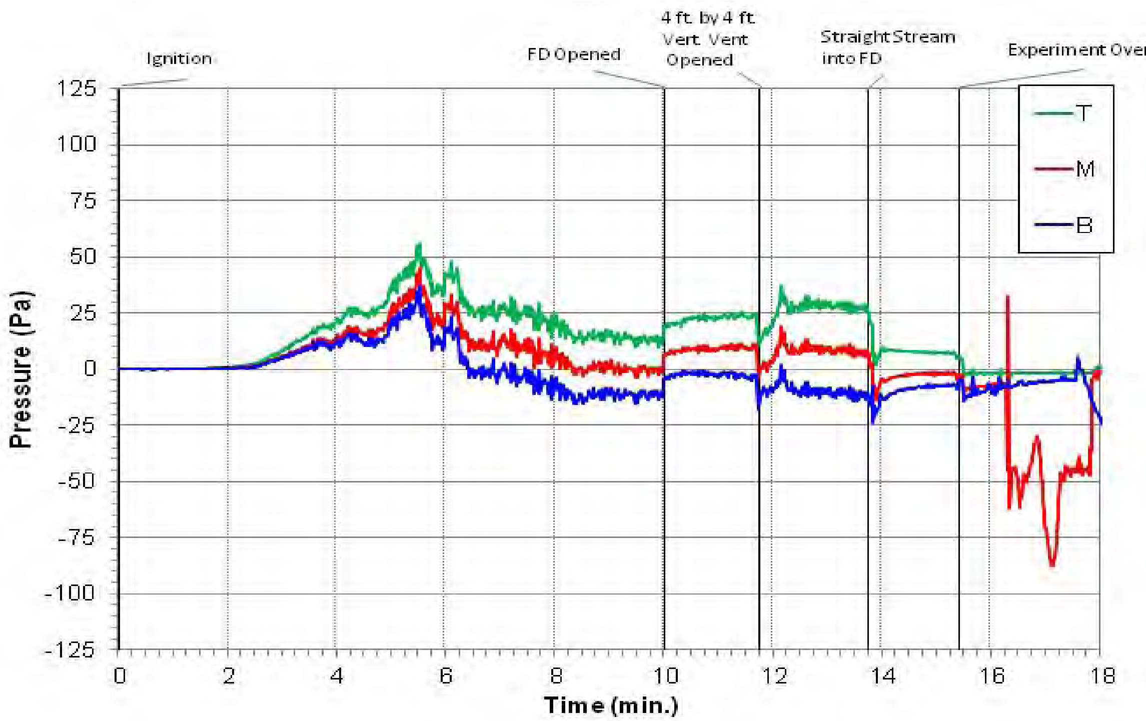


Figure E.127: Experiment 6 Family Room Pressure

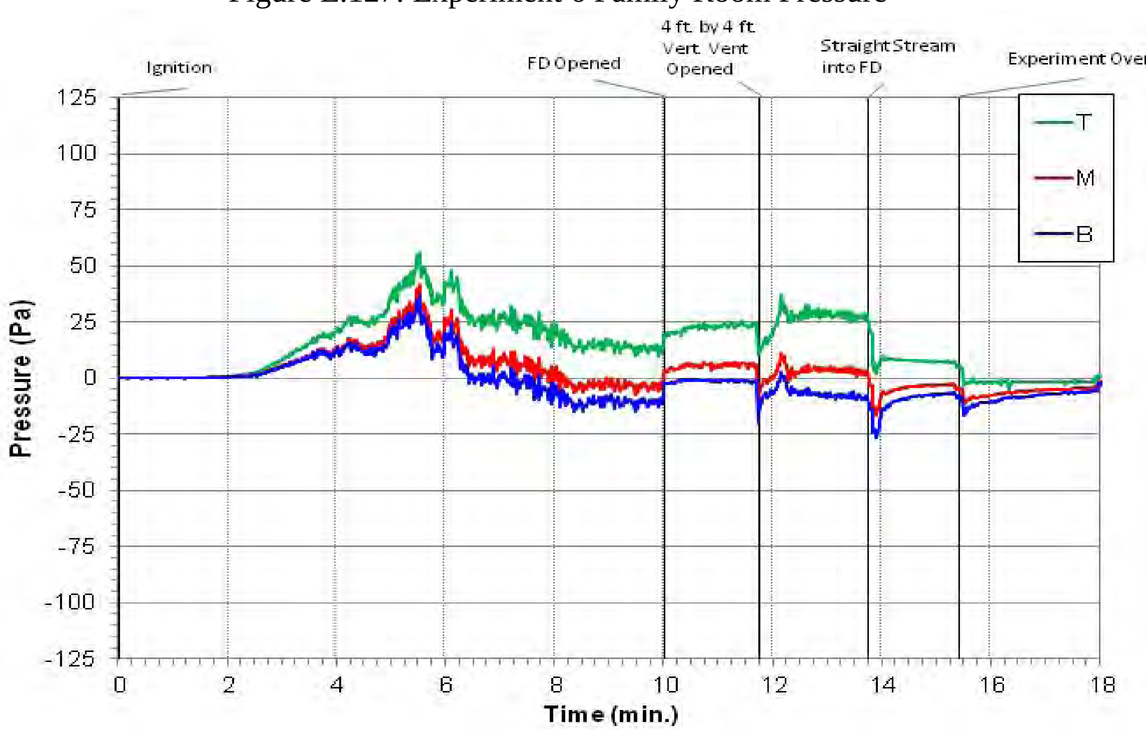


Figure E.128: Experiment 6 Foyer Pressure

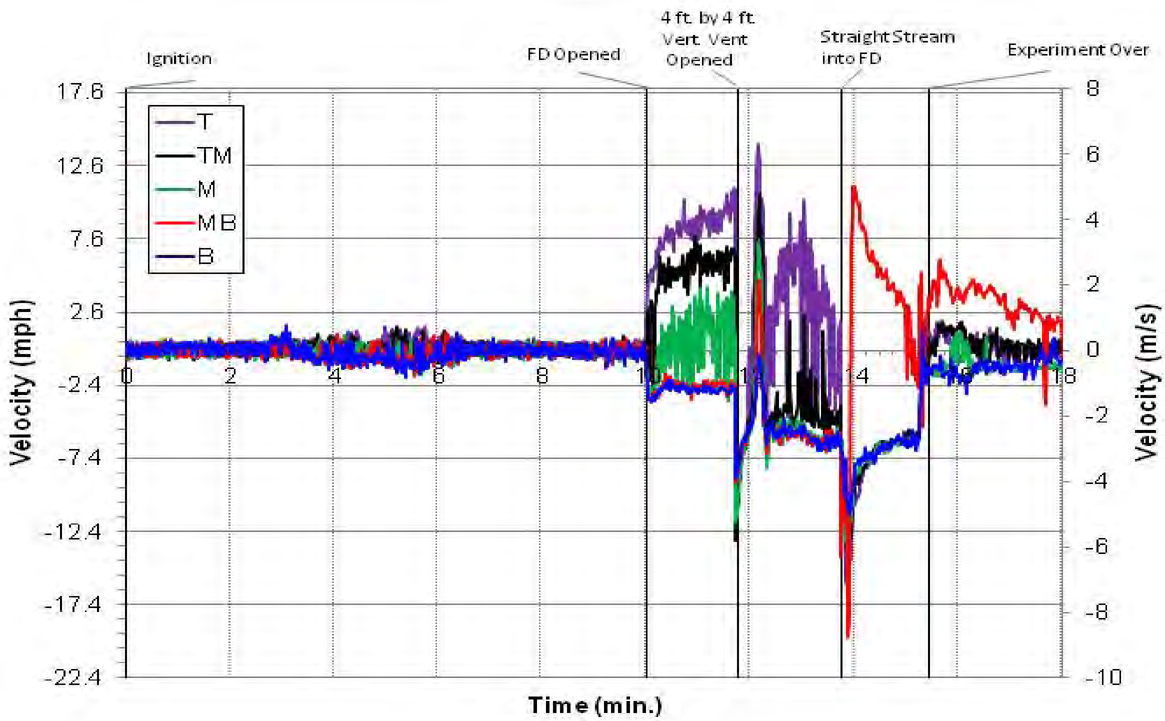


Figure E.129: Experiment 6 Front Door Velocity

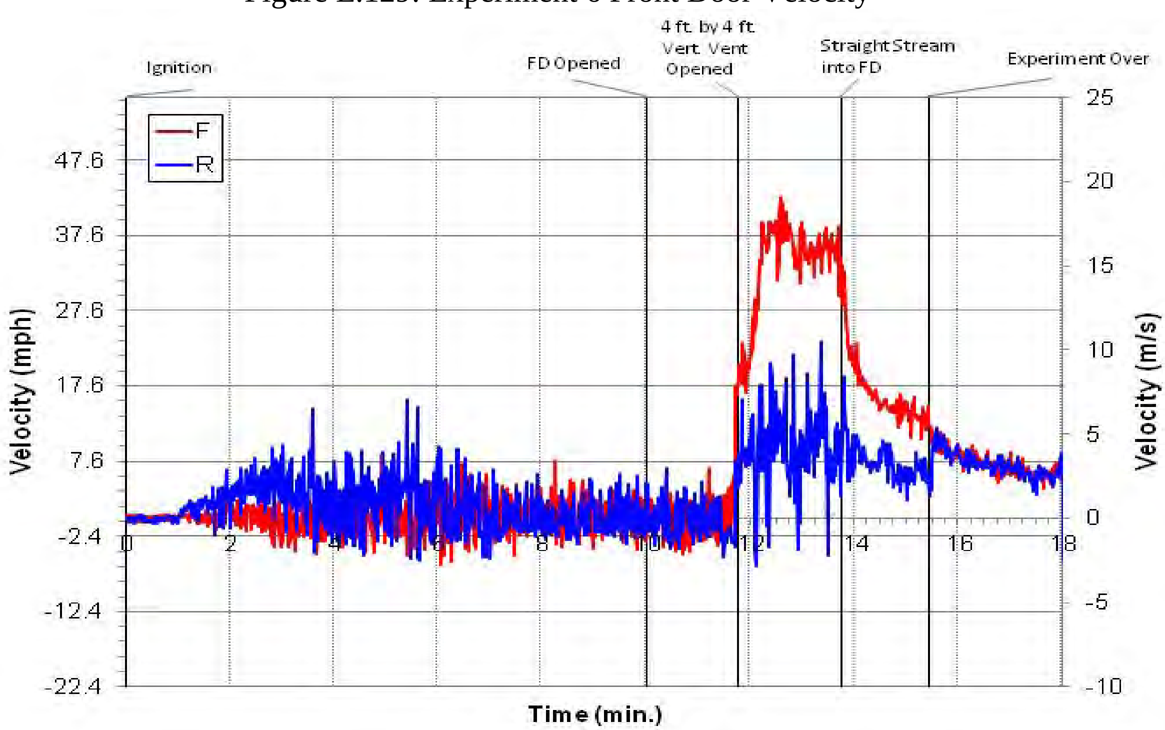


Figure E.130: Experiment 6 Vent Velocity

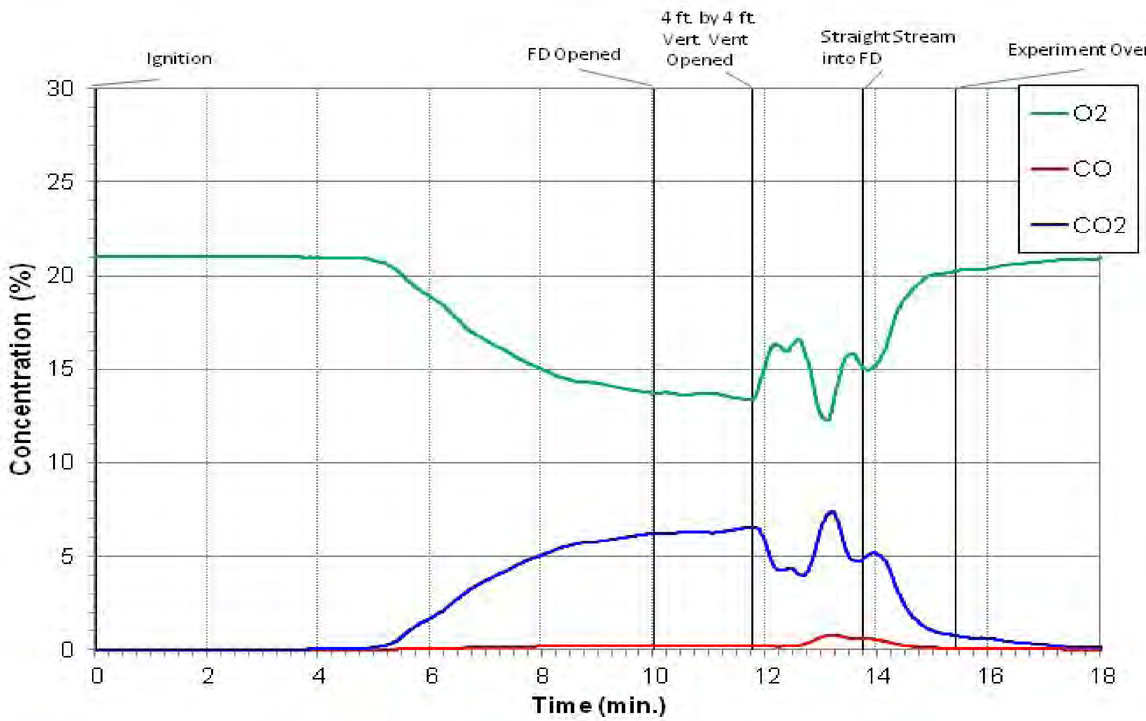


Figure E.131: Experiment 6 Front Door Gas

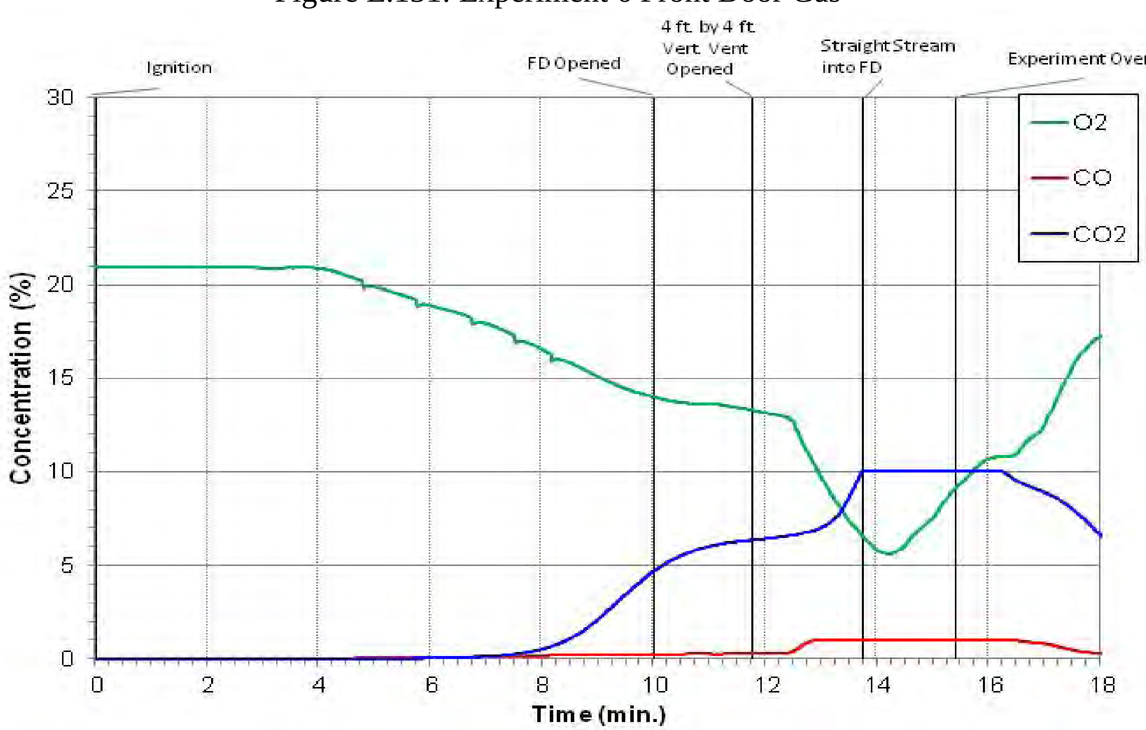


Figure E.132: Experiment 6 Bedroom 1 Gas

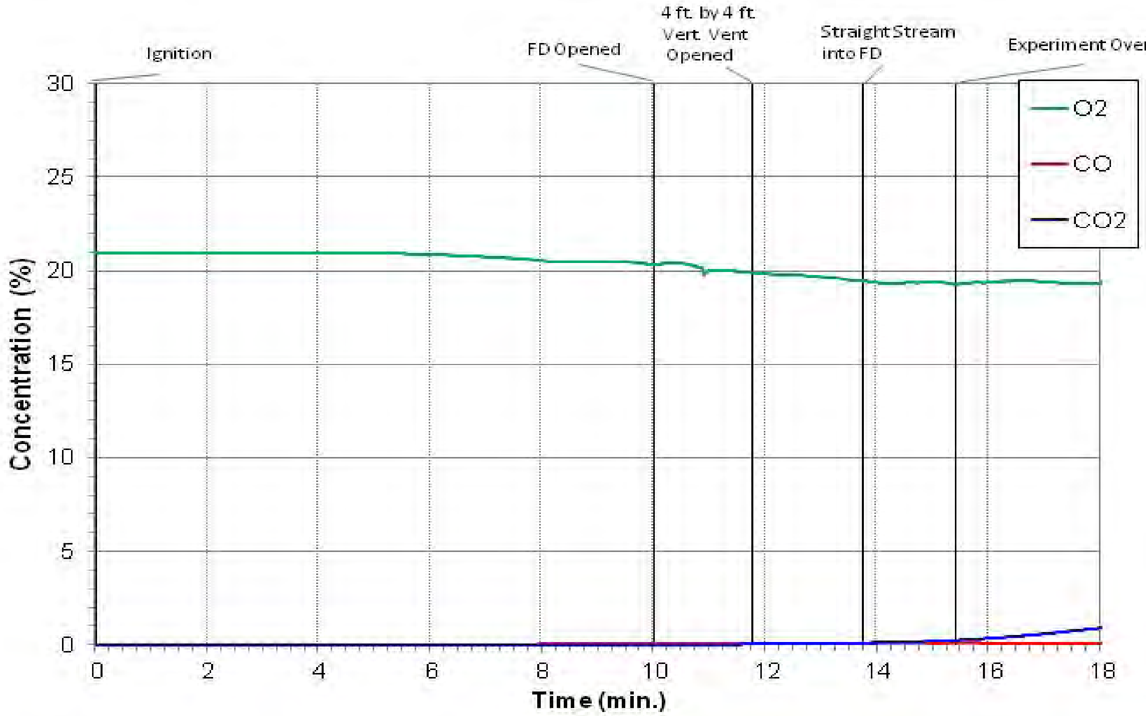


Figure E.133: Experiment 6 Bedroom 2 Gas

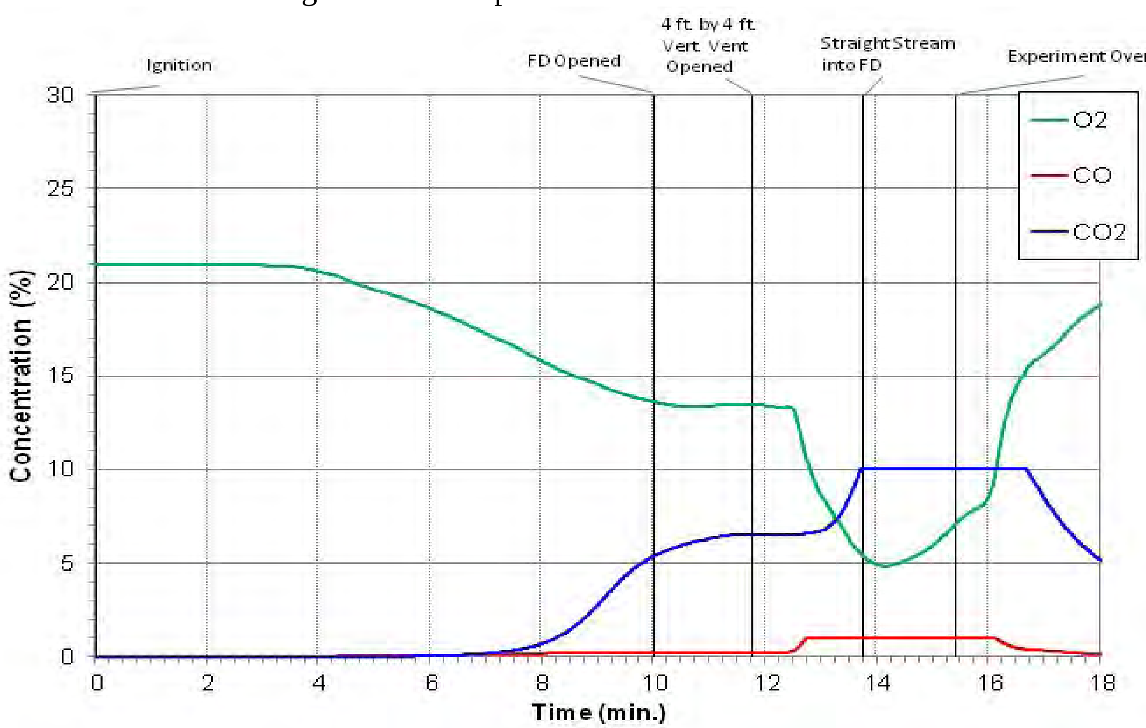


Figure E.134: Experiment 6 Bedroom 3 Gas

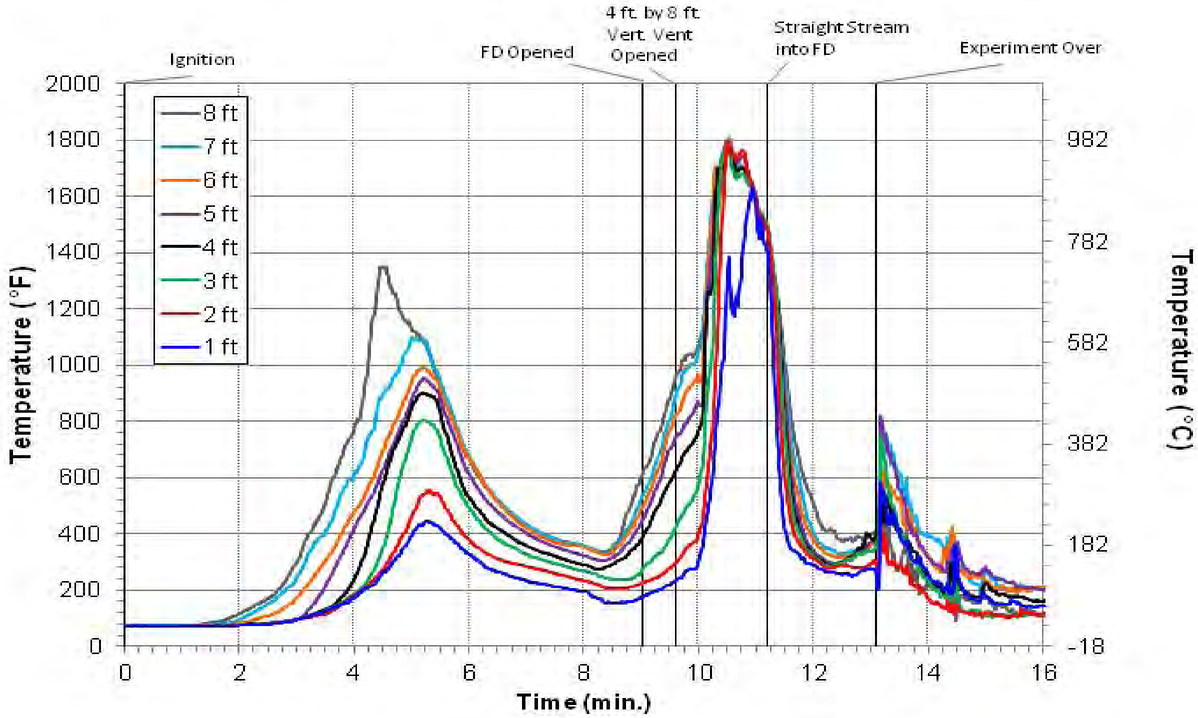


Figure E.135: Experiment 7 Living Room Temperature

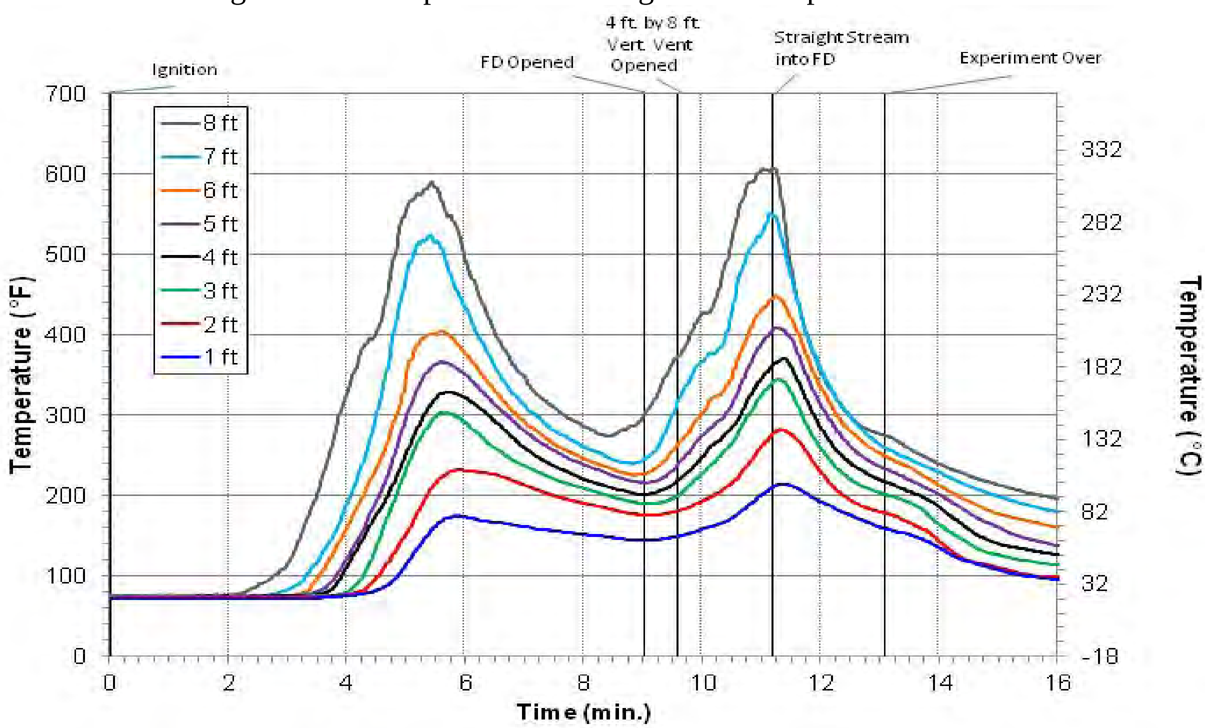


Figure E.136: Experiment 7 Bedroom 1 Temperature

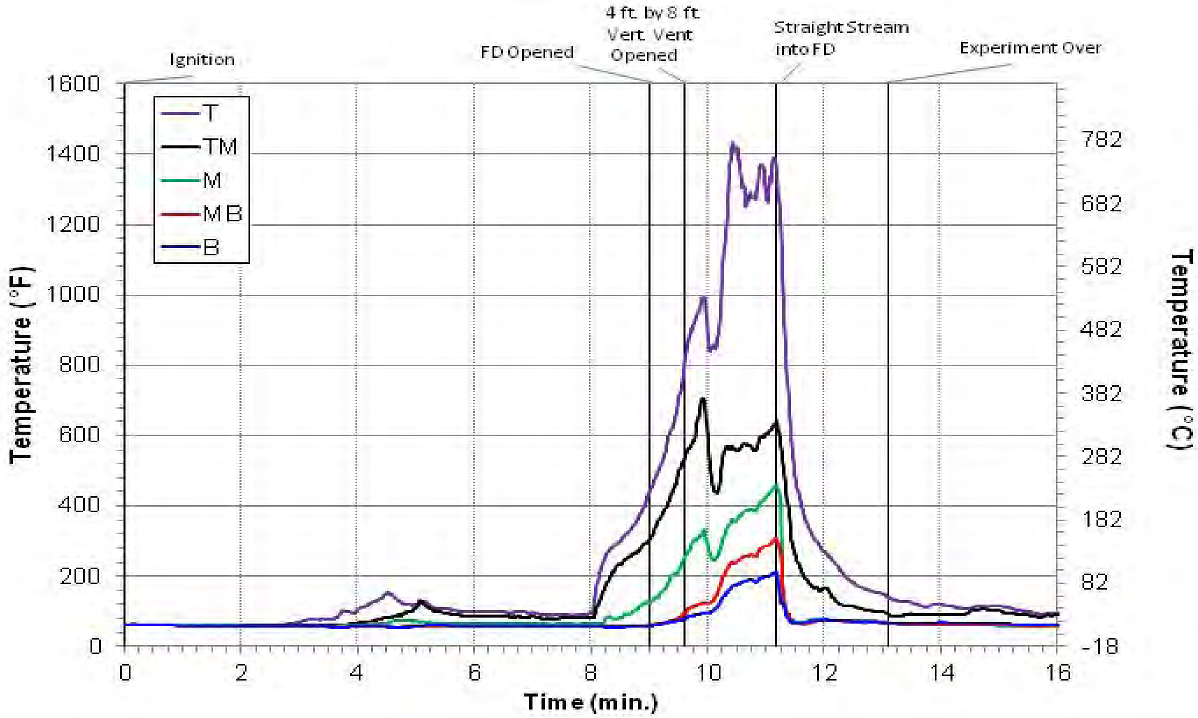


Figure E.137: Experiment 7 Front Door Temperature

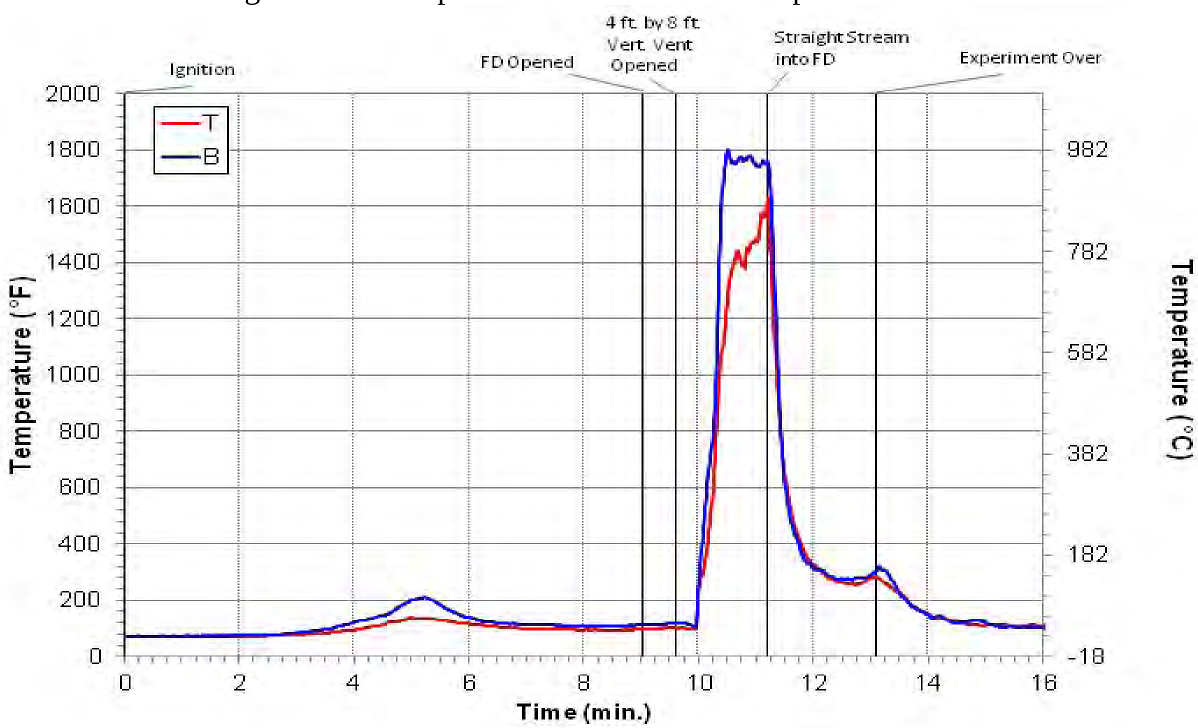


Figure E.138: Experiment 7 Vent Temperature

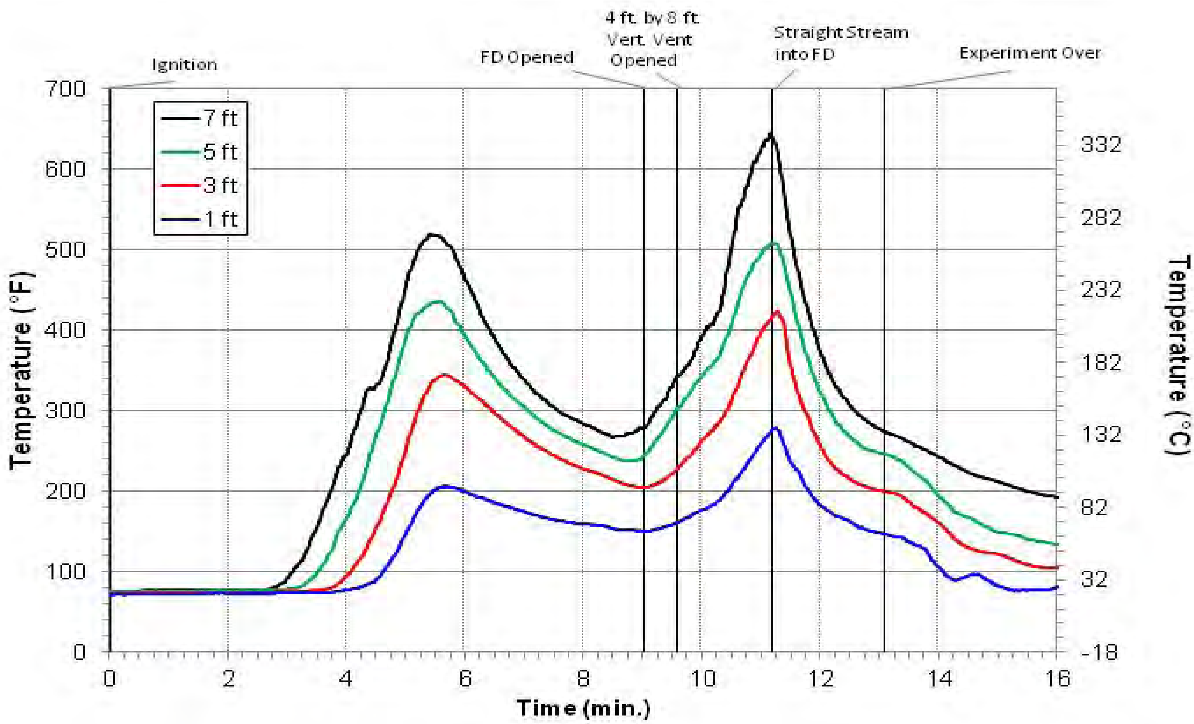


Figure E.139: Experiment 7 Bedroom 2 Temperature

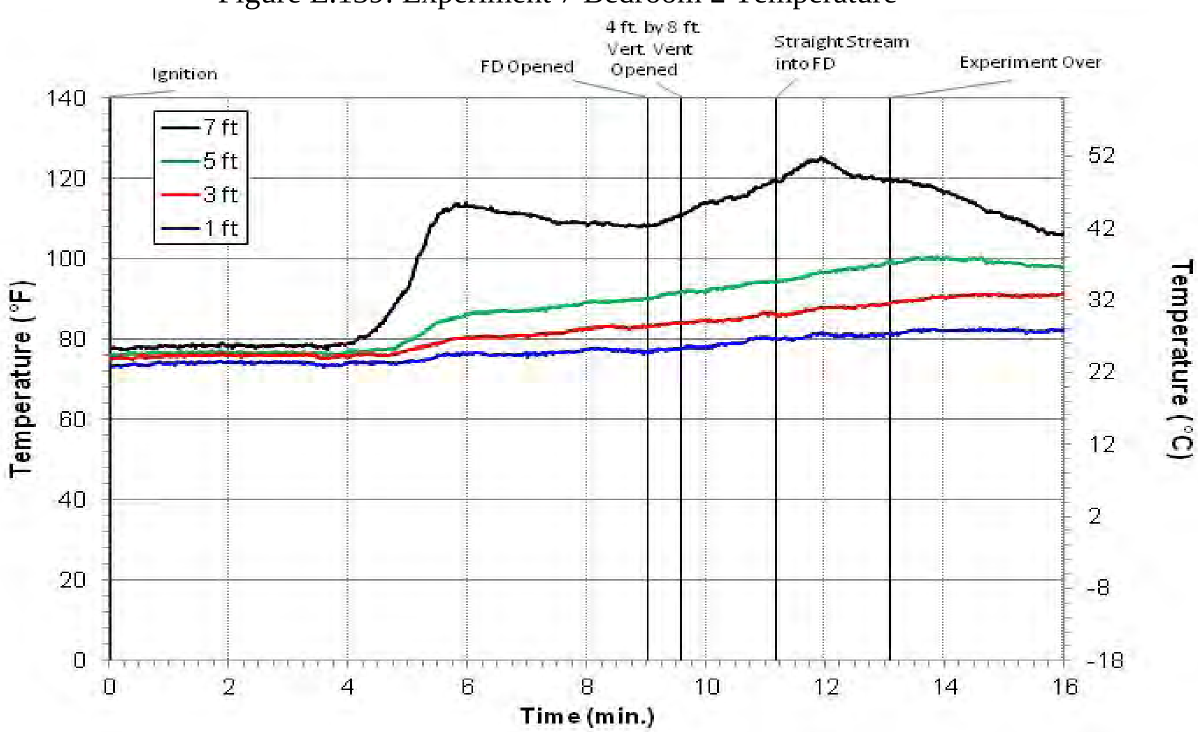


Figure E.140: Experiment 7 Bedroom 3 Temperature

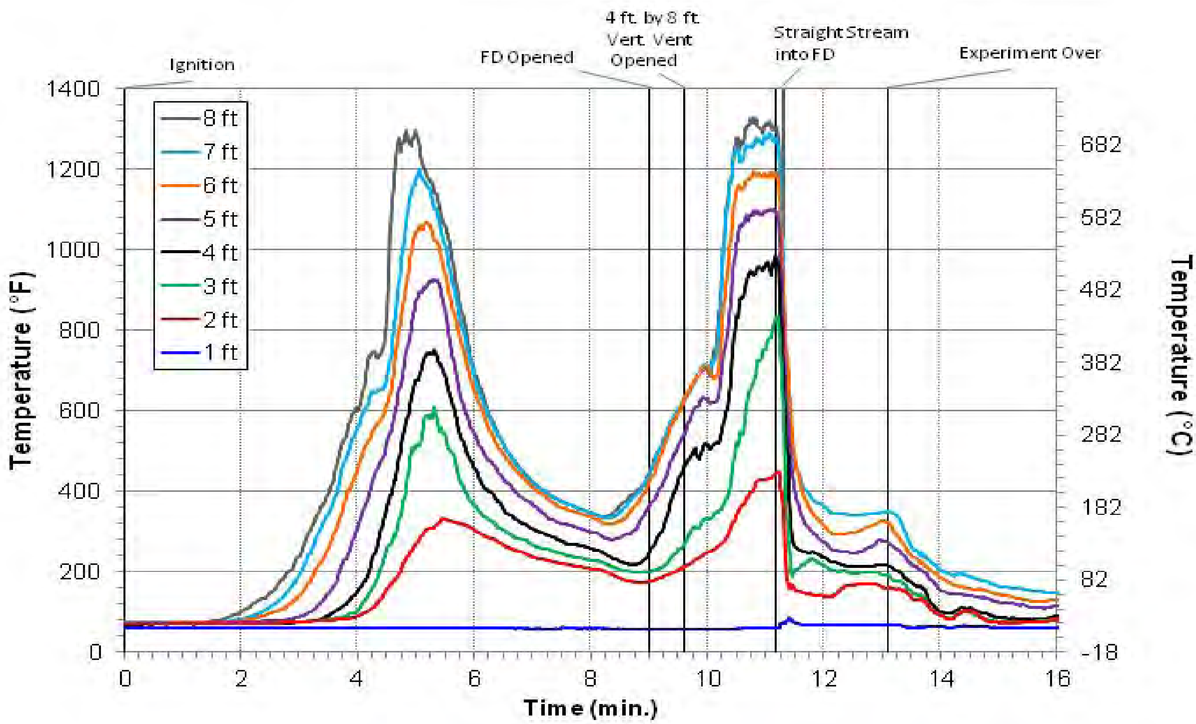


Figure E.141: Experiment 7 Hallway Temperature

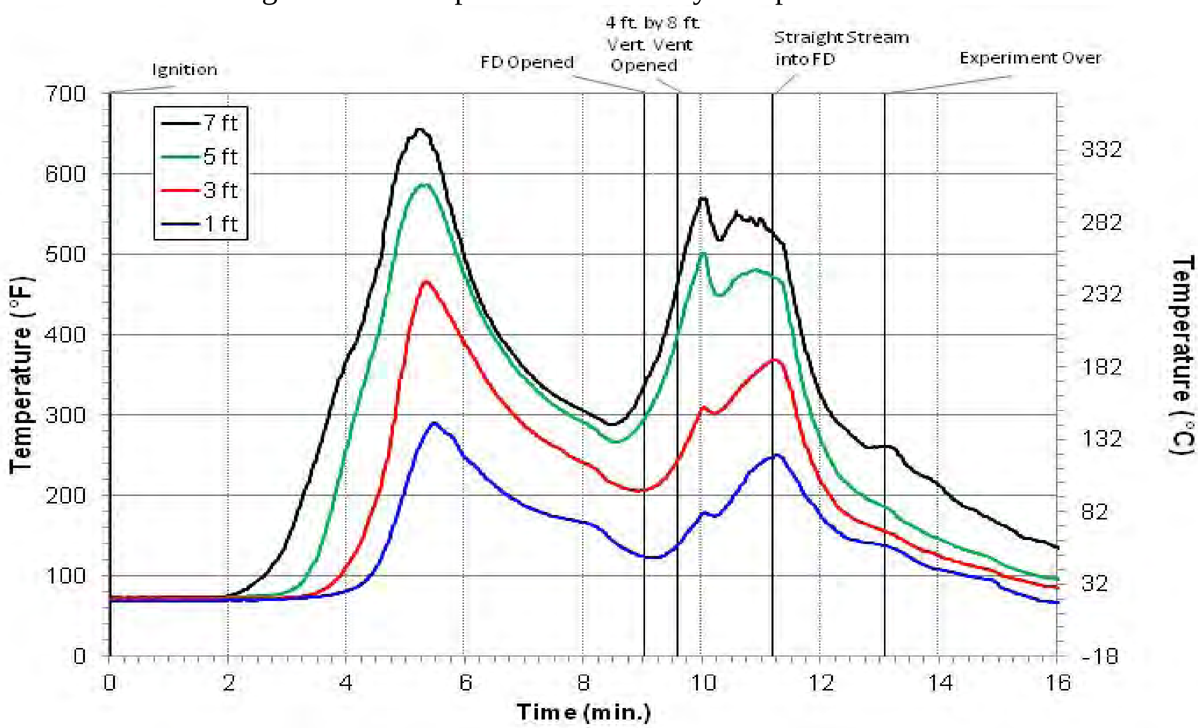


Figure E.142: Experiment 7 Dining Room Temperature

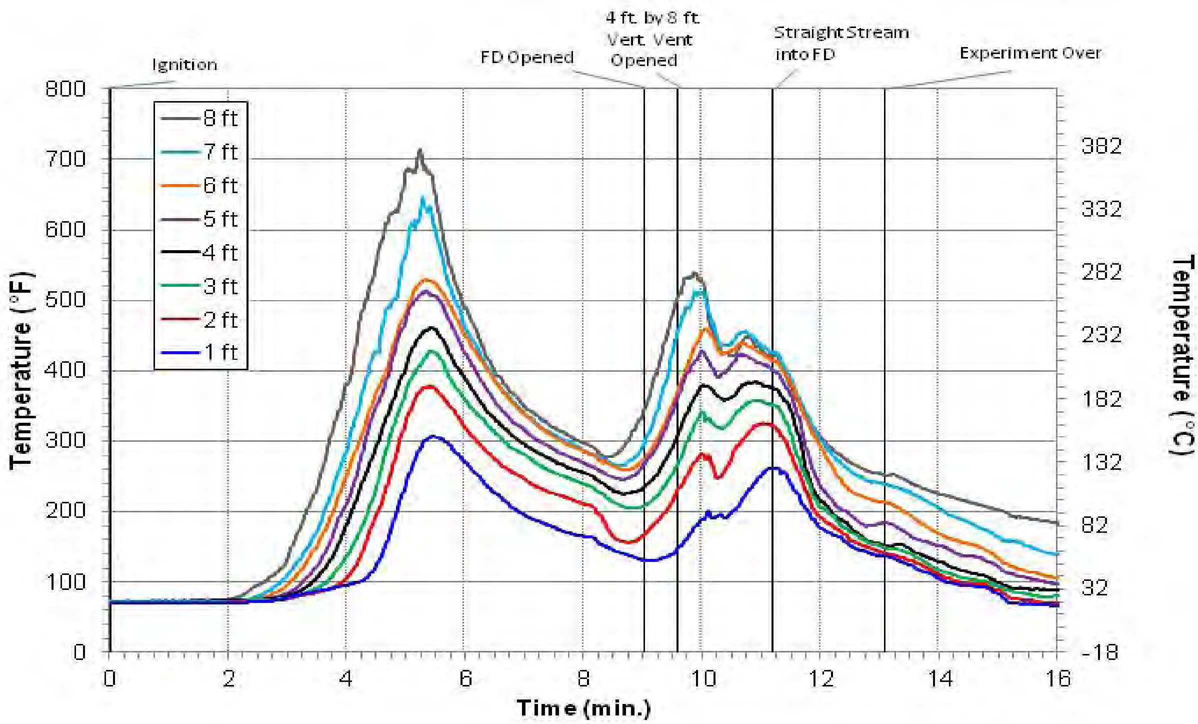


Figure E.143: Experiment 7 Kitchen Temperature

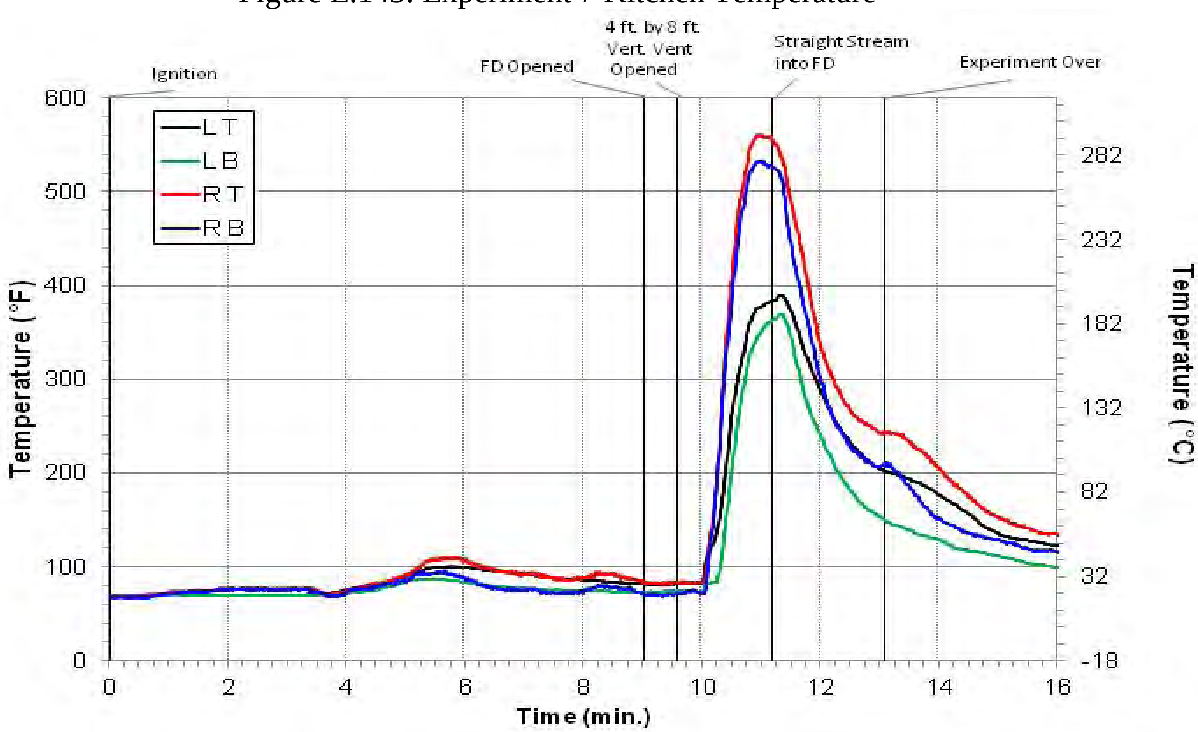


Figure E.144: Experiment 7 Attic Temperature

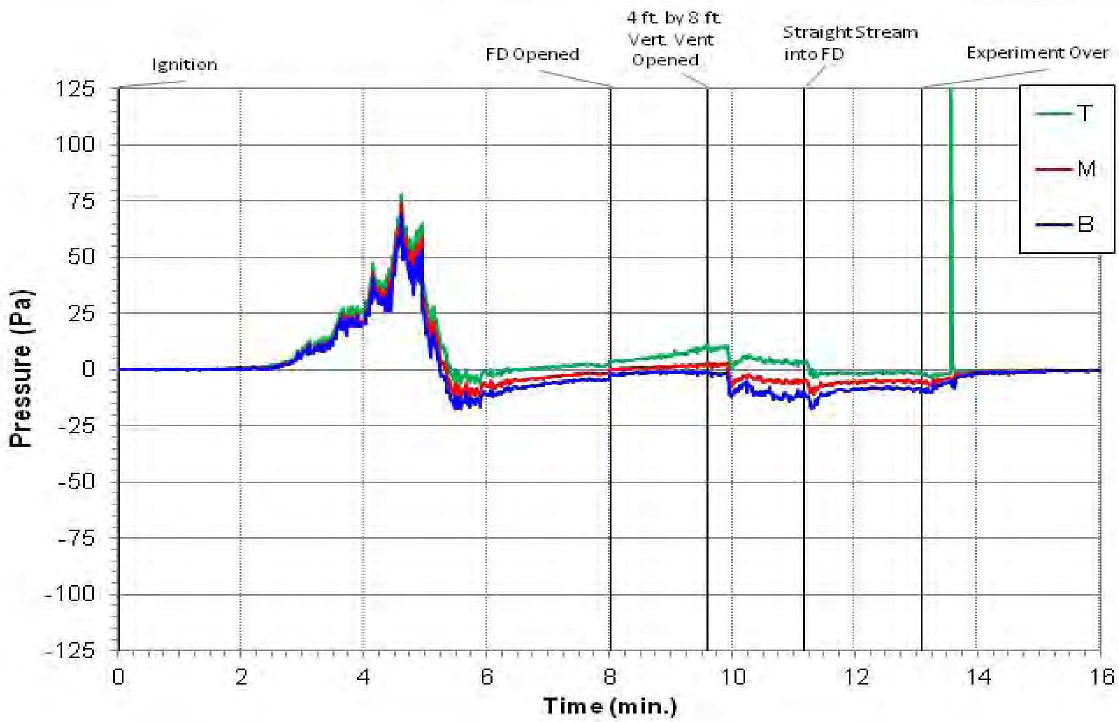


Figure E.145: Experiment 7 Living Room Pressure

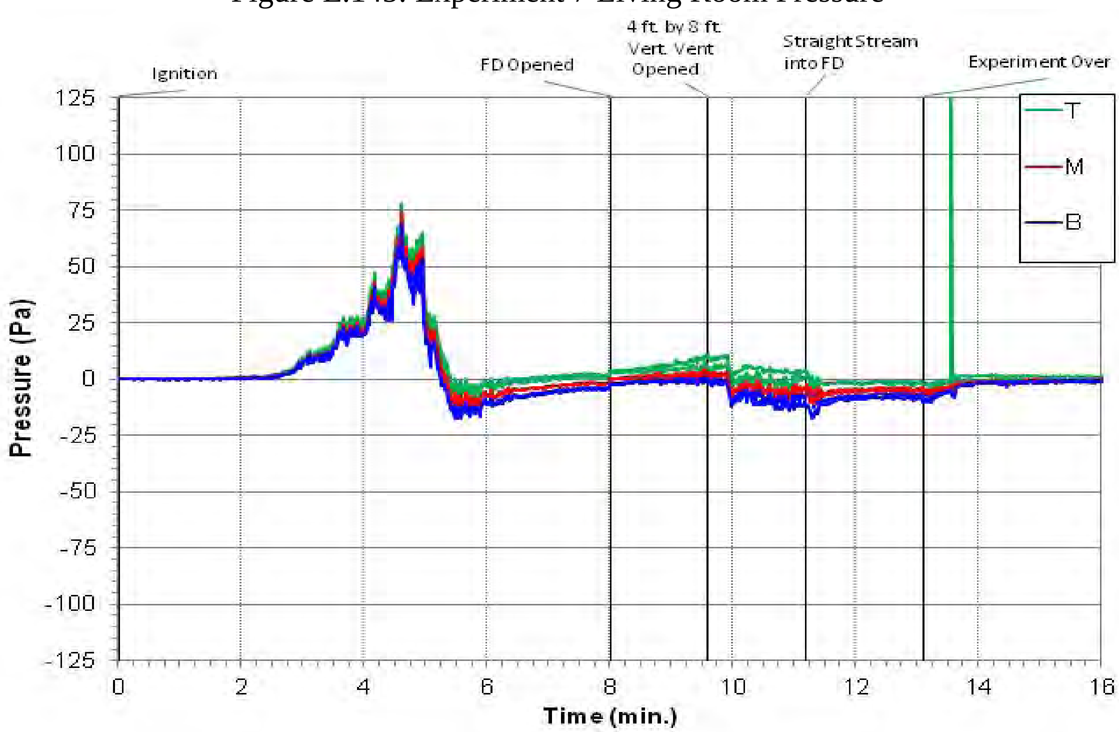


Figure E.146: Experiment 7 Bedroom 1 Pressure

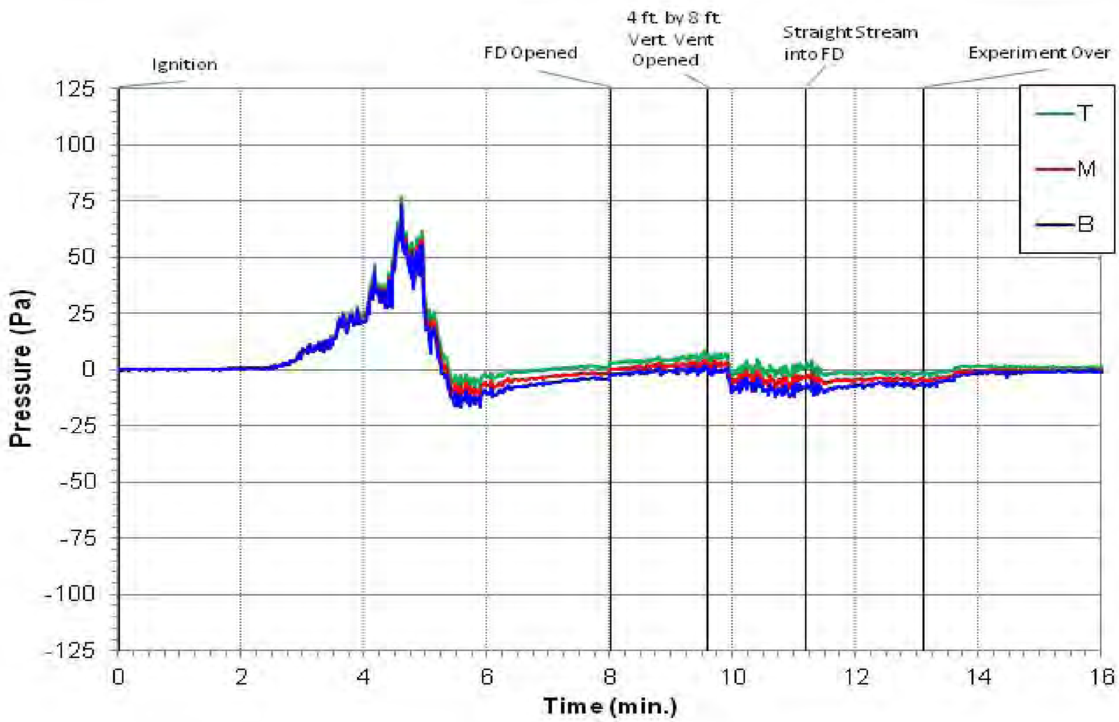


Figure E.147: Experiment 7 Bedroom 2 Pressure

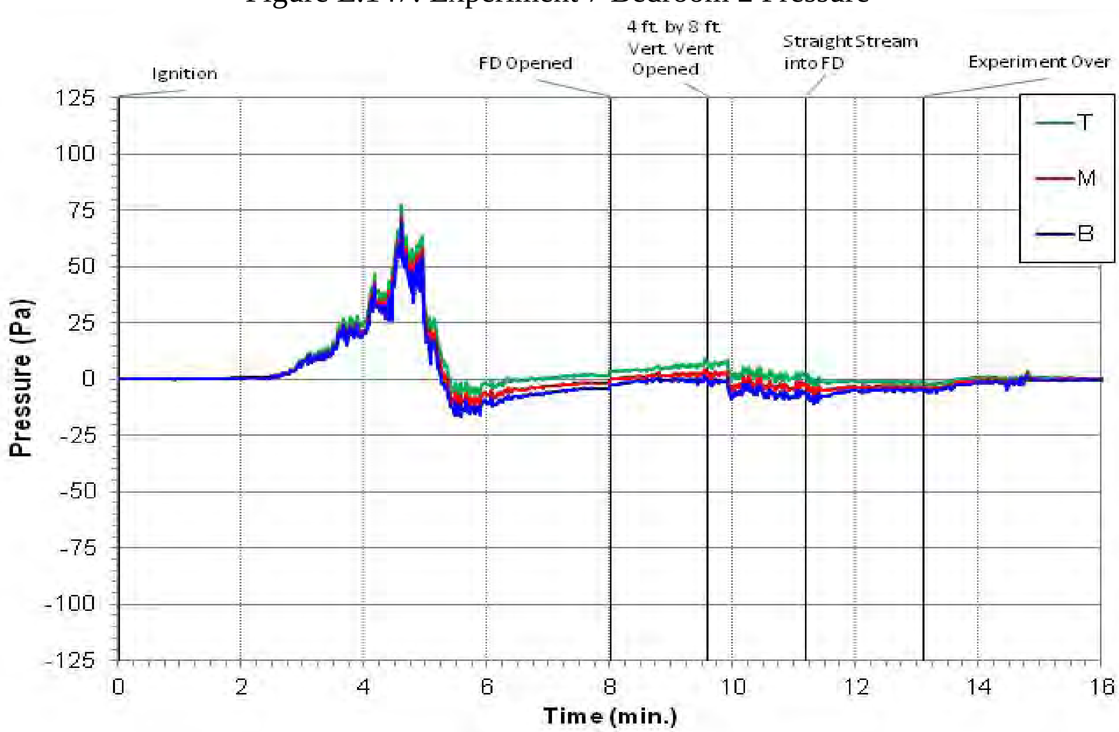


Figure E.148: Experiment 7 Kitchen Pressure

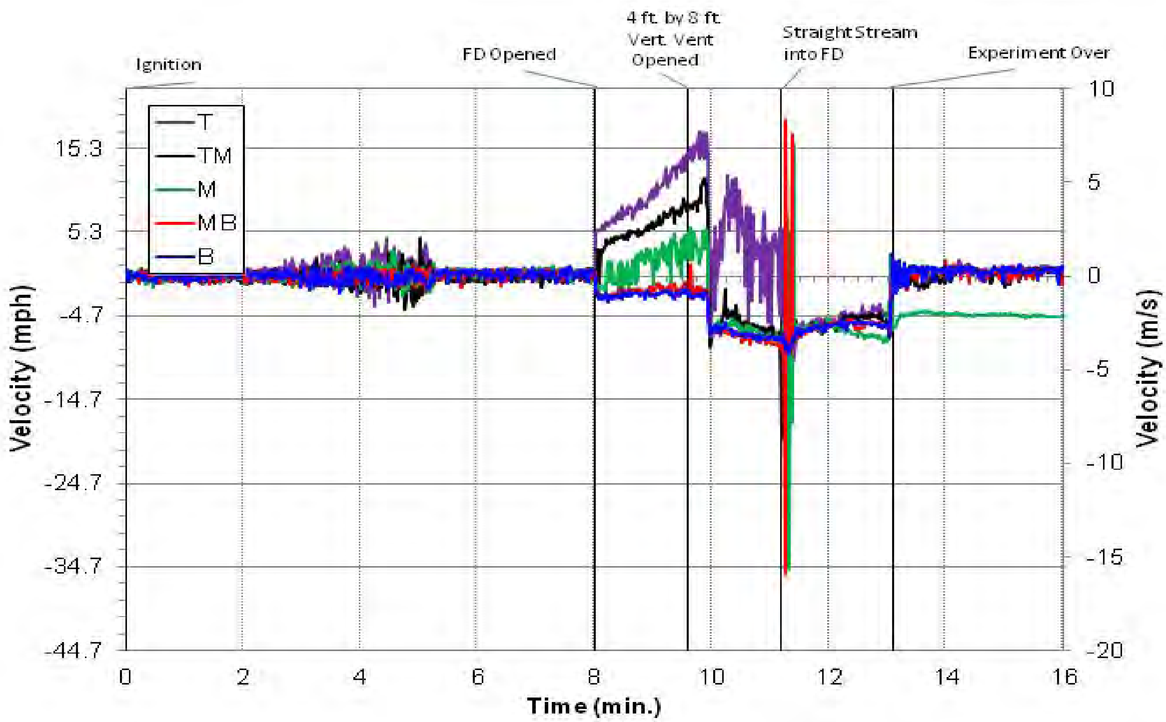


Figure E.149: Experiment 7 Front Door Velocity

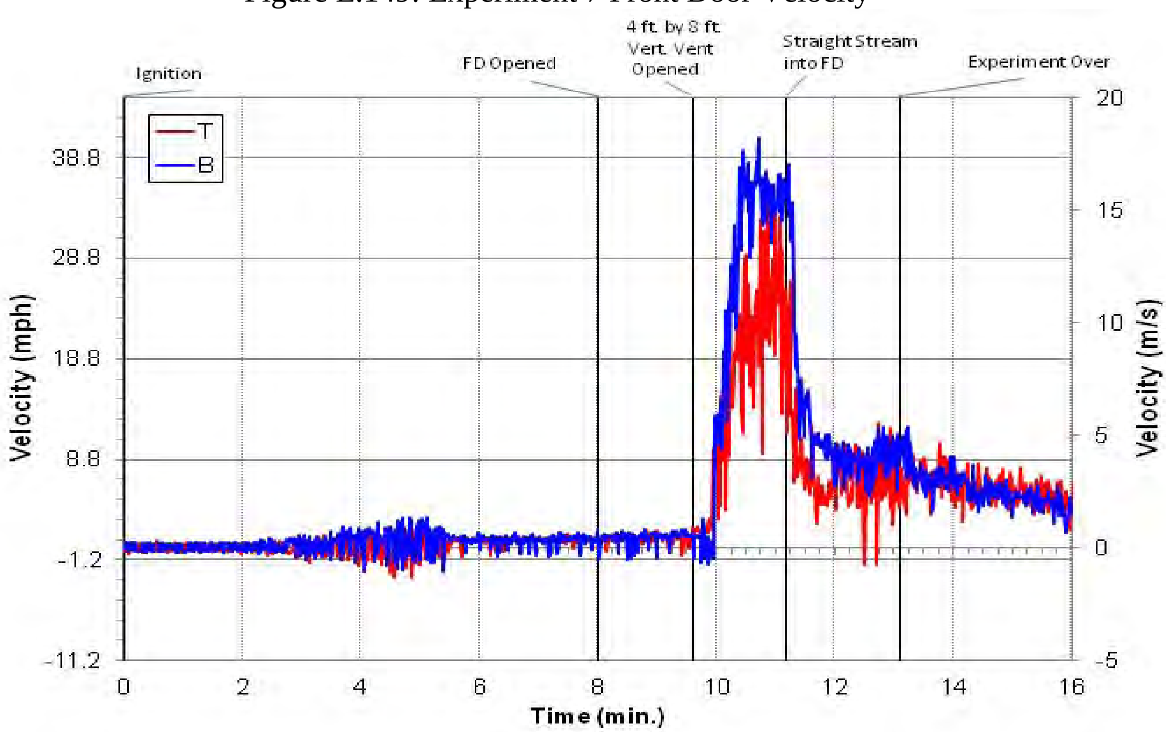


Figure E.150: Experiment 7 Vent Velocity

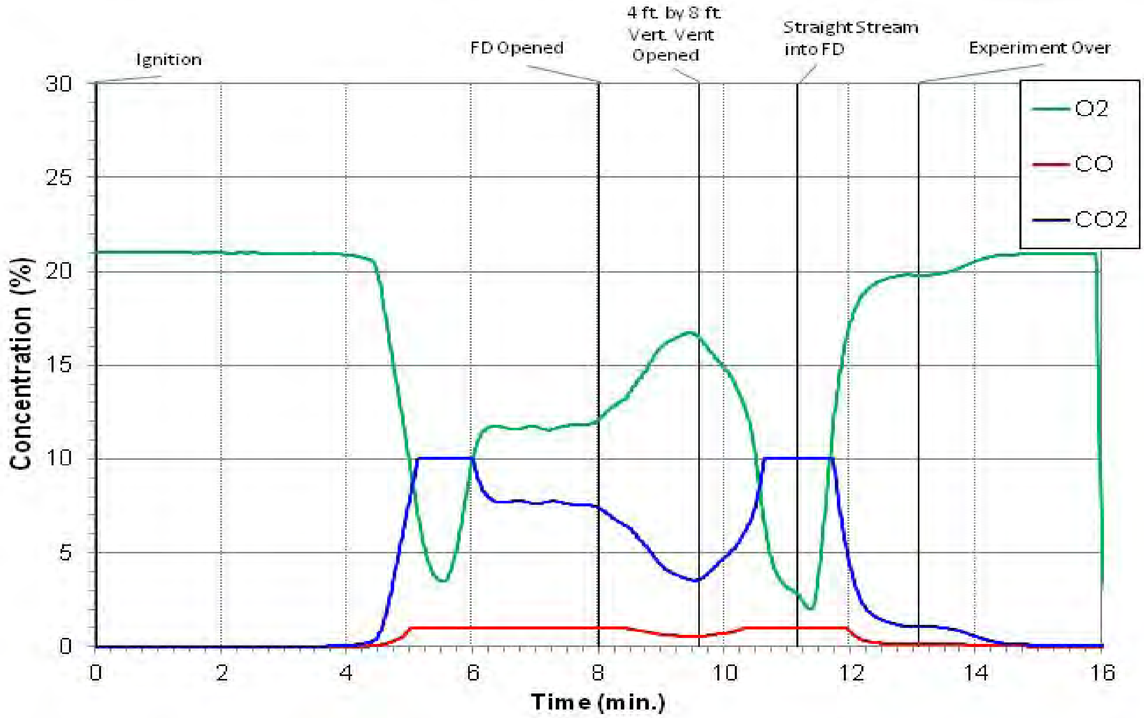


Figure E.151: Experiment 7 Living Room Gas

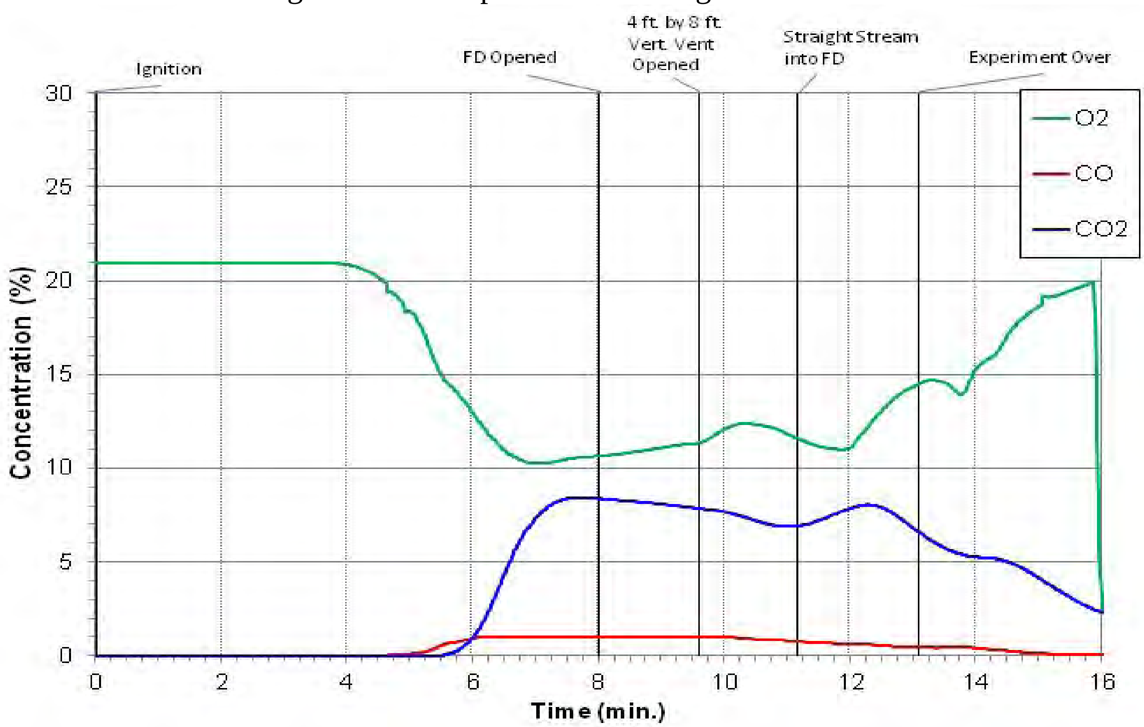


Figure E.152: Experiment 7 Bedroom 1 Gas

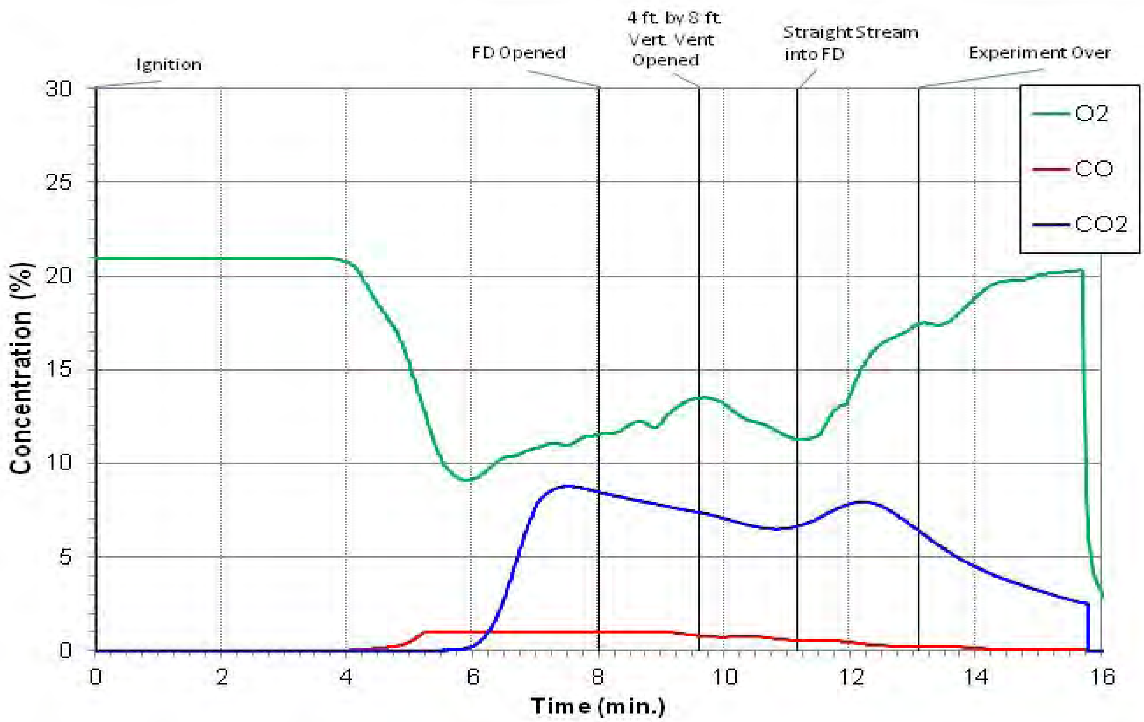


Figure E.153: Experiment 7 Bedroom 2 Gas

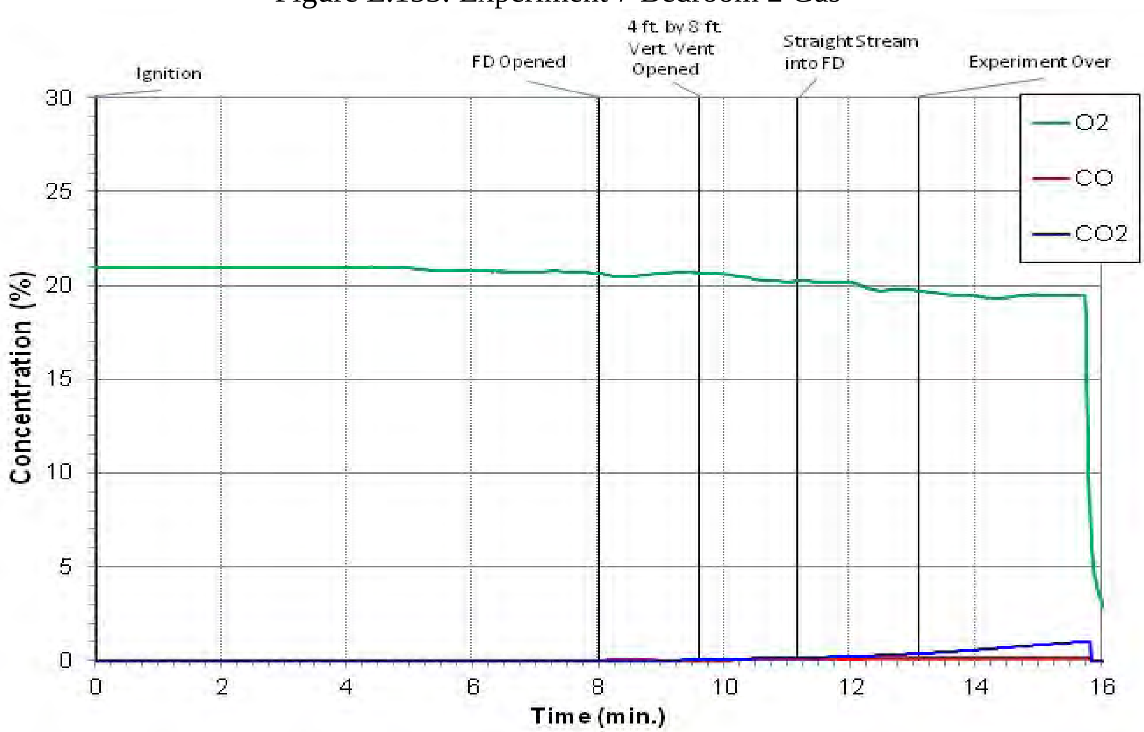


Figure E.154: Experiment 7 Bedroom 3 Gas

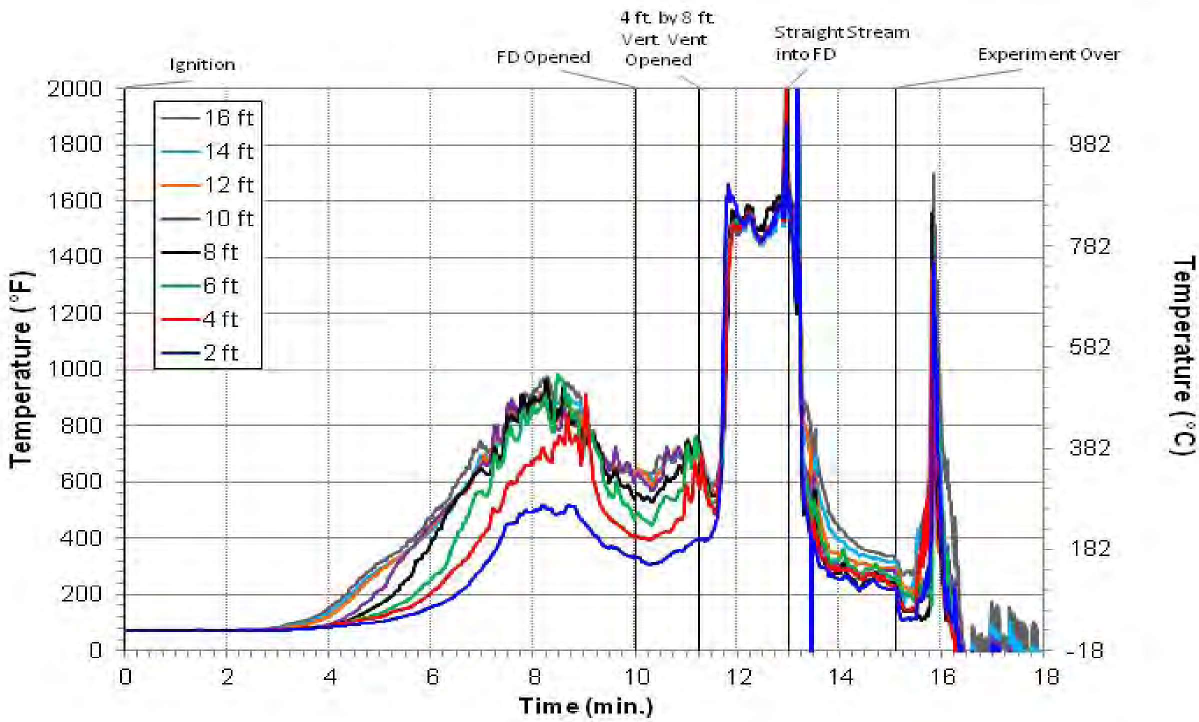


Figure E.155: Experiment 8 Family Room Temperature

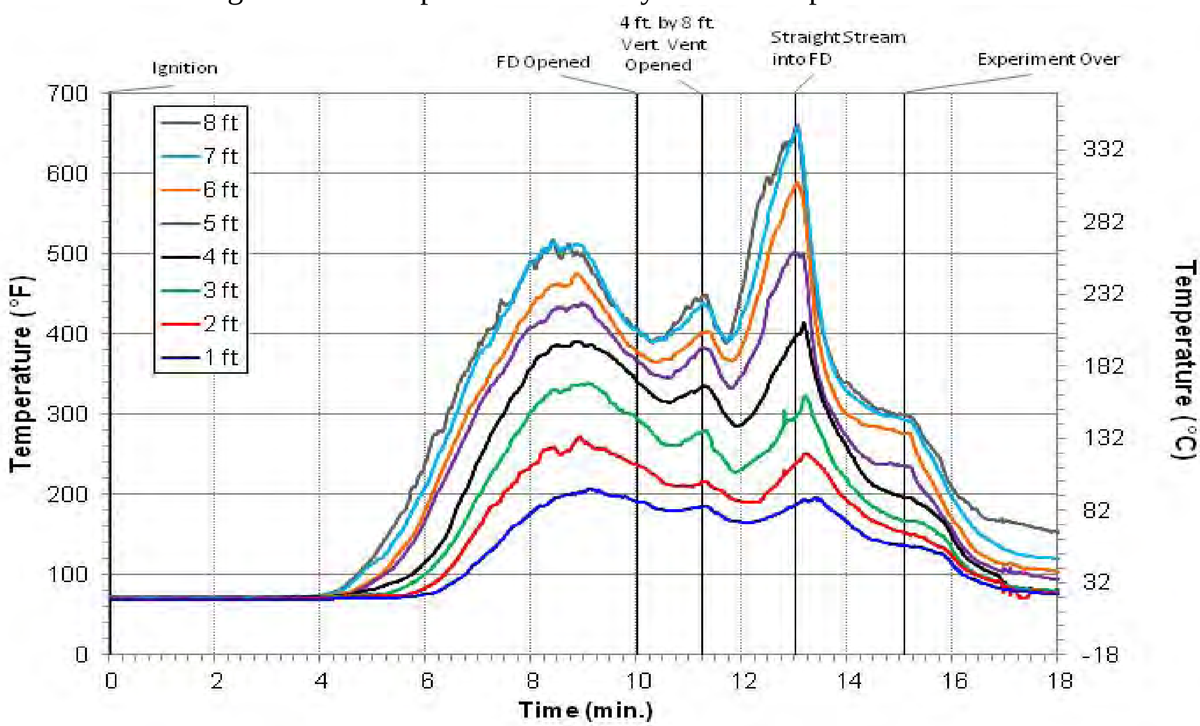


Figure E.156: Experiment 8 Kitchen Temperature

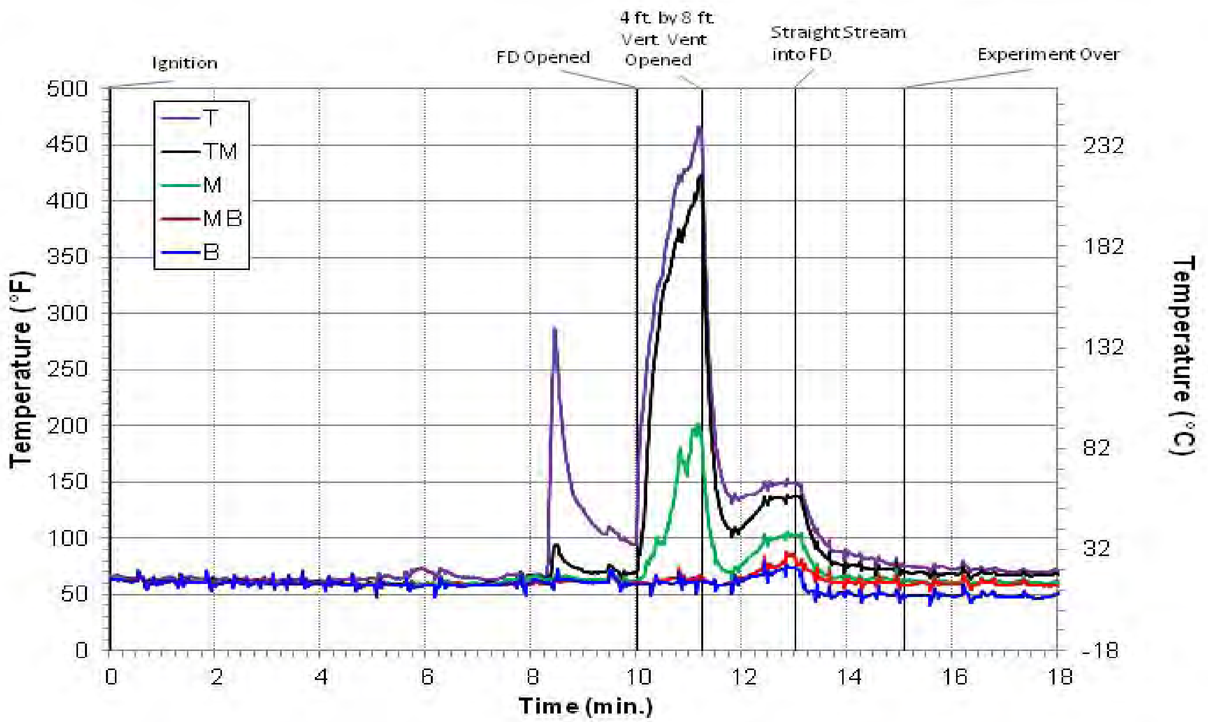


Figure E.157: Experiment 8 Front Door Temperature

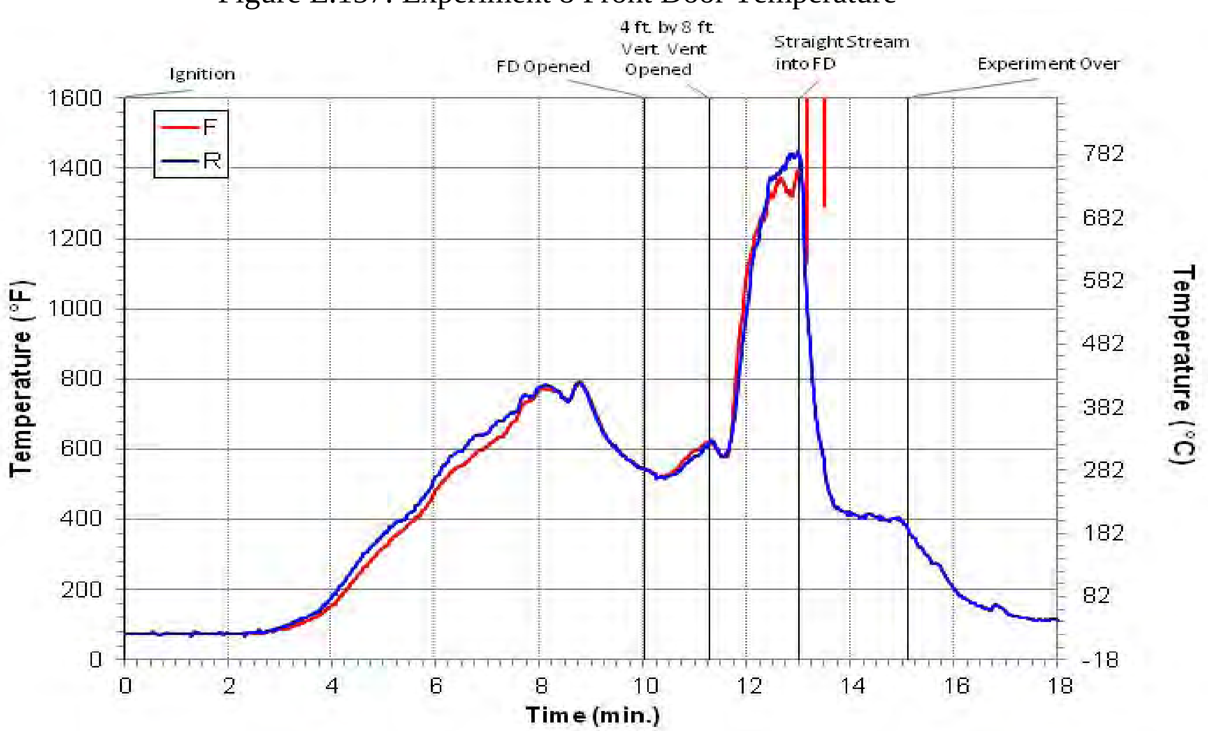


Figure E.158: Experiment 8 Vent Temperature

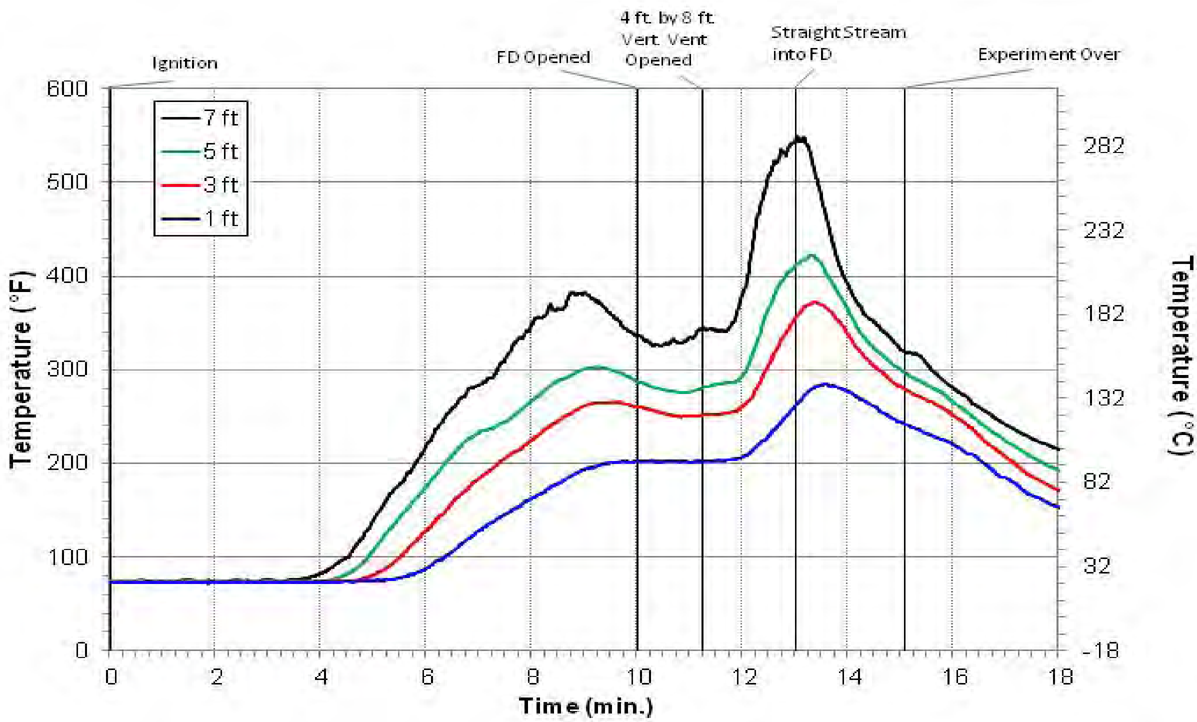


Figure E.159: Experiment 8 Bedroom 1 Temperature

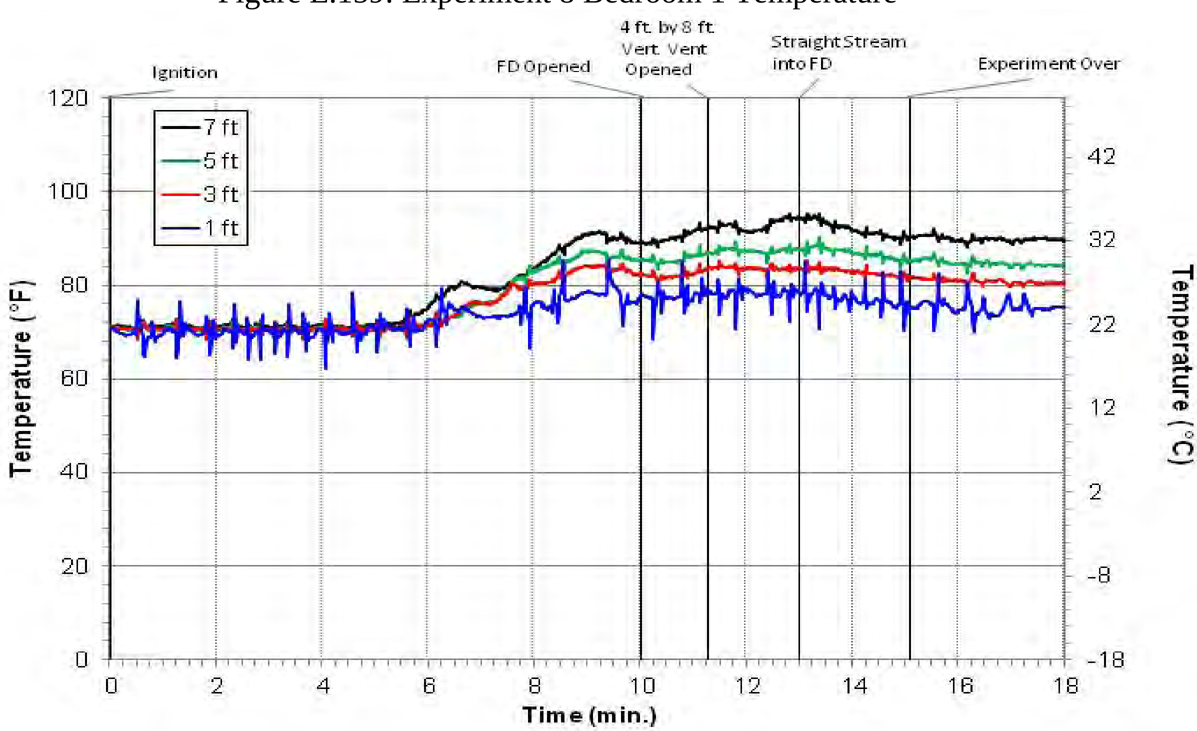


Figure E.160: Experiment 8 Bedroom 2 Temperature

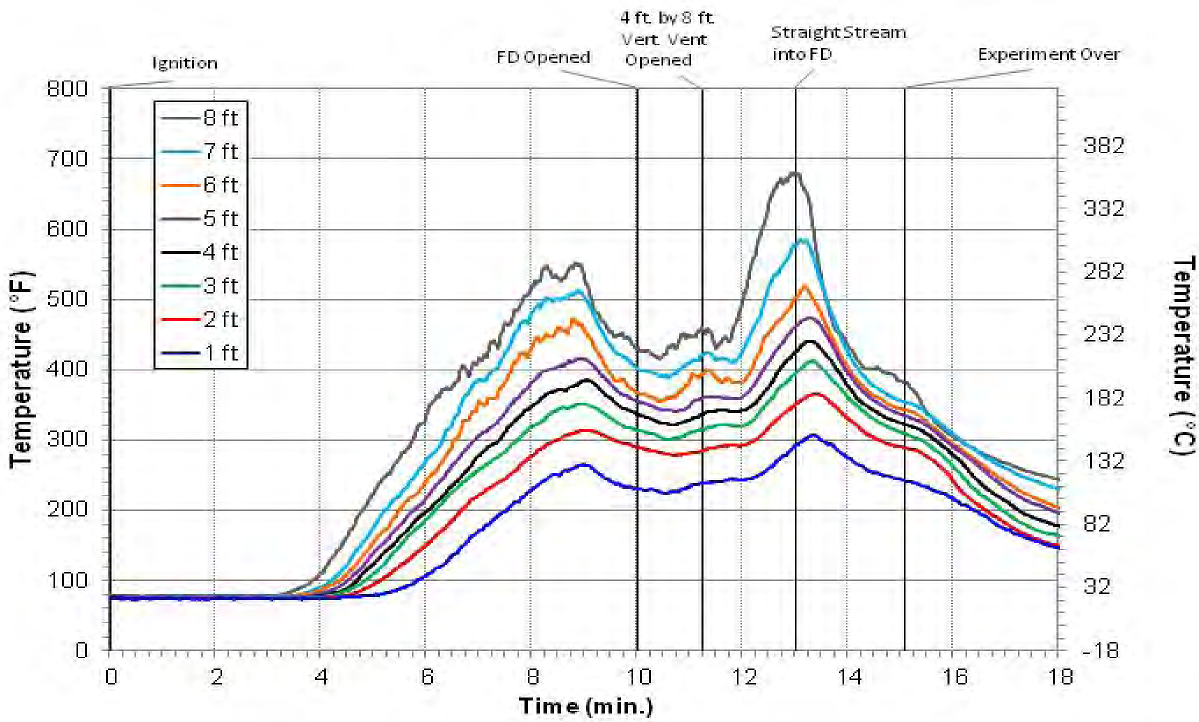


Figure E.161: Experiment 8 Bedroom 3 Temperature

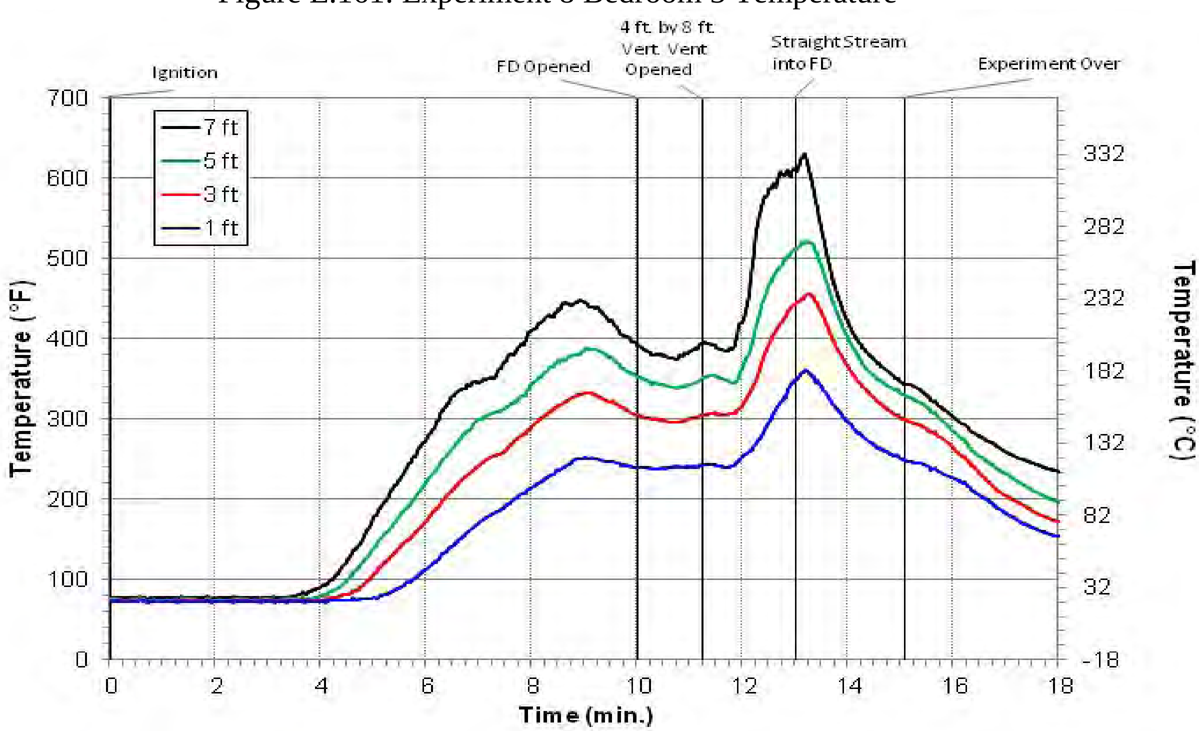


Figure E.162: Experiment 8 Bedroom 4 Temperature

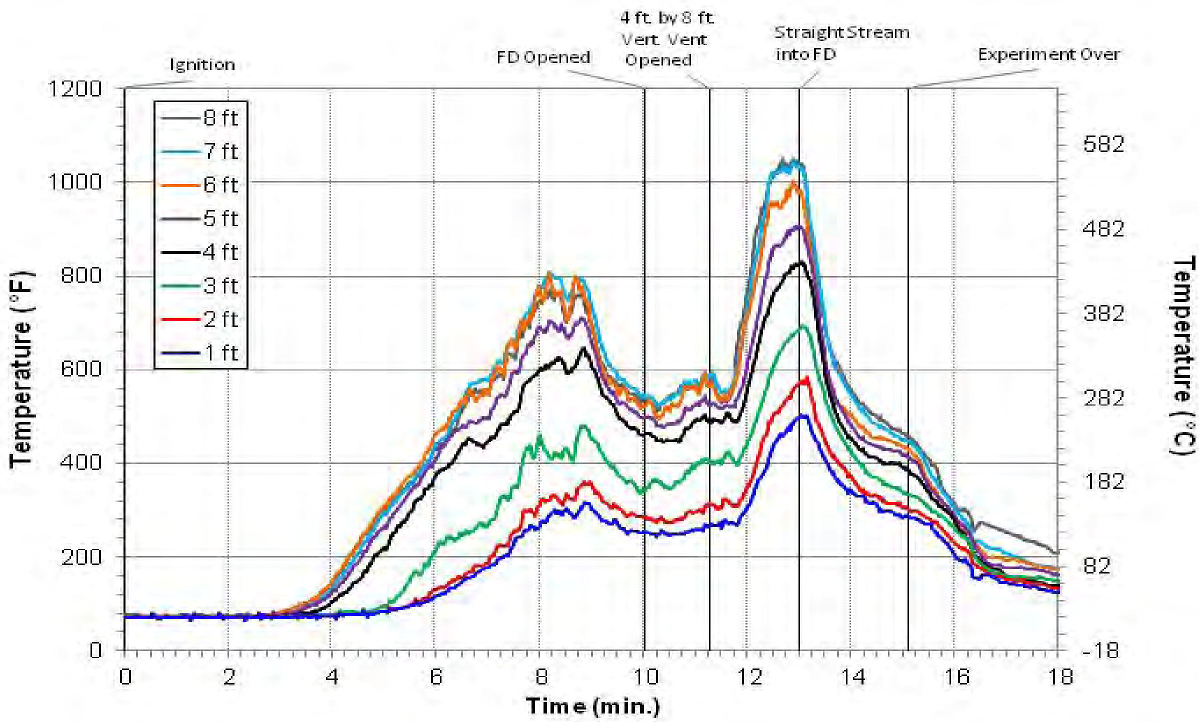


Figure E.163: Experiment 8 Hallway Temperature

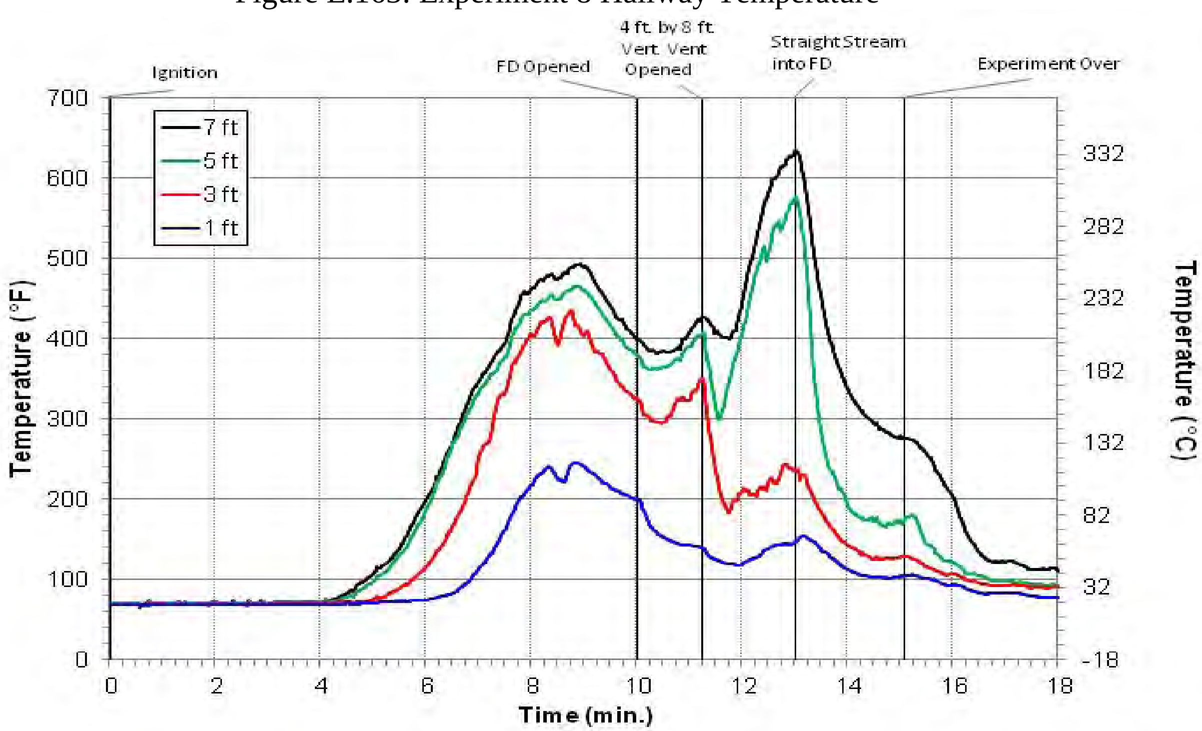


Figure E.164: Experiment 8 Dining Room Temperature

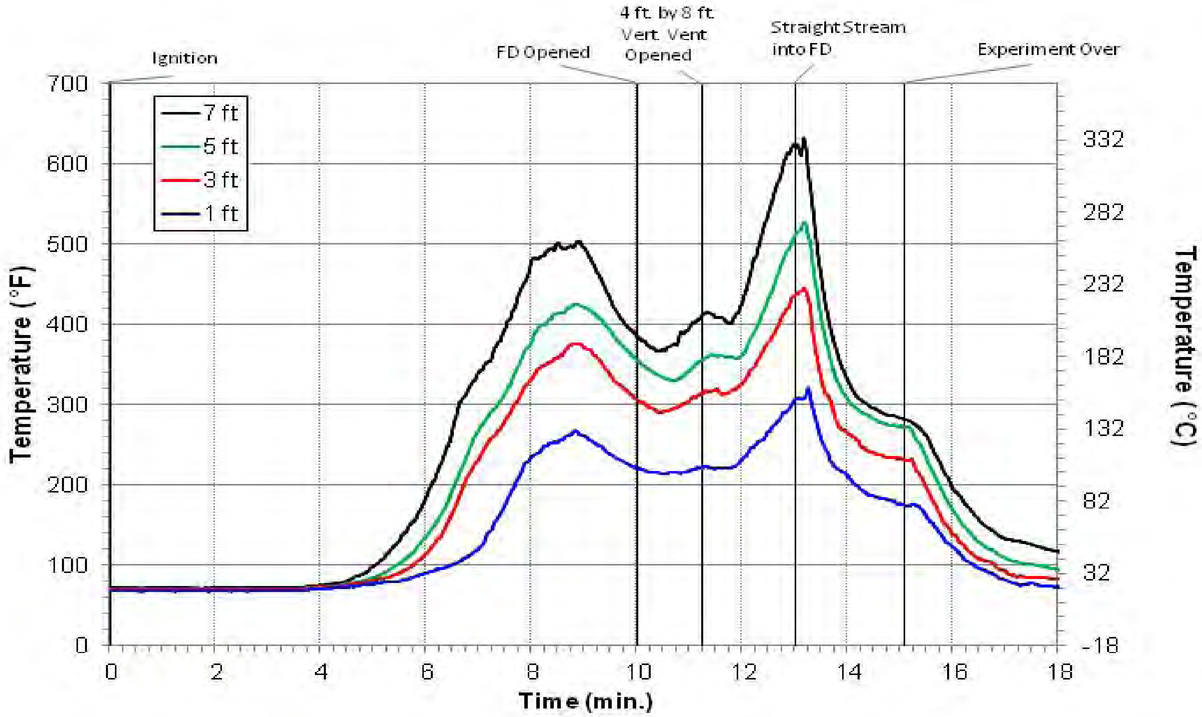


Figure E.165: Experiment 8 Living Room Temperature

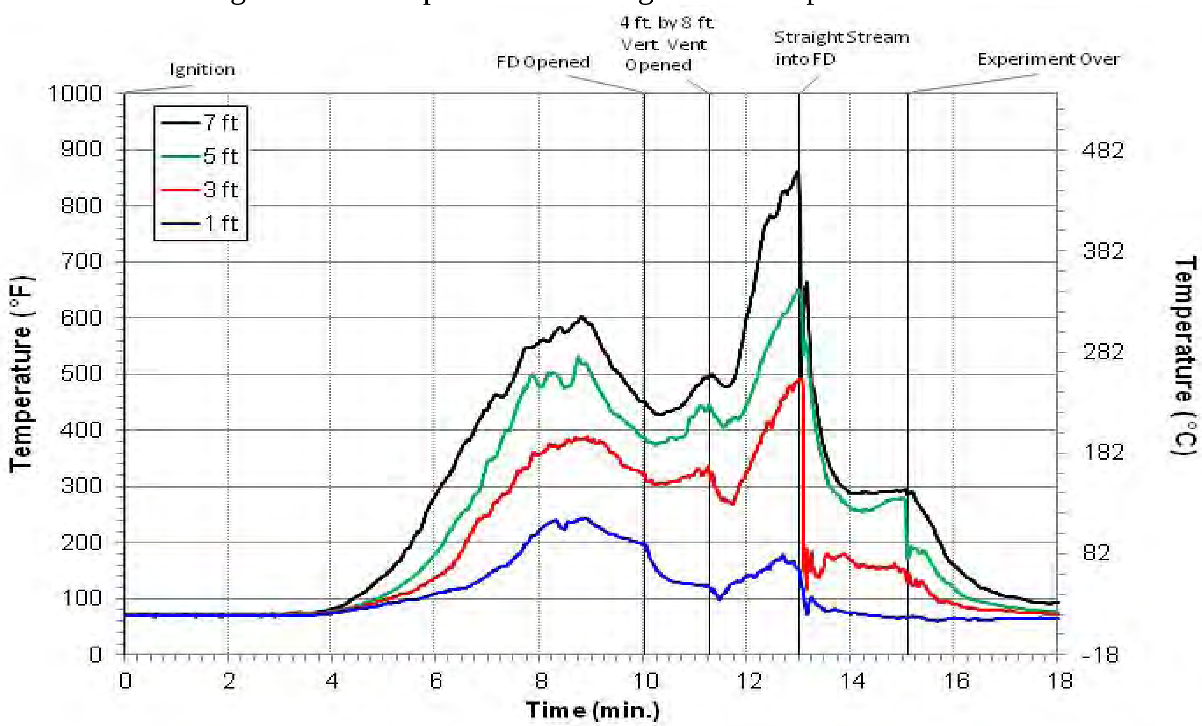


Figure E.166: Experiment 8 Foyer Temperature

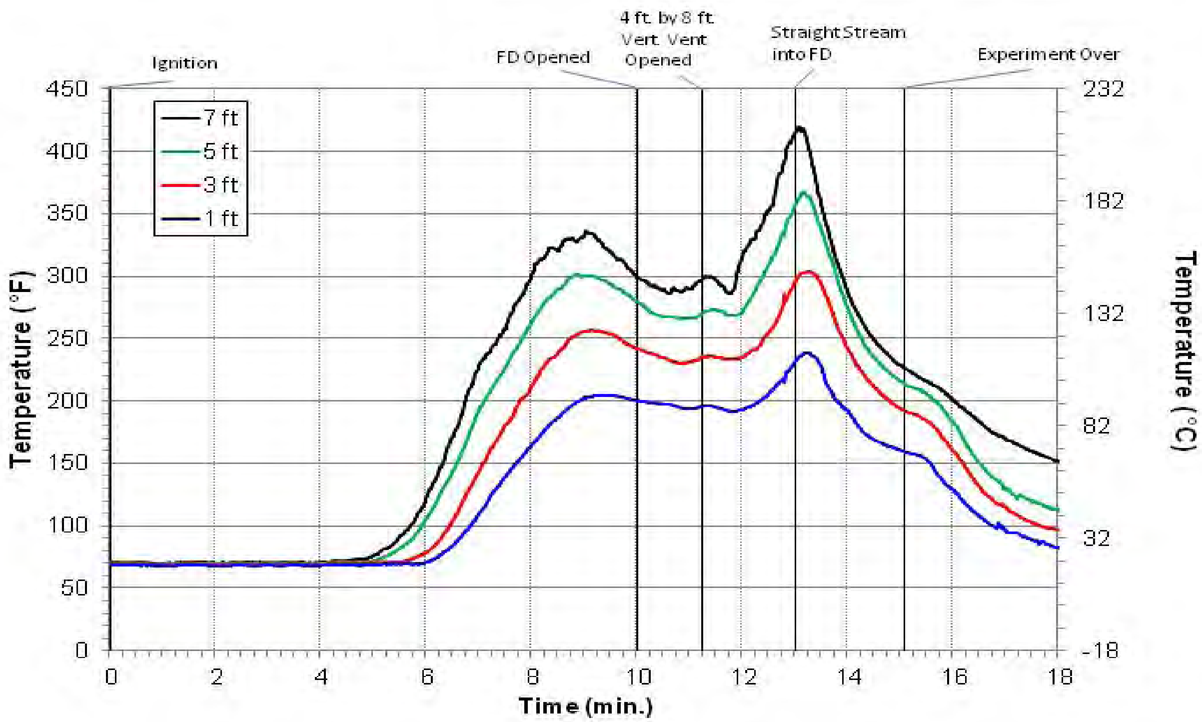


Figure E.167: Experiment 8 Den Temperature

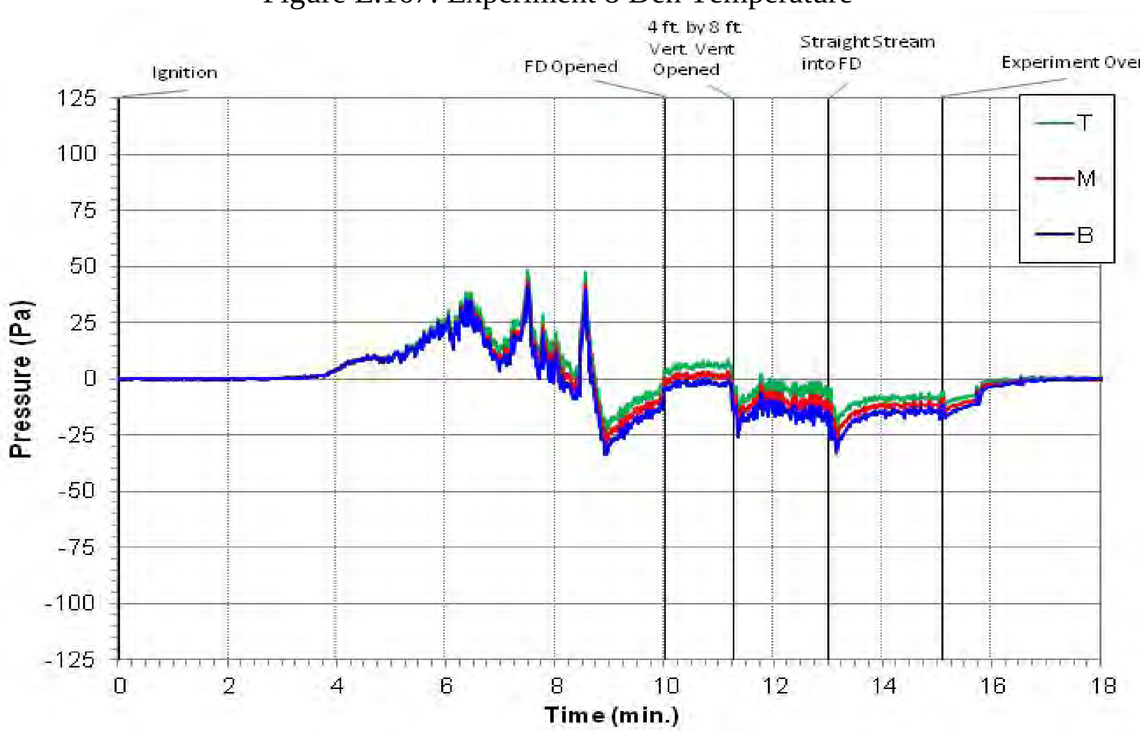


Figure E.168: Experiment 8 Living Room Pressure

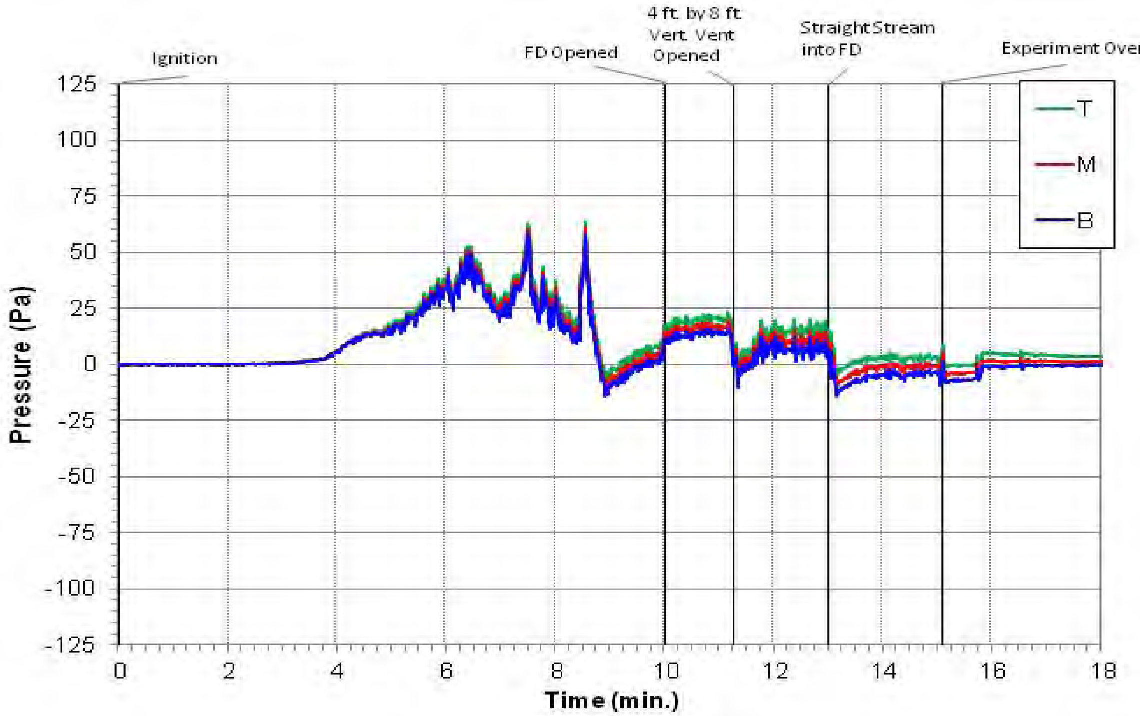


Figure E.169: Experiment 8 Bedroom 2 Pressure

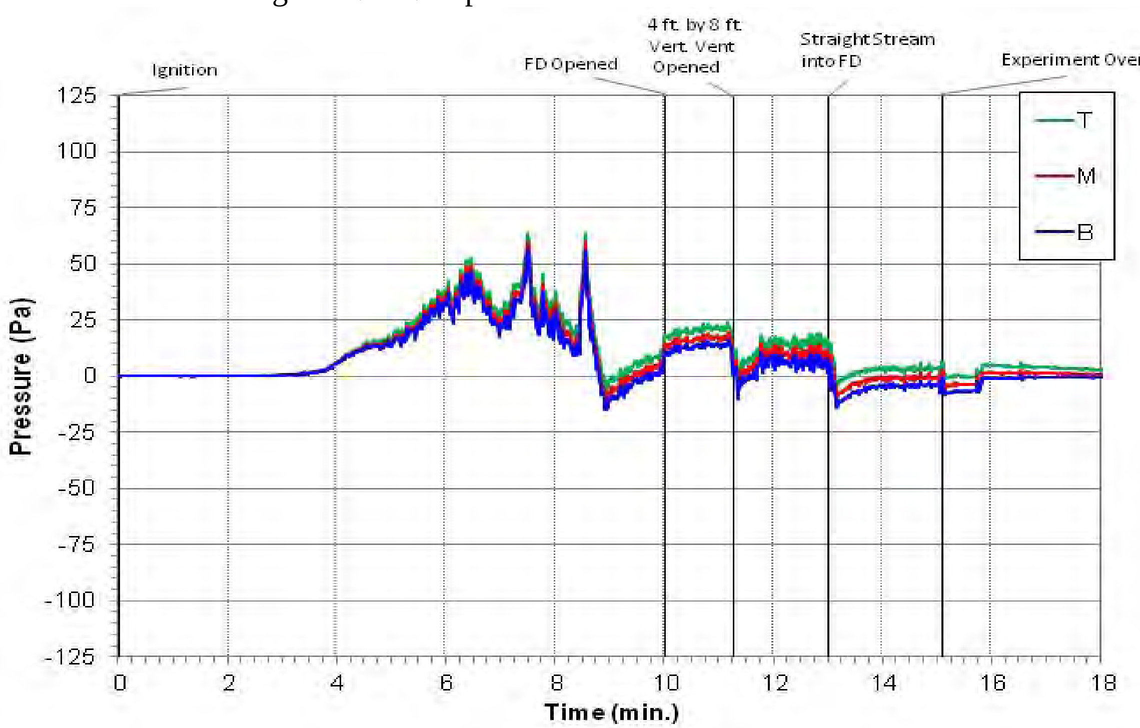


Figure E.170: Experiment 8 Bedroom 3 Pressure

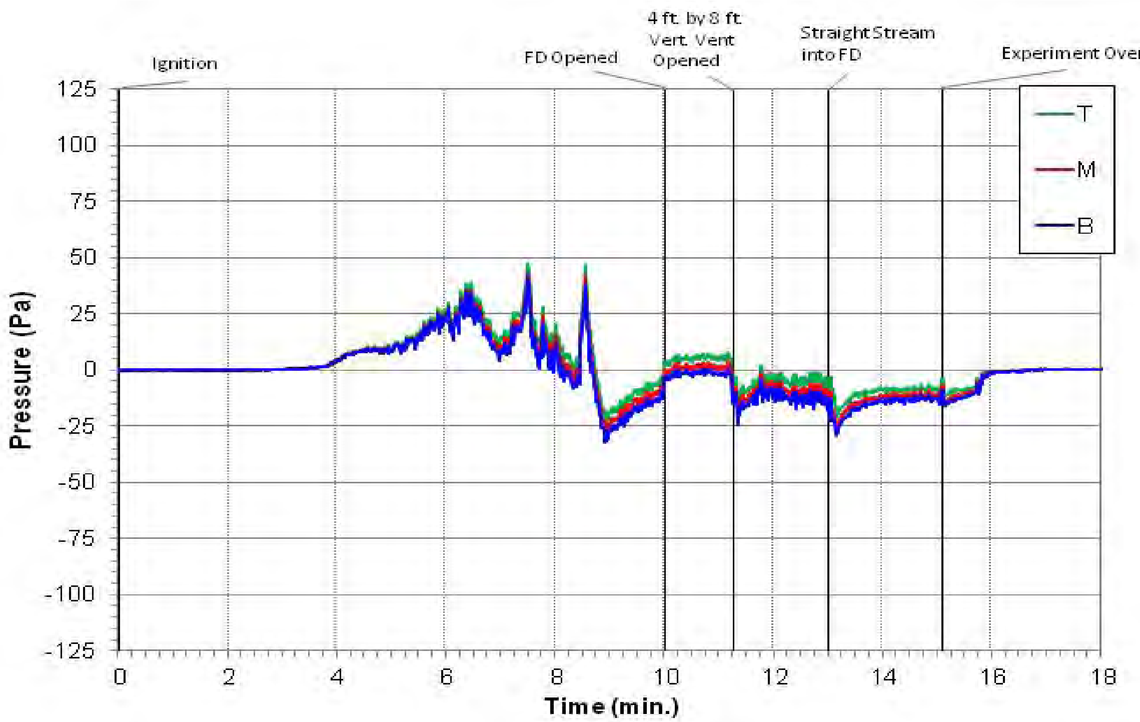


Figure E.171: Experiment 8 Kitchen Pressure

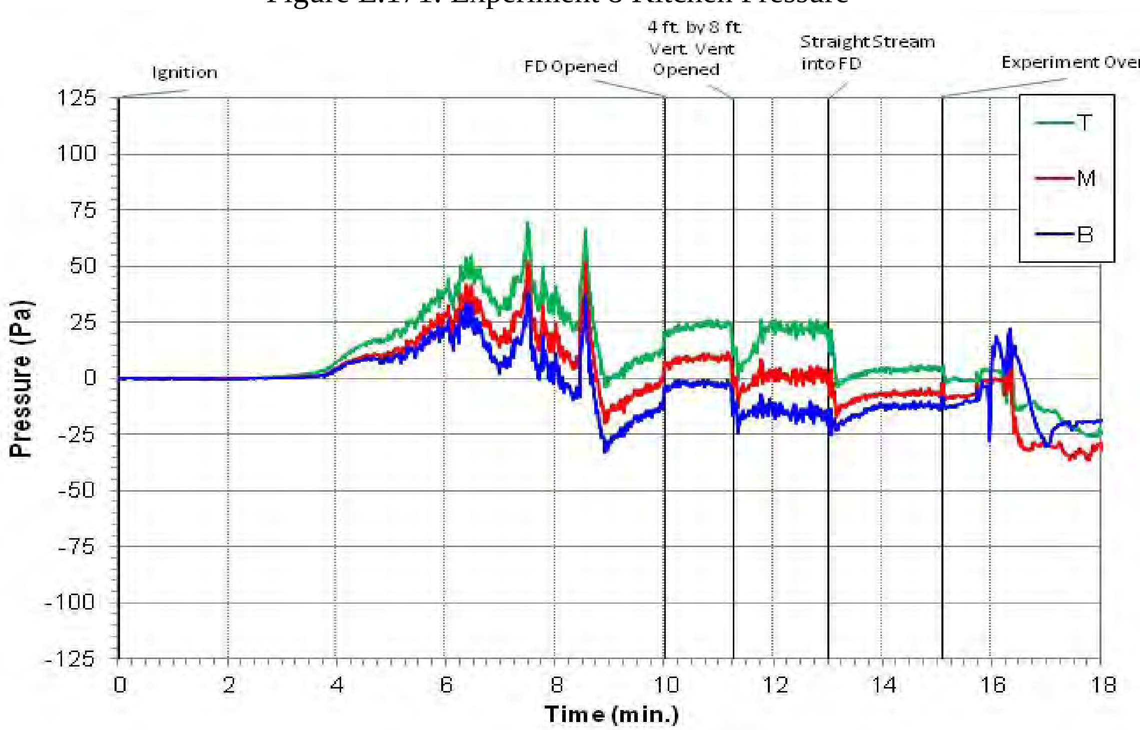


Figure E.172: Experiment 8 Family Room Pressure

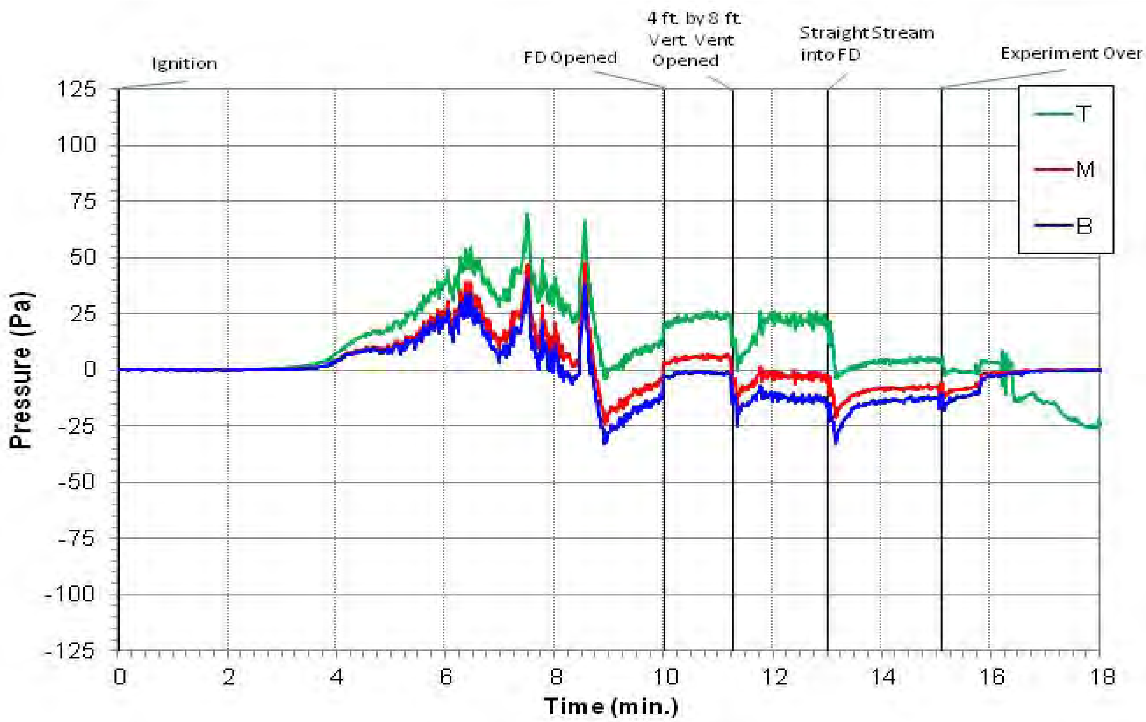


Figure E.173: Experiment 8 Foyer Pressure

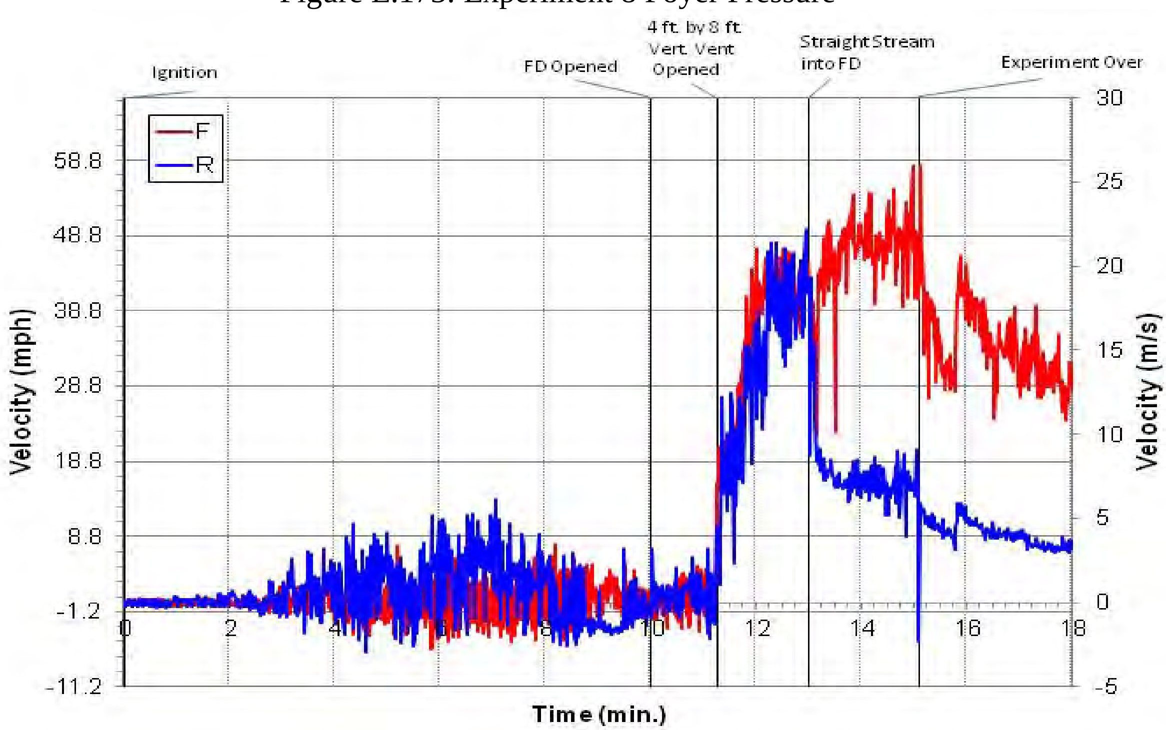


Figure E.174: Experiment 8 Front Door Velocity

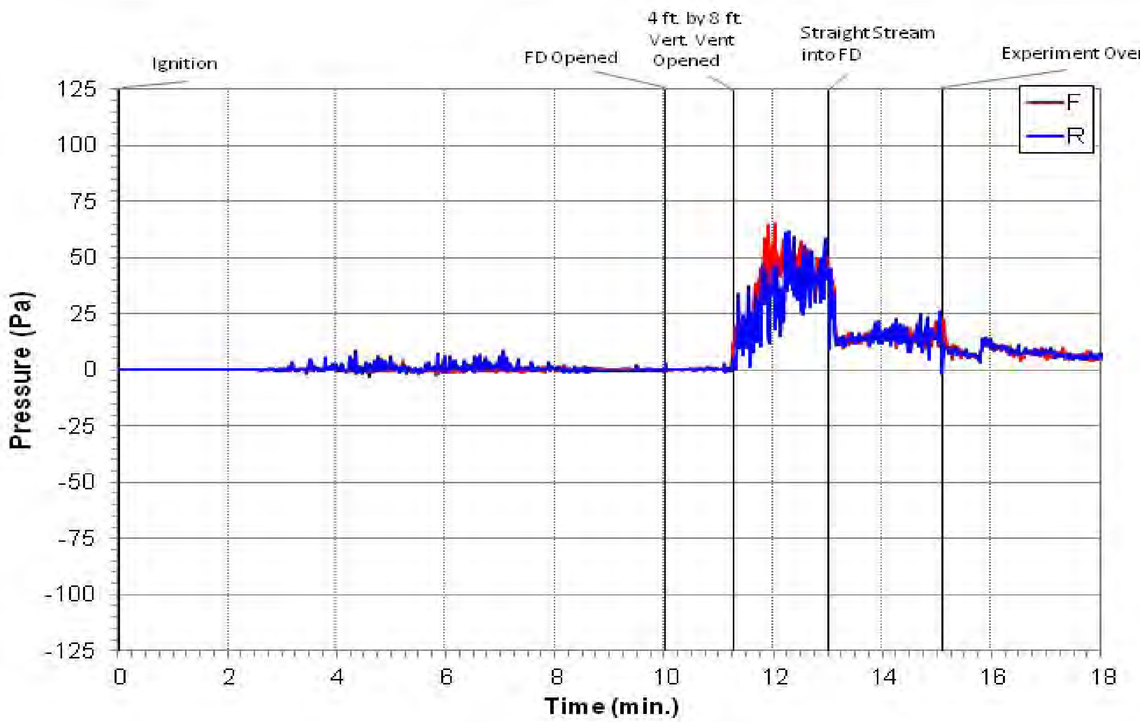


Figure E.175: Experiment 8 Vent Velocity

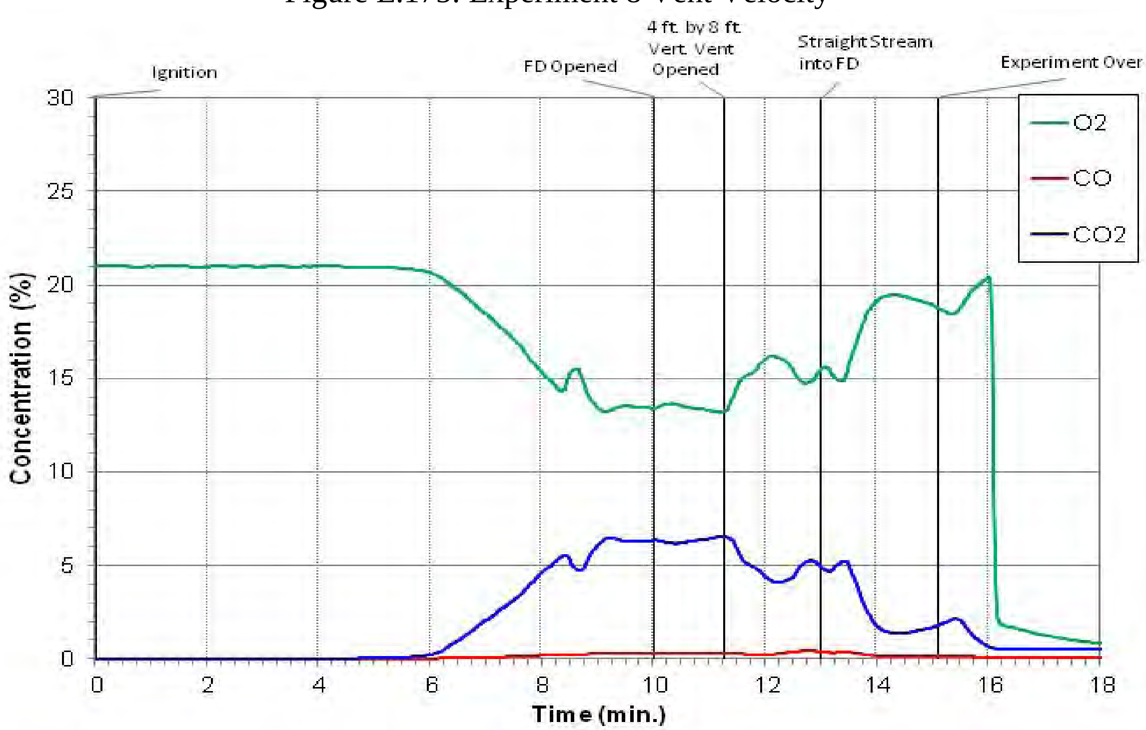


Figure E.176: Experiment 8 Front Door Gas

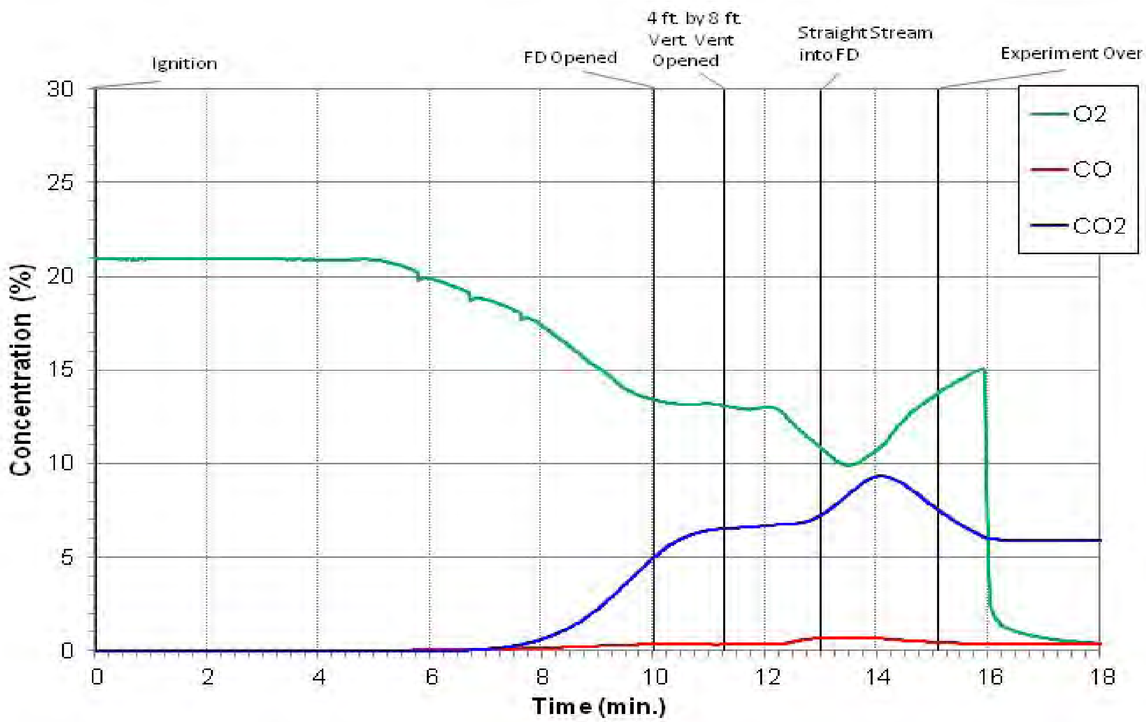


Figure E.177: Experiment 8 Bedroom 1 Gas

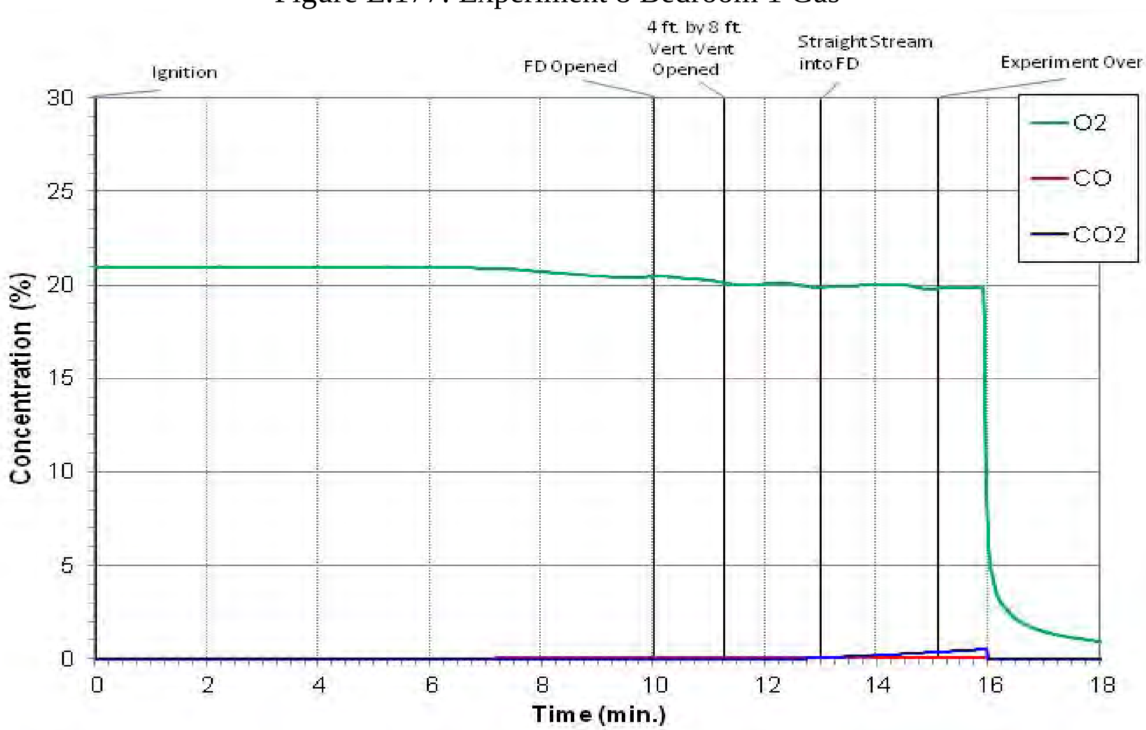


Figure E.178: Experiment 8 Bedroom 2 Gas

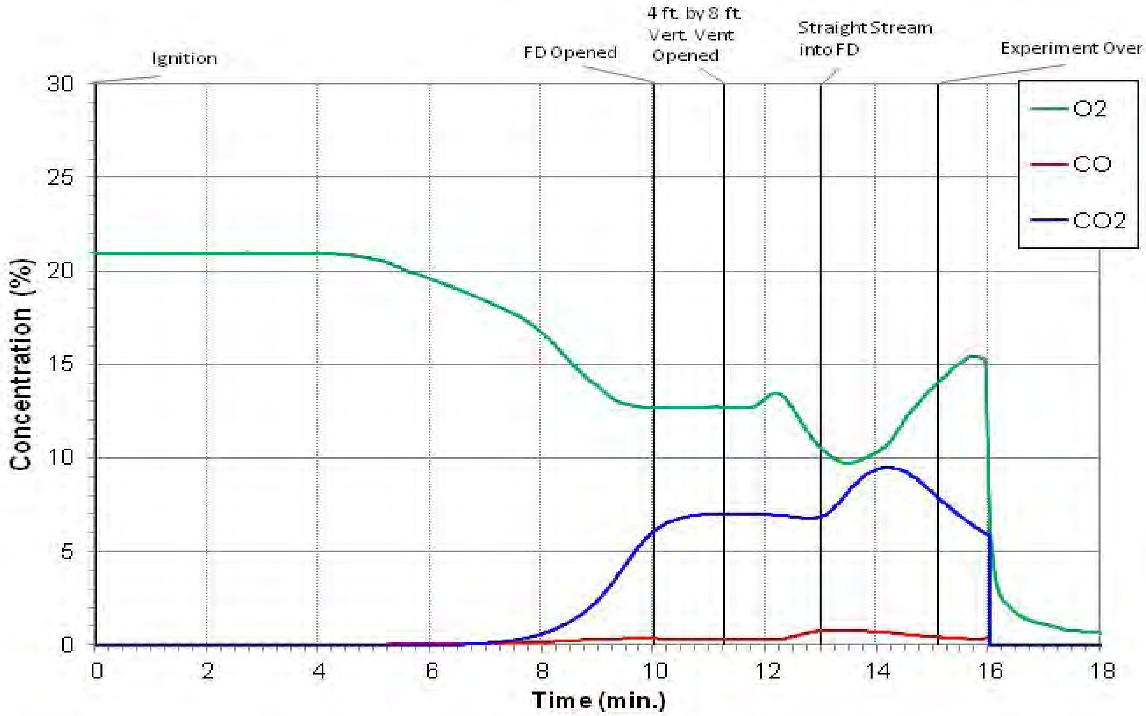


Figure E.179: Experiment 8 Bedroom 3 Gas

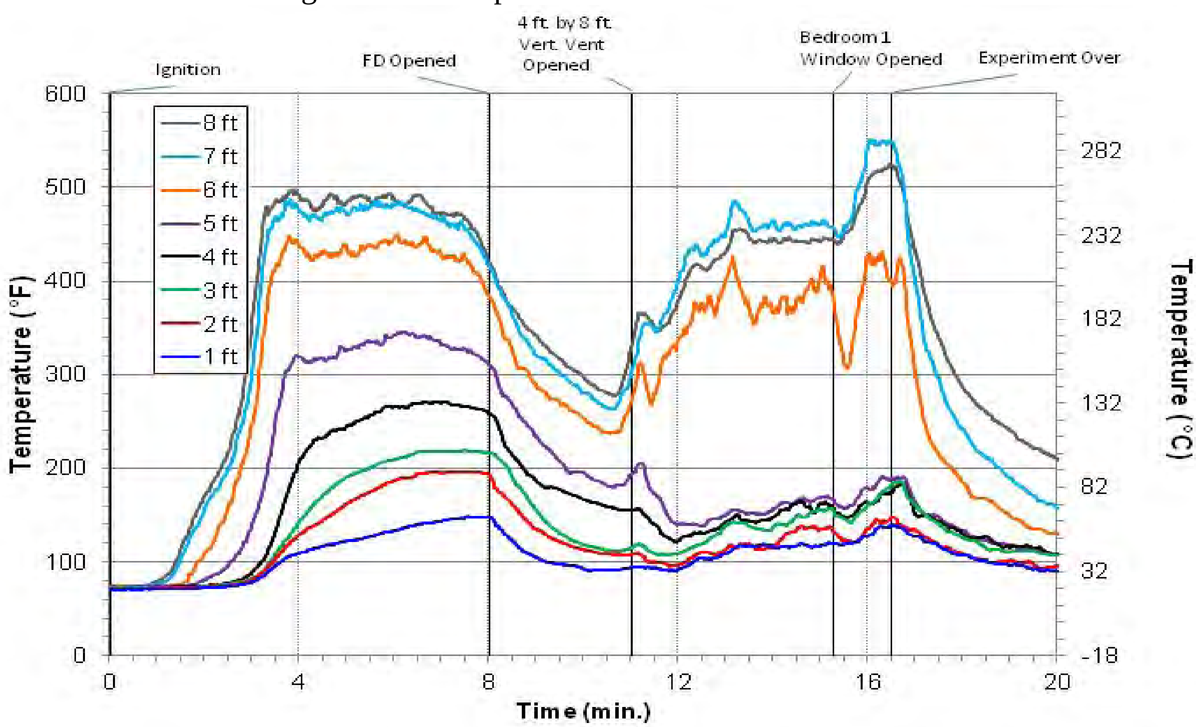


Figure E.180: Experiment 9 Living Room Temperature

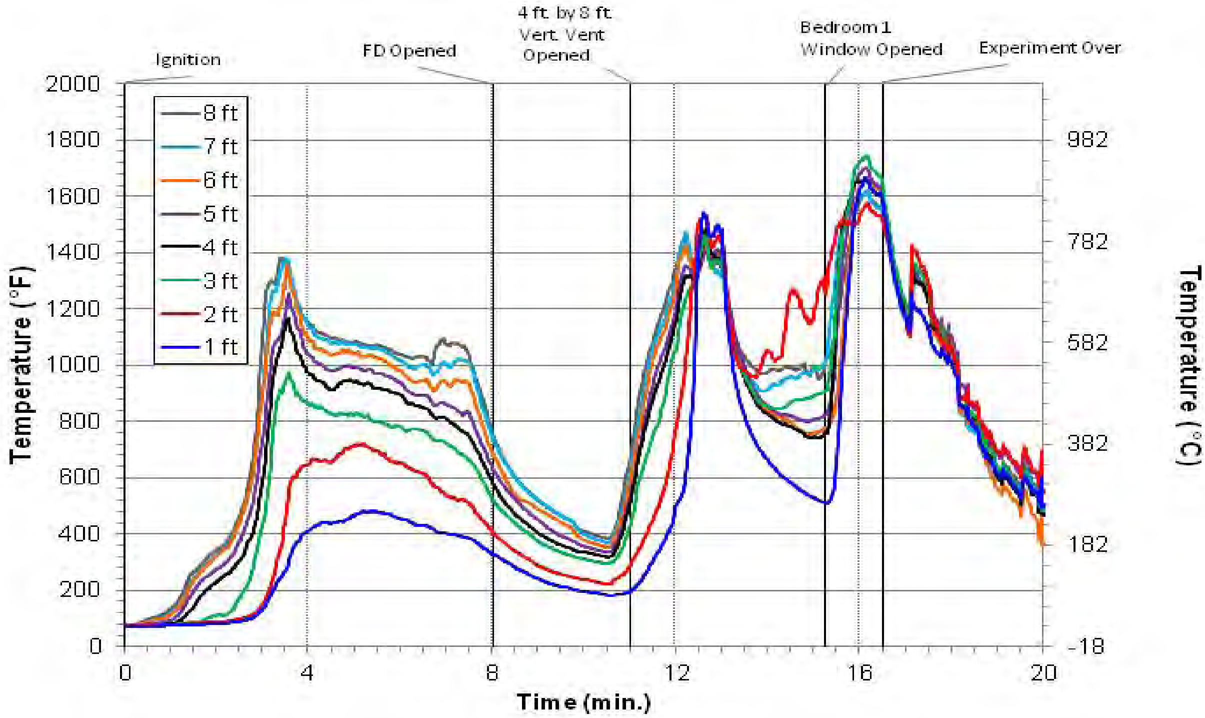


Figure E.181: Experiment 9 Bedroom 1 Temperature

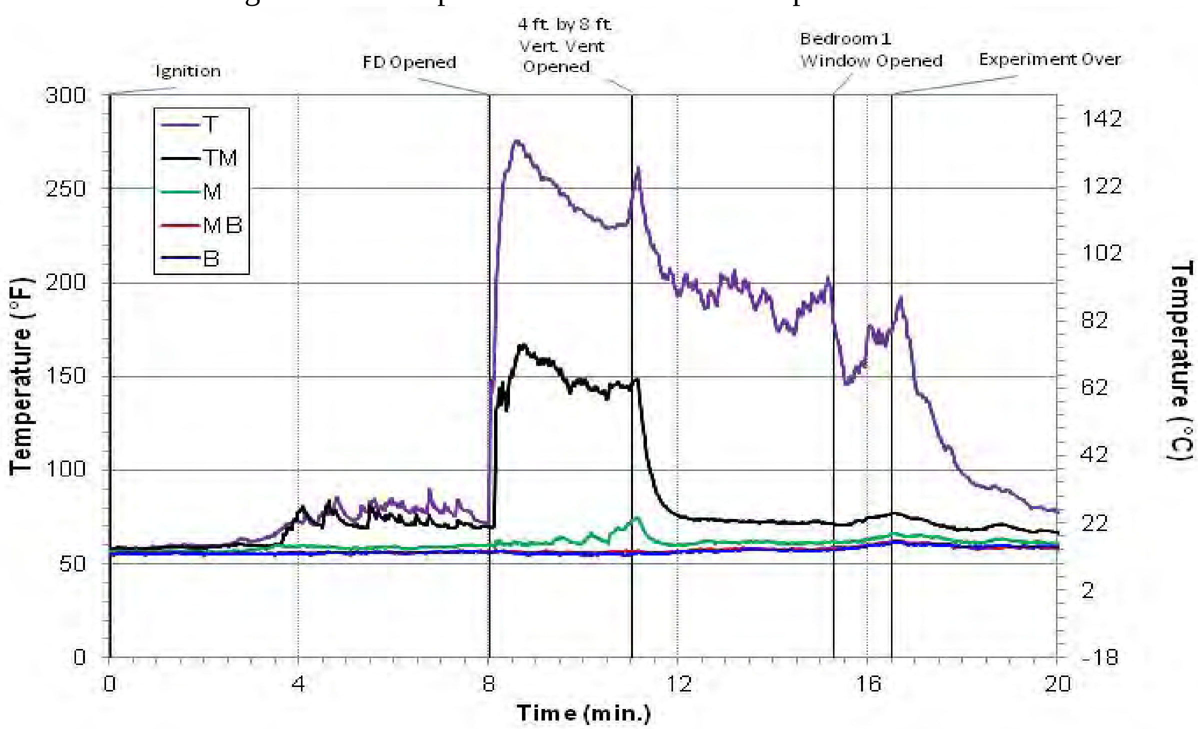


Figure E.182: Experiment 9 Front Door Temperature

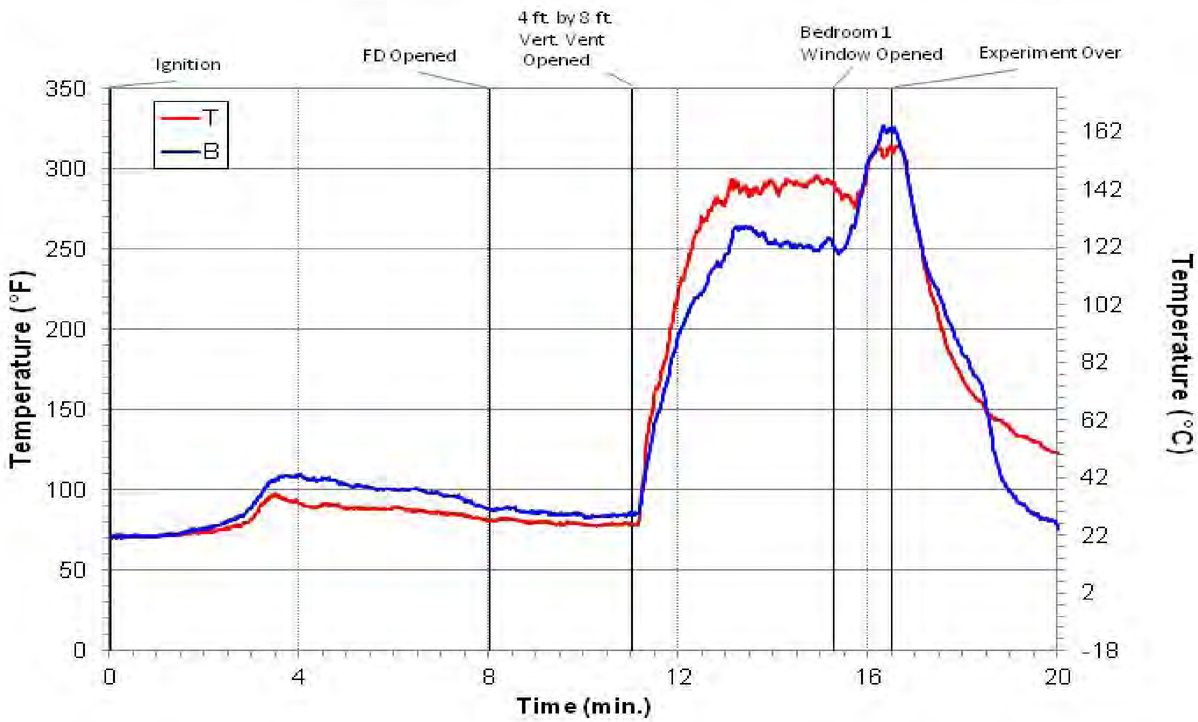


Figure E.183: Experiment 9 Vent Temperature

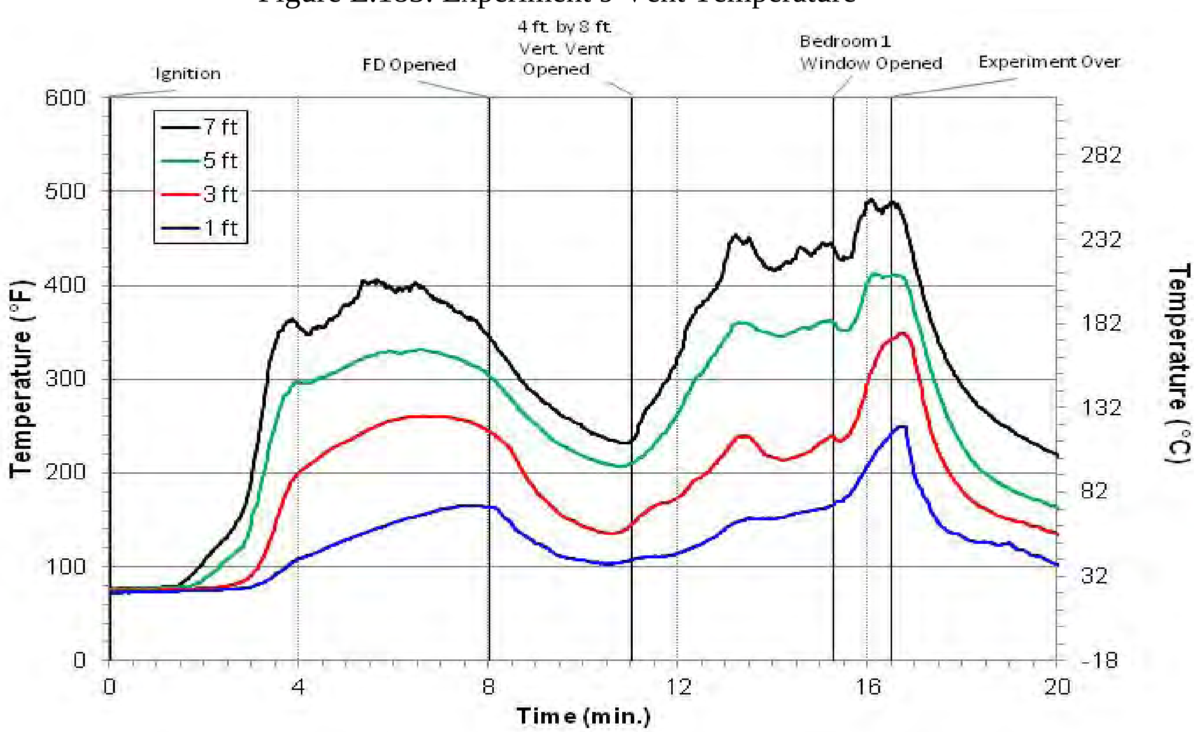


Figure E.184: Experiment 9 Bedroom 2 Temperature

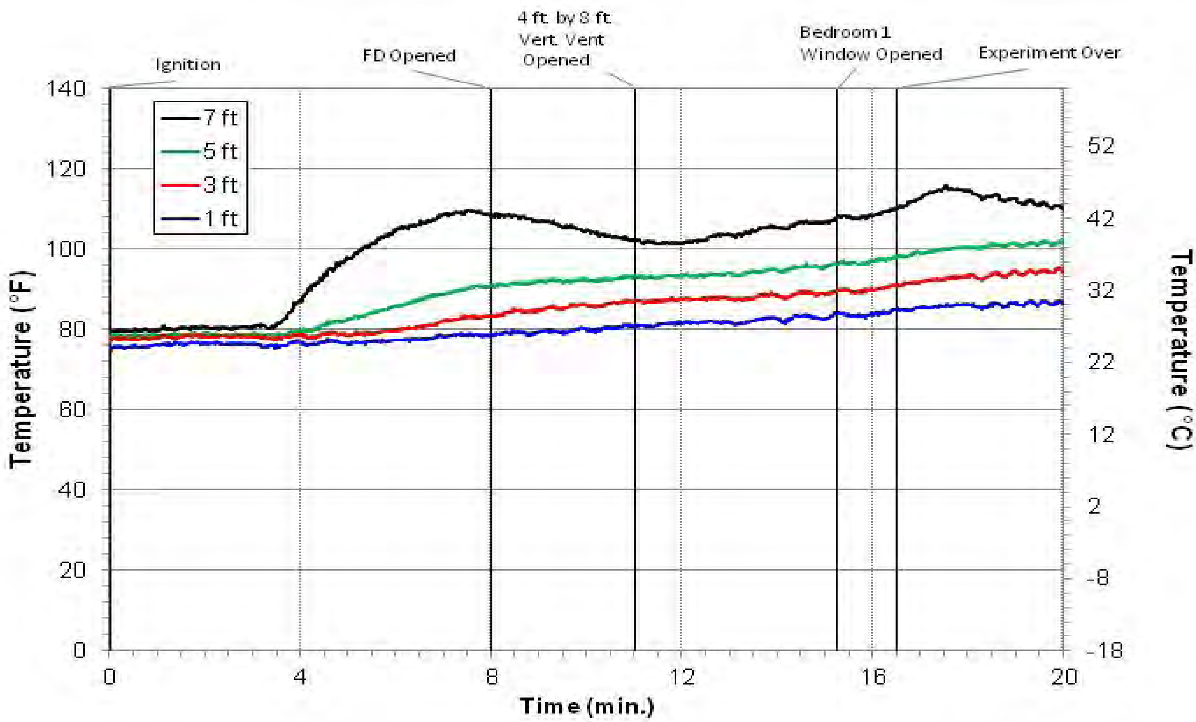


Figure E.185: Experiment 9 Bedroom 3 Temperature

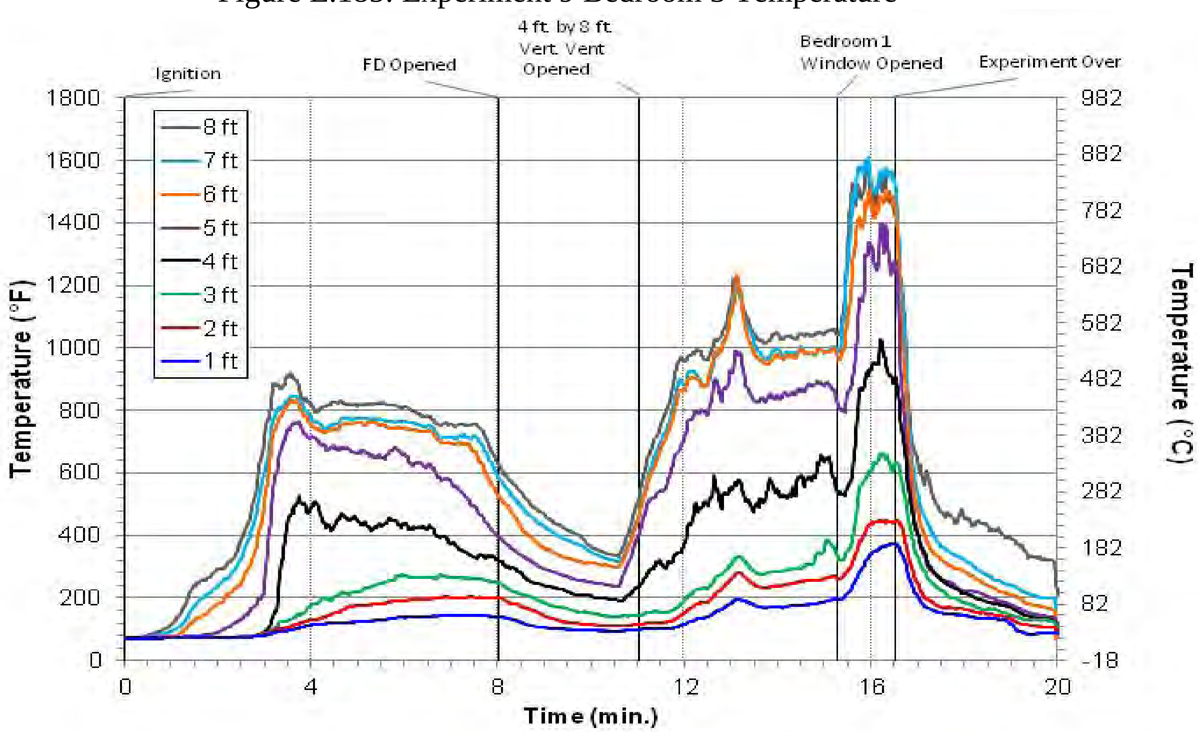


Figure E.186: Experiment 9 Hallway Temperature

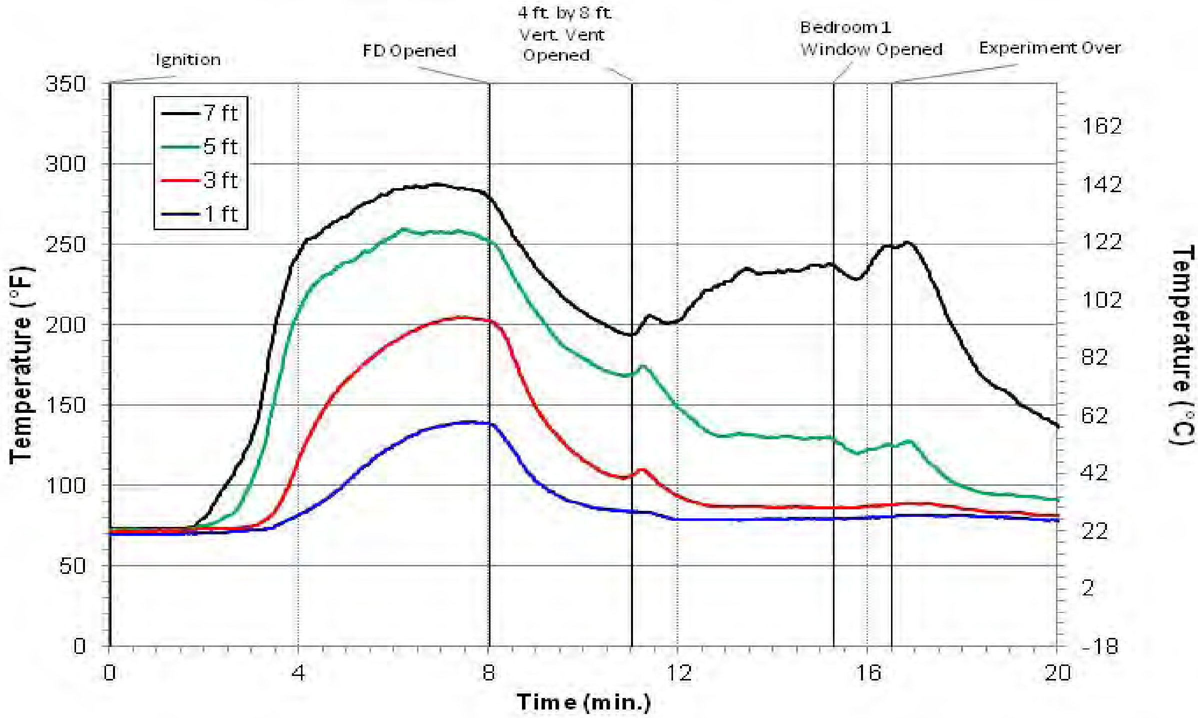


Figure E.187: Experiment 9 Dining Room Temperature

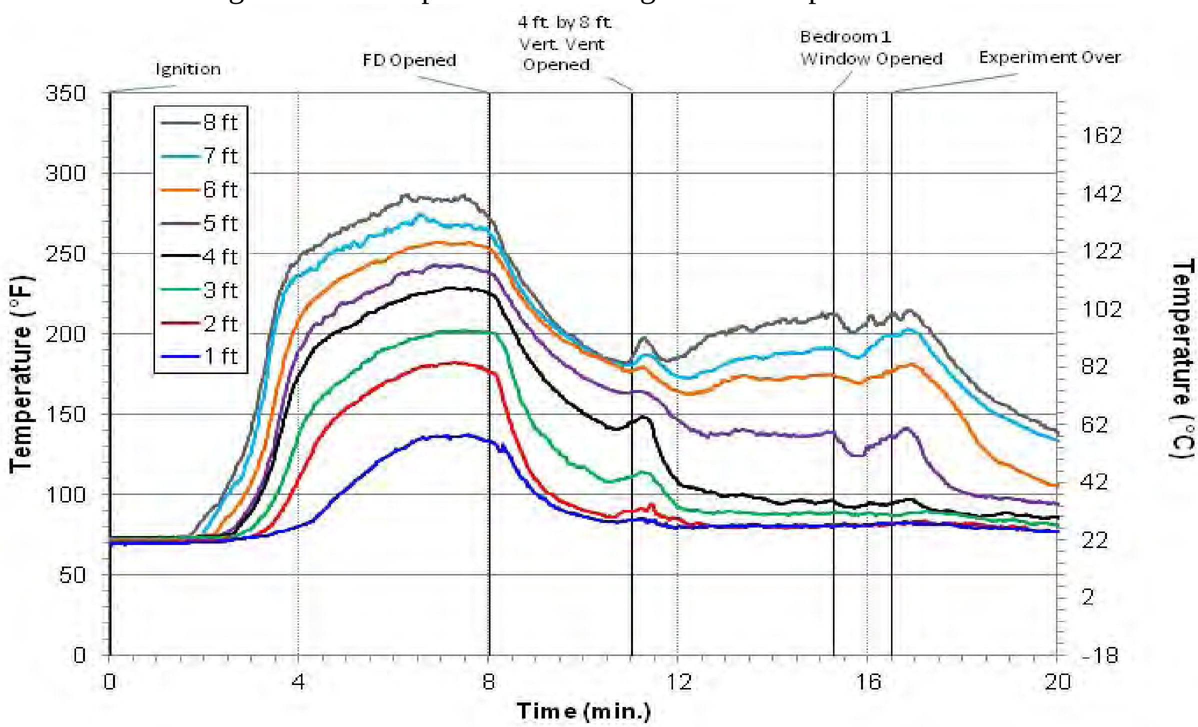


Figure E.188: Experiment 9 Kitchen Temperature

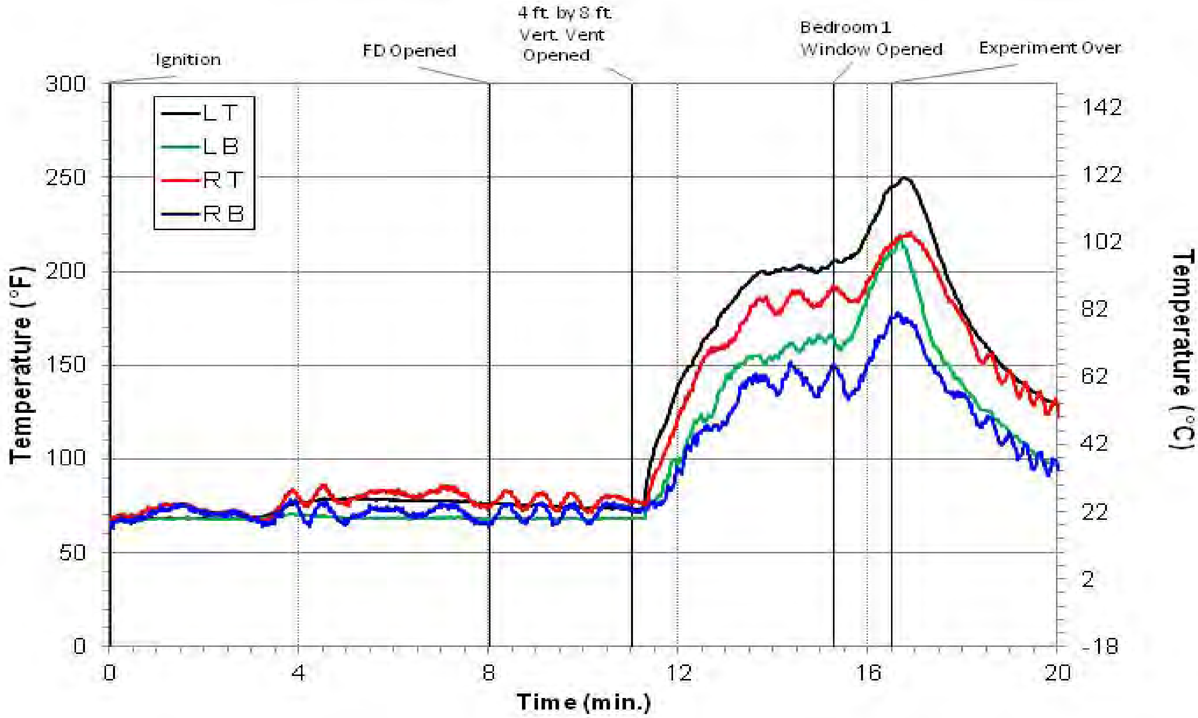


Figure E.189: Experiment 9 Attic Temperature

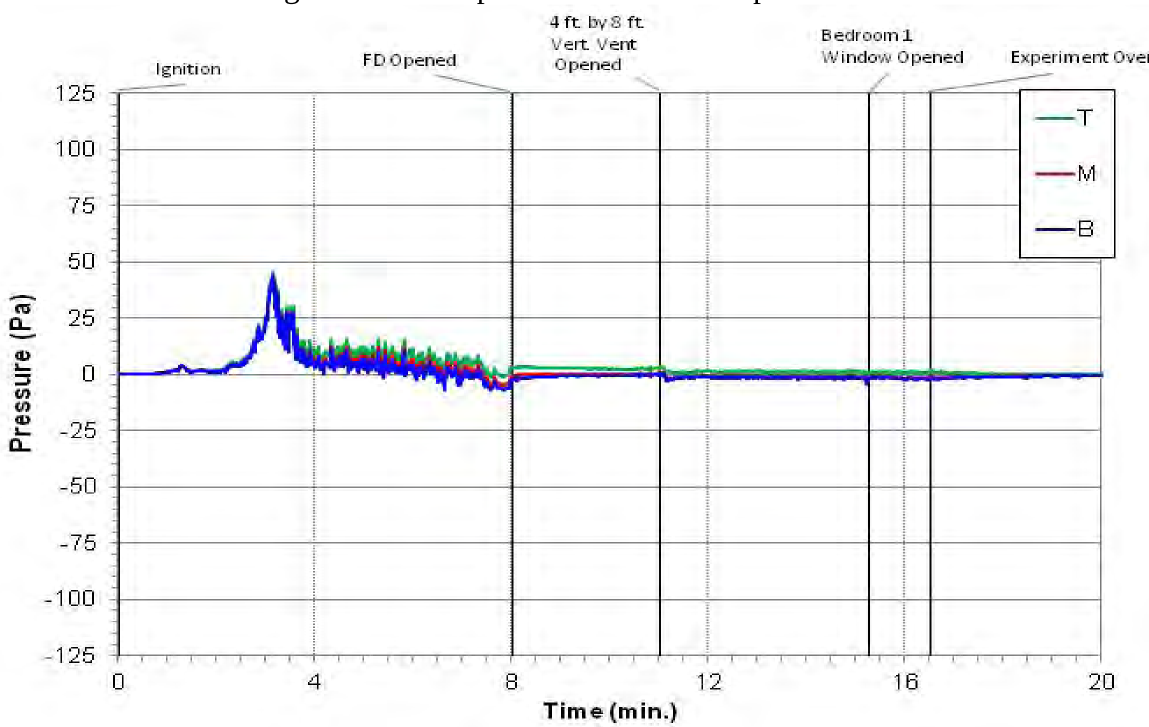


Figure E.190: Experiment 9 Living Room Pressure

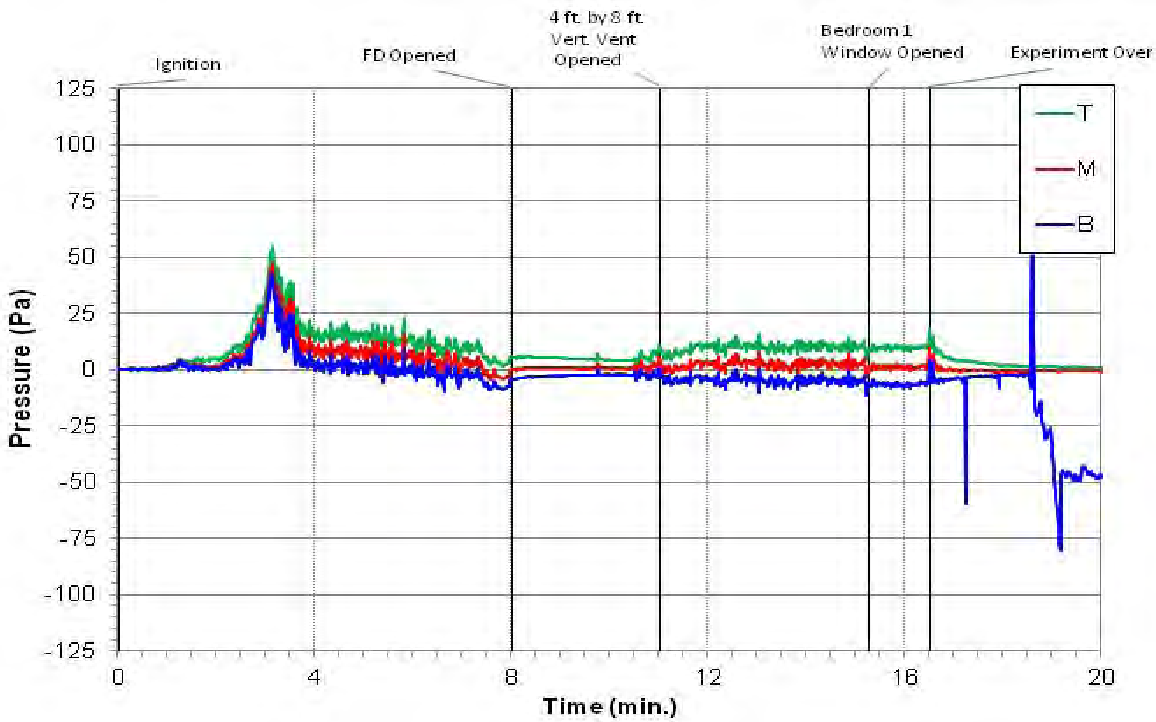


Figure E.191: Experiment 9 Bedroom 1 Pressure

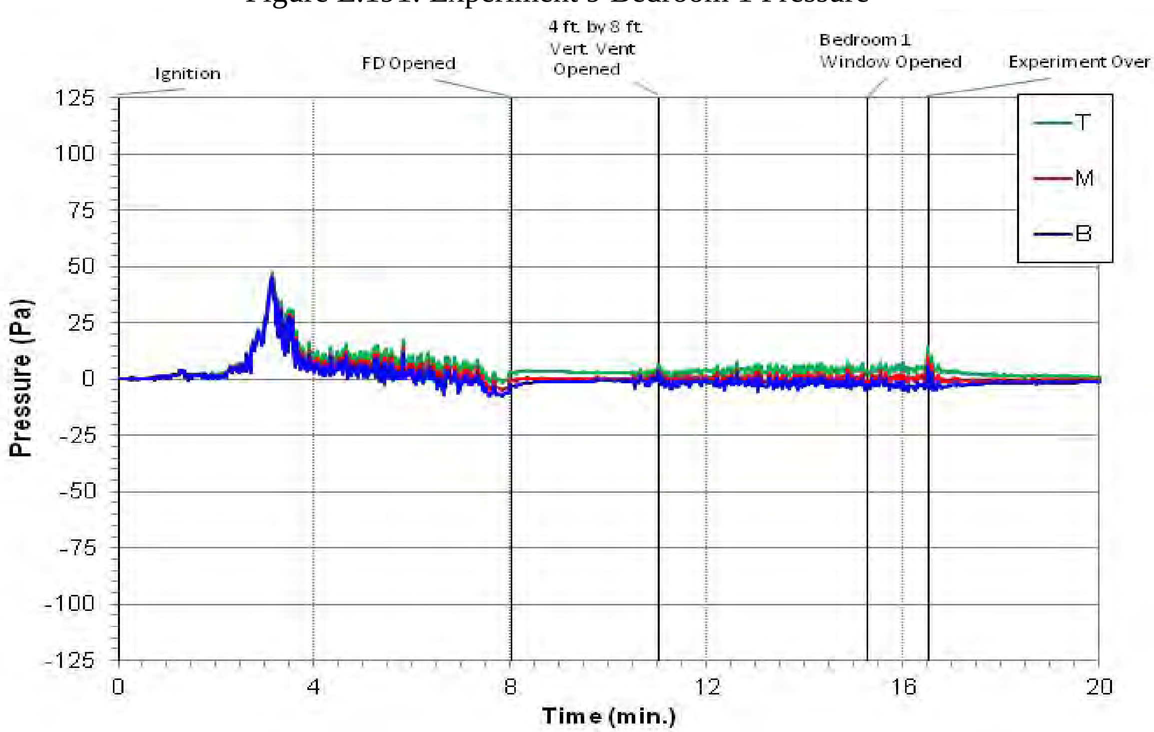


Figure E.192: Experiment 9 Bedroom 2 Pressure

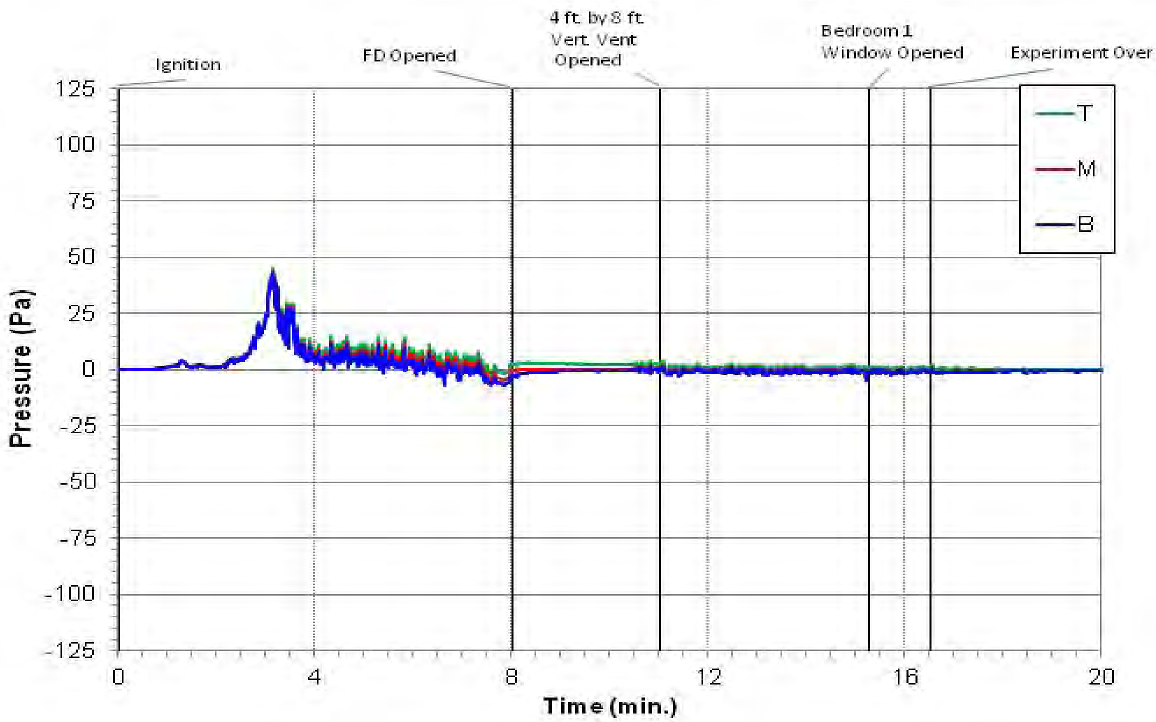


Figure E.193: Experiment 9 Kitchen Pressure

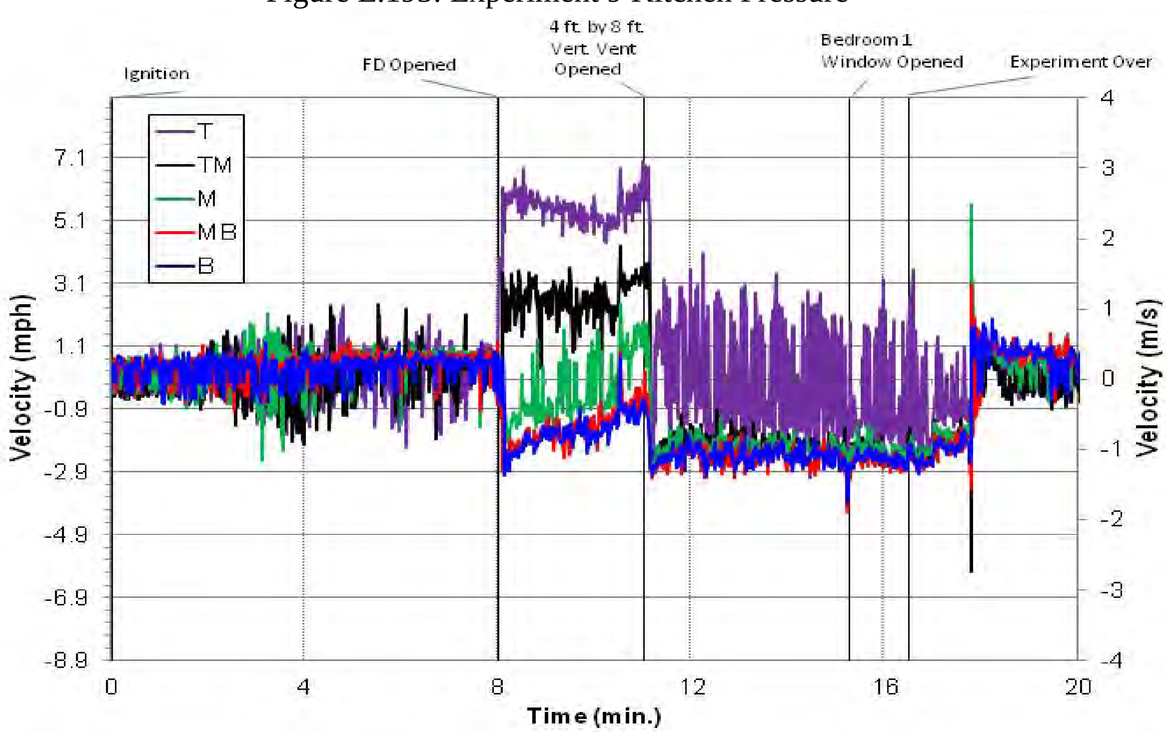


Figure E.194: Experiment 9 Front Door Velocity

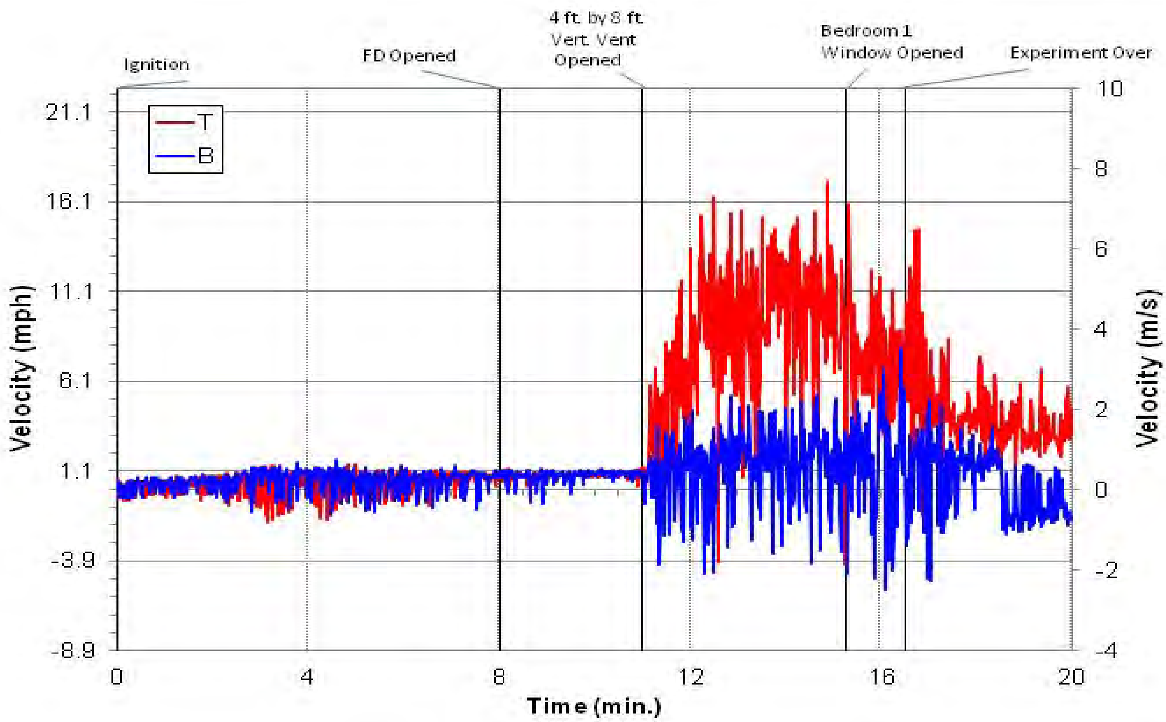


Figure E.195: Experiment 9 Vent Velocity

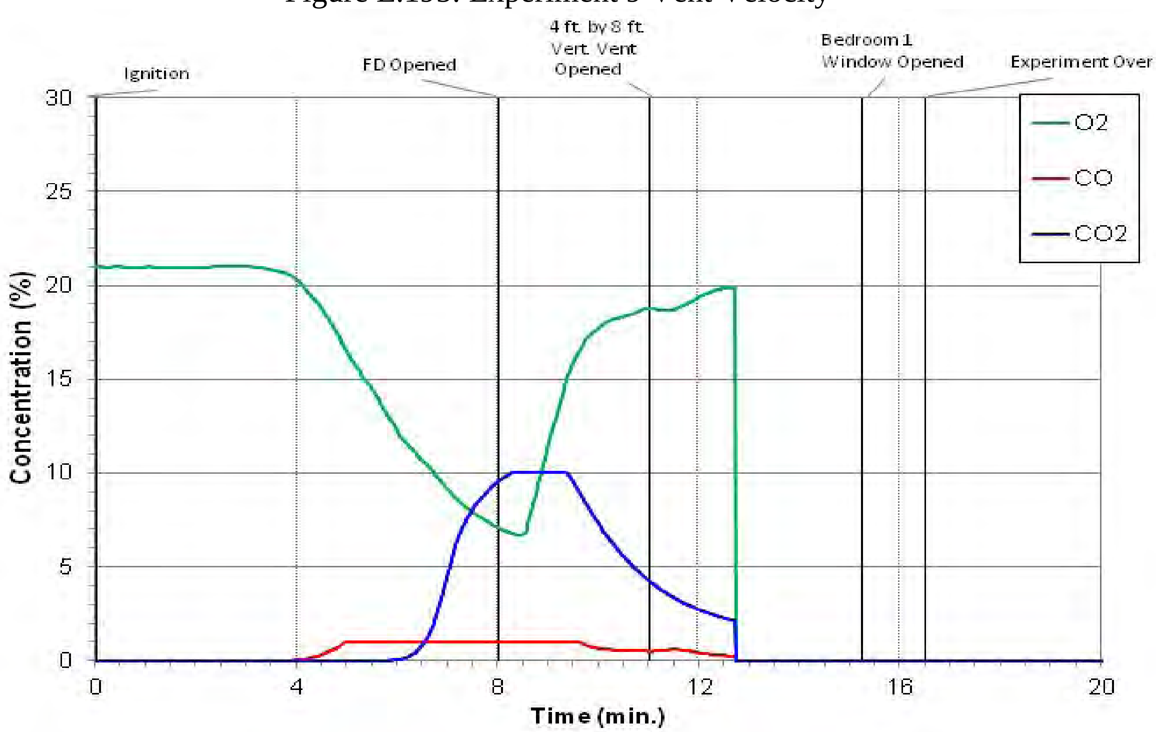


Figure E.196: Experiment 9 Living Room Gas

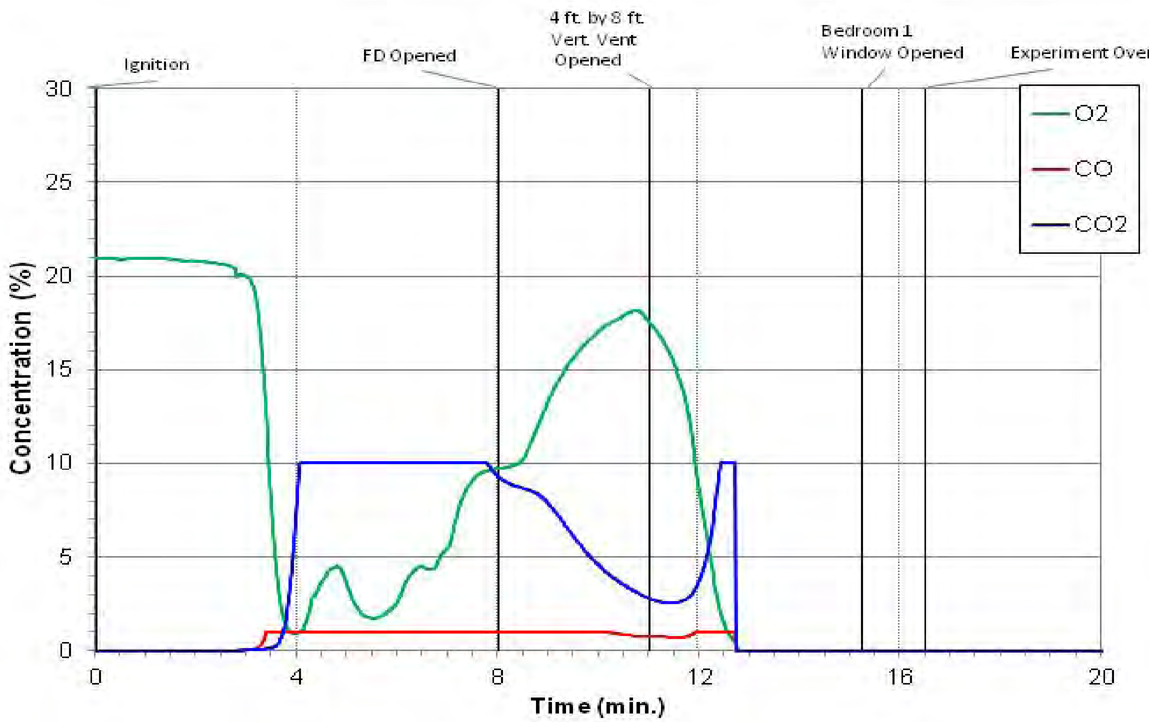


Figure E.197: Experiment 9 Bedroom 1 Gas

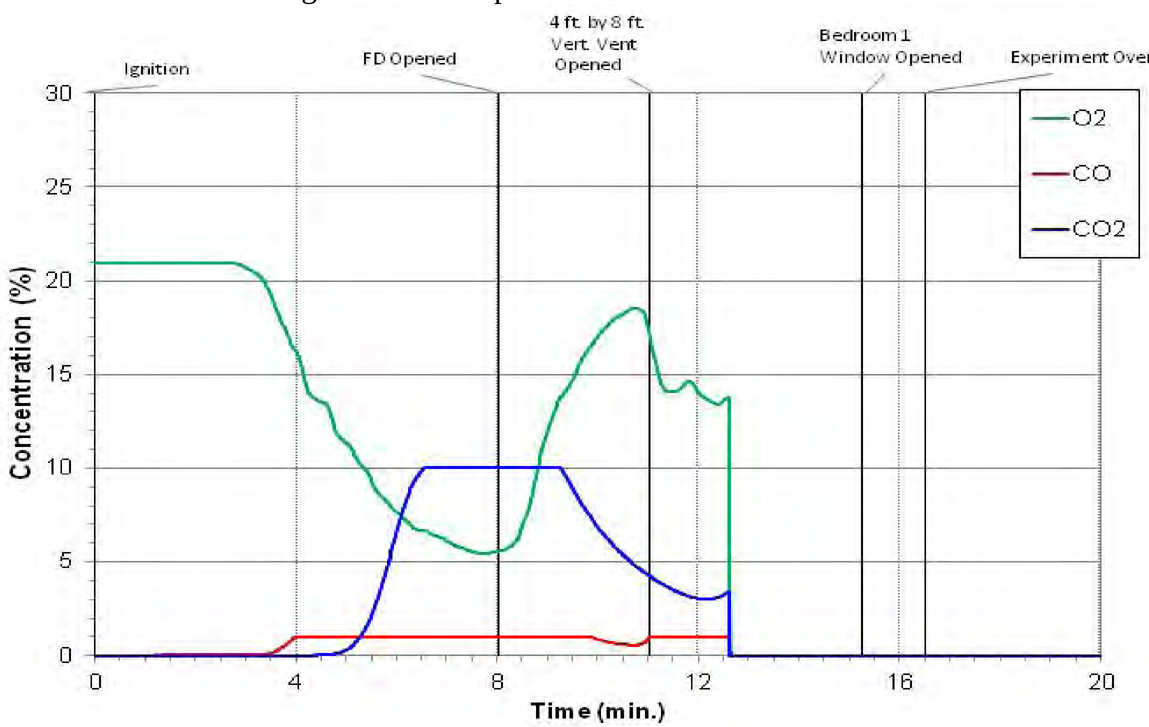


Figure E.198: Experiment 9 Bedroom 2 Gas

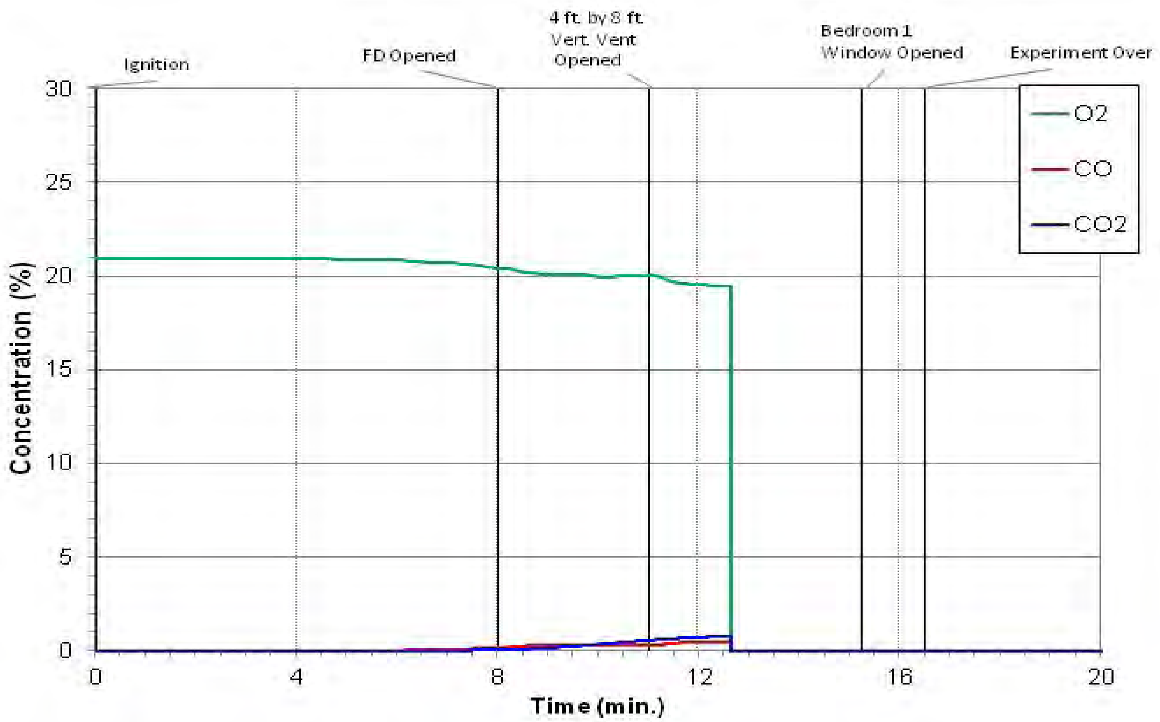


Figure E.199: Experiment 9 Bedroom 3 Gas

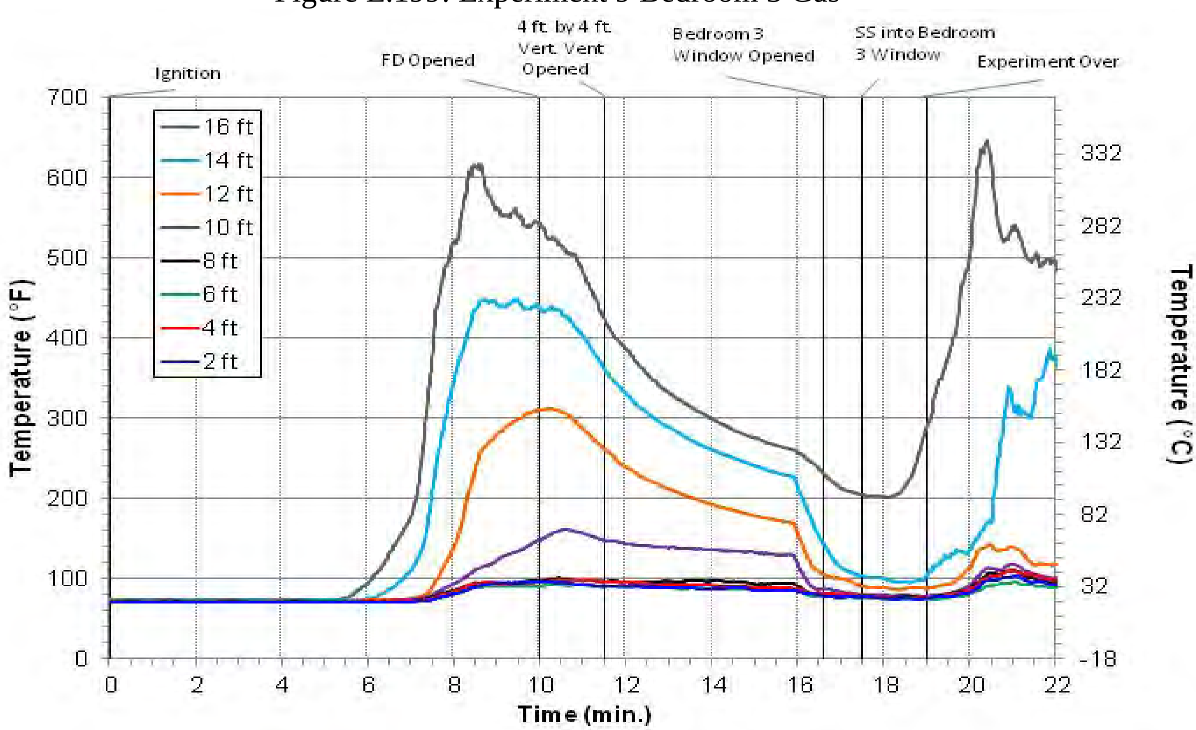


Figure E.200: Experiment 10 Family Room Temperature

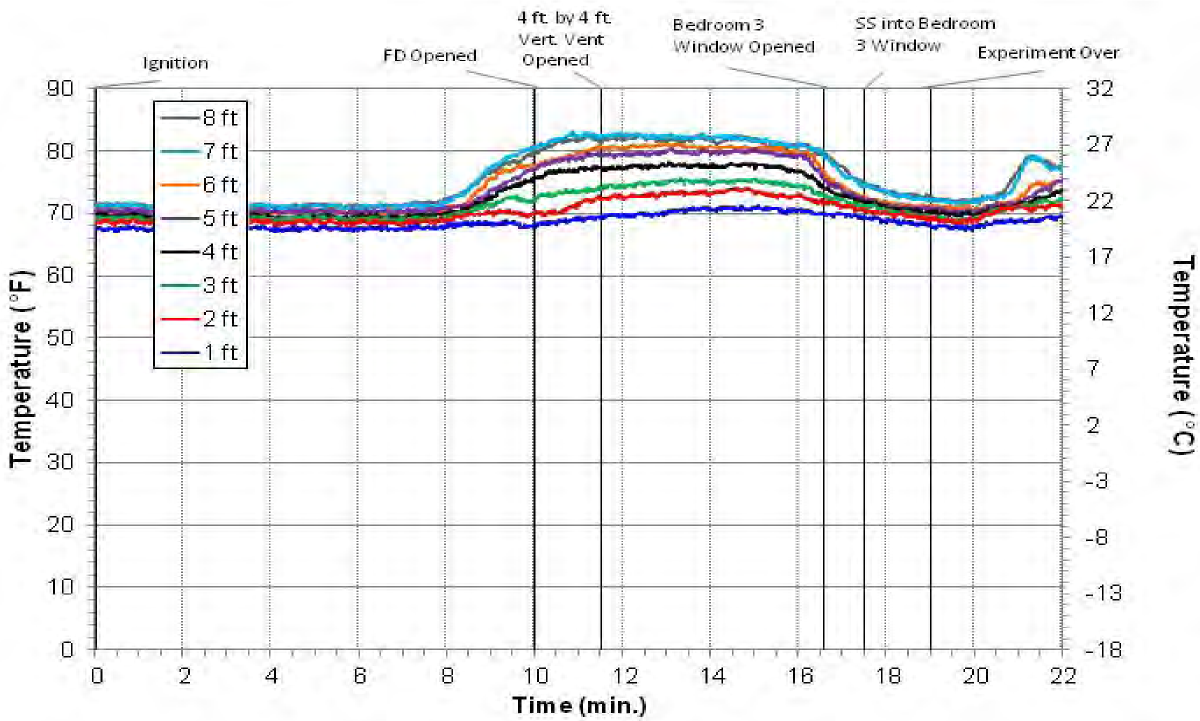


Figure E.201: Experiment 10 Kitchen Temperature

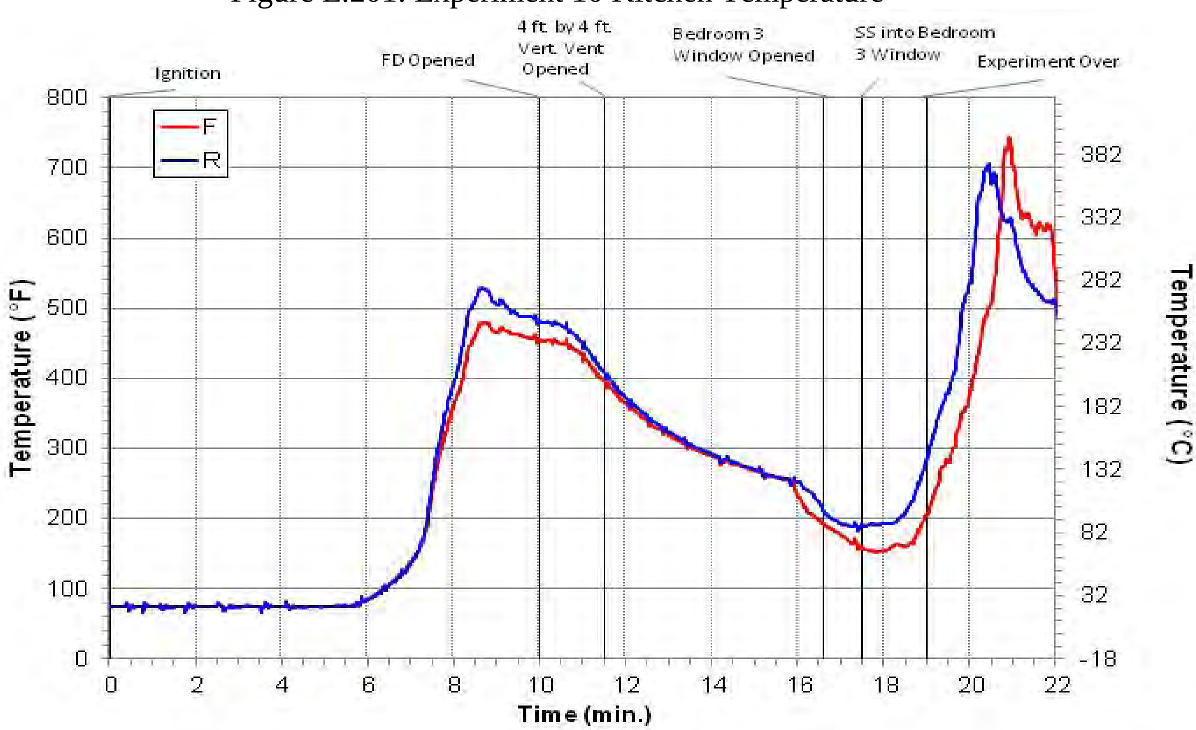


Figure E.202: Experiment 10 Vent Temperature

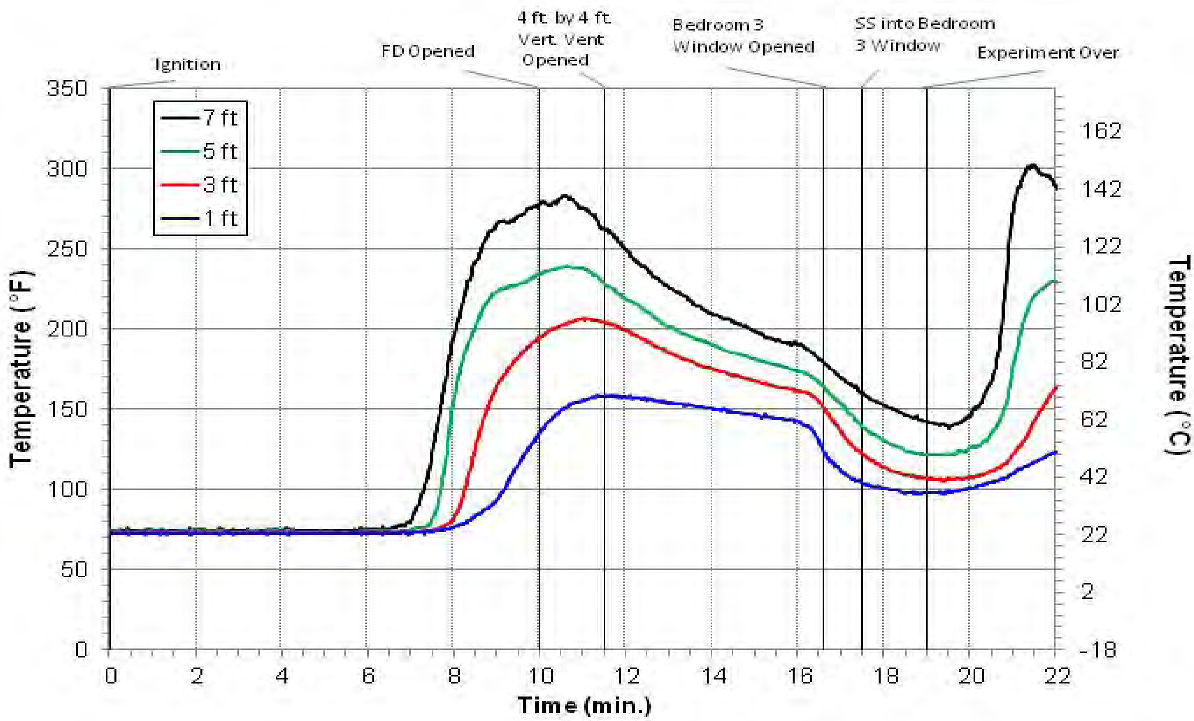


Figure E.203: Experiment 10 Bedroom 1 Temperature

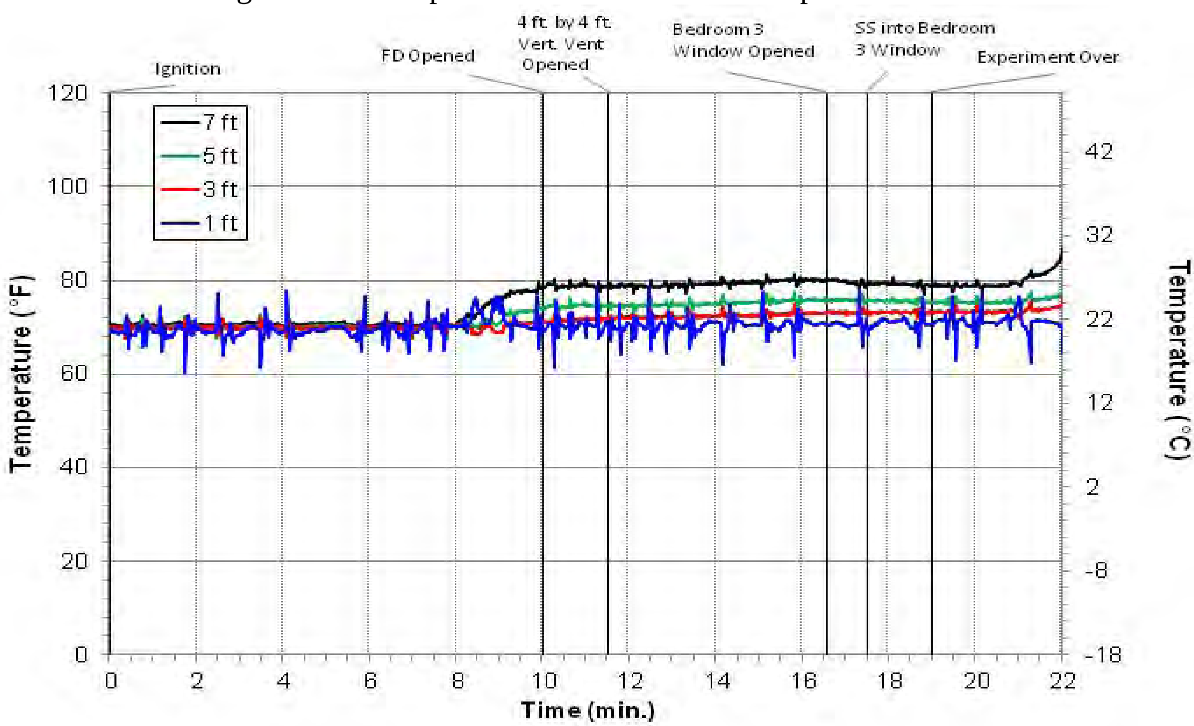


Figure E.204: Experiment 10 Bedroom 2 Temperature

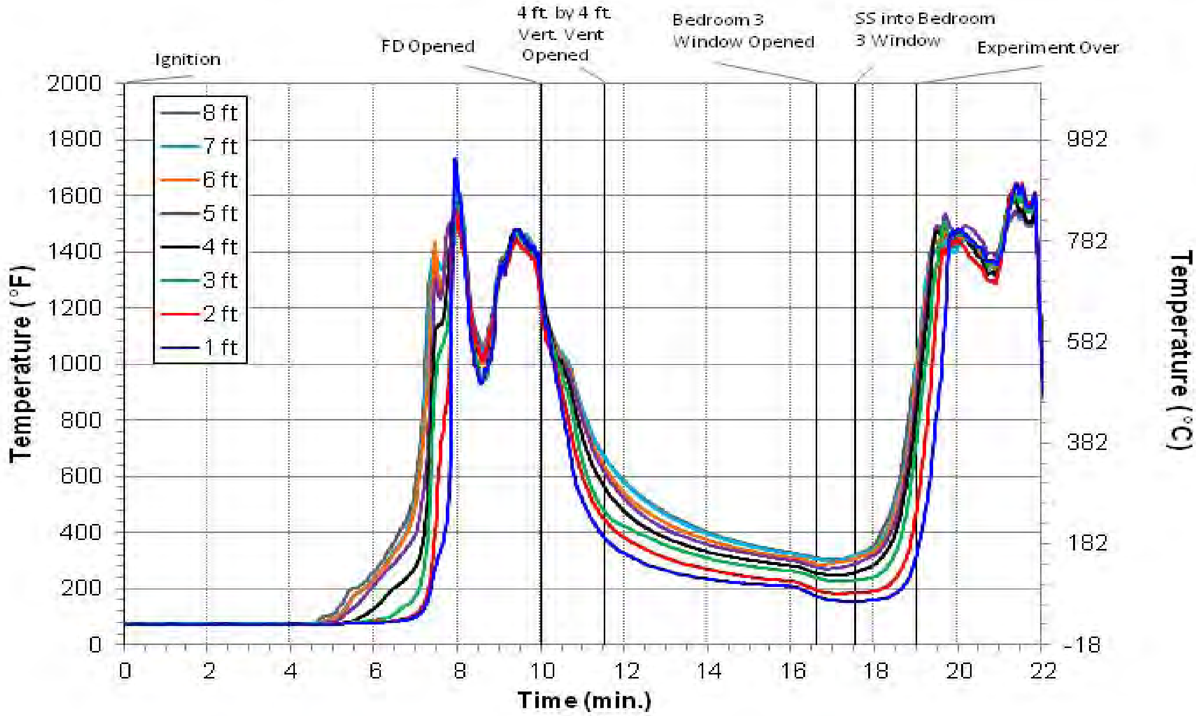


Figure E.205: Experiment 10 Bedroom 3 Temperature

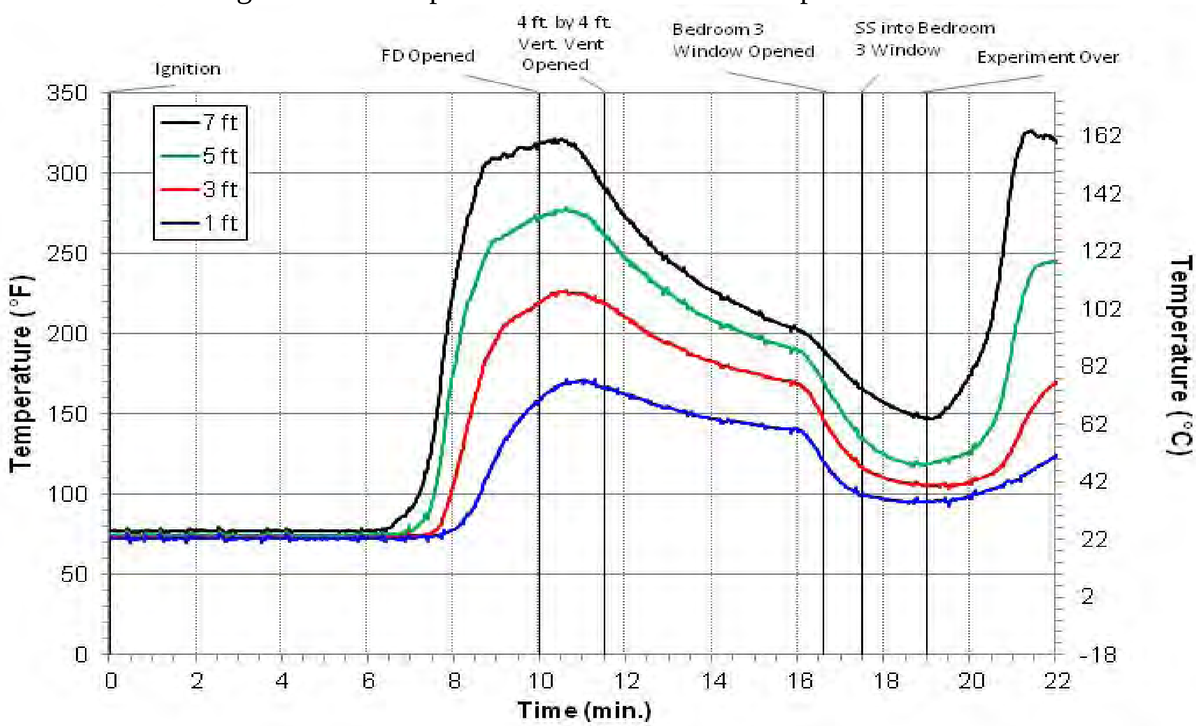


Figure E.206: Experiment 10 Bedroom 4 Temperature

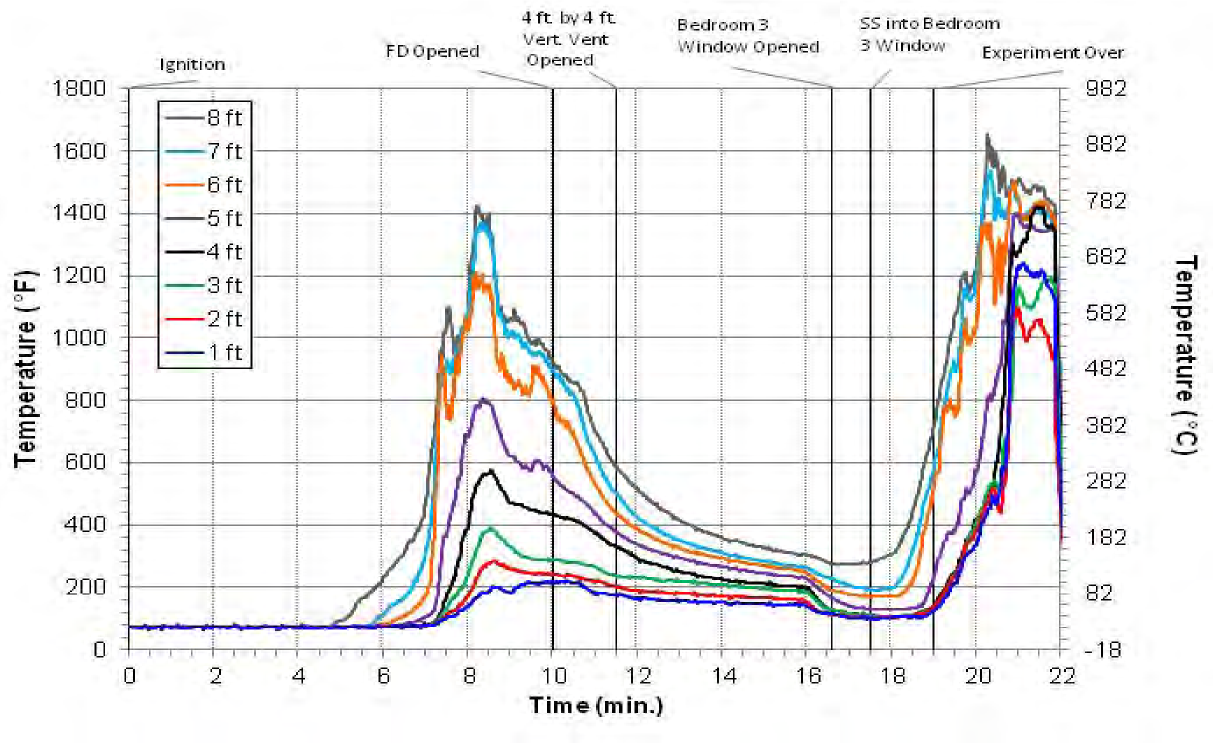


Figure E.207: Experiment 10 Hallway Temperature

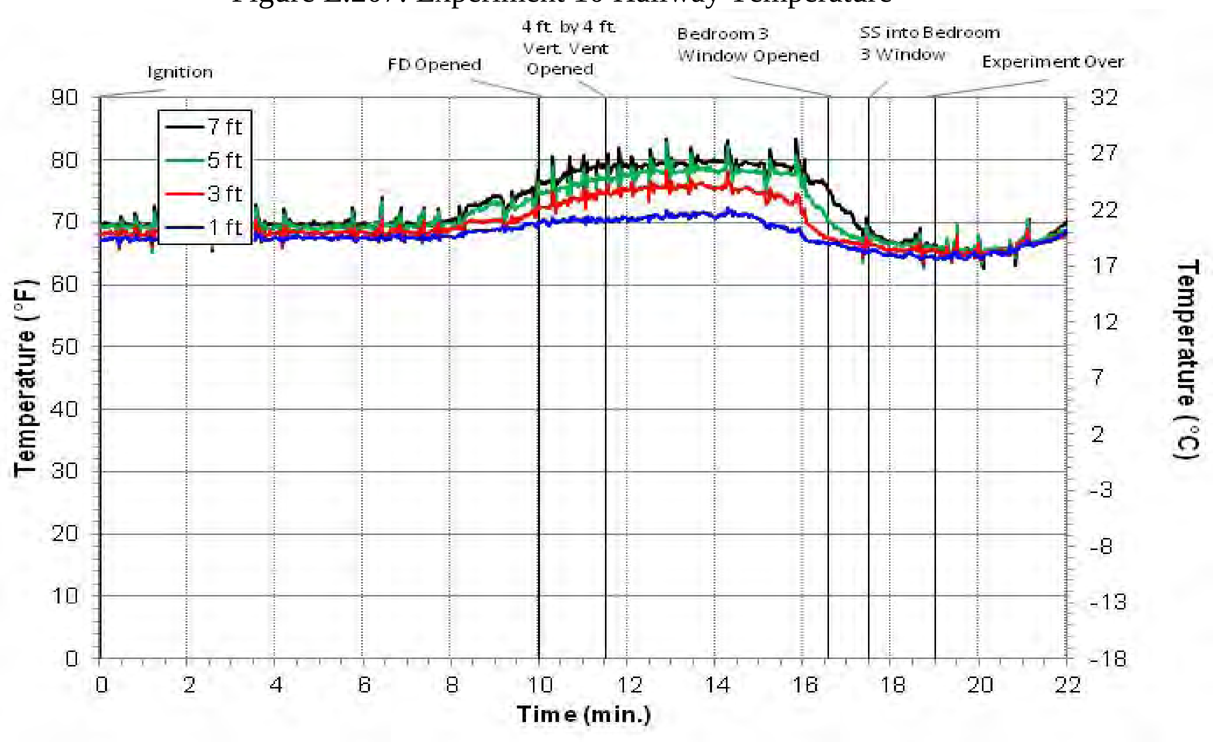


Figure E.208: Experiment 10 Dining Room Temperature

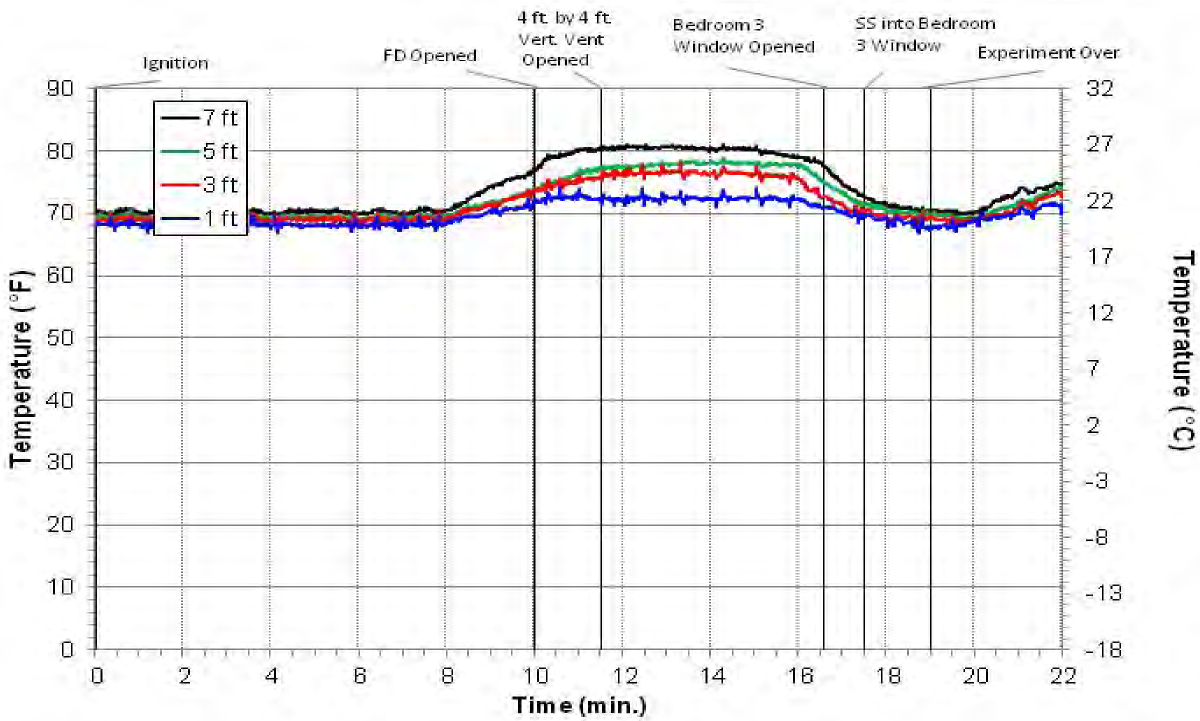


Figure E.209: Experiment 10 Living Room Temperature

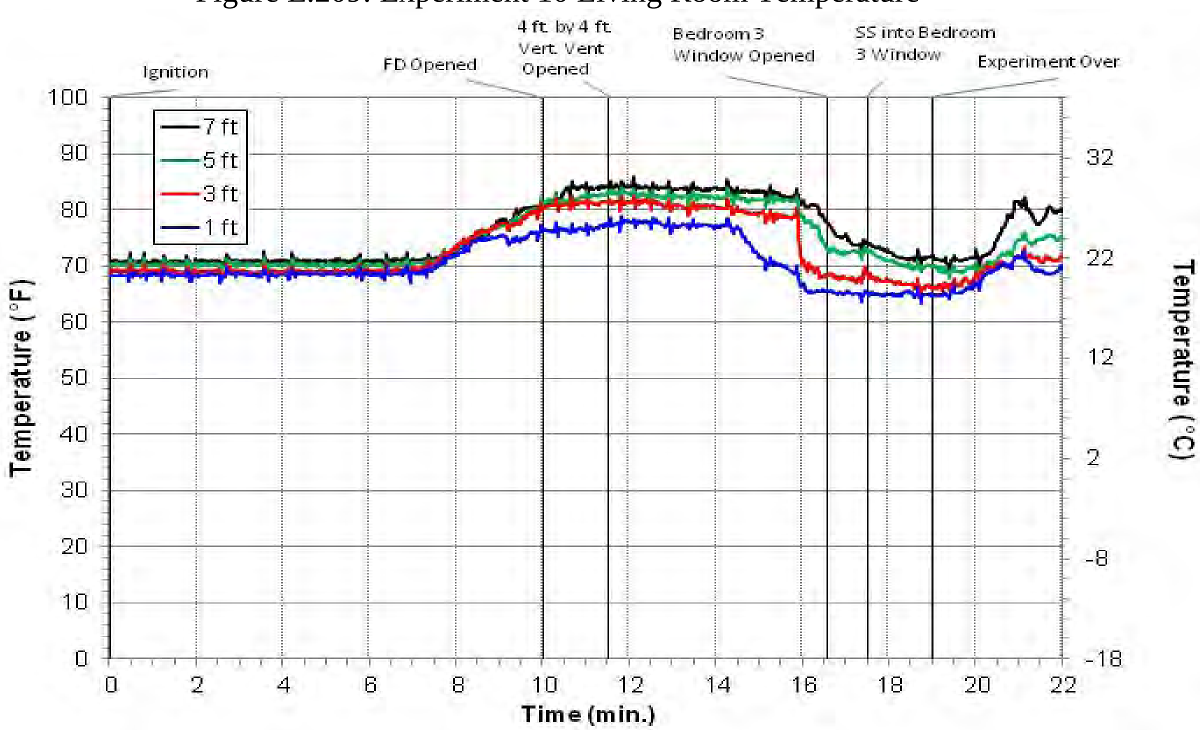


Figure E.210: Experiment 10 Foyer Temperature

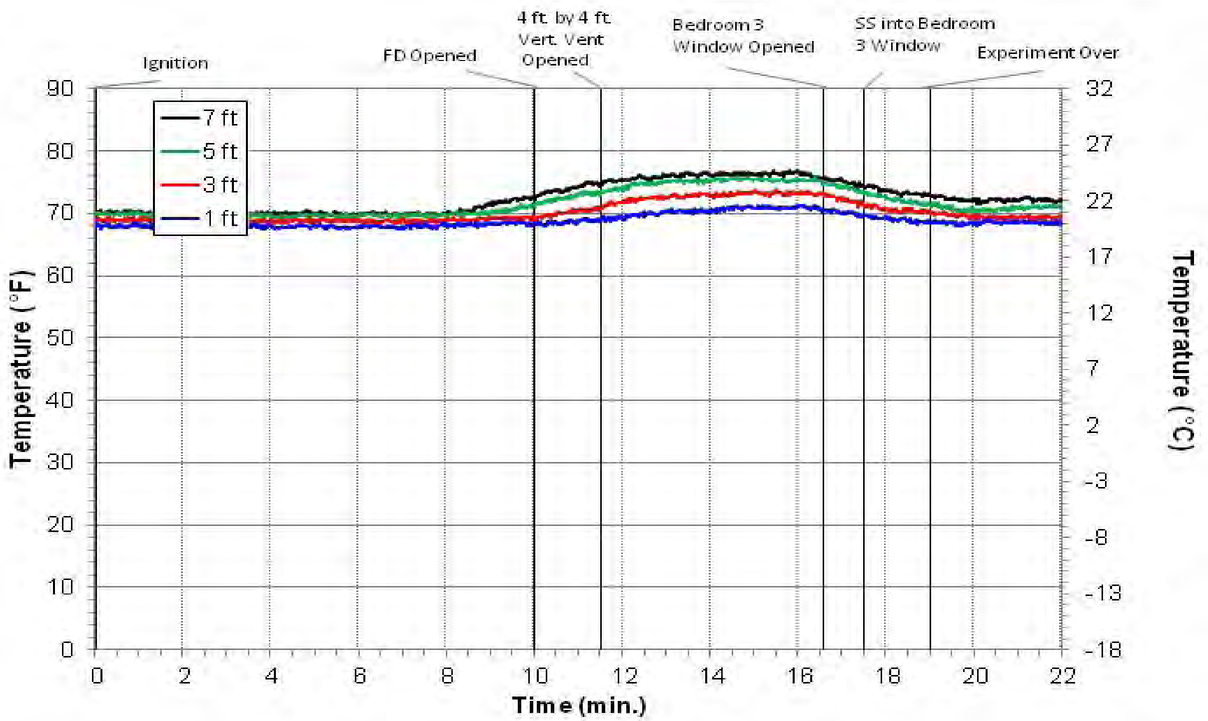


Figure E.211: Experiment 10 Den Temperature

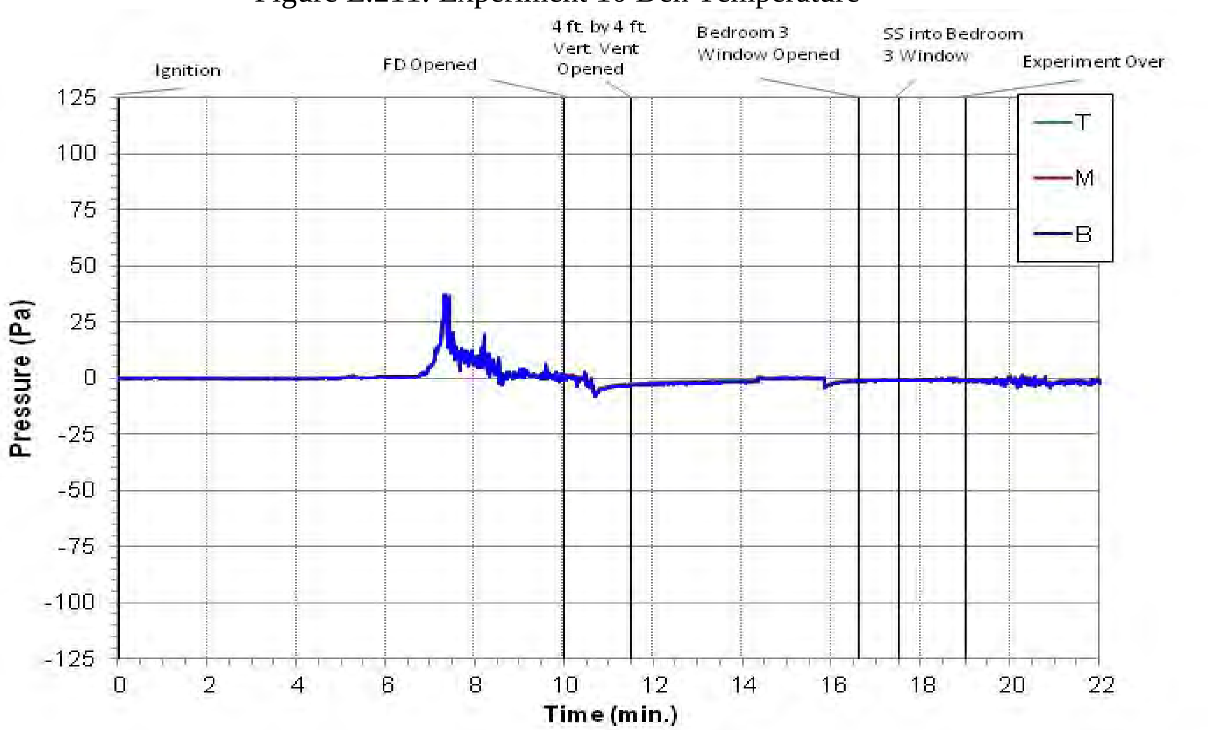


Figure E.212: Experiment 10 Living Room Pressure

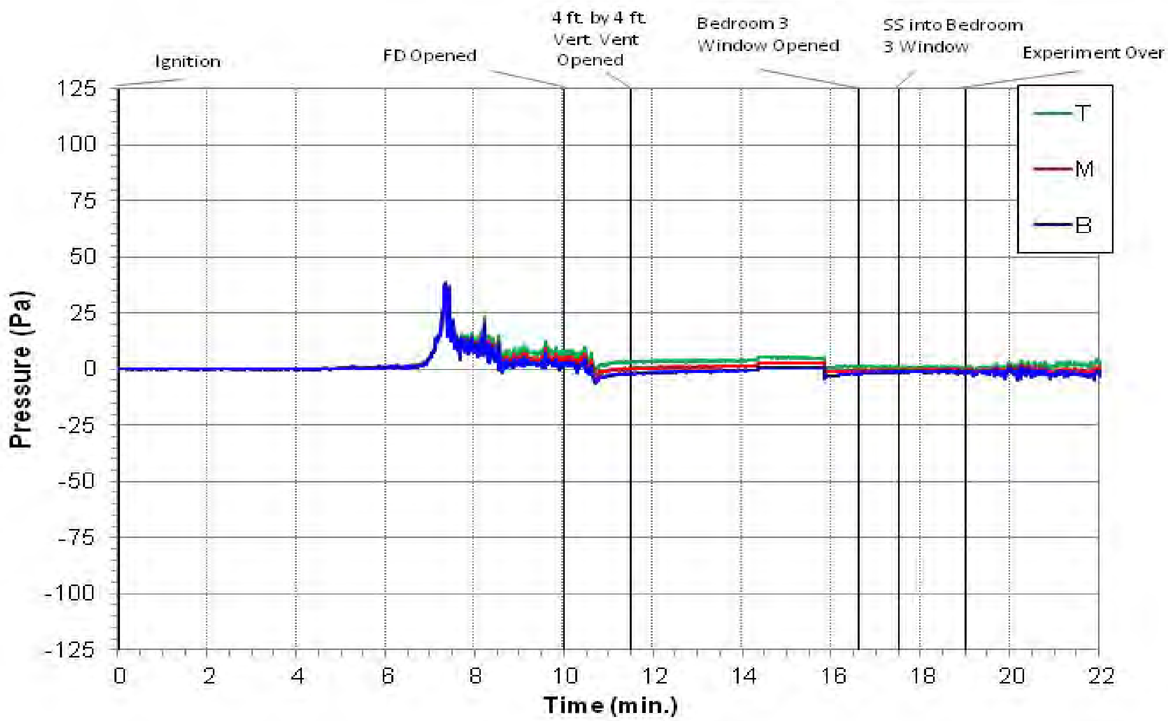


Figure E.213: Experiment 10 Bedroom 2 Pressure

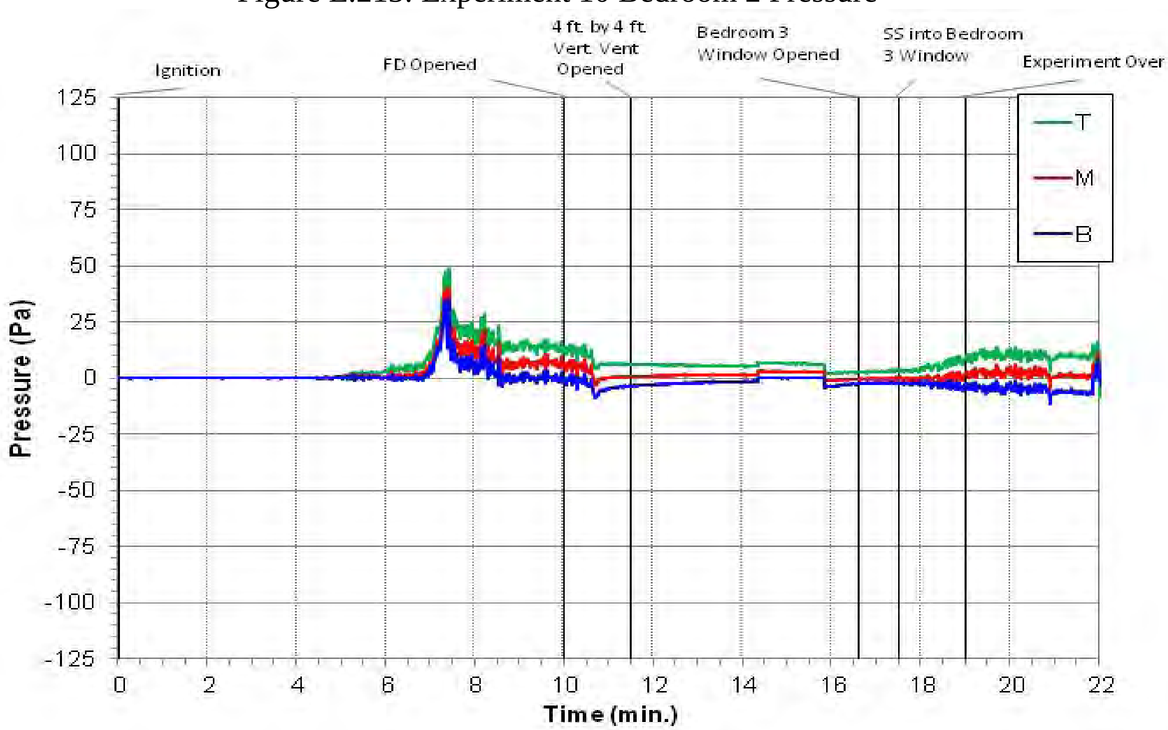


Figure E.214: Experiment 10 Bedroom 3 Pressure

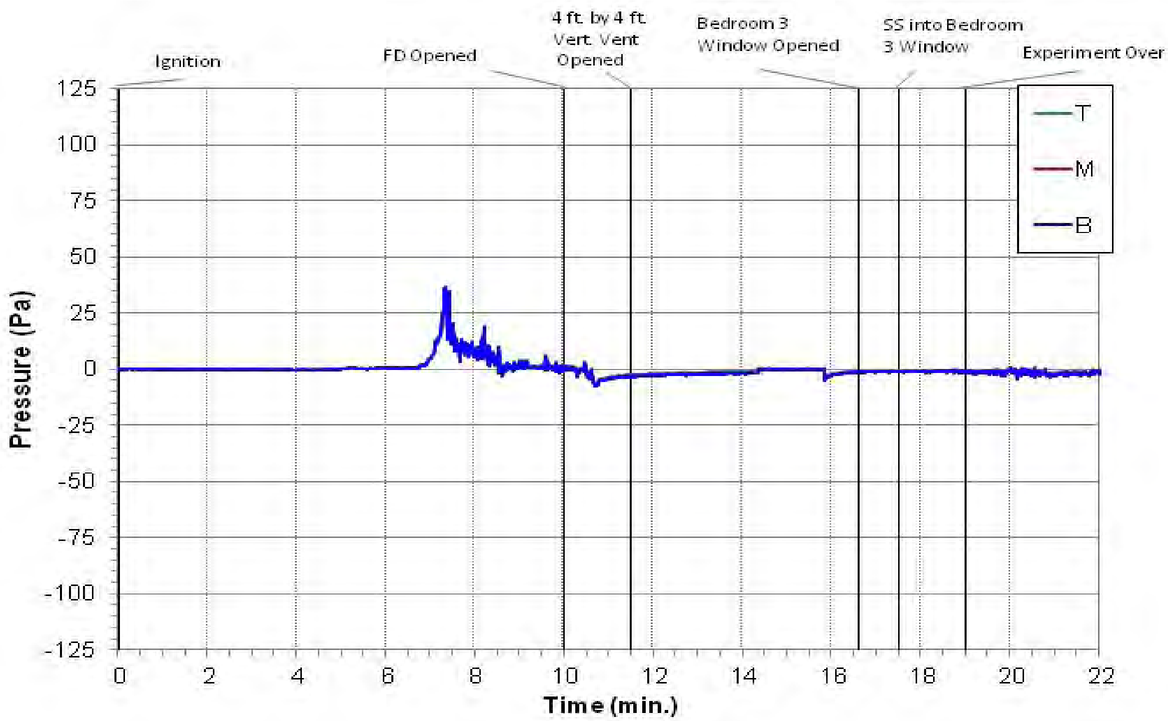


Figure E.215: Experiment 10 Kitchen Pressure

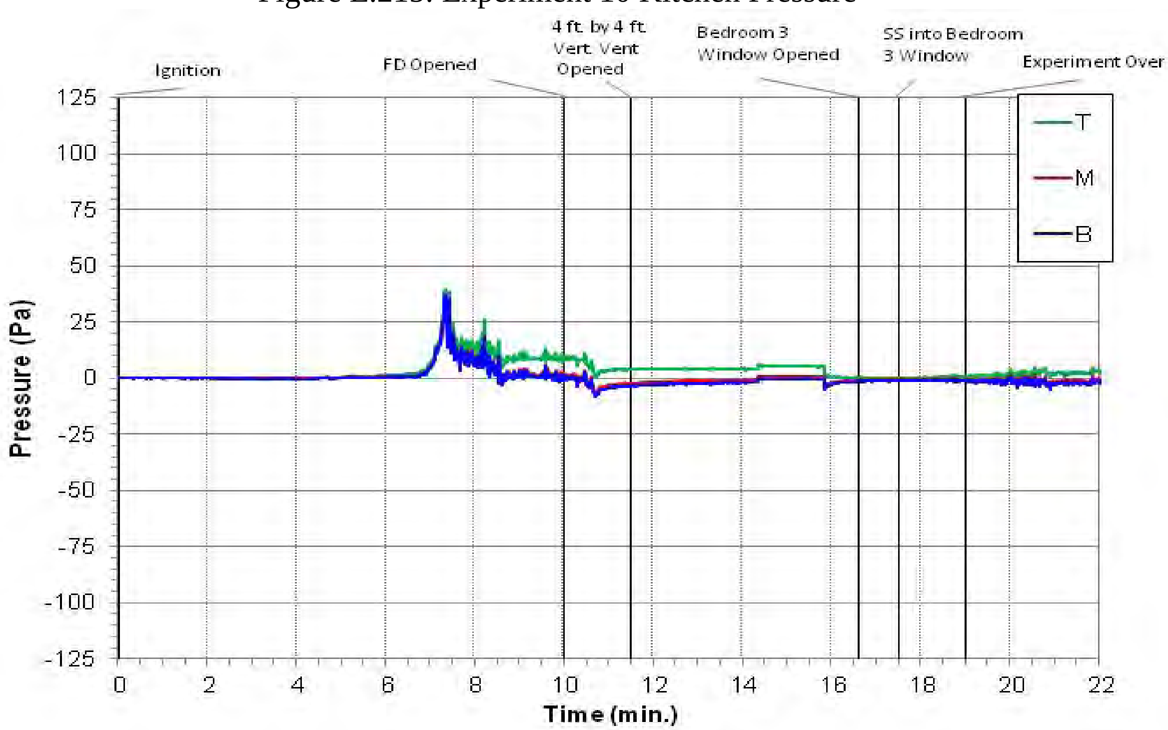


Figure E.216: Experiment 10 Family Room Pressure

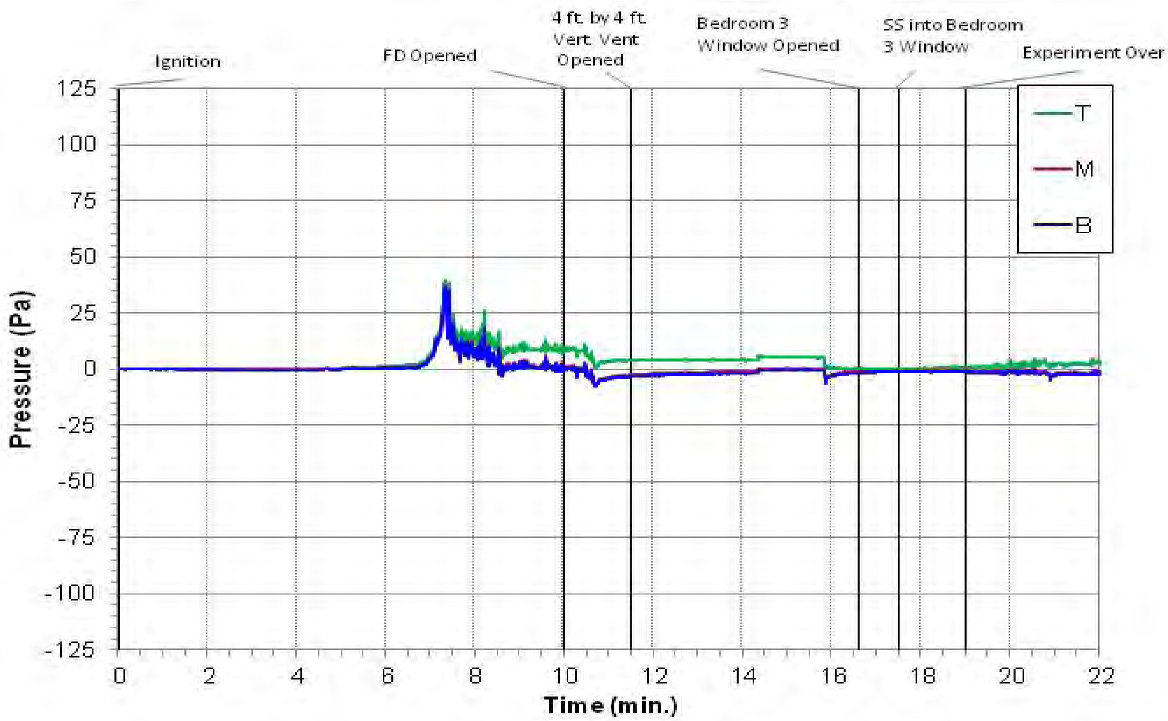


Figure E.217: Experiment 10 Foyer Pressure

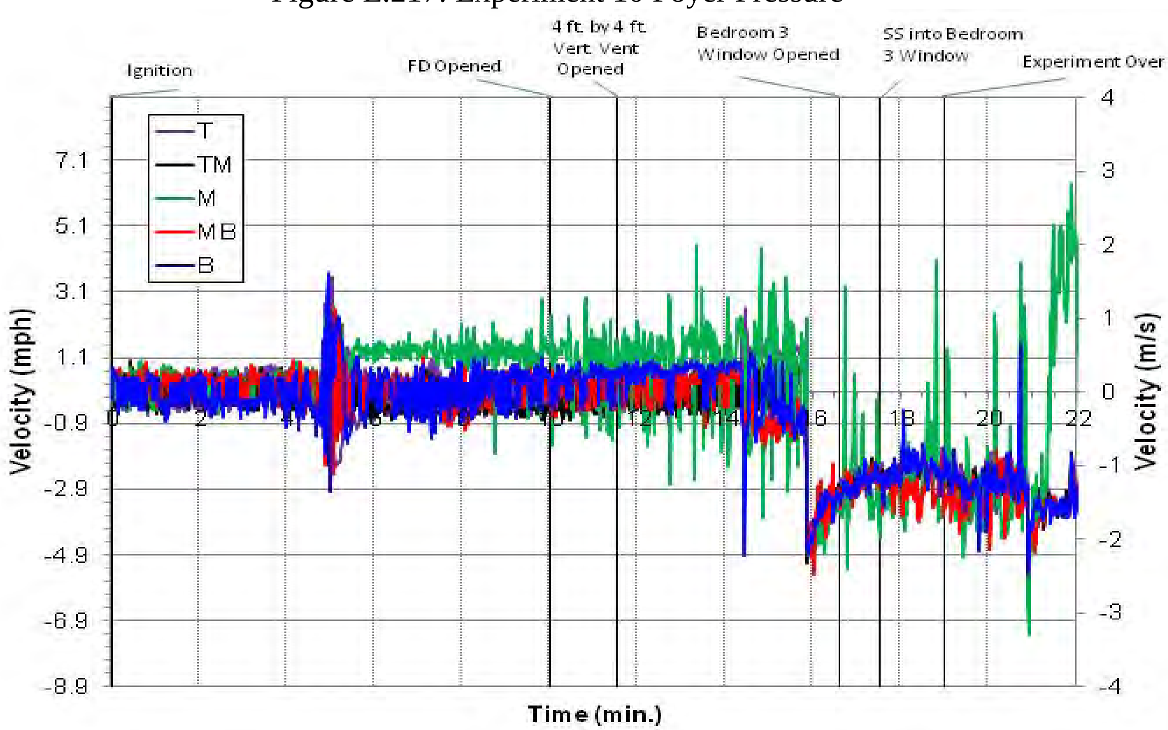


Figure E.218: Experiment 10 Front Door Velocity

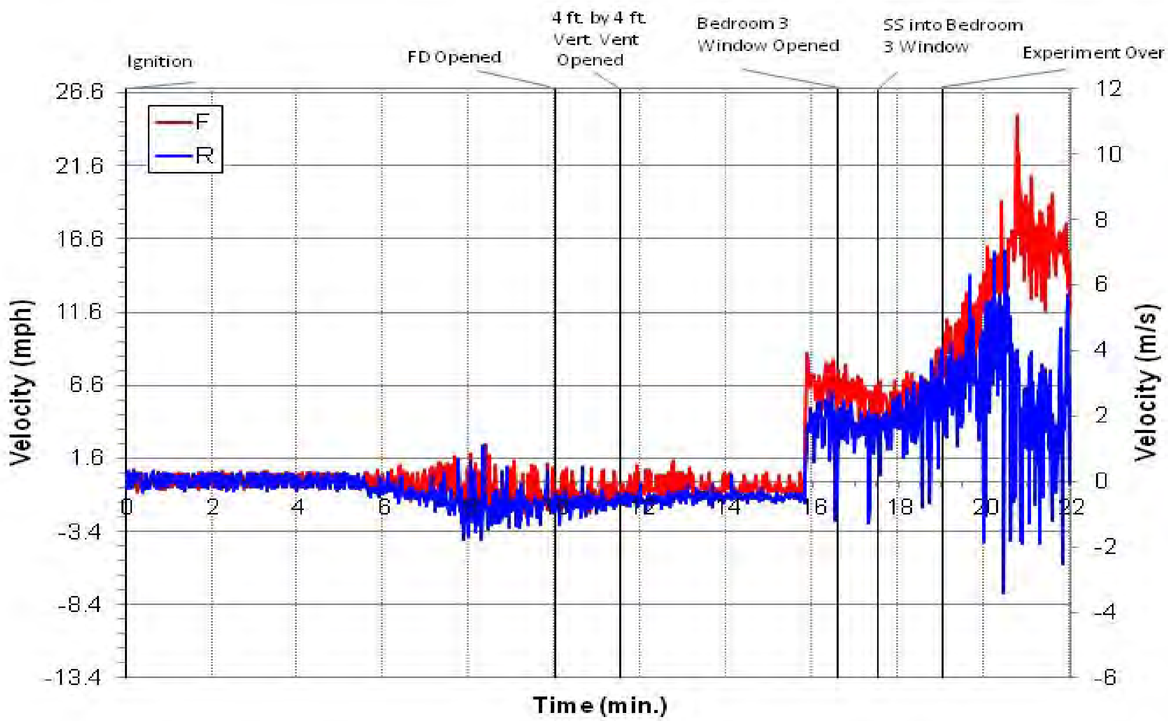


Figure E.219: Experiment 10 Vent Velocity

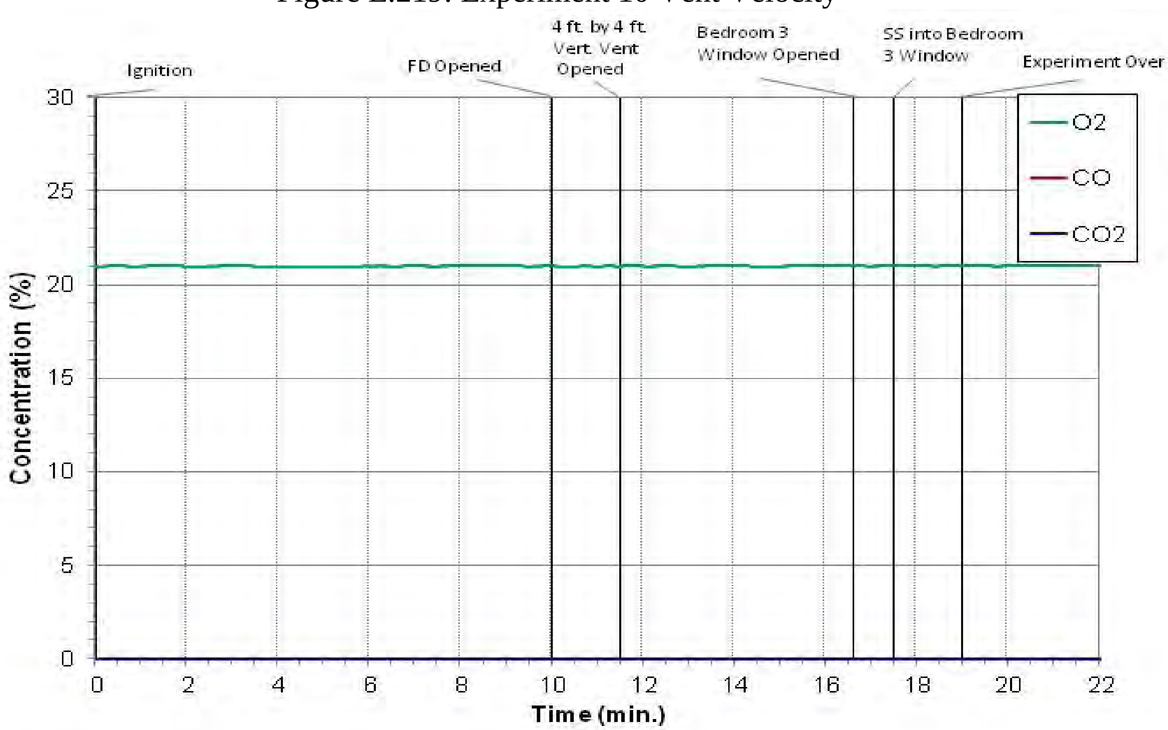


Figure E.220: Experiment 10 Front Door Gas

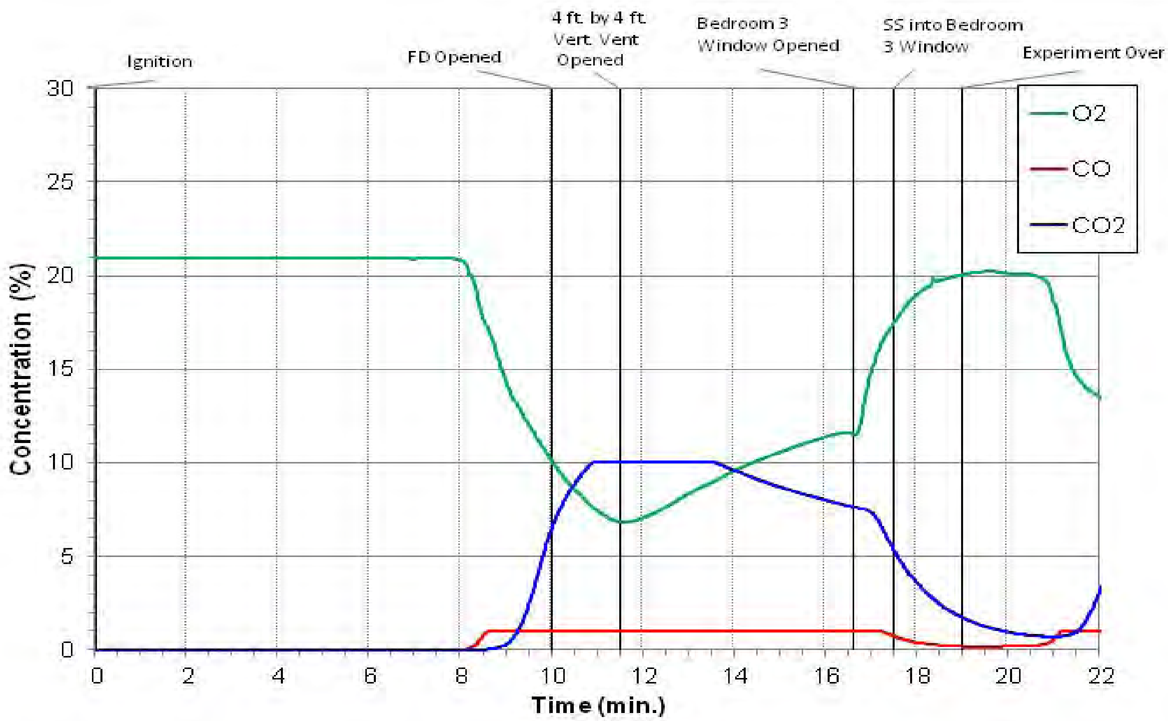


Figure E.221: Experiment 10 Bedroom 1 Gas

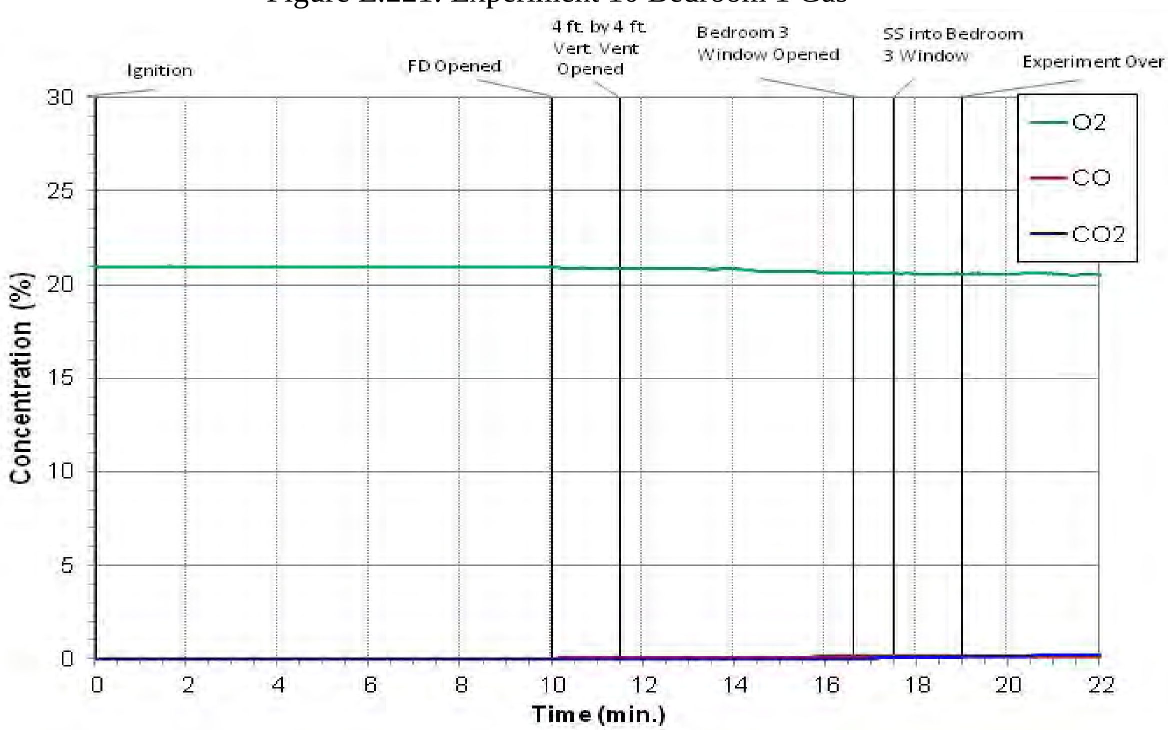


Figure E.222: Experiment 10 Bedroom 2 Gas

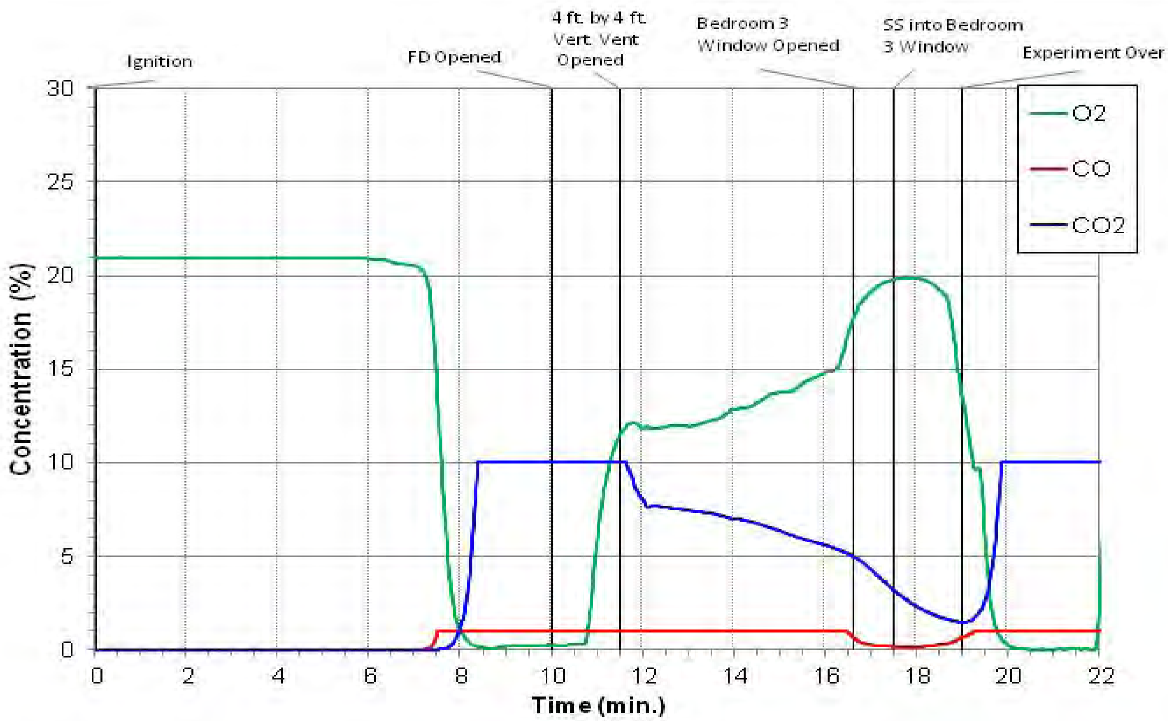


Figure E.223: Experiment 10 Bedroom 3 Gas

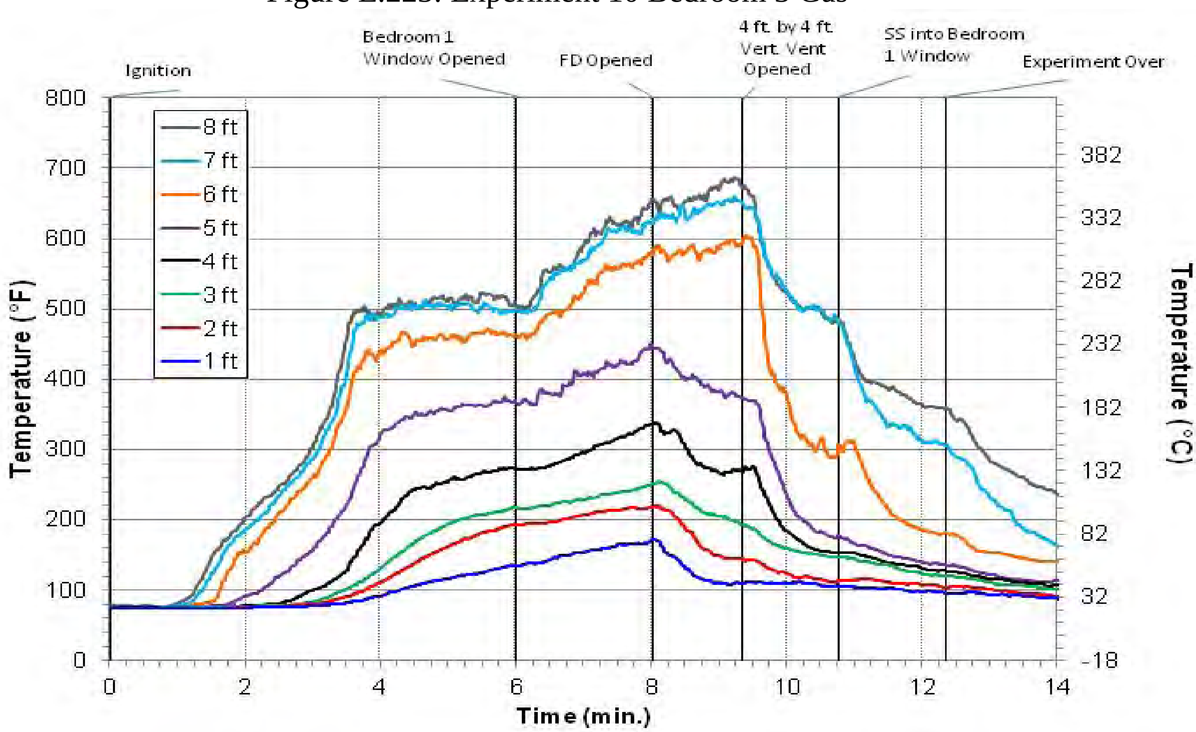


Figure E.224: Experiment 11 Living Room Temperature

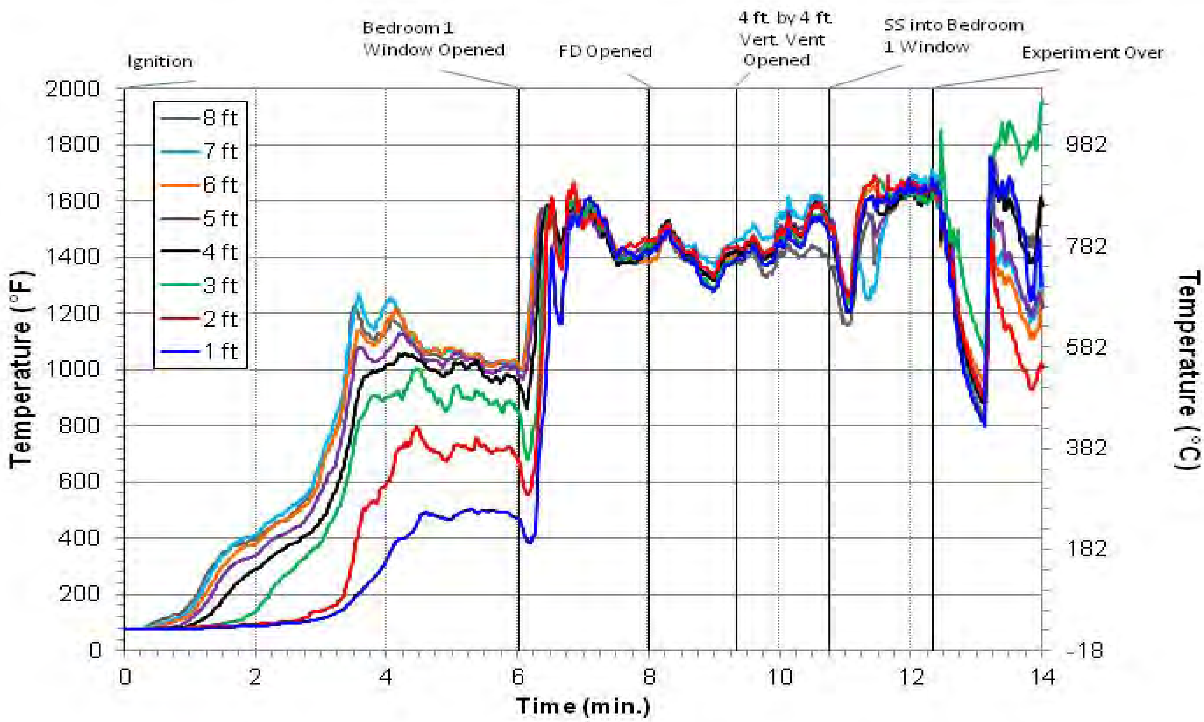


Figure E.225: Experiment 11 Bedroom 1 Temperature

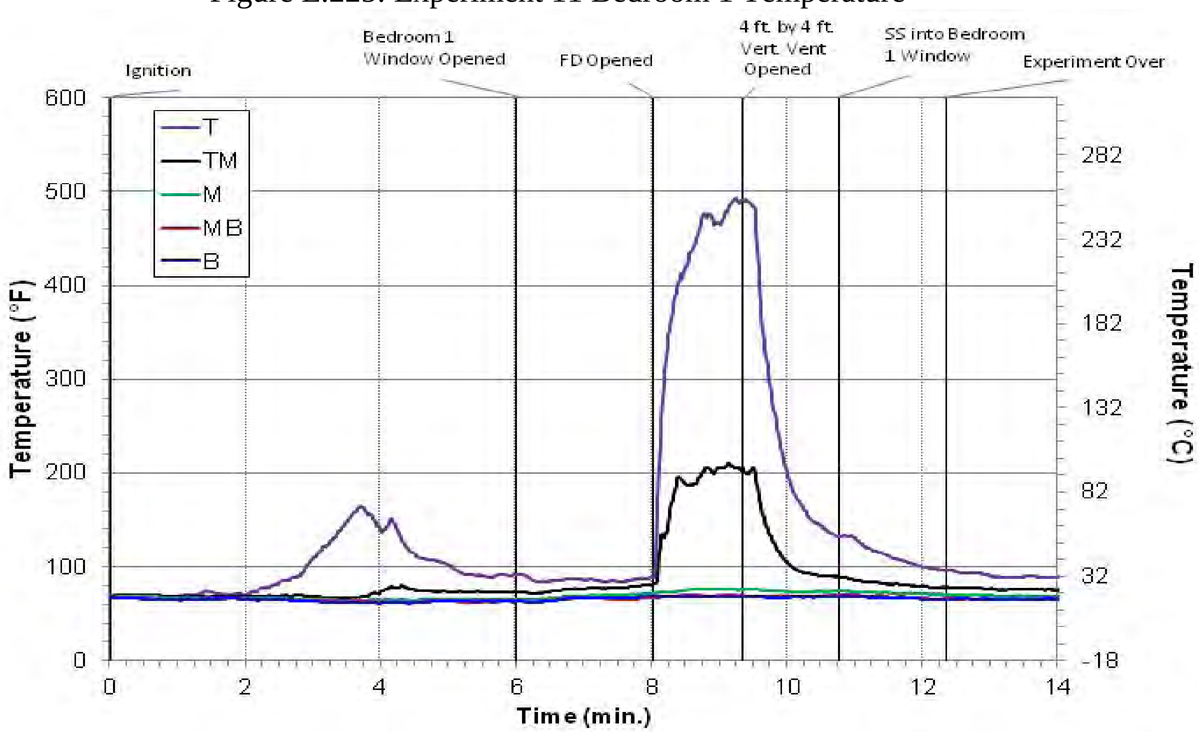


Figure E.226: Experiment 11 Front Door Temperature

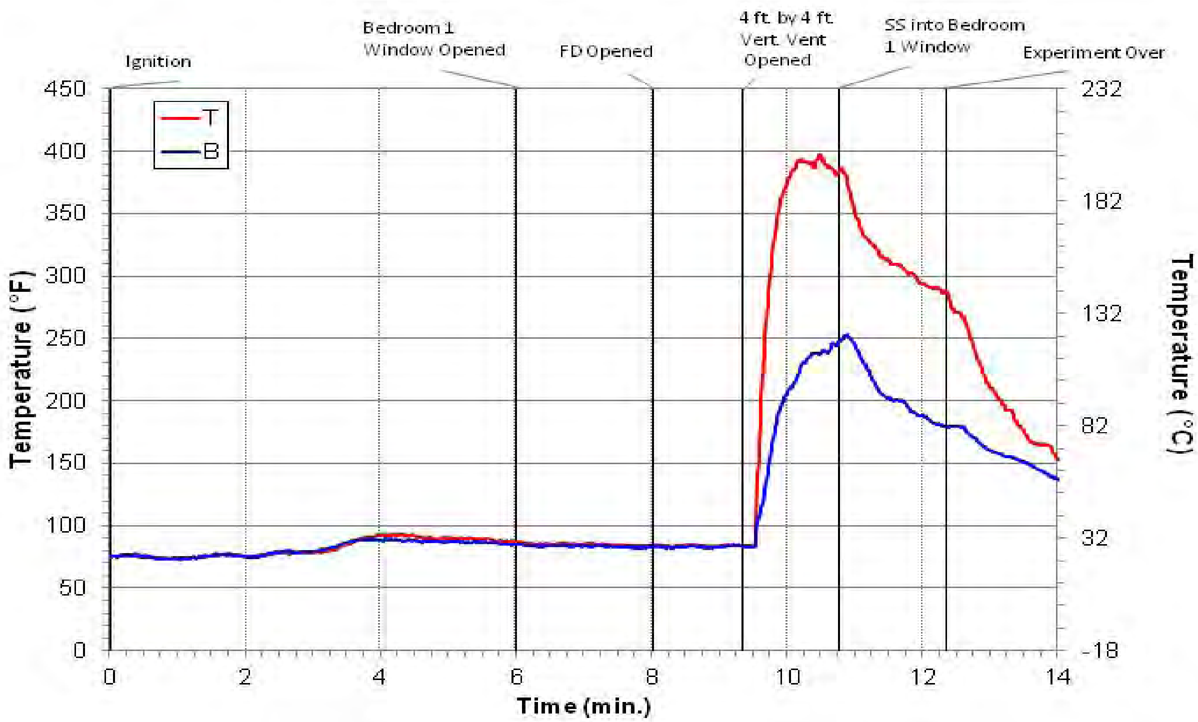


Figure E.227: Experiment 11 Vent Temperature

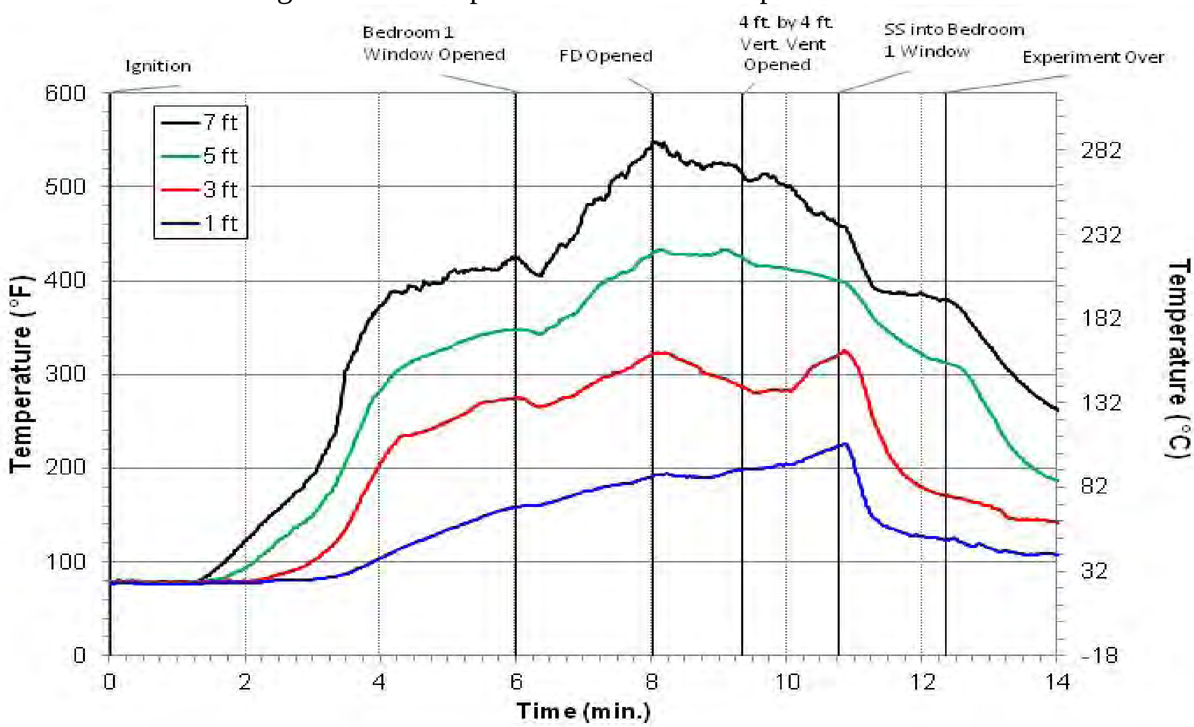


Figure E.228: Experiment 11 Bedroom 2 Temperature

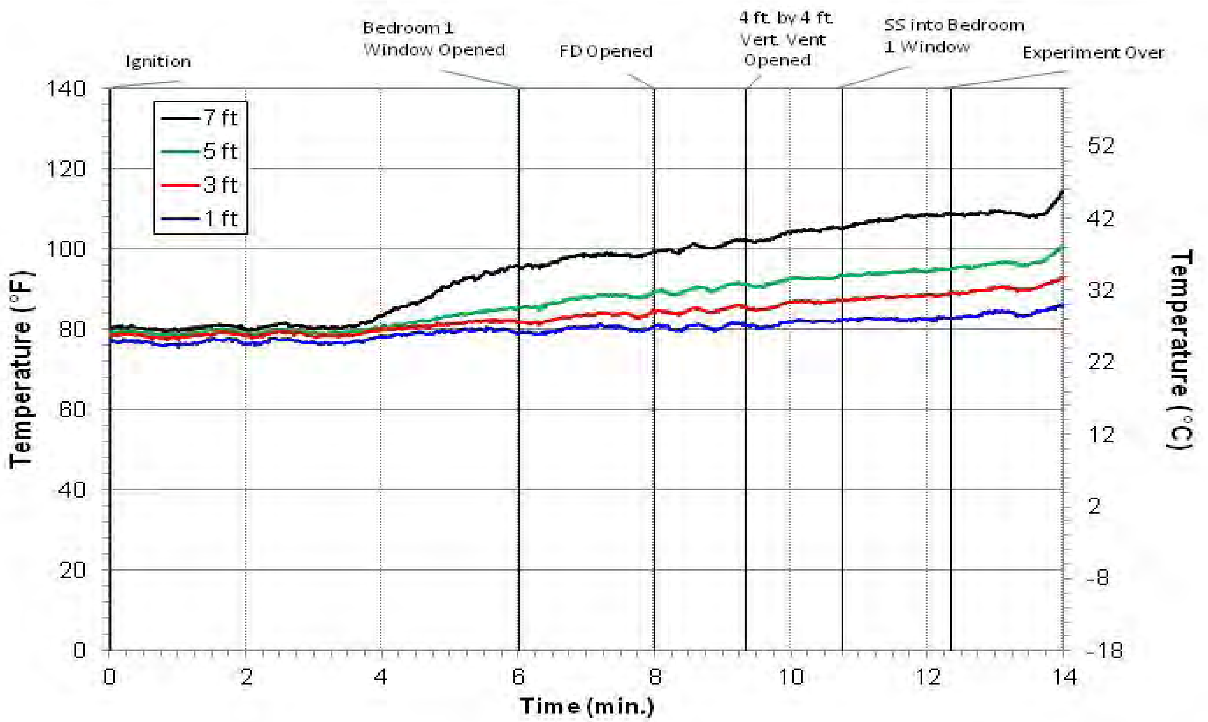


Figure E.229: Experiment 11 Bedroom 3 Temperature

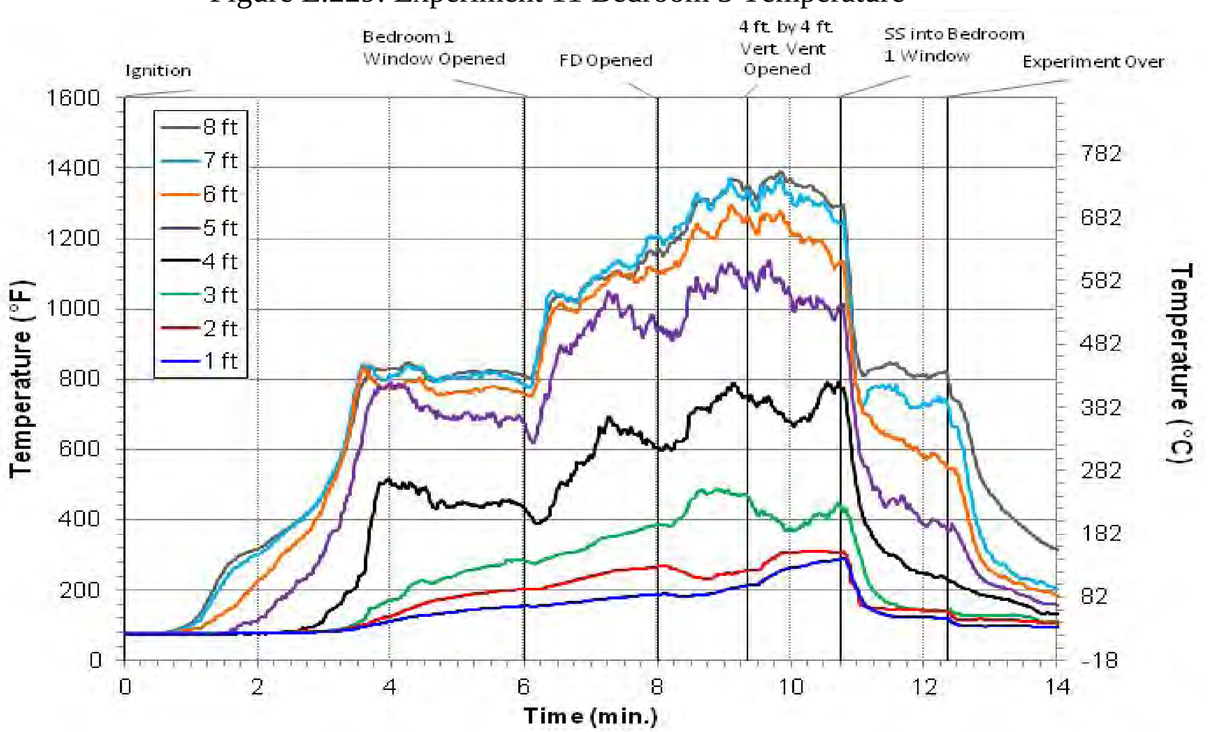


Figure E.230: Experiment 11 Hallway Temperature

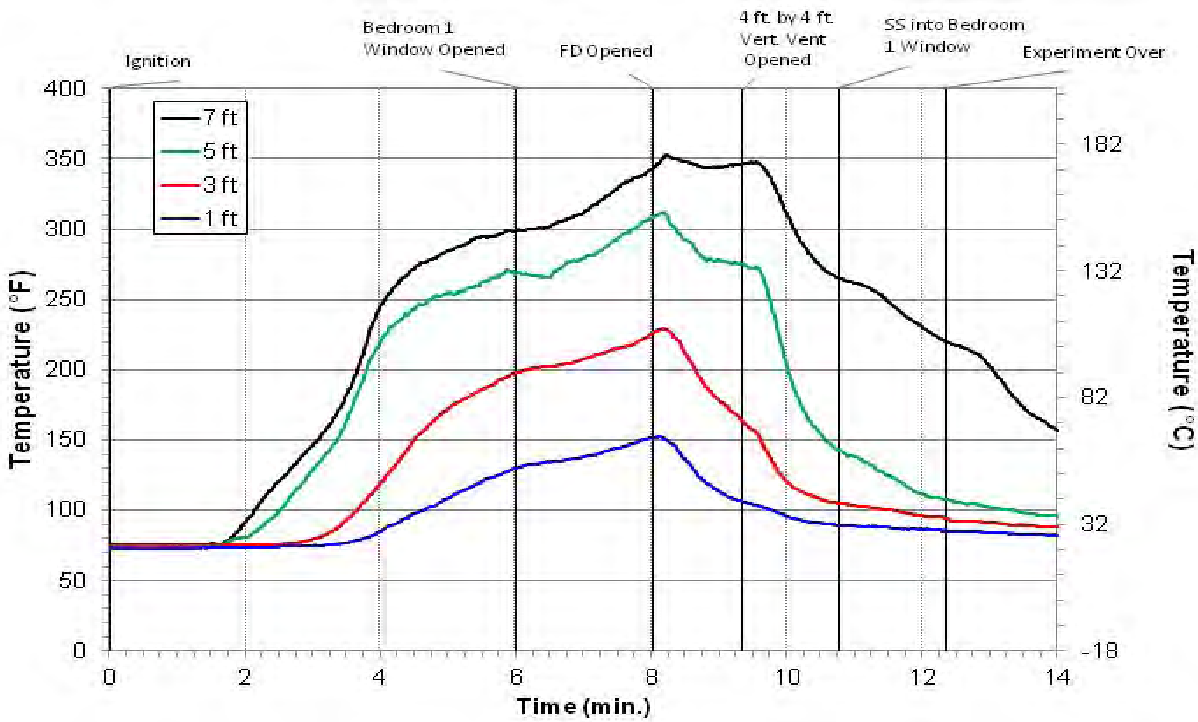


Figure E.231: Experiment 11 Dining Room Temperature

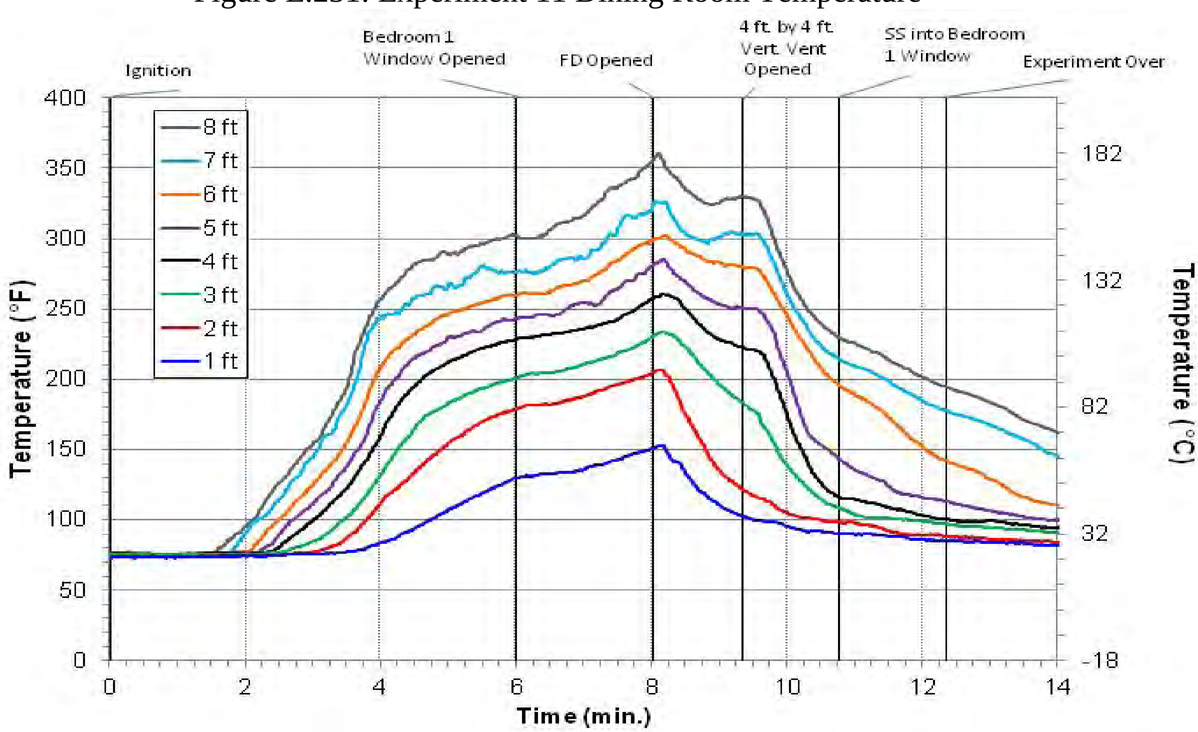


Figure E.232: Experiment 11 Kitchen Temperature

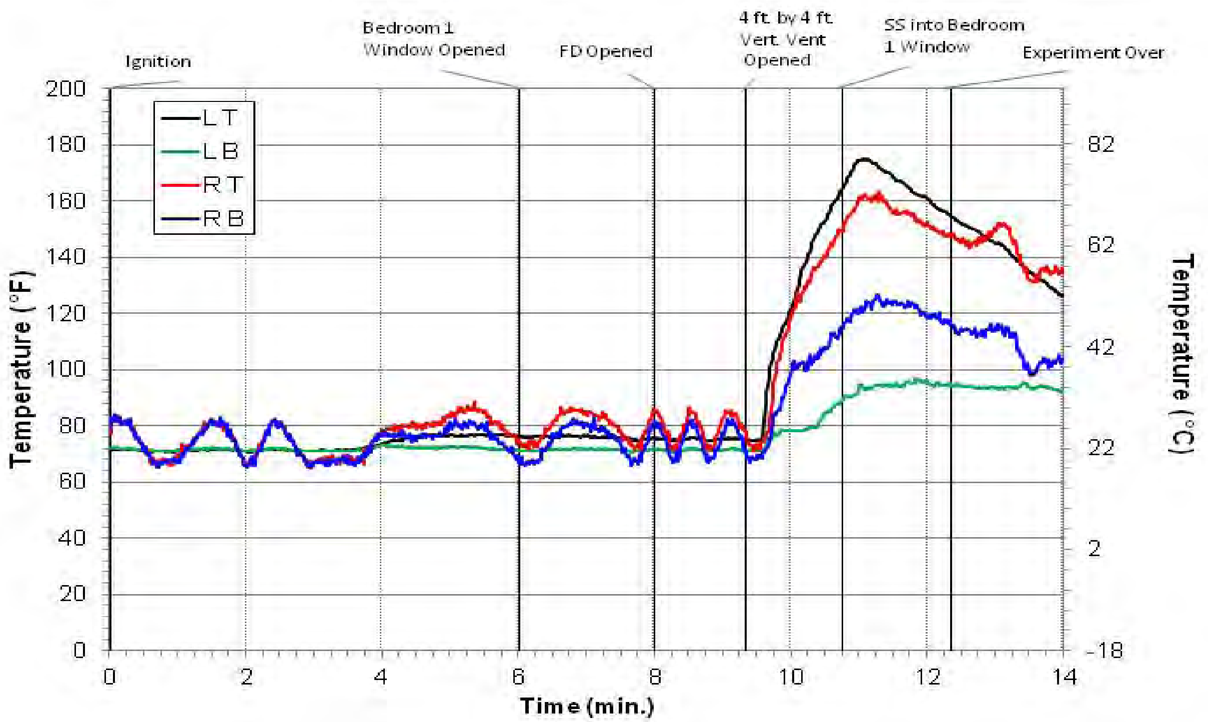


Figure E.233: Experiment 11 Attic Temperature

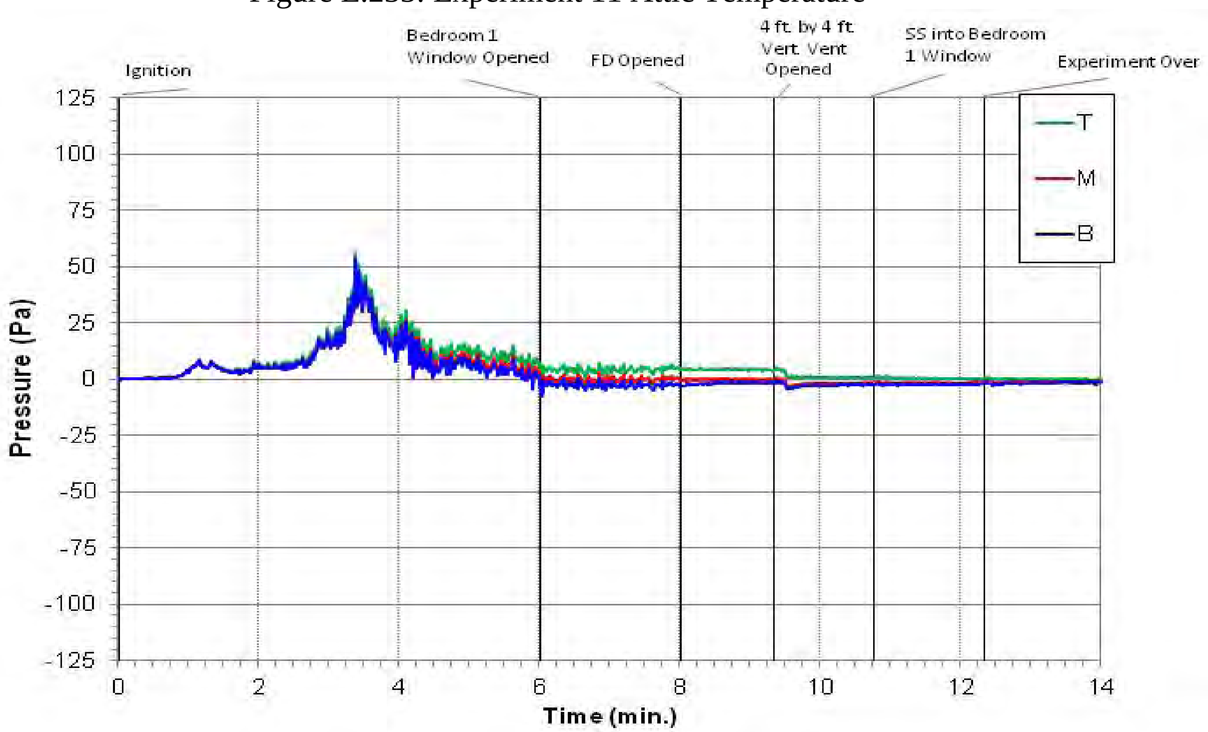


Figure E.234: Experiment 11 Living Room Pressure

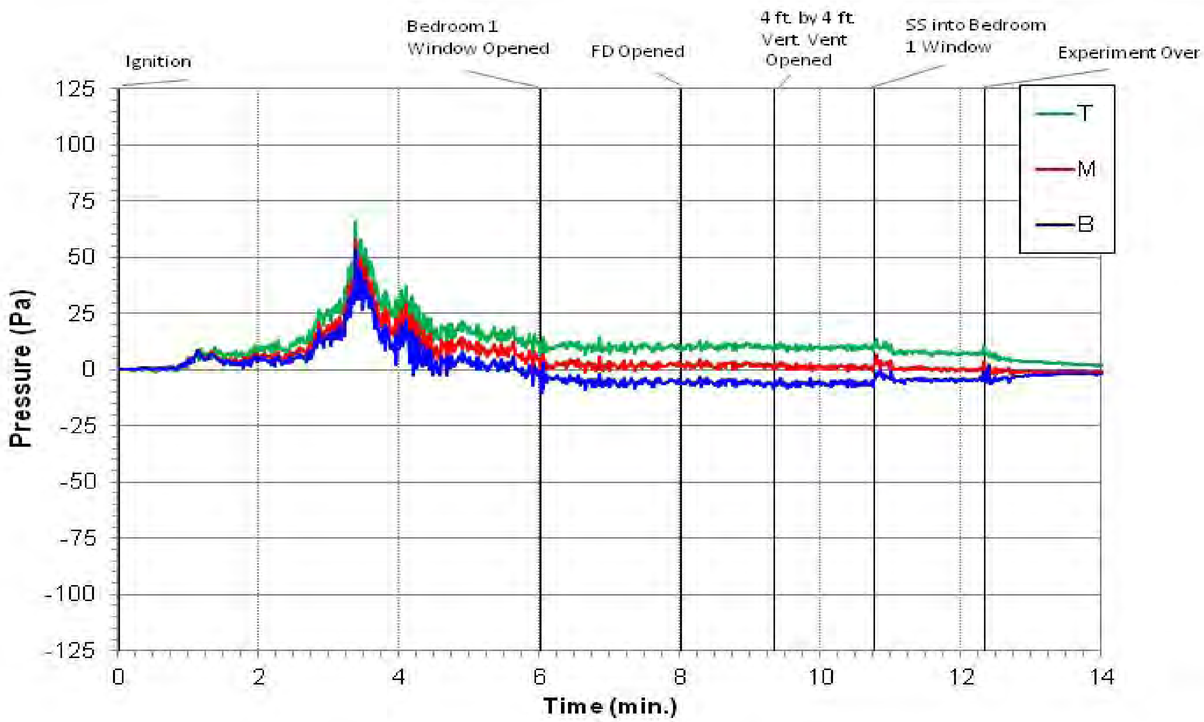


Figure E.235: Experiment 11 Bedroom 1 Pressure

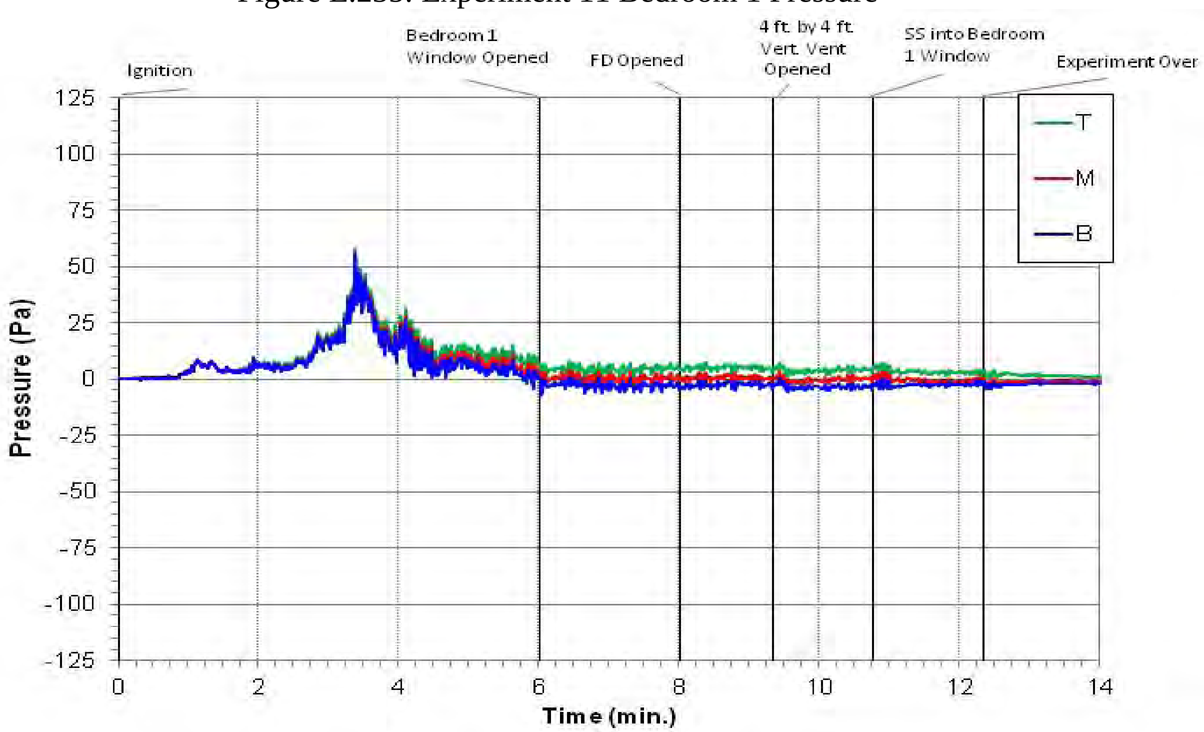


Figure E.236: Experiment 11 Bedroom 2 Pressure

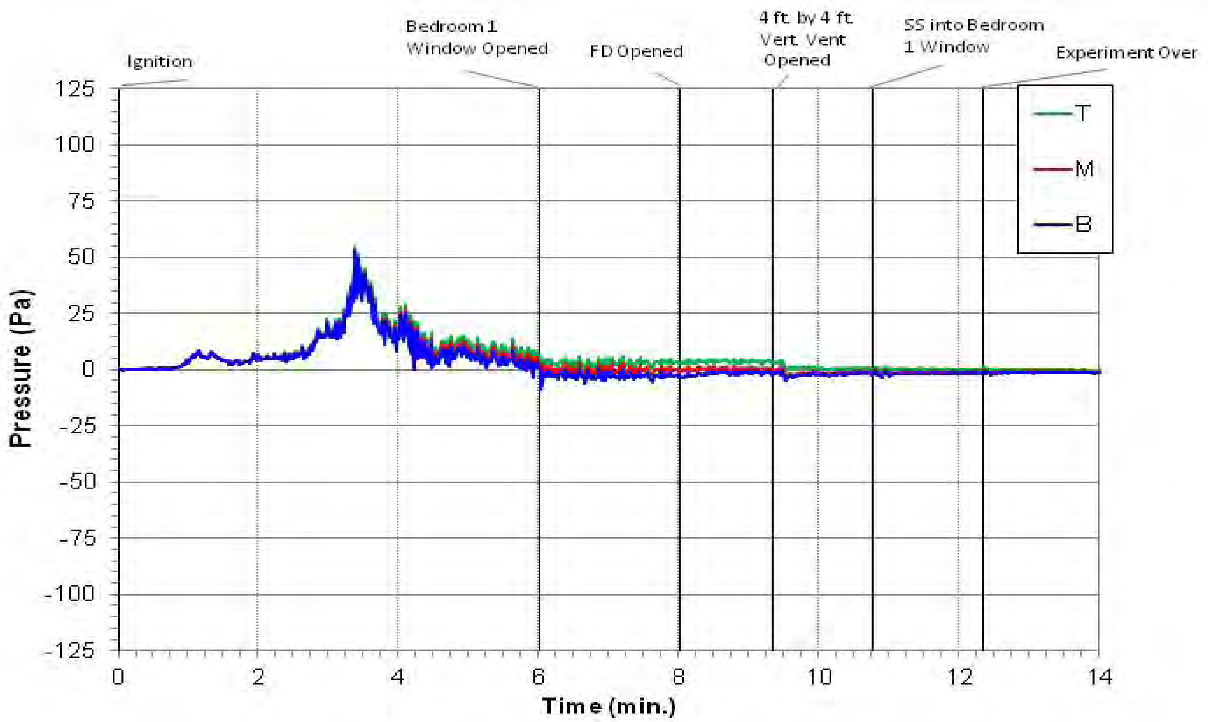


Figure E.237: Experiment 11 Kitchen Pressure

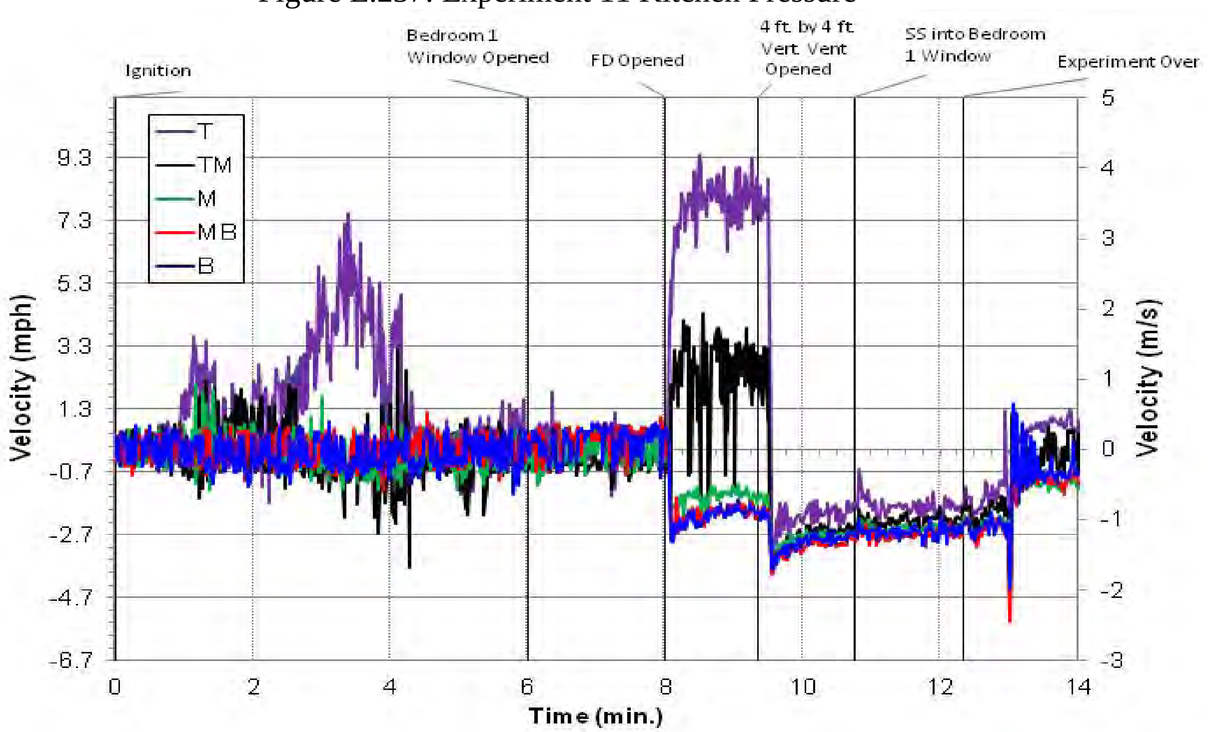


Figure E.238: Experiment 11 Front Door Velocity

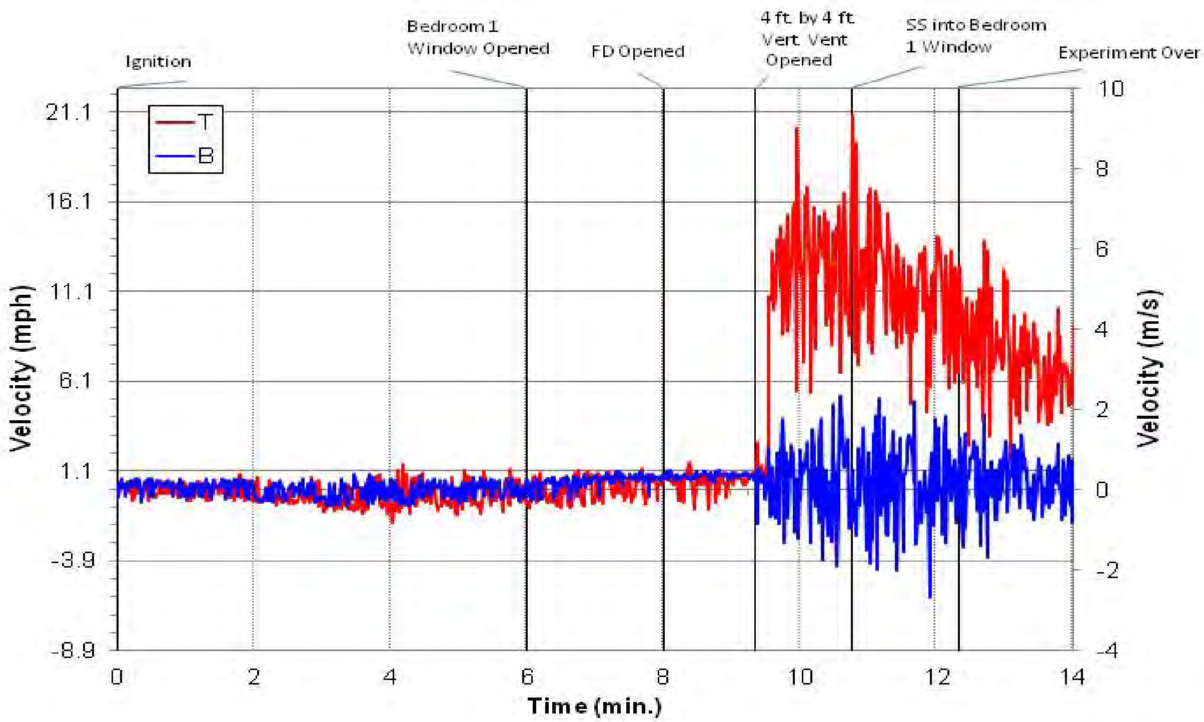


Figure E.239: Experiment 11 Vent Velocity

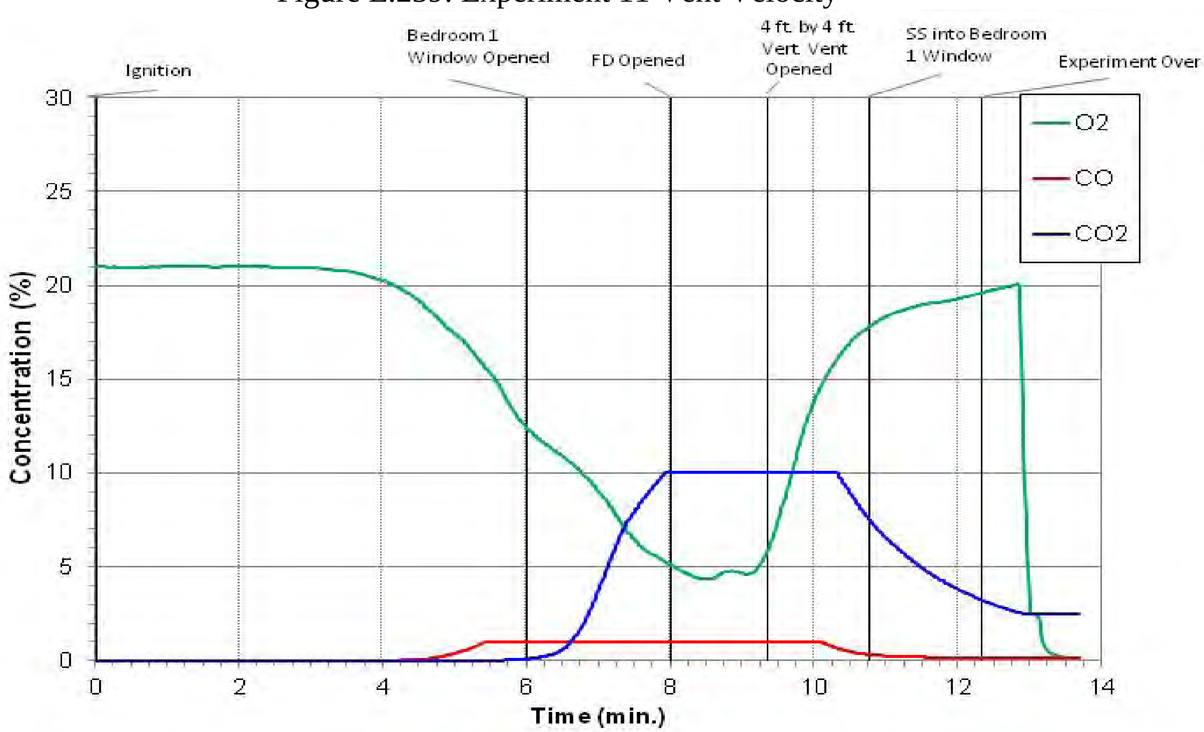


Figure E.240: Experiment 11 Living Room Gas

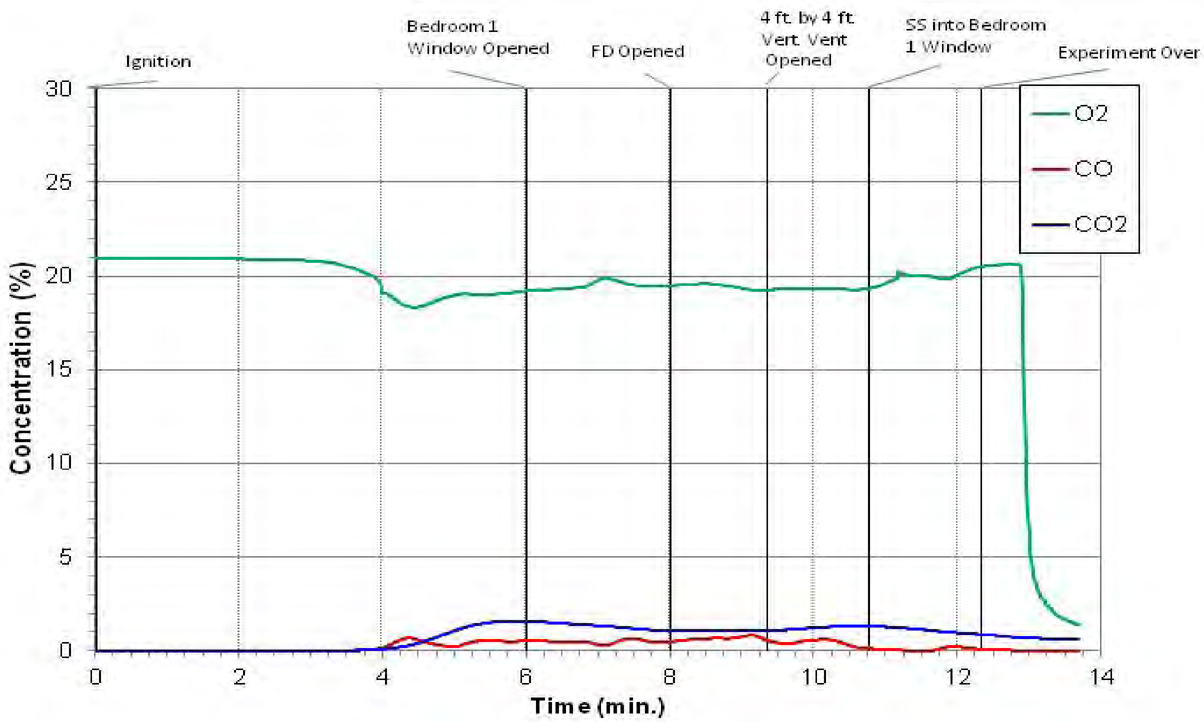


Figure E.241: Experiment 11 Bedroom 1 Gas

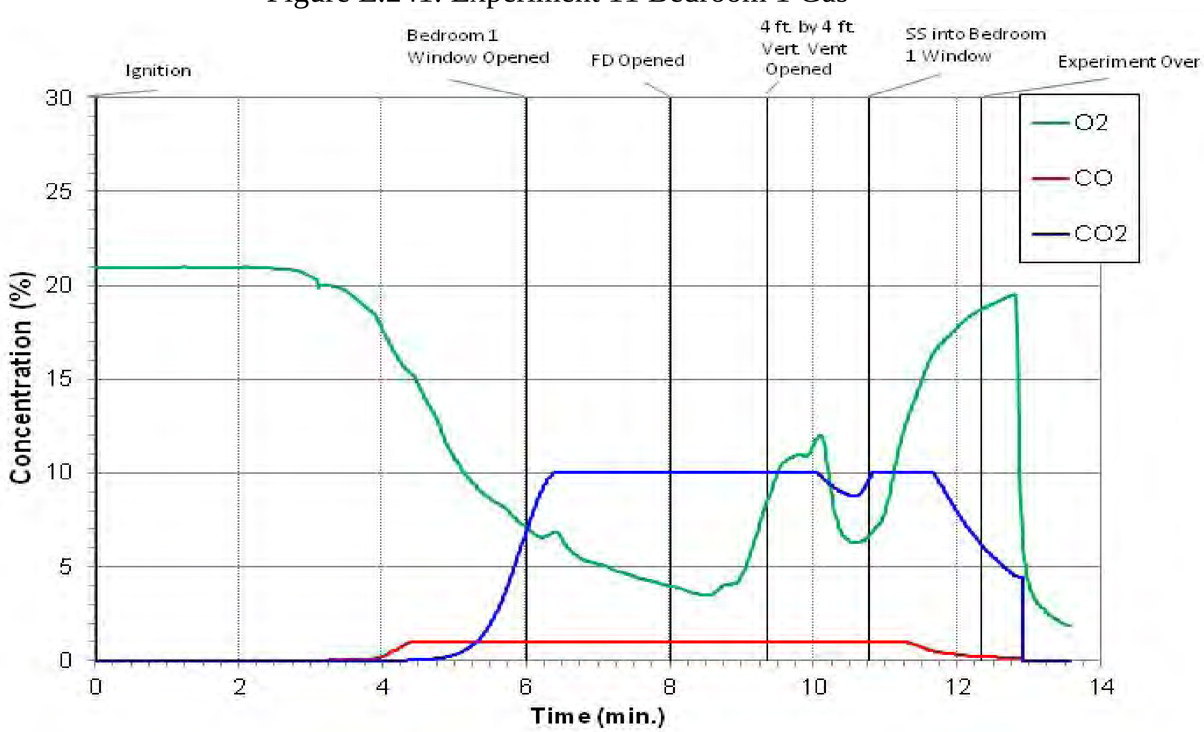


Figure E.242: Experiment 11 Bedroom 2 Gas

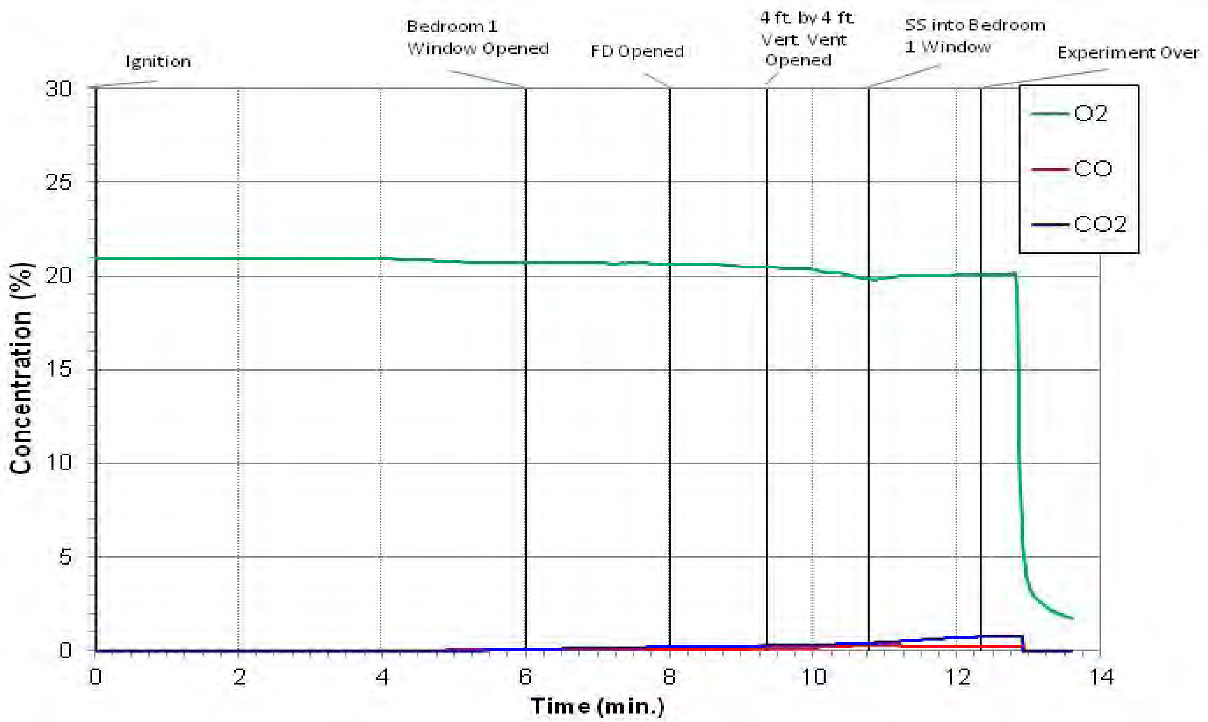


Figure E.243: Experiment 11 Bedroom 3 Gas

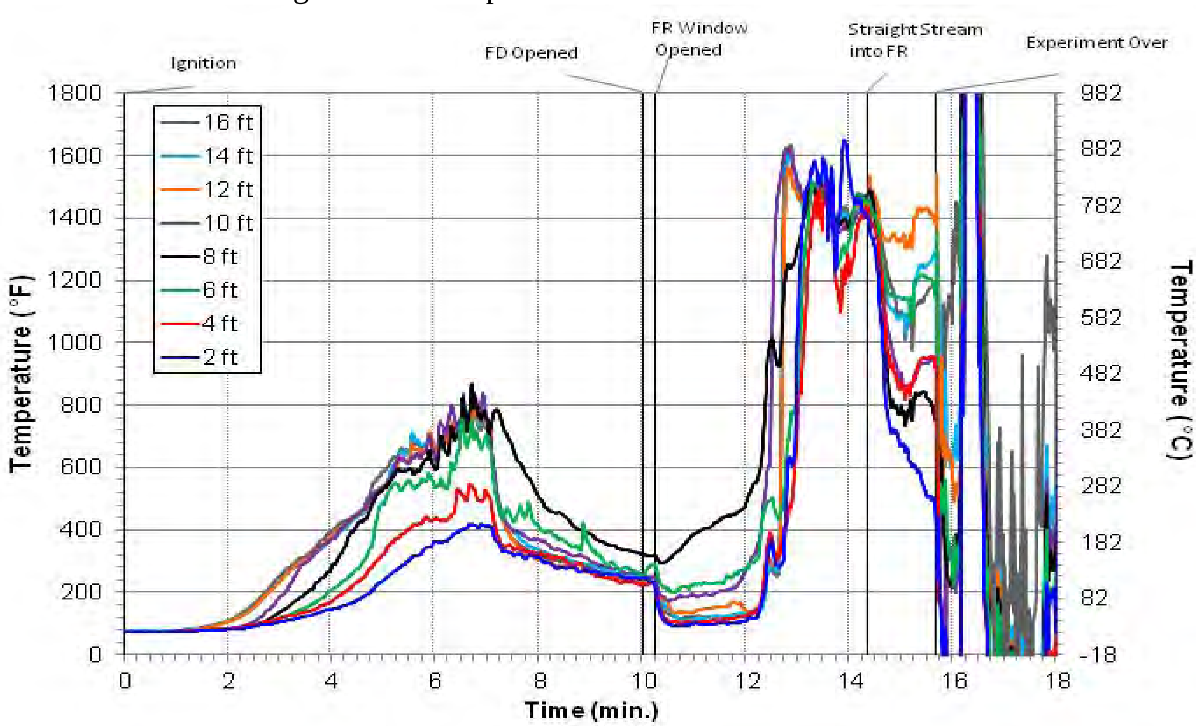


Figure E.244: Experiment 12 Family Room Temperature

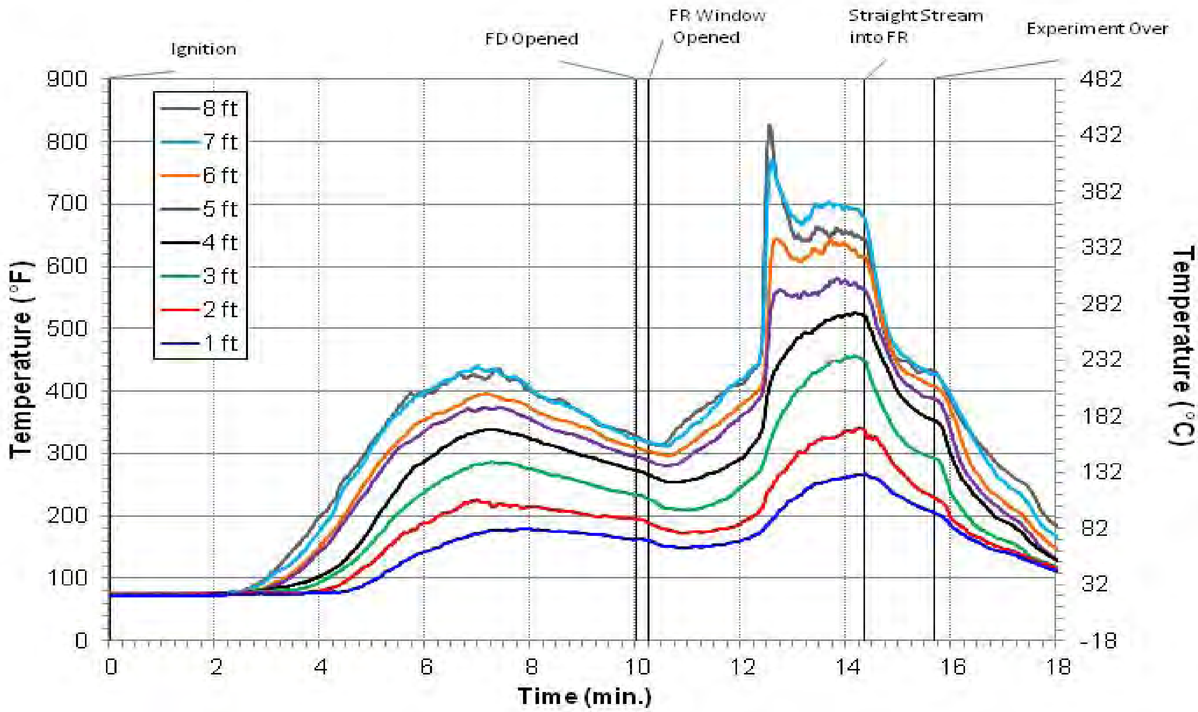


Figure E.245: Experiment 12 Kitchen Temperature

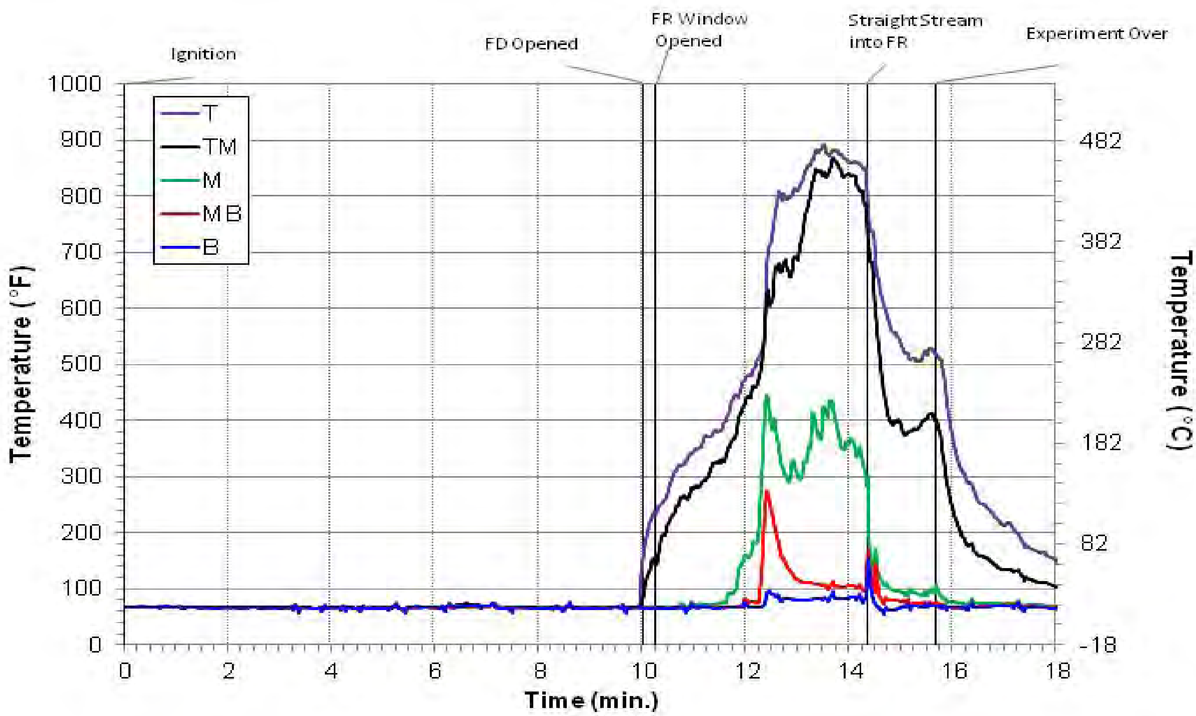


Figure E.246: Experiment 12 Front Door Temperature

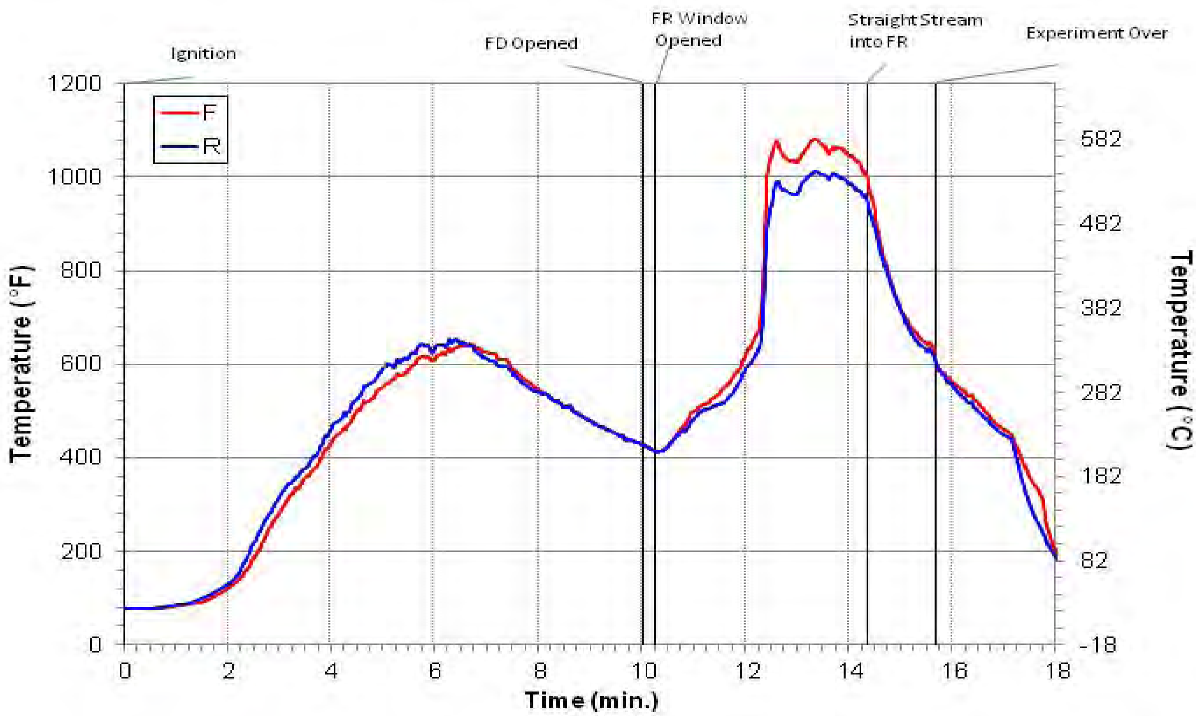


Figure E.247: Experiment 12 Vent Temperature

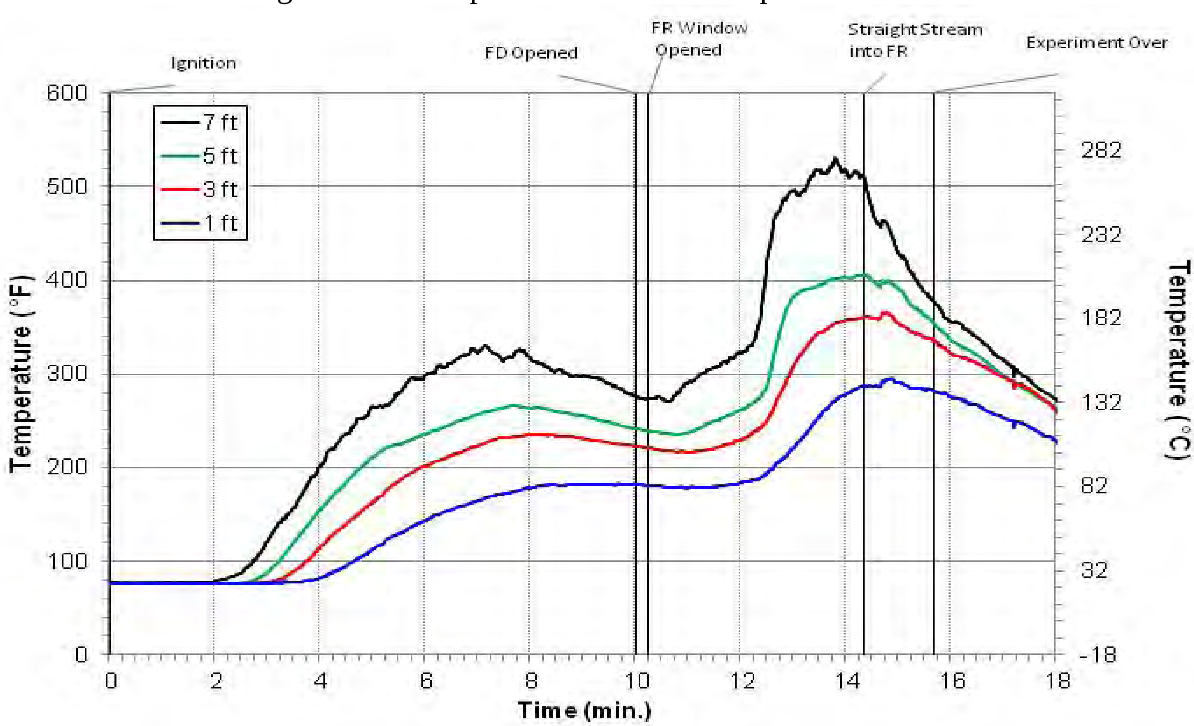


Figure E.248: Experiment 12 Bedroom 1 Temperature

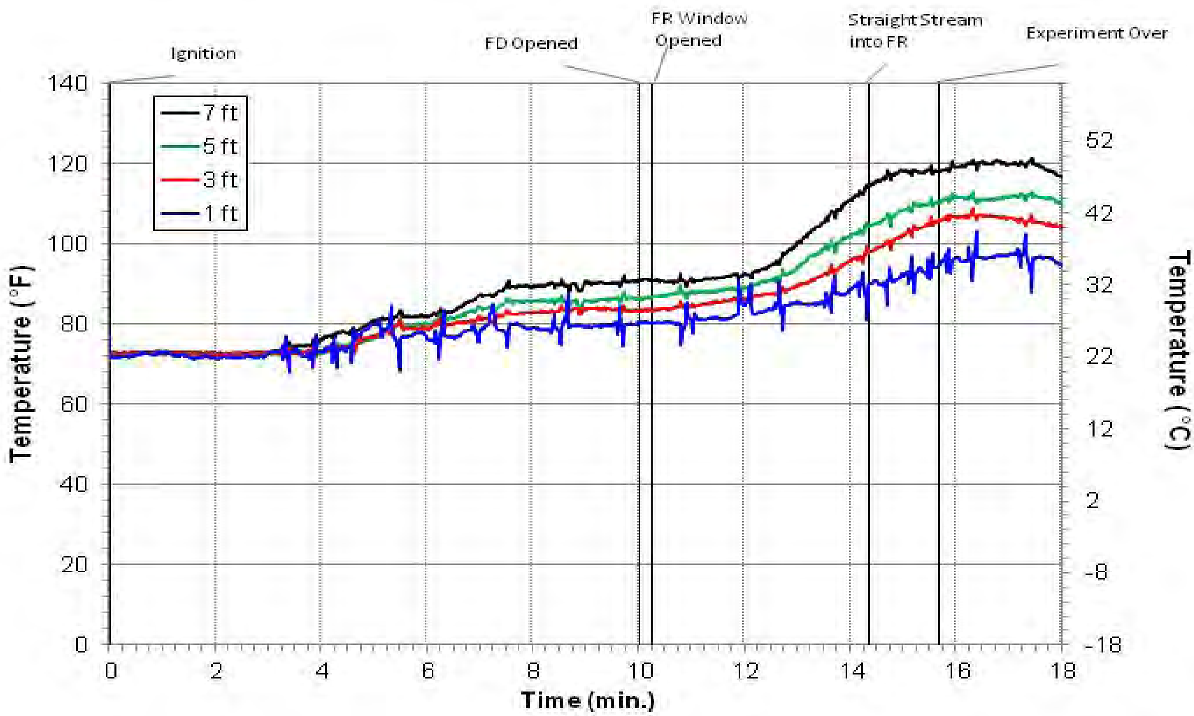


Figure E.249: Experiment 12 Bedroom 2 Temperature

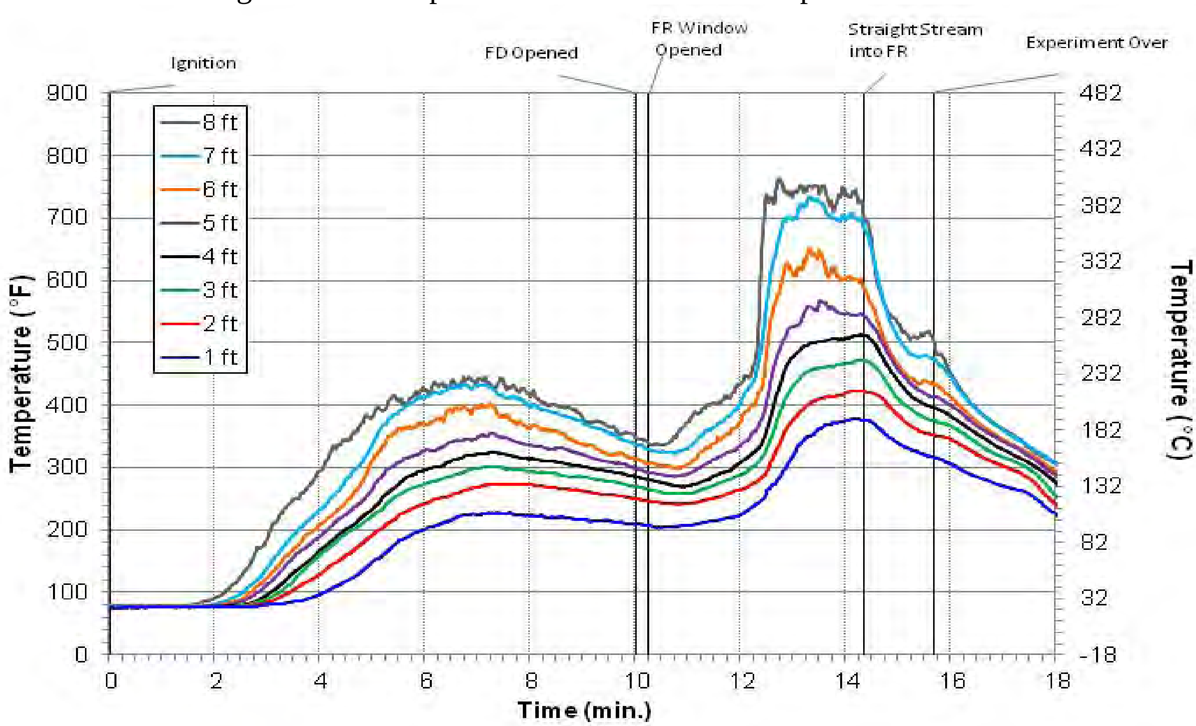


Figure E.250: Experiment 12 Bedroom 3 Temperature

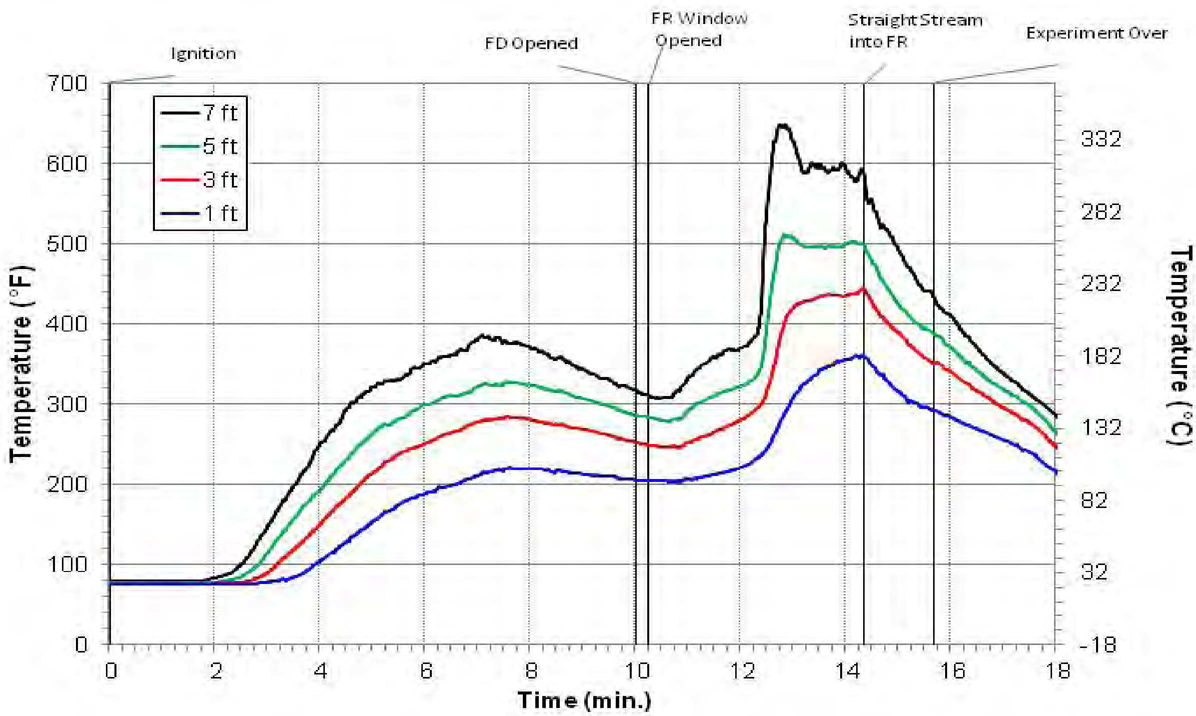


Figure E.251: Experiment 12 Bedroom 4 Temperature

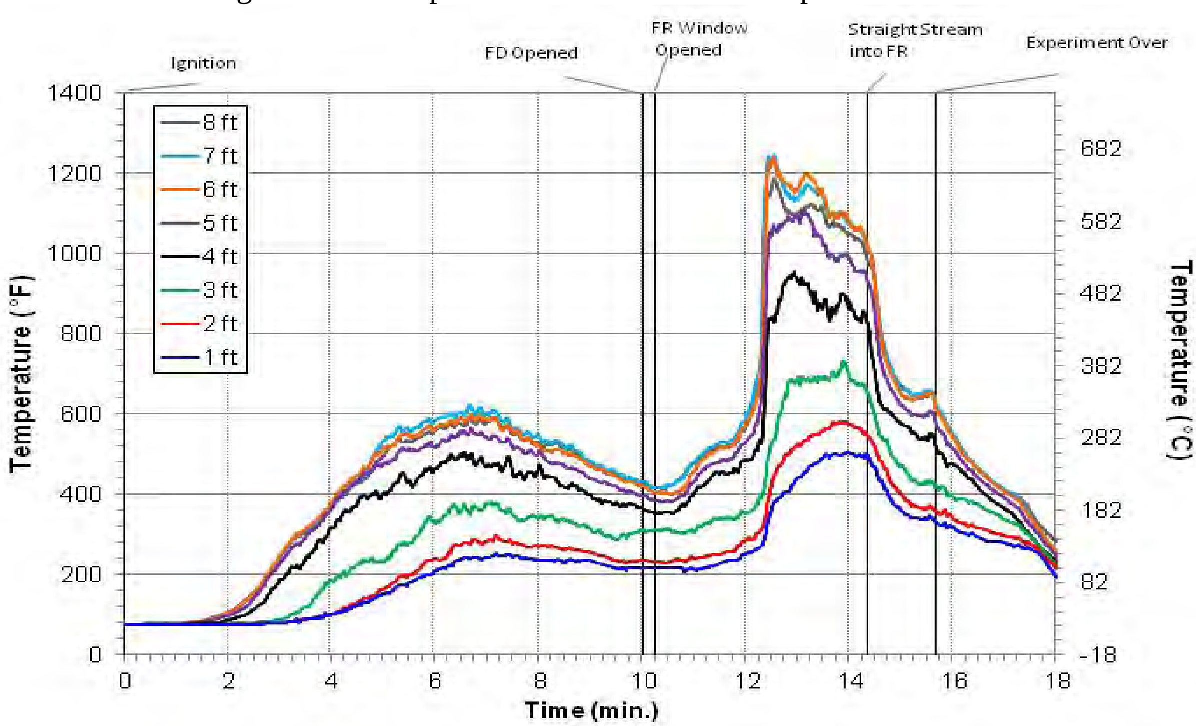


Figure E.252: Experiment 12 Hallway Temperature

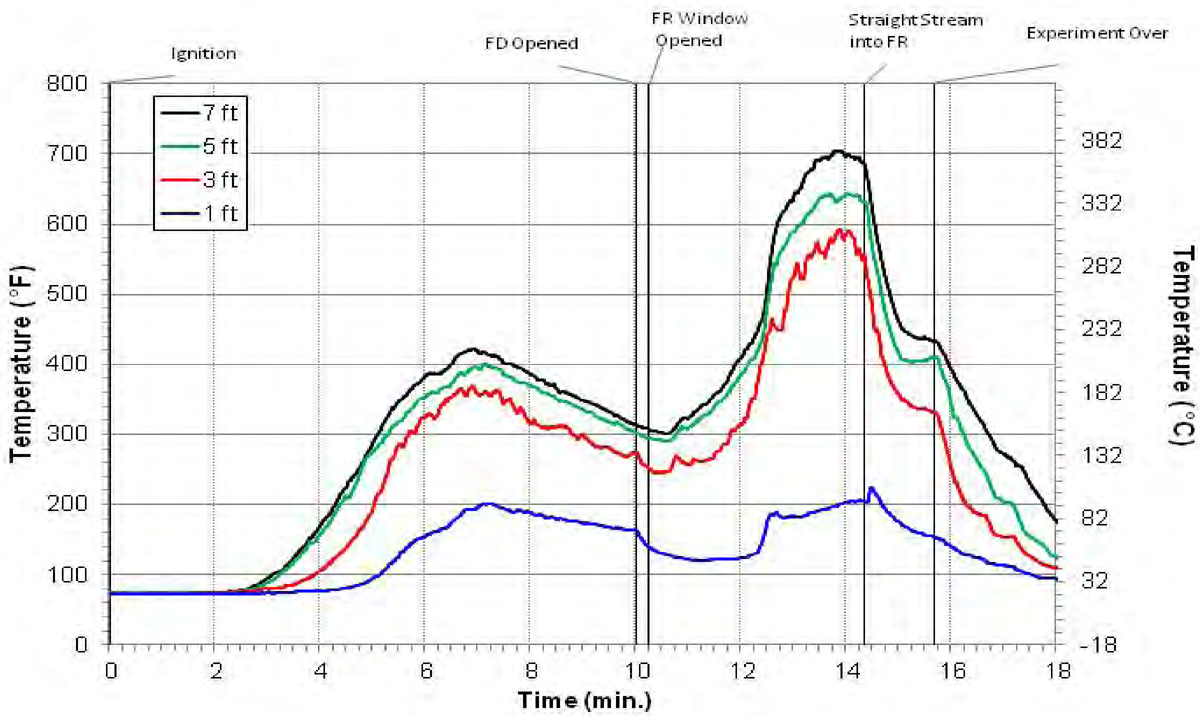


Figure E.253: Experiment 12 Dining Room Temperature

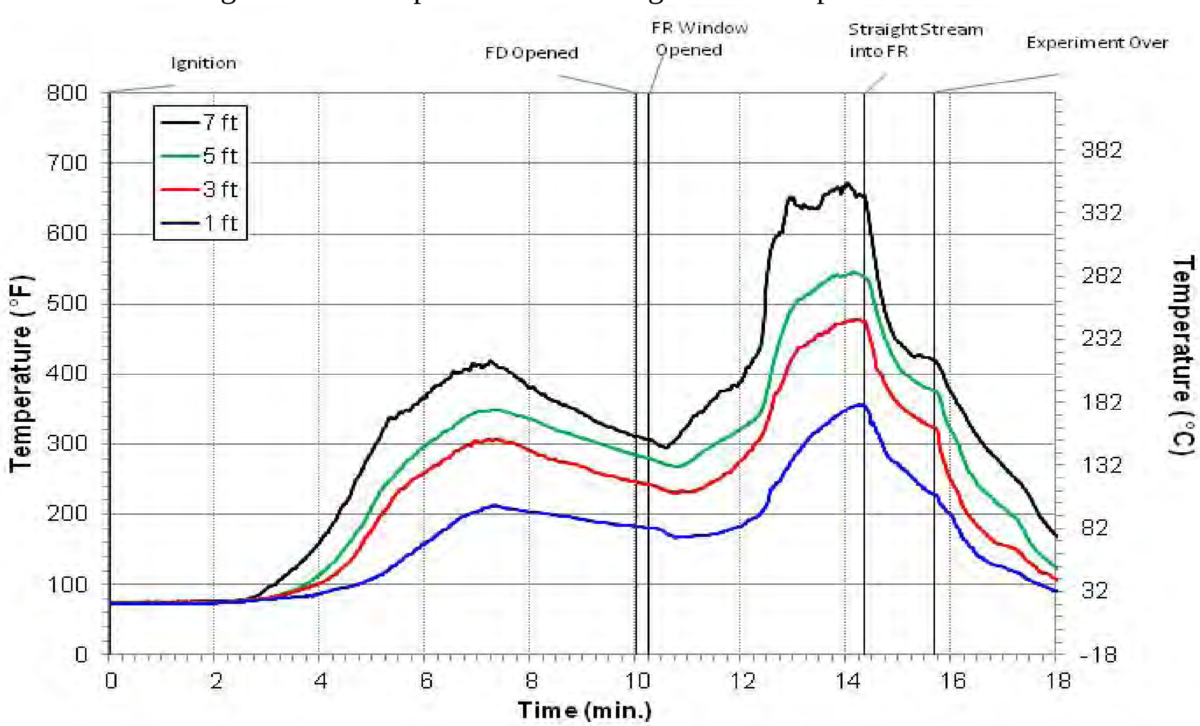


Figure E.254: Experiment 12 Living Room Temperature

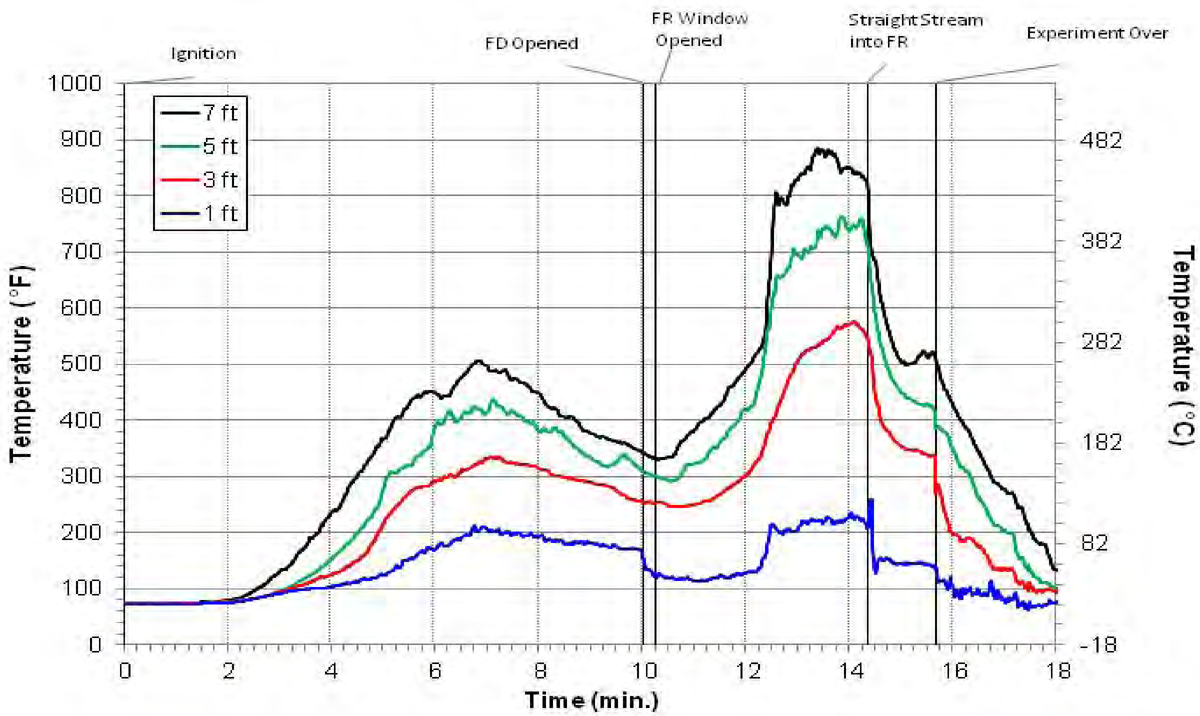


Figure E.255: Experiment 12 Foyer Temperature

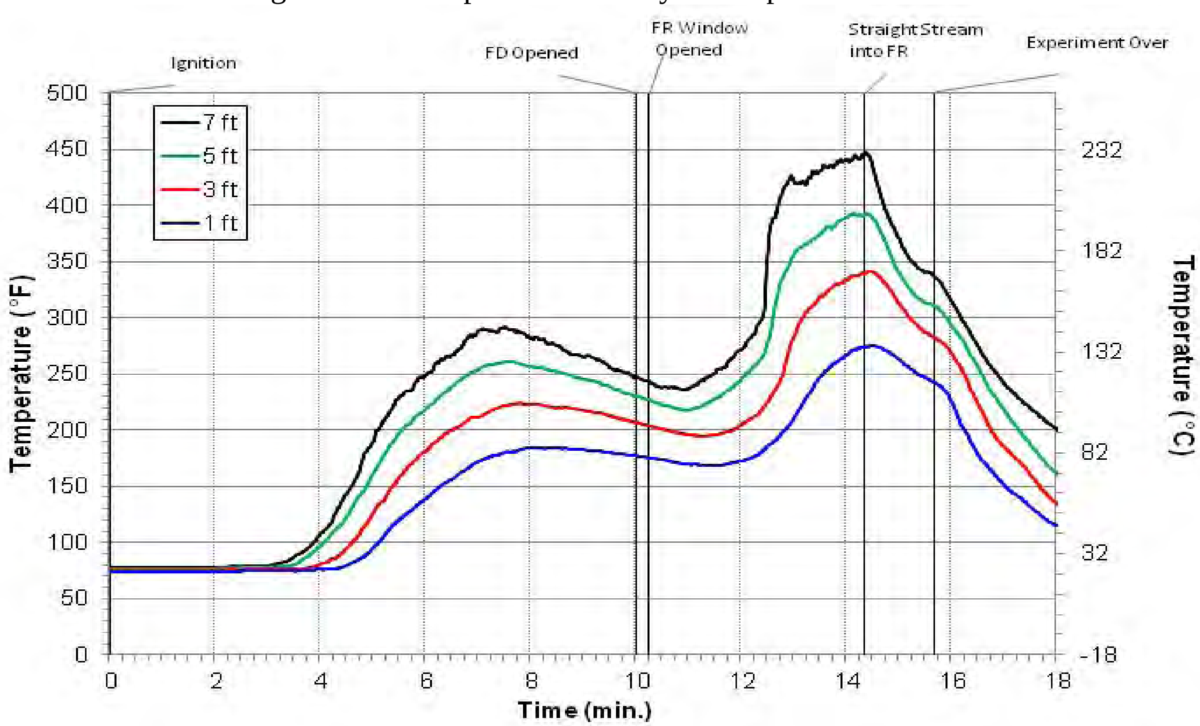


Figure E.256: Experiment 12 Den Temperature

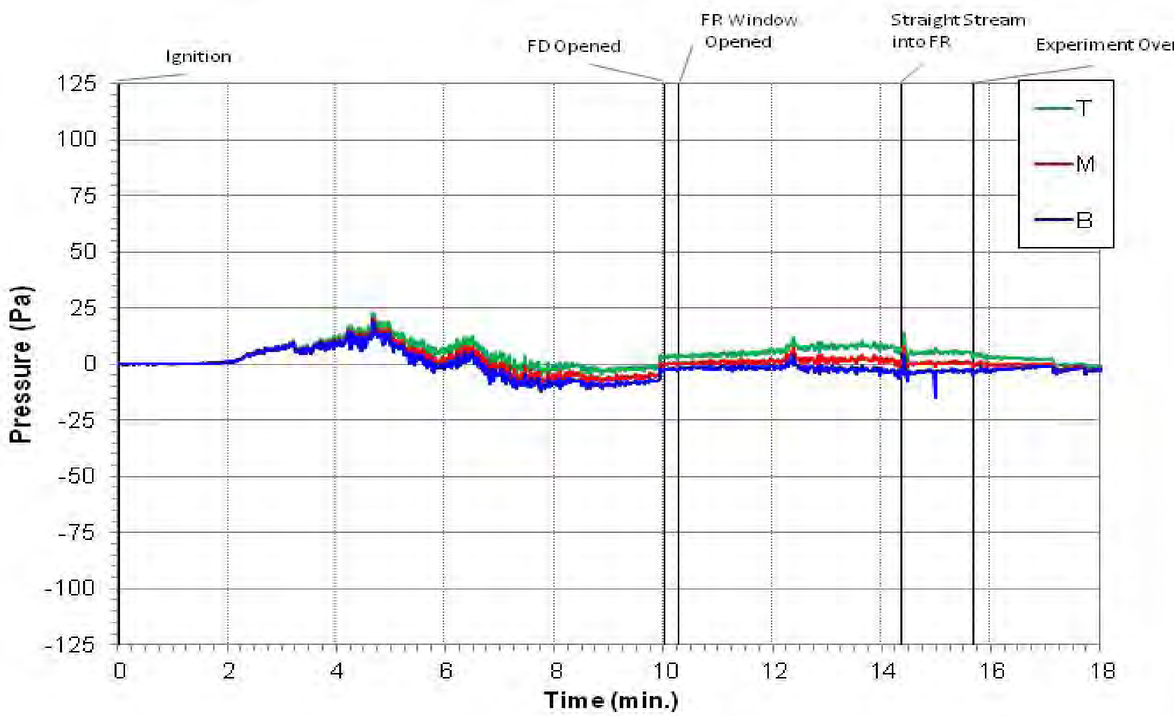


Figure E.257: Experiment 12 Living Room Pressure

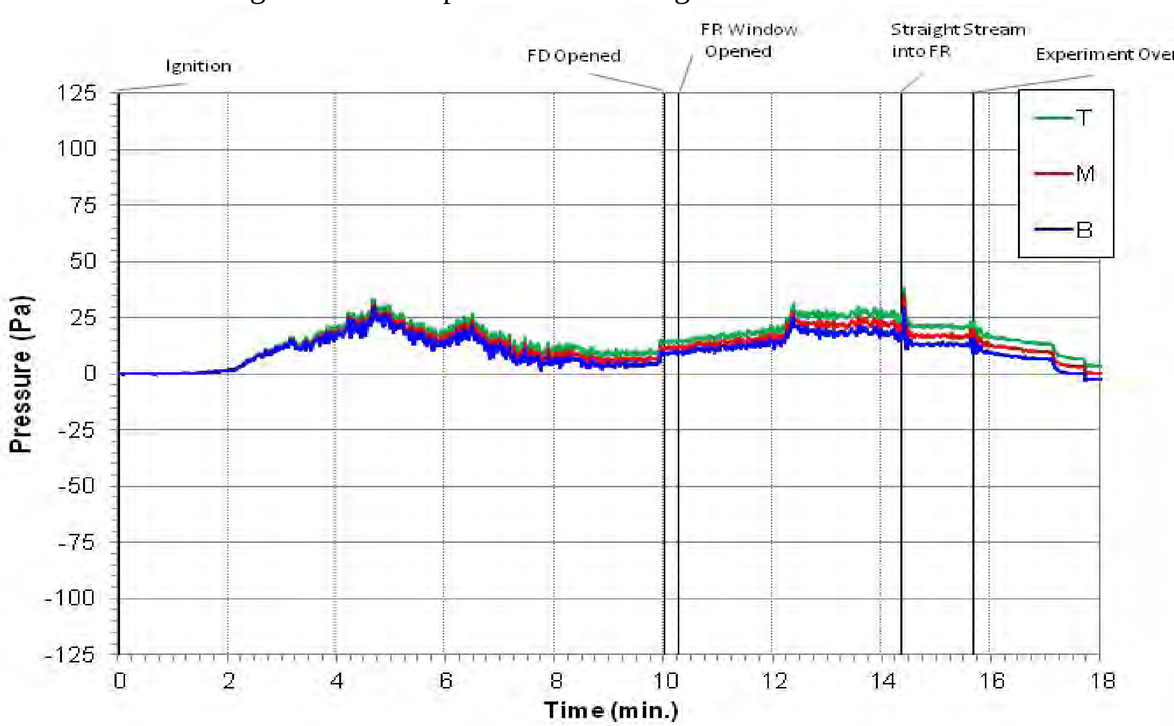


Figure E.258: Experiment 12 Bedroom 2 Pressure

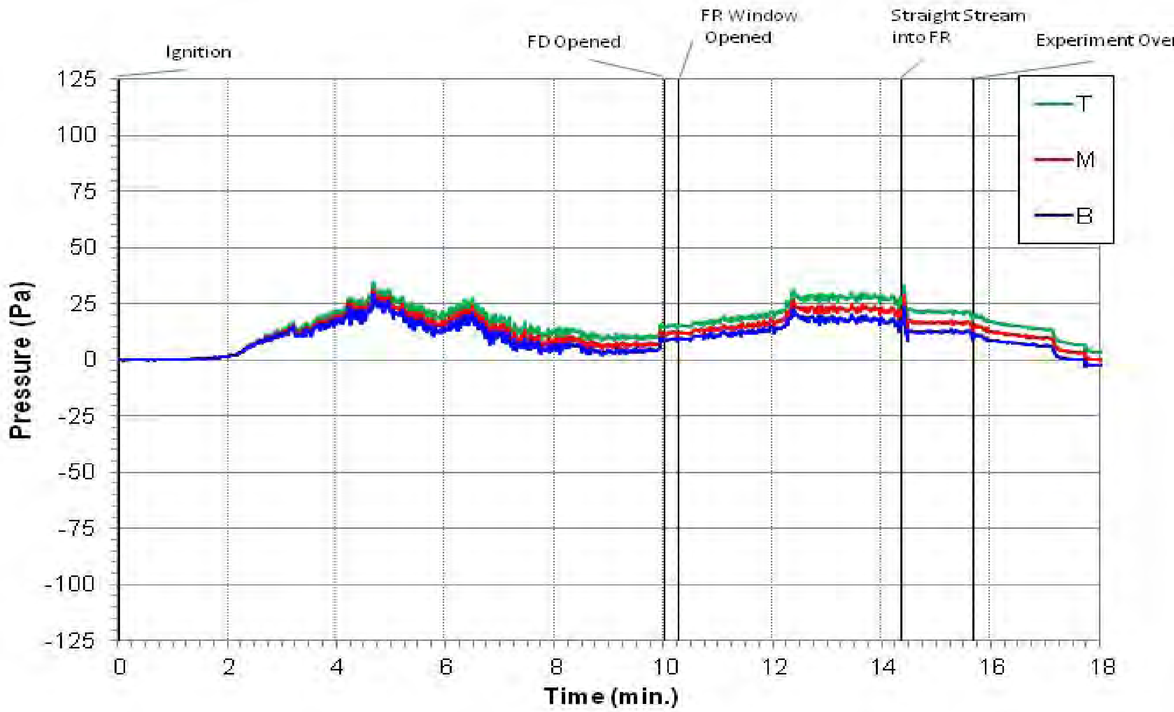


Figure E.259: Experiment 12 Bedroom 3 Pressure

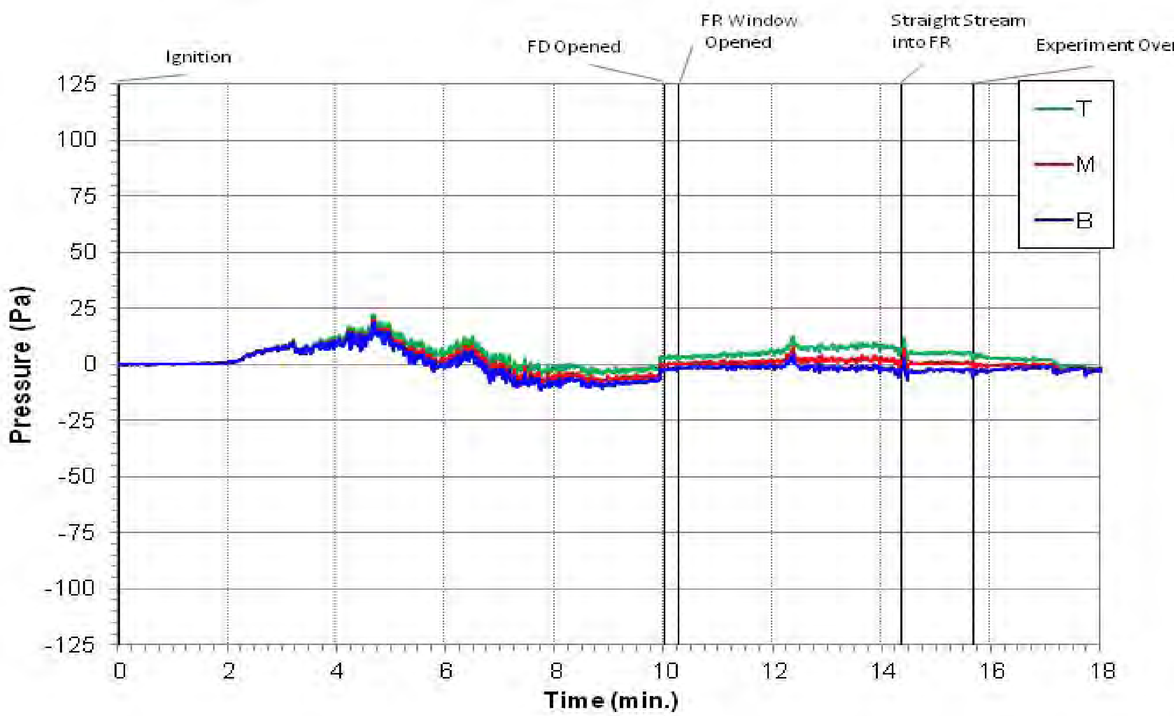


Figure E.260: Experiment 12 Kitchen Pressure

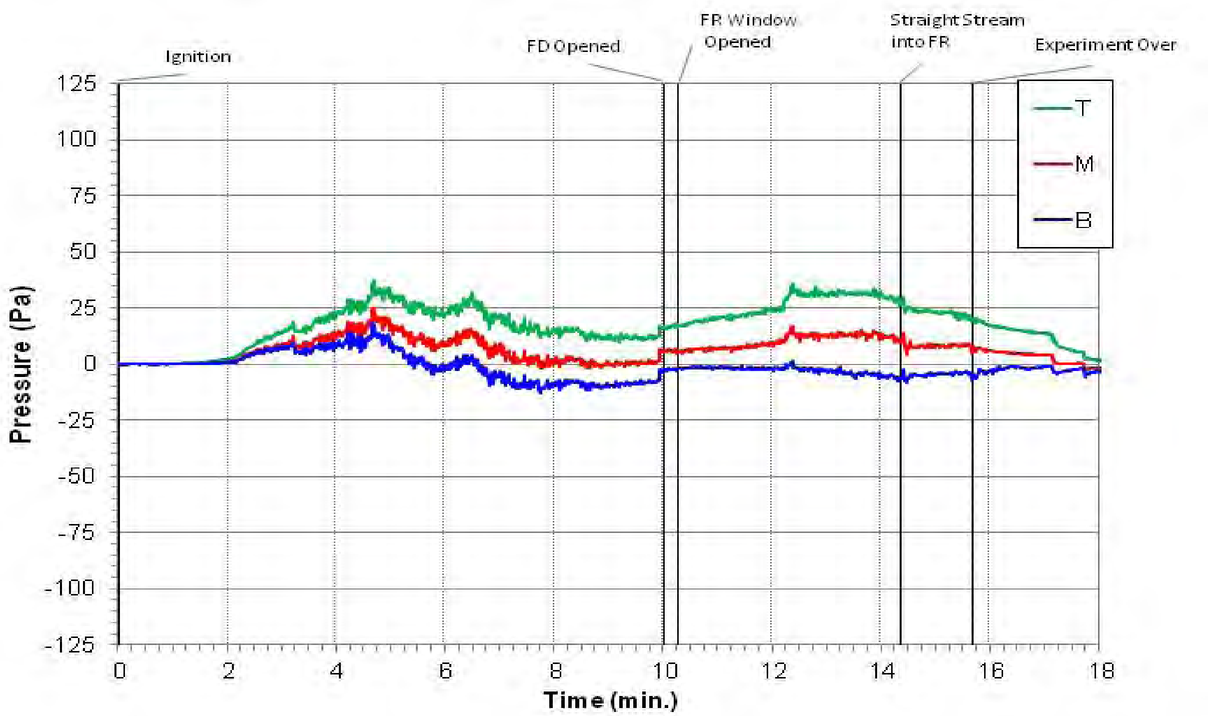


Figure E.261: Experiment 12 Family Room Pressure

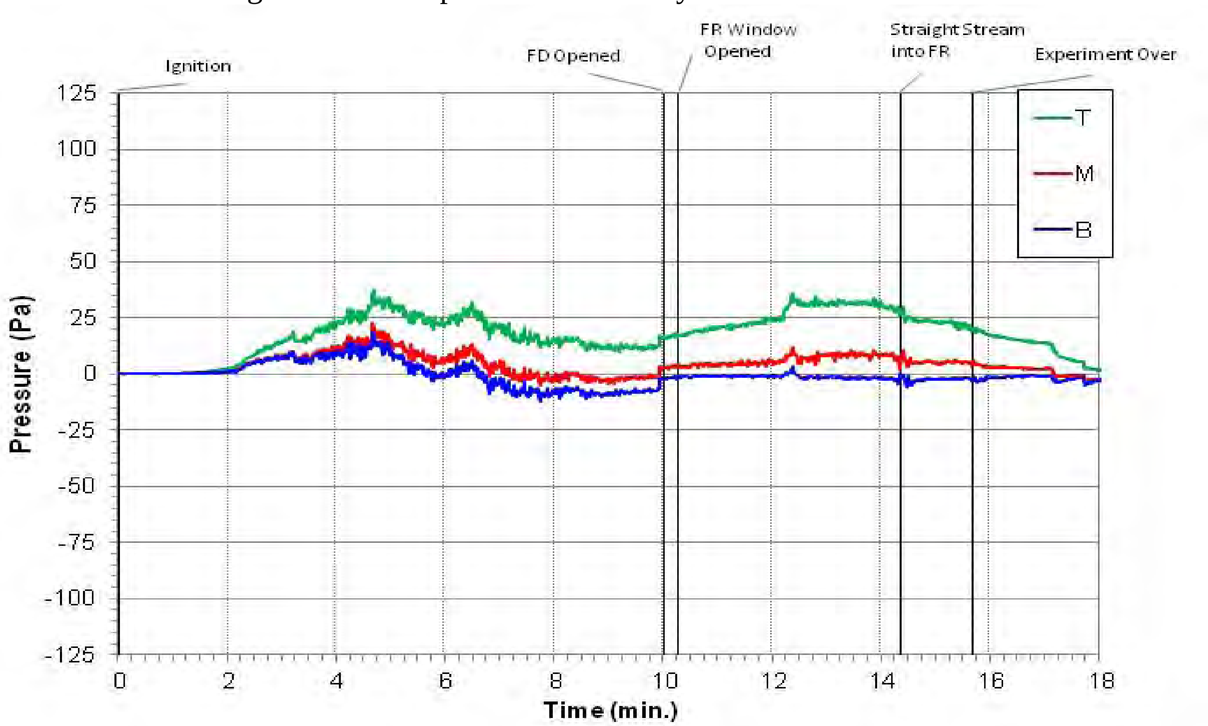


Figure E.262: Experiment 12 Foyer Pressure

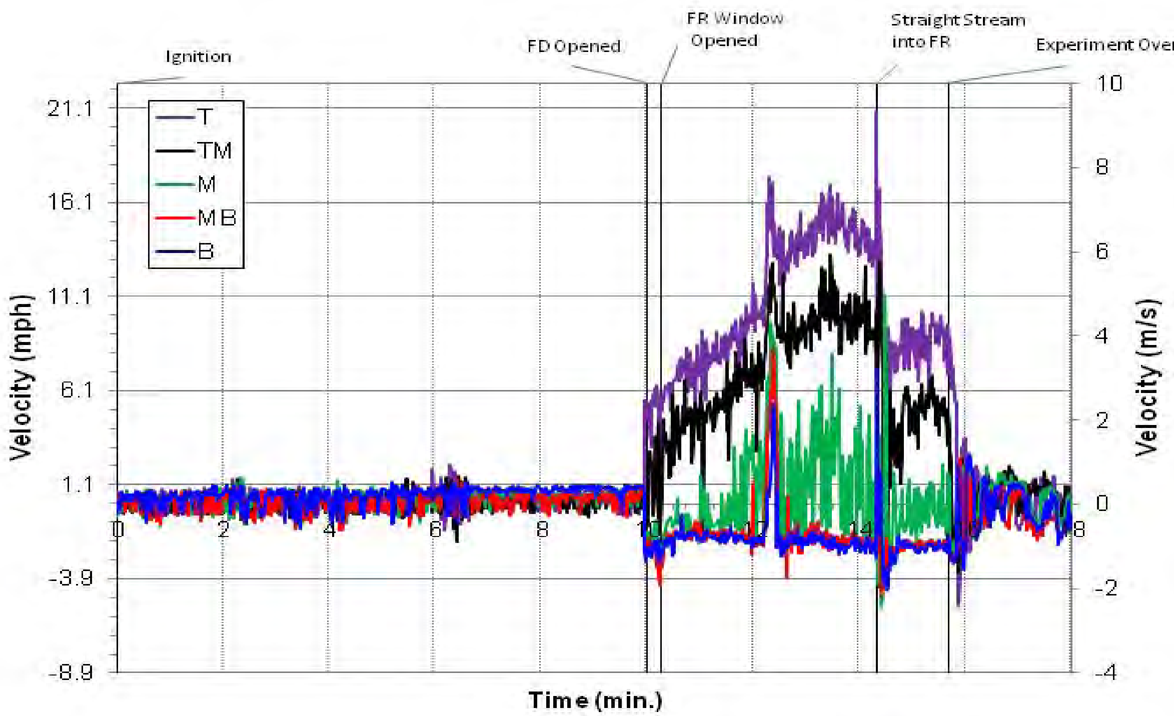


Figure E.263: Experiment 12 Front Door Velocity

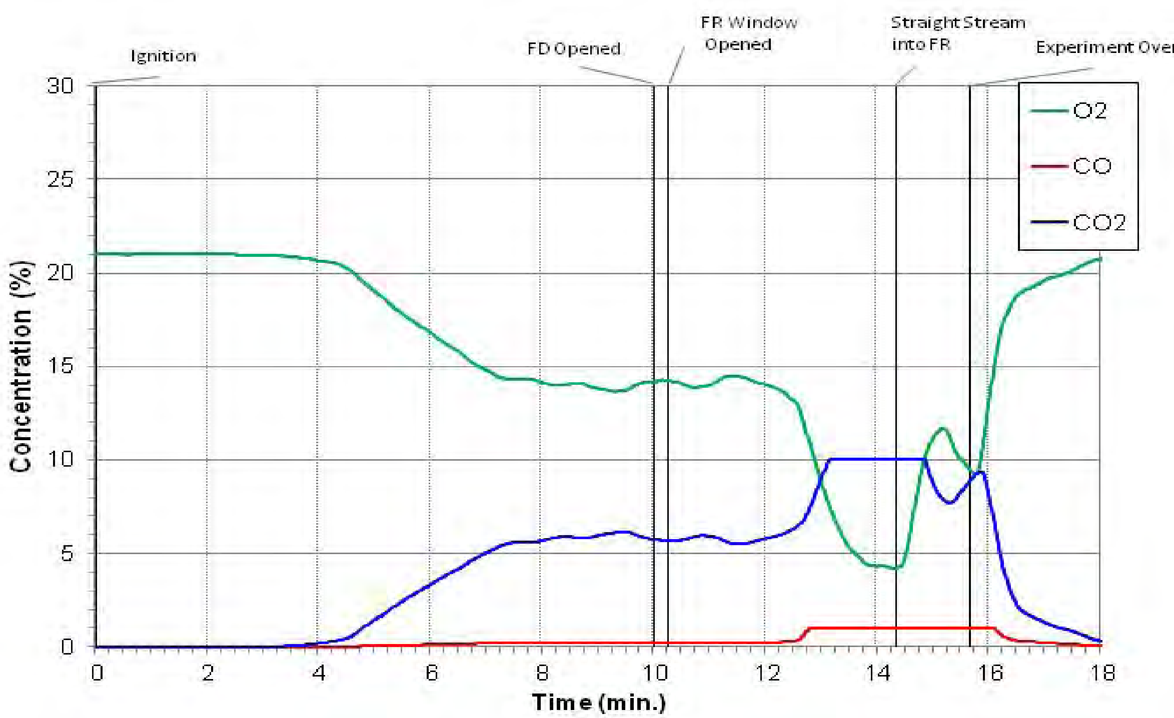


Figure E.264: Experiment 12 Front Door Gas

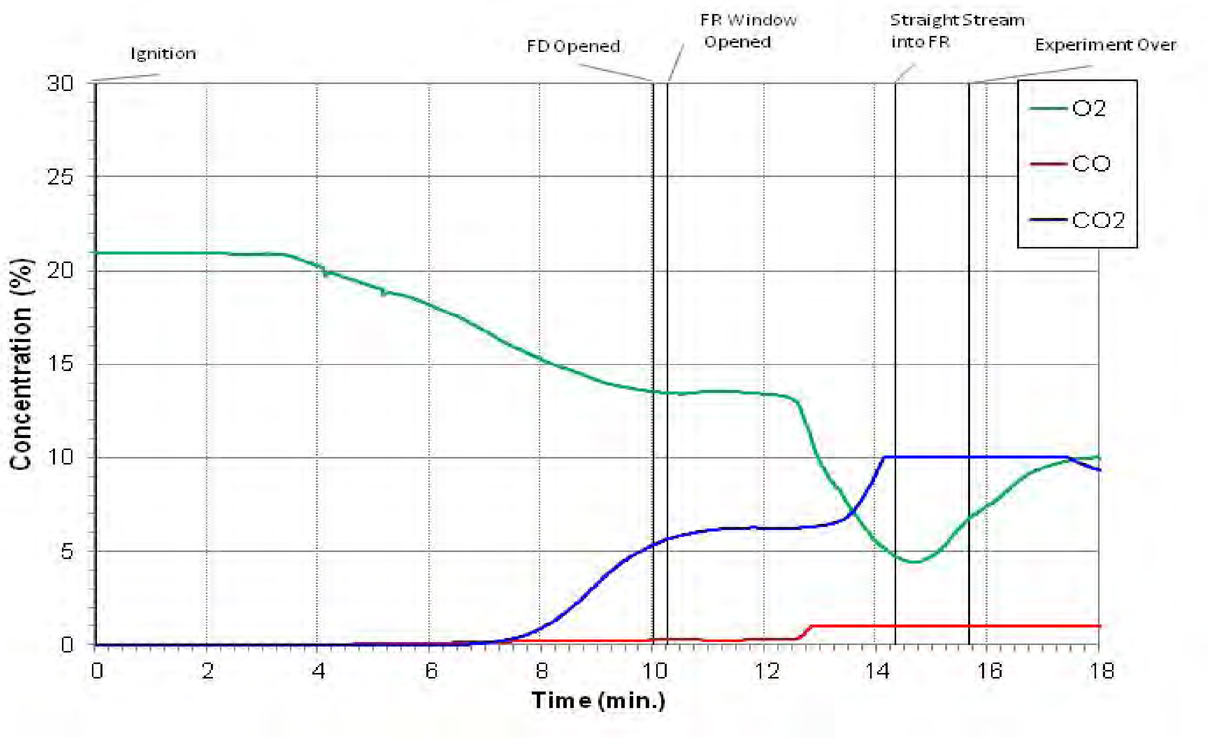


Figure E.265: Experiment 12 Bedroom 1 Gas

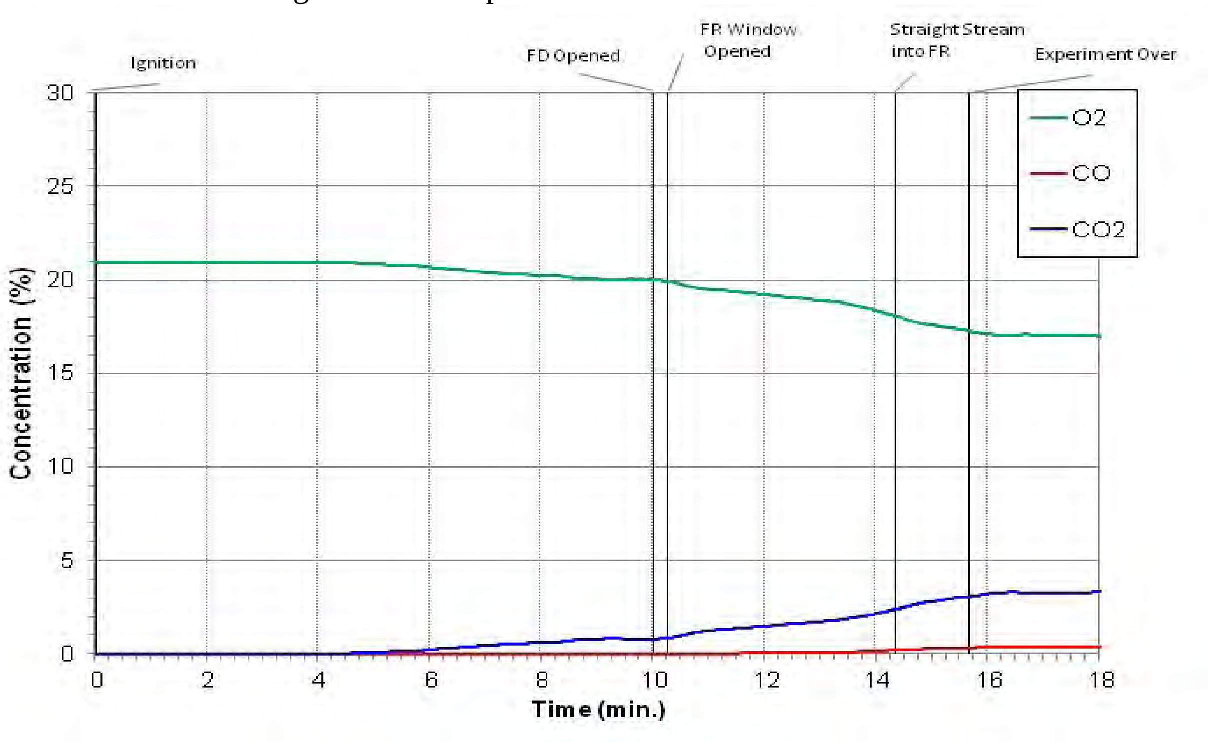


Figure E.266: Experiment 12 Bedroom 2 Gas

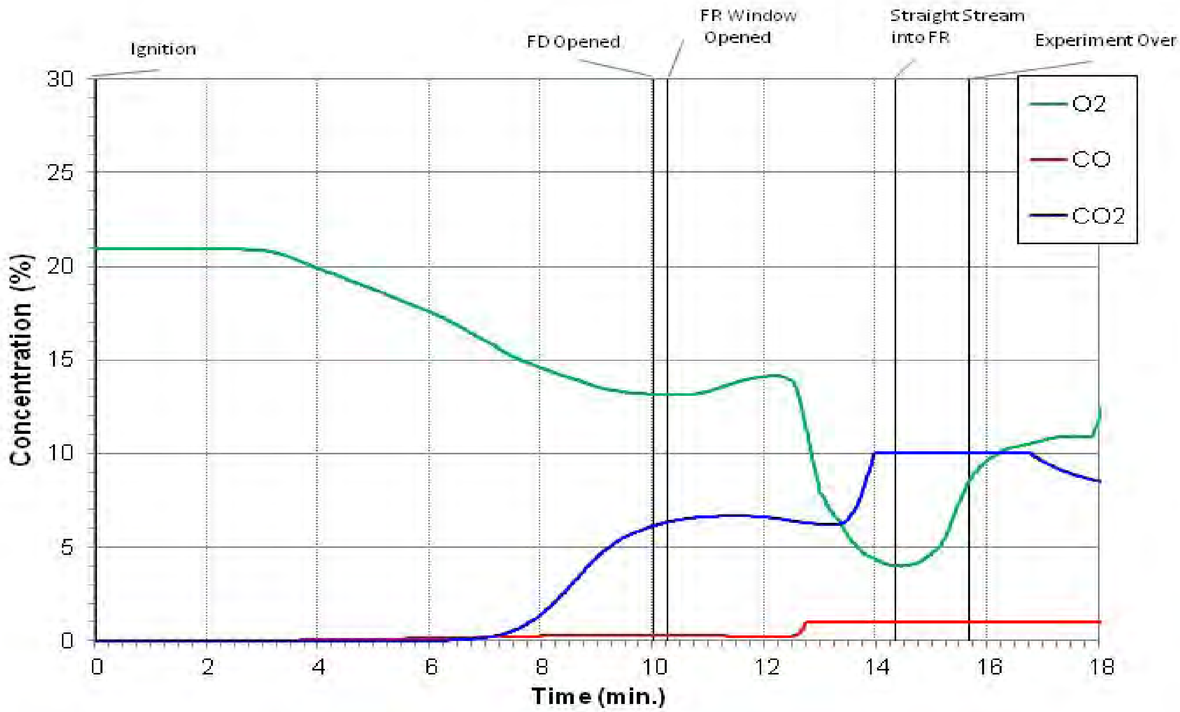


Figure E.267: Experiment 12 Bedroom 3 Gas

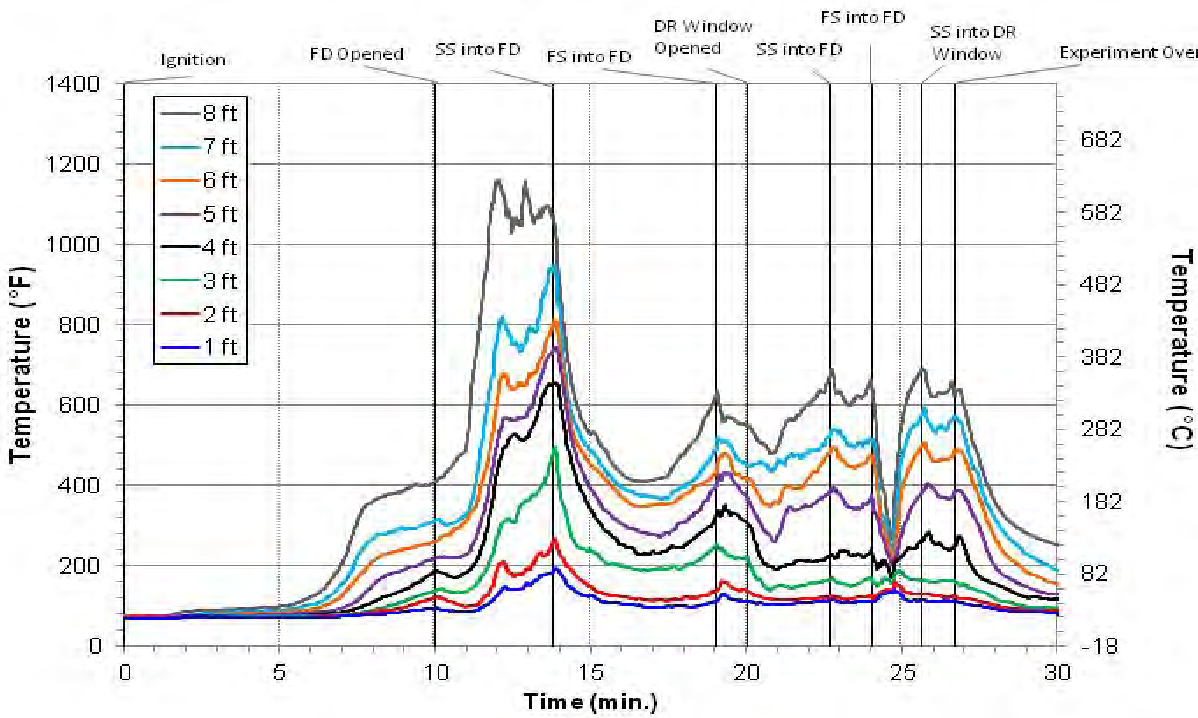


Figure E.268: Experiment 13 Living Room Temperature

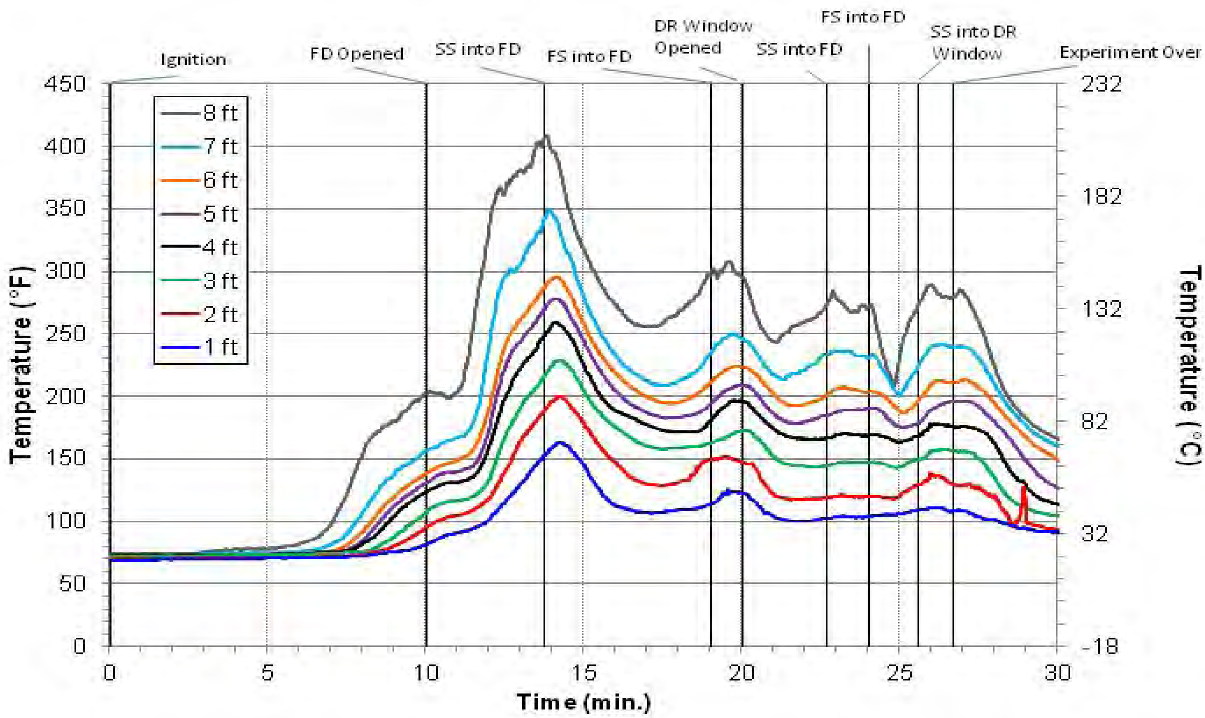


Figure E.269: Experiment 13 Bedroom 1 Temperature

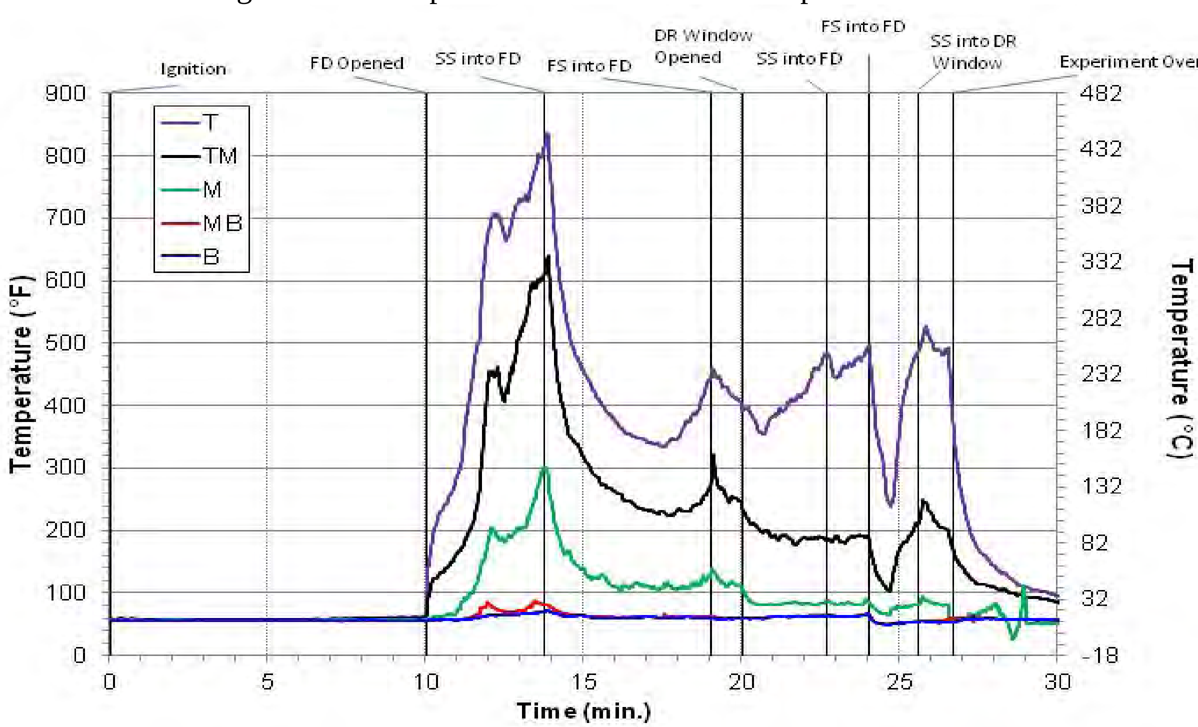


Figure E.270: Experiment 13 Front Door Temperature

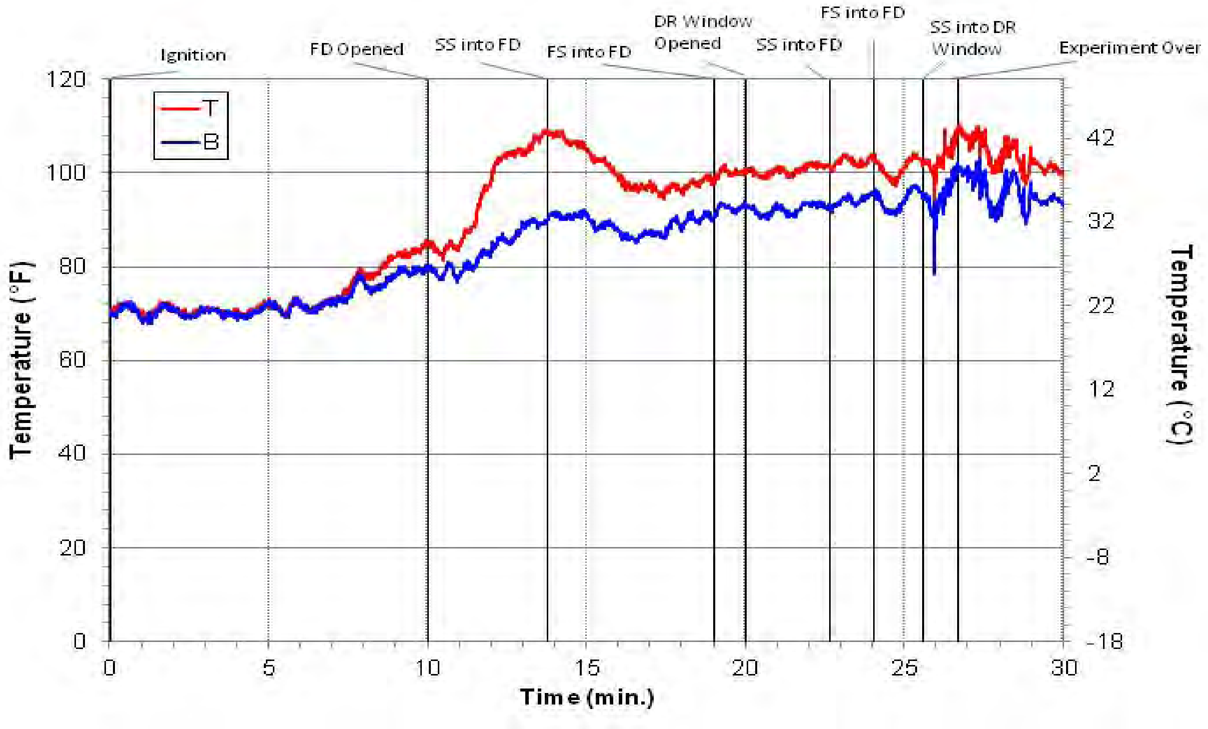


Figure E.271: Experiment 13 Vent Temperature

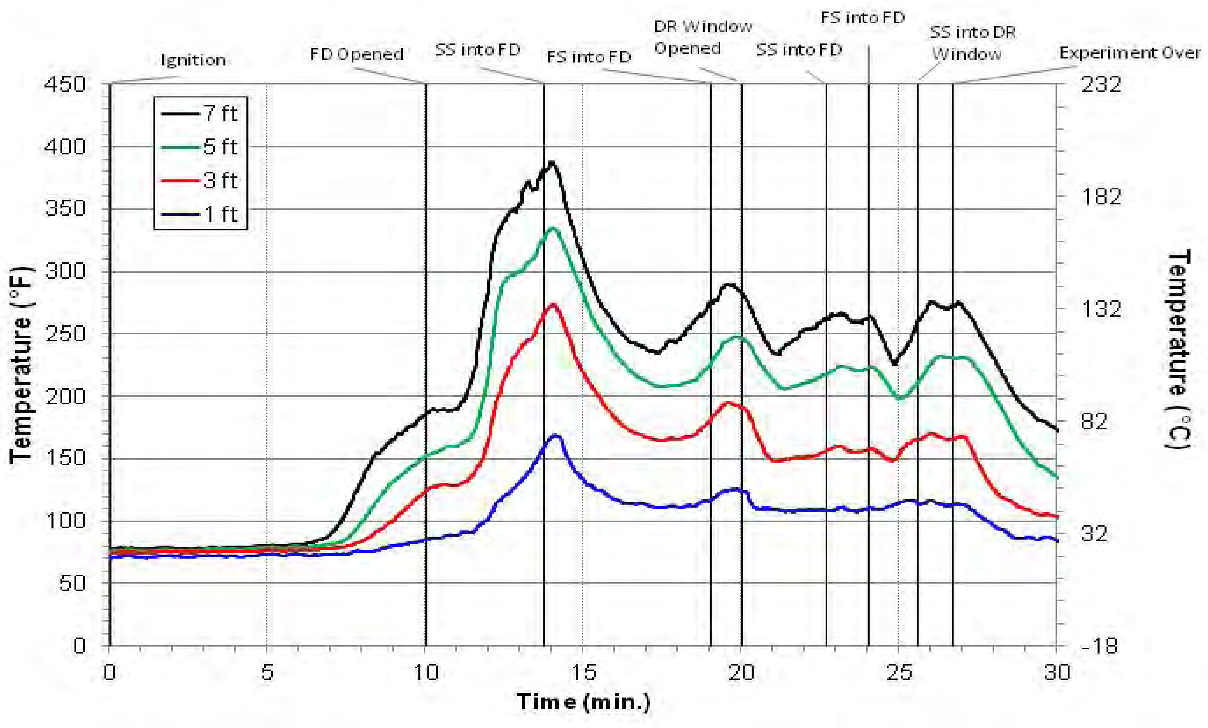


Figure E.272: Experiment 13 Bedroom 2 Temperature

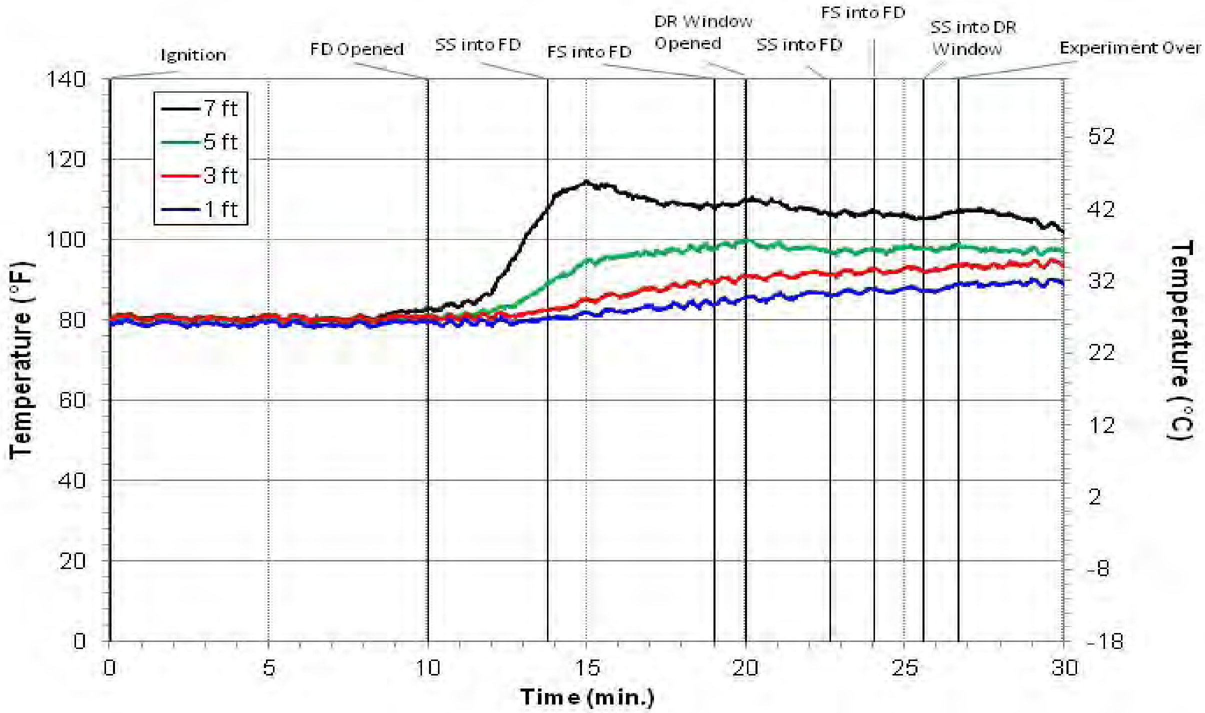


Figure E.273: Experiment 13 Bedroom 3 Temperature

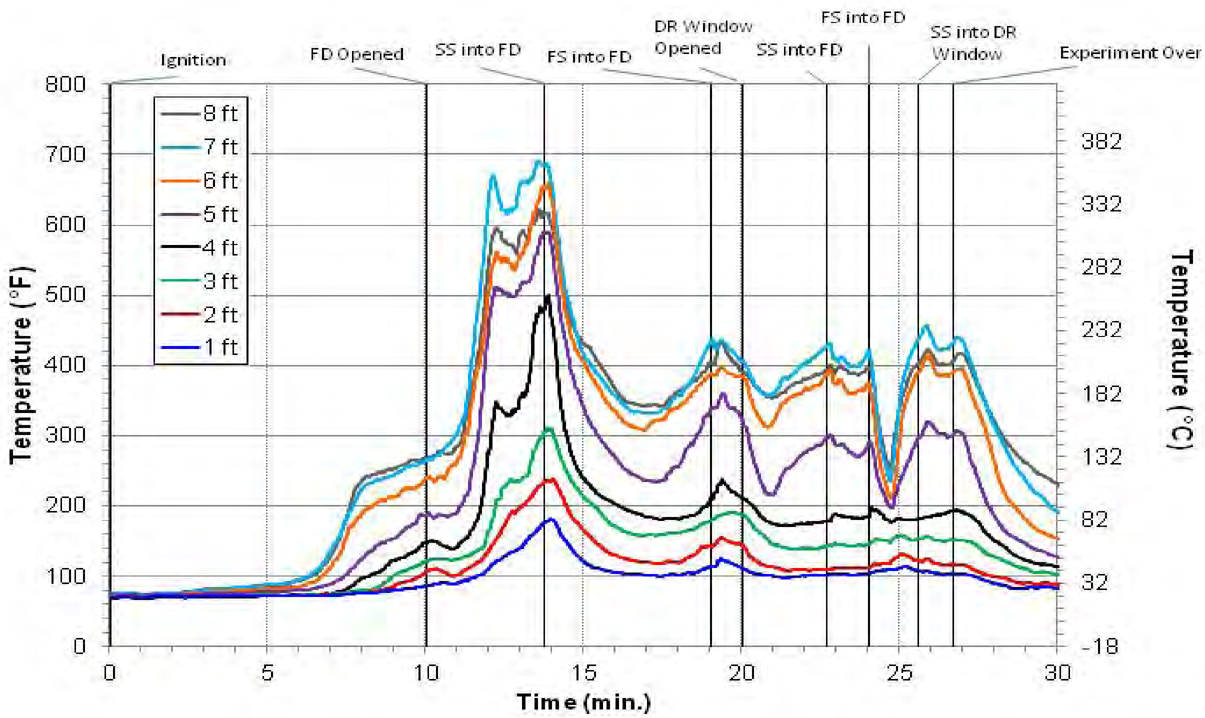


Figure E.274: Experiment 13 Hallway Temperature

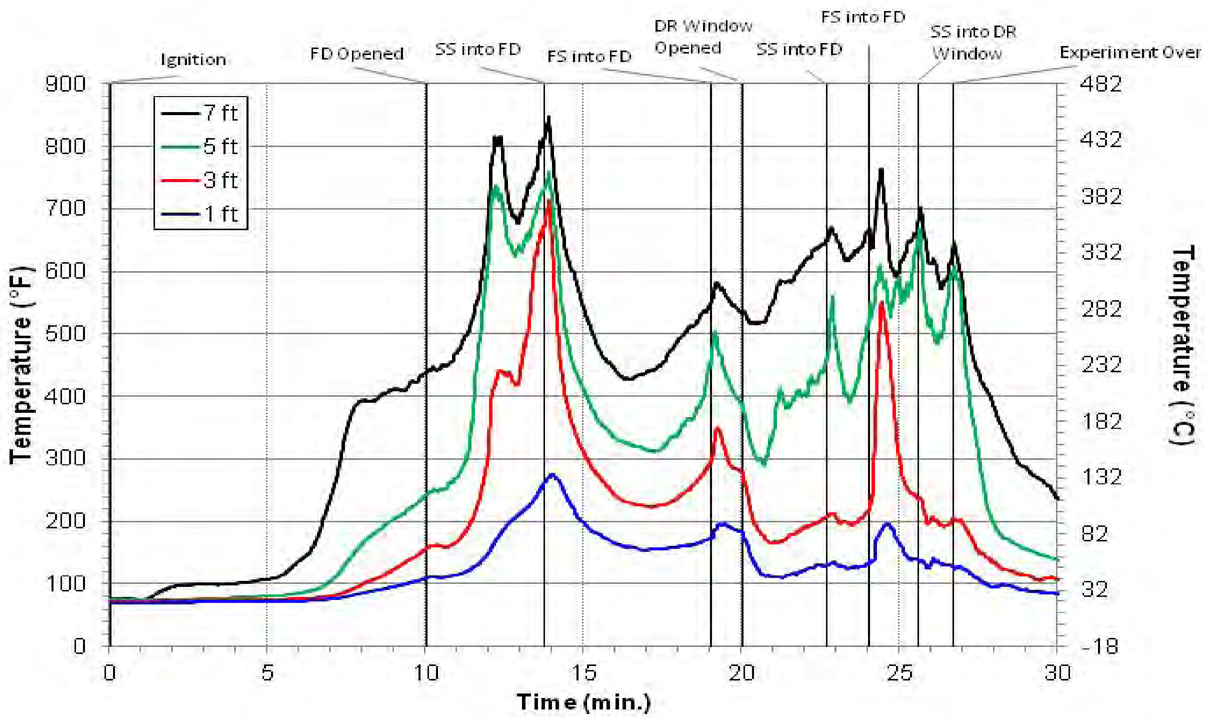


Figure E.275: Experiment 13 Dining Room Temperature

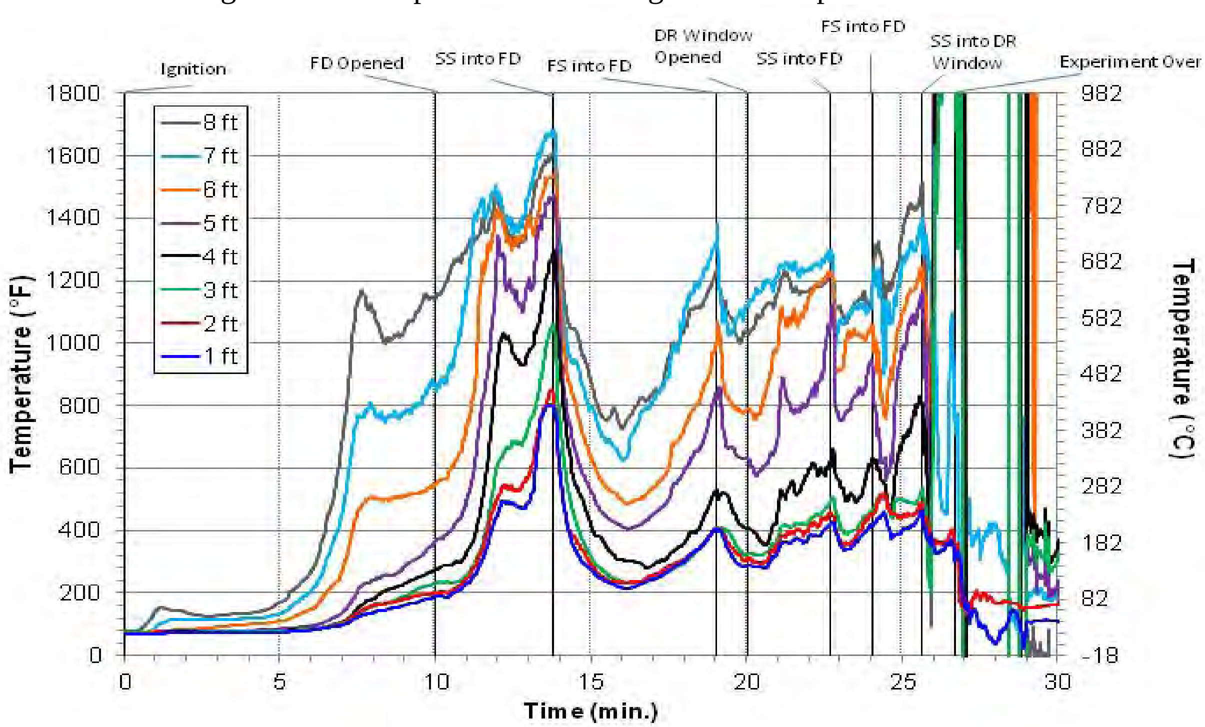


Figure E.276: Experiment 13 Kitchen Temperature

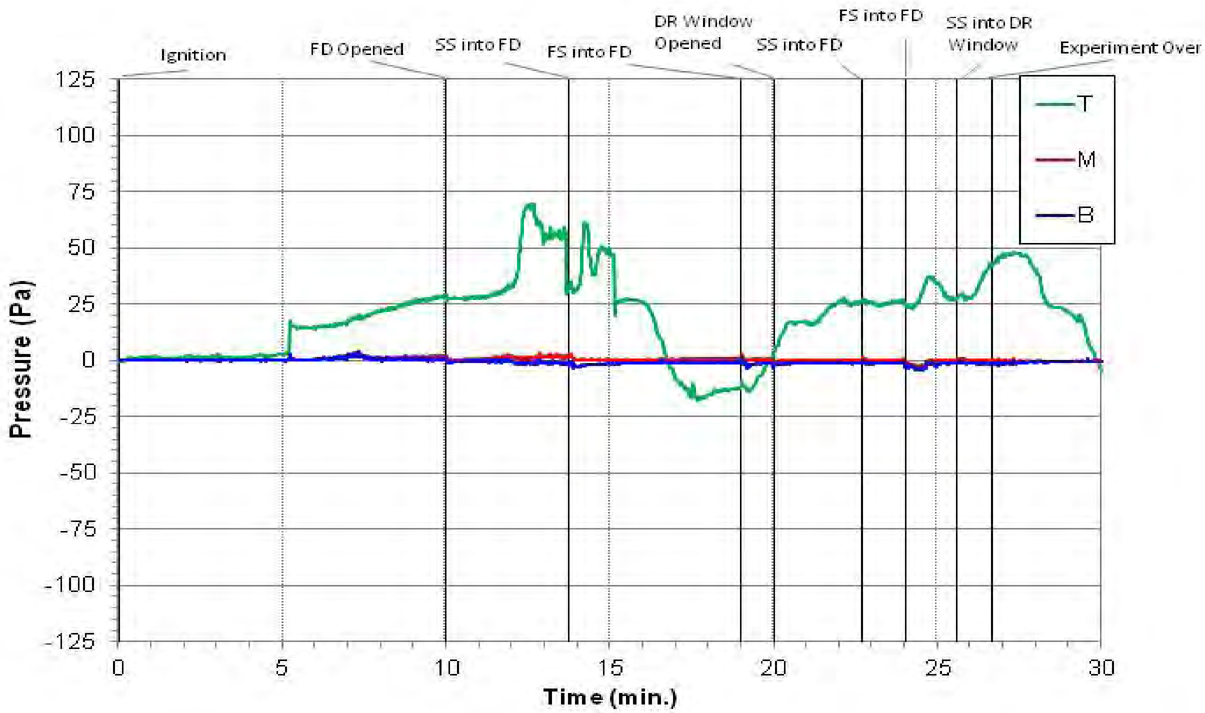


Figure E.277: Experiment 13 Living Room Pressure

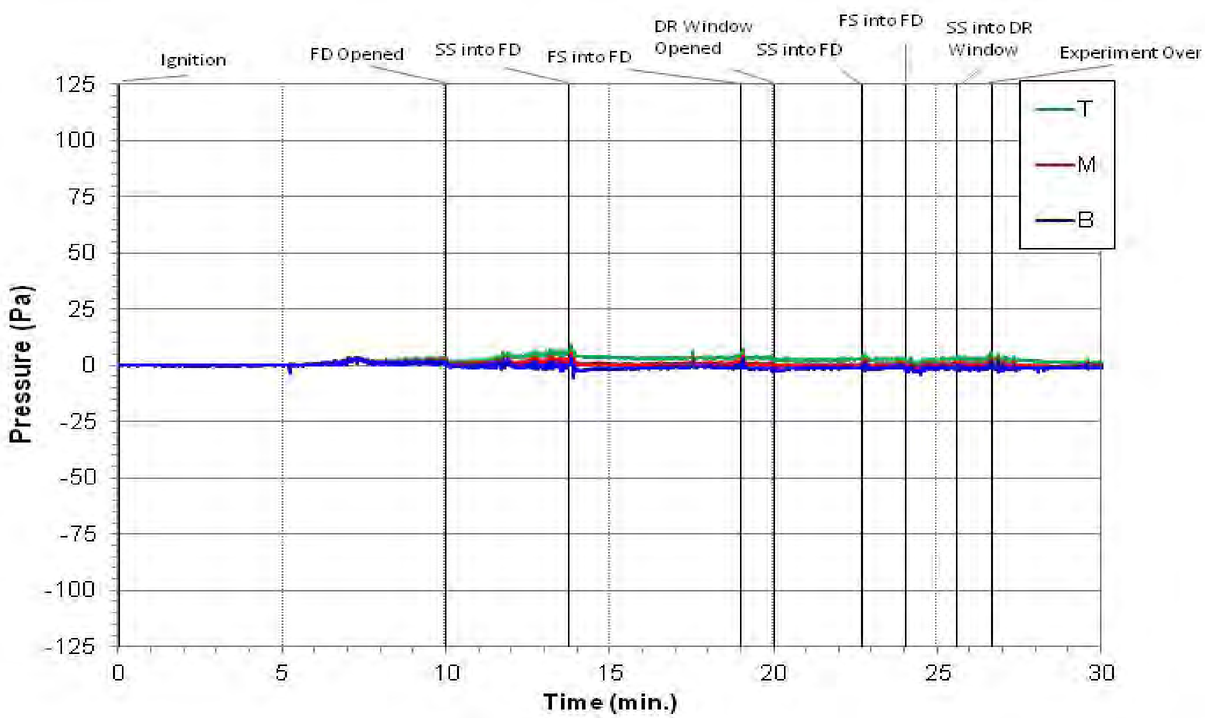


Figure E.278: Experiment 13 Bedroom 1 Pressure

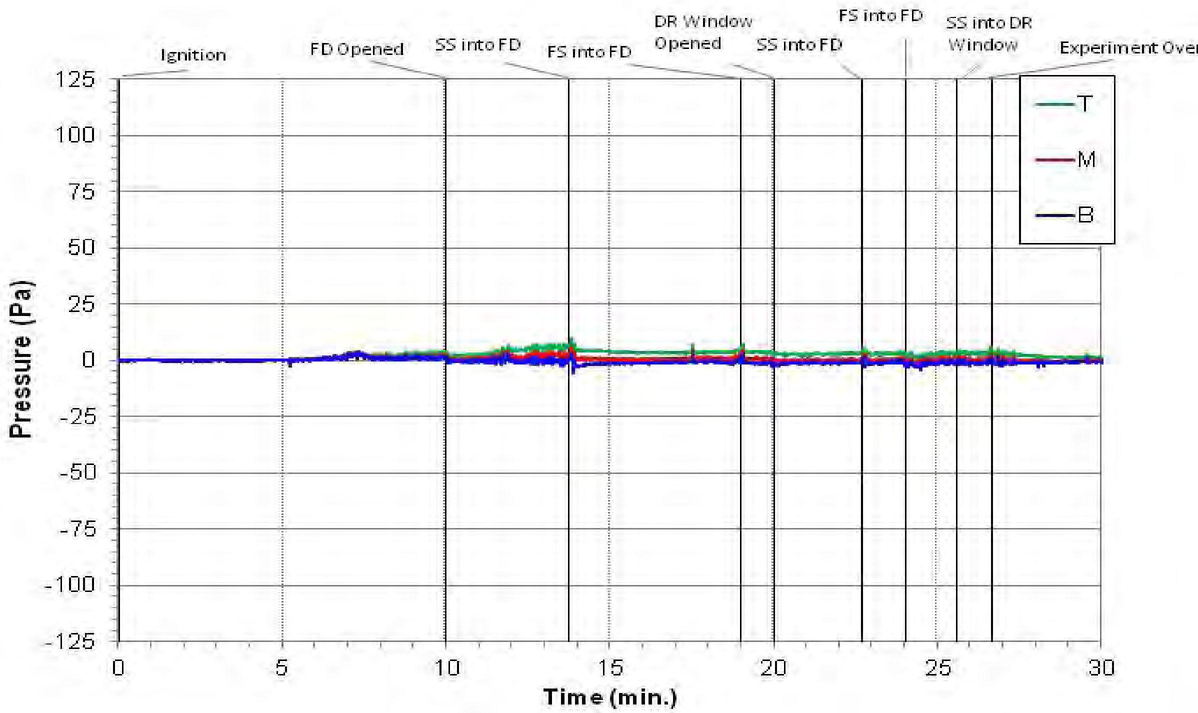


Figure E.279: Experiment 13 Bedroom 2 Pressure

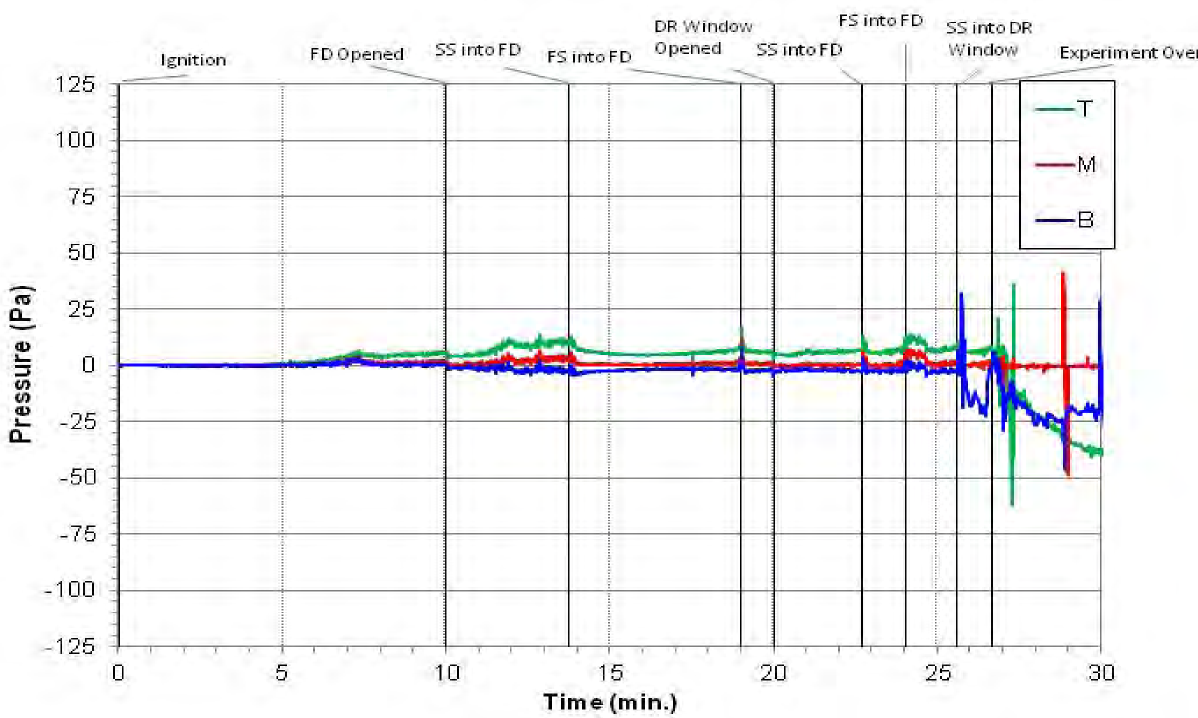


Figure E.280: Experiment 13 Kitchen Pressure

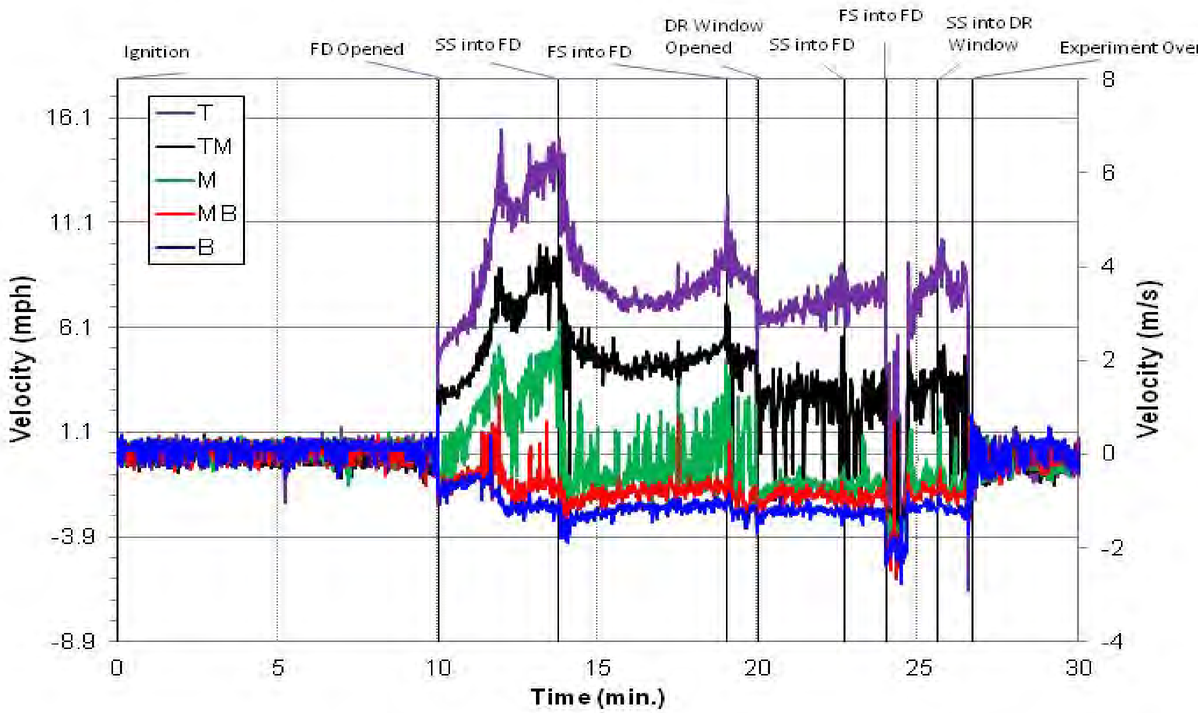


Figure E.281: Experiment 13 Front Door Velocity

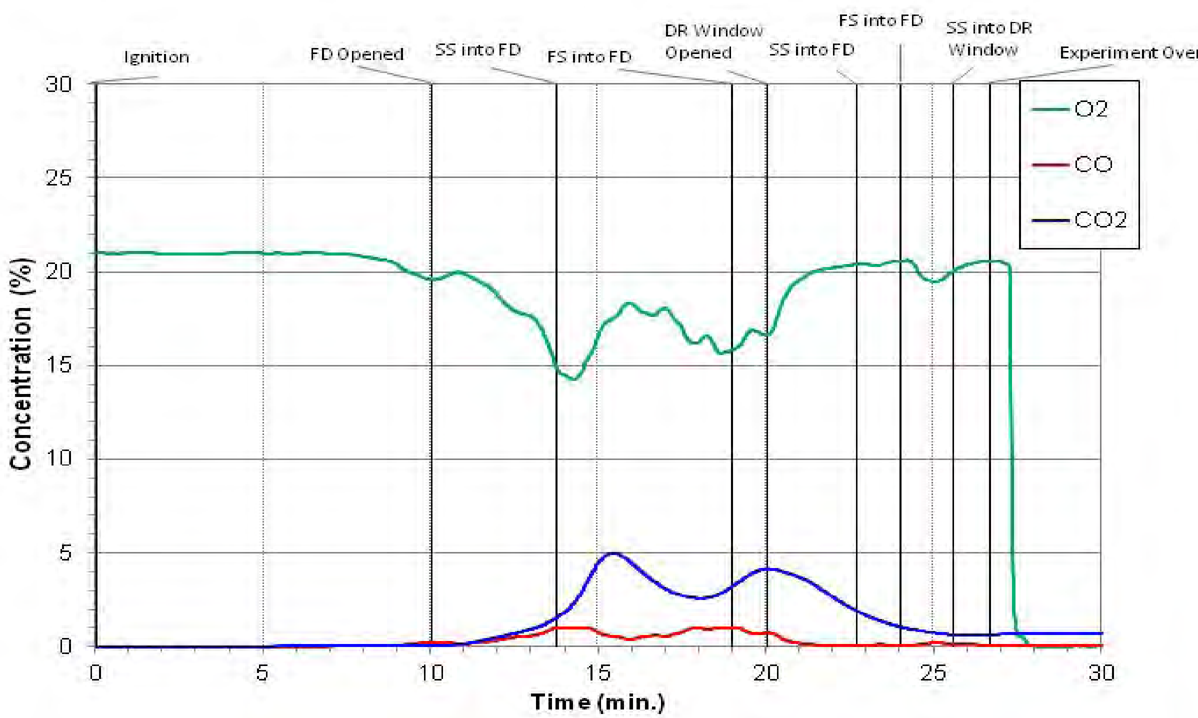


Figure E.282: Experiment 13 Living Room Gas

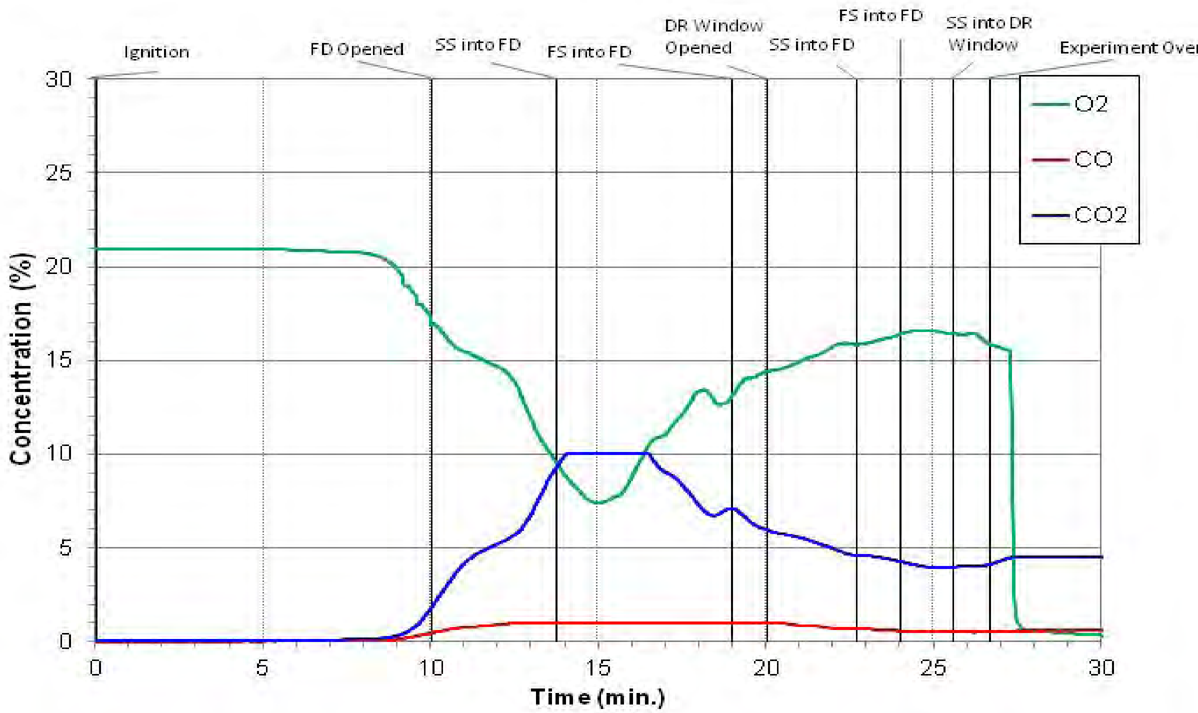


Figure E.283: Experiment 13 Bedroom 1 Gas

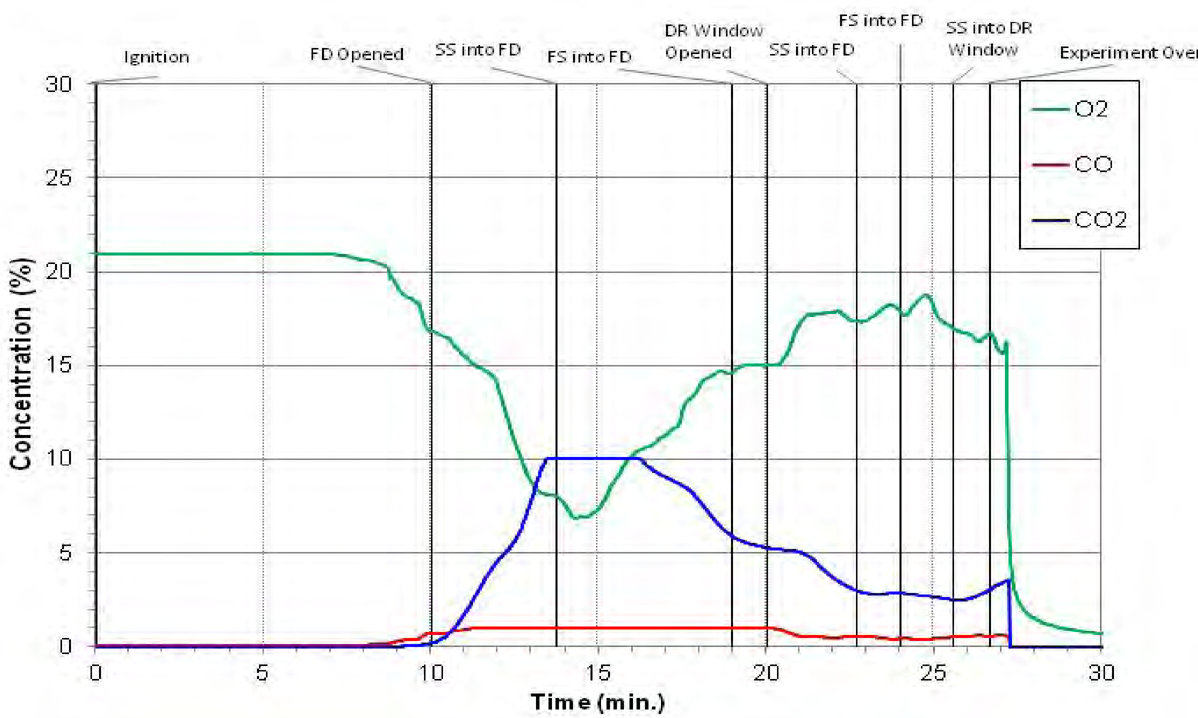


Figure E.284: Experiment 13 Bedroom 2 Gas

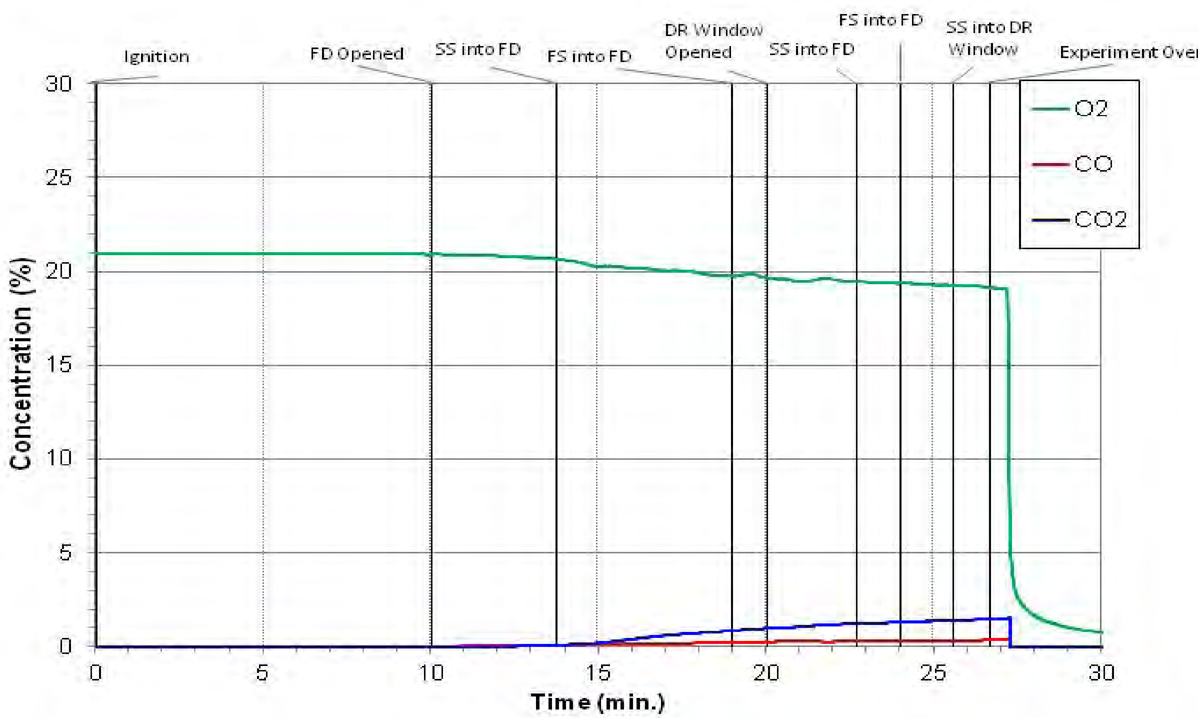


Figure E.285: Experiment 13 Bedroom 3 Gas

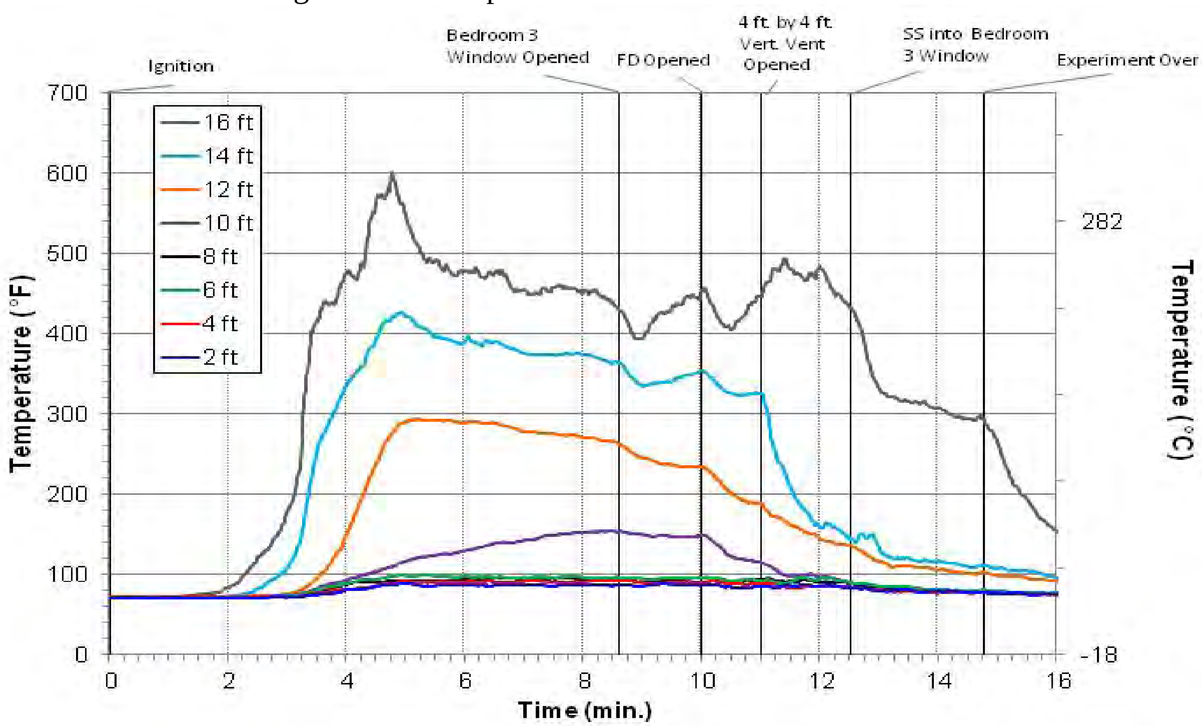


Figure E.286: Experiment 14 Family Room Temperature

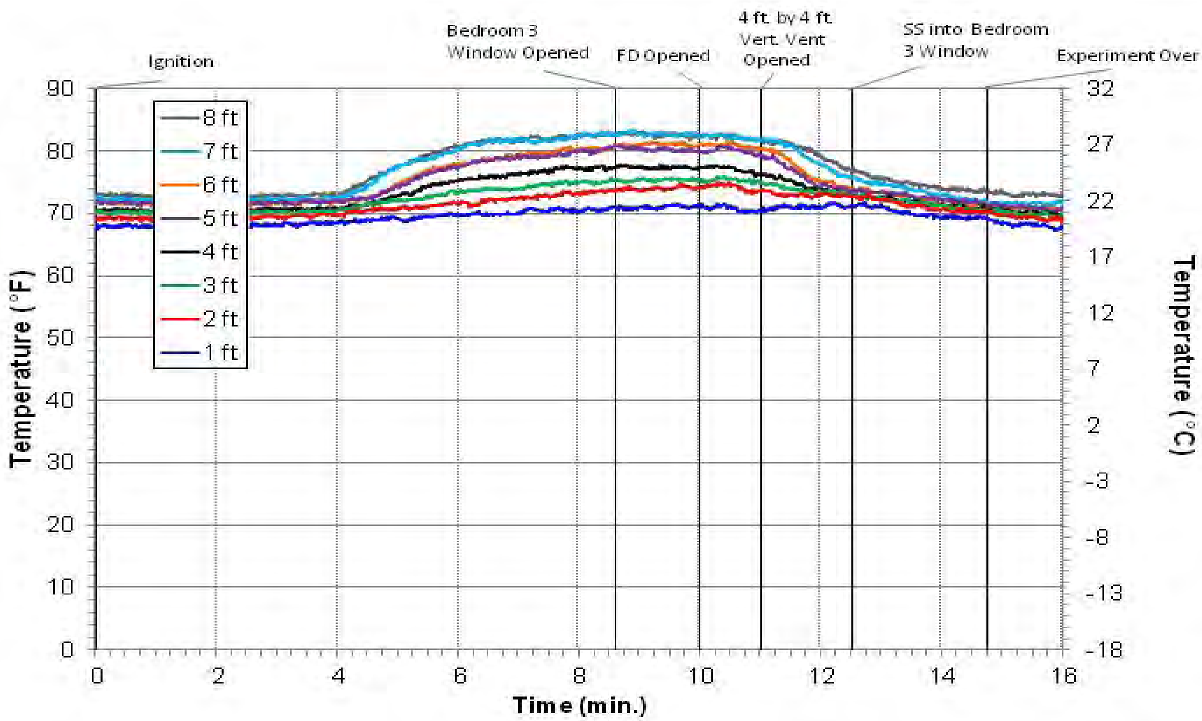


Figure E.287: Experiment 14 Kitchen Temperature

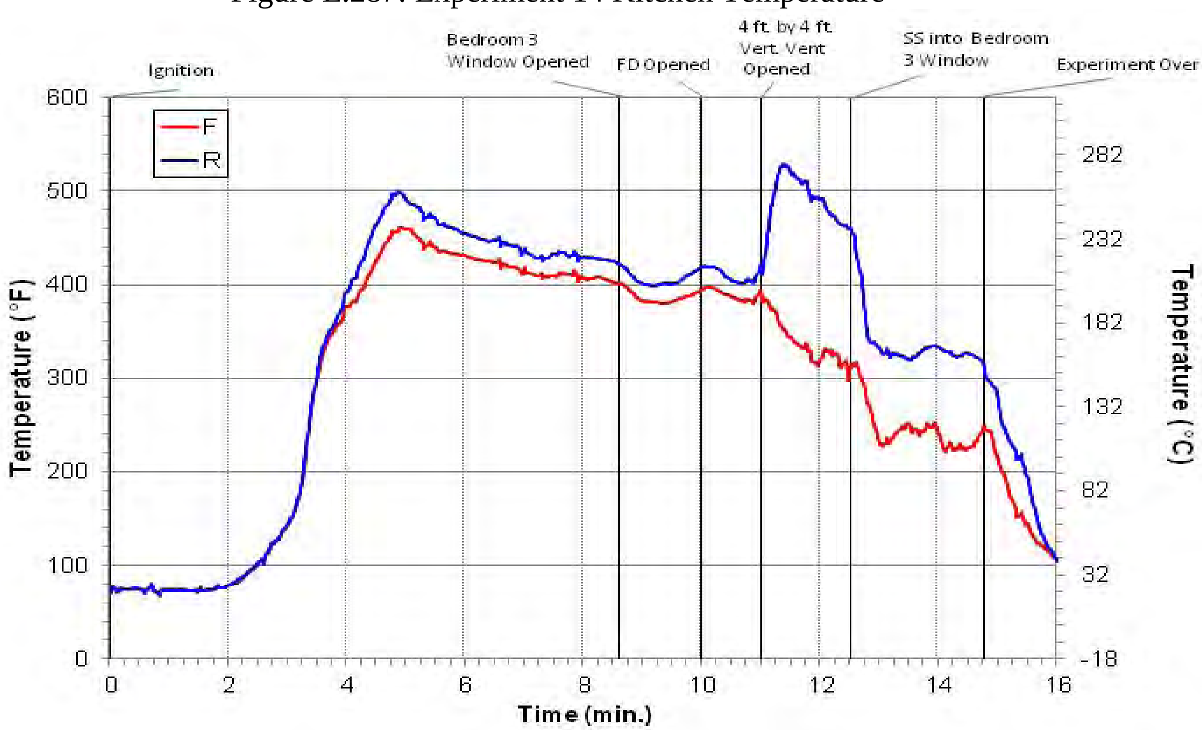


Figure E.288: Experiment 14 Vent Temperature

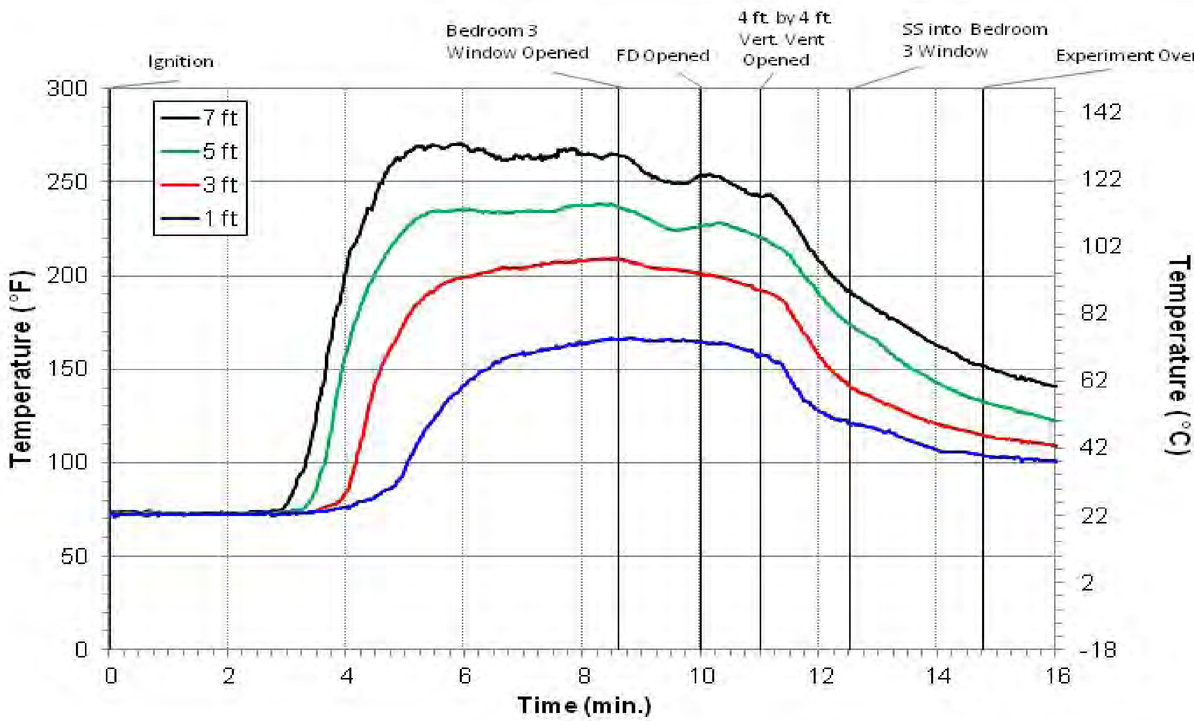


Figure E.289: Experiment 14 Bedroom 1 Temperature

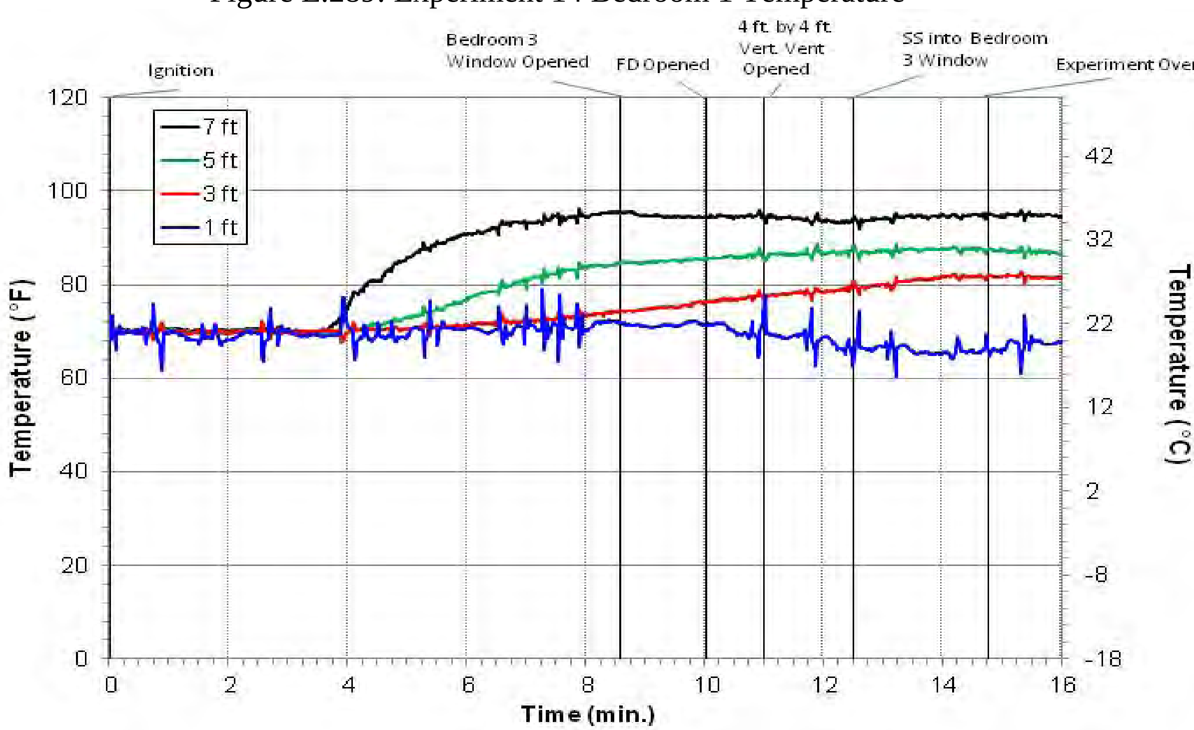


Figure E.290: Experiment 14 Bedroom 2 Temperature

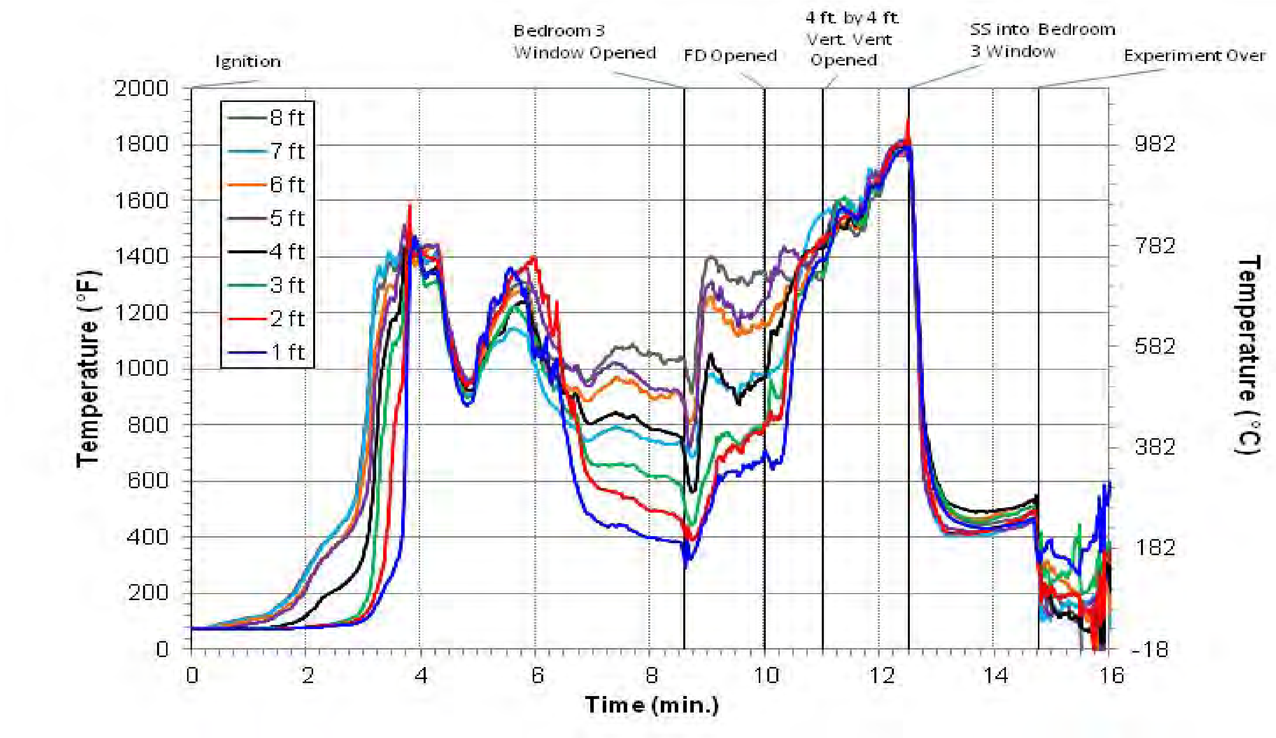


Figure E.291: Experiment 14 Bedroom 3 Temperature

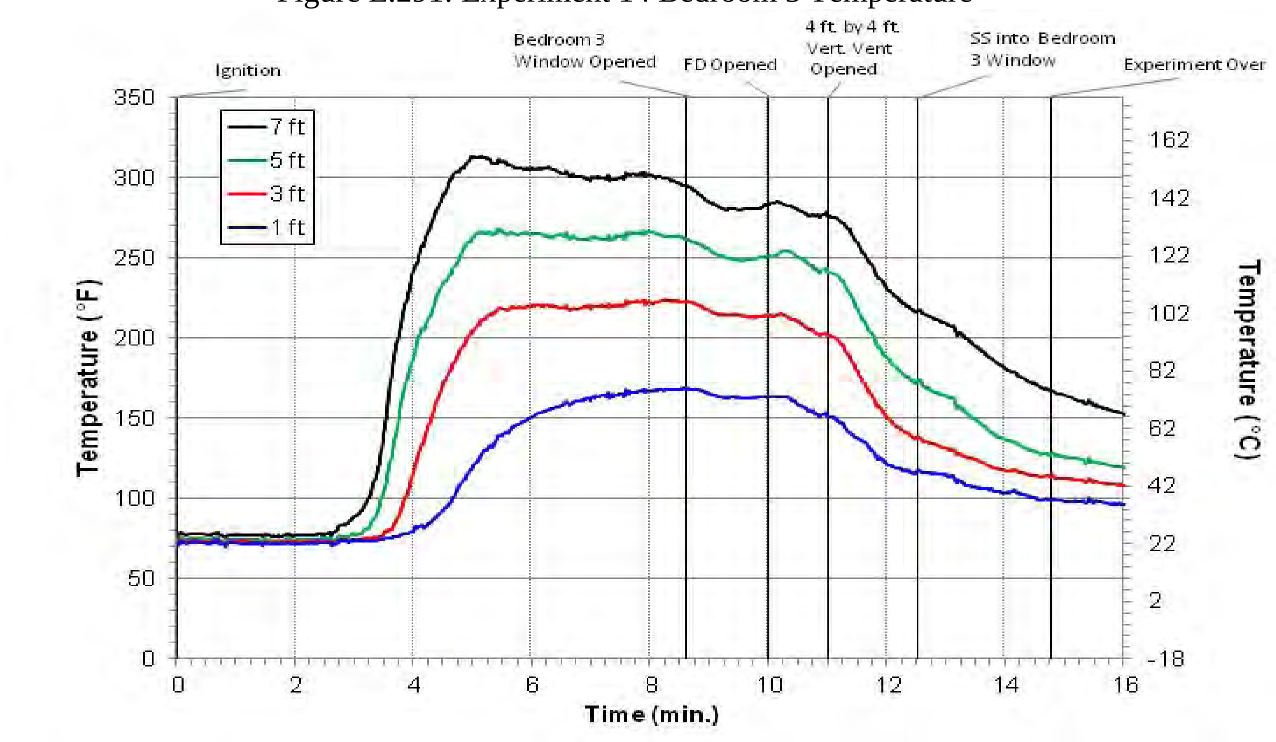


Figure E.292: Experiment 14 Bedroom 4 Temperature

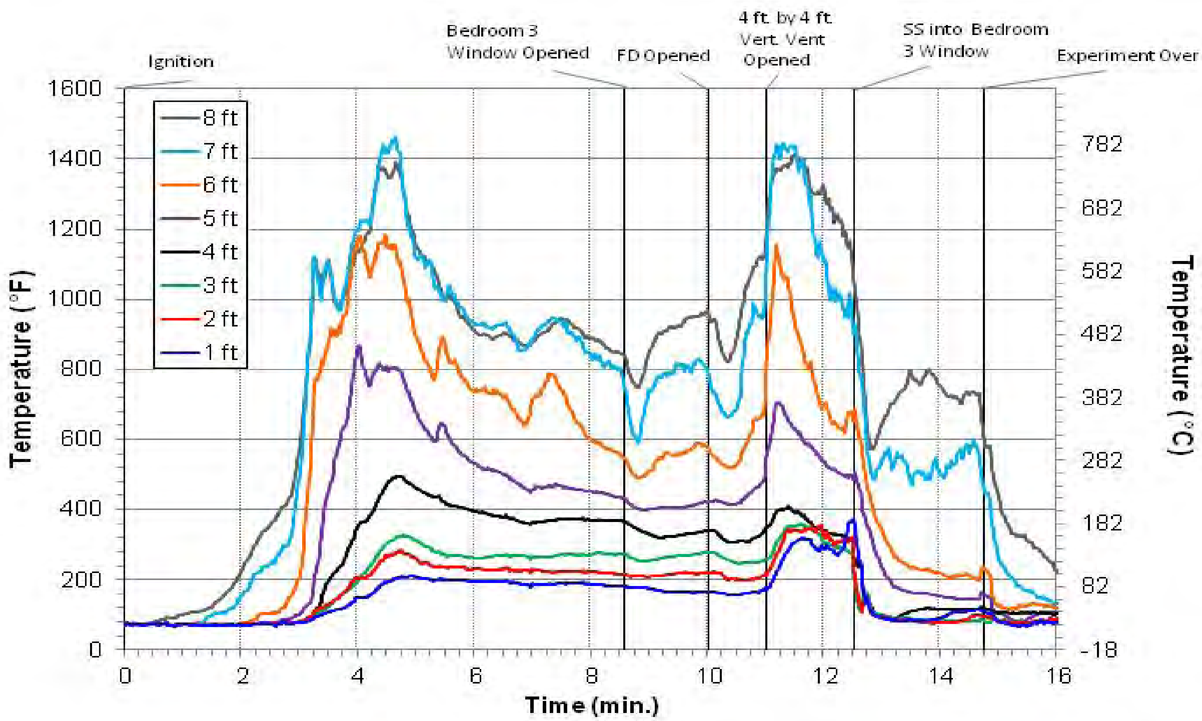


Figure E.293: Experiment 14 Hallway Temperature

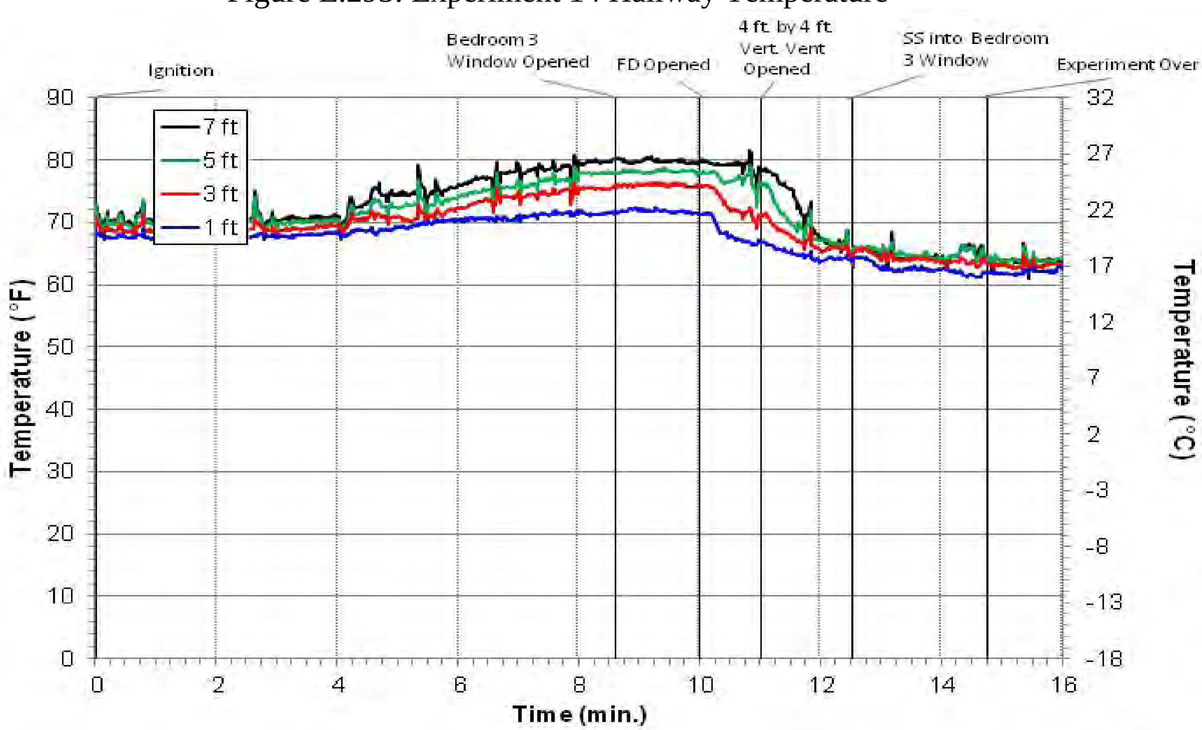


Figure E.294: Experiment 14 Dining Room Temperature

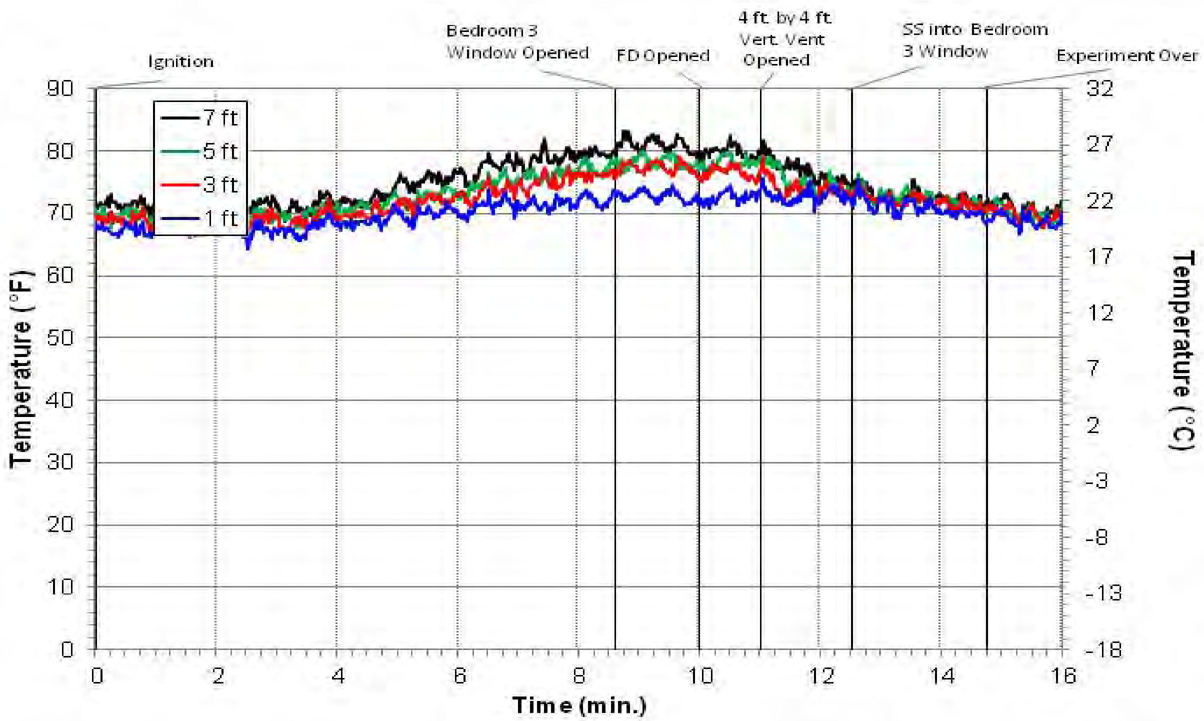


Figure E.295: Experiment 14 Living Room Temperature

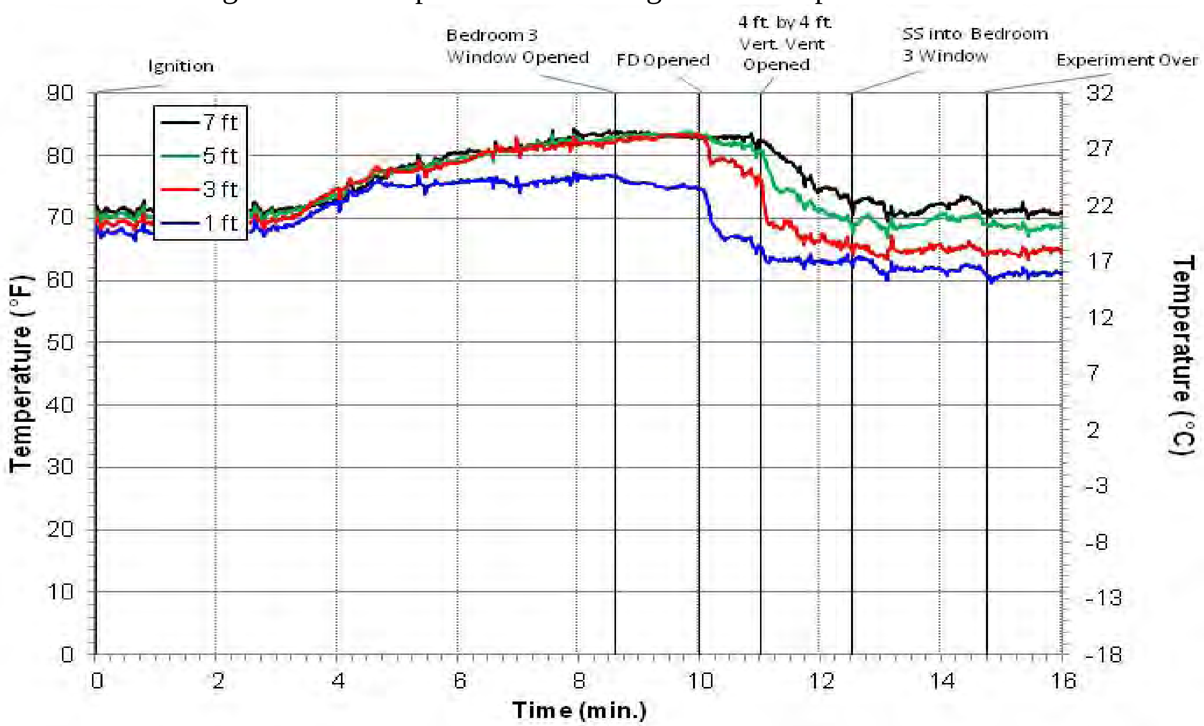


Figure E.296: Experiment 14 Foyer Temperature

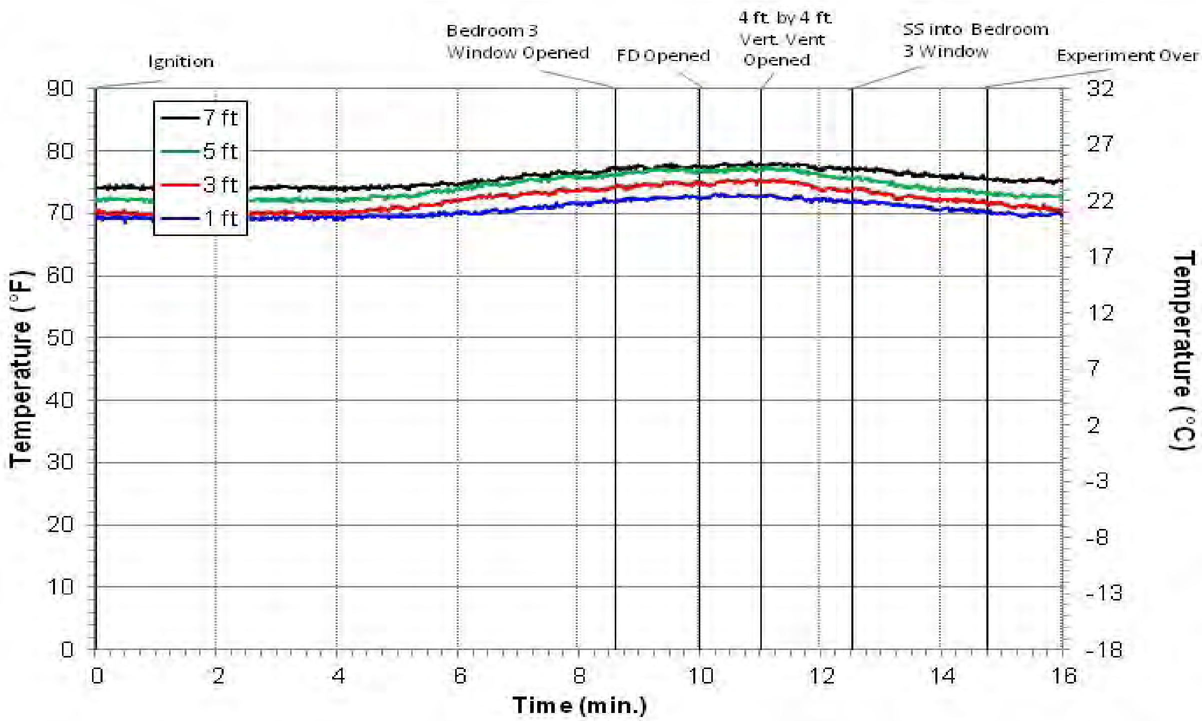


Figure E.297: Experiment 14 Den Temperature

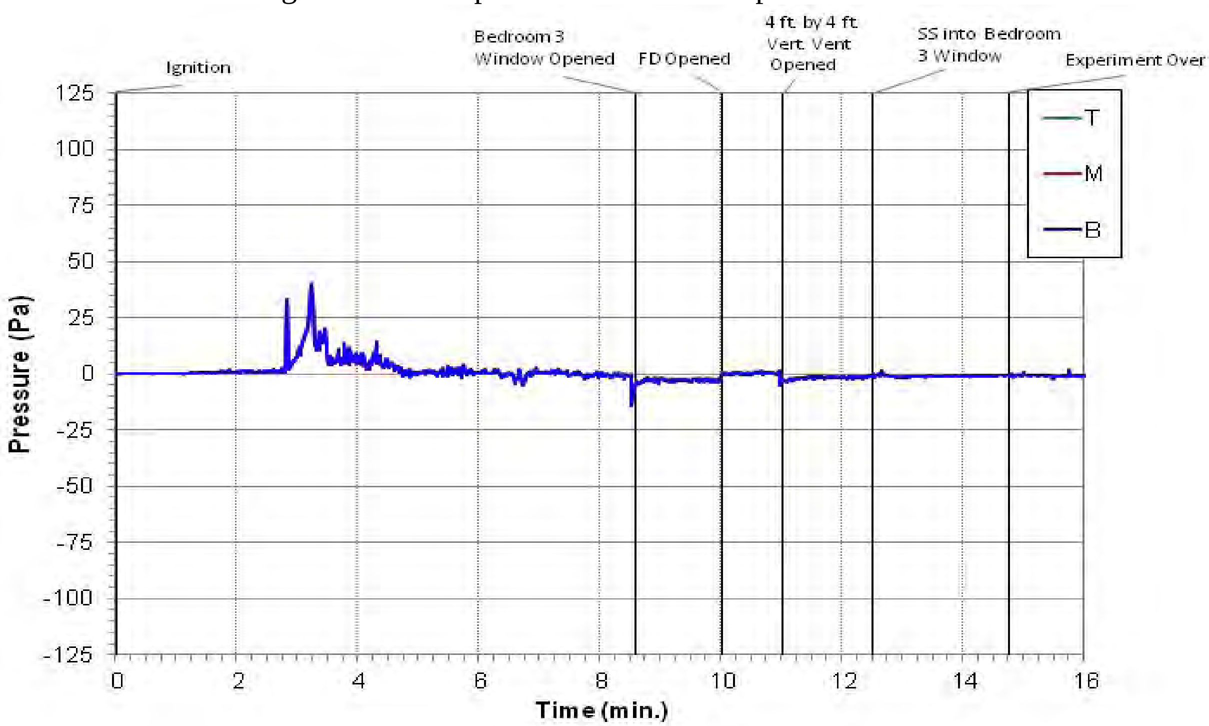


Figure E.298: Experiment 14 Living Room Pressure

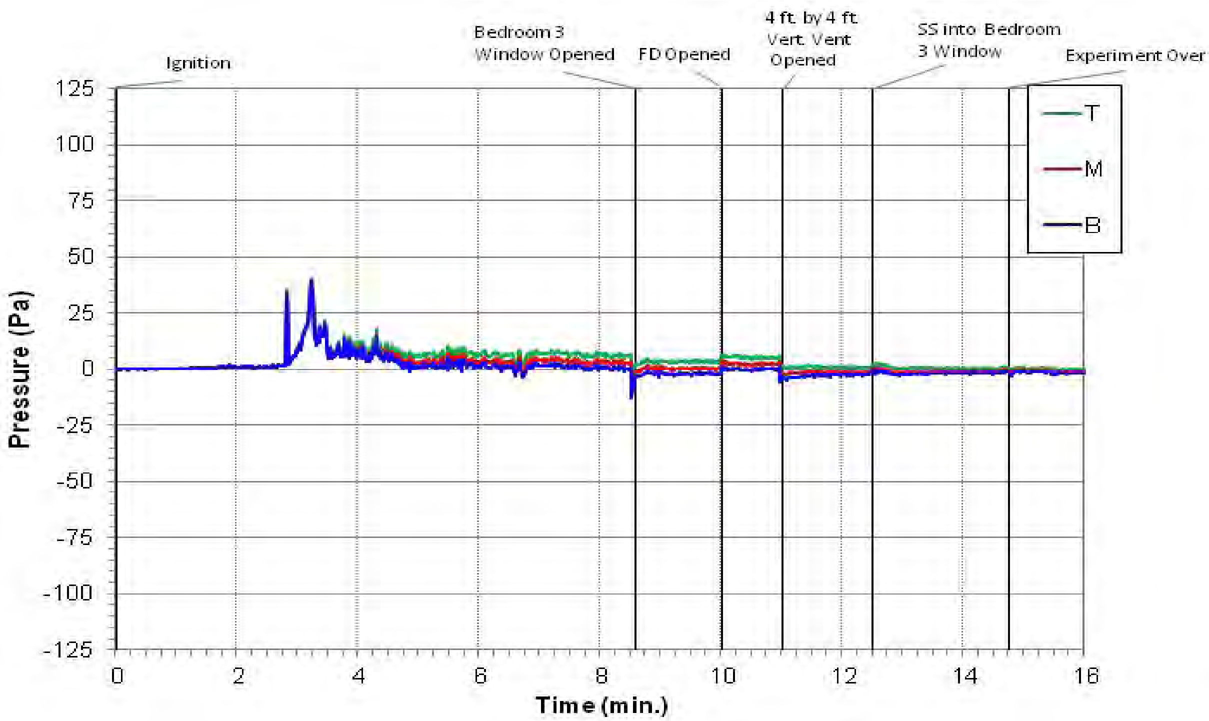


Figure E.299: Experiment 14 Bedroom 2 Pressure

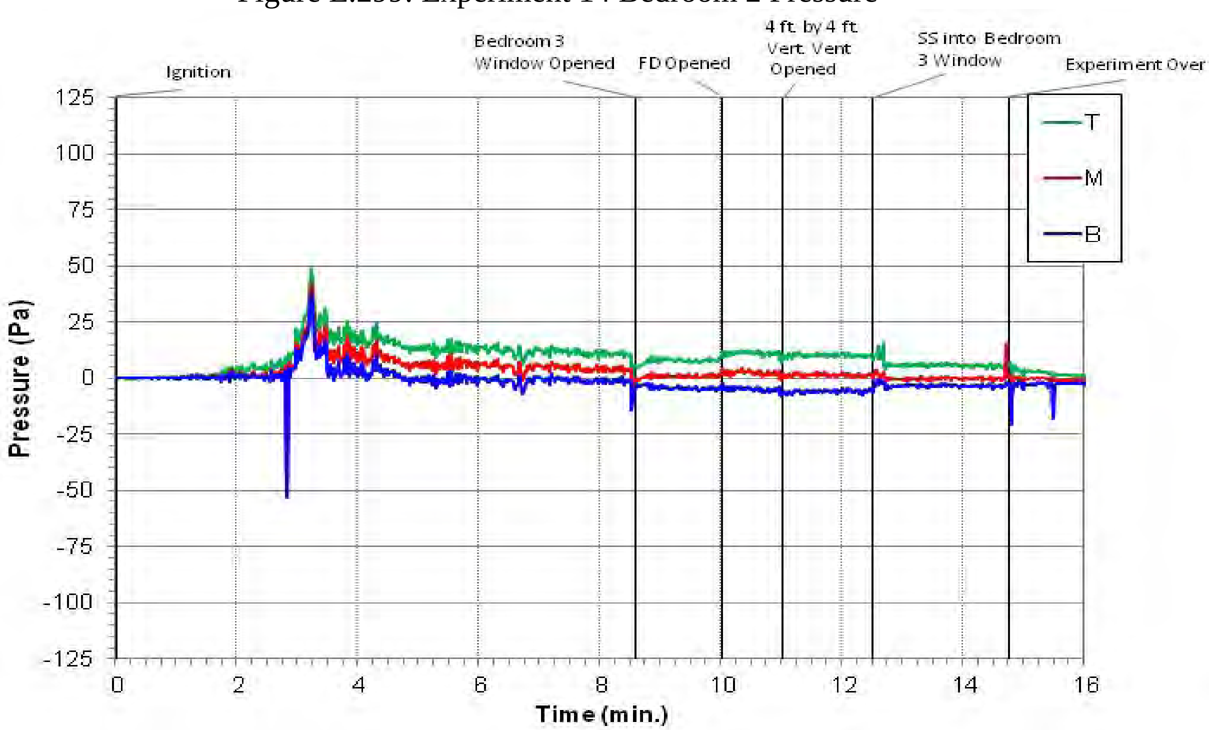


Figure E.300: Experiment 14 Bedroom 3 Pressure

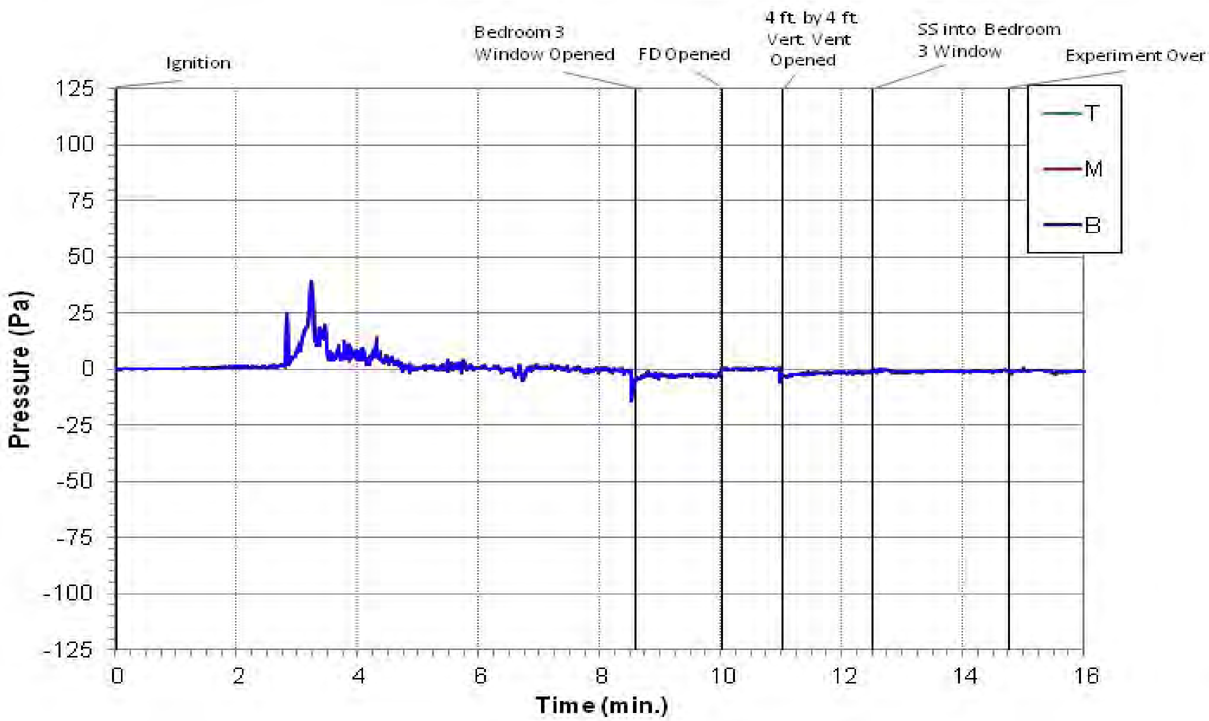


Figure E.301: Experiment 14 Kitchen Pressure

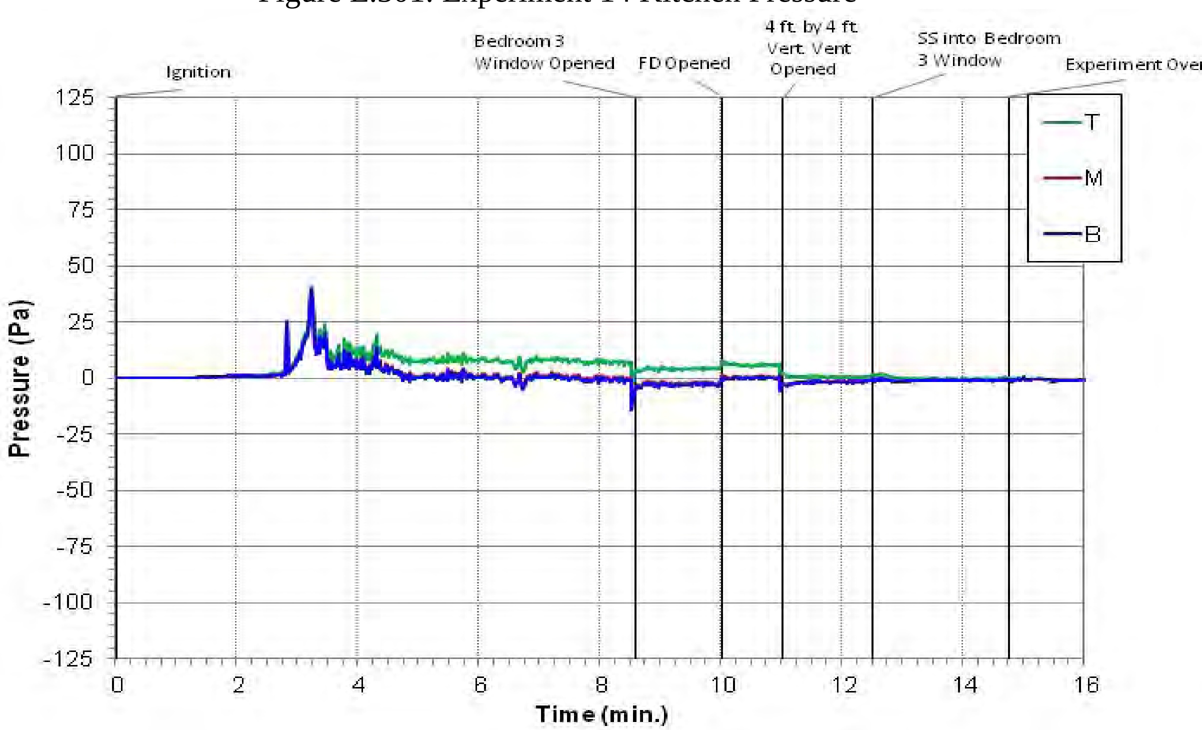


Figure E.302: Experiment 14 Family Room Pressure

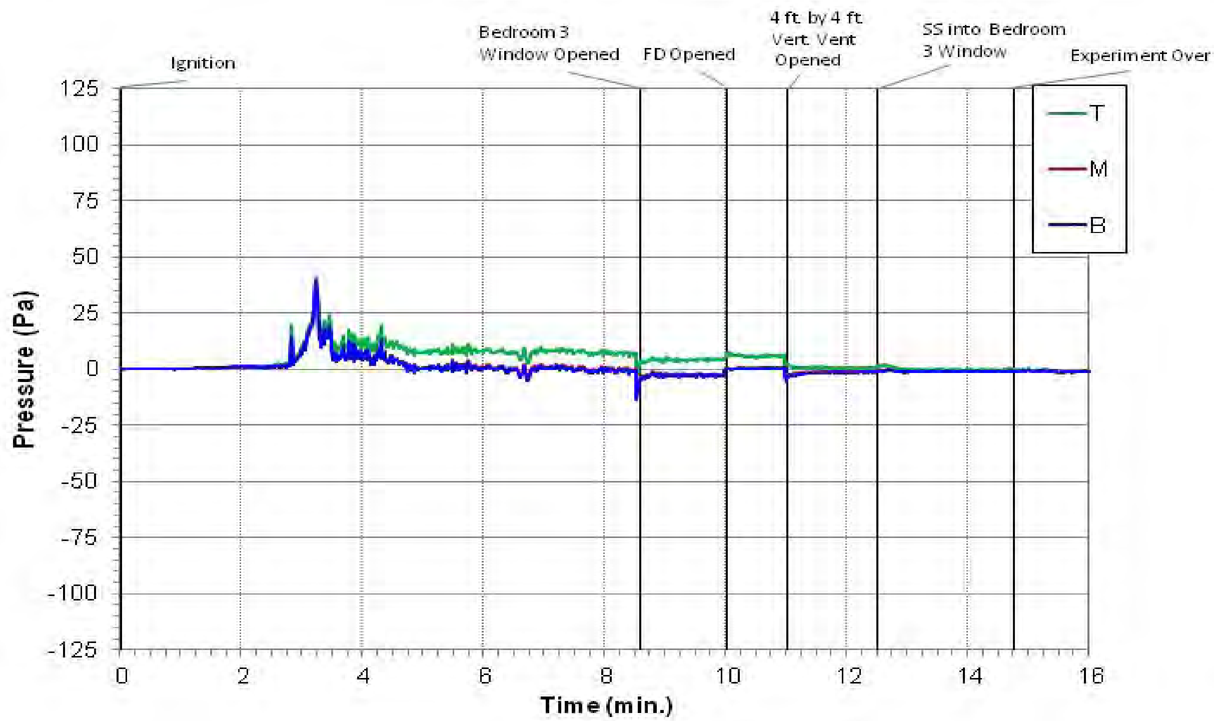


Figure E.303: Experiment 14 Foyer Pressure

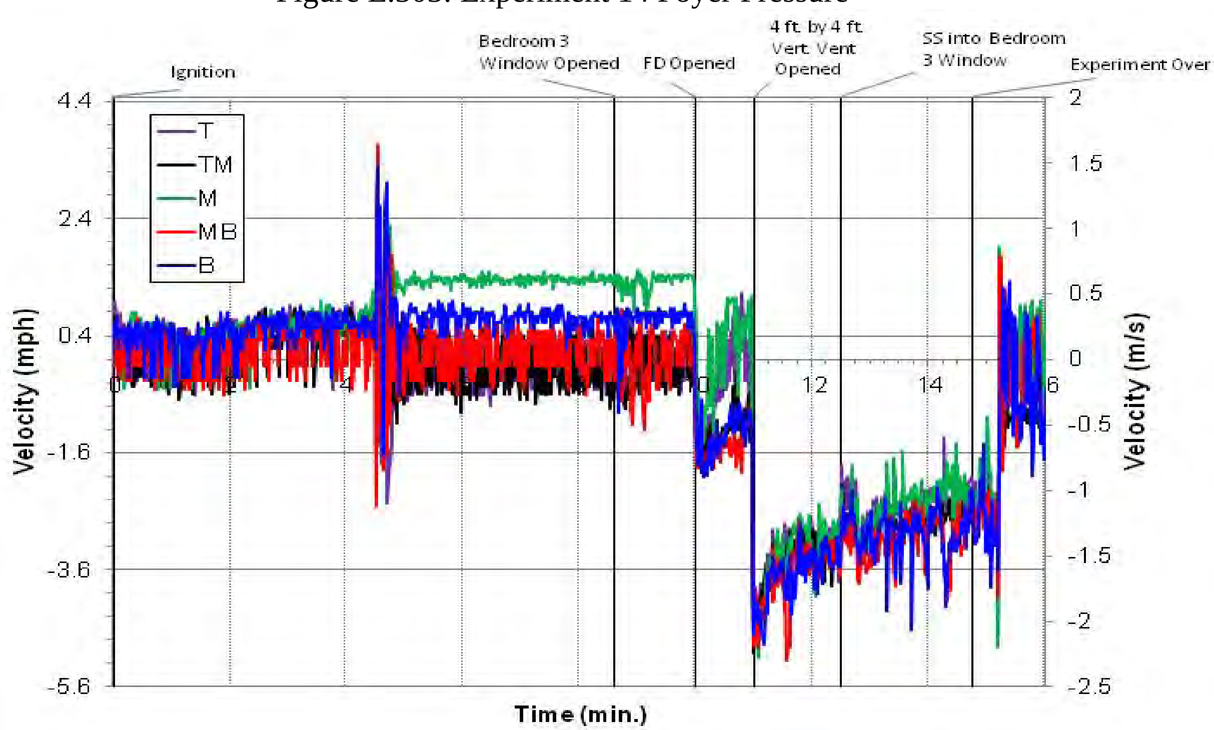


Figure E.304: Experiment 14 Front Door Velocity

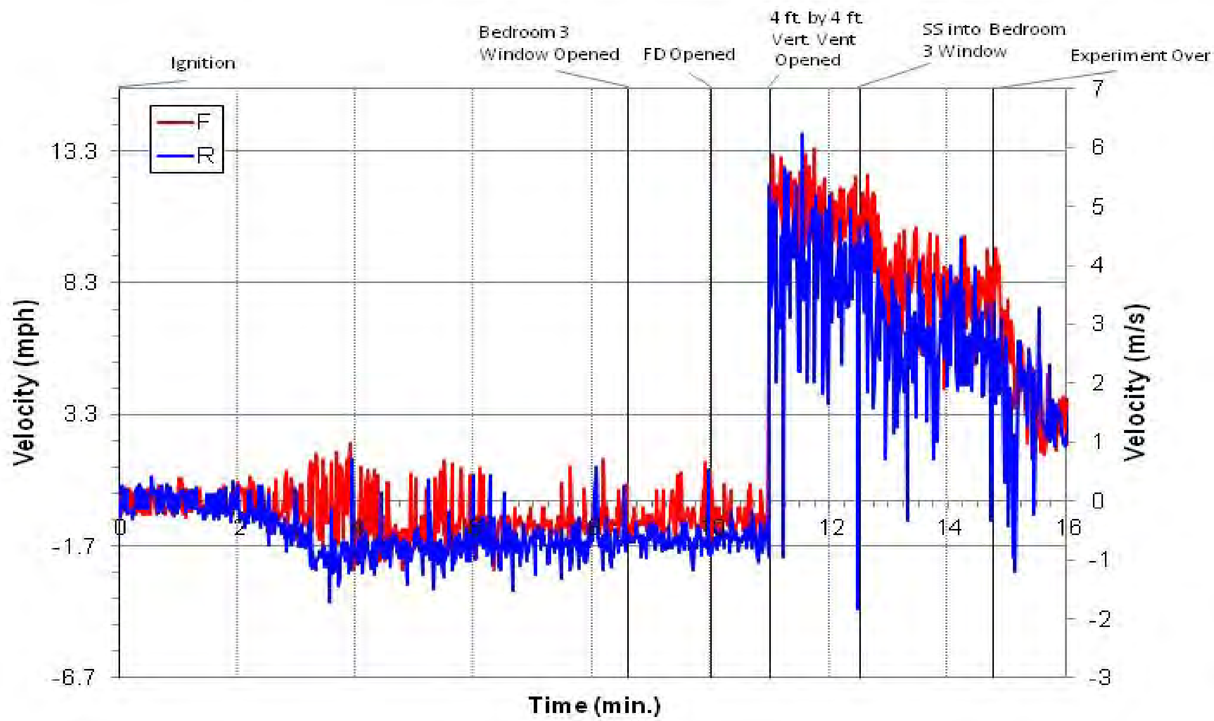


Figure E.305: Experiment 14 Vent Velocity

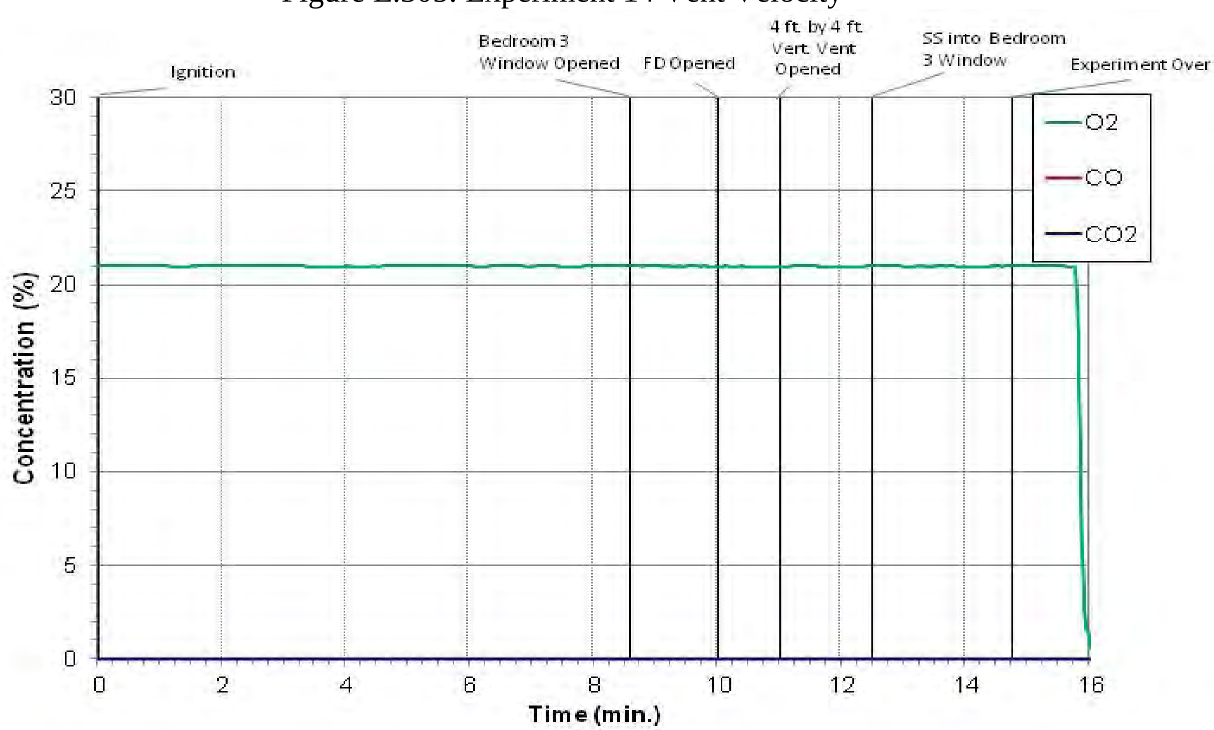


Figure E.306: Experiment 14 Front Door Gas

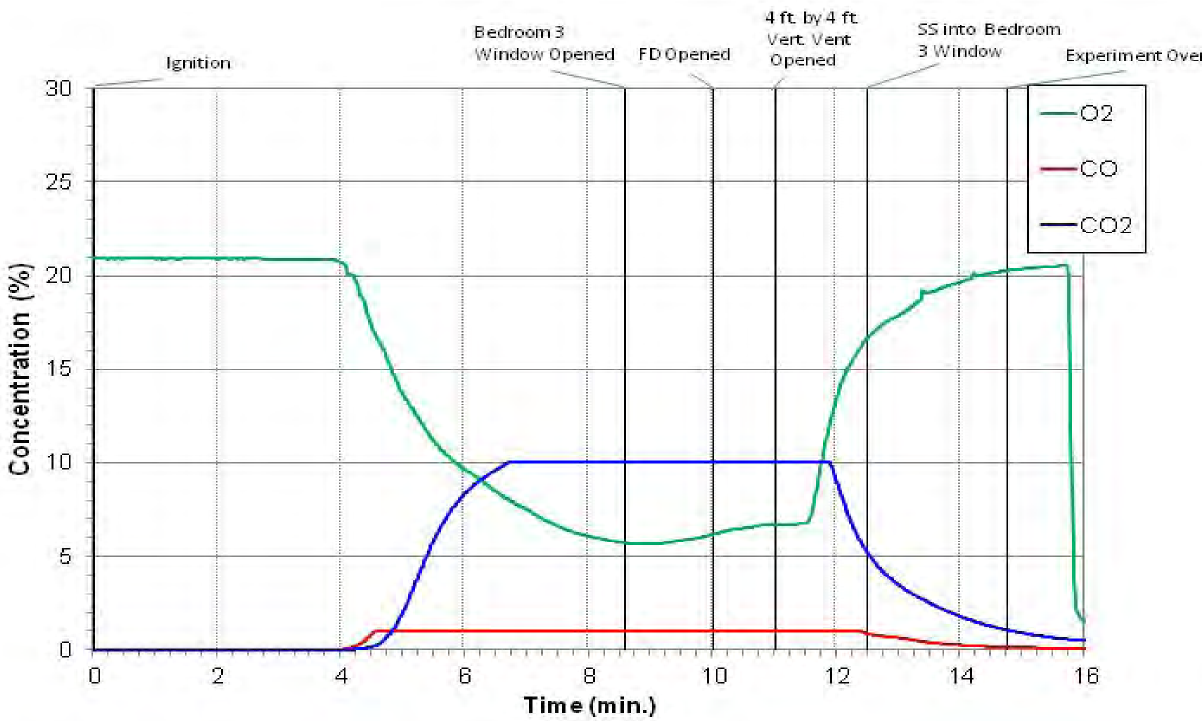


Figure E.307: Experiment 14 Bedroom 1 Gas

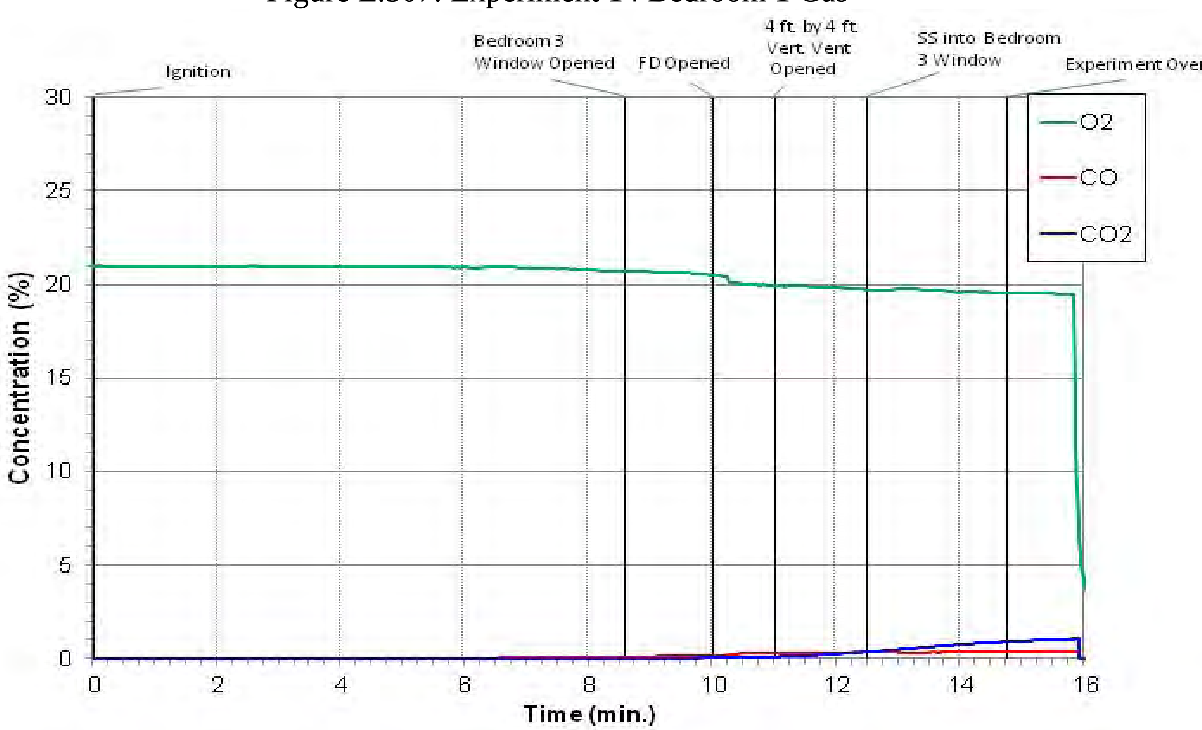


Figure E.308: Experiment 14 Bedroom 2 Gas

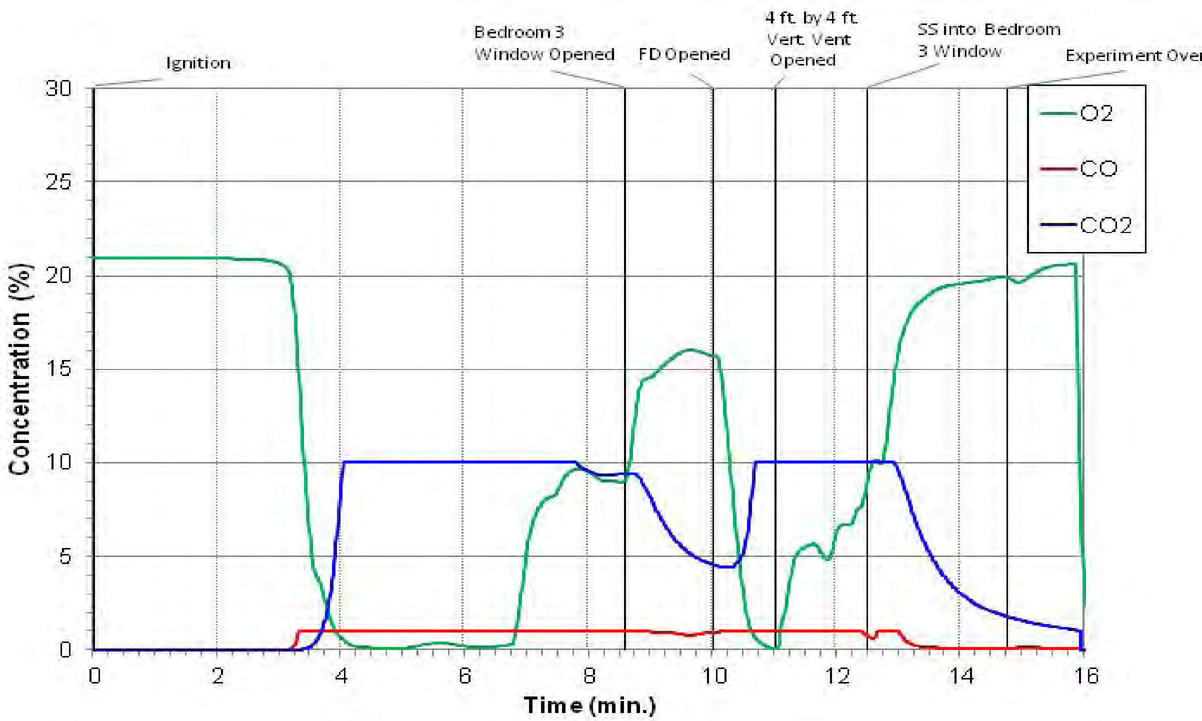


Figure E.309: Experiment 14 Bedroom 3 Gas

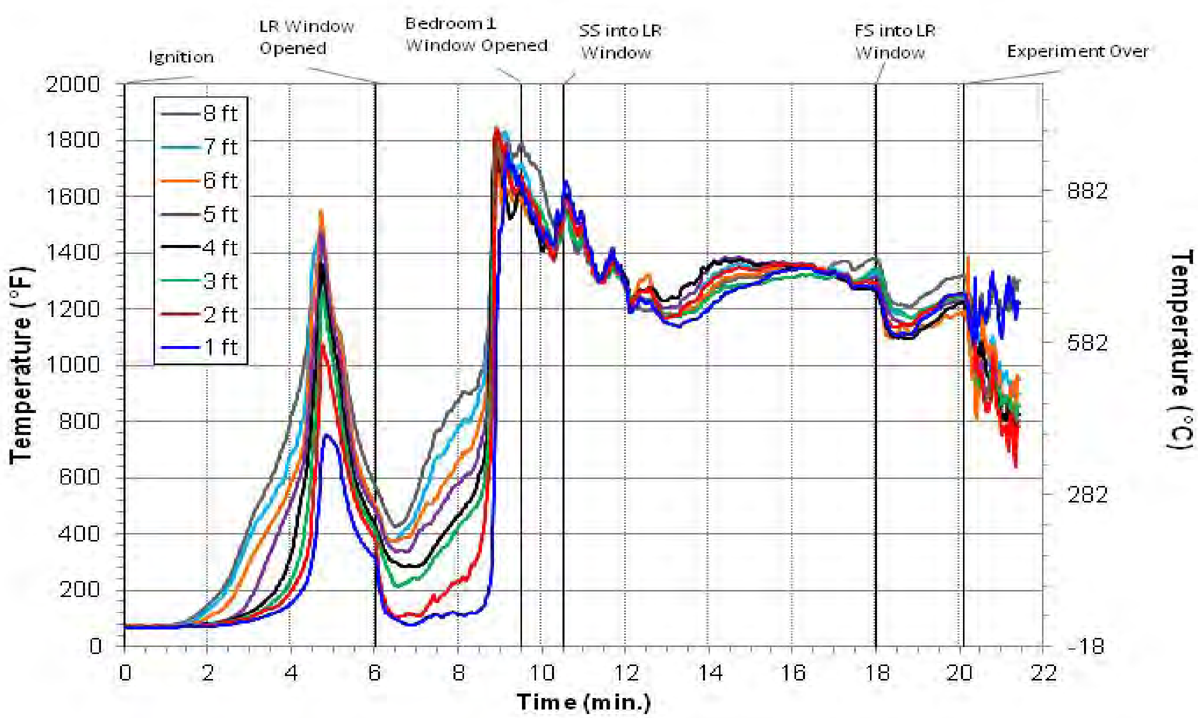


Figure E.310: Experiment 15 Living Room Temperature

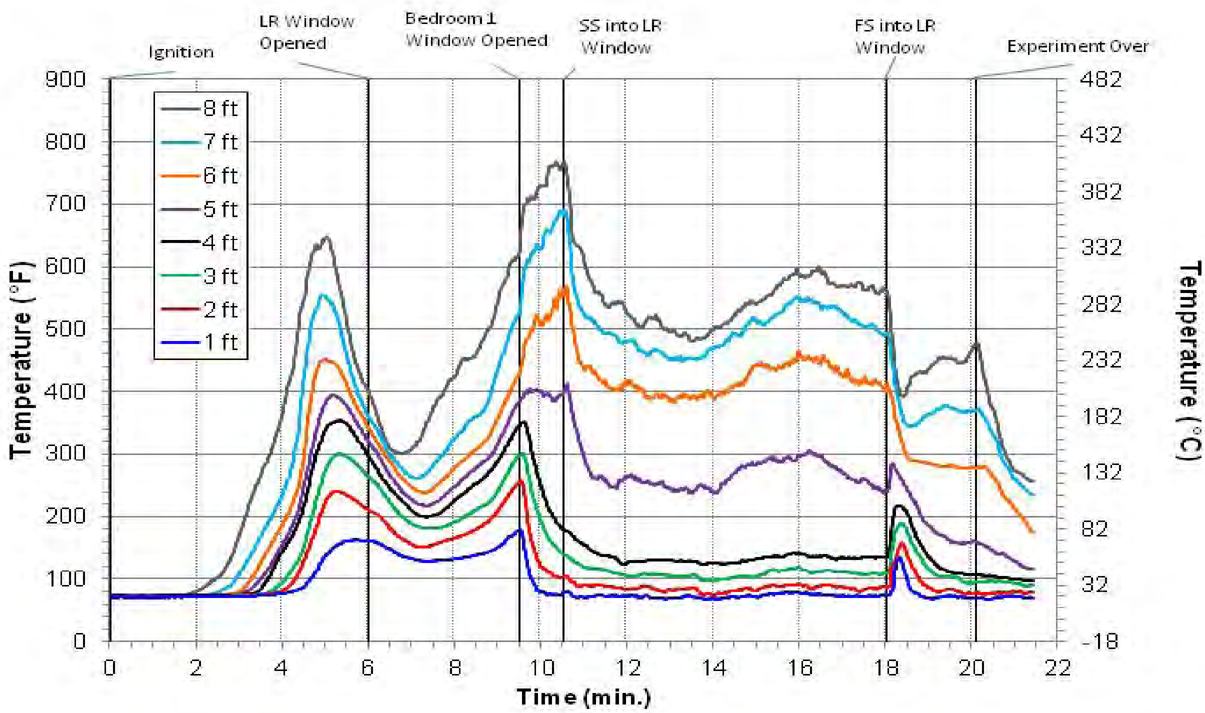


Figure E.311: Experiment 15 Bedroom 1 Temperature

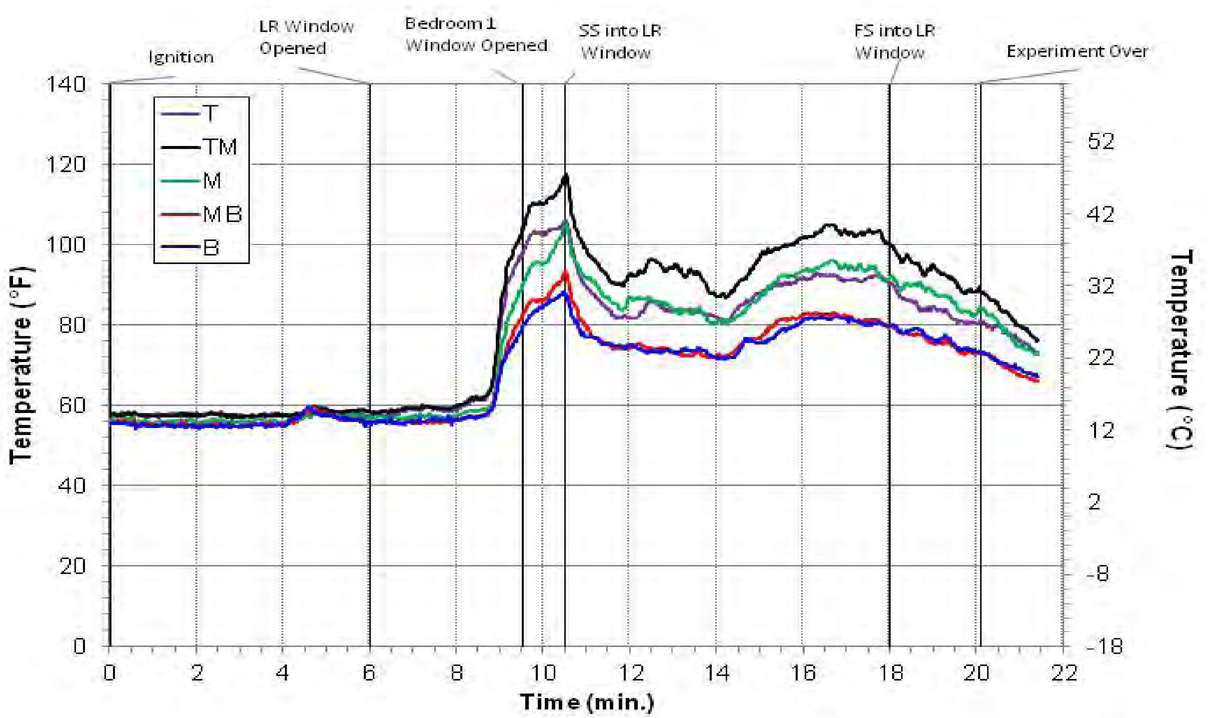


Figure E.312: Experiment 15 Front Door Temperature

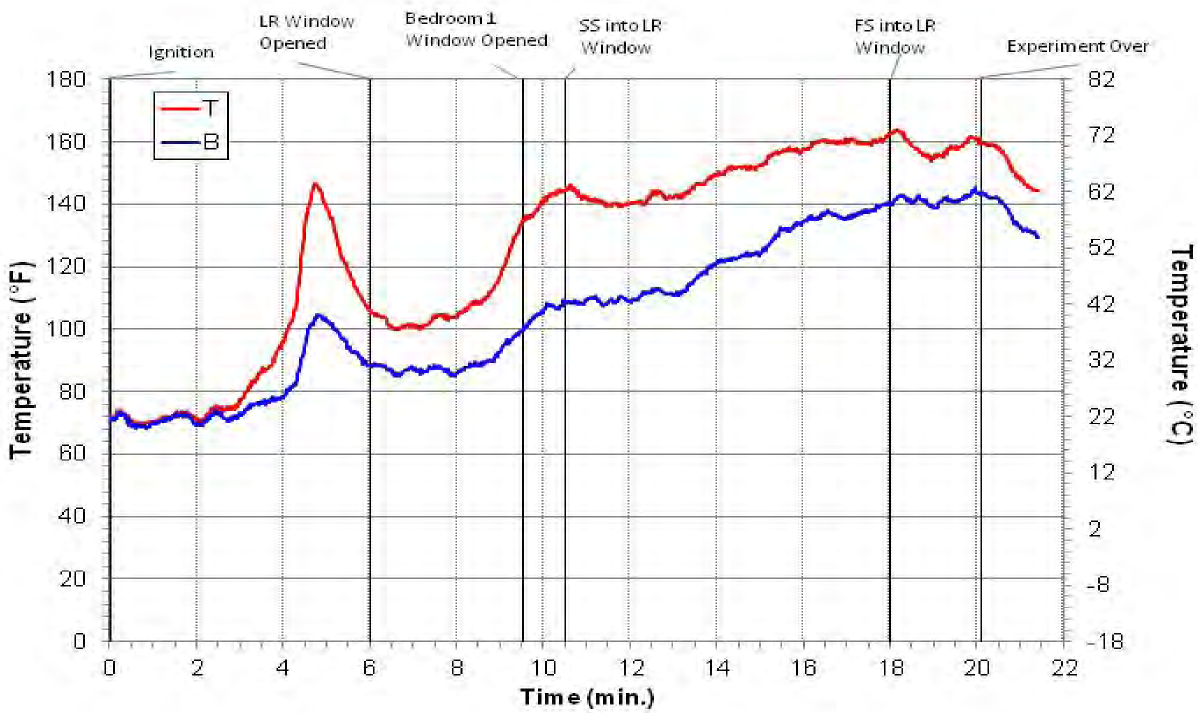


Figure E.313: Experiment 15 Vent Temperature

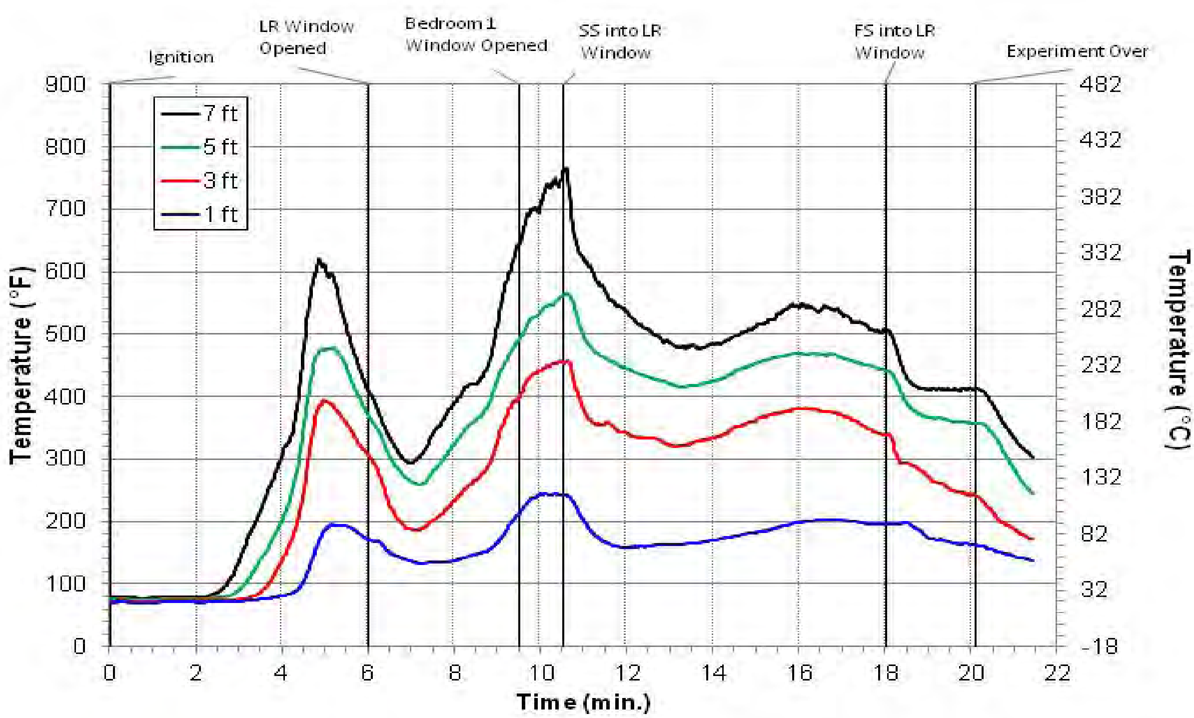


Figure E.314: Experiment 15 Bedroom 2 Temperature

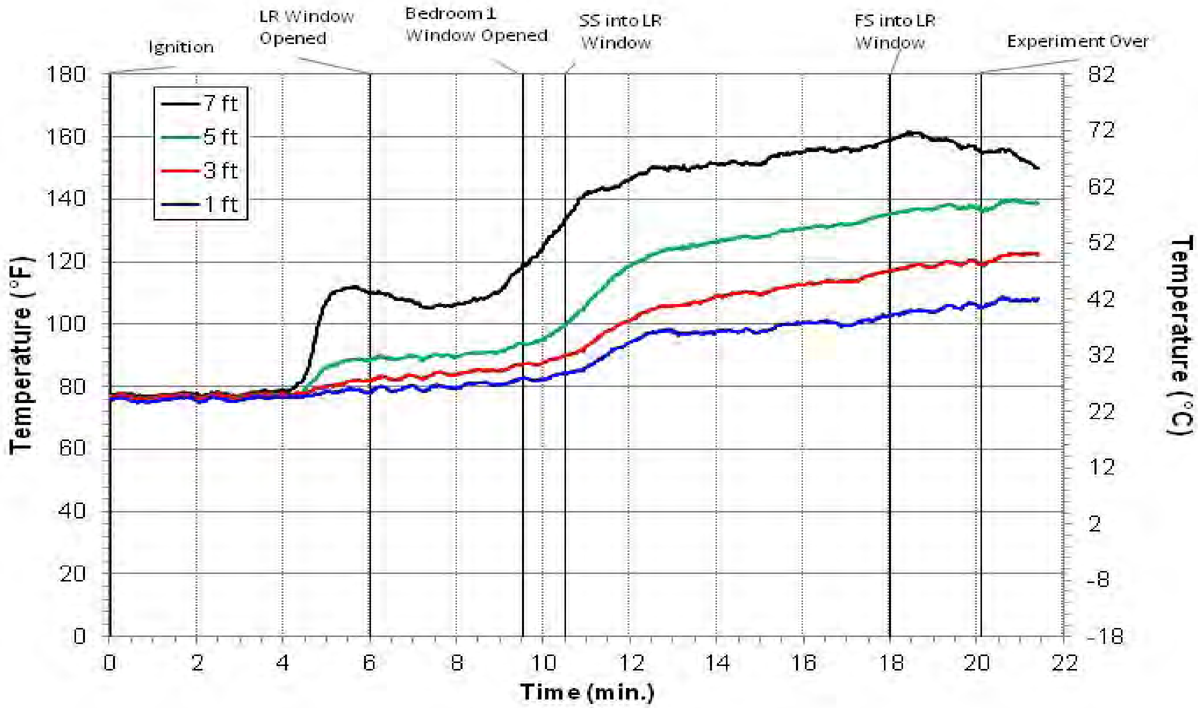


Figure E.315: Experiment 15 Bedroom 3 Temperature

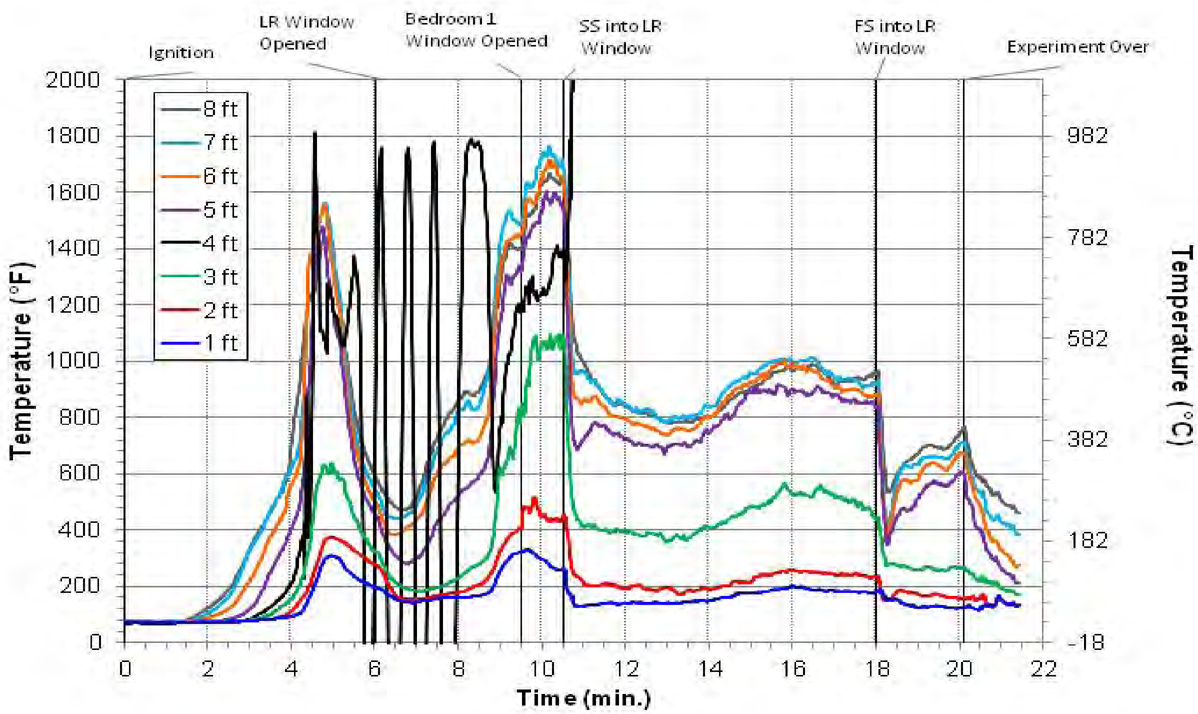


Figure E.316: Experiment 15 Hallway Temperature

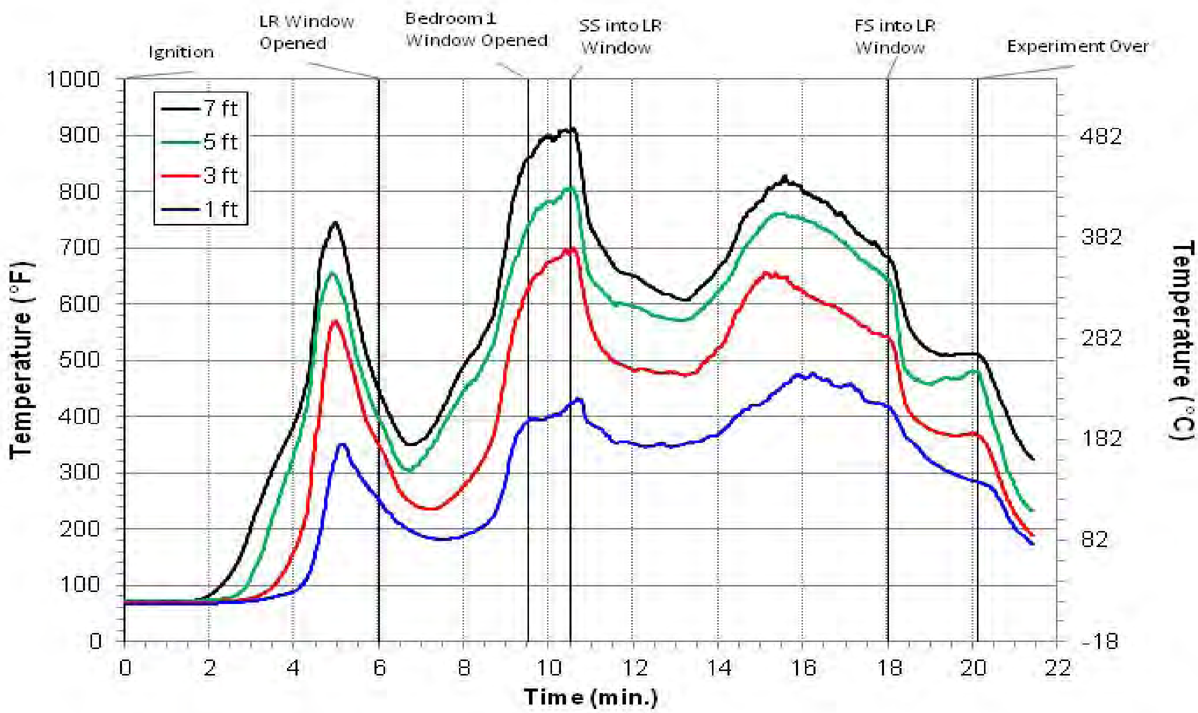


Figure E.317: Experiment 15 Dining Room Temperature

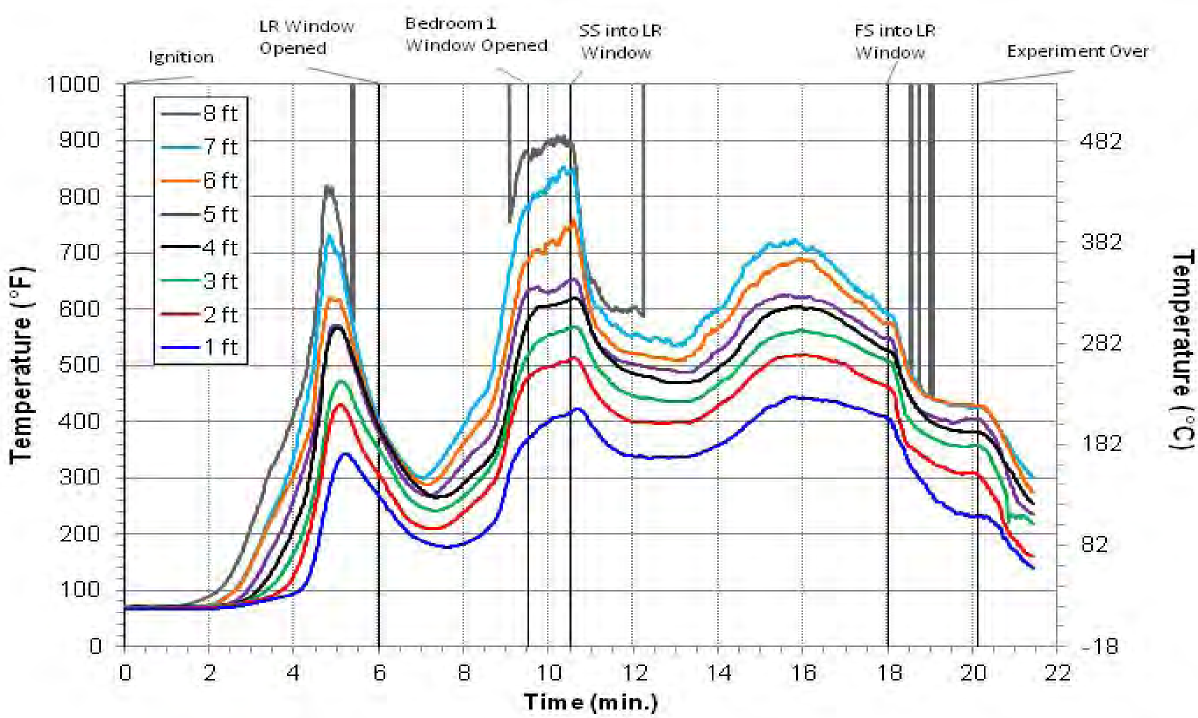


Figure E.318: Experiment 15 Kitchen Temperature

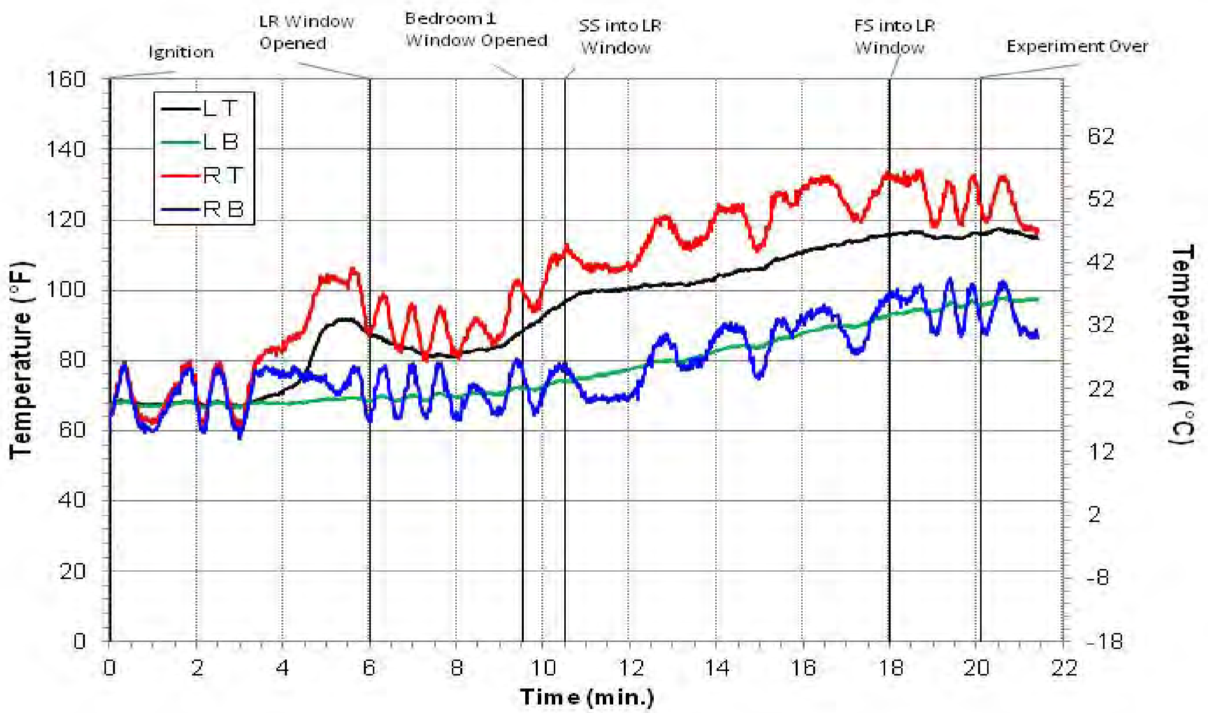


Figure E.319: Experiment 15 Attic Temperature

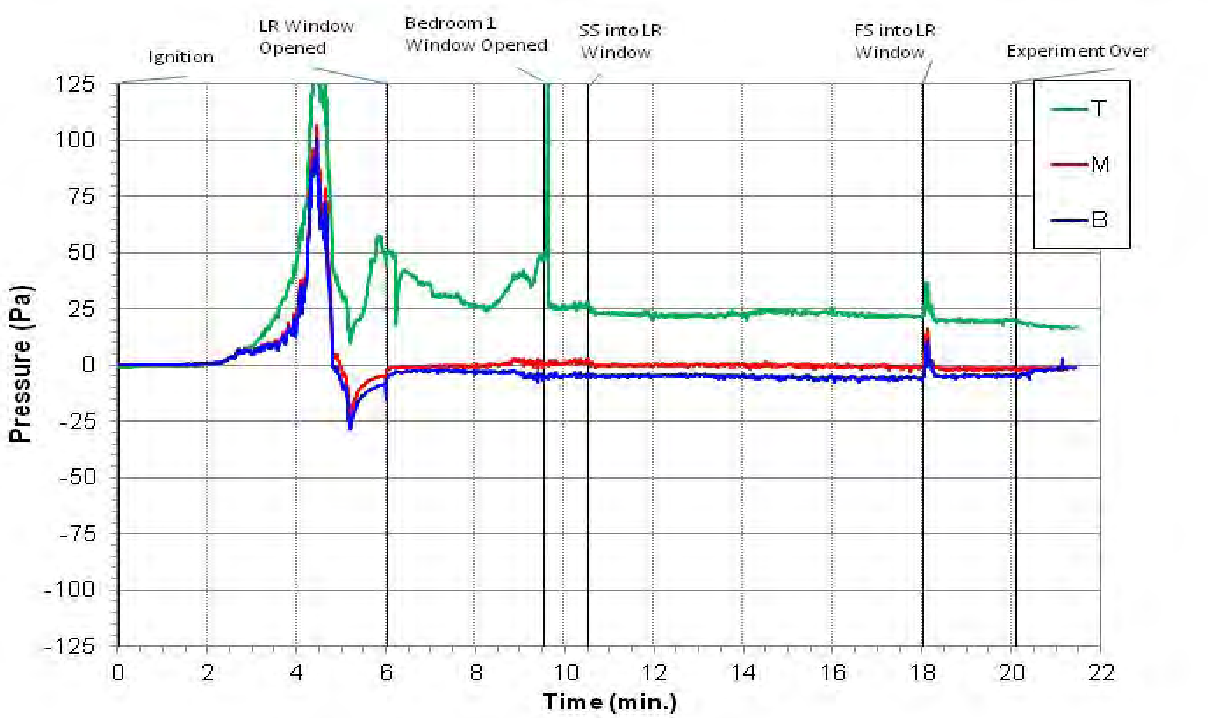


Figure E.320: Experiment 15 Living Room Pressure

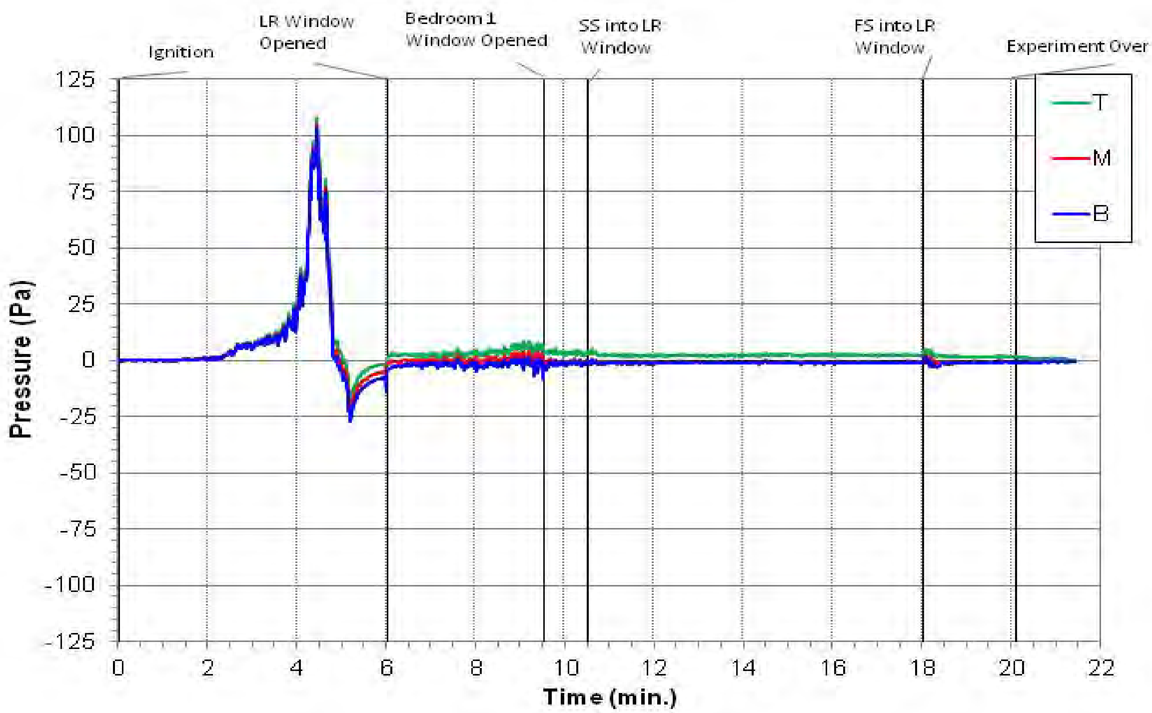


Figure E.321: Experiment 15 Bedroom 1 Pressure

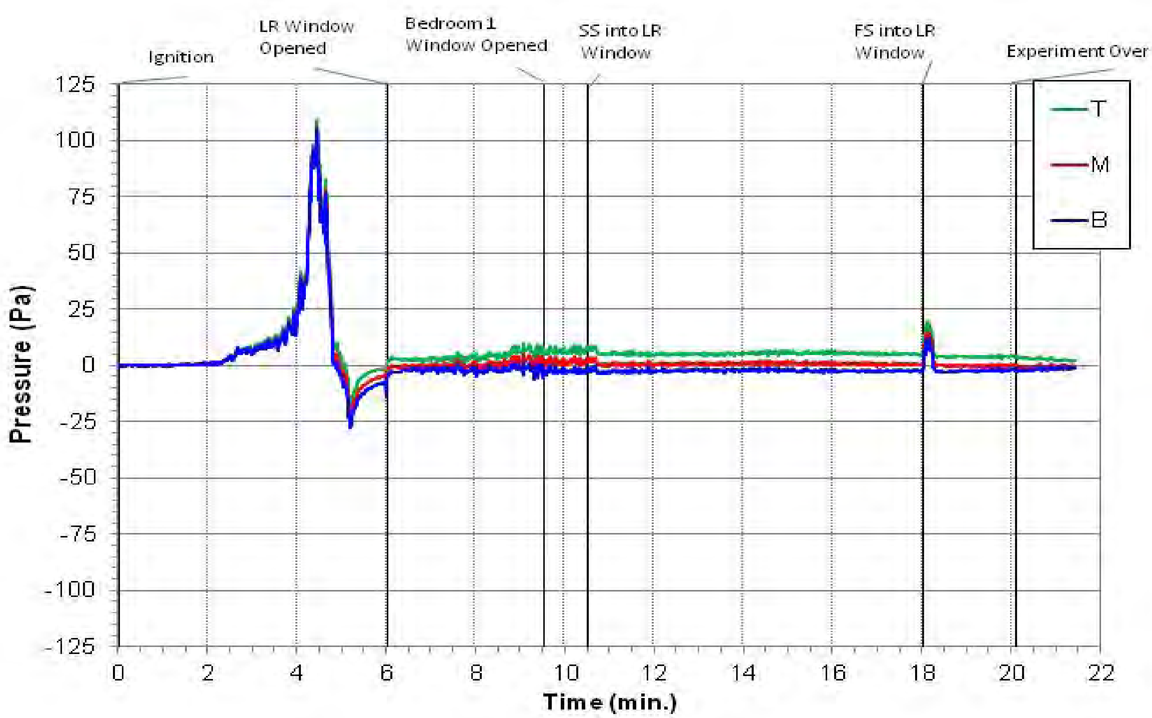


Figure E.322: Experiment 15 Bedroom 2 Pressure

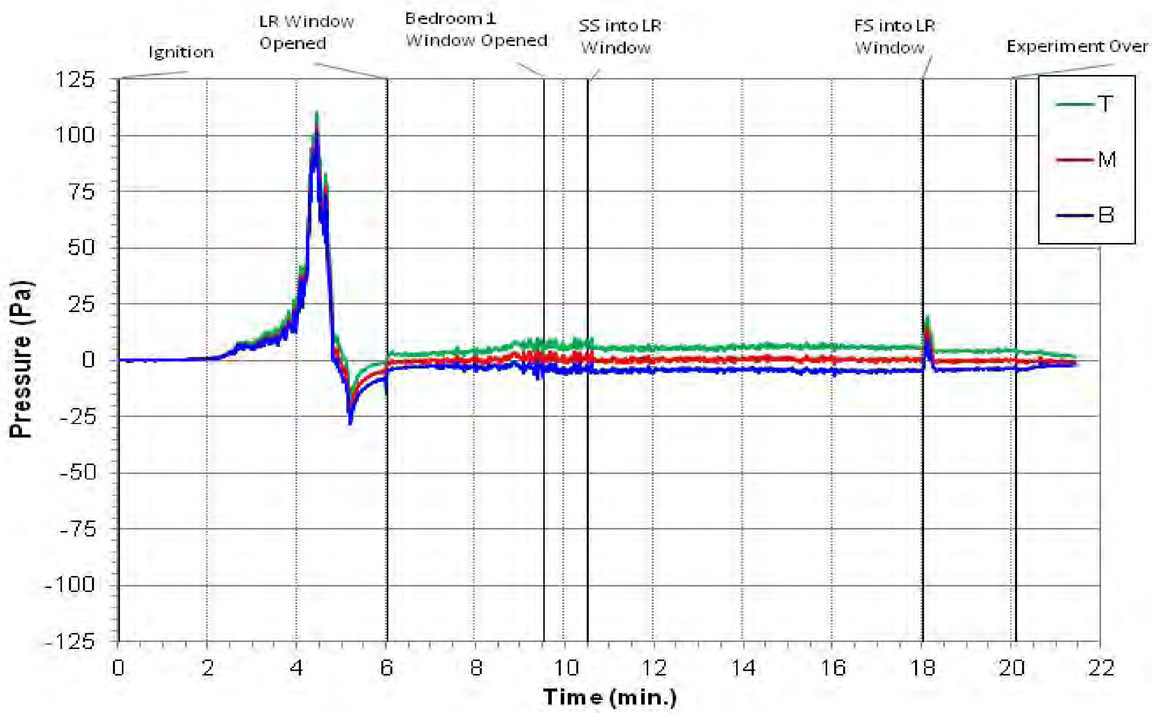


Figure E.323: Experiment 15 Kitchen Pressure

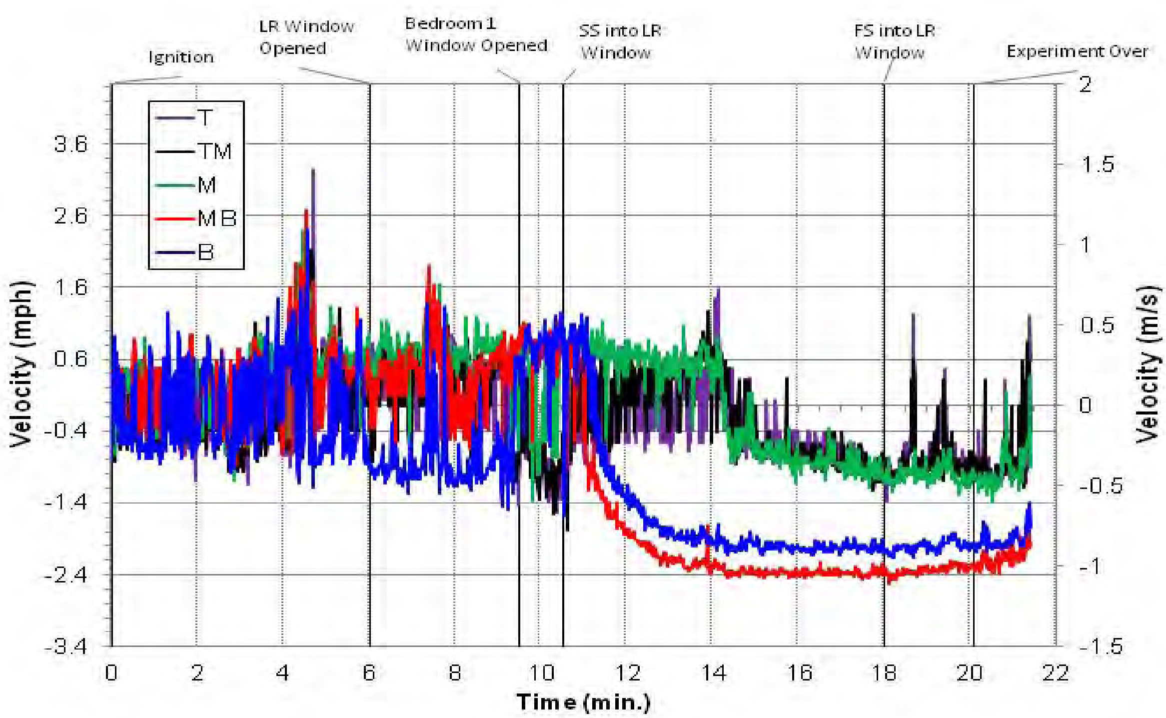


Figure E.324: Experiment 15 Front Door Velocity

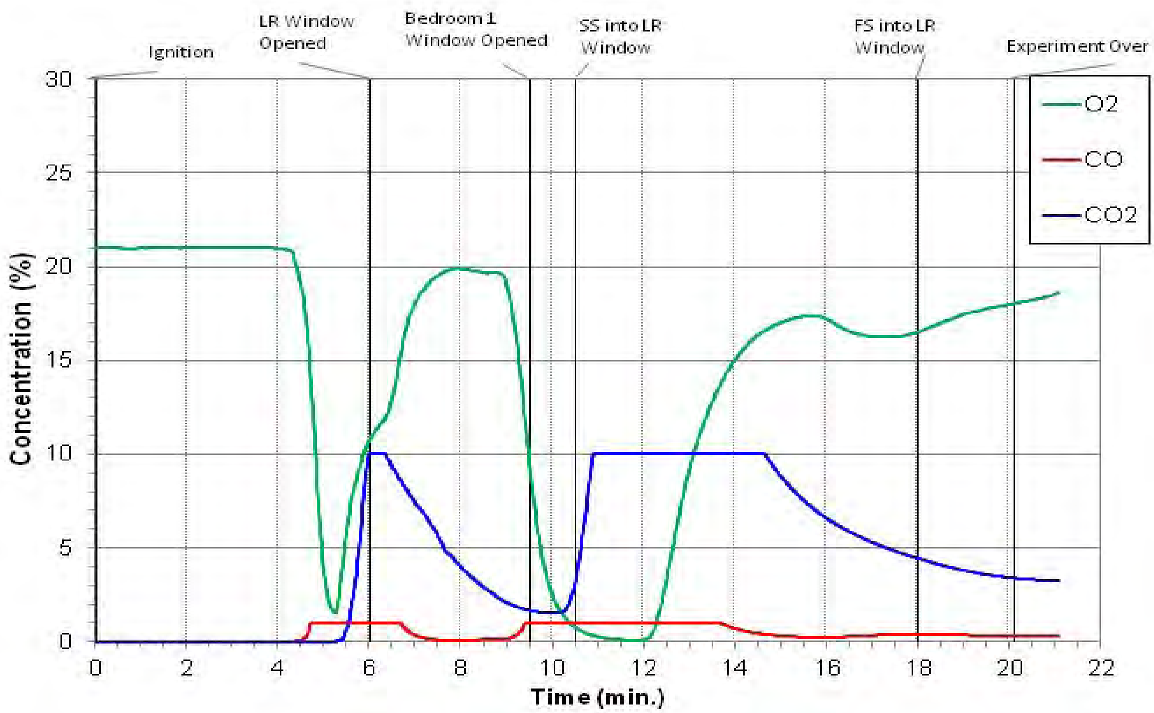


Figure E.325: Experiment 15 Living Room Gas

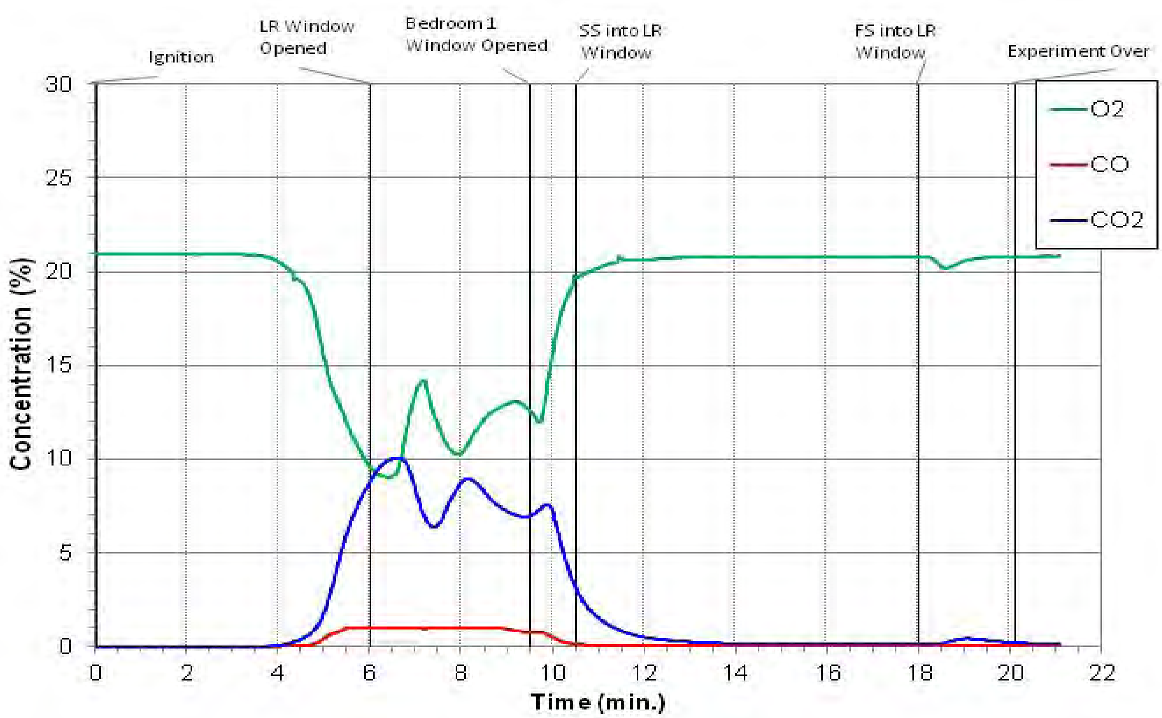


Figure E.326: Experiment 15 Bedroom 1 Gas

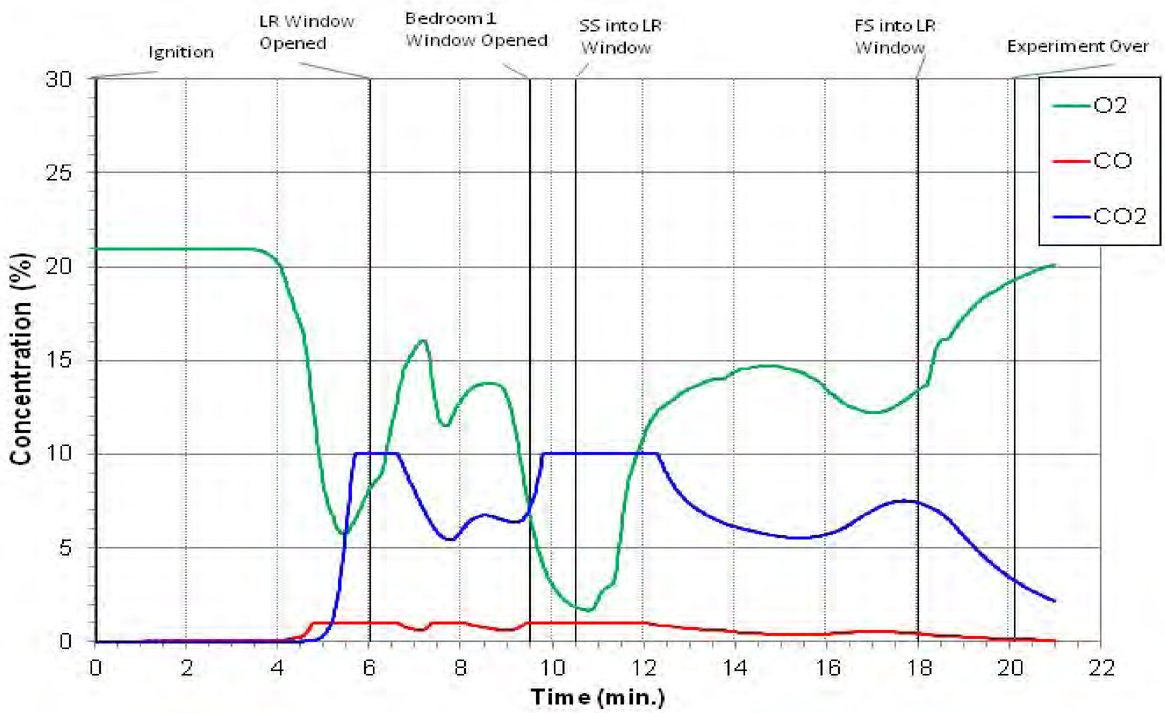


Figure E.327: Experiment 15 Bedroom 2 Gas

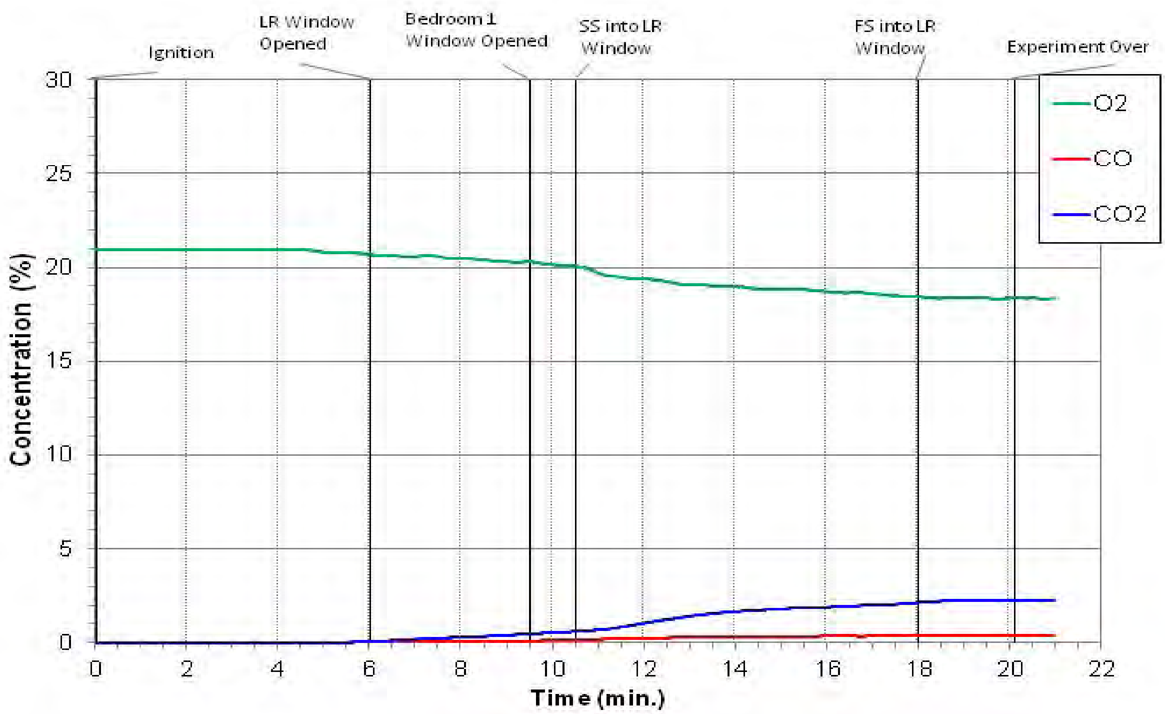


Figure E.328: Experiment 15 Bedroom 3 Gas

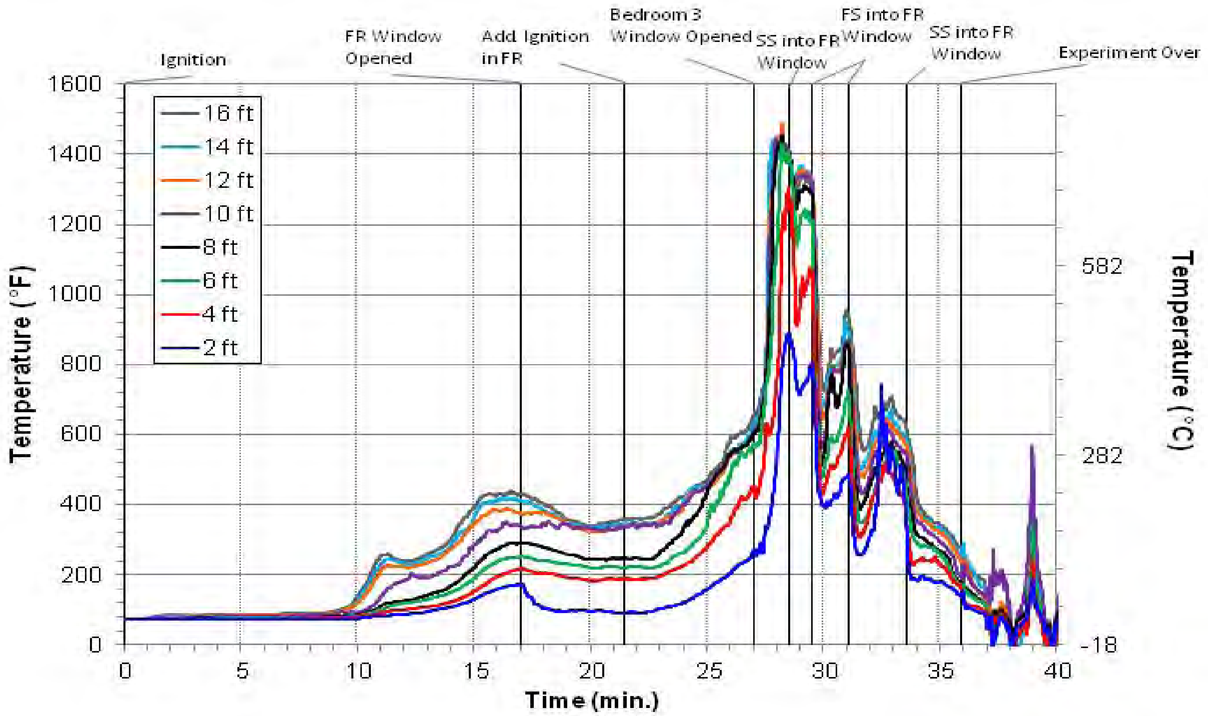


Figure E.329: Experiment 16 Family Room Temperature

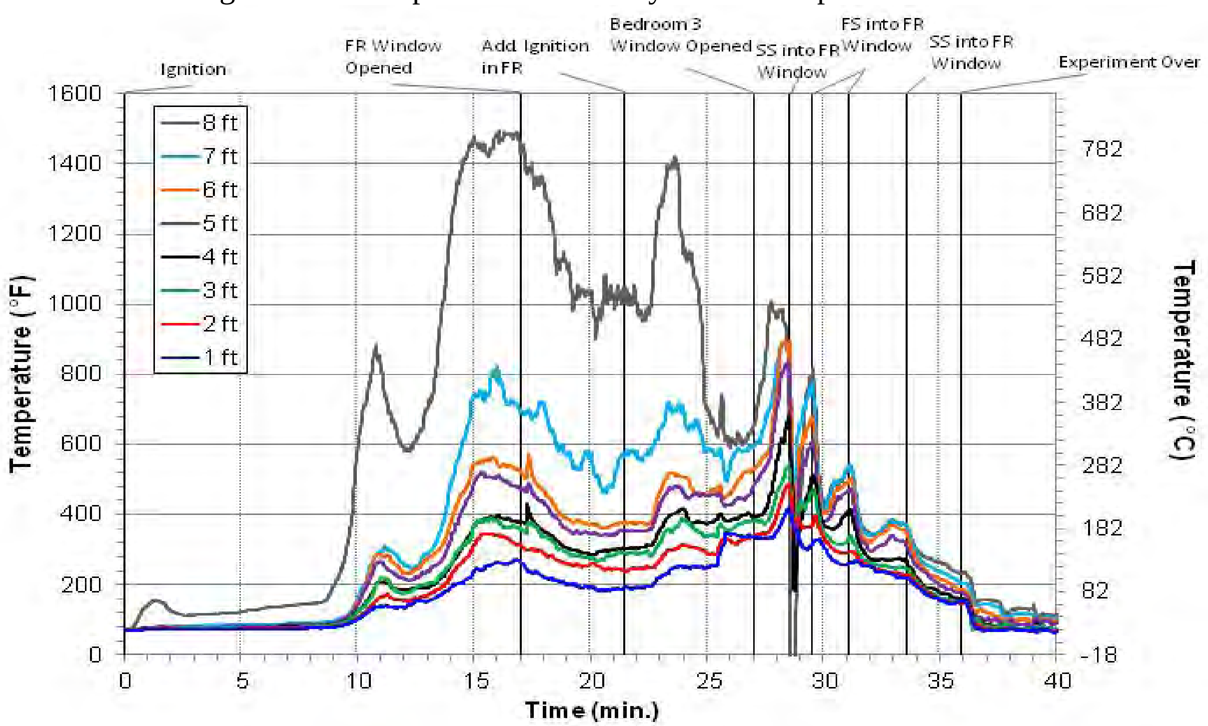


Figure E.330: Experiment 16 Kitchen Temperature

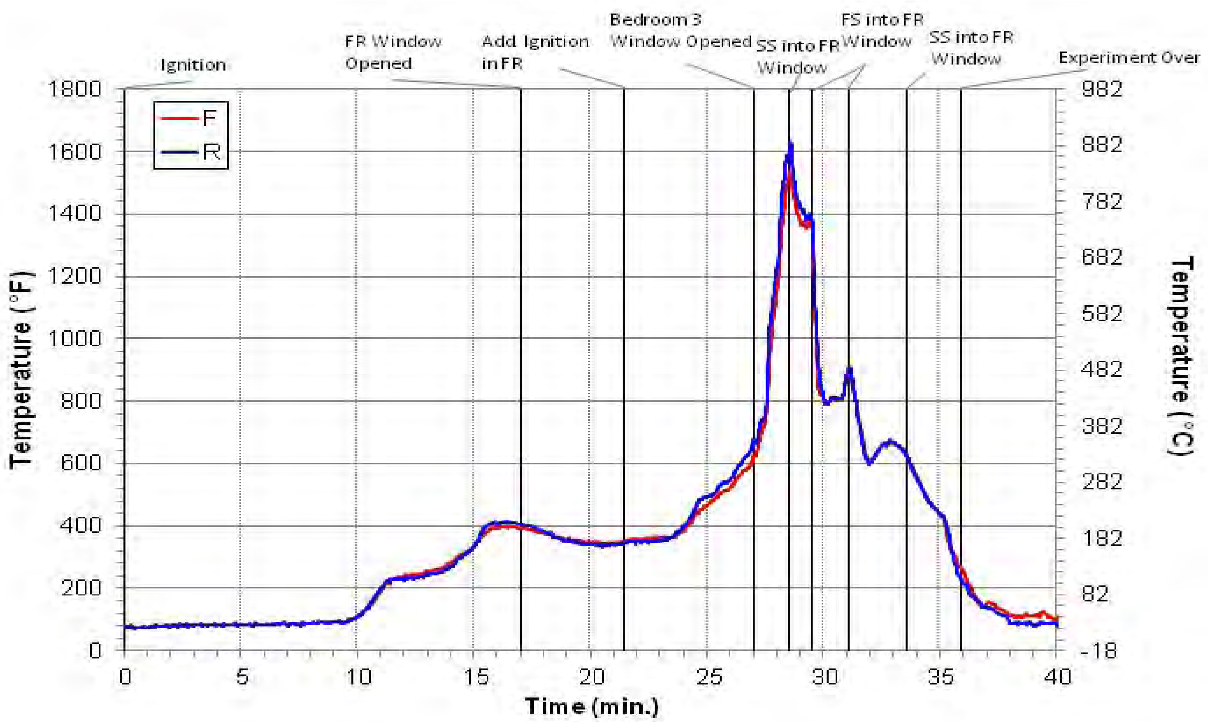


Figure E.331: Experiment 16 Vent Temperature

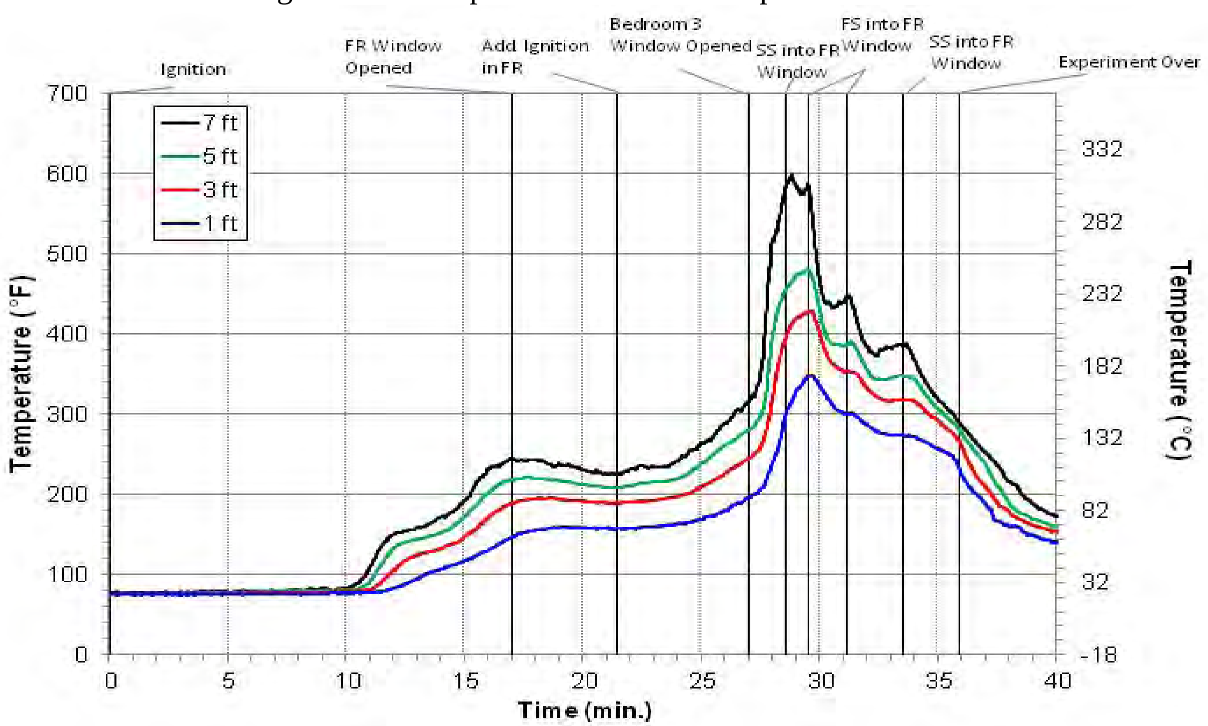


Figure E.332: Experiment 16 Bedroom 1 Temperature

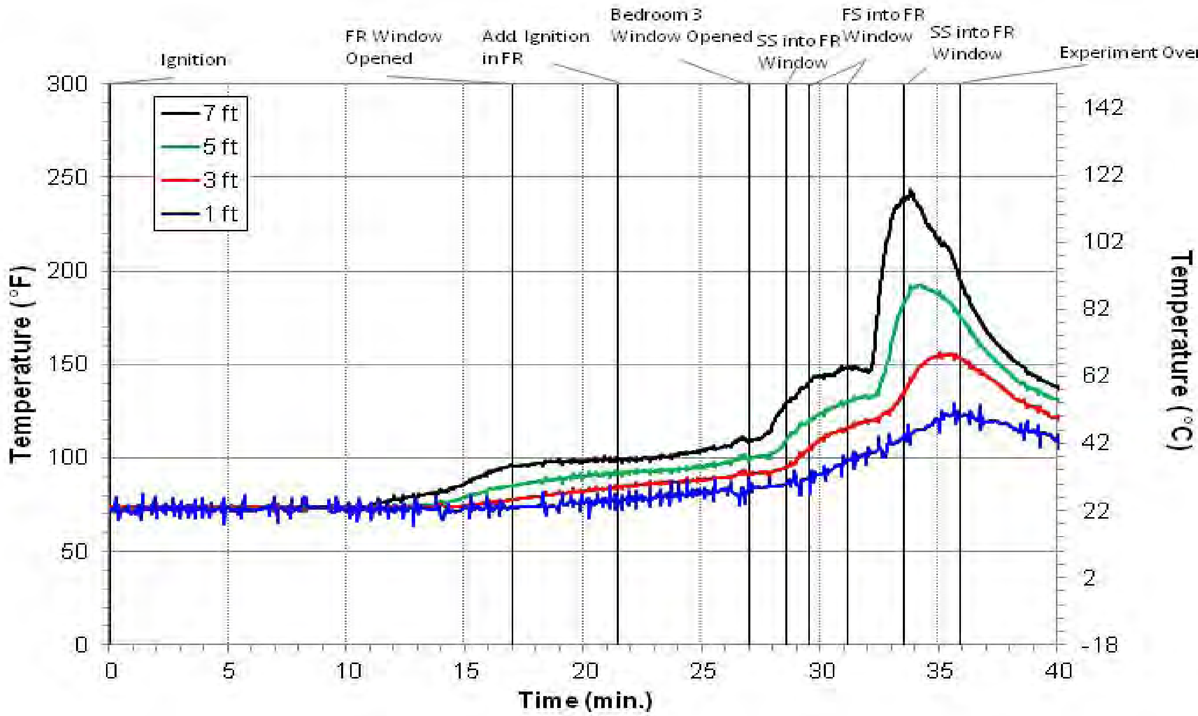


Figure E.333: Experiment 16 Bedroom 2 Temperature

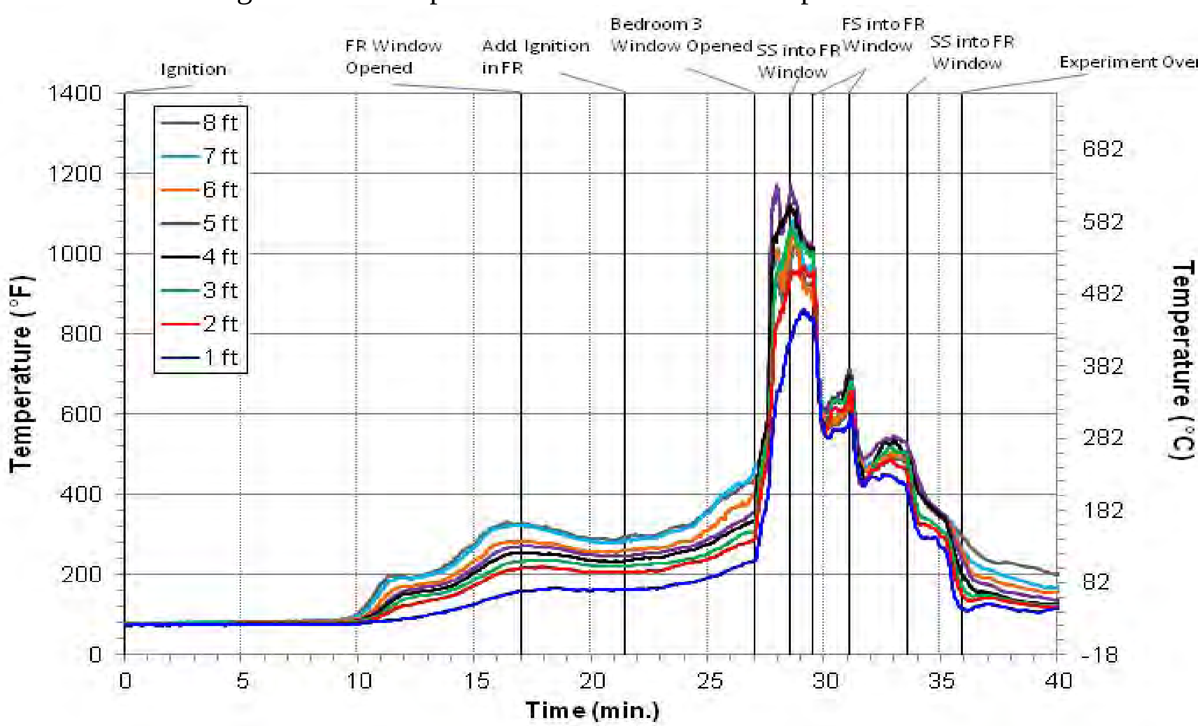


Figure E.334: Experiment 16 Bedroom 3 Temperature

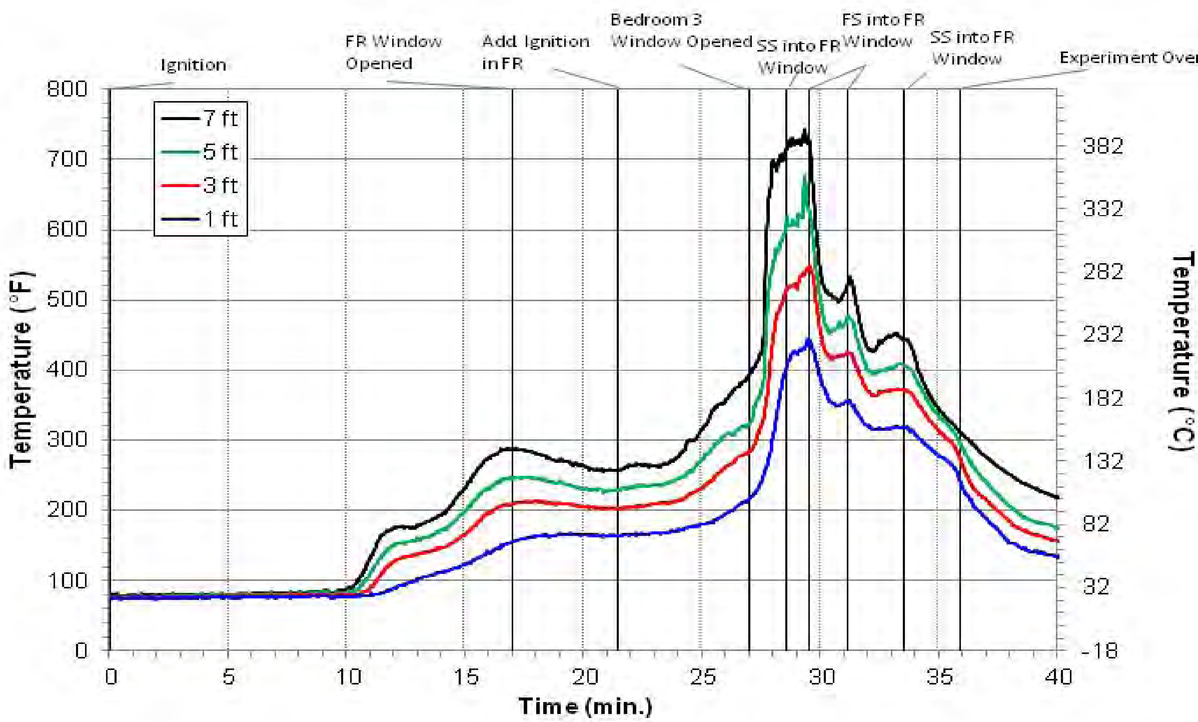


Figure E.335: Experiment 16 Bedroom 4 Temperature

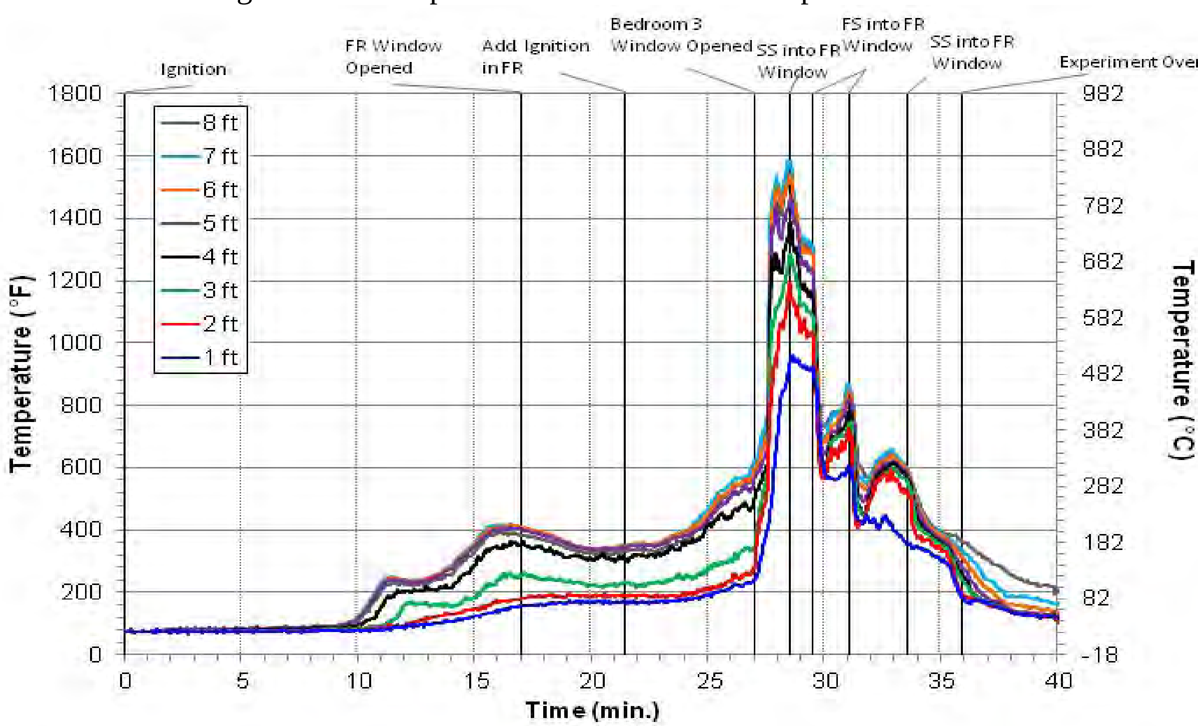


Figure E.336: Experiment 16 Hallway Temperature

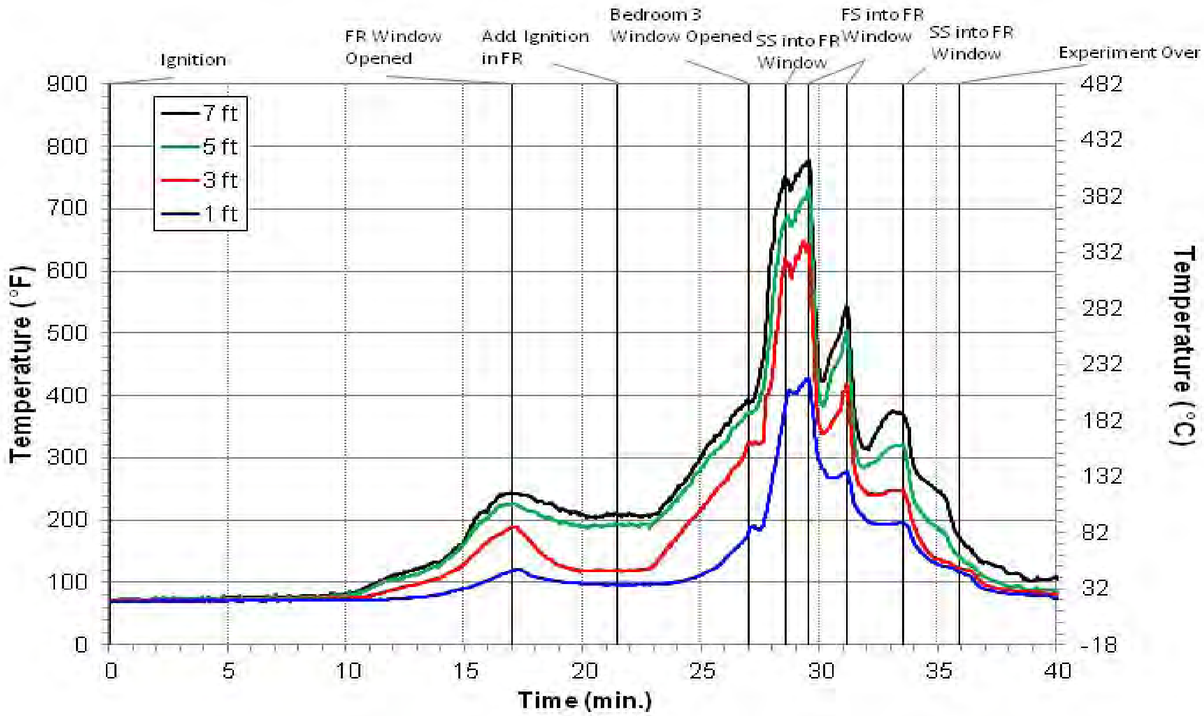


Figure E.337: Experiment 16 Dining Room Temperature

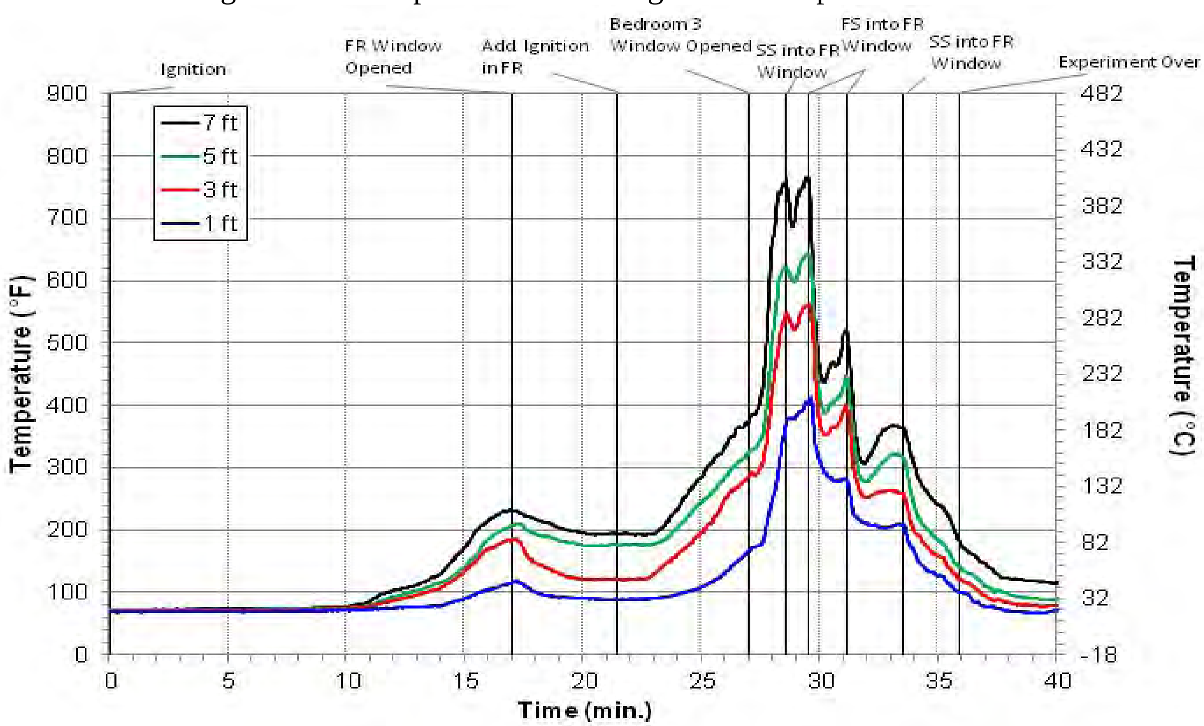


Figure E.338: Experiment 16 Living Room Temperature

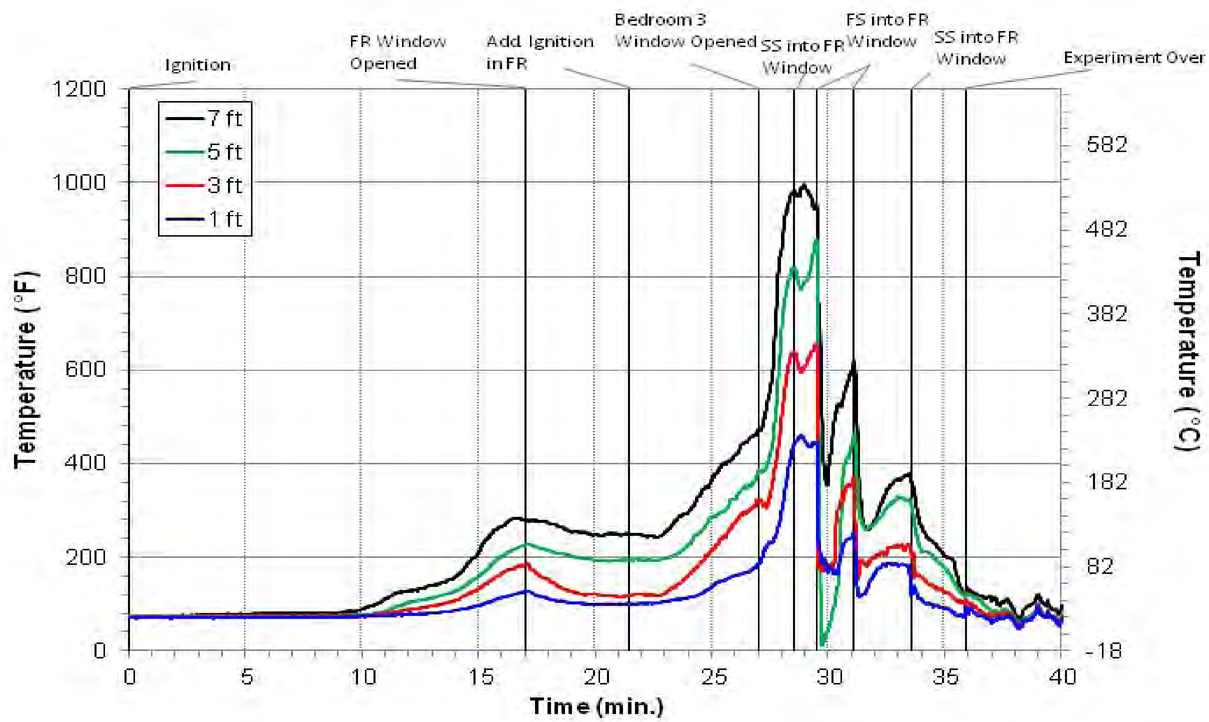


Figure E.339: Experiment 16 Foyer Temperature

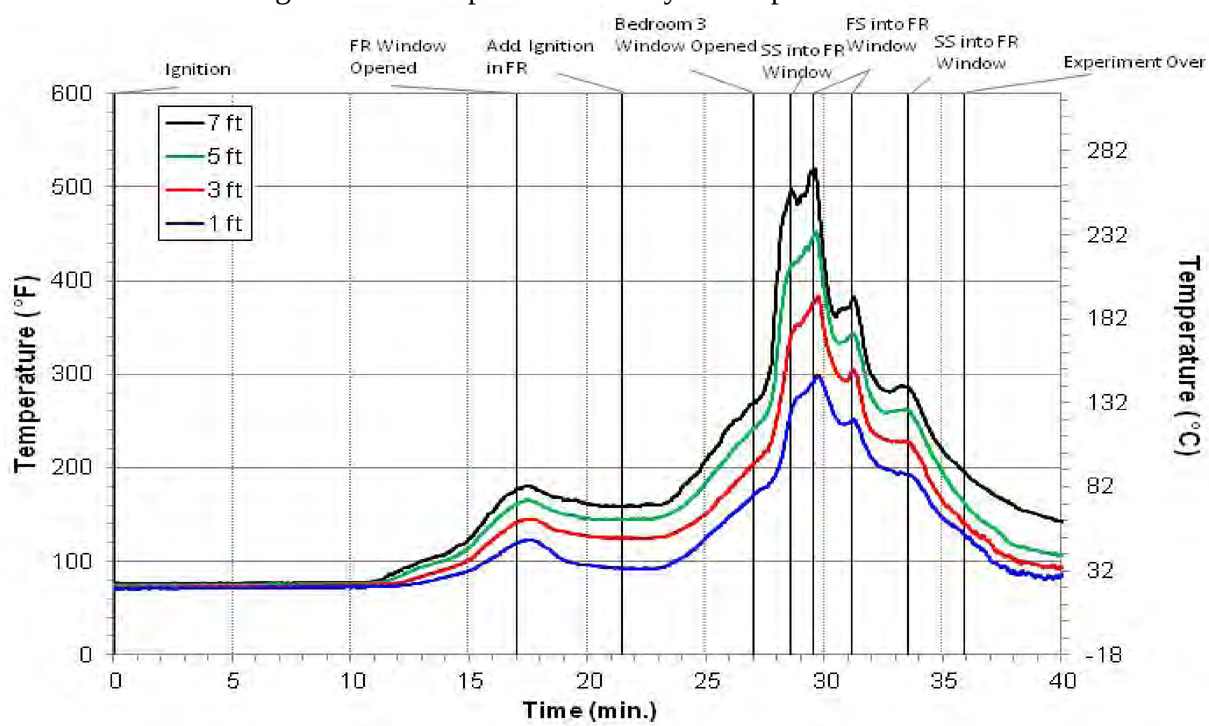


Figure E.340: Experiment 16 Den Temperature

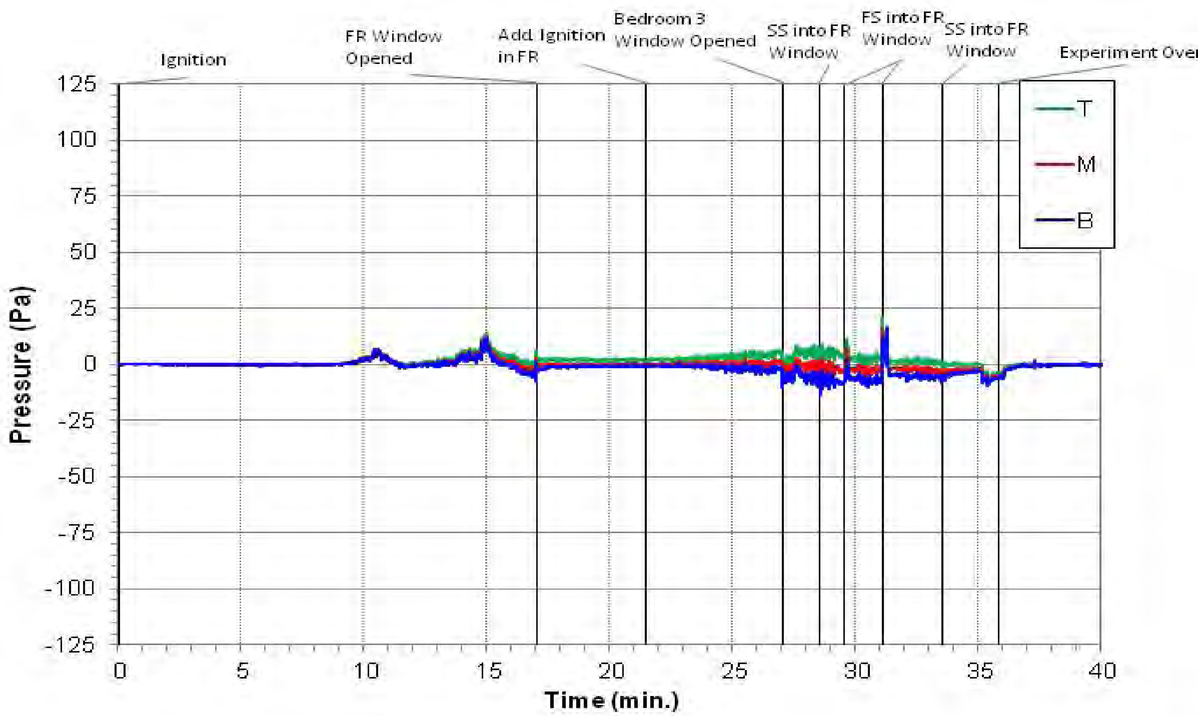


Figure E.341: Experiment 16 Living Room Pressure

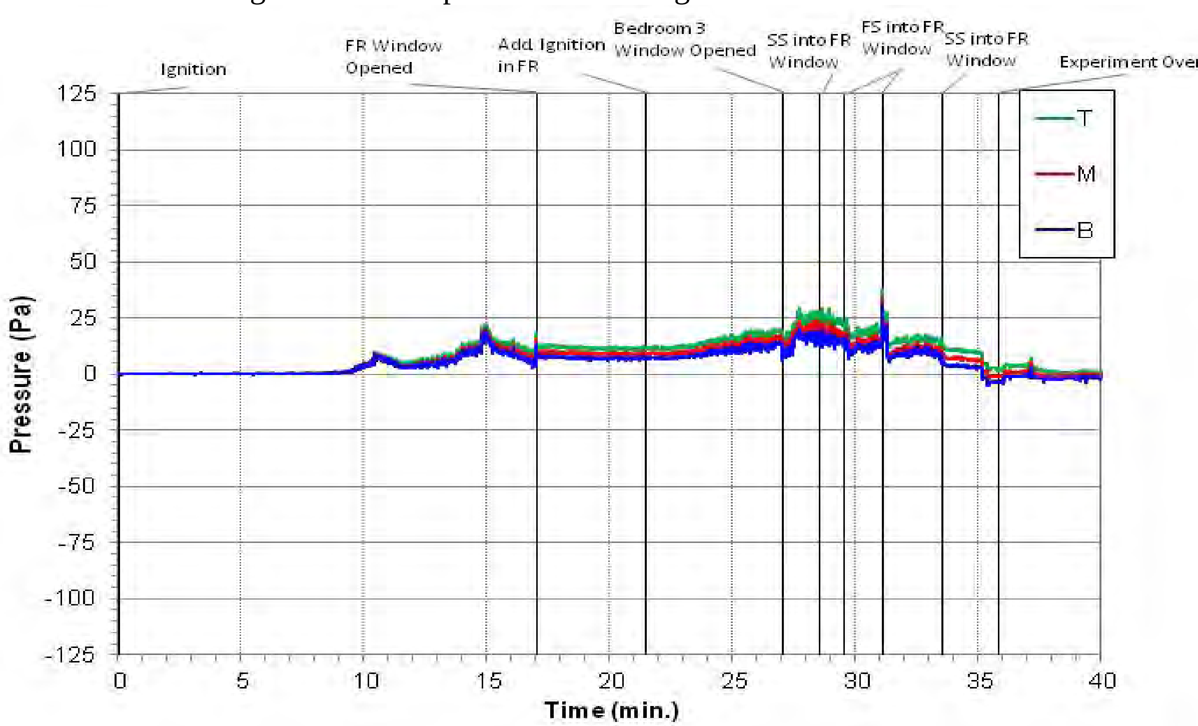


Figure E.342: Experiment 16 Bedroom 2 Pressure

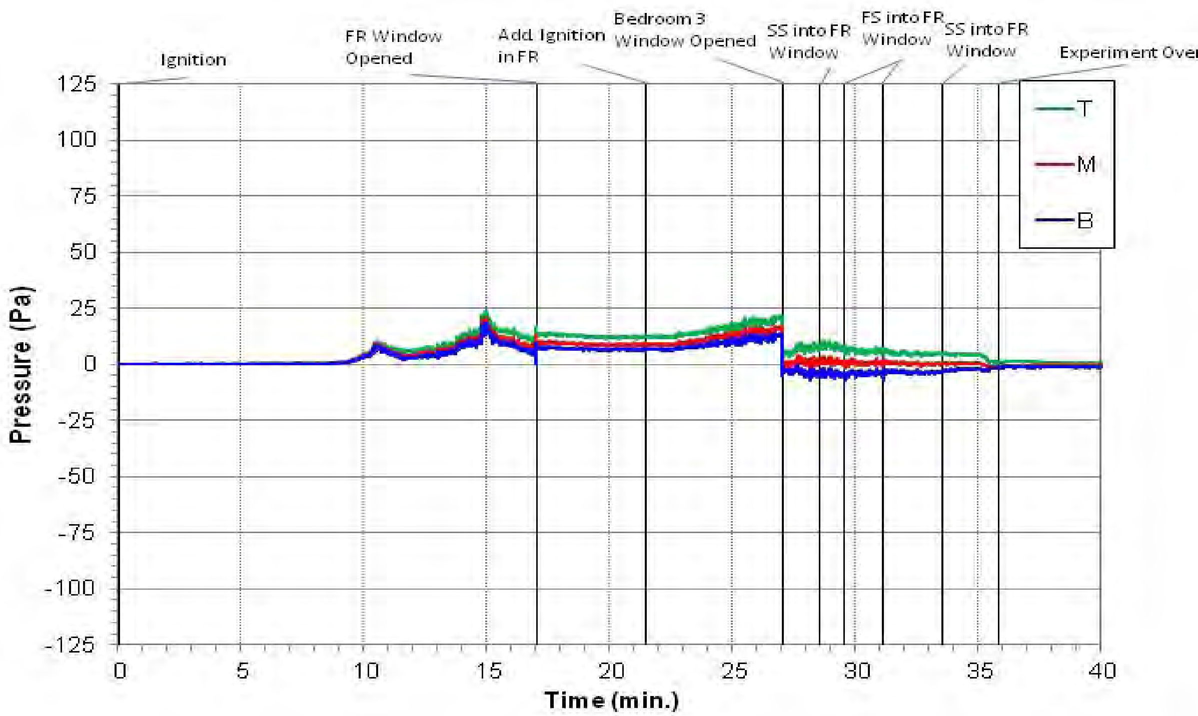


Figure E.343: Experiment 16 Bedroom 3 Pressure

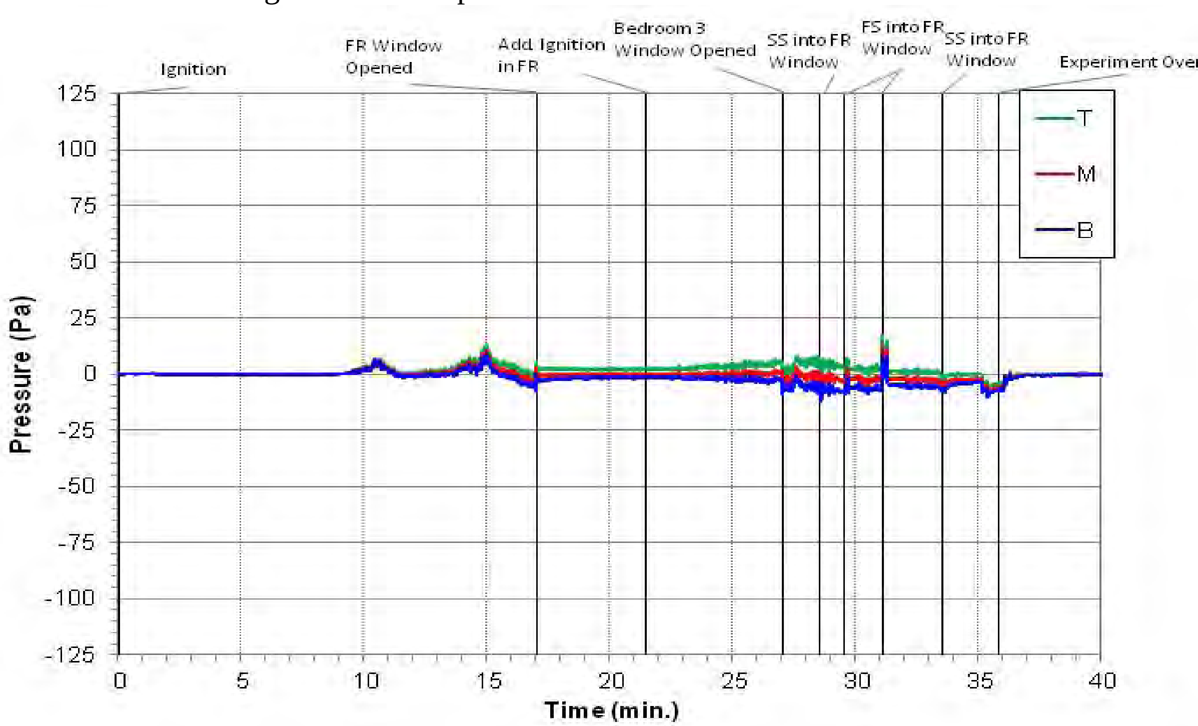


Figure E.344: Experiment 16 Kitchen Pressure

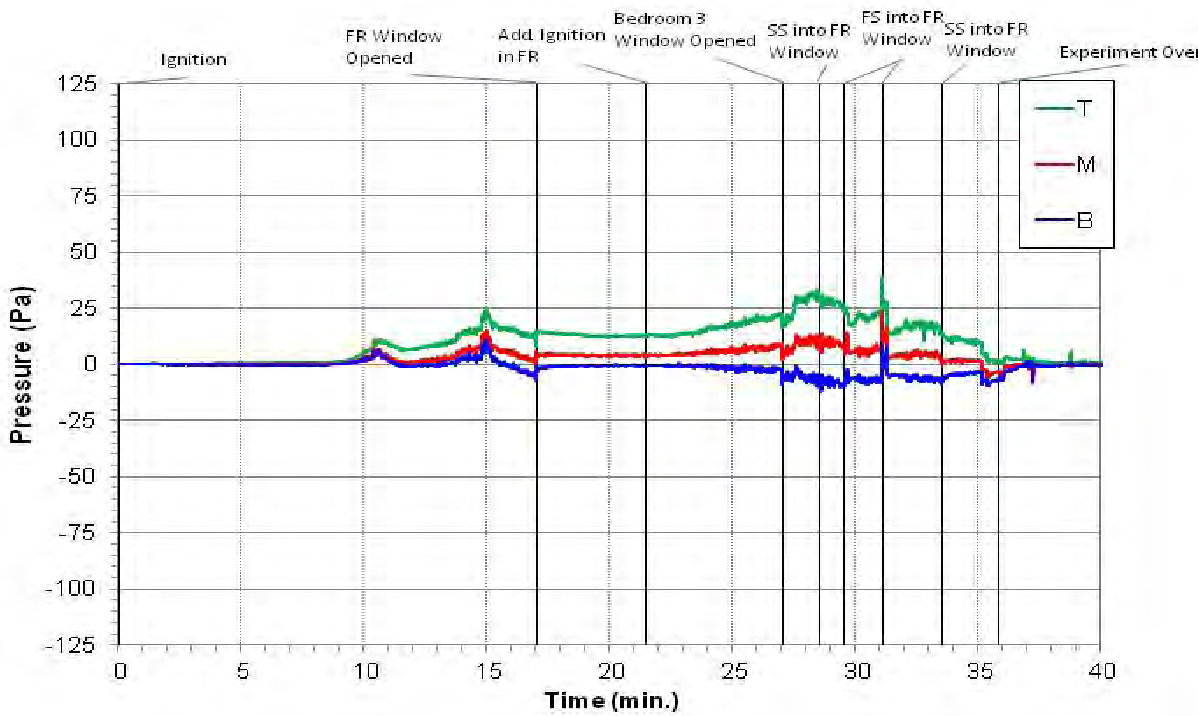


Figure E.345: Experiment 16 Family Room Pressure

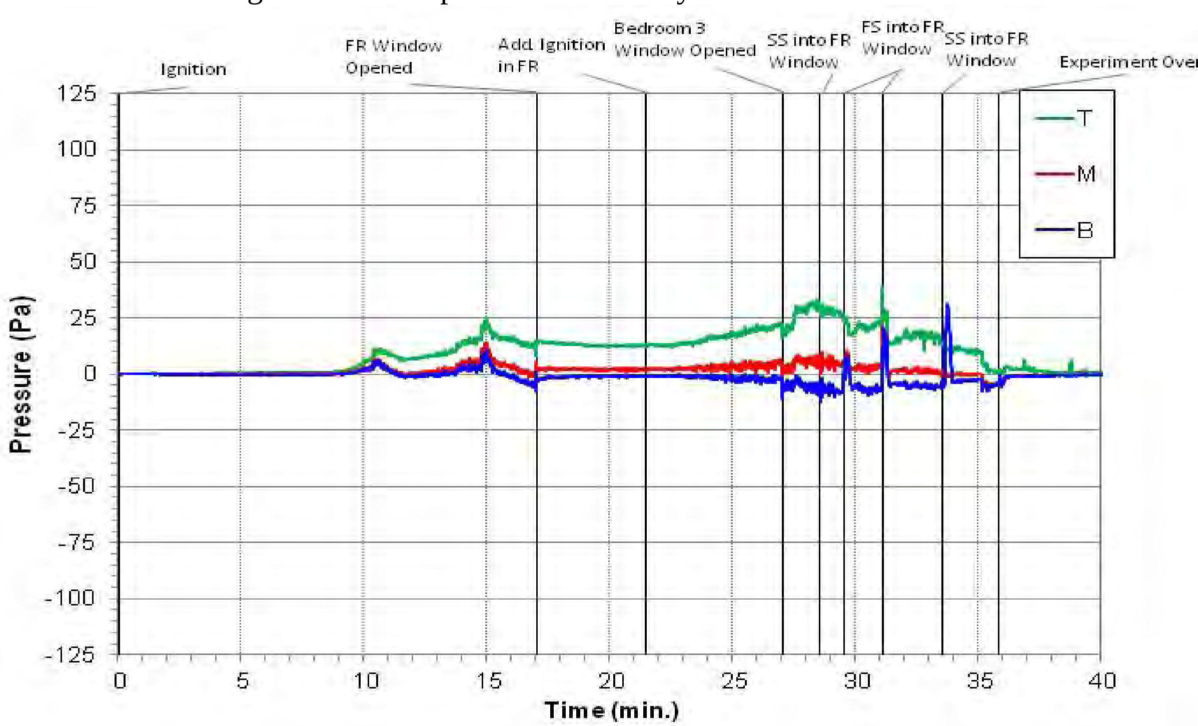


Figure E.346: Experiment 16 Foyer Pressure

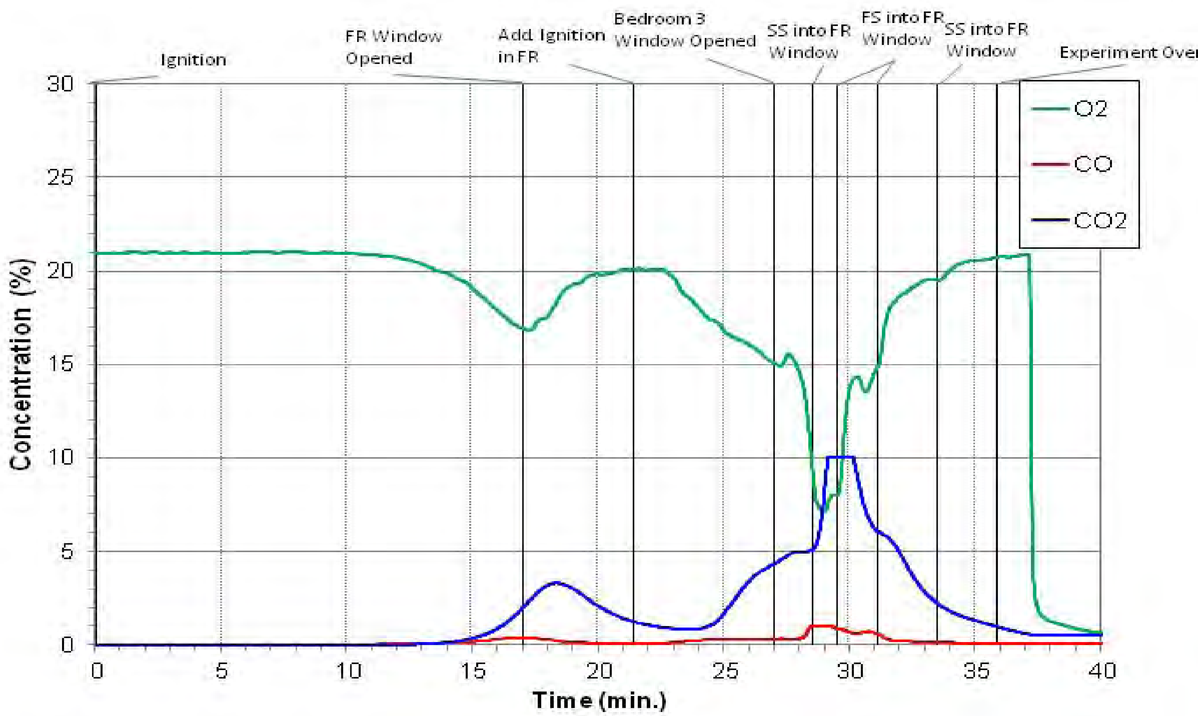


Figure E.347: Experiment 16 Front Door Gas

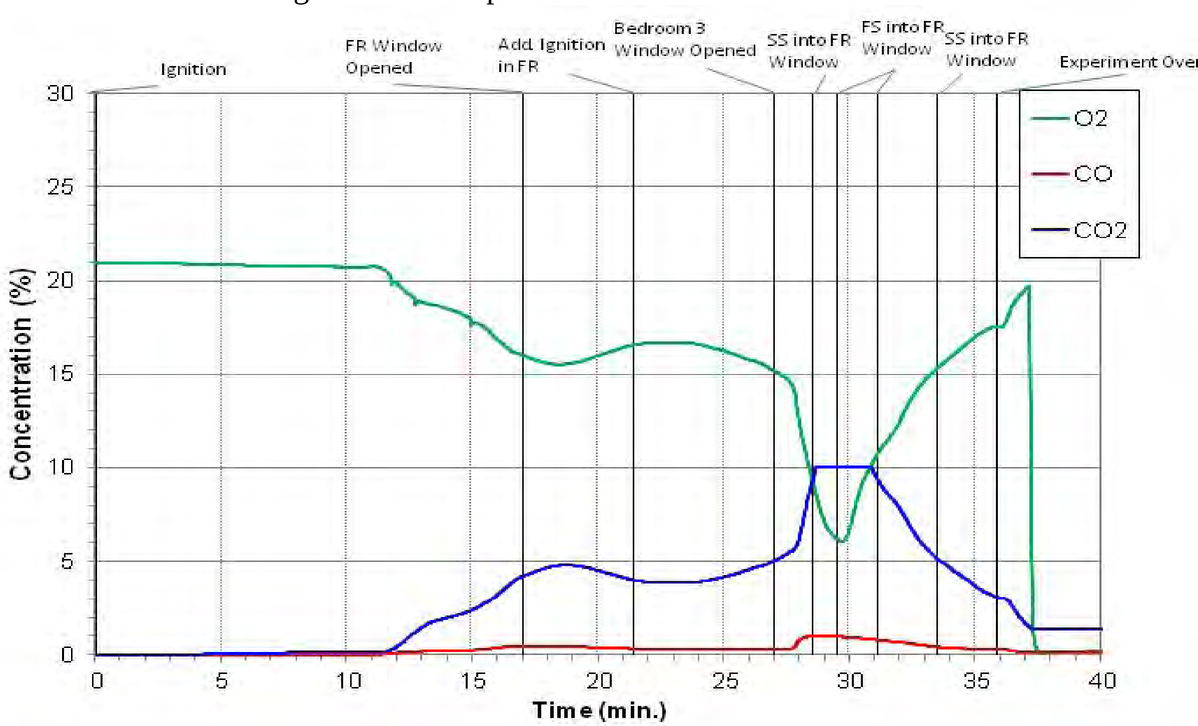


Figure E.348: Experiment 16 Bedroom 1 Gas

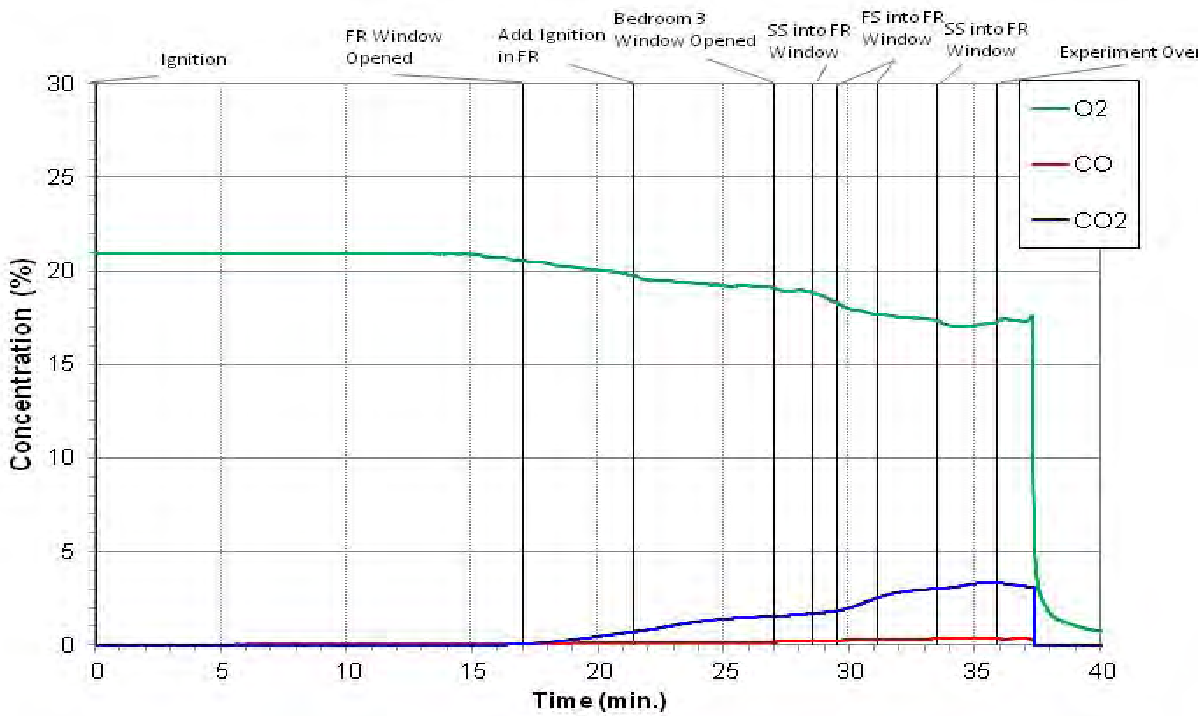


Figure E.349: Experiment 16 Bedroom 2 Gas

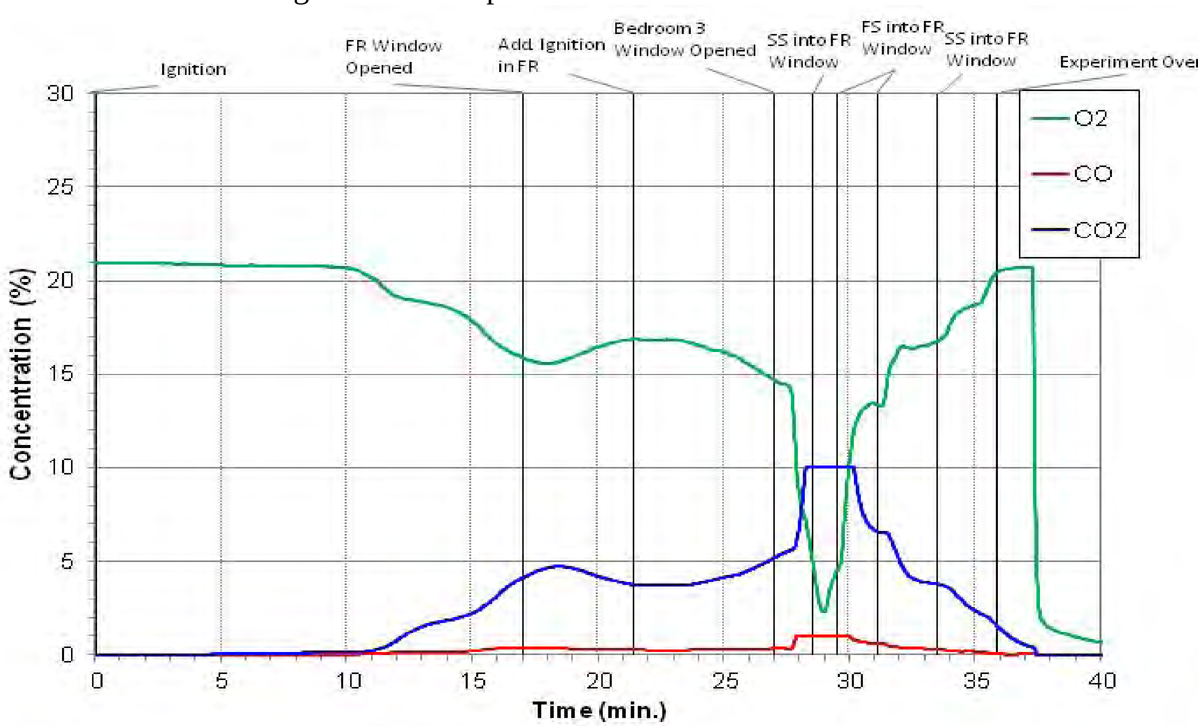


Figure E.350: Experiment 16 Bedroom 3 Gas

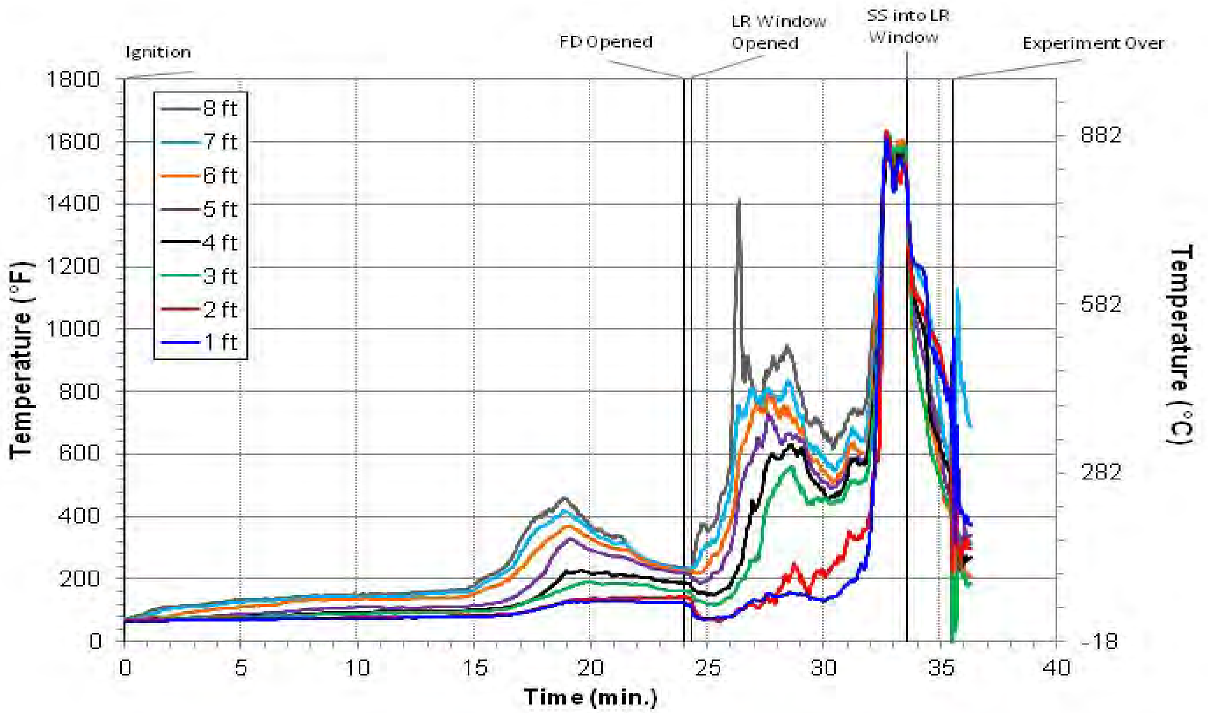


Figure E.351: Experiment 17 Living Room Temperature

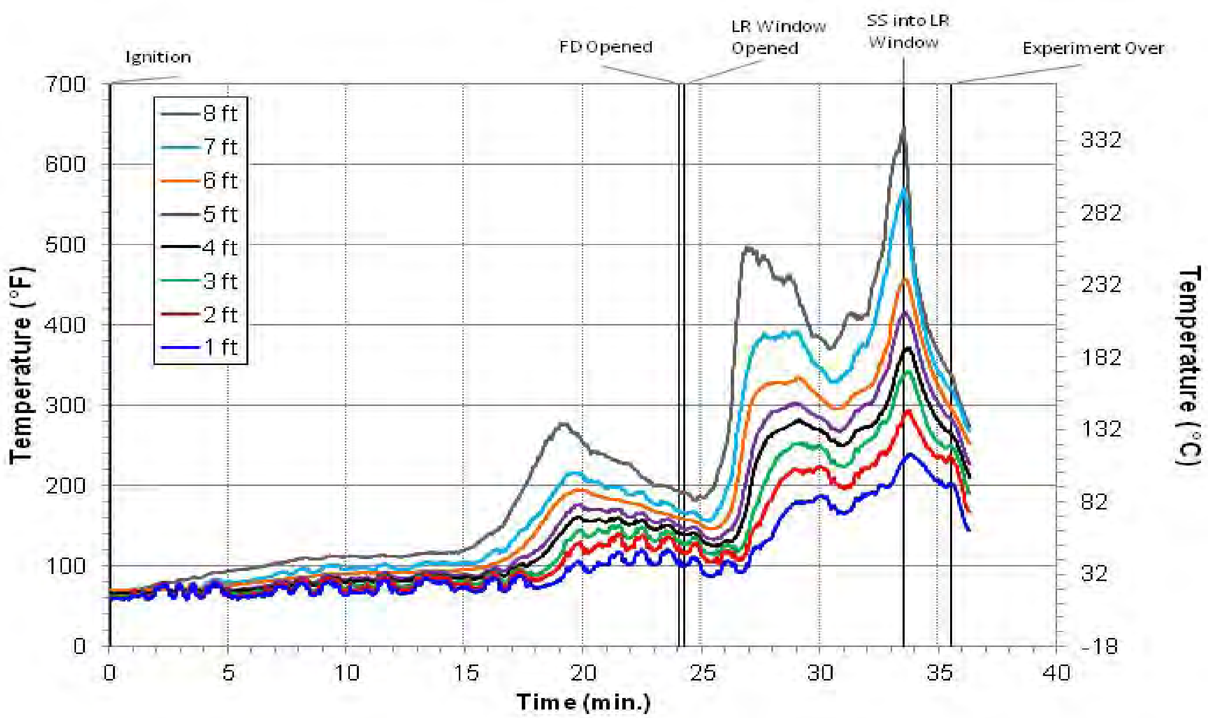


Figure E.352: Experiment 17 Bedroom 1 Temperature

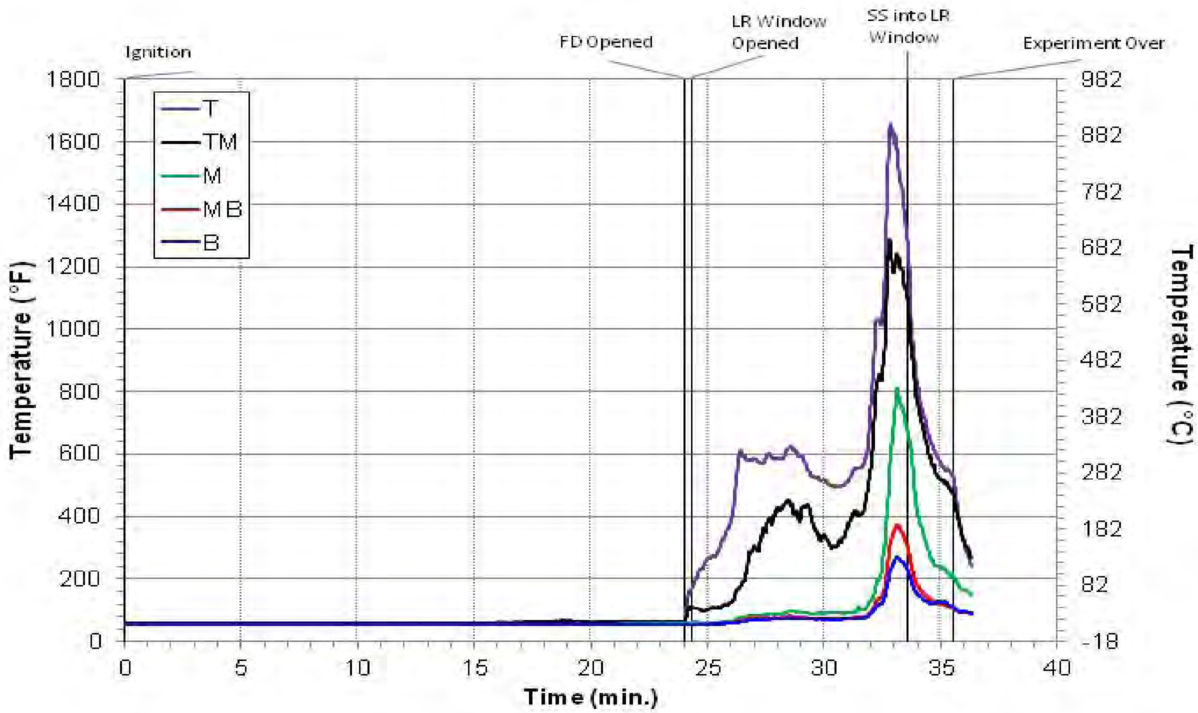


Figure E.353: Experiment 17 Front Door Temperature

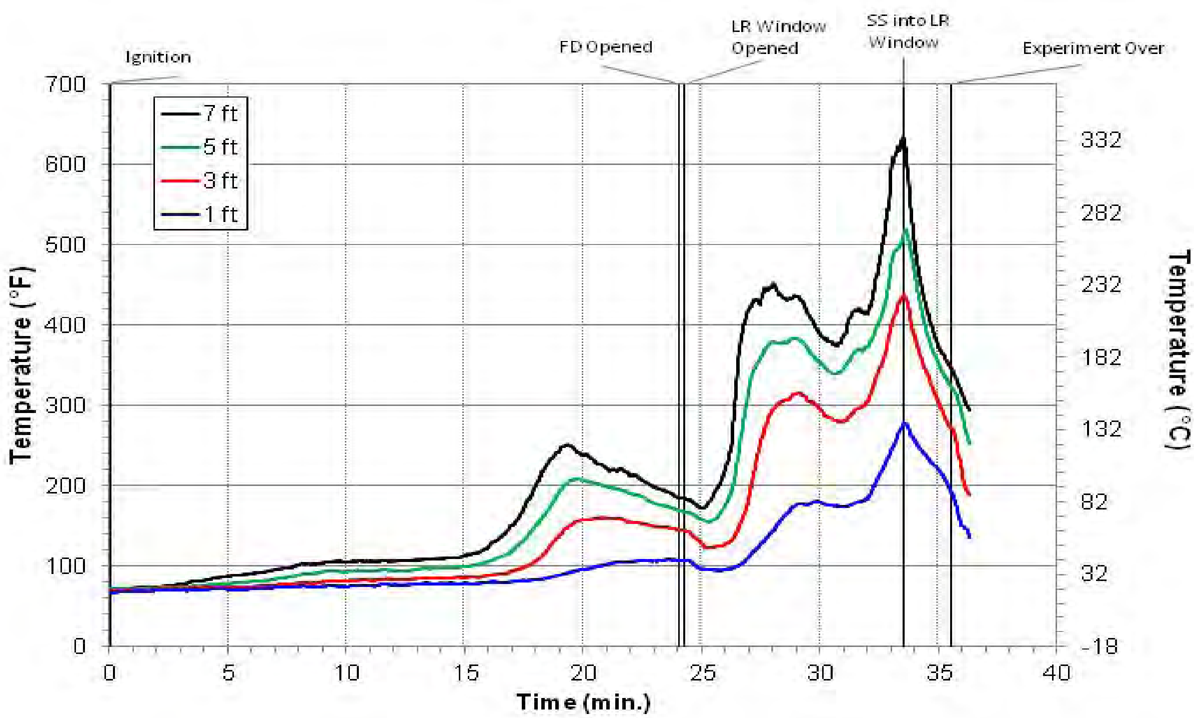


Figure E.354: Experiment 17 Bedroom 2 Temperature

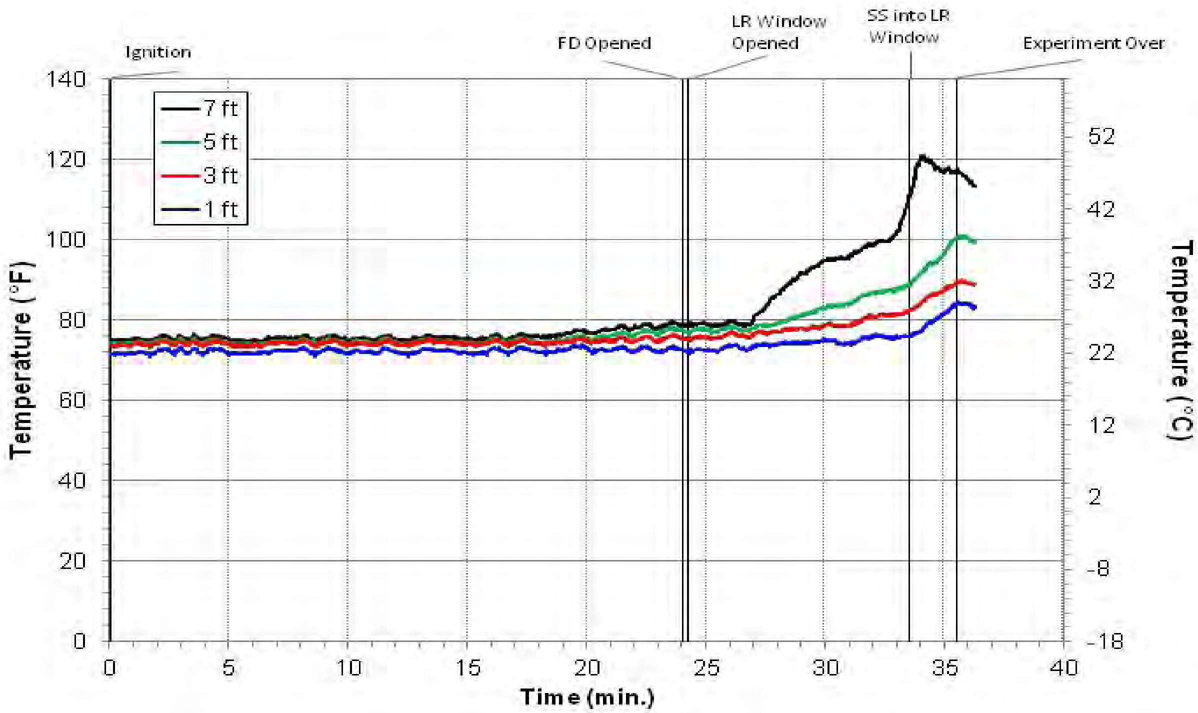


Figure E.355: Experiment 17 Bedroom 3 Temperature

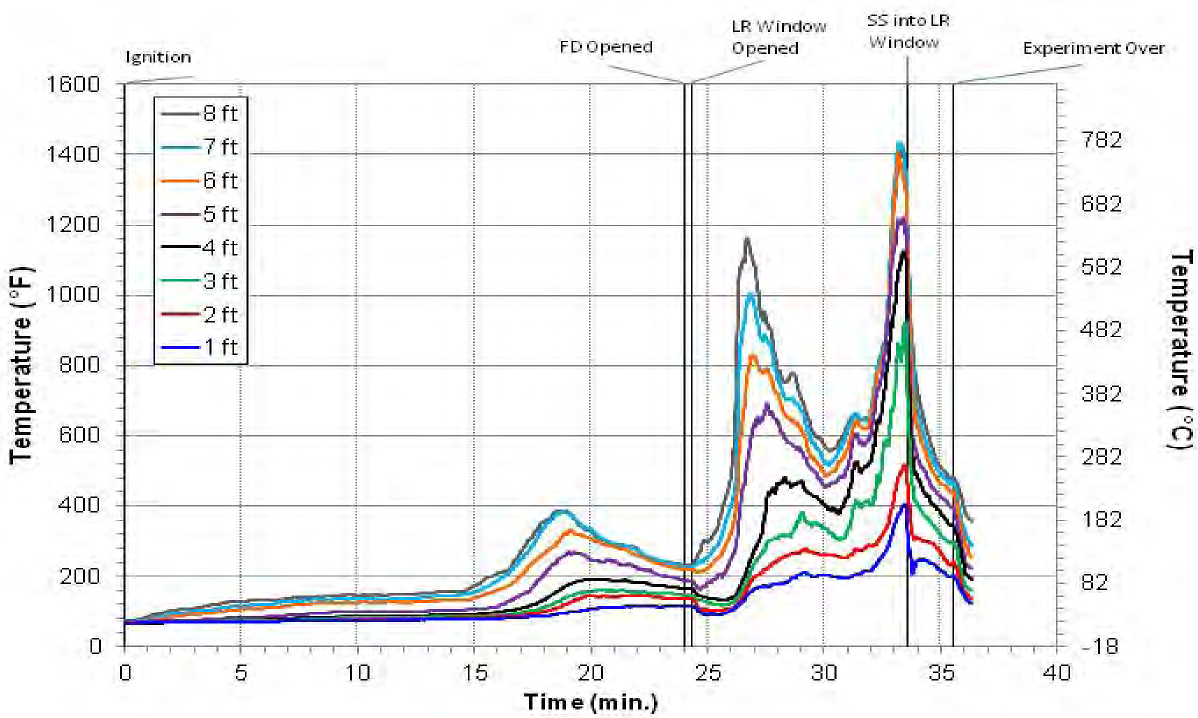


Figure E.356: Experiment 17 Hallway Temperature

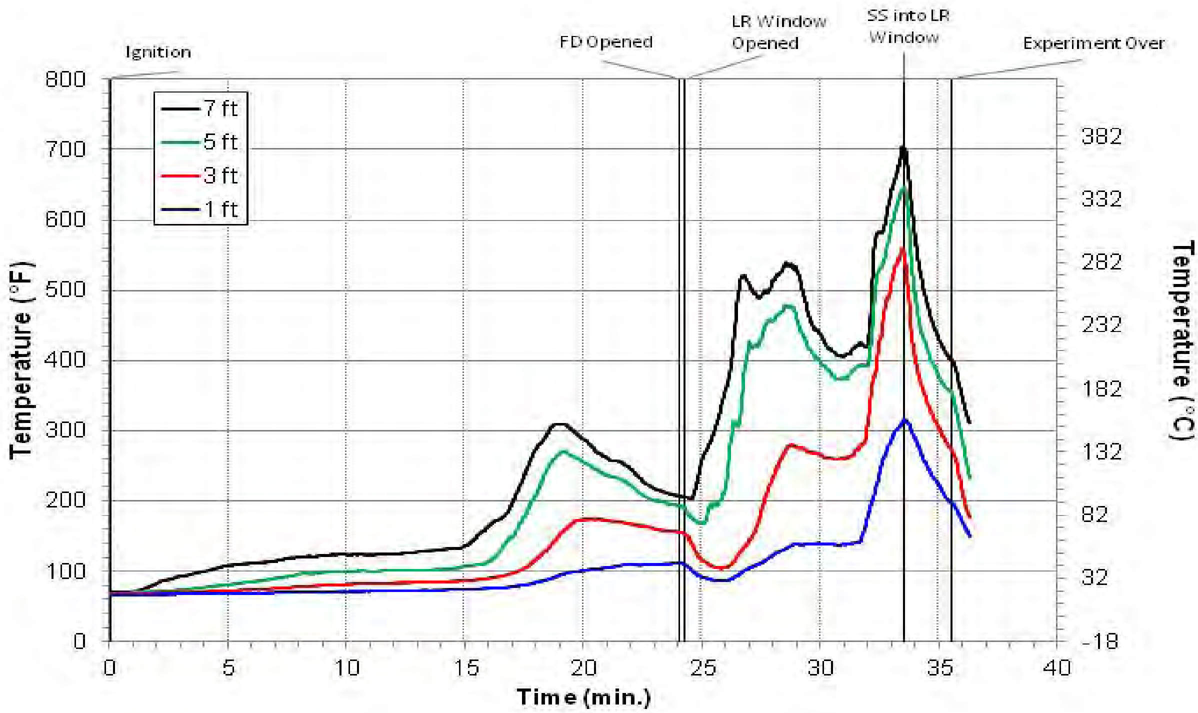


Figure E.357: Experiment 17 Dining Room Temperature

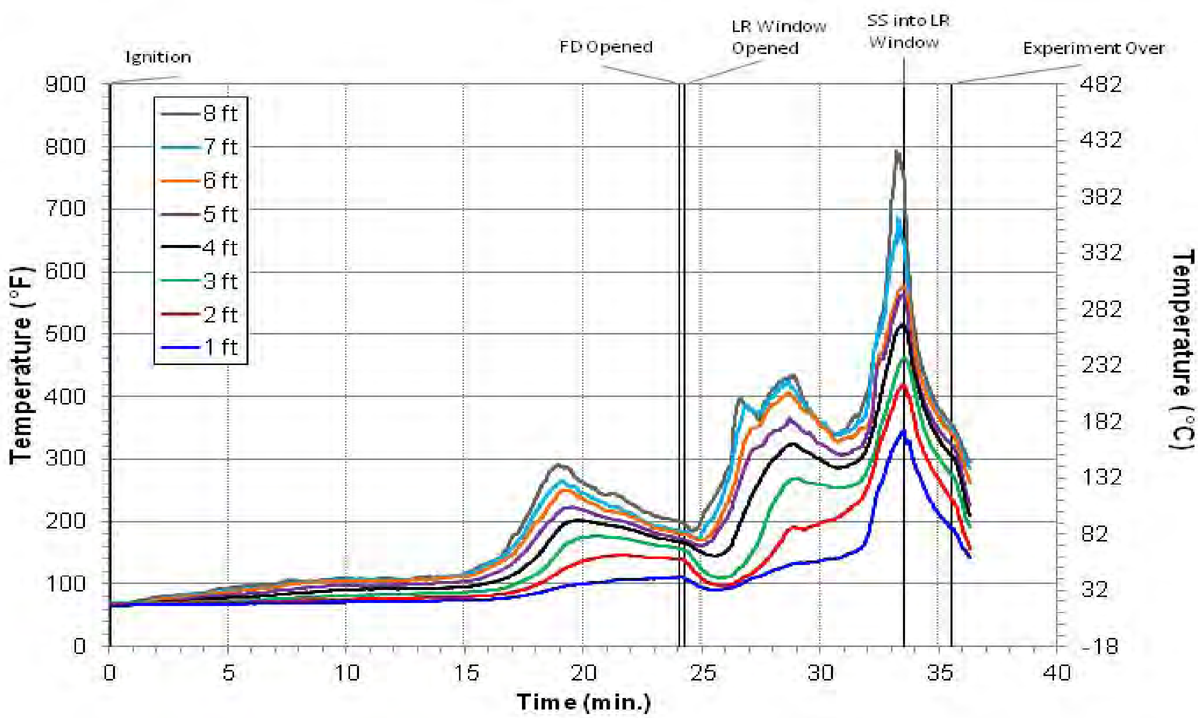


Figure E.358: Experiment 17 Kitchen Temperature

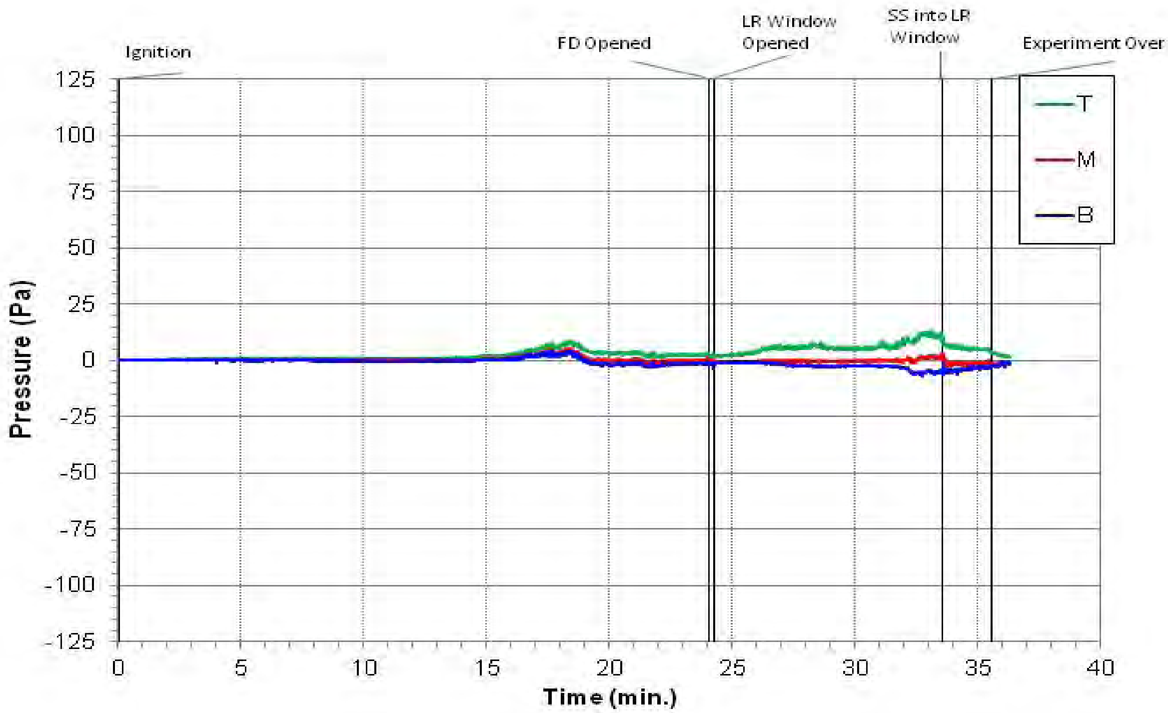


Figure E.359: Experiment 17 Living Room Pressure

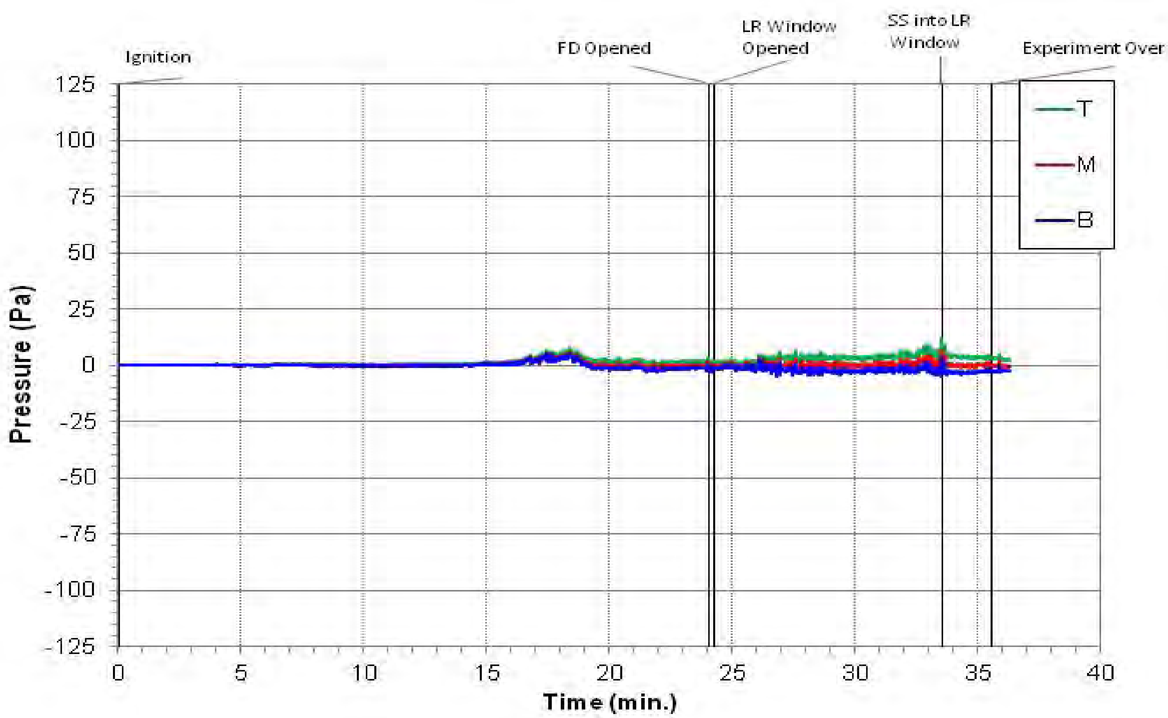


Figure E.360: Experiment 17 Bedroom 1 Pressure

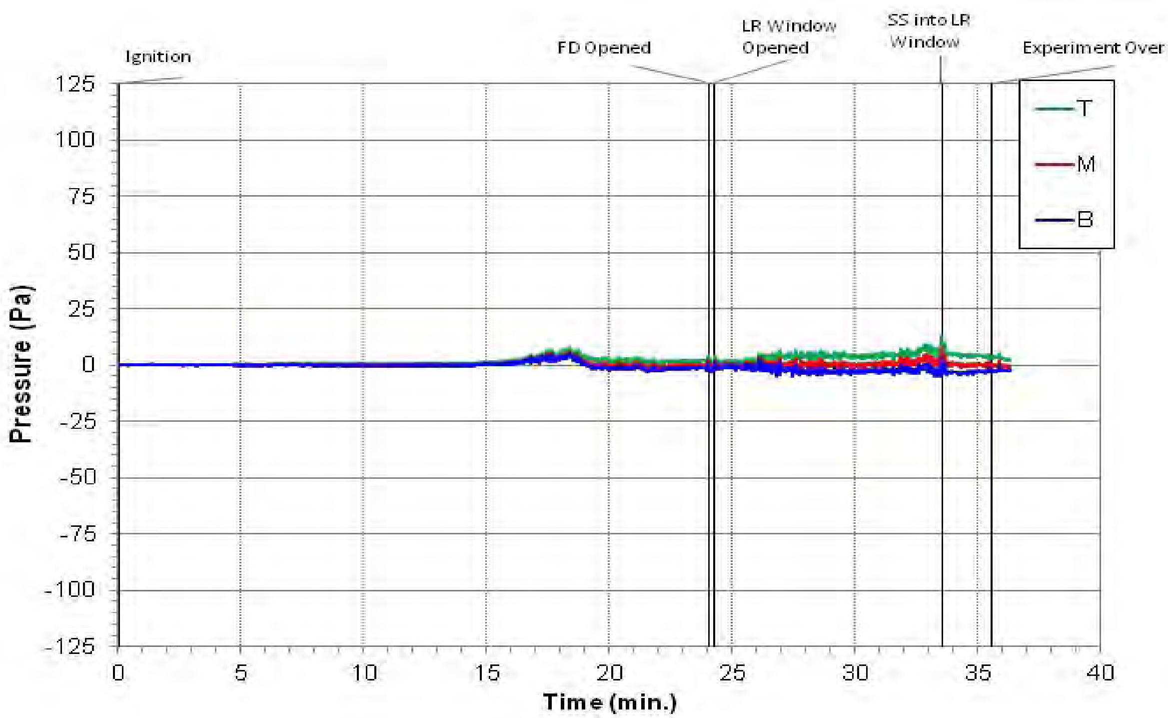


Figure E.361: Experiment 17 Bedroom 2 Pressure

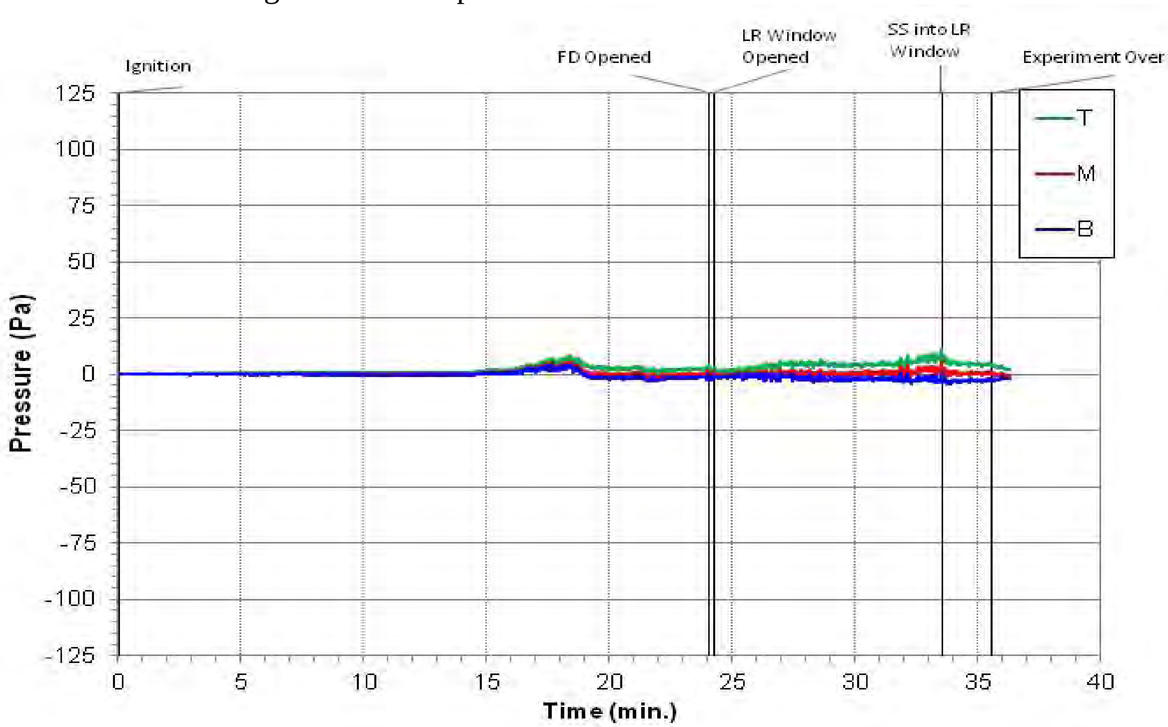


Figure E.362: Experiment 17 Kitchen Pressure

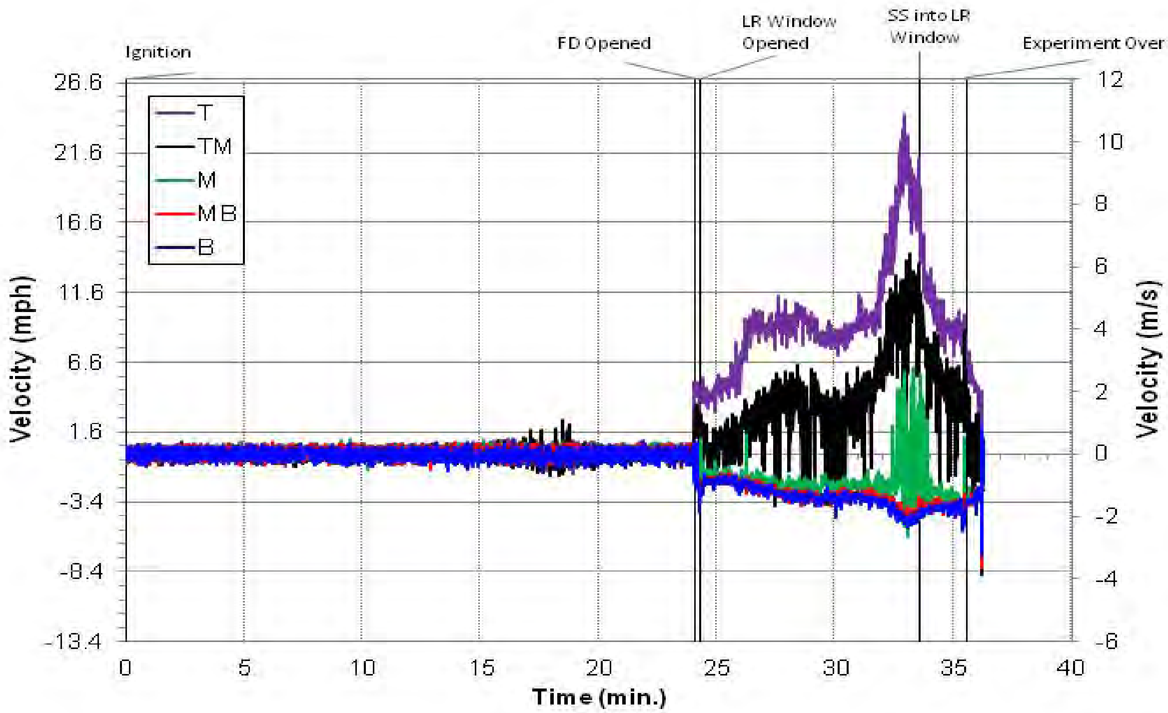


Figure E.363: Experiment 17 Front Door Velocity

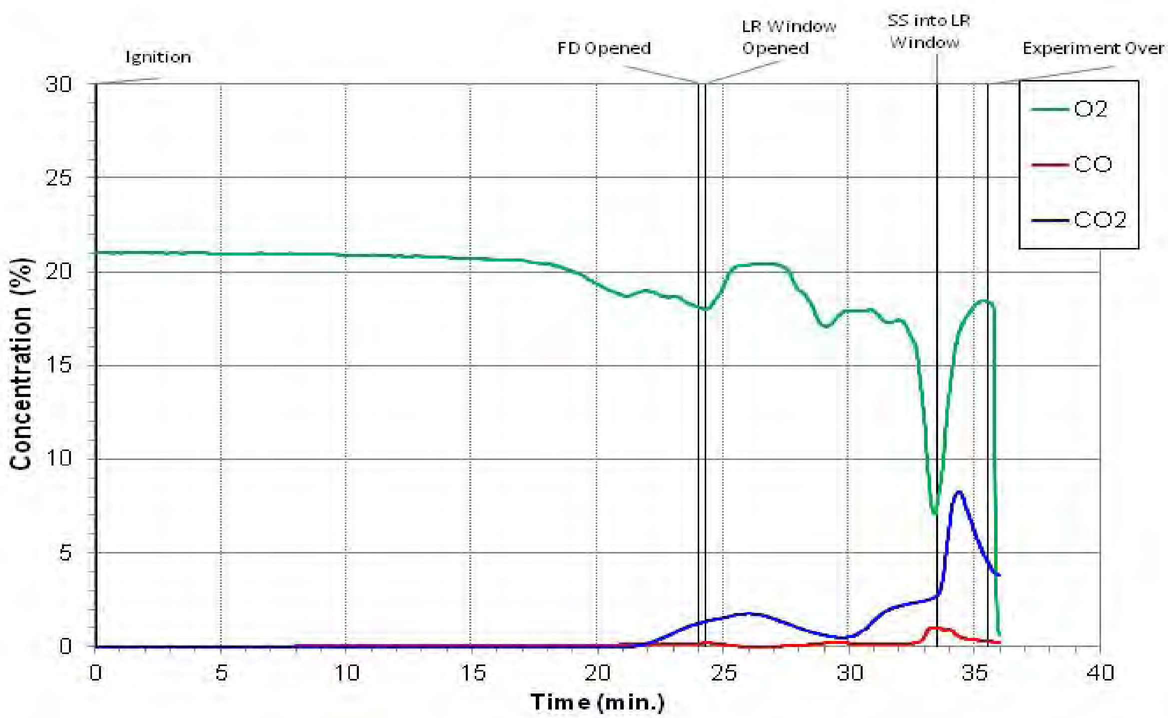


Figure E.364: Experiment 17 Living Room Gas

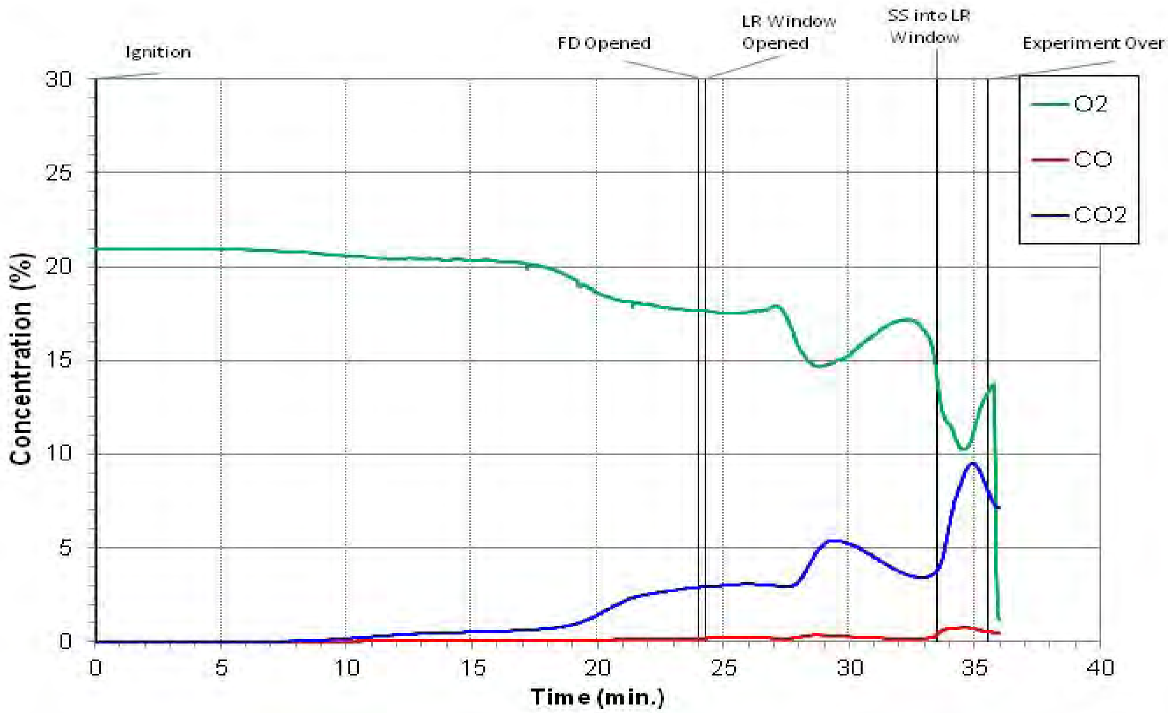


Figure E.365: Experiment 17 Bedroom 1 Gas

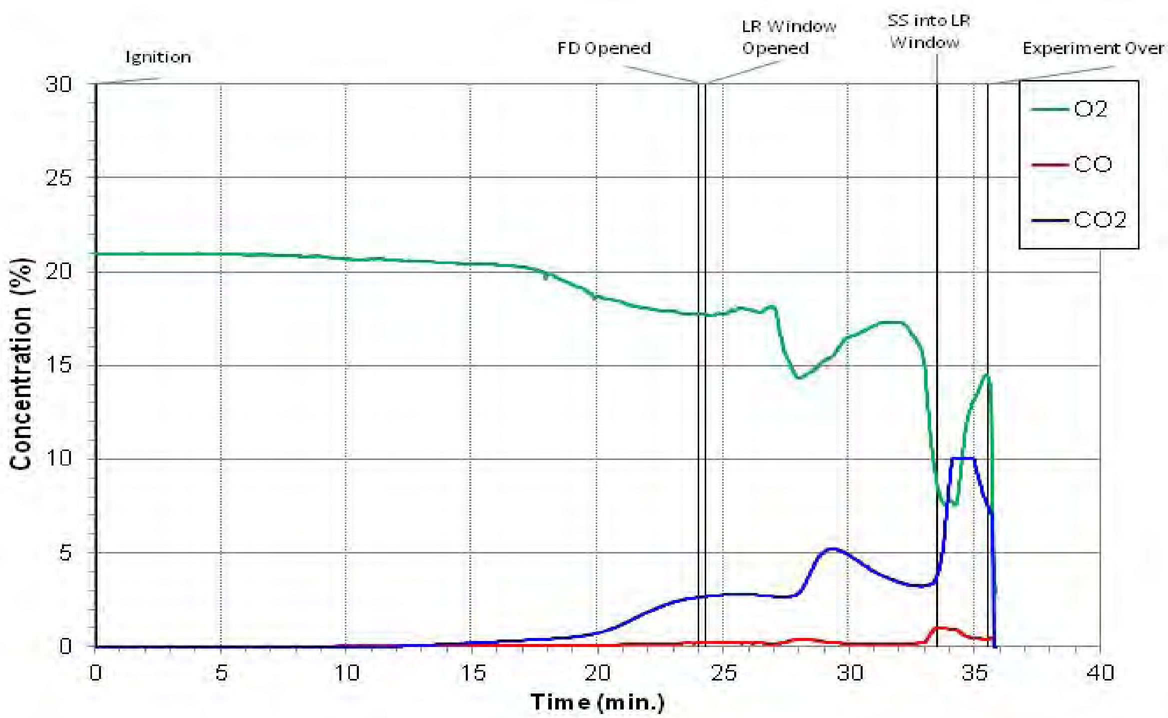


Figure E.366: Experiment 17 Bedroom 2 Gas

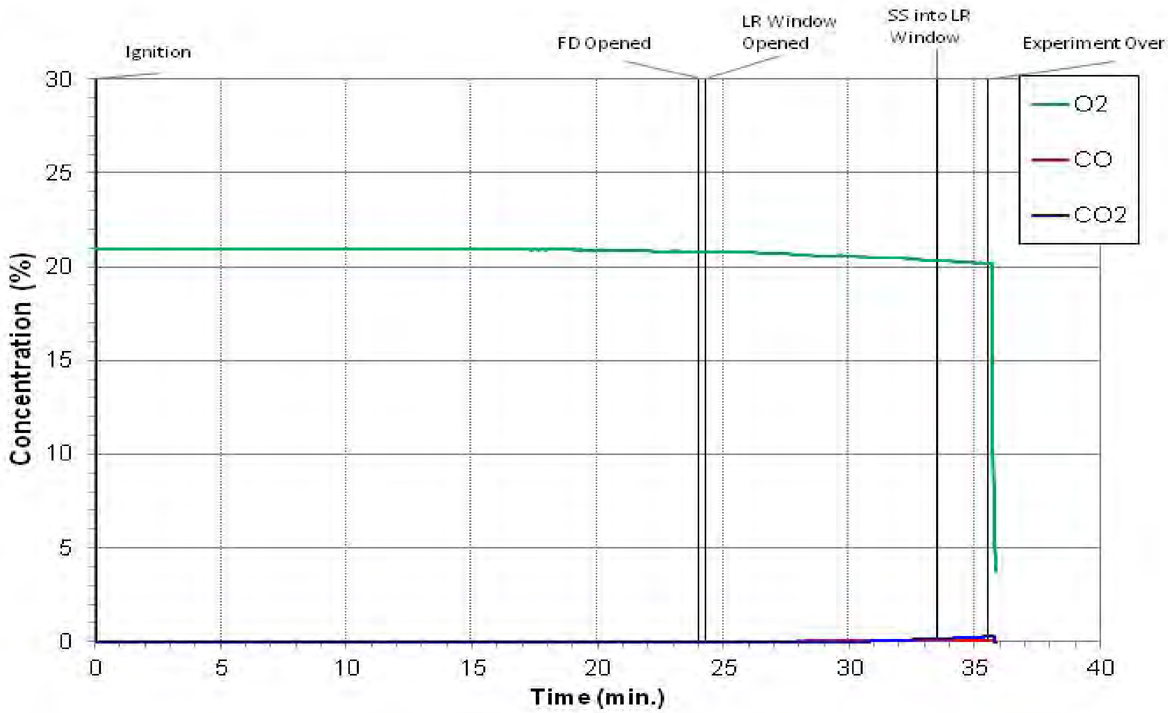


Figure E.367: Experiment 17 Bedroom 3 Gas