Study of Residential Attic Fire Mitigation Tactics and Exterior Fire Spread Hazards on Fire Fighter Safety

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EXECUTIVE SUMMARY

Under the United States Department of Homeland Security (DHS) Assistance to Firefighter Grant Program, Underwriters Laboratories led a 2-year study to examine fire service attic fire mitigation tactics and the hazards posed to firefighter safety by the changing modern residential fire environment and construction practices. The US Fire Administration estimates 10,000 residential building attic fires are reported to U.S. fire departments each year and cause an estimated 30 civilian deaths, 125 civilian injuries and $477 million in property loss. These attic fires are a very challenging for the fire service to mitigate and have led to line of duty deaths and injuries. Further complicating attic fires, current building practices include new products to achieve better energy performance to meet newer code requirements with little understanding of fire performance or the impact on firefighter safety. This study provides the fire service with the science necessary to examine their standard operating procedures utilized during fires that start of the outside of the structure and during attic fires.

To evaluate the exterior fire hazards of various wall construction types, medium scale testing was performed on 8ft x 8ft wall sections looking at ignition, flame spread, peak heat release rate and exposure potential. The results of the medium scale testing was used to establish parameters for eave experiments to further evaluate flame spread along with increasing the understanding of the dynamics of how fires transition from exterior to attic fires. Following the eave experiments full scale attics were constructed and instrumented to evaluate the effectiveness of four fire service suppression tactics on attic fires. Each tactic was evaluated both with and without vertical ventilation or simulated attic burn through to understand the fire dynamics during attic fires. Finally field experiments were conducted to investigate the fire dynamics of knee-wall fires and the effectiveness of current mitigation tactics for knee-wall and half attic space fires.

The results of the experiments were then examined with the fire service technical panel and utilized to develop 12 fire service tactical considerations for use in the mitigation of attic, knee-wall and exterior fires. An overview of these tactical considerations include (for full context see Section 10):

- **Increased use of plastics in exterior walls will change what you arrive to** - Changes in residential wall construction methods are playing an important role in how exterior fires are initiated, as well as how they spread and extend.
- **If the fire starts on the outside, start fighting it from the outside** - Rapid water application to knock down the exterior fire is a critical part of any attempt to control not only the fire's spread to adjacent structures but also the fire's migration into the interior of an exposed building. If the source of the fire is not suppressed, it will continue to supply heat energy to the fire developing on the interior, worsening conditions on the

inside for occupants and in many cases making it impossible for the interior crews to maintain or advance their positions.

- **Learn to anticipate where and how an exterior fire will migrate to the interior -** Exterior wall fires may easily spread to the interior at locations other than the eaves and soffits. Any penetrations -- such as air vents, electrical receptacles, plumbing penetrations to faucets and drains, and especially windows -- provide the opportunity for fire spread into the interior of the structure. Leaving the interior fire barrier in place until the exterior fire can be controlled will limit the extension into the structure.
- **Attic fires are commonly ventilation-limited fires –** The openings provided for natural ventilation are not sufficient to maintain steady state burning and fuel limited fire behavior. The size of the fire is limited by the available oxygen and will nearly always become ventilation-limited. Controlled openings created below the neutral plane (such as through the ceiling below the attic space) will not cause immediate growth and can provide access for suppression operations.
- **Closely time or limit vertical ventilation until water is in the attic -** A vented attic fire was more difficult to control with the indirect methods applied to the unvented attic test. The, "open up above and then attack it from below" tactic can and has been successfully used at attic fires. However, it can create a large amount of property damage and puts both civilians and firefighters at high risk during the initial stages of the operation if not timed properly. Once initial water absorbs some energy, a vertical vent will assist the crews with suppression and overhaul because standard fire ground ventilation tactics will be sufficient for exhausting the smoke and fire gasses produced by the remaining fire. In the absence of suppression, the positive effect of a roof opening is a very short lived phenomena. The accelerating fire can overwhelm all openings and push back into the occupied space. Increased visibility does not automatically mean a reduction in the size of the fire over your head.
- **Plastic ridge vents can affect size-up and fire dynamics -** As the vents heat, the plastic melts and collapses on the opening at the peak, creating a very effective seal. Once the ridge vent seals, the eaves will act as both the source of air as well as the exhaust and you may notice a pulsing of smoke out of the eaves.
- **Wetting Sheathing with an Eave Attack Slows Attic Fire Growth -** If crews wet the sheathing, either as part of an offensive fire attack or defensively to slow fire spread to uninvolved sections of the structure, the major flame spread mechanism in the attic is eliminated until the moisture evaporates. Removing the soffit and flowing water along the eave line of these structures was the most effective way to gain the upper hand on a fire that was venting through the roof.
- **Attic construction affects hose stream penetration -** The most effective water application takes into consideration the construction of the attic, using the natural channels created by the rafters or trusses to direct the water onto the vast majority of the surfaces.

- **Consider flowing up instead of down with a master stream - C**onsider using an aerial device or portable ladders and hand lines to open up the eaves and flow water into the attic. This approach could result in controlling the fire enough to permit firefighting crews to transition back inside the structure to complete searches, suppression, and overhaul.
- **Knee Wall Fire Dynamics -** During a structure fire, it is possible for fire to enter void spaces and surround crews conducting interior operations. Even though there is a delay between making the breach and the change in conditions, once initiated, the transition to untenable conditions in the area of operation occurs in seconds. Knee wall construction often provides the potential for ideal fire growth, with air entering low at the eave line and combustion gases exiting the peak through mushroom vents, ridge vents or gable vents.
- **Apply water on a knee wall fire at the source and toward the direction of spread before committing to the attic -** Applying water utilizing the same path the fire took to enter the void space may be the most effective method at slowing fire growth. Water application to the knee wall will not be effective until the source below it is controlled with direct water application.
- **Interior operations on knee wall fires** - Tests have demonstrated that the most effective way to get a handle on knee wall fires is to control the source fire, cool the gasses prior to making large breaches in the barrier, and then aggressively open the knee walls to complete extinguishment, focusing on wetting the underside of the roof decking.

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1. Introduction

Research Study Purpose

The purpose of this study is to increase firefighter safety by providing the fire service with scientific knowledge on the dynamics of attic and exterior fires and the influence of coordinated fire mitigation tactics from full-scale fire testing in realistic residential structures.

1.1. Background

Attic fires pose many hazards for the fire service. When a fire occurs in an attic, it is common that it will go unnoticed until smoke or flames are visible from the outside of the structure. Because they take longer to detect, attic fires are more dangerous for firefighters and residents. A fire in the attic may involve insulation and wood structural members as well as a variety of stored belongings. In a fire situation, the attic ventilation system, which is designed to reduce moisture accumulation by drawing fresh air low from the eaves and exhausting moisture laden warm air near the peak, create an optimal fire growth and spread situation by supplying oxygen to the fire and exhausting hot gases. An estimated 10,000 residential building attic fires are reported to U.S. fire departments each year and cause an estimated 30 civilian deaths, 125 civilian injuries and $477 million in property loss[1].

The location of the attic creates several difficulties for the fire service. Firefighters must decide whether to fight the fire from inside the structure, from the outside or a combination of the two. In all of these incidents, firefighters have to consider that the ceiling can collapse creating rapidly deteriorating conditions inside the structure and the roof structure can collapse creating deadly conditions for firefighters operating on and under the roof. Structural collapse accounted for 180 firefighter deaths between 1979 and 2002 of which one-third occurred in residential structures[2]. Many of these incidents involved a roof falling on firefighters[3,4] or firefighters falling through the roof [5] during firefighting operations on attic fires. Compounding these hazards is the speed at which conditions can deteriorate. A piece of gypsum board may fall or be pulled from the ceiling making the relatively clear and cool conditions in the living space change very quickly endangering firefighters executing a search and rescue operation as part of their life safety mission.

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[1] Attic Fires in Residential Buildings. Topical Fire Report Series. US Fire Administration, Volume 11, Issue 6, January 2011.

[2] Brassell, L.D. and Evans, D.D., "Trends in Firefighter Fatalities Due to Structural Collapse, 1979-2002," NISTIR 7069, National Institute of Standards and Technology, Gaithersburg, MD, November 2003.

[3]" Career Fire Fighter Dies After Single-Family-Residence House Fire - South Carolina" Fire Fighter Fatality Investigation Report F2001-27, National Institute for Occupational Safety and Health, January 2002.

[4] "Career fire captain dies when trapped by partial roof collapse in a vacant house fire – Texas" Fire Fighter Fatality Investigation Report F2005-9, National Institute for Occupational Safety and Health, February 2005.

[5] "Career Fire Fighter Dies After Roof Collapse Following Roof Ventilation – Iowa" Fire Fighter Fatality Investigation Report F2002-40, National Institute for Occupational Safety and Health, May 2003.

Figure 1. 1: A fire that started in the garage spread up the exterior of the home and into the attic.

In several fires, rapidly changing conditions have occurred during firefighting efforts, resulting in fatalities and injuries. In one incident, Fire Fighter Kyle Wilson of Prince William County, VA was lost fighting an attic fire in 2007[6]. This was an exterior fire which propagated up the exterior into the attic space. While this fire was wind aided, the large attic space allowed a substantial amount of fire to build until the pressure forced the fire downwards into the second floor of the residence where fire fighter Wilson was performing search and rescue. The sudden changes in the environment created an unsurvivable atmosphere, even with full personal protective equipment, and fire fighter Wilson perished. A second incident involved an interior chimney fire originating in the basement[7]. Due to the void spaces within the structure, the fire propagated into the large attic space where a large amount of air and unchecked fire growth created a high pressure build up that forced the fire downwards, explosively by some accounts, onto fire fighters operating on the second floor. The rapidly changing environment caused critical injuries to ten fire fighters.

Fires in attic may also be challenging to attack due to specific design and construction features such as half-story Cape Cod or bungalow style homes. These attic spaces are common throughout the United States and present unique challenges to the fire service. The presence of knee walls and collar ties create void spaces for fire to travel around the finished attic space. A St. Louis Chief Officer has observed that more than half of the serious firefighter injuries occur

[6] "Career Fire Fighter Dies in Wind Driven Residential Structure Fire." Fire Fighter Fatality Investigation Report F2007-12, National Institute for Occupational Safety and Health, May 2008.
[7] "Significant Injury Investigative Report 3380 Soper Road March 19, 2011." Huntington Volunteer Fire Department and Rescue Squad, Inc. March 2012.

in half-story fires[8]. Two tragic firefighter death fires, in Syracuse, NY[9] and Hyattsville, MD[10], occurred in half-story buildings. In both fires the firefighters wore full gear with SCBA, firefighters operated in teams, and additional firefighters were on the scene.

Recently the Chicago Fire Department experienced a close call in a one and a half story home where two firefighters were critically injured[11]. Commissioner Robert Hoff stated, "After firefighters chopped holes in the roof to release smoke and toxic gas, they tried to extinguish the flames in the attic, unaware of the flames hidden behind the walls, without warning the fire lit up the attic and trapped Ruane and Carter." Many other incidents in these types of structures have created near misses for fire fighters. One incident reported to the National Fire Fighter Near-Miss Reporting System occurred in a two-story structure with fire in the attic[12]. While fire fighters were operating in the attic space the structure collapsed sending them onto firefighters on the second floor. During the collapse burning debris fell onto a hot tub outside the structure creating a fire condition that spread along the outside of the house and into a first floor window trapping firefighters operating on the second floor. Several firefighters received serious burns and were rescued by the RIT team.

Figure 1. 2: Chicago Fire Department fighting a fire in the attic of a one and a half story house

8 Sachen, John. "Killer in the Attic." University of Missouri Fire and Rescue Training Institute. Accessed March 2012.
9 "One Fire Fighter Dies of Smoke Inhalation, One Overcome by Smoke While Fighting an Attic Fire--New York." National Institute for Occupational Safety and Health. FACE 97-16.
10 Smith, Bryan. "Student dies of burns sustained attempting rescue." The Diamondback, March 16, 1988.
11 Rhodes and Haggerty. "Fire Captain tells rescuers: 'My guy is still up there. My guy is still up there.'" Chicago Tribune, August 26, 2011.
12 Lyon, G. O. "National Fire Fighter Near-Miss Reporting System. January-Attic Fires." http://www.firefighternearmiss.com/home. 2008.

Fire fighters have been battling fires in attics for many years. In recent times the fireground has changed for a number of reasons. First, fire service is encountering larger attic spaces because the average size of a home built in the United States has increased from approximately 1600 ft^2 to 2600 ft^2 from the 1970's to today[13]. Fires in these larger attic spaces are growing into a substantial size, due to the amount of available air, thereby putting the fire fighters at risk as they operate unknowingly below the fire. Second, the construction practices have also changed over this time frame. Older homes tend to have attics that are framed with larger size lumber and are built with one continuous volume[14]. Newer home attics typically are constructed with more complex attic spaces created with smaller dimension wood member trusses. Fires in these attics can create concealed fires that are more difficult to locate and extinguish[5]. In addition, "green" initiatives to increase energy efficiency, utilize products (e.g., foam insulation) that have the potential to lead to faster fire propagation and create new challenges such as rapid exterior fire penetration into the attic space for the fire service[15].

Figure 1. 3: Attic fires with older (left) and newer (right) attic construction

The number of residential structure fires originating from the building exterior such as an adjacent structure fire, garage fire, deck or porch fire, mulch/vegetation fire or a wildland fire has been increasing. Exterior fires can transition to attic fires either directly via eave/soffit and wall vents or indirectly by burning through eaves/soffits, exterior walls and/or windows. USFA estimates source fires account for about 12,100 fires, 255 deaths and 825 injuries annually while the subsequent exposure fires account for 18,600 fires, 15 deaths and 50 injuries[16]. Furthermore, in fires that that spread beyond the room of origin, structural members or framing were the most common contributing item to flame spread (26%) followed by structural components or finishes (11%) and exterior wall surfaces (10%)[17].

Changes in residential wall construction over time are thought to play an important role in how exterior fires are initiated and spread. Older homes commonly had brick, wood clapboard or

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[13] 2010 Characteristics of New Housing. (2010) US Department of Commerce.

[14] Jeff S. Case. "Residential Attic Fires," http://www.fireenginnering.com, April 1, 2010.

[15] "Spray Foam Insulation." Green Home Source, http://green-home-source.com/spray-foam-insulation.html. 2011.

[16] "Fires and Exposures" Topical Fire Report Series. US Fire Administration, Volume 7, Issue 2, January 2007.

[17] Ahrens, Marty. Home Structure Fires. National Fire Protection Association, May 2011.

stucco on the exterior of the structures walls. Construction practices evolved and vinyl siding was introduced over a wood sheathing with a vapor barrier. Today, it is common to find vinyl siding over a rigid foam sheathing to increase energy efficiency in homes. Residential construction allows architects to use expanded polystyrene and polyisocyanurate foam core sheathings in their designs[18]. The 2012 International Energy Conservation Code wall insulation requirements have become more stringent in several climate zones. For the first time, builders in some climate zones will be required to install exterior rigid foam insulation (or to use some other comparable wall insulation strategy)[19]. For example, in Northern Illinois exterior walls are required to have an insulative value of R20 or R13 cavity insulative value with an additional R5 continuous insulation provided by the foam sheathing (because the foam sheathing is continuous over the studs it is equivalent to R20). To accomplish this the exterior walls are constructed with nominal 2 by 6's and filled with insulation, which achieves a R18 insulative value. In order to get to R20 equivalent a layer of rigid foam would be added.

Figure 1. 4: Rigid foam insulation applied to an exterior wall

The research proposed herein is not to critique modern construction products and practices that assist in reducing our energy footprint but to understand the impact of these decisions on the dynamics (i.e., fire initiation, growth, spread, etc.) of fires originating either in the attic or on the home exterior and the hazards to firefighters on the scene.

Previous research on exterior wall fires has focused on flame spread along wall surfaces,[20] particularly in commercial applications[21]. Existing tests address flame spread and penetration

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[18] Grupe, Robert. "A Specification Guide for Exterior Wall Sheathings." AIA/Architectural Record Continuing Education Series. March 2011.

[19] International Energy Conservation Code. International Code Council, 2012.

[20] Oleszkiewicz, "Fire Exposure to Exterior Walls and Flame Spread on Combustible Cladding", National Research Council of Canada, Fire Technology, November 1990.

[21] Albert and Davis, FM Global Research, "Evaluation of Exterior Insulation and Finish System Fire Hazard for Commercial Applications", Journal of Fire Protection Engineering, November 2002.

along planar roof and wall surfaces. [22] Fire test committee activity is concentrated on developing small scale tests to evaluate the safety of specific portions of a structure – walls, soffits or eaves. [23] None of the previous research analyses the interface at the top of the wall where it meets the eave line and enters the attic space. None of the current fire tests or those under development address exterior fires breaching into the structure on an assembly level. There has also been no research that shows firefighter best practices for extinguishing attic fires when the ignition source is an exposure fire from an exterior wall.

Changes in Energy Code

Over the last eight years the International Energy Conservation Code (IECC) for single family residential structures has changed significantly, requiring more thermal resistance. This increase in thermal resistance has changed the construction of wall assemblies inadvertently changing the fire hazard of exterior walls.

The IECC establishes eight different climate zones across the US as seen in Figure 1. 5. With zone 8 being climate with the coldest temperatures and zone 1 with the mildest temperatures. The climates relate directly to the thermal resistance or R-Value required for the structure.

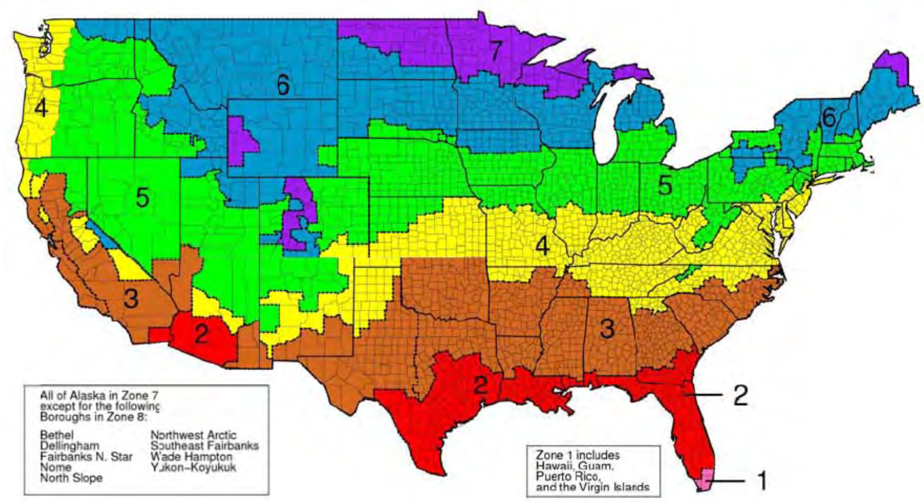

Figure 1. 5: Climate Zones in the U.S. [Impact 2009 2012 IECC]

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[22] ASTM E05 Fire Test Committee, Current Tests - ASTM E108-11 "Standard Test Methods for Fire Tests of Roof Coverings", ASTM E2707-09 "Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure", ASTM E2726 / E2726M-12 "Standard Test Method for Evaluating the Fire-Test-Response of Deck Structures to Burning Brands.

[23] ASTM E05.14 External Fire Exposure Committee, Tests Under Development, - Work Item 12052 "New Test Method for Evaluating the Under-Deck Fire Test Response of Deck Materials", Work Item 21343 "New Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Flames Resulting from Wildfire", Work Item 23700 "New Test Method for Evaluating Roof Field Vent Response to Wind Blown Flame and Burning Ember Exposure", Work Item 25760 "New Guide for Quantification of Fire Exposures".

Over the last three code cycles, 2006-2012, there has been a trend of increasing R-Values required in exterior wall construction. Table 1. 1 shows that for the 2006 code R-13 was required for the majority of the climate zones which by 2012 has been increased to R-20. The most significant increase occurred in 2012 where the insulation value in zones 3 and 4 went from R-13 to R-20. This change mandated that new home construction in over 90% of the US must achieve or exceed an R-20 wall thermal resistance value. Options are provided to achieve this, builders may also opt to utilize an R-13 insulation with an R-5 sheathing or utilize the cavity insulation alone to achieve the R-20 value.

If the cavity insulation alone is intended to provide the thermal resistance an increase in framing from 2 by 4 inch framing to 2 by 6 inch framing as is required to achieve R-20. With a 2 x 4 inch framed wall, R-15 is the maximum rating achievable according to the North American Insulation Manufacturers Association[24]. As this change to 2 x 6 inch framing is costly the second option of a 2 x 4 inch framed wall with R-13 insulation combined with a sheathing material possessing an R-5 rating has become popular. The most commonly used sheathing material with an R-5 insulation rating is 1 in. rigid polystyrene foam insulation board which behaves much differently than the conventional plywood sheathing during fire exposure.

Table 1. 1: Comparison of R-Value Requirements for Wood Frame Walls[25,26,27]

	Wood Frame Wall R-Value		
Climate Zone	IECC 2006	IECC 2009	IECC 2012
1	13	13	13
2	13	13	13
3	13	13	20 or 13+5[2]
4 except Maine	13	13	20 or 13+5[2]
5 and Maine 4	19 or 13+5[1]	20 or 13+5[1]	20 or 13+5[2]
6	19 or 13+5[1]	20 or 13+5[1]	20+5 or 13+10[2]
7 and 8	19 or 13+5[1]	21	20+5 or 13+10[2]

1- “13+5” means R-13 cavity insulation plus R-5 insulated sheathing. If Structural sheathing covers 25% or less of the exterior, insulating sheathing is not required where structural sheathing is used. If structural sheathing covers more than 25% of exterior, structural sheathing shall be supplemented with insulated sheathing of at least R-2
2- First value is cavity insulation, second is continuous insulation or insulated siding, so "13+5" means R-13 cavity insulation plus R-5 continuous insulation or insulated siding. If structural sheathing covers 40 percent or less of

[24] NAIMA, “Building Insulation a Performance Comparison for Today’s Environmental Home Builder”. North American Insulation Manufacturers Association, Alexandria, VA. October 2009.
[25] International Code Council “International Energy Conservation Code 2006”, International Code Council, Inc., Country Club Hills, IL. 2006
[26] International Code Council “International Energy Conservation Code 2009”, International Code Council, Inc., Country Club Hills, IL. 2009
[27] International Code Council “International Energy Conservation Code 2012”, International Code Council, Inc., Country Club Hills, IL. 2012

the exterior, continuous insulation R-value shall be permitted to be reduced by no more than R-3 in the locations where structural sheathing is used- to maintain a consistent total sheathing thickness.

Applicable Standards

California SFM Standard 12-7A-1 “Materials and Construction Methods for Exterior Wildfire Exposure” deals specifically with the requirement of exterior wall on a single family structure to resist ignition and propagation of flame.[28] The standard specifies a wall module of 4 ft. by 8 ft. comprised of cladding, sheathing and 2 by 4 inch stud framing. The source fire is a 4 inch by 39 inch line burner capable providing 150kW heat release rate to the wall module. The module is exposed for 10 minutes followed by a 60 minute observation period. Conditions of acceptance include the “absence of flame penetration through the wall assembly at any time” and “absence of evidence of glowing combustion on the interior surface of the assembly at the end of the 70 minute test”.[29]

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 include wall construction types, attic geometry, fuel loading, tactical choices, hose stream flow rates and ventilation locations. By bounding these variables and controlling the test conditions during firefighting operations, the exterior fire spread hazard was evaluated, the fire dynamics of attic fires were observed and suppression tactics were tested for effectiveness. The results enable the establishment of a scientific basis that may be used for other types of structures that do not match exactly the geometry of the test structures such as different sized rooms, different fuel loads, different interior geometries, different timing of operations, etc.

The purpose of this study is to increase the fire service’s knowledge of how exterior fires become structure fires along with how their tactics impact the specific conditions encountered during attic fires. It focused on common construction types, siding materials and insulation materials as they relate to an exterior wall or truss constructed residential attic. In addition attic fire dynamics were evaluated in a single acquired structure along with knee wall fires in two additional acquired structures. Since all fire ground circumstances cannot be analyzed, it is anticipated that the data developed and this analysis will enable firefighters to complement their previous observations and experiences.

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[28] California State Fire Marshall “Materials and Construction Methods for Exterior Wildfire Exposure, Exterior Wall Siding and Sheathing SFM Standard 12-7A-1.” California State Fire Marshall, Clovis, CA 2001.
[29] California State Fire Marshall “Materials and Construction Methods for Exterior Wildfire Exposure, Exterior Wall Siding and Sheathing SFM Standard 12-7A-1.” California State Fire Marshall, Clovis, CA 2001.

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.

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 national average response times.

2. Objectives and Technical Plan

2.1. Objectives

- Improve firefighter safety by increasing knowledge of fire behavior.
- Develop an understanding of the impact of new construction materials and techniques and 'green' building technologies on fire spread spreading along the building envelope and propagation into and growth within the attic.
- Identify and disseminate standard best practices for mitigating attic fires based on science.
- Provide the knowledge to better understand the fire dynamics and building response factors that cause and contribute to fireground injuries and fatalities during attic fire incidents.
- Disseminate knowledge gained pertaining to the built environment to stakeholders that are able to impact the code process to improve the safety of the public and the fire service.
- Bring the 'Science to the Streets' by transferring science based tactical considerations founded on experimental results that can be incorporated into firefighting standard operating guidelines. Research findings will be communicated to the fire service community through an eLearning training course and class room presentations at major fire department conferences.

2.2. Technical Plan

This studies technical plan is detailed in Figure 2. 1, with ten separate tasks.

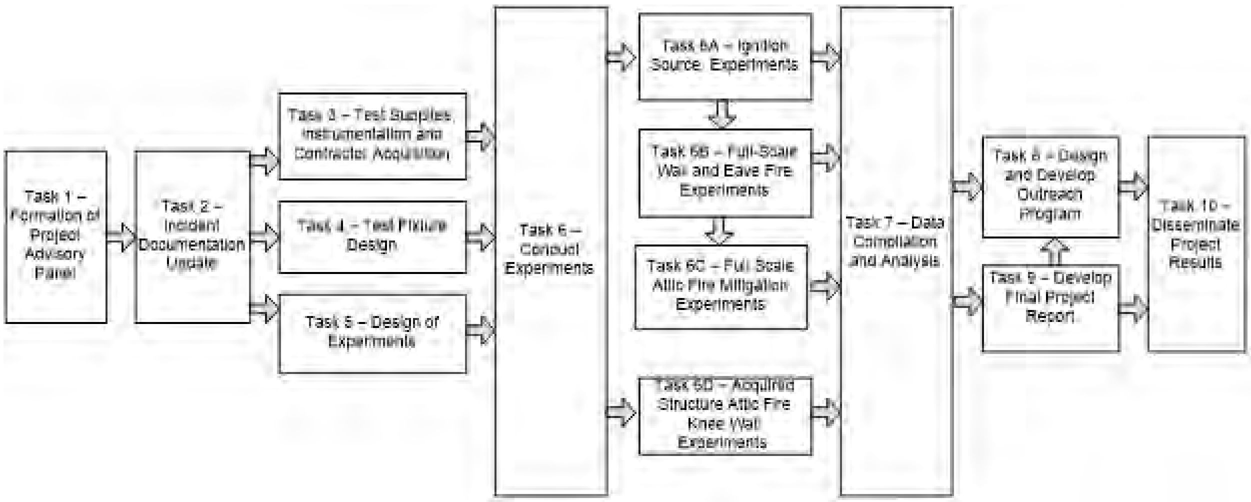

Figure 2. 1: Project Technical Plan

3. Project Technical Panel

This study was executed with the fire service. A technical panel of fire service and research experts was assembled based on their previous experience with research studies, attic fires, 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:

Derek Alkonis, Battalion Chief, LA County Fire Department
John Ceriello, Captain, Fire Department of New York
James Dalton, Coordinator of Research, Chicago Fire Department
Sean DeCrane, Battalion Chief, Cleveland Fire Department
Harvey Eisner, Editor Emeritus, Firehouse Magazine
Mike Gagliano, Captain, Seattle Fire Department
Sean Gray, Firefighter, Cobb County (GA) Fire Department
Bobby Halton, Editor-in-chief, Fire Engineering Magazine
Todd Harms, Assistant Chief, Phoenix Fire Department
Ed Hartin, Chief, Central Whidbey Island Fire Rescue Department

George Healy, Deputy Chief, Fire Department of New York
Dan Madrzykowski, Fire Protection Engineer, NIST
Tim Nemmers, Firefighter, Des Moines Fire Department
Mark Nolan, Fire Chief, City of Northbrook (IL) Fire Department
P.J Norwood, Battalion Chief, East Haven (CT) Fire Department
David Rhodes, Battalion Chief, Atlanta Fire Department
Erich Roden, Battalion Chief, Milwaukee Fire Department
John Shafer, Lieutenant, Greencastle (IN) Fire Department
Tim Sendelbach, Editor-in-chief, Firehouse Magazine
Pete Van Dorpe, Assistant Chief, Algonquin-Lake in the Hills Fire Protection District
Matt Verlaque, Firefighter, Arlington County (VA) Fire Department
Chris Willis, Firefighter, Falmouth (KY) Volunteer Fire Department

4. Previous Literature

4.1. Fire Service Publications

In a June of 2012 Dr. Harry Carter wrote “Danger overhead: Attic Fires” for firehouse.com which discussed attic construction, highlighted the challenges and dangers of attic fires along with identified some tactical considerations for fires located in an attic space. Challenges identified included confined fire with difficult access, potential for lateral fire spread as the fire drops down and difficulty in ventilation. The importance of removing the smoke is discussed through the use of vertical ventilation, removing lovers or potentially removing windows if available. The best suppression tactic is the application of water to the seat of the fire, although this may be difficult and require taking “a bit of punishment from heat”. Dr. Carter also stresses the tactical error of applying water through the roof once ventilation occurs or the fire burns through the roof. This tactic will “drive the heat and smoke downward”, making “entry to the attic impossible”[30].

In March 2013 Mike Daley wrote “Attic Fires: Hazards From Above” for FireEngineering.com which discussed the various types of void spaces above commercial and residential units along with their construction. He discussed the tactical considerations of accessing, ventilating and suppressing attic fires in residential and commercial structures. The importance of coordination of ventilation with suppression is highlighted with an emphasis on strategic ventilation in conjunction with sufficient water flow. The order of operations are reviewed with the importance of having the “vertical vent team in place to open up the attic space prior to pulling any ceiling/floor area from below.” Tactics for fully involved attics include master streams however

[30] Carter, Harry, Dr. "Danger Overhead: Attic Fires | Firehouse." Firehouse. N.p., 19 June 2012. Web. 19 Nov. 2014.

stress the need for applying water to the underside of the roof assembly which is difficult with elevated master streams[31].

The above examples are two of the more recent articles written in the fire service media. There are many more examples written throughout the last few decades all with similar considerations for tactics. The information is based on experience at incidencts, reviewing what was effective and relating it to fire service education of fire behavior and suppression tactics. Very little work exsists where the scientific method was utilized to answer the question of fire behavior and fire service intervention at attic and exterior fires.

4.2. Fire Service Training Manuals

A review of the *Essentials fo Firefighting and Fire Department Operations 6th Ed* along with the *Fundamentals of Firefighter Skills 2nd Ed* did not reference any tactics or considerations for attic or exterior siding fires. Information in both addressed the construction of the attic and the ventilation of a peaked roof. They also discussed the challenges of concealed fires but in reference to below grade and shipboard fires not attic spaces. [32,33]

Attacking and Extinguishing Interior Fires has a reference to attic fires as a potential application for indirect attack or, employing water in the form of finely divided particles. In discussing the operations Lloyd Layman suggests a low-velocity fog head, inserted through a small opening on a concealed unfinished attic fire will be effective. His assessment is based on the experience in shipboard firefighting with the NAVY. Shipboard firefighting employed interact attack in confined spaces with petroleum based fires. The book does not reference any particular testing done in residential structures or analyze the natural ventilation of attic spaces.[34]

The Fire Officers Handbook of Tactics discusses exterior fire hazards and combustible siding materials the chapter on private dwelling fires. Exterior fires are discussed as a potential hazard in basement fires where the fire can vent out the window and ignite “combustible exterior siding, extending up to the eaves”. The exterior fire hazard is significant as “Fire will readily burn through the eaves into the attic, often bypassing the floor above the fire”. Tactics for addressing this type of fire require the outside fire be controlled and the line “sweep the eaves”. There is significant discussion as to if this should be the first line or the secondary line, with the conclusion that this must be based on conditions and resources.[35]

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[31] Daley, Mike. "Attic Fires: Hazards From Above." Fire Engineering. N.p., 01 Mar. 2013. Web. 19 Nov. 2014.
[32] Stowell, Frederick M., and Lynne Murnane. Essentials of Fire Fighting and Fire Department Operations. Upper Saddle River, NJ: Brady Pub., 2013. Print.
[33] Fundamentals of Fire Fighter Skills. Sudbury, MA: Jones and Bartlett, 2009. Print.
[34] Layman, Lloyd. *Attacking and Extinguishing Interior Fires*. Boston: National Fire Protection Association, 1960.
[35] Norman, John. *Fire Officer's Handbook of Tactics*. Tulsa, OK: PennWell, 2005.

4.3. Firefighter Line of Duty Deaths

July 4th, 1997 one fire fighter was killed and one seriously injured during interior operations at a 2 ½ story structure with fire in the ½ attic space. Information from the NIOSH report FACE 96-16 indicates the firefighter who was killed attempted to leave the attic space due to high heat while the injured firefighter experienced an SCBA malfunction and failure. The investigation focused on the lack of personal alert safety system usage and SCBA maintenance. Little was discussed as to the fire dynamics associated with the attic fire itself, the high heat conditions or ventilation/suppression operations.[36]

September 14th, 2002 one fire fighter was killed after falling through the roof of a 96 year old, 2 ½ story balloon frame wood structure while preforming vertical ventilation. The fire started in the space above the second floor ceiling but below the roof, due to an electrical failure. Initial size up indicated smoke from the eave line. An interior attack was attempted but crews were pushed back from the 2nd floor due to high heat and smoke. Ventilation was requested, after the victim and another fire fighter finished the ventilation cuts but prior to opening the roof they attempted to exit to the roof via an aerial platform. During the evacuation the victim fell through the roof between the location of the cut and the location of the aerial platform, over 23 minutes into the incident. The NIOSH investigation focused on command and operational items not necessarily the fire behavior or building construction concerns which led to the incident[37].

April 16th, 2007 one fire fighter was killed during a wind driven structure fire where the fire started on the exterior of the structure and spread to the interior of the house. Moderate smoke conditions were encountered as search and interior suppression were initiated immediately following arrival. Fire conditions rapidly changed trapping the victim in the second floor master bedroom of the structure. As the fire spread from the exterior to the interior and attic space driven by strong winds interior crews were forced to evacuate the structure[38].

4.4. Previous Research Work

The National Institute of Standards and Tecnhnology (NIST), Building Fire and Research Laboratory (BFRL) studied the ability of durable agents to reduce ignition of exterior siding and limit flame spread in when applied to the exterior of homes threaned by wildland fires. The study examined the use of a protein-based, compressed air foam and two types of gelling agents or water thicnkers for exposire protection. Agents were applied to two 8 ft. walls forming an inward

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[36] CDC/NIOSH, "Administrative Report FACE 97-16", NIOSH Division of Safety Research, Atlanta, GA 1997
[37] CDC/NIOSH, "Career Firefighter Dies After Roof Collapse Following Roof Ventilation – Iowa Firefighter Fatality Investigation Report F2002-40", NIOSH Division of Safety Research, Atlanta, GA 2003
[38] CDC/NIOSH, "Career Firefighter Dies in Wind Driven Residential Structure Fire - Virginia Firefighter Fatality Investigation Report F2002-40", NIOSH Division of Safety Research, Atlanta, GA 2003

corner under an eave line. The walls were covered with three different wall coverings, vinyl siding, T1-11 textured plywood, and aluminum siding. The soffit and eave materials remainded constant over all the experiments. Fifteen minutes after application of the agents a 50kW burner was used as an exposure fire for 10 minutes. The ability of the agents to prevent ignition spread was quantified by the time it took for flames to attach to the wall and spread up the siding to the eaves. The results illustrated significant ignition, and flame spread prevention for the agents tested.

Fire spread between adjacent structures was tested by NIST in 2008 with the project "Residential Structure Separation Fire Experiments". The work looked at developing data to assess the ability of Fire Dynamics Simulator (FDS) and Smoke View to accurately predict fire spread from one structure to another. The focus was a room and contents with a window open towards an adjacent structure 6 ft. away. The project tested two different target wall configurations. One without a fire separation barrier (gypsum wall board) and with the separation layer present. The test fixture was an 11 ft. by 12 ft. room with a 2 ft. by 3.3 ft. window facing a target wall 16 ft. high and 16 ft. wide. Temperature within the room and on the window were monitored along with heat flux at the top of the target wall and within a window in the target wall. The fire was ignited in the room, permitted to fail the window and expose the target wall. The time to ignition of the target wall was obtained along with the heat flux and temperature data. The project found the inclusion of a fire separation layer within the exterior wall provided significant delay to ignition and reduction in flame spread.[39]

A National Fire Academy (NFA) Executive Fire Officer (EFO) project in 2009 focused on the fire hazards of exterior vinyl siding as they relate to fire service operations. The author, Anthony McDowell, identified the need for further research in actual fire scenarios where a fire ignited and spread up the exterior of a vinyl sided structure. The work reviewed previous research by NIST on the fire hazards along with several case studies from fires in the Virginia area. Results of the research identified a significant training need for firefighters as to the fire hazards associated with vinyl siding. Tactical considerations included suppressing the exterior fire first before interior operations, continually checking for extension while conducting interior operations and supporting all interior operations with a charged hose line. A training PowerPoint was developed which provided an overview of vinyl siding fire hazards, reviewed case studies and extrapolated the experience into tactical considerations for operations at fires involving vinyl siding.[40]

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[39] Maranghid & Johnsson, "Residential Structure Separation Fire Experiment", National Institute of Standards and Technology, Gaithersburg, MD. 2008

[40] McDowell, Anthoney E., "The Wall of Fire: Training Firefighters to Survive Fires in Vinyl-clad Houses", Henrico County Division of Fire, Richmond, VA. 2009

5. Instrumentation

Throughout this project measurements were taking of temperature, heat flux, pressure, gas velocity and heat release rate. The same instrumentation was utilized for all three sets of experiments. The following describes the instrumentation used and potential uncertainty.

Heat flux measurements were made using a 2.54 cm nominal diameter water-cooled Schmidt-Boelter heat flux gauge (Figure 5. 1). The gauges measured the combined radiative and convective heat flux. For these experiments, the dominant form of heat flux is radiative due to the distance of the heat flux gauges from the flames. It should be noted that the convective contribution to the heat flux is dependent upon the surface temperature of the heat flux gauge. The manufacturer gives an uncertainty of ±3% and results from a study on heat flux calibration found the typical expanded uncertainty to be ±8%.[41]

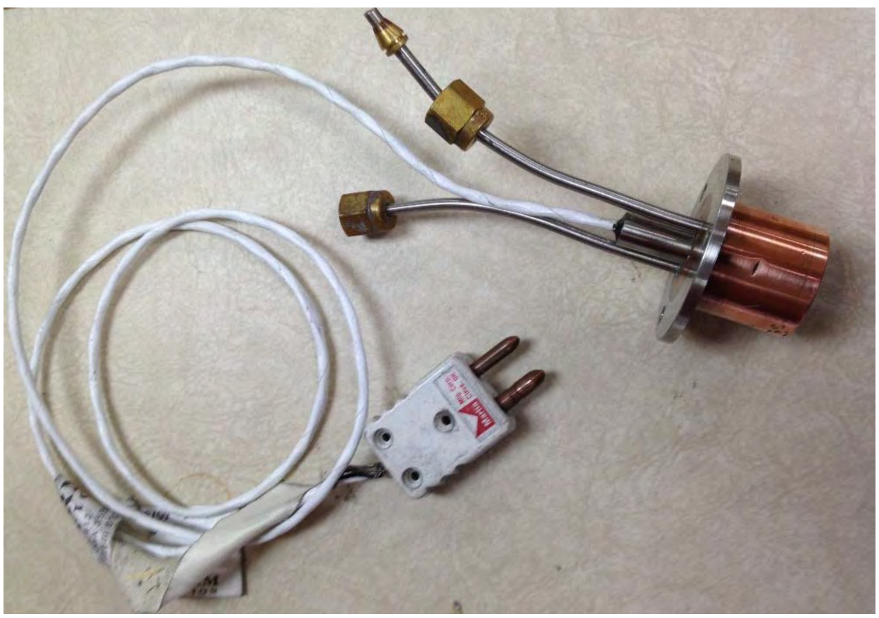


Figure 5. 1: Water Cooled Schmidt-Boelter Heat Flux Gauge

Temperatures were recorded using a bare-bead, Chromel-Alumel (type K) thermocouple with a 0.5 mm nominal diameter (Figure 5. 2). The uncertainty given by the manufacturer for the temperature measurements is ±2.2 ºC for temperatures below 293 ºC and ±0.75 % for higher temperatures.[42] The thermocouple readings will be lower than the air temperature when the

[41] Pitts, William M., Annageri V. Murthy, John L. De Ris, Jean-Rémy Filtz, Kjell Nygård, Debbie Smith, and Ingrid Wetterlund. "Round Robin Study of Total Heat Flux Gauge Calibration at Fire Laboratories." Fire Safety Journal 41.6 (2006): 459-75. Web.
[42] The Temperature Handbook. Stamford, CT: Omega Engineering, 2005. Print.

thermocouple is in the flame region, due to radiative losses to the surrounding cooler environment. When the thermocouples are farther from the flame region, the impact of radiation will result in temperature readings higher than the air temperature. Due to the effect of radiative heat transfer to the thermocouples, the expanded uncertainty is approximately ±15%.

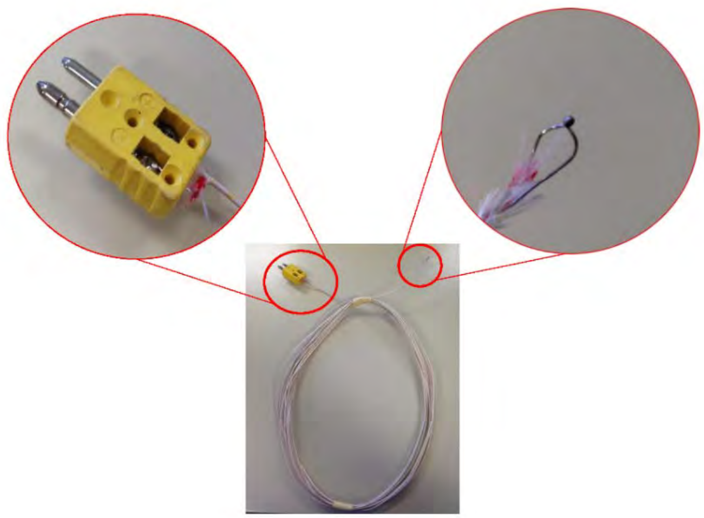


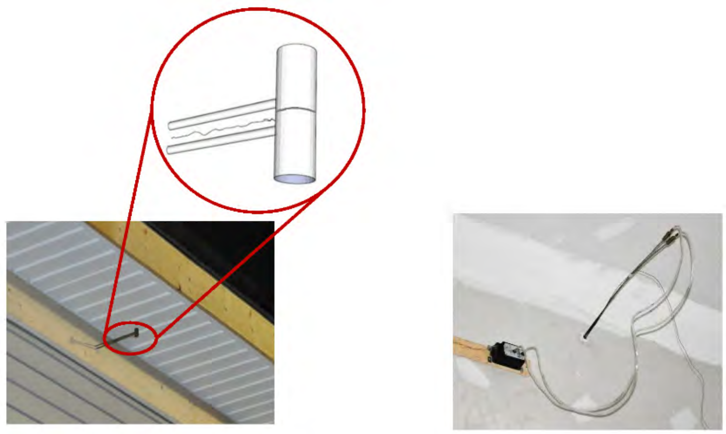
Figure 5. 2: Chromel-Alumel (Type K) Thermocouple

Pressure was recorded through the use of a Setra Model 264 differential pressure transducer with a range of ±0.5” Wc (±124.5 Pa) (Figure 5. 3). The transducer was used to evaluate the pressure difference from ambient. The uncertainty given by the manufacture is ±1 % or ±1.2 Pa.[43]

43 Setra System, “Installation Guide Setra Systems Model 265 Differential Pressure Transducer.” SS22009 Rev.G, Boxborough, MA. 2009

Figure 5. 3: Setra Model 264 Differential Pressure Transducer.

Gas velocity was obtained through the use of a bi-directional probe in conjunction with a differential pressure transducer and iconel thermocouple (Figure 5. 4). The probe was constructed of stainless steel. The iconel thermocouple was a 0.063in. diameter type KSL iconel 600 sheathed grounded junction with a type K, 24 gauge glass/glass insulation lead. The differential pressure transducer was a Setra Model 264 with a range of $\pm$0.5in. WC ($\pm$124.5 Pa). The configuration had a velocity range of $\pm$12.1 m/s ($\pm$27 mph). Velocity measurement with this configuration was determined to have an uncertainty of $\pm$5%.[44]



Front Back

Figure 5. 4: Bi-Directional Probe

The heat release rate is measured through the use of oxygen consumption techniques. The oxygen consumption calorimeter is capable of accurately measuring the heat release rate up to 10 MW. Above 10 MW, larger inaccuracies are expected due to the combustion products overflowing the collection hood. Figure 5. 5 shows the collection hood utilized for the calorimetry data.

[44] Lent, L.A. & Schneider, M.E, "The Design and Application of Bi-Directional Velocity Probes for Measurements in Large Pool Fires." Instrument Society of America, Vol. 26, No. 4 (1987): 25-32. Web.

Figure 5. 5: Calorimetry Hood

Stand video was obtained through the use of Marshall Electronics V-1255-B-BNC and Bosch VTC-206F03-4 video cameras (Figure 5. 6). Thermal imaging of the front and rear of the structure was taken using ISG Infrasys Elite XR (Figure 5. 7). The thermal imaging camera has a fixed emissivity value of 0.9 and was utilized for visual representation of relative conditions, no temperature measurements or analysis were derived using the camera. All cameras were recorded using a TriCaster 8200 video acquisition system.

Figure 5. 6: Bosh VTC-206F03-4 B&C Video Camera

Figure 5. 7: ISG Elite XR Fire Service Thermal Imaging Camera

All data was logged through the use of a national instruments data acquisition system incorporating a SCXI-1001 chassis with 8 SCXI-1102C 32-Channel modules (Figure 5. 8). The system is configured for a total of 256 channels capable of reading values between 0-10 volts DC. Values are recorded once a second and translated to quantities of interest through the use of LabVIEW software specifically programmed for use with the system.

Figure 5. 8. Data acquisition and video systems

6. Wall Experiments

There were 28 separate wall burn experiments examining 13 different wall constructions. For each burn, the wall was 8 ft. tall and 8 ft. wide simulating a small section of wall exposed to an exterior fire. The purpose of these experiments is to better understand how different wall constructions perform when exposed to an exterior fire and what that could mean to the fire service responding to that emergency.

6.1. Experimental Details

Individual wall burns were conducted under the oxygen consumption calorimeter at Underwriters Laboratories facilities in Northbrook, Illinois. The wall burns were designed to analyze the effect of several different parameters on ignition, flame spread and heat release rate. Those parameters included 1) burner heat release rate, 2) type of siding material, 3) type of sheathing material, and 4) type of insulation. Measurements of a) temperature, b) heat release rate, and c) heat flux were made to examine the effect of different wall materials on the burning characteristics of the wall, the ability of applicable standards to explain the fire behavior, and the building code requirements on exterior walls and fire separation distance.

For most of the experiments, the heat source was a line burner with dimensions 39 in. wide, 4 in. thick, and 16 in. high. A picture of the natural gas flow controller and burner can be seen in Figure 4.12 and Figure 4.13, respectively. The burner operated at 50 kW, 100 kW, 150 kW, 200 kW, and 300 kW. The actual heat release rate of the burner fell within ±10% of the targeted heat release rate. This was determined by examining the actual data in the early stages of the experiment before the wall became involved. For Experiments 15 and 16, a Nexgrill 720-0783C propane gas grill was located 1 in. off the wall and used as the heat source. For Experiments 23 and 24, a 1 ft. by 1 ft. sand burner operated at a heat release rate of 25 kW, with the fuel flow rate to the burner controlled by the natural gas flow controller. The uncertainty of the sand burner heat release rate was determined by examining the heat release rate in the early stages of the experiment before the wall became involved and was determined to be ±20% of the targeted heat release rate.

Table 6. 1 details each experiment including ignition source, main wall construction layers and the wall type identifier used throughout the report. Sidings used include; vinyl (Double 4 in. Dutch lap siding, 0.042 in. thickness), wood lap (8 in. cedar with no treatment), polypropylene shingle (Double 7 in. profile, 0.080 in. thickness), aluminum, and stucco. Sheathings examined include; plywood (untreated), polystyrene, polyisocyanurate and Exterior Insulation Finishing System (EIFS). Insulations used include; fiberglass, open-cell spray foam and closed-cell spray foam.

Figure 6. 1: Exposed Side of Wall

Figure 6. 2. Unexposed side of wall

Figure 6. 3. 100 kW fire from 36 in. line burner

Figure 6. 4. Line burner

Table 6. 1 Wall Experimental Description

Exp	Ignition Source	Siding	Sheathing	Insulation	Wall Type
1	150kW	4" Vinyl	Plywood	Fiberglass	1
2	50kW	4" Vinyl	Plywood	Fiberglass	1
3	100kW	4" Vinyl	Plywood	Fiberglass	1
4	150kW	4" Vinyl	1" Polystyrene	Fiberglass	8
5	100kW	4" Vinyl	1" Polystyrene	Fiberglass	8
6	50kW	4" Vinyl	1" Polystyrene	Fiberglass	8
7	100kW	4" Vinyl	1" Polyisocyanurate	Fiberglass	8-I
8	100kW	4" Vinyl	1/2" Polystyrene	Open Cell Spray Foam*	9
9	100kW	4" Vinyl	1/2" Polystyrene	Closed Cell Spray Foam*	9-C
10	100kW	4" Vinyl	1/2" Polyisocyanurate	Fiberglass	9-I
11	100kW	4" Vinyl	1/2" Polystyrene & Plywood	Open Cell Spray Foam*	9-S
12	100kW	4" Vinyl	1/2" Polystyrene	Open Cell Spray Foam*	9-R
13	100kW	4" Vinyl	1" Polystyrene	Fiberglass	8-R
14	100kW	8" Wood Lap	1/2" Polystyrene	Open Cell Spray Foam*	11
15	Propane Grill	4" Vinyl	1" Polystyrene	Fiberglass	8
16	Propane Grill	4" Vinyl	Plywood	Fiberglass	1
17	100kW	8" Wood Lap	Plywood	Fiberglass	2
18	100kW	Polypropylene Shingle	1" Polystyrene	Fiberglass	14
19	100kW	8" Fiber Cement	1" Polystyrene	Fiberglass	13
20	100kW	4" Aluminum Lap	1" Polystyrene	Fiberglass	12
21	100kW	8" Wood Lap	1" Polystyrene	Fiberglass	10
22	100kW	None	Plywood	None	18
23	25kW	4" Vinyl	Plywood	Fiberglass	1
24	25kW	4" Vinyl	1/2" Polystyrene	Closed Cell Spray Foam*	9-C
25	100kW	2 Coat Stucco	Plywood	Fiberglass	6
25.1	200kW	2 Coat Stucco	Plywood	Fiberglass	6
26	100kW	2 Coat Stucco	1" Polystyrene	Fiberglass	16
26.1	200kW	2 Coat Stucco	1" Polystyrene	Fiberglass	16
27	100kW	EIFS	Plywood	Fiberglass	7
27.1	200kW	EIFS	Plywood	Fiberglass	7
28	100kW	EIFS	1" Polystyrene	Fiberglass	17
28.1	300kW	EIFS	1" Polystyrene	Fiberglass	17

6.2. Experimental Methodology

Medium Scale wall experiments were conducted to evaluate the ignition, flame spread hazard, peak heat release rate and exposure potential of different wall construction types. Twenty eight experiments testing 13 different wall types were conducted and instrumented to compare how different siding, sheathing and insulation materials effect the exterior fire hazard. In addition experiments were conducted to evaluate the effect of power receptacles on fire propagation through the wall cavity.

The primary exterior surface provides weather resistance however is the initial exposure during an exterior fire. To evaluate the effect different siding materials have on exterior fire hazards a total of seven different siding types ranging from synthetic types such as vinyl to cementitious types such stucco and EIFS were tested with the same sheathing and insulation to compare the ignition, flame spread, peak heat release rate and exposure.

As construction practices have evolved not only has the exterior surface change but the sheathing and insulation materials have also evolved to provide greater isolative properties to residential homes. To evaluate the effect these materials have on exterior fire hazards vinyl siding was chosen as it currently dominates the U.S. market with 33 percent of new homes constructed[45] and 30 percent of homes sold[46] in 2012. The sheathing and insulation were varied to identify impacts on ignition, flame spread, peak heat release rate and exposure.

The size of the exterior fire source has a large impact on the fire hazard thus three wall types were evaluated using an ignition source (gas burner) ranging from 25kW to 150kW to identify the impact changing the source has on the hazard. The difference in ignition, flame spread, peak heat release rate and exposure were compared to identify a source which represented a realistic hazard and provided consistent results. Along with the gas burners ignition from a propane gas grill was evaluated for two experiments to identify the time and hazard from an ignition source without flame direct flame impingement.

The results of the medium scale wall experiments were used to establish the ignition source and wall construction for the larger eave experiments to further evaluate the flame spread potential and how fire extends from the exterior into the attic of a residential structure.

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[45] "United States Census Bureau." Characteristics of New Housing Sold. https://www.census.gov/construction/chars/sold.html. 25 Nov. 2014.
[46] "United States Census Bureau." Characteristics of New Housing Completed. https://www.census.gov/construction/chars/completed.html. 25 Nov. 2014.

6.3. Wall Experiment Instrumentation

The experiments were performed in a 50 by 50 ft. test cell with a 25 ft. hood to measure the heat release rate. In the test cell four inlet ducts provide air to the room and are located 5 ft. above the floor to minimize induced drafts within the room. Heat flux measurements were made 6 ft., 12 ft., and 18 ft. from the front surface of the wall at a height of 4 ft. above the ground. Temperatures were recorded under the siding and halfway in the depth of the wall cavity.

Video of the front surface and rear surface of the wall was recorded during the experiments, along with thermal imaging of the front and rear of the structure. The IR imaging of the surfaces is largely meant for qualitative observations. The layout for the instrumentation utilized in the experiments is shown in Figure 6. 7.

Figure 6. 5: Picture of Natural Gas Flow Controller

Figure 6. 6: Picture of Line Burner

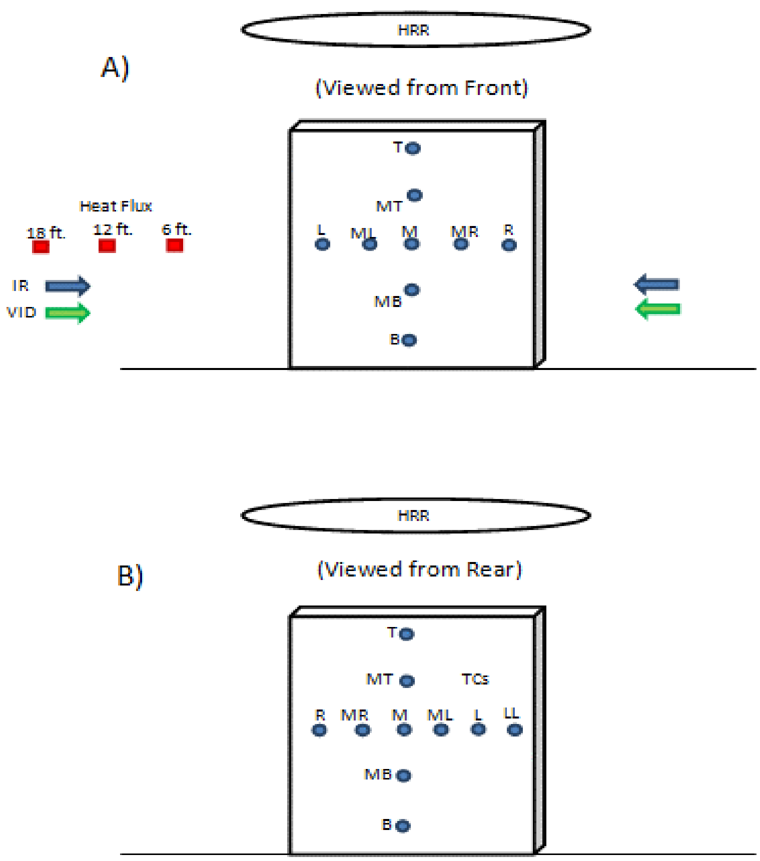


Figure 6. 7: Instrumentation for Wall Burn Experiments, (A) Thermocouple Locations under siding, (B) Thermocouple Locations in the wall cavity (viewed from back of the wall)

6.4. Wall Experiment Results

Experiment 1

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 2. A side view of the wall is shown in Figure 6. 8. The burner heat release rate (HRR) was 150 kW for Experiment 1 while the burner was on. Photos from Experiment 1 are displayed in Table 6. 3, and a timeline of the events within Experiment 1, matching with the photos in Table 6. 3, is shown in Table 6. 4. Heat release rate data, heat flux data, and temperature data from Experiment 1 are shown in appendix G figures G.1-G.6.

Table 6. 2: Wall Type and Material for Experiment 1 (150 kW)

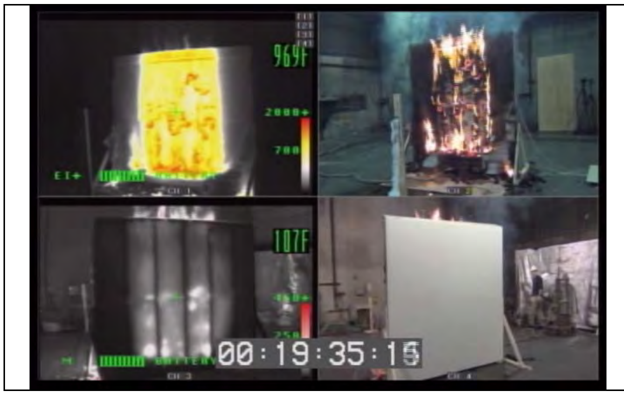
Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 1	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB*	1/2" Gypsum Board

*Kraft Faced Insulation with Integral Vapor Barrier

Figure 6. 8: Wall Type 1 Side View

Table 6. 3: Experiment 1 Pictures (Timeline starts at ignition [hr:min:sec:frames])



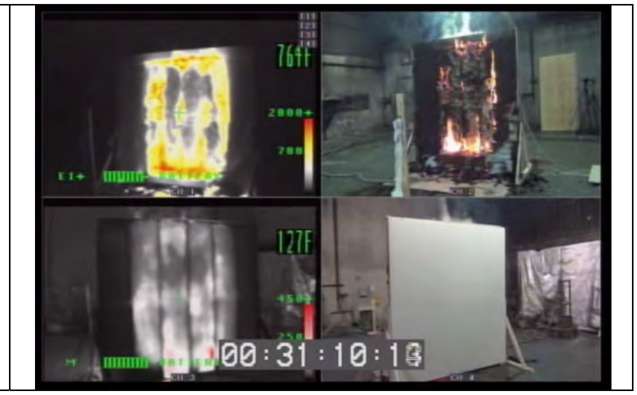


Table 6. 4: Experiment 1 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner reaches 150 kW
01:00	Vinyl Siding is melting and burning, flames are beginning to spread up the wall
01:40	Flames have reached the top of the wall
02:15	Flames have extended above the wall, the fire is beginning to spread horizontally along the wall
05:00	Most the vinyl siding has burned or fallen off the wall, smaller pieces of still burning vinyl siding can be seen on the ground in front of the wall
11:45	Insulation and the studs get involved in the fire
19:20	Shows the fire just before the burner is turned off
19:35	The burner is turned off, there is still a small amount of fire near the bottom of the wall by the burner and near the top of the wall
31:10	Most of the fire has self-extinguished, end of experiment

Experiment 2

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 5. A side view of the wall is shown in Figure 6. 9. The burner heat release rate (HRR) was 50 kW for Experiment 1 while the burner was on. Photos from Experiment 2 are displayed in Table 6. 6. A timeline of the events within Experiment 2, matching with the photos in Table 6. 6, is shown in Table 6. 7. Heat release rate data, heat flux data, and temperature data from Experiment 2 are shown in appendix G, figures G.7-G.12.

Table 6. 5: Wall Type and Material for Experiment 2 (50 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 1	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 9: Wall Type 1 Side View

Table 6. 6: Experiment 2 Pictures

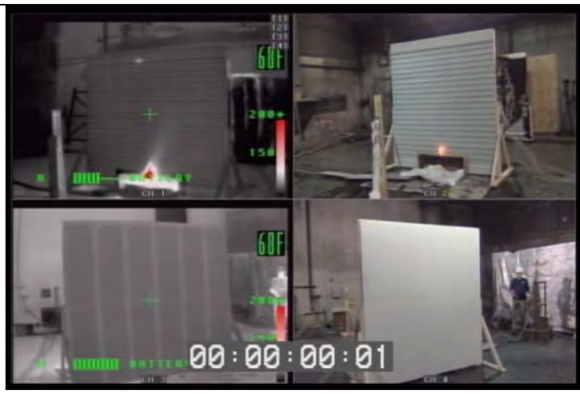
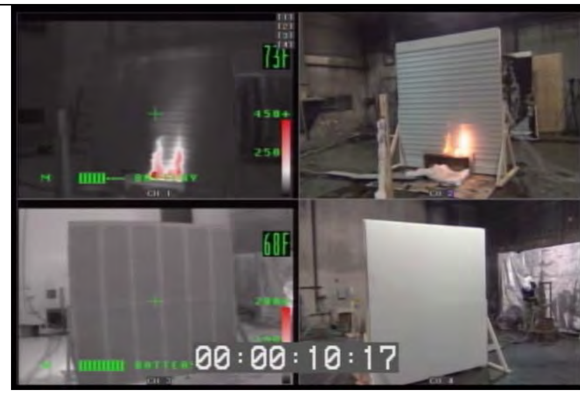
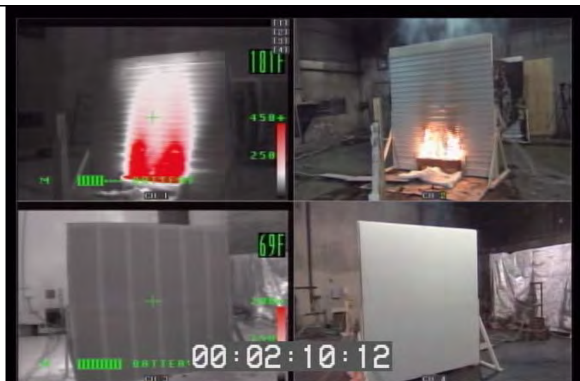
	
	
	
	

Table 6. 7: Experiment 2 Timeline

Time (mm:ss)	Description
00:00	Experiment pre-ignition
00:10	Burner is on and reaching desired 50 kW heat release rate
02:10	Vinyl siding is beginning to melt and burn, flames are spreading up the wall
04:45	The vinyl siding at the top of the wall has melted and fallen to the sides, flames have almost reached the top of the wall
07:15	Large portion of the vinyl siding has melted and burned away, the flames have reached the top corners of the wall
15:20	Small amount of burning extending up the insulation and studs
20:05	The burner is turned off, fire remains in the center of the wall
30:00	Still some flame near the top of the wall but most the fire has self-extinguished, the experiment ended

Experiment 3

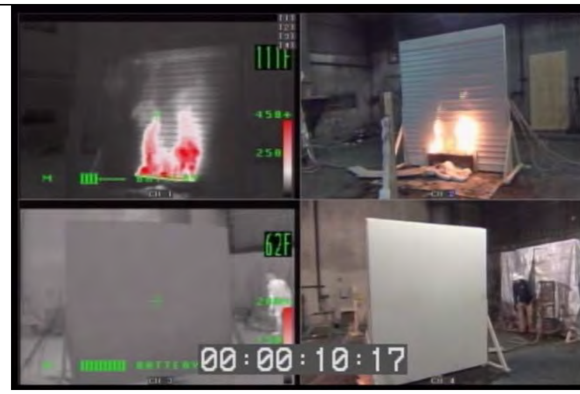
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 8. A side view of the wall is shown in Figure 6. 10. The burner heat release rate (HRR) was 100 kW for Experiment 3 while the burner was on. Photos from Experiment 3 are displayed in Table 6. 9. A timeline of the events within Experiment 3, matching with the photos in Table 6. 9, is shown in Table 6. 10. Heat release rate data, heat flux data, and temperature data from Experiment 3 are shown in appendix G, figures G.13-G18.

Table 6. 8: Wall Type and Material for Experiment 3 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 1	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 10: Wall Type 1 Side View

Table 6. 9: Experiment 3 Pictures



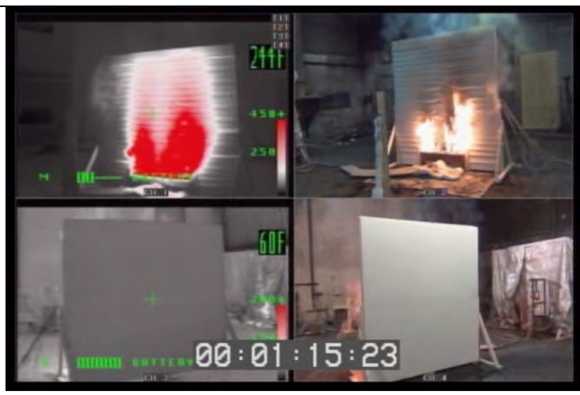


Table 6. 10: Experiment 3 Timeline

Time (mm:ss)	Description
00:00	Experiment pre-ignition
00:10	Burner is on and reaching desired 100 kW heat release rate
01:15	Vinyl siding begins to melt and burn, flames are spreading up the wall
02:30	Flames have reached the top of the wall
04:30	Most of the vinyl siding has fallen off or burned
15:00	Insulation and wall studs are involved and fire has again reached the top of the wall
20:00	The burner is turned off, fire is still present near top of the wall
29:55	Most of the fire has self-extinguished, the experiment is over

Experiment 4

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 11. A side view of the wall is shown in Figure 6. 11. The burner heat release rate (HRR) was 150 kW for Experiment 4 while the burner was on. Photos from Experiment 4 are displayed in Table 6. 12. A timeline of the events within Experiment 4, matching with the photos in Table 6. 12, is shown in

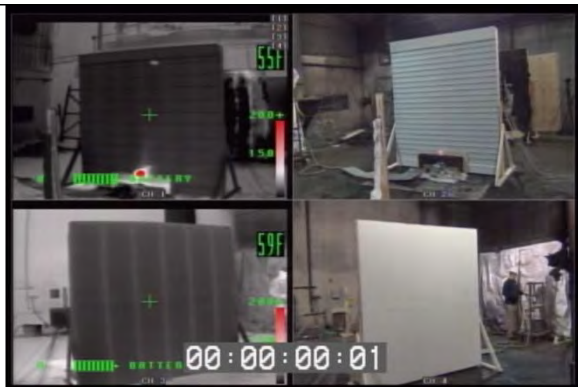
Table 6. 13. Heat release rate data, heat flux data, and temperature data from Experiment 4 are shown in appendix G, figures G.19-G.24.

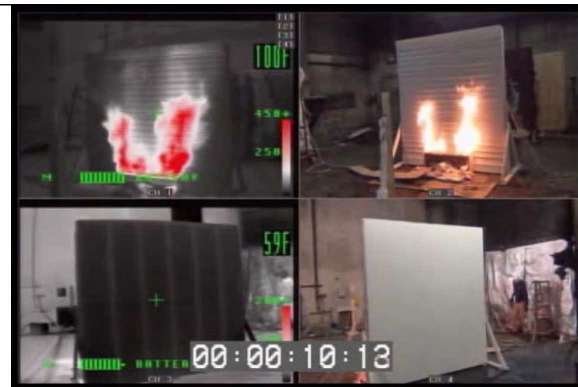
Table 6. 11: Wall Type and Material for Experiment 4 (150 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 11: Wall Type 8 Side View

Table 6. 12: Experiment 4 Pictures





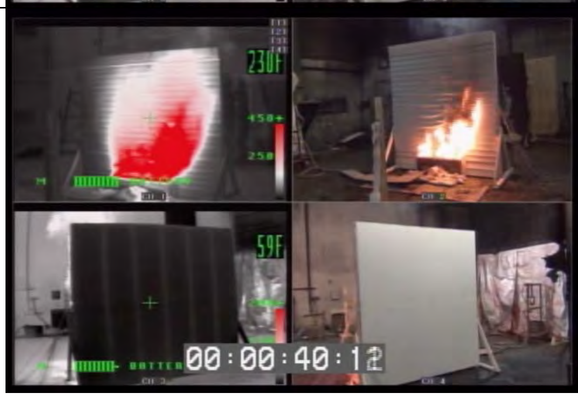


Table 6. 13: Experiment 4 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 150 kW heat release rate
00:40	Vinyl siding begins to melt and burn, flames begin spreading up the wall
01:15	Flames extend to the top of the wall and above the wall
03:30	Most of the vinyl siding has burned off, large pieces of vinyl siding are still burning on the ground in front of the wall
05:00	Pieces of vinyl siding are still burning on the ground in front of the wall, the wall is not burning much
20:01	The burner is turned off, only a small amount of insulation is burning
29:55	The burning has self-extinguished, the experiment is over

Experiment 5

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 14. A side view of the wall is shown in Figure 6. 12. The burner heat release rate (HRR) was 100 kW for Experiment 5 while the burner was on. Photos from Experiment 5 are displayed in

Table 6. 15. A timeline of the events within Experiment 5, matching with the photos in

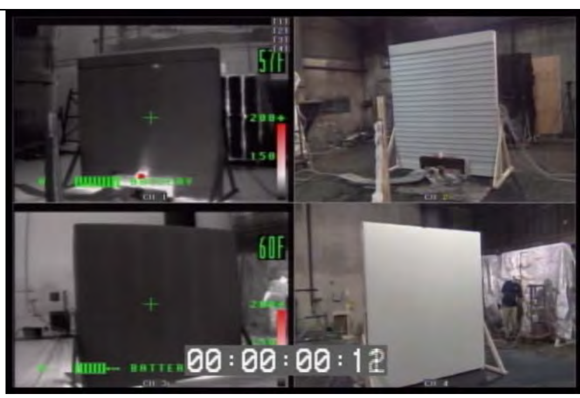
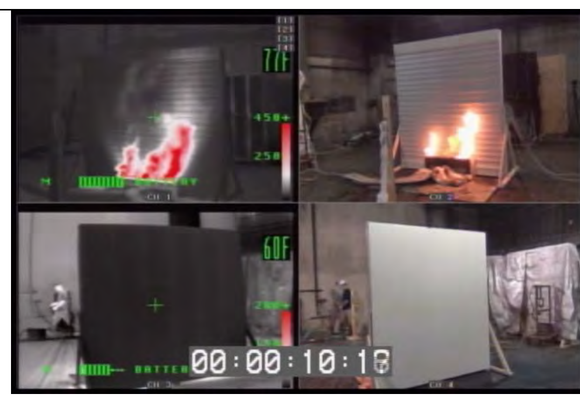
Table 6. 15, is shown in Table 6. 16. Heat release rate data, heat flux data, and temperature data from Experiment 5 are shown in appendix G, figures G.25-G.30.

Table 6. 14: Wall Type and Material for Experiment 5 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 12: Wall Type 8 Side View

Table 6. 15: Experiment 5 Pictures

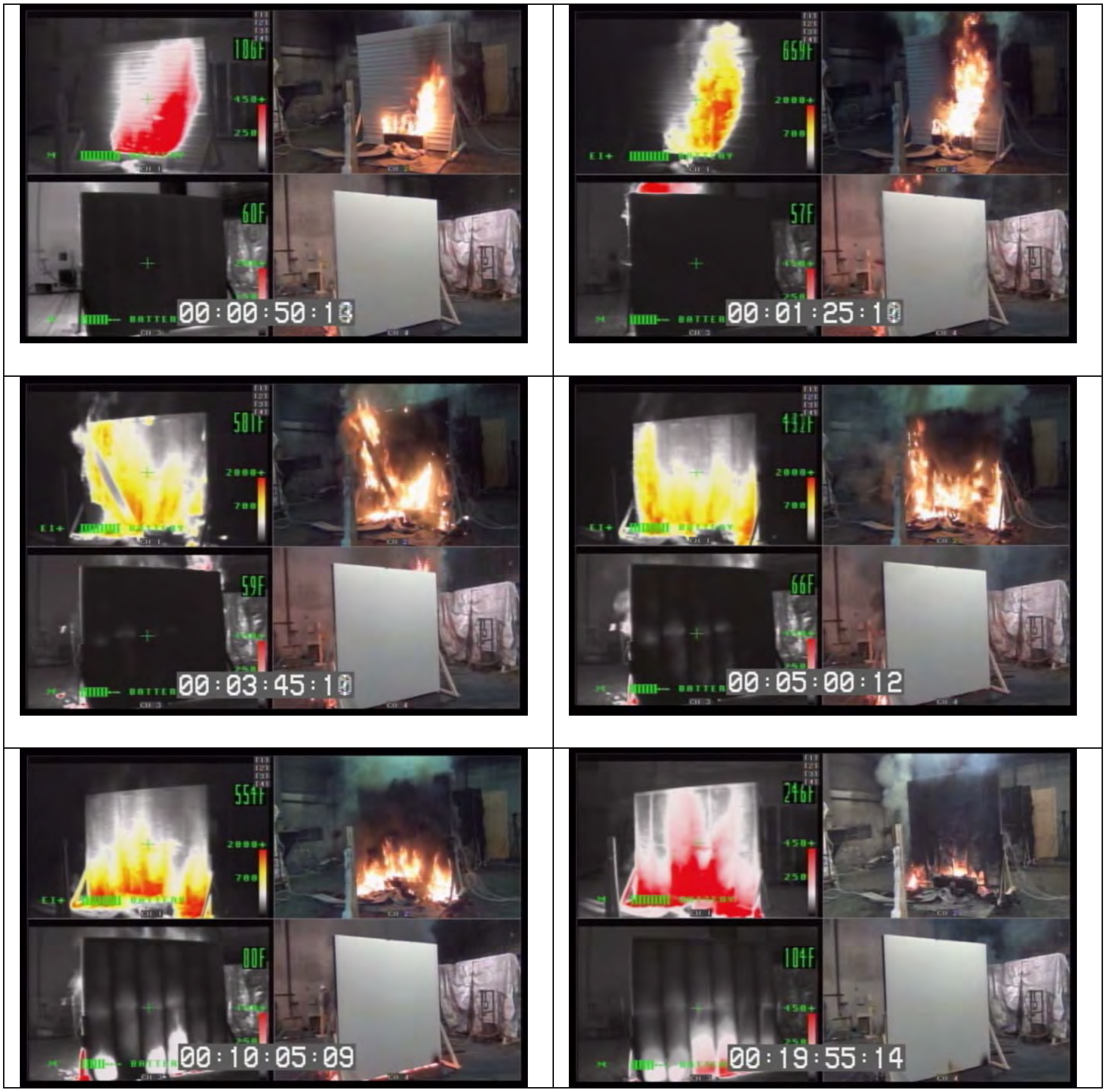


Table 6. 16: Experiment 5 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
00:50	Vinyl siding begins to burn and melt, flames begin extending up the wall
01:25	Flames reach top of the wall and extend above the wall
03:45	The vinyl siding has burned off
05:00	Pieces of vinyl siding are burning on the ground in front of the wall, not much of the wall is burning
10:05	Burner is turned off, small amount of flame is still above the burner, pieces of vinyl siding are still burning on the ground
19:55	Most of the fire has self-extinguished, the experiment is over

Experiment 6

The layout of the wall and materials used for each layer of the wall are specified in Table 6. **17**. A side view of the wall is shown in Figure 6. 13. The burner heat release rate (HRR) was 50 kW for Experiment 6 while the burner was on. Photos from Experiment 6 are displayed in

Table 6. 18. A timeline of the events within Experiment 6, matching with the photos in

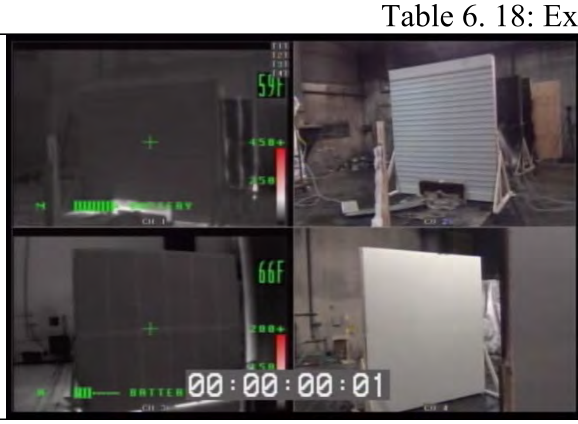
Table 6. 18, is shown in Table 6. 19. Heat release rate data, heat flux data, and temperature data from Experiment 6 are shown in appendix G, figures G.31-G.36.

Table 6. 17: Wall Type and Material for Experiment 6 (50 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 13: Wall Type 8 Side View

Table 6. 18: Experiment 6 Pictures

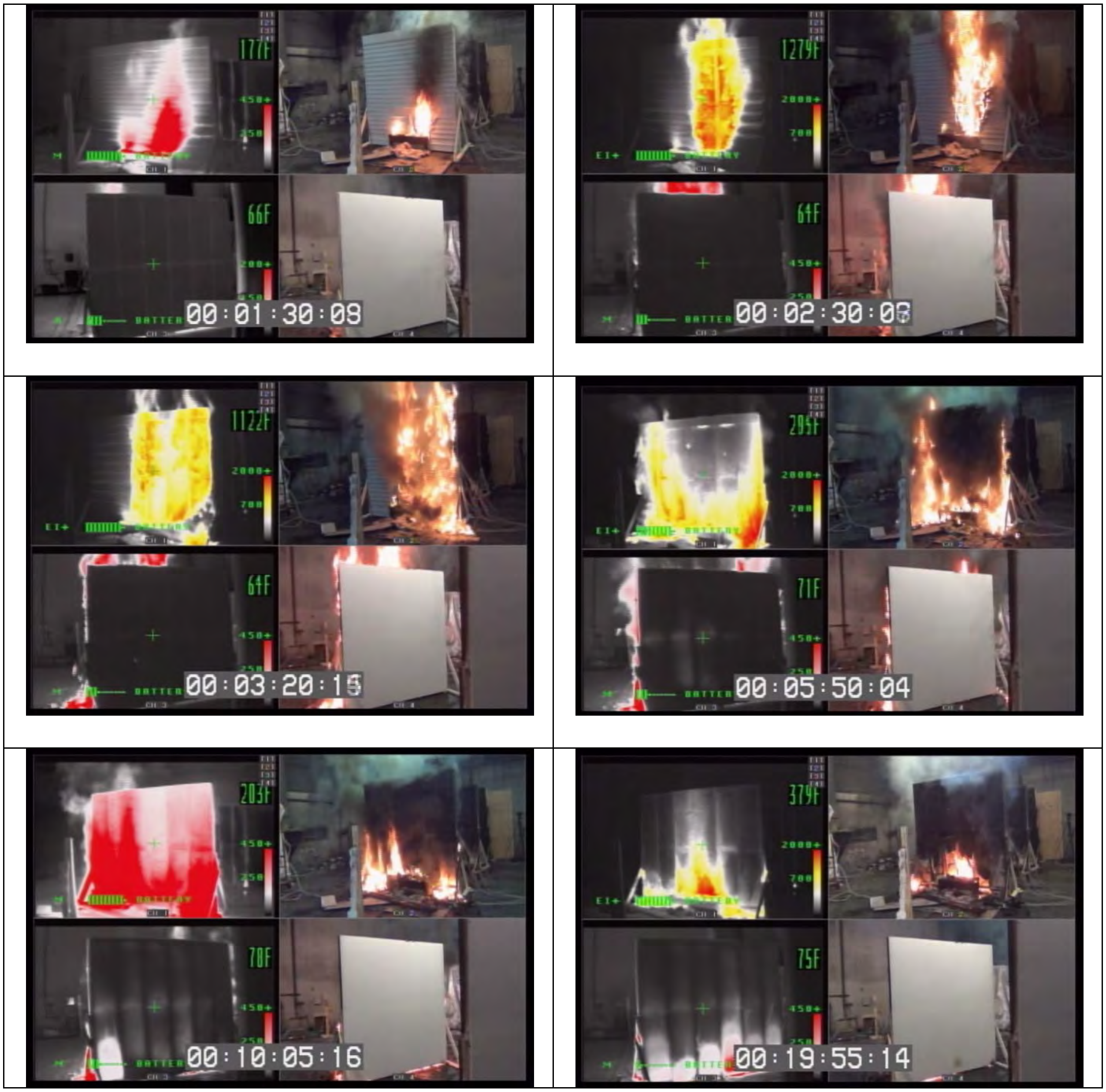


Table 6. 19: Experiment 6 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 50 kW heat release rate
01:30	Vinyl siding begins to melt and burn, flames spread up the wall
02:30	Flames extend to the top of the wall and above the top of the wall
03:20	Right side of the wall has burned off all the vinyl siding
05:50	All of the vinyl siding has now burned off, pieces of vinyl siding are burning on the ground
10:05	Burner is turned off, only a small part of the wall is still burning, pieces of vinyl siding are still burning on the ground

19:55	Most of fire, except a small portion just above the burner, has self-extinguished, the experiment is over

Experiment 7

The layout of the wall and materials used for each layer of the wall are specified in Table 6. **20**. A side view of the wall is shown in Figure 6. 14. The burner heat release rate (HRR) was 100 kW for Experiment 7 while the burner was on. Photos from Experiment 7 are displayed in

Table 6. 21. A timeline of the events within Experiment 7, matching with the photos in

Table 6. 21, is shown in Table 6. 22. Heat release rate data, heat flux data, and temperature data from Experiment 7 are shown in appendix G, figures G.37-G.42.

Table 6. 20: Wall Type and Material for Experiment 7 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8-I	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" Polyisocyuranate Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 14: Wall Type 8-I Side View

Table 6. 21: Experiment 7 Pictures

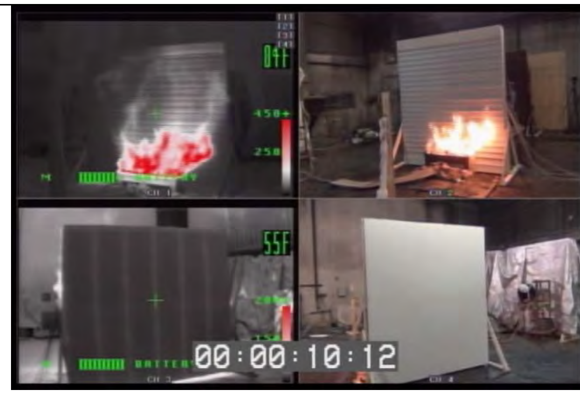
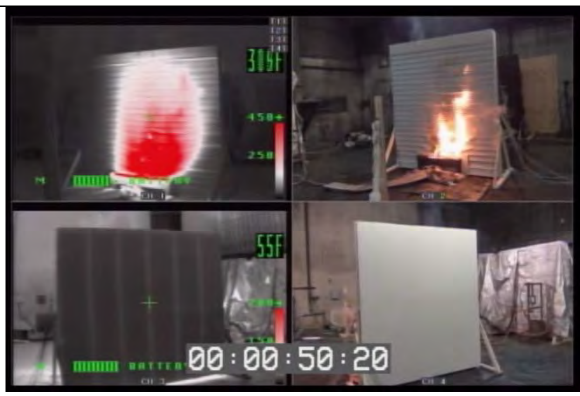
	
	
	

Table 6. 22: Experiment 7 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
00:50	Vinyl siding begins to melt and burn, flames spread up the wall
01:50	Flames have reached the top of the wall and extend above the wall
04:30	Most of the vinyl siding has burned off, pieces of vinyl siding are burning on the ground in front of the wall
07:20	Flames extend up the wall along a stud, pieces of vinyl siding are still burning on the ground
10:05	The burner is turned off, there is still a small amount of flame near the top of the wall, just above the burner, and on the ground
19:55	Flames have self-extinguished except for just above the burner, the experiment is over

Experiment 8

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 23. A side view of the wall is shown in Figure 6. 15. The burner heat release rate (HRR) was 100 kW for Experiment 8 while the burner was on. Photos from Experiment 8 are displayed in

Table 6. 24. A timeline of the events within Experiment 8, matching with the photos in

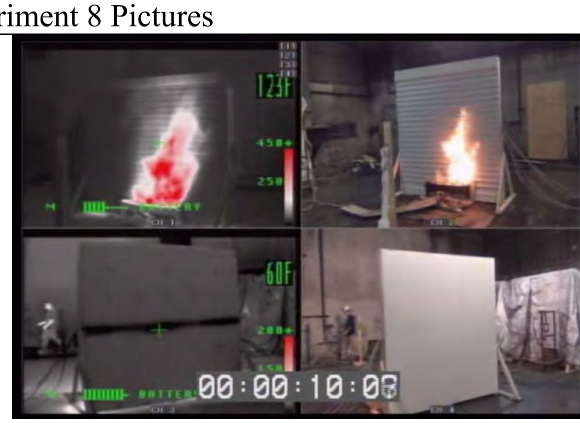
Table 6. 24, is shown in Table 6. 25. Heat release rate data, heat flux data, and temperature data from Experiment 8 are shown in appendix G, figures G.43 through G-48.

Table 6. 23: Wall Type and Material for Experiment 8 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 9-O	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, Open Cell Foam	1/2" Gypsum Board

Figure 6. 15: Wall Type 9-O Side View

Table 6. 24: Experiment 8 Pictures

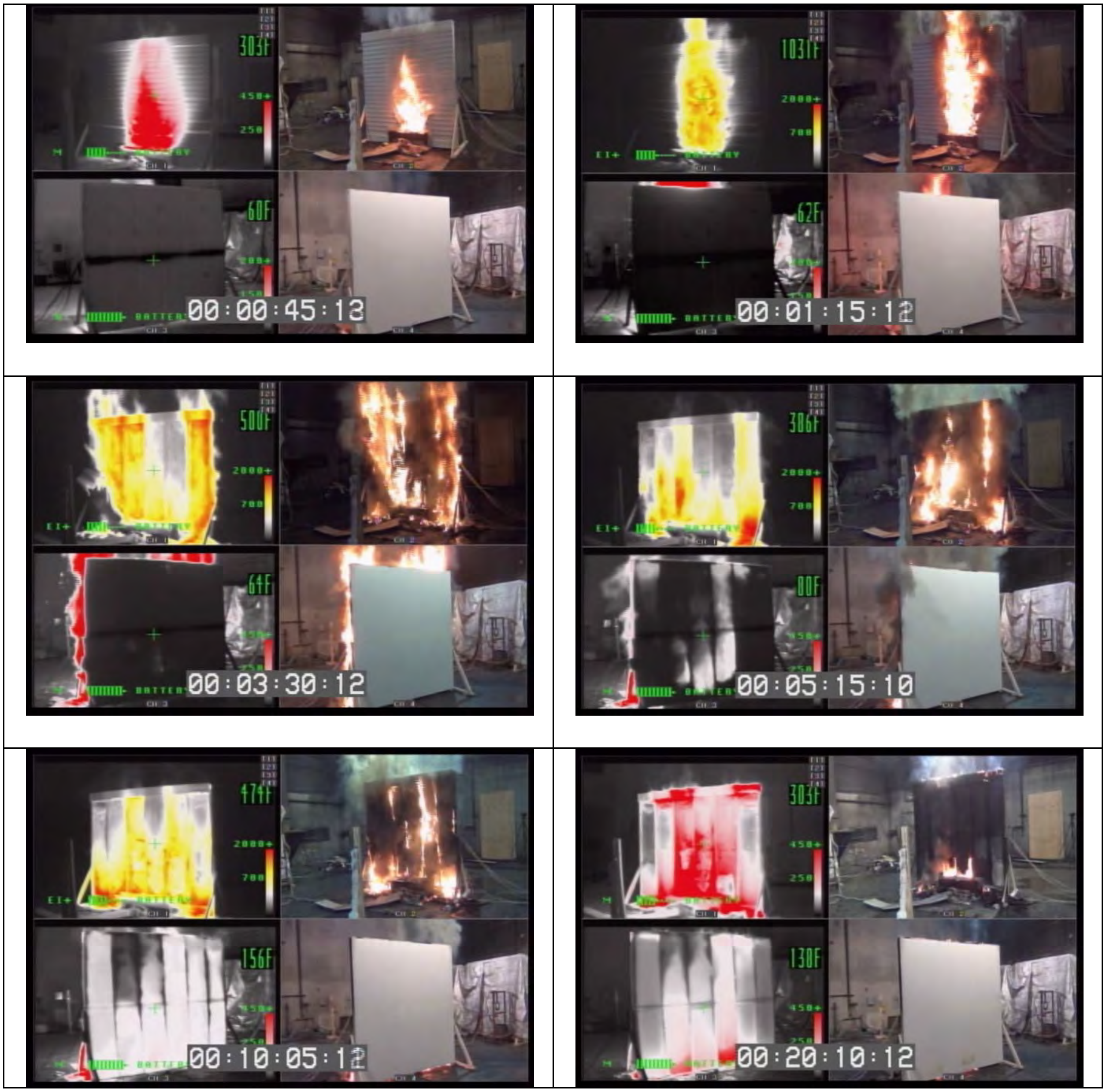


Table 6. 25: Experiment 8 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
00:45	Vinyl siding begins to melt and burn and flames begin to spread up the wall
01:15	Flames have reached the top of the wall and extend above the wall
03:30	Large amount of the vinyl siding has burned off the wall
05:15	All of the vinyl siding has burned off the wall, pieces of vinyl siding are burning on the ground in front of the wall
10:05	The burner is turned off, flames are still on the ground and along the studs

20:10	Most of the fire has self-extinguished except for the flames just above the burner, the experiment is over

Experiment 9

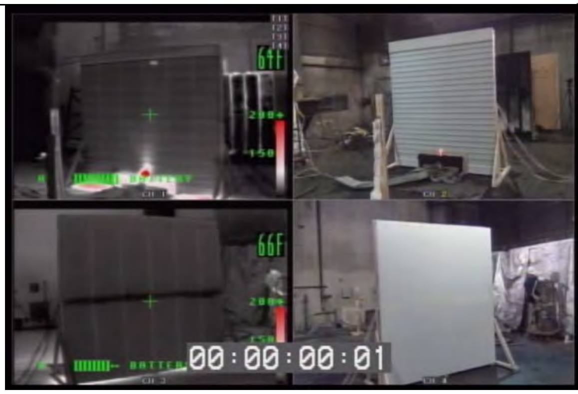
The layout of the wall and materials used for each layer of the wall are specified in Table 6. **26**. A side view of the wall is shown in Figure 6. 16. The burner heat release rate (HRR) was 100 kW for Experiment 9 while the burner was on. Photos from Experiment 9 are displayed in Table 6. 27. A timeline of the events within Experiment 9, matching with the photos in Table 6. 27, is shown in Table 6.28. Heat release rate data, heat flux data, and temperature data from Experiment 9 are shown in appendix G, figures G.49-G.54.

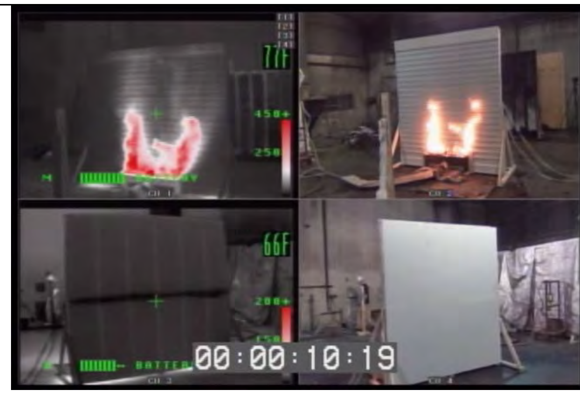
Table 6. 26: Wall Type and Material for Experiment 9 (100 kW)

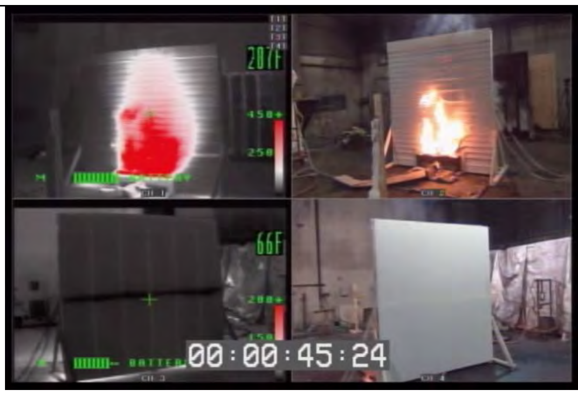
Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 9-C	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, Closed Cell Foam	1/2" Gypsum Board

Figure 6. 16: Wall Type 9-C Side View

Table 6. 27: Experiment 9 Pictures







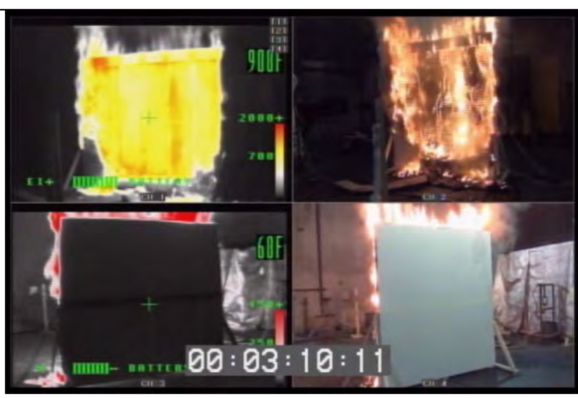


Table 6. 28: Experiment 9 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
00:45	Vinyl siding begins to melt and burn, flames spread up the wall
01:30	Flames have reached the top of the wall and extend above the wall
03:10	Large portion of the wall is still burning, the flames have spread to the sides of the wall
05:45	The vinyl siding has burned off, flames are rising along the studs and in the insulation, pieces of vinyl siding are burning on the ground in front of the wall
11:20	Burner is turned off, flames still just above the burner and on the ground
19:55	Most of the fire has self-extinguished except for just above the burner, the experiment is over

Experiment 10

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 29. A side view of the wall is shown in Figure 6. 17. The burner heat release rate (HRR) was 100 kW for Experiment 10 while the burner was on. Photos from Experiment 10 are displayed in Table 6. 30. A timeline of the events within Experiment 10, matching with the photos in Table 6. 30, is shown in

Table 6. 31. Heat release rate data, heat flux data, and temperature data from Experiment 10 are shown in appendix G, figures G.55-G.60.

Table 6. 29: Wall Type and Material for Experiment 10 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 9-I	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Polyisocyuranate Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 17: Wall Type 9-I Side View (Side View of 8-I same as Side View of 9-I)

Table 6. 30: Experiment 10 Pictures

Table 6. 31: Experiment 10 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:00	Vinyl siding begins to melt and burn, flames spread up the wall
01:45	Flames reach the top of the wall and extend above the wall
03:45	Most of the vinyl siding has burned or fallen off, still some vinyl siding burning on the left side of the wall
05:30	Vinyl siding has burned off, fire rising along studs and in insulation reaching top of the wall
10:05	Burner has turned off, small amount of flame in the wall and on the ground
19:55	Most of the flame has self-extinguished, experiment is over

Experiment 11

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 32. A side view of the wall is shown in Figure 6. 18. The burner heat release rate (HRR) was 100 kW for Experiment 11 while the burner was on. Photos from Experiment 11 are displayed in

Table 6. 33. A timeline of the events within Experiment 11, matching with the photos in

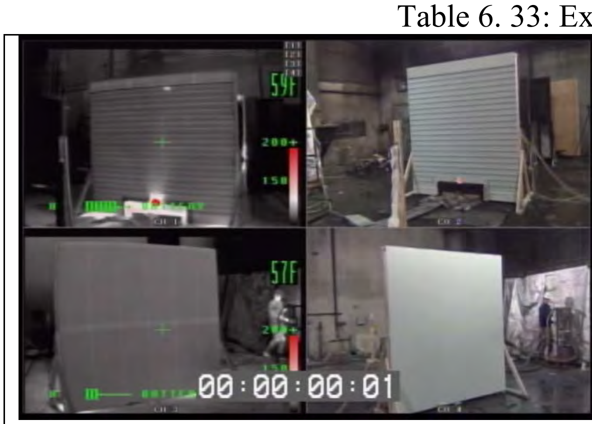
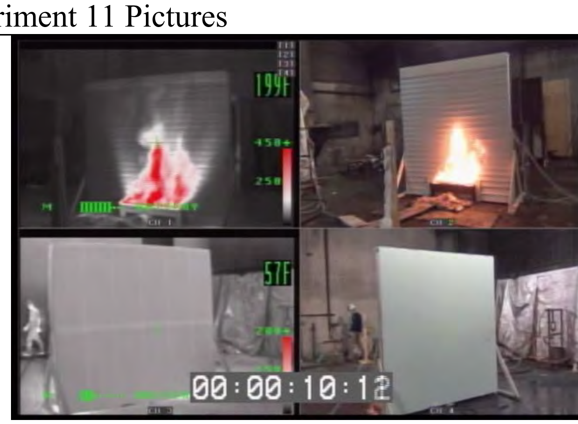
Table 6. 33, is shown in Table 6. 34. Heat release rate data, heat flux data, and temperature data from Experiment 11 are shown in appendix G, figures G.61-G.66.

Table 6. 32: Wall Type and Material for Experiment 11 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 9-S	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood followed by 1" R-5 EPS Insulation Board	2x6, Spray Polyurethane Foam	1/2" Gypsum Board

Figure 6. 18: Wall Type 9-S Side View

Table 6. 33: Experiment 11 Pictures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53F


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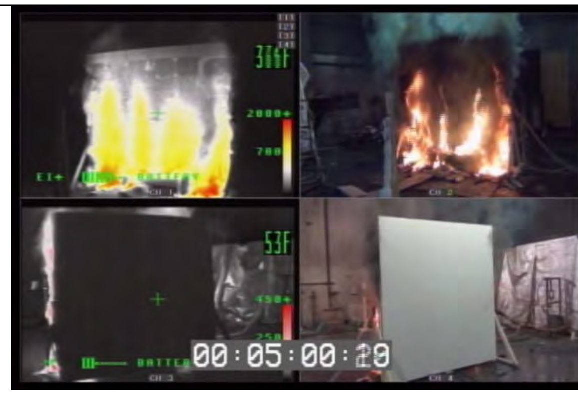
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753F
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00:31:00:13

Table 6. 34: Experiment 11 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:23	Vinyl Siding has begun melting, additionally some of it is burning increasing the flame height from the burner.
02:30	The melting of the siding has extended all the way up to the top of the wall. Small puddles are forming at the base of the wall and burning.
03:50	Most of the vinyl siding has melted off the wall, some vinyl siding is still burning on the left side
05:00	The vinyl siding has now completely melted or burned off the wall, the flames not from the burner are the result of melted off vinyl siding that is now burning.
10:10	The burner is turned off, pieces of vinyl siding are still burning on the ground though the flame height is significantly reduced.
15:00	Flames are now extending from the wall, the spray polyurethane foam is beginning to burn, and flames are extending out of the view of the camera.
21:30	A large area of the wall is now involved and the polyurethane foam in the wall cavity is being burned.
31:00	The studs in the wall cavity are visible, much of the polyurethane foam has been consumed, though some foam is still burning on the left side, discoloration of the back wall is visible and small amounts of smoke are being released from the back wall.

Experiment 12

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 35. A side view of the wall is shown in Figure 6. 19. This wall also had receptacles, which were outlets placed on the back of the wall. The burner heat release rate (HRR) was 100 kW for Experiment 12 while the burner was on. Photos from Experiment 12 are displayed in

Table 6. 36. A timeline of the events within Experiment 12, matching with the photos in

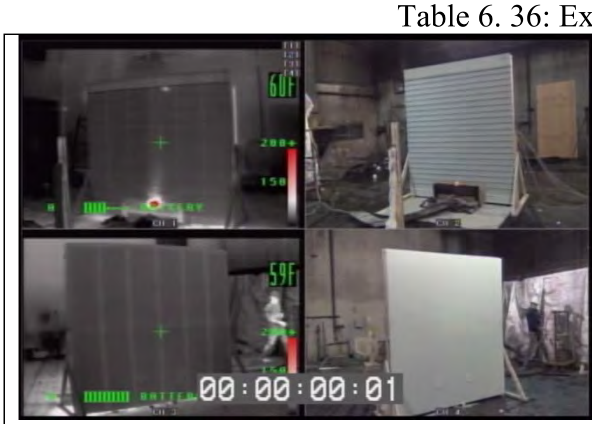
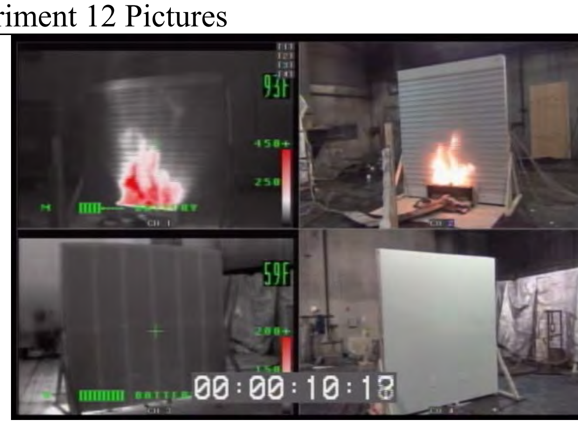
Table 6. 36, is shown in Table 6. 37. Heat release rate data, heat flux data, and temperature data from Experiment 12 are shown in appendix G, figure G.67-G.72.

Table 6. 35: Wall Type and Material for Experiment 12 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 9-R	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, Spray Polyurethane Foam	1/2" Gypsum Board

Figure 6. 19: Wall Type 9-R Side View

Table 6. 36: Experiment 12 Pictures


00:00:55:12

00:01:45:15

00:03:40:08

00:07:30:02

00:10:05:08

00:13:02:28

00:16:25:12

00:19:55:16

Table 6. 37: Experiment 12 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
00:55	Vinyl siding begins to melt and burn, flames spread up the wall
01:45	Flames reach top of the wall and extend above the wall
03:40	Large amounts of smoke and flame extending from the wall, also large amount of burning occurring on the ground
07:30	Flames still present in the studs and insulation, burning still occurring on the ground
10:05	Burner turned off, flames still near the top of the wall, above the burner, and on the ground
13:02	Much of the flame has reduced, only remaining above the burner and on the ground, back of the wall has been burned through at the receptacle, smoke rising out of the hole in the back of the wall
16:25	Another hole in the back of the wall is created, flames actually exit out of the back of the wall through the receptacle hole and rise several inches up the back of the wall
19:55	Still some flame on the front of the wall, large amount of charring on the back of the wall, experiment is over

Experiment 13

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 38. A side view of the wall is shown in Figure 6. 20. This wall also had receptacles on the back wall. The burner heat release rate (HRR) was 100 kW for Experiment 13 while the burner was on. Photos from Experiment 13 are displayed in Table 6. 39. A timeline of the events within Experiment 13, matching with the photos in Table 6. 39, is shown in Table 6. 40. Heat release rate data, heat flux data, and temperature data from Experiment 13 are shown in appendix G, figures G.73-G.78.

Table 6. 38: Wall Type and Material for Experiment 13 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8-R	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 20: Wall Type 8-R Side View

Table 6. 39: Experiment 13 Pictures

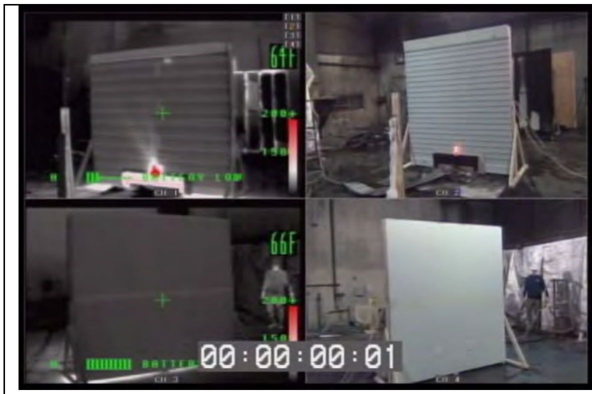
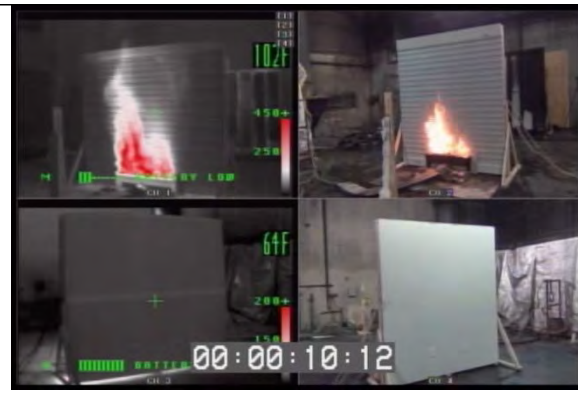
	
	
	
	

Table 6. 40: Experiment 13 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
00:50	Vinyl siding begins to melt and burn, flames spread up the wall
01:30	Flames reach top of the wall and extend above the wall
03:45	Most of the vinyl siding has burned off, still large amounts flame originating on the ground and right side of the wall
05:00	Burning still occurring on the ground in front of the wall
10:05	Burner turned off, flames still on the ground and above the burner, discoloration seen on back of the wall
14:25	Two holes on back of the wall, flames coming from one of the receptacle holes
19:55	The fire has self-extinguished, large amount of charring on the back wall, experiment is over

Experiment 14

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 41. A side view of the wall is shown in Figure 6. 21. The burner heat release rate (HRR) was 100 kW for Experiment 14 while the burner was on. Photos from Experiment 14 are displayed in Table 6. 42. A timeline of the events within Experiment 14, matching with the photos in Table 6. 42, is shown in Table 6. 43. Heat release rate data, heat flux data, and temperature data from Experiment 14 are shown in appendix G, figures G.79-G.84.

Table 6. 41: Wall Type and Material for Experiment 14 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 11	8" Wood Lap Siding	Weather-Resistant Barrier	1/2" EPS Insulation Board	2x6, Spray Polyurethane Foam	1/2" Gypsum Board

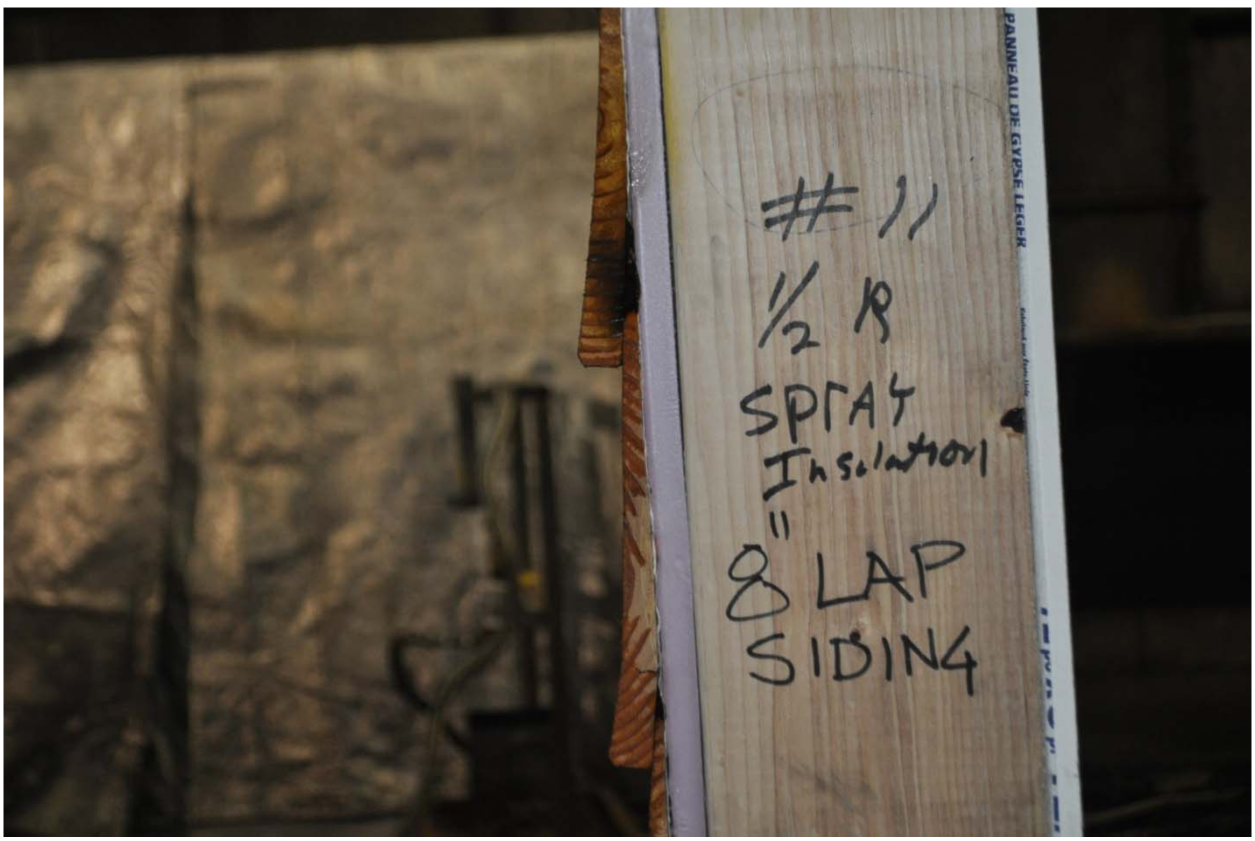
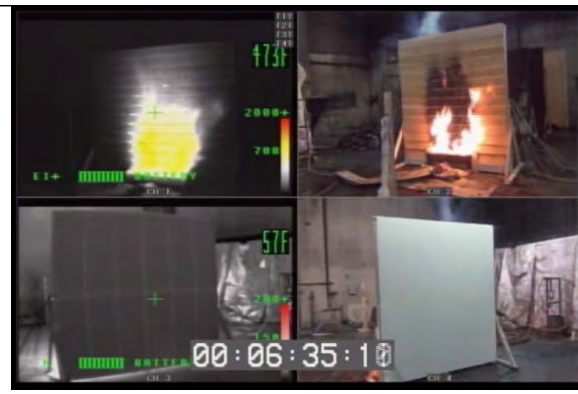
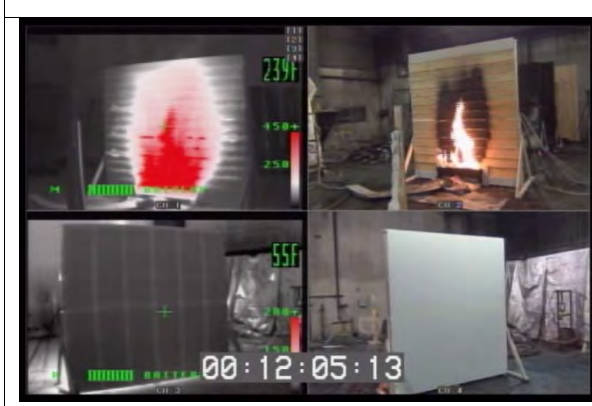


Figure 6. 21: Wall Type 11 Side View

Table 6. 42: Experiment 14 Pictures

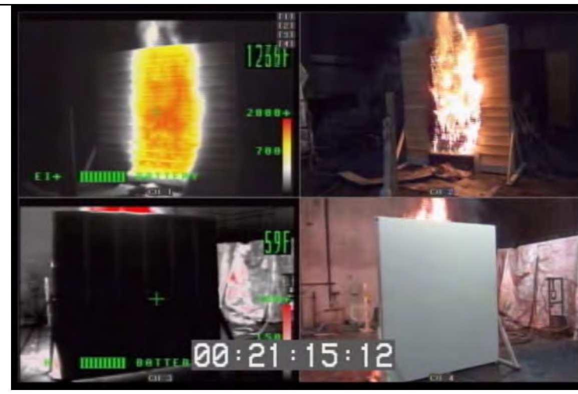


Table 6. 43: Experiment 14 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:15	Some initial charring is visible but the siding is not yet involved
06:35	The charring has extended up most the wall but the siding is still mostly not involved
09:55	Almost unchanged from the previous picture
10:05	Burner is turned off, siding is just smoldering, barely involved in the fire
12:05	Burner is turned back on
17:20	Flames extend to the top of the wall and slightly above it, the siding is beginning to get involved
18:30	Flames are back to below the top of the wall, charring extends all the way up the wall
21:15	Siding finally gets fully involved, flames shoot up the wall extending above the top of the wall
24:05	Burner is turned off, siding is still burning, flames still extending above the wall
29:35	Bottom center of the siding is mostly done burning, top of wall is still burning, flames still extend above the top of the wall, experiment is over

Experiment 15

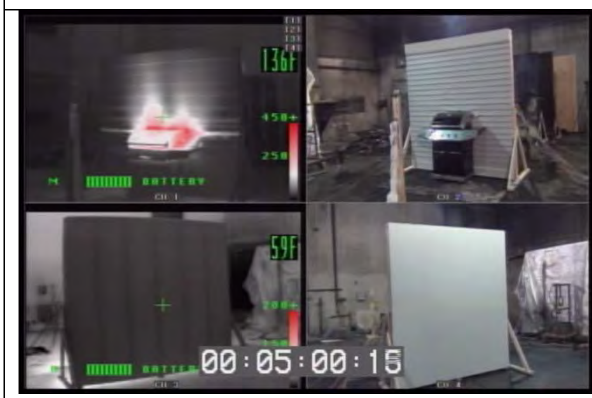
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 44. A side view of the wall is shown in Figure 6. 22. A grill was used for the heat source. Photos from Experiment 15 are displayed in Table 6. 45. A timeline of the events within Experiment 15, matching with the photos in Table 6. 45, is shown in Table 6. 46. Heat release rate data, heat flux data, and temperature data from Experiment 15 are shown in appendix G, figures G.84-G.90.

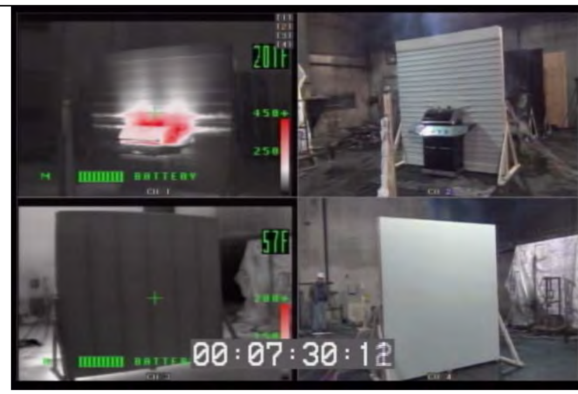
Table 6. 44: Wall Type and Material for Experiment 15 (Grill)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 22: Wall Type 8 Side View

Table 6. 45: Experiment 15 Pictures





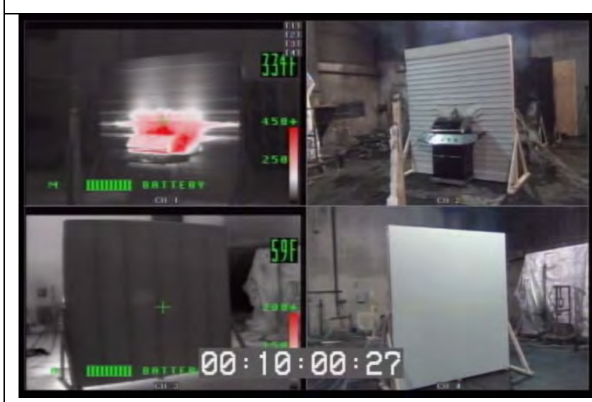


Table 6. 46: Experiment 15 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Grill is on and heating up
05:00	Only a very small amount of melting of the vinyl siding
07:30	The vinyl siding above the grill is melting and warping
10:00	Vinyl siding begins to separate and expose the sheathing underneath
15:00	More of the vinyl siding begins to break away, exposing more of the sheathing
40:02	Grill pushed up against wall.
45:00	More vinyl siding (above the exposed sheathing) begins to warp
45:10	First sighting of flames just above the grill
46:05	Fire begins to grow, grill is removed
46:30	Flames reach top of wall and extend above the wall
49:55	Flame has spread horizontally reaching the top corners of the wall but has died down a bit, experiment is over

Experiment 16

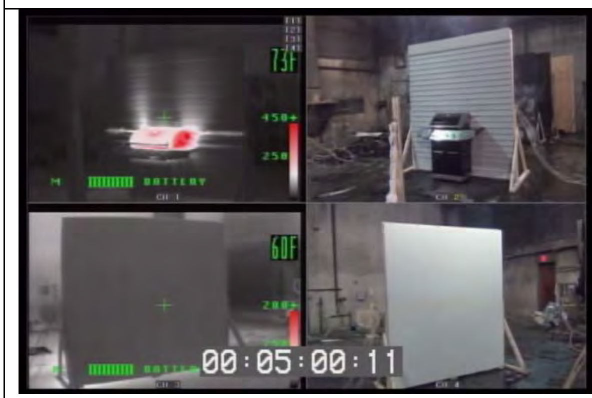
The layout of the wall and materials used for each layer of the wall are specified in Table 6.47. A side view of the wall is shown in Figure 6.23. A grill was used for the heat source. Photos from Experiment 16 are displayed in Table 6.48. A timeline of the events within Experiment 16, matching with the photos in Table 6.48, is shown in Table 6.49. Heat release rate data, heat flux data, and temperature data from Experiment 16 are shown in appendix G, figures G.91-G.96.

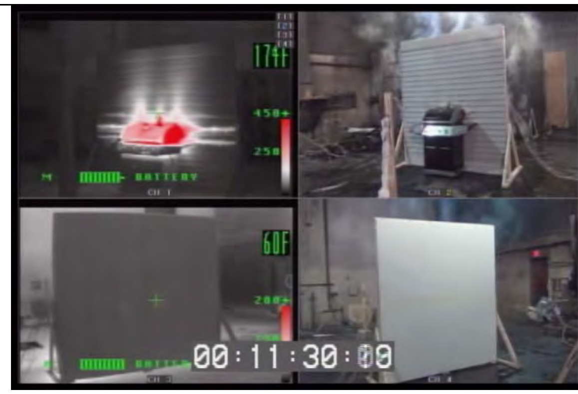
Table 6. 47: Wall Type and Material for Experiment 16 (Grill)

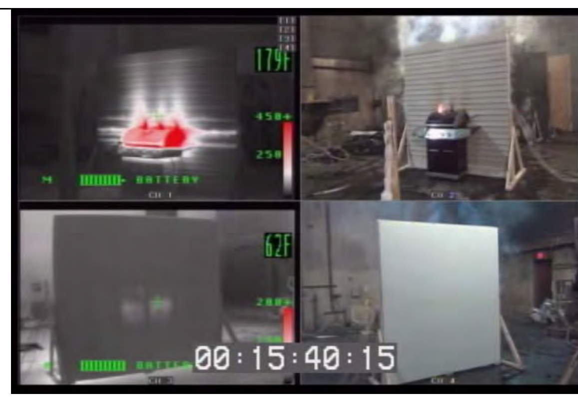
Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 1	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 23: Wall Type 8 Side View

Table 6. 48: Experiment 16 Pictures







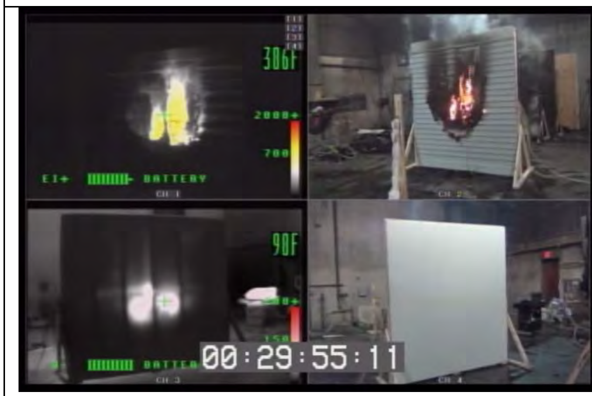
	

Table 6. 49: Experiment 16 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Grill is on and heating up
05:00	Only a very small amount of melting of the vinyl siding
11:30	First separating of vinyl siding is seen just above the grill
15:00	Another separation point of the vinyl siding is seen above the grill
15:40	Flames are seen for first time
17:05	Fire begins to grow, grill is removed
20:00	Fire begins to die down, does not reach top of the wall
29:55	Some fire still remains but it has not grown, soot and charring is seen on some of the wall, experiment is over

Experiment 17

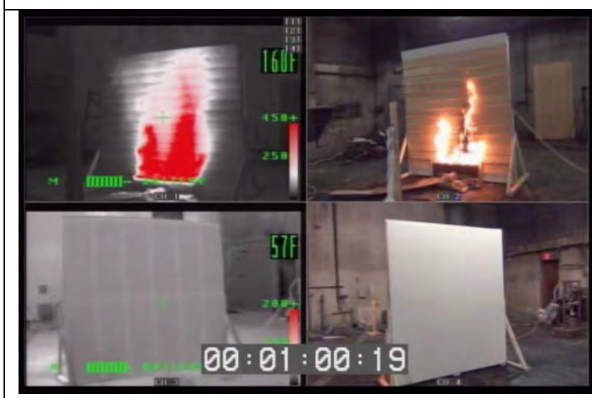
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 50. A side view of the wall is shown in Figure 6. 24. The burner heat release rate (HRR) was 100 kW for Experiment 17 while the burner was on. Photos from Experiment 17 are displayed in Table 6. 51. A timeline of the events within Experiment 17, matching with the photos in Table 6. 51, is shown in Table 6. 52. Heat release rate data, heat flux data, and temperature data from Experiment 17 are shown in appendix G, figures G.97-G.102.

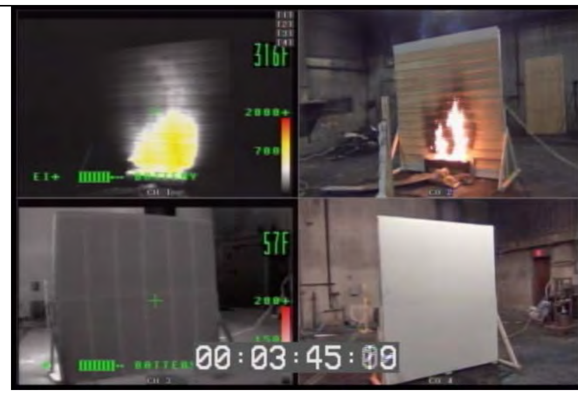
Table 6. 50: Wall Type and Material for Experiment 17 (100 kW)

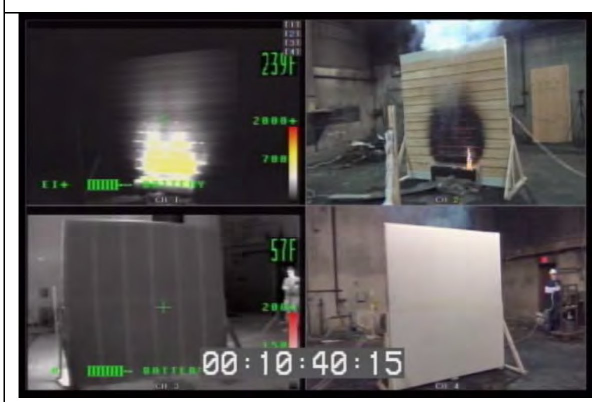
Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 2	8" Wood Lap Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board

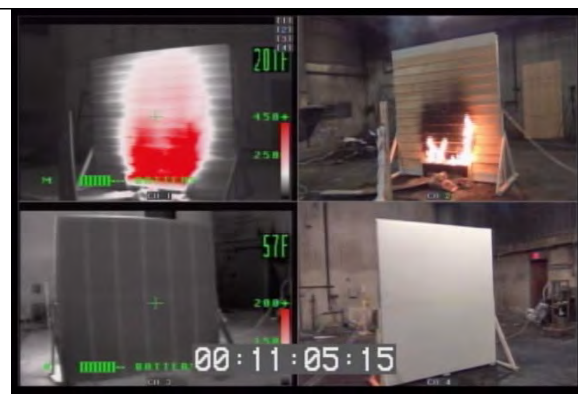
Figure 6. 24: Wall Type 2 Side View

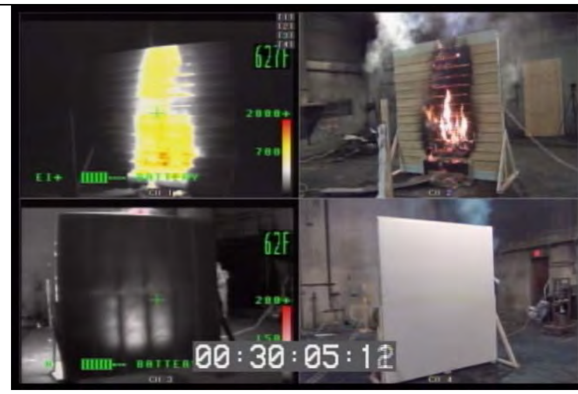
Table 6. 51: Experiment 17 Pictures











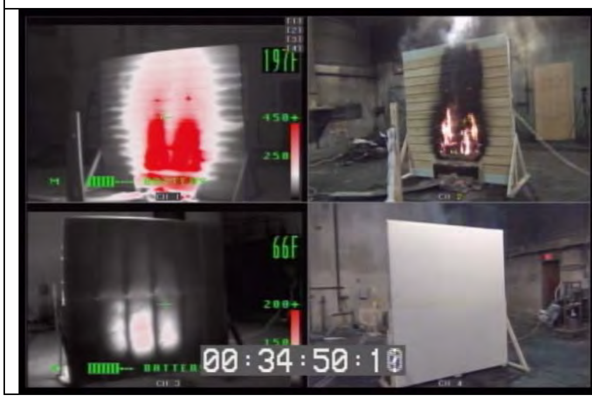


Table 6. 52: Experiment 17 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:00	Charring is visible but most the flame is from the burner
03:45	Charring has increased along the surface of the siding but still most of the flame is from the burner
10:40	Burner is turned off, no flame remains on the wall
11:05	Burner is turned back on
15:25	Charring increases up along the wall, reaching the top
27:00	Flame is again reduced to mostly just the burner
29:25	Flame spread up the wall, again reaching the top
30:05	Burner is turned off, some flame remains just above the burner in the center of the wall
34:50	Some fire still remains on the lower center part of the wall, experiment is over

Experiment 18

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 53. A side view of the wall is shown in Figure 6. 25. The burner heat release rate (HRR) was 100 kW for Experiment 18 while the burner was on. Photos from Experiment 18 are displayed in Table 6. 54. A timeline of the events within Experiment 18, matching with the photos in Table 6. 54, is shown in

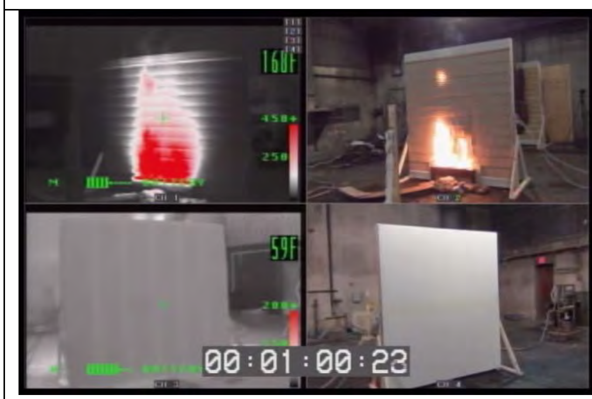
Table 6. 55. Heat release rate data, heat flux data, and temperature data from Experiment 18 are shown in appendix G, figures G.103-G.108.

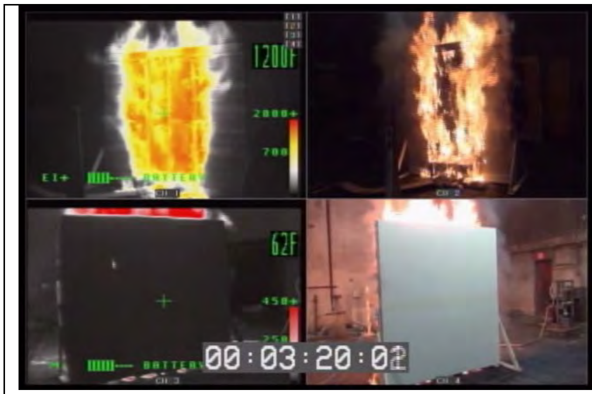
Table 6. 53: Wall Type and Material for Experiment 18 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 14	Double 7" Polypropylene Shingle Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 25: Wall Type 14 Side View

Table 6. 54: Experiment 18 Pictures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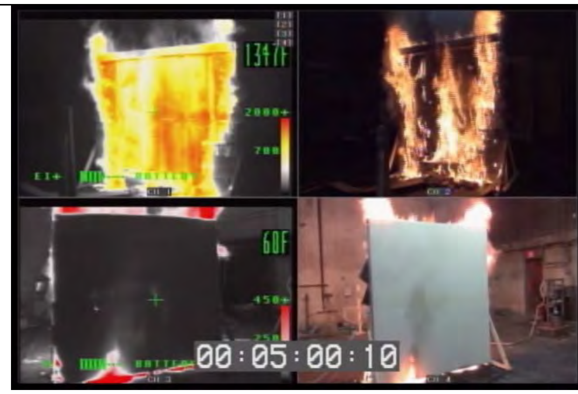
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00:09:15:10


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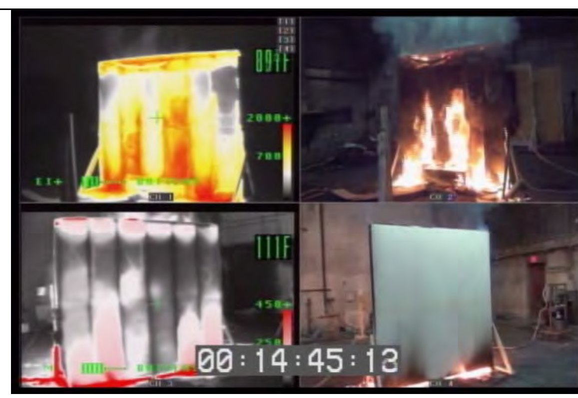
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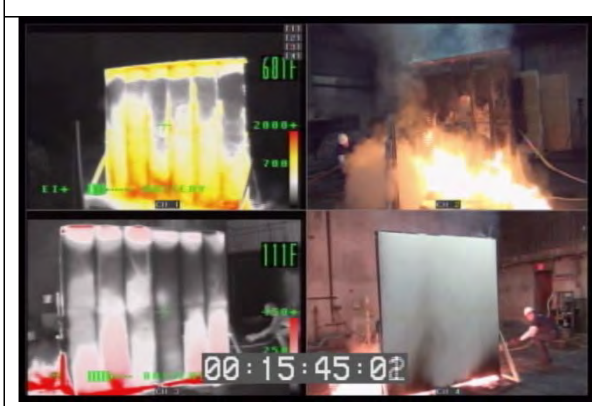
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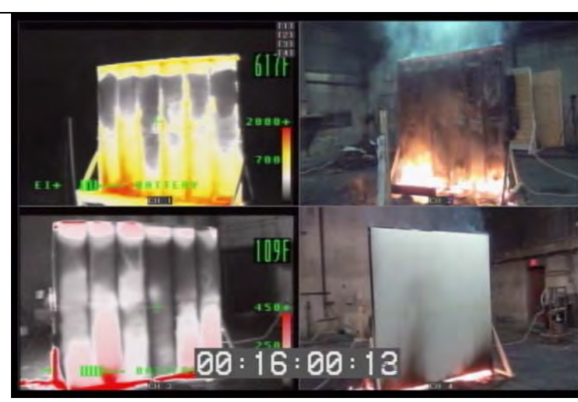
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Table 6. 55: Experiment 18 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:00	Some of the siding begins to melt and burn
02:00	Flames have spread up the wall, not yet reaching the top
02:20	Flames have reached the top of the wall, extending well above it
02:40	The most intense burning of the siding is seen
03:20	The centerline of the wall seems to have decreased burning, the outer edges of the flame region are still burning
05:00	Flames have reached the top corners of the wall
06:40	The siding has burned off, larger flames are rising up from the ground in front of the wall due to the siding that fell from the wall onto the ground
09:15	The fire on the ground continues, burning up some of the studs and insulation in the wall cavity
10:05	The burner is turned off, but the fire on the ground continues to supply the wall with a heat source
14:45	The fire is rising up into different sections of the wall cavity burning the studs and insulation
15:45	The burner continued to burn due to the residue from the siding, the burner was pulled away from the wall and water was applied to put that part of the fire out
16:00	Fire still remains on the floor in the wall cavity
20:20	Still a small amount of burning on the ground on left side, experiment is over

Experiment 19

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 56. A side view of the wall is shown in Figure 6. 26. The burner heat release rate (HRR) was 100 kW for Experiment 19 while the burner was on. Photos from Experiment 19 are displayed in

Table 6. 57. A timeline of the events within Experiment 19, matching with the photos in

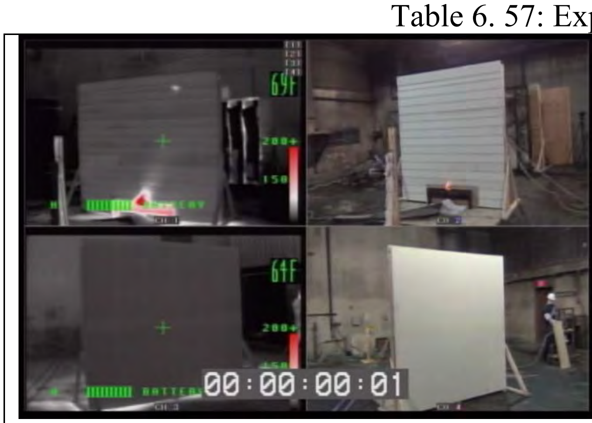
Table 6. 57, is shown in Table 6. 58. Heat release rate data, heat flux data, and temperature data from Experiment 19 are shown in appendix G, figures G.109-G.114.

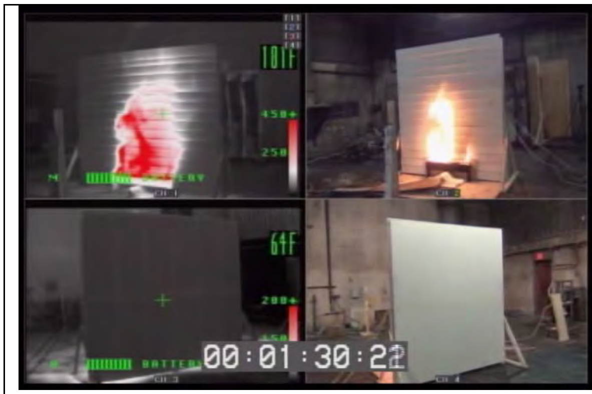
Table 6. 56: Wall Type and Material for Experiment 19 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 13	8" Fiber Cement Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 26: Wall Type 13 Side View

Table 6. 57: Experiment 19 Timeline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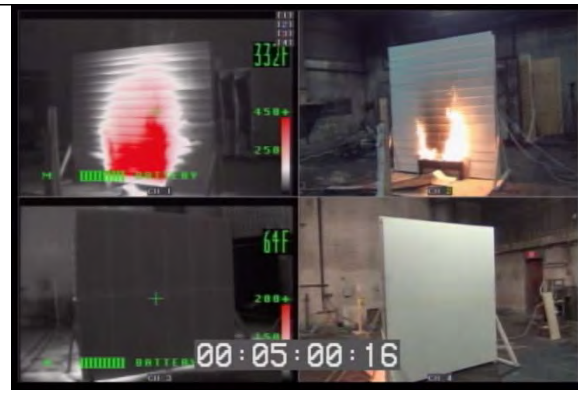
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217F
64F
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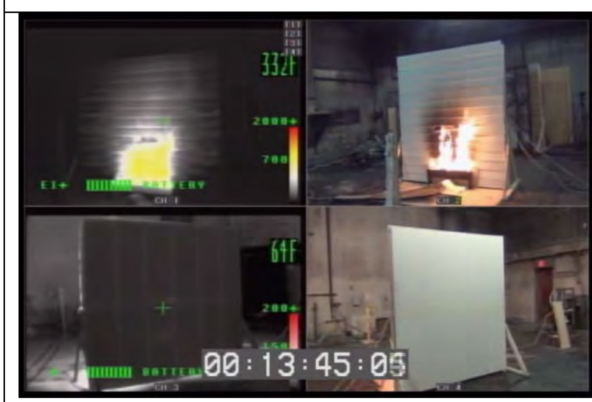
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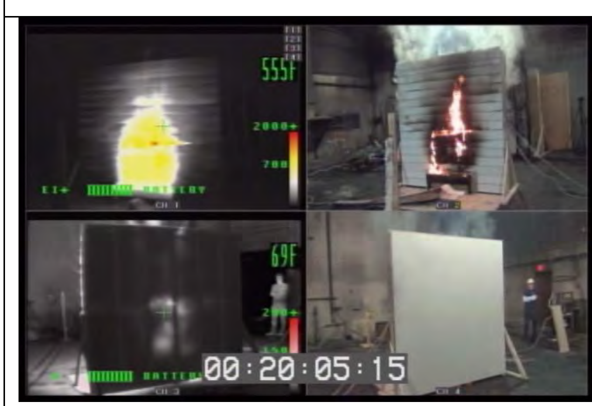
251F
64F
00:15:45:08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601F
132F
00:24:00:28

Table 6. 58: Experiment 19 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:30	Small amount of charring on the siding
05:00	More charring seen on the siding, it is still not involved in the fire
10:05	Burner is turned off, charring of siding can be seen but no flame on the wall
10:20	Burner is turned back on
13:45	Some holes form in the siding exposing the sheathing underneath
15:45	Flame can be seen coming from the hole in the siding as the sheathing gets involved, smoke can be seen coming from the sides and top of the wall from under the siding
20:05	Burner is turned off, flames are now coming from the burning of the material under the siding
24:00	Large portions of the siding are falling off, flames can be seen underneath
27:55	Most of the flames are gone, only some burning in the upper right corner
29:55	Most of the fire has self-extinguished, experiment is over

Experiment 20

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 59. A side view of the wall is shown in Figure 6. 27. The burner heat release rate (HRR) was 100 kW for Experiment 20 while the burner was on. Photos from Experiment 20 are displayed in

Table 6. 60. A timeline of the events within Experiment 20, matching with the photos in

Table 6. 60, is shown in

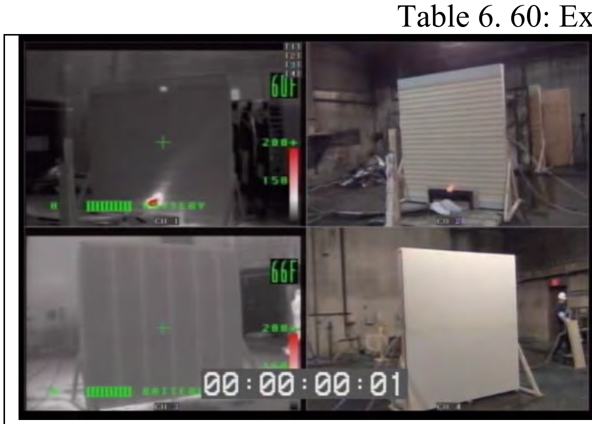
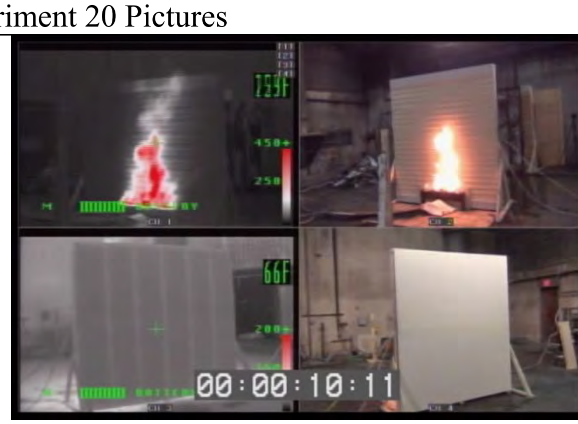
Table 6. 61. Heat release rate data, heat flux data, and temperature data from Experiment 20 are shown in appendix G, figures G.115-G.120.

Table 6. 59: Wall Type and Material for Experiment 20 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 14	Double 4" Aluminum Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 27: Wall Type 12 Side View

Table 6. 60: Experiment 20 Pictures


00:01:30:13



00:07:15:00

00:08:25:15

00:10:05:11

00:13:30:14


Table 6. 61: Experiment 20 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:30	Some initial charring on the siding
03:00	Smoke exiting out the side and top of the wall from under the siding
05:00	Siding begins to catch fire
07:15	Flame height increases on the siding, charring reaches top of the siding, flames are shooting up from under the siding
08:25	More flames are shooting up from under the siding at the top of the wall and also the side of the wall
10:05	Burner is turned off, flames burning out sides and top of the wall
13:30	Flames burn out of the left side of the wall
19:55	Most of the fire has self-extinguished, some fire is still on the ground, experiment is over

Experiment 21

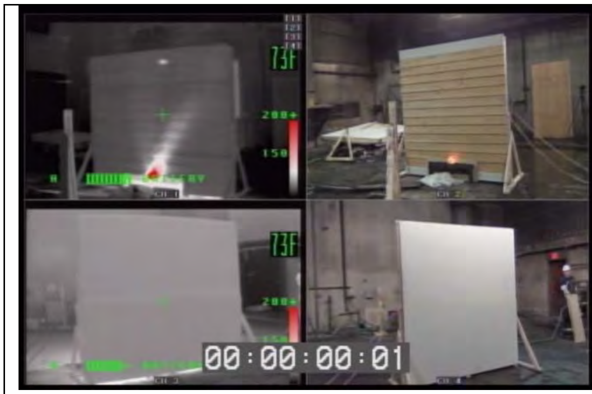
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 62. A side view of the wall is shown in Figure 6. 9. The burner heat release rate (HRR) was 100 kW for Experiment 21 while the burner was on. Photos from Experiment 21 are displayed in Table 6. 63. A timeline of the events within Experiment 21, matching with the photos in Table 6. 63, is shown in Table 6. 64. Heat flux data and heat release rate data from Experiment 21 are shown in appendix G, figures G.121-G.122. The heat flux measurements failed 22 minutes after ignition, and the thermocouple readings for this experiment malfunctioned from the outset.

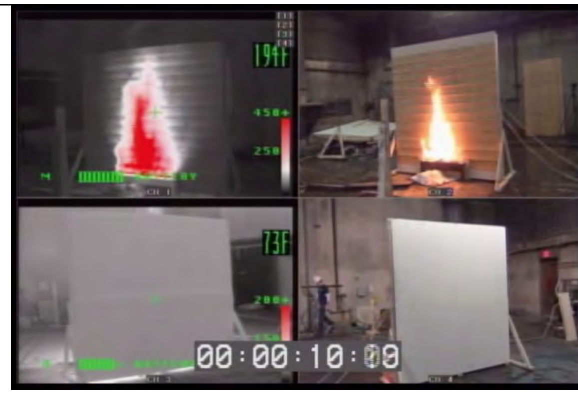
Table 6. 62: Wall Type and Material for Experiment 21

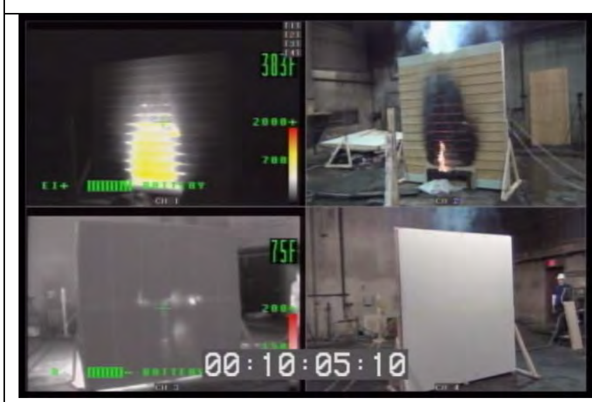
Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 10	8" Wood Lap Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

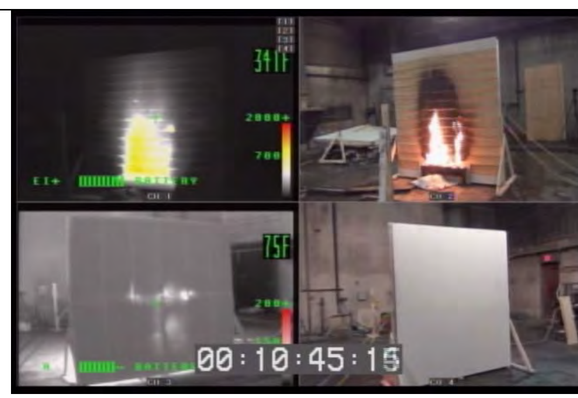
Figure 6. 28: Wall Type 10 Side View

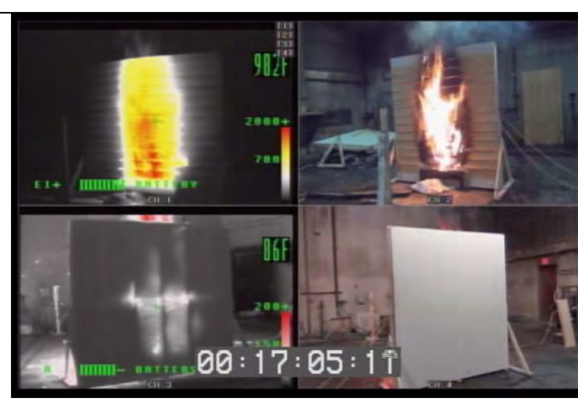
Table 6. 63: Experiment 21 Pictures











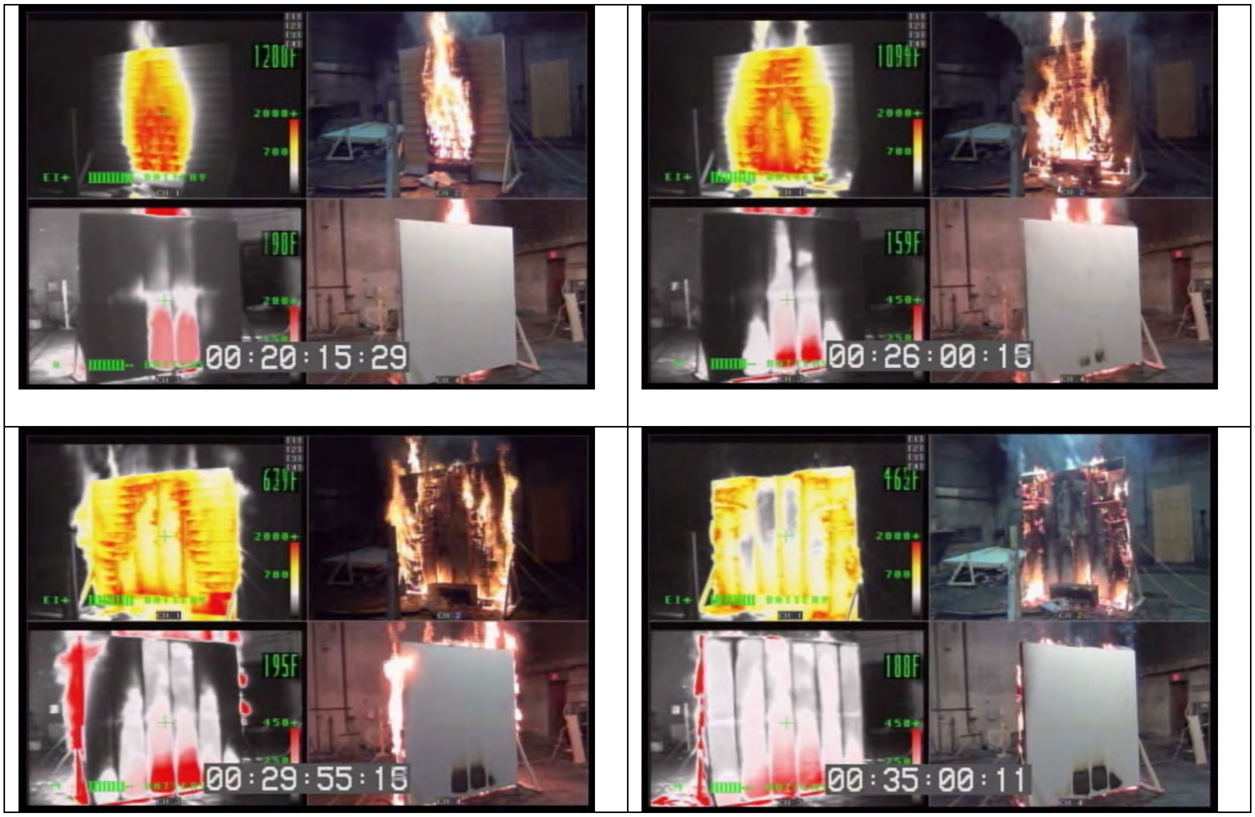


Table 6. 64: Experiment 21 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:00	Some initial charring on the siding
05:00	The charred area on the siding has increased, growing higher on the left side
10:05	Burner is turned off, no fire remains on the siding
10:45	Burner is turned back on
15:55	Siding gets involved, flames grow to the top of the wall and extend above the wall
17:05	Burner is turned off, flames drop back below the top of the wall
20:15	Fire again grows and flames again extend past the top of the wall
26:00	Flame begins spreading horizontally
29:55	Fire is on the outer edges of the wall now, studs are visible, more charring of the back wall
35:00	Much of the fire has self-extinguished, only some flames remain near the ground and in the upper corners, experiment is over

Experiment 22

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 65. A side view of the wall is shown in Figure 6. 29. The burner heat release rate (HRR) was 100 kW for Experiment 22 while the burner was on. Photos from Experiment 22 are displayed in Table 6. 66. A timeline of the events within Experiment 22, matching with the photos in Table 6. 66, is shown in Table 6. 67. Heat release rate data from Experiment 22 is shown in appendix G, figure G.123.

Table 6. 65: Wall Type and Material for Experiment 22 (100 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
N/A	None	None	1/2" Plywood	2x4 Studs w/ Open Space	None

Figure 6. 29: Experiment 22 Side View

Table 6. 66: Experiment 22 Pictures

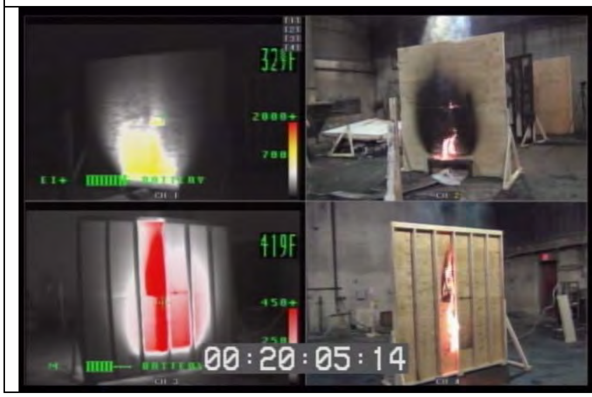
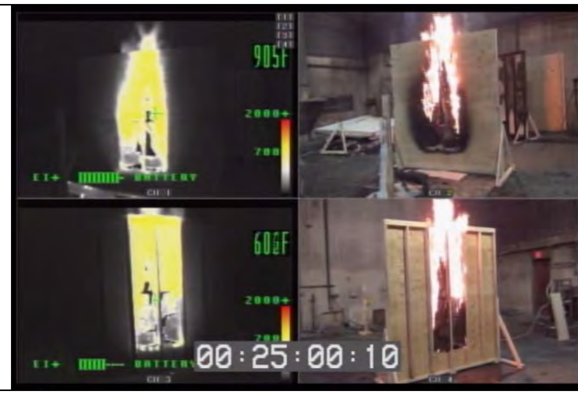
	

Table 6. 67: Experiment 22 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
01:30	Some initial charring of the plywood
05:00	Charred area on the surface increases
10:05	Burner is turned off, no flame remains
10:40	Burner is turned back on
15:45	Flame breaks through plywood and burns out the other side
19:40	Flame breaks through plywood in an additional location
20:05	Burner is turned off, still some flame remains mostly on the back side of the plywood
25:00	Flame has grown on the back side and spread on both sides of the plywood, extending above the wall, experiment is over

Experiment 23

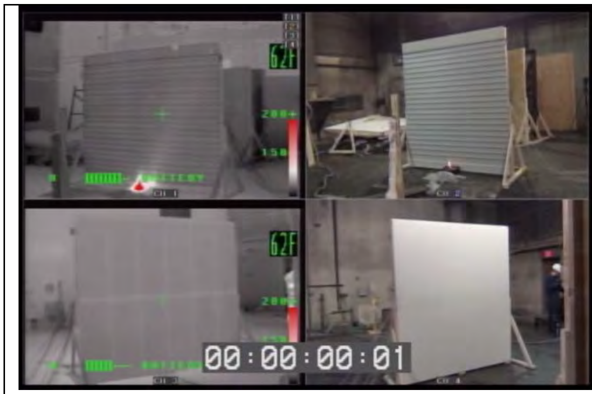
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 68. A side view of the wall is shown in Figure 6. 30. The burner heat release rate (HRR) was 25 kW for Experiment 23 while the burner was on. Photos from Experiment 23 are displayed in Table 6. 69. A timeline of the events within Experiment 23, matching with the photos in Table 6. 69, is shown in Table 6. 70. Heat release rate data, heat flux data, and temperature data from Experiment 23 are shown in appendix G, figure G.124-G.129.

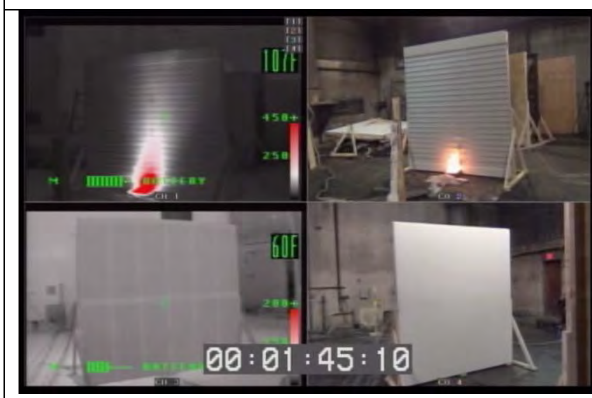
Table 6. 68: Wall Type and Material for Experiment 23 (25 kW)

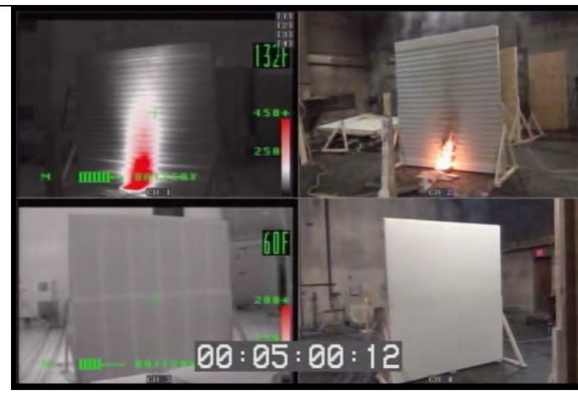
Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 1	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board

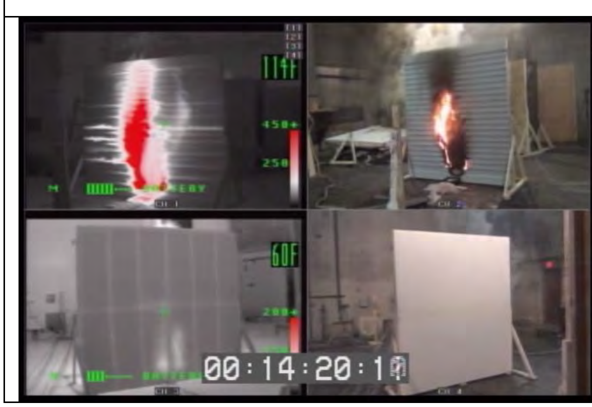
Figure 6. 30: Wall Type 1 Side View

Table 6. 69: Experiment 23 Pictures









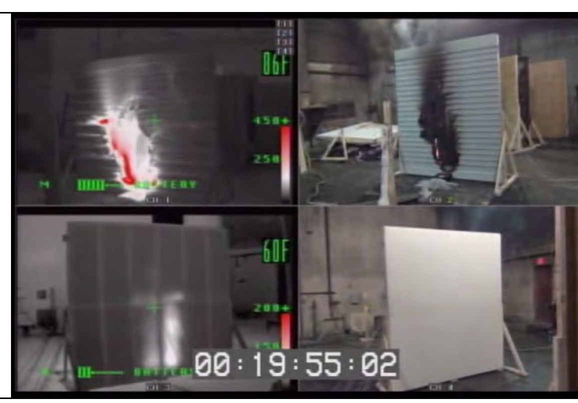


Table 6. 70: Experiment 23 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 25 kW heat release rate
01:45	Some charring on the siding
05:00	Fire begins to grow, rising slightly up the wall
10:05	Burner is turned off, only the outer edge of the burnt region is flaming
12:45	Flame is dying out, has not gotten any higher
14:20	Left side of burnt region continues to burn
19:55	Fire has self-extinguished, never reached the top of the wall, experiment is complete

Experiment 24

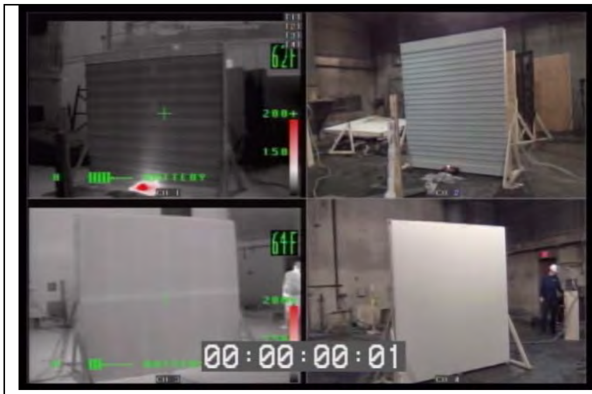
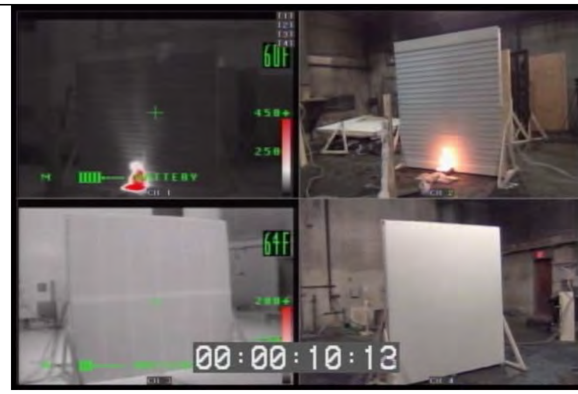
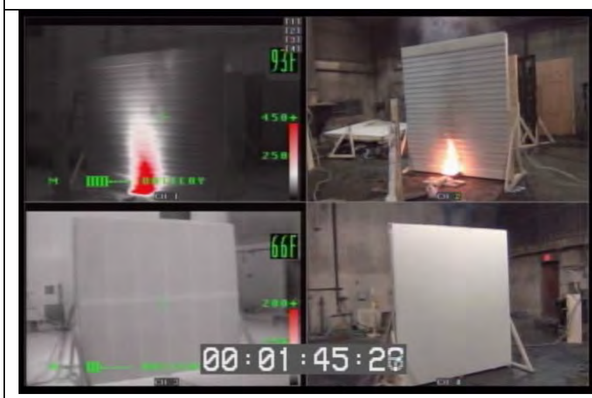
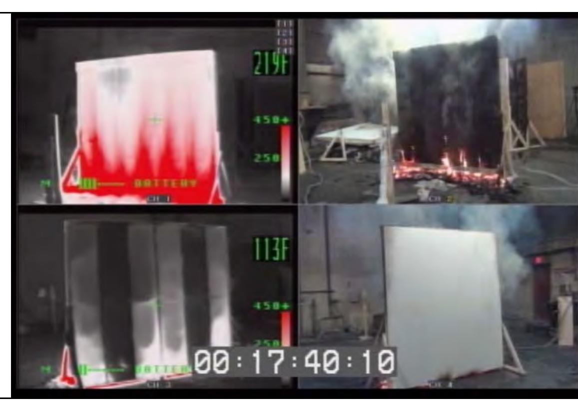
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 71. A side view of the wall is shown in Figure 6. 31. The burner heat release rate (HRR) was 25 kW for Experiment 24 while the burner was on. Photos from Experiment 24 are displayed in Table 6. 72. A timeline of the events within Experiment 24, matching with the photos in Table 6. 72, is shown in Table 6. 73. Heat release rate data, heat flux data, and temperature data from Experiment 24 are shown in appendix G, figures G.130-G.135.

Table 6. 71: Wall Type and Material for Experiment 24 (25 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 9-C	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, Closed Cell Foam	1/2" Gypsum Board

Figure 6. 31: Wall Type 9-C Side View

Table 6. 72: Experiment 24 Pictures

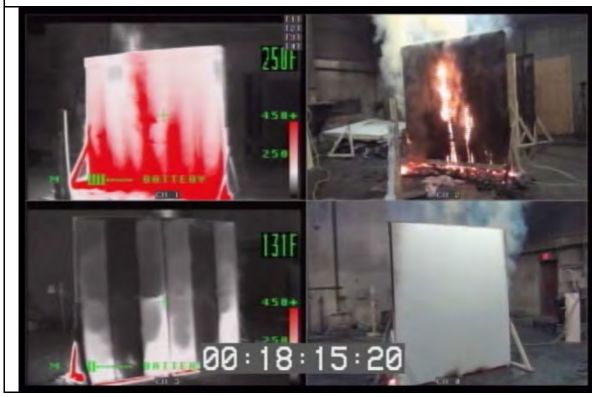
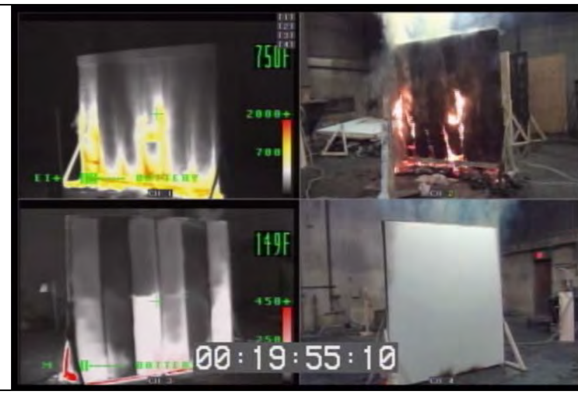
	

Table 6. 73: Experiment 24 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 25 kW heat release rate
01:45	Siding begins to burn, flame begins to grow
03:30	Flames reach top of the wall and extend above the wall
06:00	Most of the siding has burnt off, right side of the wall is still producing flames above the wall
08:40	Most of the flame is on the ground, flames extend to the top of the wall on the left side
10:05	Burner is turned off, flames still remain on the ground in front of the wall
17:40	Fire has basically self-extinguished, just a small amount of flame near the bottom of the wall
18:15	Flame extends up the wall along some of the studs
19:55	Fire is still seen on the wall along some of the studs, experiment is over

Experiment 25

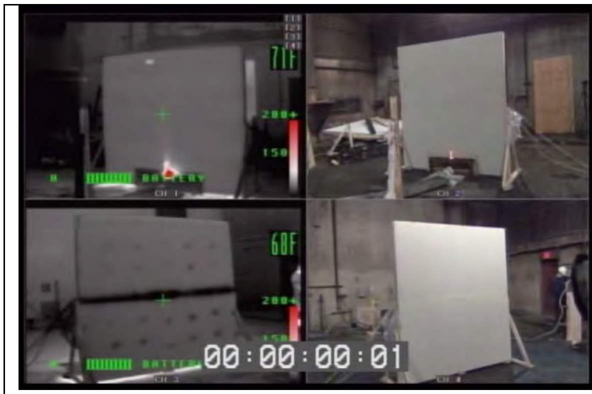
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 74. A side view of the wall is shown in Figure 6. 32. The burner heat release rate (HRR) was initially 100 kW for Experiment 25 and then raised to 200 kW after 20 minutes passed. Photos from Experiment 25 are displayed in Table 6. 75. A timeline of the events within Experiment 25, matching with the photos in Table 6. 75, is shown in
Table 6. 76. Heat release rate data, heat flux data, and temperature data from Experiment 25 are shown in appendix G, figures G.136-G.141.

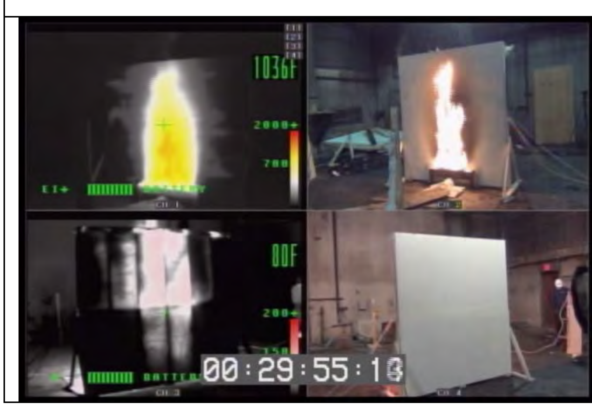
Table 6. 74: Wall Type and Material for Experiment 25 (100 kW initially, then 200 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 6	3/8" Elastomeric Base Coat (Stucco)	Weather resistant barrier	1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 32: Wall Type 6 Side View

Table 6. 75: Experiment 25 Pictures





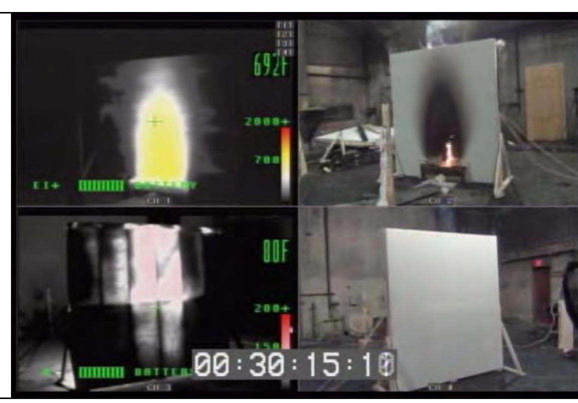


Table 6. 76: Experiment 25 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
02:00	Some initial charring on the siding
10:00	The charred area on the siding is now larger but the siding is still not involved in the fire
20:15	The siding is still not involved the burner HRR is increased
25:00	The siding is still not involved, some smoke is exiting out of the top of the wall
29:55	Siding still not involved or degrading
30:15	The burner is turned off, no flame remains, experiment is over

Experiment 26

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 77. A side view of the wall is shown in Figure 6. 33. The burner heat release rate (HRR) was initially 100 kW for Experiment 26 and then raised to 200 kW after 20 minutes passed. Photos from Experiment 26 are displayed in Table 6. 78. A timeline of the events within Experiment 26, matching with the photos in Table 6. 78, is shown in
Table 6. 79. Heat release rate data, heat flux data, and temperature data from Experiment 26 are shown in appendix G, figures G.142-G.147.

Table 6. 77: Wall Type and Material for Experiment 26 (100 kW initially, then 200 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 16	3/8" Elastomeric Base Coat (Stucco)	Layer of W.R.B.	1" R-5 EPS followed by 1/2" Plywood Sheathing	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 33: Wall Type 16 Side View

Table 6. 78: Experiment 26 Pictures

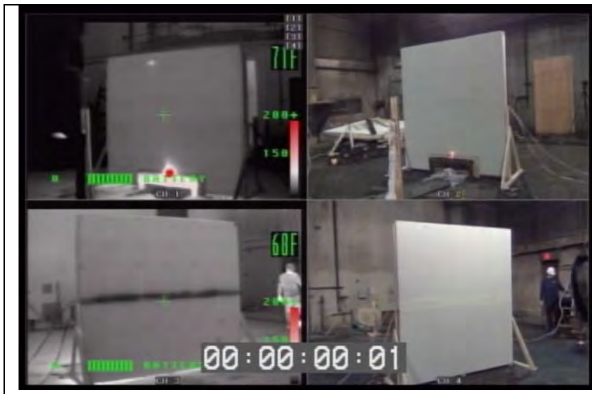
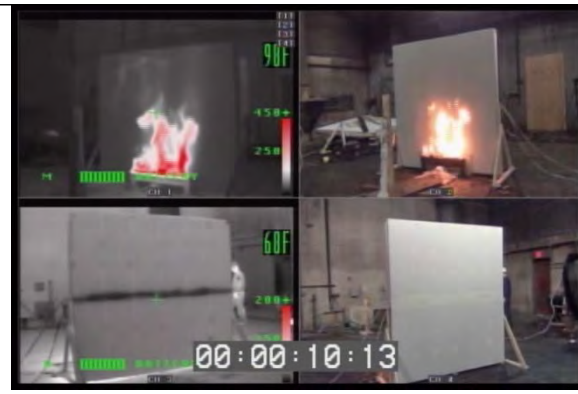
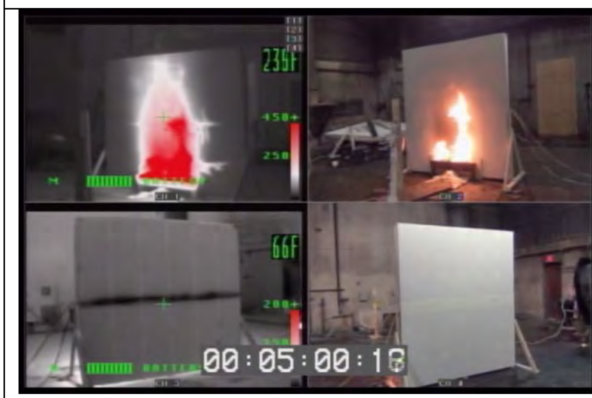
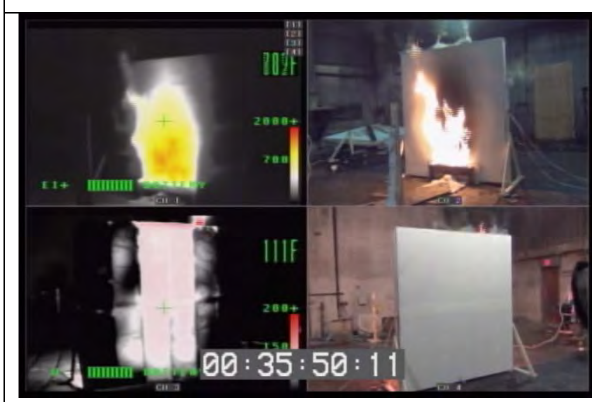
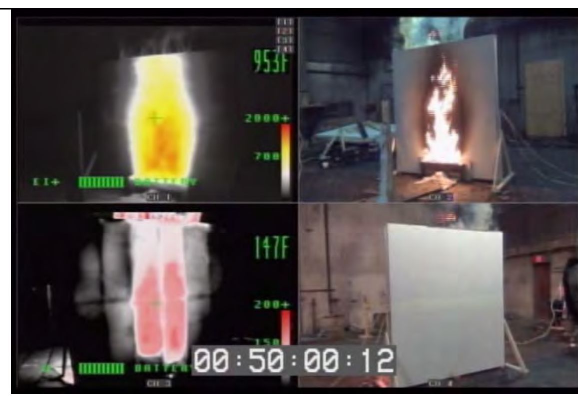
	
	
	
	

Table 6. 79: Experiment 26 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
05:00	Some initial charring of the siding
20:10	Burner HRR is increased
35:50	Smoke and flame seen coming out the top of the wall
50:00	More smoke is exiting out the top of the wall as well as a small amount of flame
53:15	Flame is exiting out most of the top of the wall
60:00	Burner is turned off, no flame on siding, flame is still exiting out the top of the wall, experiment is over

Experiment 27

The layout of the wall and materials used for each layer of the wall are specified in Table 6. 80. A side view of the wall is shown in Figure 6. 34. The burner heat release rate (HRR) was initially 100 kW for Experiment 27 and then raised to 200 kW after 20 minutes passed. Photos from Experiment 27 are displayed in Table 6. 81. A timeline of the events within Experiment 27, matching with the photos in Table 6. 81, is shown in Table 6. 82. Heat release rate data, heat flux data, and temperature data from Experiment 27 are shown in appendix G, figures G.148-G.153.

Table 6. 80: Wall Type and Material for Experiment 27 (100 kW initially, then 200 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 7	3/16" Base Coat on fiberglass mesh w/ Acrylic Finish (E.I.F.S.)	Weather-Resistant Barrier	1.5" EPS followed by 1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 34: Wall Type 7 Side View

Table 6. 81: Experiment 27 Pictures

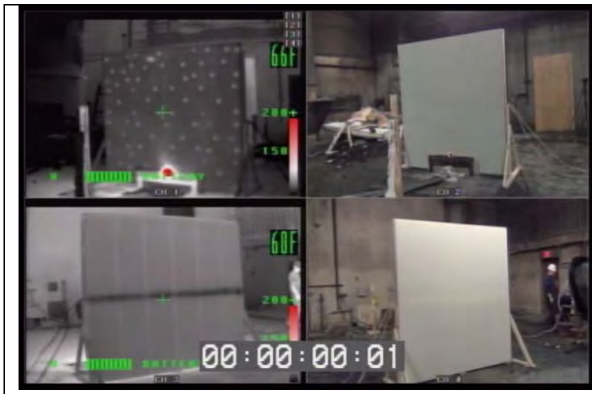


Table 6. 82: Experiment 27 Timeline

Time (mm:ss)	Description
00:00	Ignition
00:10	Burner is on and reaching desired 100 kW heat release rate
02:00	Some initial charring on the siding
05:00	The charred area has increased, the siding is still not involved
19:55	Siding still not involved, some smoke is coming out the top of the wall
20:05	The burner HRR is increased
24:20	Flame is seen exiting out the top of the wall

37:30	Flame and large amounts of smoke exiting out the top of the wall, siding still not involved
50:15	Burner is turned off, hole is punched in the siding to expose the wall materials underneath, small amount of flame exits out one of the holes
53:20	Larger hole is made again and more flame is now visible from burning materials underneath the siding
55:45	Another large hole is made and the fire grows larger
57:00	Flames reach top of the wall and extend above the wall
59:55	Still some flame is visible, the damage to the siding is from holes made during the experiment, experiment is over

Experiment 28

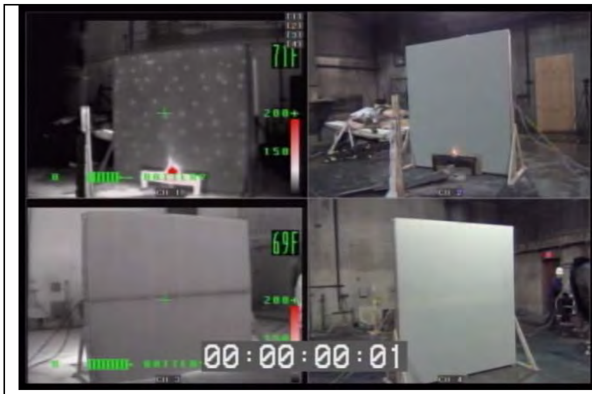
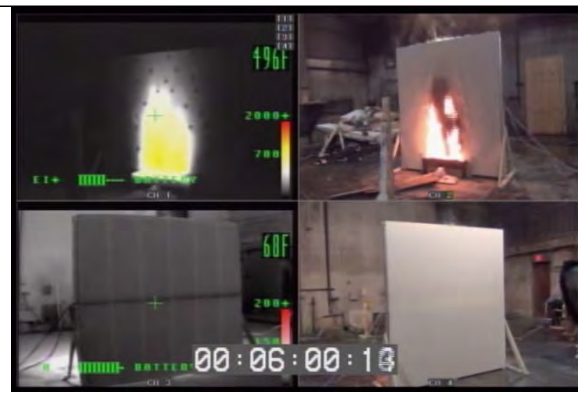
The layout of the wall and materials used for each layer of the wall are specified in Table 6. 83. A side view of the wall is shown in Figure 6. 35. The burner heat release rate (HRR) was initially 100 kW for Experiment 28 and then raised to 300 kW after 10 minutes passed. Photos from Experiment 28 are displayed in Table 6. 84. A timeline of the events within Experiment 28, matching with the photos in Table 6. 84, is shown in Table 6. 85. Heat release rate data, heat flux data, and temperature data from Experiment 28 are shown in Appendix G, figures G.154-G.159.

Table 6. 83: Wall Type and Material for Experiment 28 (100 kW initially, then 300 kW)

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 17	3/16" Base Coat on fiberglass mesh w/ Acrylic Finish (E.I.F.S.)	Weather-Resistant Barrier	1.5" EPS followed by 1/2" Sheathing	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 35: Wall Type 17 Side View

Table 6. 84: Experiment 28 Pictures

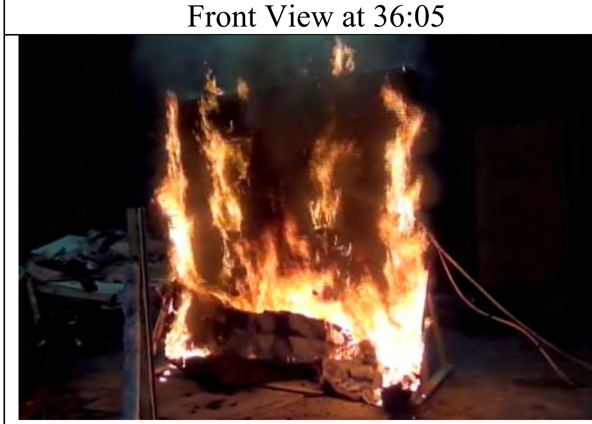
	
	
	


Front View at 30:05


Front View at 34:50


Front View at 36:05


Back View at 39:05


Front View at 40:00


Front View at 45:00

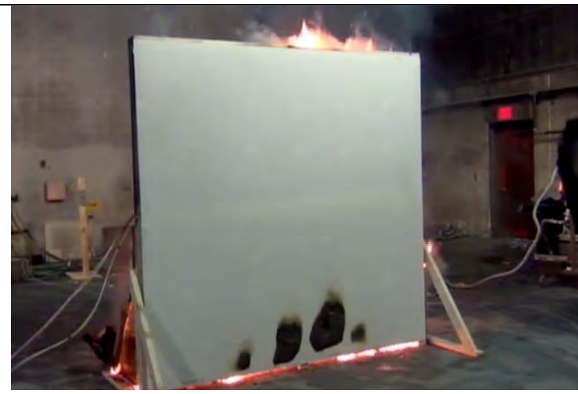
	
Front View at 50:00	Back View at 50:00

Table 6. 85: Experiment 28 Timeline

Time (mm:ss)	Description
00:00	Experiment begins
00:10	Burner is on and reaching desired 100 kW heat release rate
02:00	Some initial charring of the siding
06:00	The charred area on the wall has increased, siding is still not involved, smoke is exiting out the top of the wall
10:15	Burner HRR is increased
12:45	Charring has reached the top of the wall, some flame is exiting out the top of the wall
19:00	Flame is exiting out the entire width of the top wall, siding is still not involved
27:45	Conditions mostly unchanged from 19:00, video ends
30:05	Burner is turned off, flames still exiting out the top of the wall, siding is no longer burning except for a small portion near the bottom right of the wall
34:50	Smoke is still exiting out the top of the wall, no more flame is visible on the siding or out the top of the wall
36:05	Siding is manually ripped off, materials under siding exposed and can be seen to be involved in the fire
39:05	Initial charring on the back of the wall
40:00	Materials under siding still involved, heaviest burning is on the outside of the wall where the supports of the wall have gotten involved in the fire
45:00	Most of the fire is near the bottom of the wall now, there is still fire rising up two of the exposed studs
50:00	Fire is almost all at the bottom now, with some fire rising up the left side of the wall, four different spots of discoloration are visible on the back wall, experiment is over

6.5. Wall Experiment Analysis

In order to evaluate the effects of ignition source, siding material, sheathing material, insulation material, ignition time, flame spread rate, peak heat release rate and exposure time were analyzed. Table 6. 86 contains the results for each experiment.

Wall ignition time was extracted from heat release rate data assuming the wall ignited when additional heat release rate was recorded. The value of 20kW above the intended burner rate was chosen to signify ignition of the wall as it was above the +/- 15% accuracy of the calorimeter. Heat release rate data was corrected for the transport time from the burner to the sensor location within the calorimetry hood.

Flame spread rate was derived through the use of image analysis by extracting a still image every second from the standard video footage of each experiment. The images were cropped to only include the wall surface. Each image was processed through the use of a free ware program ImageJ [http://imagej.nih.gov/ij/] with the flame region identified as the area between a threshold of 210 and 255 on an 8-Bit image. The region was bounded by a rectangle in order to determine the extents and location of the flame region. The resulting data was evaluated to determine the tip of the flame at each second of the experiment and averaged over a ten point moving average to determine the flame height. This flame height was utilized to determine the time for the flame to reach 7ft. above the burner surface, approximately the wall height. Due to the ignition of the 2 x 4 stud at the top of the wall, flame region location was not applicable after the height exceeded the top of the wall.

Heat release rate data was evaluated for the maximum measured during the experiment used to identify the potential fire size for a give wall type.

The exposure time was defined as the time the flames were located 7ft. above the burner, determined by subtracting the time to the 7ft. point from the time at which the fire receded down below the top of the wall. This value is intended to identify the time the give wall type would have exposed a potential eve at the top of the wall potentially resulting in transition from an exterior fire to a structure fire. Higher values of exposure relate to the higher potential of transition from exterior to structure fire.

Table 6. 86. Wall Experimental results

Exp	Wall Type	Ignition Source	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (mm:ss)
1	1	150kW	00:55	01:54 [00:59]	515	2:03
2	1	50kW	01:14	04:38 [03:24]	285	1:39
3	1	100kW	01:13	02:25 [01:12]	440	2:18
4	8	150kW	00:39	01:06 [00:27]	1293	2:18
5	8	100kW	01:06	01:19 [00:13]	958	3:19
6	8	50kW	01:35	01:53 [00:18]	694	5:08
7	8-I	100kW	00:48	01:19 [00:31]	723	4:18
8	9	100kW	00:45	00:55 [00:10]	1502	3:51
9	9-C	100kW	00:59	01:14 [00:15]	1515	4:32
10	9-I	100kW	00:52	01:16 [00:24]	760	3:11
11	9-S	100kW	01:14	02:31 [01:17]	1294	1:21
12	9-R	100kW	01:13	01:16 [00:03]	1261	8:40
13	8-R	100kW	01:01	01:19 [00:18]	985	3:00
14	11	100kW	01:24	07:59 [06:35]	880	N/A
15	8	Propane Grill	45:11*	N/A	213	N/A
16	1	Propane Grill	15:35	N/A	35	N/A
17	2	100kW	00:35	24:08 [23:33]	213	N/A
18	14	100kW	01:41	02:03 [00:22]	1276	4:41
19	13	100kW	16:00**	16:59 [00:59]	214	N/A
20	12	100kW	04:24	05:07 [00:43]	637	5:45
21	10	100kW	00:55	08:41 [07:46]	1517****	N/A*
22	18	100kW	02:01	21:45 [19:44]***	218	N/A
23	1	25kW	08:46	N/A	73	N/A
24	9-C	25kW	02:14	2:22 [00:08]	1027	6:26
25	6	100kW	NSI	N/A	N/A	N/A
25.1	6	200kW	NSI	N/A	N/A	N/A
26	16	100kW	NSI	N/A	59	N/A
26.1	16	200kW	NSI	N/A	N/A	N/A
27	7	100kW	NSI	N/A	N/A	N/A
27.1	7	200kW	NSI	N/A	N/A	N/A
28	17	100kW	NSI	N/A	219	N/A
28.1	17	300kW	NSI	N/A	N/A	N/A

*Grill was located 2" from the wall surface and failed to ignite wall after 40:02. Grill was pushed back against the wall and ignited wall in 05:11.

** Burner was cycled off for 00:30 at 10:00 to show lack of wall ignition.

*** Flame spread at 7ft. level at 17:30, burner turned off and it took until 21:45 for it to return 7ft.

NSI – No sustained ignition

6.5.1. Effect Siding Material Used with 1-inch EPS Insulation Board

To evaluate the effect of siding material on ignition, flame spread, heat release rate and exposure, 5 different sidings were tested with the same sheathing, and insulation material see Table 6. 87 for the construction of each wall.

Table 6. 87: Wall Types and Materials for Siding Comparison

Wall Type	Siding	Vapor Barrier	Sheathing	Insulation	Back Wall
Vinyl (Exp 5)	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
Polypropylene Shingle (Exp 18)	Double 7" Polypropylene Shingle Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
Fiber Cement (Exp 19)	8" Fiber Cement Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
Aluminum (Exp 20)	Double 4" Aluminum Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
Wood Lap (Exp 21)	8" Wood Lap Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
Stucco (Exp 26)	2 Coat Stucco	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
EIFS (Exp 28)	EIFS	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

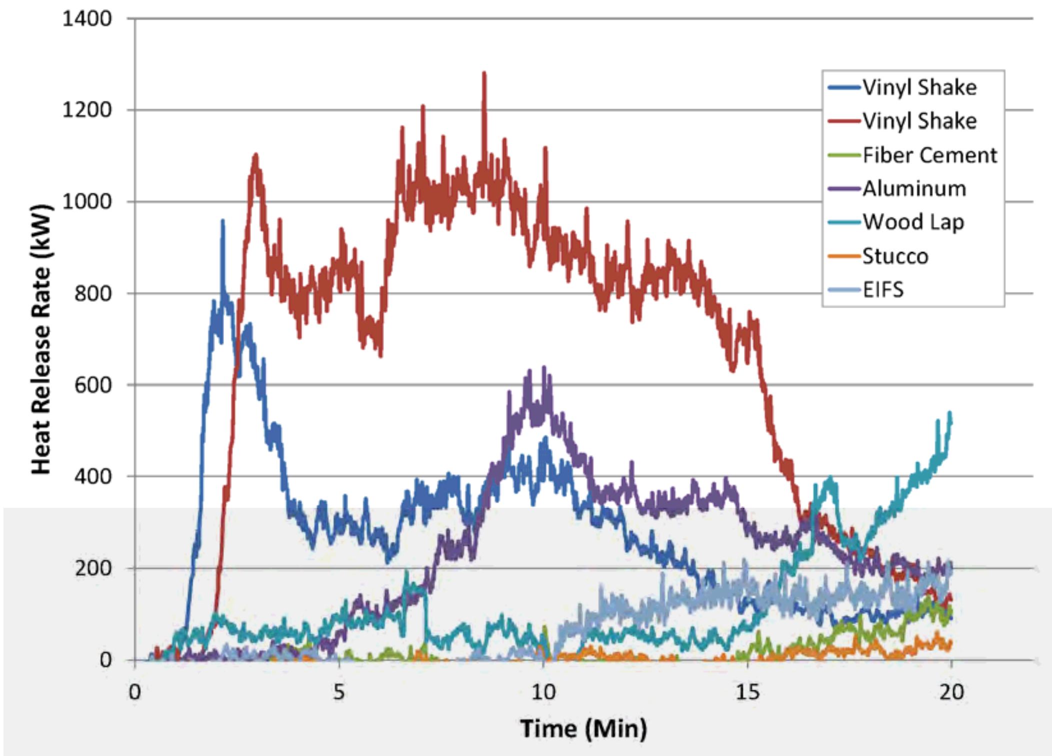


Figure 6. 42 shows heat release rate for the wall types specified in Table 6. 87.

Table 6. 88 compares the ignition time, time to top 7ft on the wall, peak heat release rate and exposure time for the wall types listed in Table 6. 87. As listed the shortest ignition time was in the combustible materials such as vinyl, Polypropylene Shingle and wood lap. The Aluminum siding delayed ignition significantly until it melted away after 04:52 minutes of exposure. The Fiber Cement delayed ignition until it broke apart at 16:00 minutes. The cementitious materials did not ignite at the 100kW burner and did not permit penetration into the sheathing and insulation limiting the fire hazard.

The synthetic materials contributed to the most rapid flame spread as seen in Table 6. 87 with all materials spreading to the top of the wall in under 01:00 minute of ignition with the exception of the wood lap which ignited on the surface but did not penetrate into the polystyrene until 08:02 minutes after ignition. This indicates that regardless of the siding material, once the polystyrene became involved rapid flame spread occurred.

After the initial growth of the fire, the heat release for wall type 8, the double 4 in. vinyl siding begins to decrease as the fuel is consumed, with the polypropylene shingle siding maintaining a high heat release rate due to the larger mass of fuel. The differences observed in the performance of the polypropylene shingle and the vinyl siding is likely due to the thickness differences of the sidings. The thickness of vinyl siding can be as low as 0.035 in., while the thickness of polypropylene shingle siding is usually in the range of 0.08 in. to 0.09 in [43]. From the total heat released as shown in Figure 6. 37 it is evident that the wood lap siding experiment and the polypropylene shingle siding experiments have the largest amount fuel content. However, the big difference is again the quick growth of the polypropylene shingle siding, as the wood lap siding does not have flame at the top of the wall until 8 min 41 s after the start of the experiment.

The total heat released show in Figure 6. 37 indicates the fire resistive materials delayed the penetration into the sheathing in siding materials resulting in lower heat release rates and over all energy release whereas synthetic materials that melted or burned away showed larger heat release rates due to the additional fuel in the sheathing and insulation materials.

Table 6. 88: Comparison of Siding Types over 1" Polystyrene and Fiberglass Bat Insulation.

Wall Type	Experiment Number	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (mm:ss)
Vinyl	5	00:40	01:19 [00:39]	958	03:19
Polypropylene shingle	18	01:27	02:03 [00:36]	1276	04:41
Fiber Cement	19	16:00**	16:59 [00:59]	214	N/A
Aluminum	20	04:52	05:07 [00:15]	637	05:45
Wood Lap	21	00:39	08:41 [08:02]	1517****	N/A*
Stucco	26	N/A	N/A	59	N/A
EIFS	28	N/A	N/A	219	N/A

* Burner was turned off at 10:00 and fire self-extinguished. Burner was re-ignited at 11:00 and resulted in an exposure of 19:18 once polystyrene ignited below siding surface.
** Burner was cycled off for 00:30 at 10:00 to show lack of wall ignition.
*** Burner increased to 300kW at 10:15 results occurred after increase.
**** Occurs at 30:41

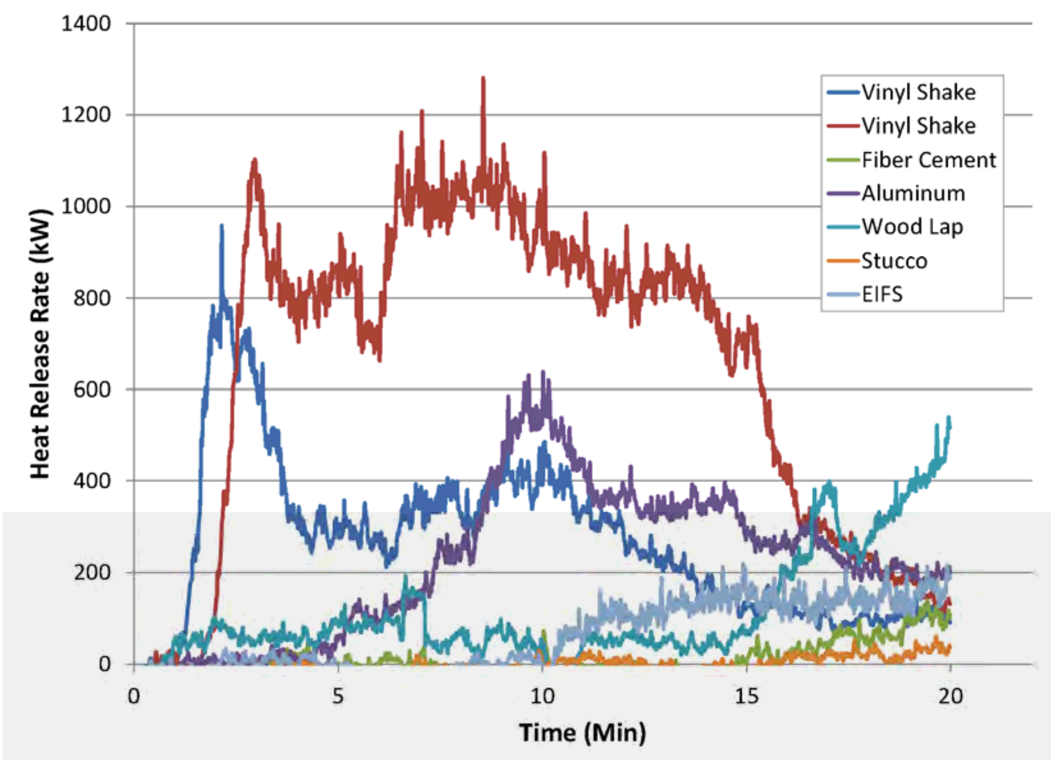


Figure 6. 36: Heat Release Rate (w/o burner) for Walls with Different Sidings

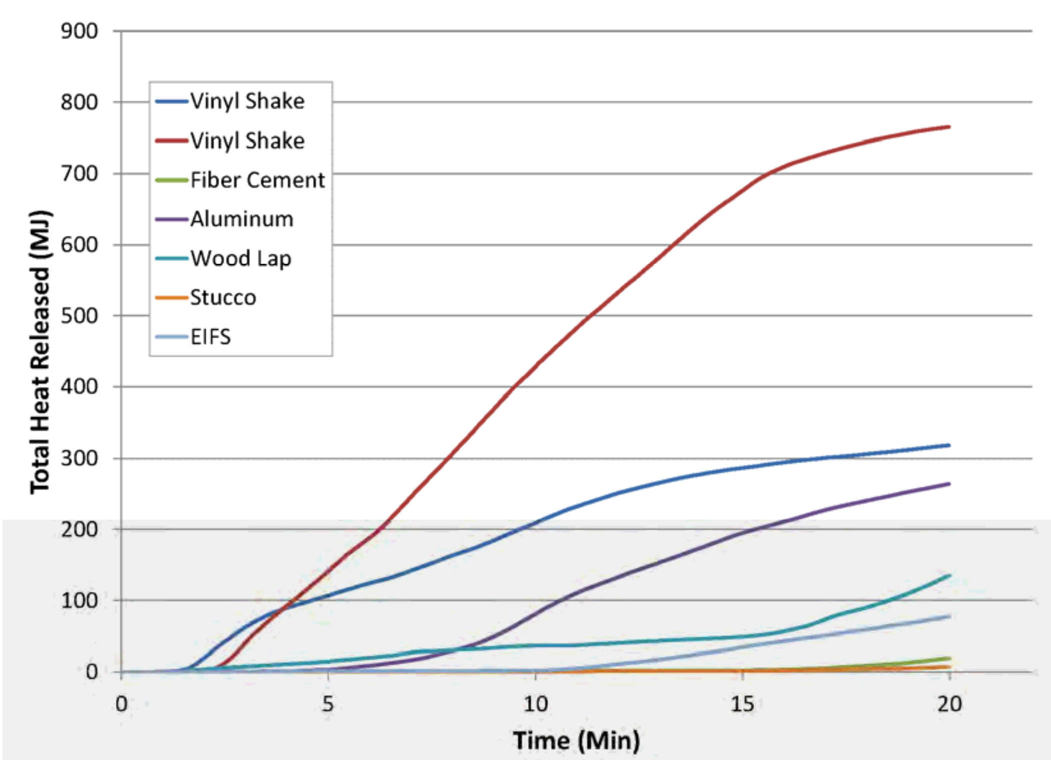


Figure 6. 37: Total Heat Released (w/o burner) for Walls with Different Sidings

6.5.2. Effect of Sheathing with Vinyl Siding

Three wall types were utilized to test the effect of different sheathing material under vinyl siding. Table 6. 89 indicates the three experiments for vinyl where sheathing was varied.

Table 6. 89: Wall Types and Materials for Sheathing Comparison under Vinyl

Sheathing	Siding	Additional Material	Insulation	Back Wall
1/2" Plywood (Exp 3)	Double 4" Vinyl Siding	Weather-Resistant Barrier	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board
1" Polystyrene (Exp 5)	Double 4" Vinyl Siding	Weather-Resistant Barrier	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
1" Polyisocyuranate (Exp 7)	Double 4" Vinyl Siding	Weather-Resistant Barrier	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

The ignition time, flame spread, peak heat release rate and exposure time are shown in Table 6. 90 for the various sheathing materials under vinyl siding. The ignition times of the wall were within 17 seconds of each other indicating the sheathing material had no impact on the ignition of the wall. The sheathing material installed under the siding is no in contact with the sheathing uniformly across its surface thus it cannot impact the ignition.

Flame spread up the wall surface varies considerably over the three types of sheathing with slowest rate being plywood taking 01:17 to reach the top of the wall and the fastest being the Polyisocyanurate in 0:29 as shown in Table 6. 90. This difference can be attributed to the tendency of the vinyl siding to melt away exposing the sheathing surface and making flame spread very dependent on the type of sheathing material underneath. Figure 6. 38 shows the Polystyrene and Polyisocyanurate fire growth track similar through the first 02:00 of the test at which the Polyisocyanurate peaks and the Polystyrene continues to grow. The plywood grows at a much slower rate and peaks at half the value of the others.

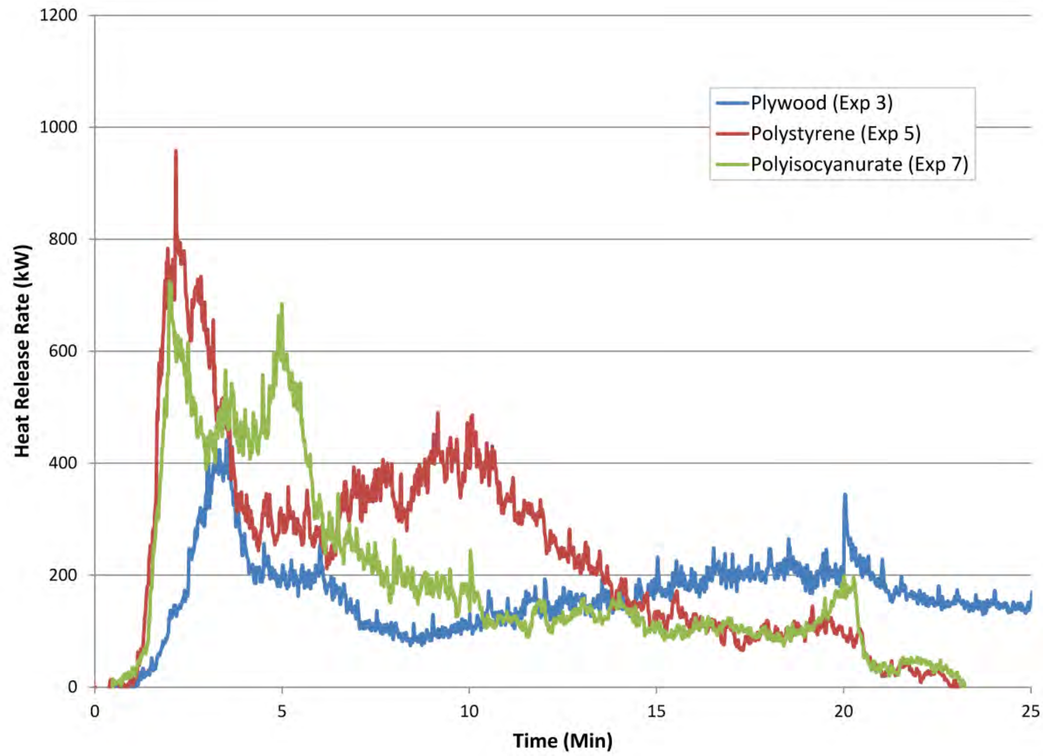


Figure 6. 38: Sheathing Comparison with Vinyl Siding – Heat Release Rate

The exposure shown in Table 6. 90 varies greatly with different sheathing materials. The Polyisocyanurate provided the highest exposure at 04:18 which can be seen additionally in Figure 6. 38 as the heat release rate peaks and maintains a value in excess of 400 kW for almost 07:00. The Polystyrene has less of an exposure time however as seen in Figure 6. 39 the energy release over the first 20 minutes of the experiment was over 50 MJ greater for the Polystyrene than the Polyisocyanurate with the Plywood releasing the lease amount of energy.

Table 6. 90: Comparison Sheathing Material under Vinyl Siding with Fiberglass Insulation

Sheathing	Experiment Number	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (mm:ss)
Plywood	3	01:08	02:25 [1:17]	440	2:18
Polystyrene	5	00:40	01:19 [0:39]	958	3:19
Polyisocyanurate	7	00:51	01:19 [0:29]	723	4:18

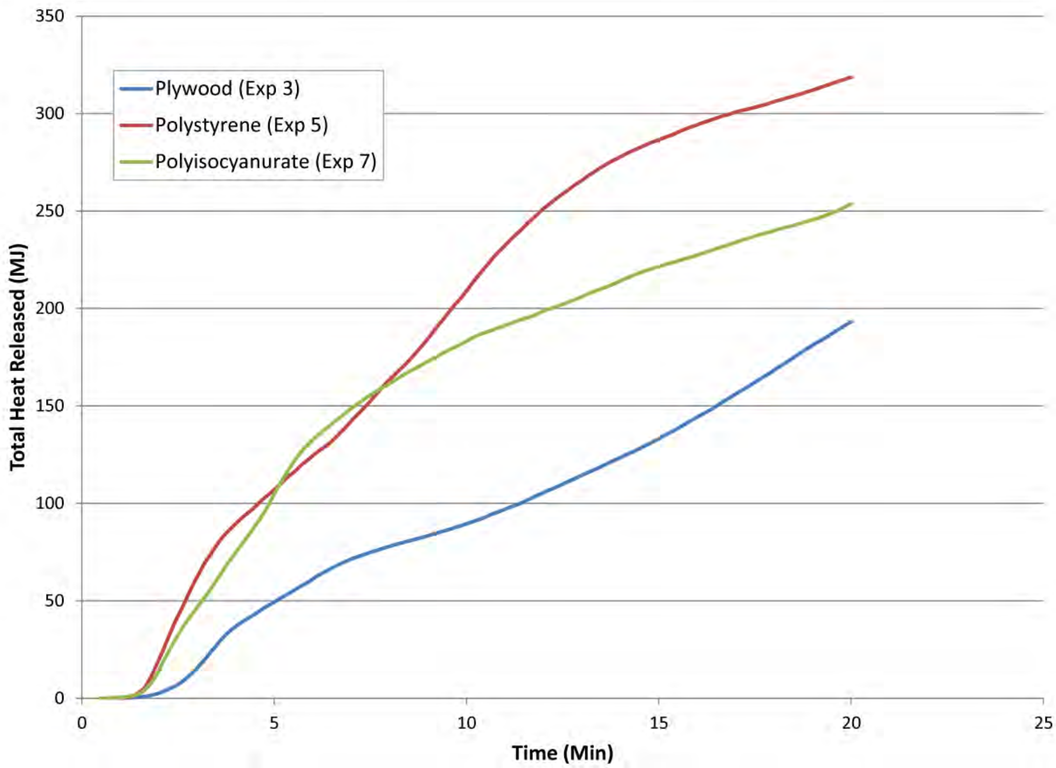


Figure 6. 39: Sheathing Comparison with Vinyl Siding – Total Heat Released

6.5.3. Effect of Insulation with Vinyl Siding and EPS Insulation Board

The insulation below a vinyl wall surface was varied over four experiments to evaluate the effect of insulation on ignition, flame spread, heat release rate and exposure time. Table 6. 91 shows insulations compared and the remainder of the wall construction including Fiberglass, Open Cell Spray Foam and Closed Cell Spray Foam. Sheathing was varied to include the appropriate R-Value based on IBC requirements.

Table 6. 91: Wall Type for Insulation Comparison - Vinyl

Insulation	Siding	Additional Material	Sheathing	Back Wall
Fiberglass R-19 (Exp 5)	4” Vinyl Siding	Weather-Resistant Barrier	1” EPS Insulation Board	1/2" Gypsum Board
Open Cell Spray Foam (Exp 8)	4” Vinyl Siding	Weather-Resistant Barrier	½” EPS Insulation Board	1/2" Gypsum Board
Open Cell Spray Foam (Exp 12)	4” Vinyl Siding	Weather-Resistant Barrier	½” EPS Insulation Board	1/2" Gypsum Board
Closed Cell Spray Foam (Exp 9)	4” Vinyl Siding	Weather-Resistant Barrier	½” EPS Insulation Board	1/2" Gypsum Board

Ignition times for the four experiments were all under 1 minute as shown in Table 6. 92 with the shortest being the Open Cell Spray Foam and the longest being the Closed Cell Spray Foam. The two tests with Open Cell Spray Foam varied by 00:17 and all tests varied by 00:32 indicating the insulation material used has little to no effect on ignition of a vinyl wall surface due to the limited contact between the vinyl siding and the sheathing and insulation below.

Table 6. 92 indicates the flame spread reached the 7ft mark on the wall all in under 01:30 with the fastest being the Closed Cell Spray foam in 0:15 from wall ignition and the slowest being Fiberglass being 0:39 from wall ignition. The insulation appears to have little effect on the flame spread which is dominated by the synthetic sheathing. This can be seen in Figure 6. 40 as the growth of each experiment tracks together after ignition.

Table 6. 92: Insulation Comparison with Vinyl Siding

Insulation	Experiment Number	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (m:ss)
Fiberglass	5	00:40	01:19 [0:39]	958	3:19
Open Cell Spray Foam (1)	8	00:27	00:55 [0:28]	1502	3:51
Open Cell Spray Foam (2)	12	00:44	01:16 [0:32]	1261	8:40
Closed Cell Spray Foam	9	00:59	01:14 [0:15]	1515	4:32

The peak heat release rate varies with the highest in the Open Cell Spray Foam (1) and Closed Cell Spray Foam both over 1500kW and the lowest being the Fiberglass at 958kW from Table 6. 92. The Fiberglass, Open Cell Spray Foam (1) and Closed Cell Spray Foam all peak approximately 01:00 after ignition where the Open Cell Spray Foam (2) Peaks 04:18 into the test, 03:34 after ignition shown in Figure 6. 40. This occurs as the vinyl siding did not fall away as effectively as it did with the Open Cell Spray Foam (1) case limiting the exposed insulation material and limiting the fire size. Overall the insulation material of Fiberglass vs Spray Foam indicates Spray Foam has a much larger potential fire size as confirmed by a graph of the total heat released in the first 20:00 of the experiment shown in Figure 6. 41.

The exposure time from Table 6. 92 indicates the more potential fire size due to the additional synthetic fuel in the Spray Foam the longer the potential fire exposure and more hazard exists at transition from an exterior fire to a structure fire. The lower exposure time for fiberglass as compared to the Spray Foam insulations indicates that insulation does have an impact on exposure.

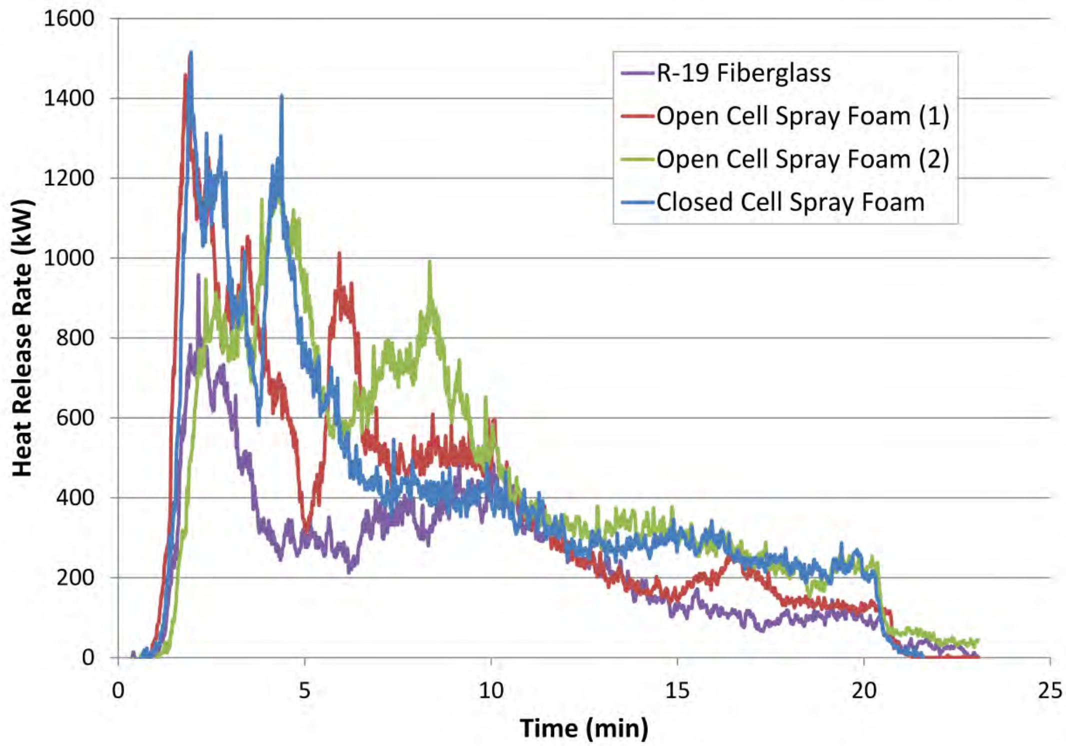


Figure 6. 40: Insulation Comparison Vinyl Siding – Heat Release Rate

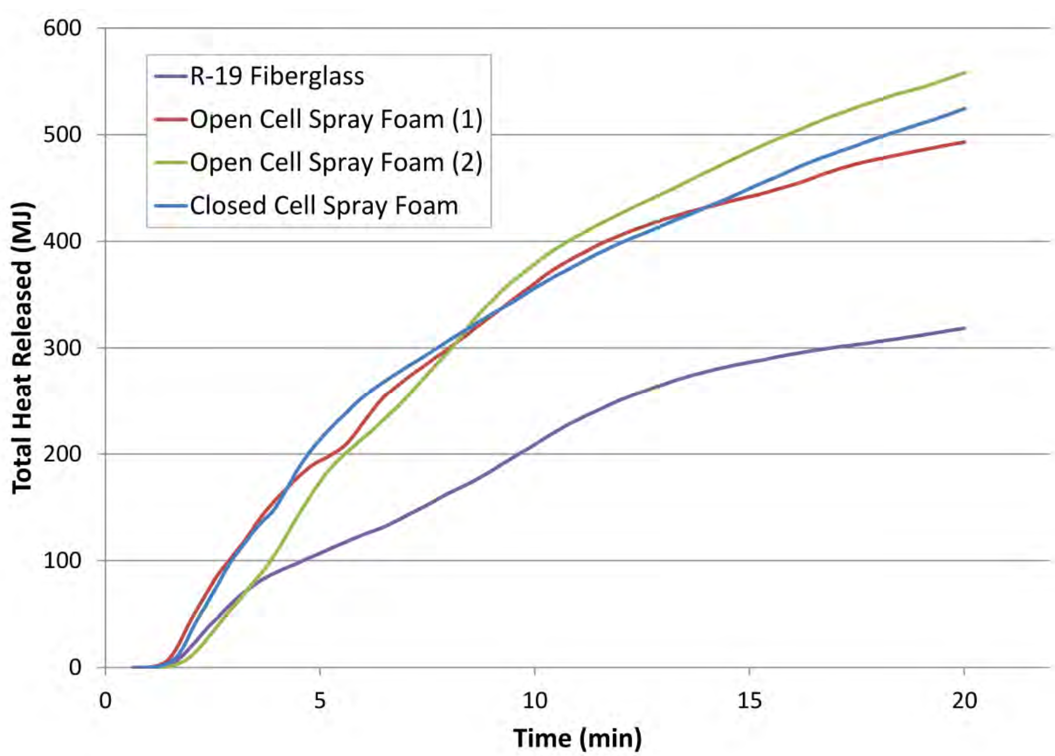


Figure 6. 41: Insulation Comparison Vinyl Siding – Total Heat Released

6.5.4. Effect of the ignition source

Three wall types, wall type 1 and wall type 8 and wall type 9-C were repeated with various burner sizes to determine the effect of the exposure fire on the ignition and flame spread of the wall. In addition wall types 8 and 1 were tested using a propane gas grill to evaluate the potential of ignition from a grill located against an exterior wall.

Table 6. 93: Effect of Ignition Source Wall Type 1 (4" Vinyl, Plywood, Fiberglass)

Burner HRR (kW)	Experiment Number	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (mm:ss)
25	23	08:53	N/A	73	N/A
50	2	01:32	04:38 [3:06]	285	01:39
100	3	01:08	02:25 [1:17]	440	02:18
150	1	01:10	01:54 [0:44]	515	02:03

Table 6. 93 shows the various burner sizes utilized on wall type 1 and the resulting ignition, flame spread, peak heat release rate and exposure time. A significant difference was noted between 25kW and 50kW where the ignition of the wall occurred 7:21 later with 25kW and the flame never spread up the wall. A contributing factor for this was the exposure area. The line burner (used for 50 kW-300kW) was 39 in. long while the sand burner used for 25 kW was 1 ft. square. The line burner was not able to accurately adjust down to 25kW so an alternative was used. The difference in ignition was much less for the 50kW, 100kW and 150kW burner all between 01:10 and 01:32 indicating burner size above 50kW has limited effect on ignition time.

The effect of burner size on flame spread can be seen with wall type 1 as the 25kW burner failed to produce flame spread and the 50kW burner took over 3 minutes to reach 7 ft. up the wall. The 100kW and 150kW each had a progressively fast spread due to the taller flame height from the burner itself causing a larger amount of the surface to be adjacent the flame, pre-heating that surface and increasing spread. For wall type 1 burner size was directly proportional to flame spread rate with an increase in burner size resulting in a more rapid flame spread.

Similar conclusions can be drawn about the peak heat release rate as the height of the burner flame increased as the energy increased. This additional flame height exposed more of the wall to higher energy fluxes resulting in more of the wall being involved simultaneously.

Figure 6. 42 shows the heat release rate with the burner subtracted out and illustrates the larger the burner size the higher and earlier the peak heat release rate occurred. For wall type 1 the burner size has a significant impact on peak heat release rate, with the highest being for the largest burner.

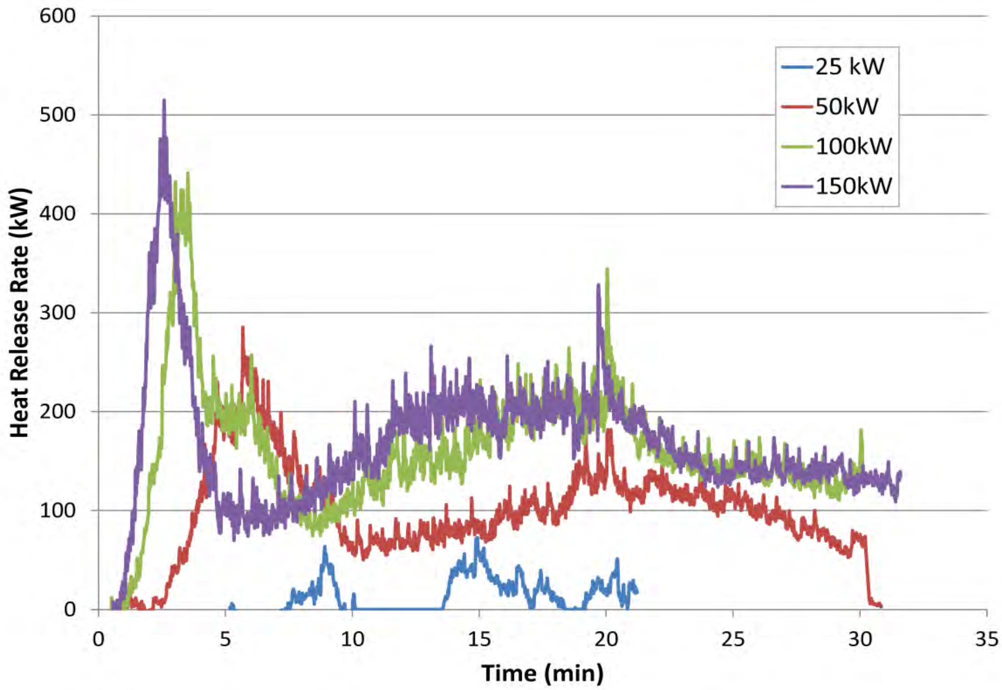


Figure 6. 42: Heat Release Rates (w/o burner) for Wall Type 1 with Different Burner Heat Release Rates

The exposure time shows in Table 6. 93 indicates for 25kW the lack of flame spread resulted in no exposure. For the 50kW, 100kW and 150kW the exposure time was similar ranging from 1:38 for the 50kW to 2:18 for the 100kW with the 150kW burner falling in the middle at 2:09. This indicates that for above 50kW burner size has a limited impact on the exposure time.

Table 6. 94 shows the various burner sizes utilized on wall type 8 and the resulting ignition, flame spread, peak heat release rate and exposure time. A slight difference was noted between 50kW and 100kW where the ignition of the wall occurred 0:22 later with 50kW. The difference in ignition was the same for the 100kW and 150kW burner indicating burner size above 100kW has limited effect on ignition time.

A detectable effect of burner size on flame spread can be seen with in Table 6. 94 as the 50kW burner took 0:47 to reach 7 ft. up the wall, the 100kW took 0:39 and the 150 kW took 0:26. Thus for wall type 8 burner size was directly proportional to flame spread rate with an increase in burner size resulting in a more rapid flame spread.

Table 6. 94: Effect of Ignition Source Wall Type 8 (4" Vinyl, 1" Polystyrene, Fiberglass)

Burner HRR (kW)	Experiment Number	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (mm:ss)
50	6	01:02	01:49 [0:47]	694	05:08
100	5	00:40	01:19 [0:39]	958	03:19
150	4	00:40	01:06 [0:26]	1293	02:18

Similar to wall type 1 there is a detectible impact of burner size on peak heat release rate as seen in Table 6. 94 with the 50kW burner resulting in the lowest peak and the 150kW burner the highest of the wall type 8 peak values.

The exposure time has the inverse correlation due to the burning rate of the foam insulation. The 50kW burner caused a rapid vertical spread but the horizontal spread was slower resulting in a larger exposure time than both the 100kW and 150kW burners. The increased energy at ignition caused a rapid vertical and horizontal spread resulting in more material burning at the same time (peak heat release rate) however the more material burning at once the faster the fuel is consumed and the fire size decreases.

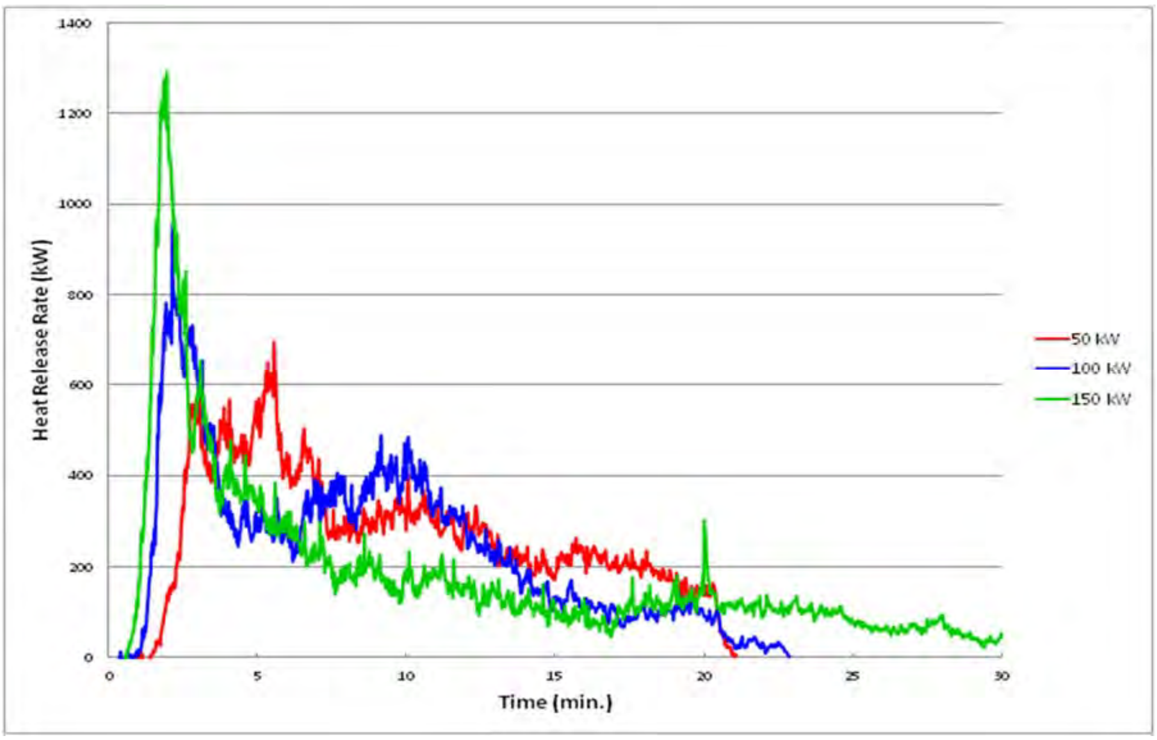


Figure 6. 43: Heat Release Rates (w/o burner) for Wall Type 8 with Different Burner Heat Release Rates

The same conclusions drawn from wall type 1 and wall type 8 are confirmed in wall type 9-C show in Table 6. 95. The burner size has an impact on the ignition time as the larger burner the shorter the time to ignition. It also shows more rapid spread, higher peak heat release rate and less exposure time.

Table 6. 95: Effect of Ignition Source Wall Type 9-C (4” Vinyl, ½” Polystyrene, Closed Cell Spray Foam)

Burner HRR (kW)	Experiment Number	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (mm:ss)
25	24	02:14	02:53 [0:39]	1026	06:26
100	9	00:59	01:14 [0:15]	1515	04:32

To evaluate the hazards of exposure propane gas grills as an ignition source two experiments were conducted, the wall type and materials used are shown in Table 6. 96. The only differences between the wall types being compared are the different sheathing material used and the stud depth.

Table 6. 96: Wall Types and Materials for Grill Fire Experiments

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8 (Exp 15)	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board
Wall 1 (Exp 16)	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x4, R-19 KFI w/ IVB	1/2" Gypsum Board

Table 6. 97: Effect of Ignition Source – Gas Grill

Wall Type	Experiment Number	Ignition of Wall (mm:ss)	Time to Flame at 7ft (mm:ss) [Time from Wall Ignition to 7ft]	Peak HRR (w/o burner) (kW)	Exposure Time (mm:ss)
8	15	45:11*	45:52 [0:42]	-	04:09
1	16	15:35	N/A	-	N/A

*Grill was located 2” from the wall surface and failed to ignite wall after 40:02. Grill was pushed back against the wall and ignited wall in 05:11.

The ignition times shown in Table 6. 97 for experiment 15 and 16 are not comparable as the grill was not in contact with the wall for the first 40:02 of experiment 15 and was in constant contact during experiment 16. The magnitude of the ignition however was significantly higher than those from gas burners above 50kW. For experiment 16 it was over three times as long to ignite the wall.

The grill source was a low hazard with wall type 1 as ignition took on the order of tens of minutes the fire self-extinguished when the grill was removed. It was only able to generate a small area of flame as seen in Figure 6. 45 For wall type 8 with the polystyrene sheathing the fire spread up the wall surface and would have exposed a potential eave line indicating the grill source would have a been a hazard for that wall type for this configuration see Figure 6. 44.

Figure 6. 44: Picture of Peak Heat Release Rate for Wall Type 8 Grill Fire

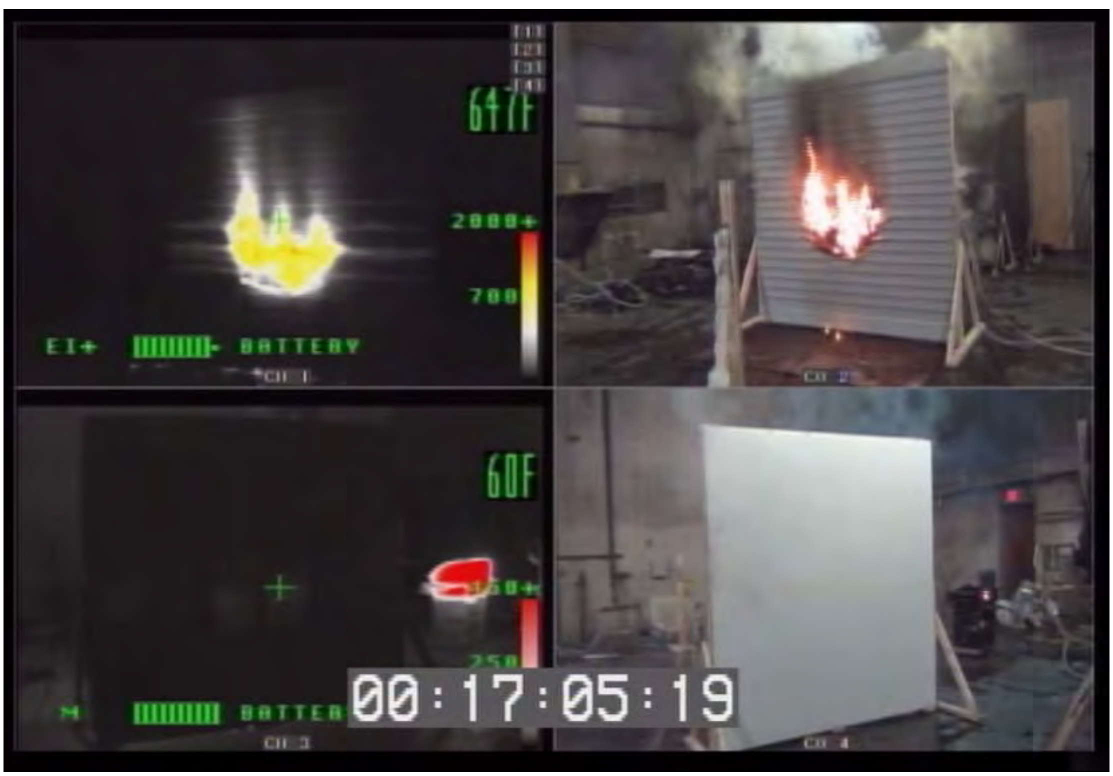


Figure 6. 45: Picture of Peak Heat Release Rate for Wall Type 1 Grill Fire

In general ignition source does have an impact on the ignition times, flame spread rate, peak heat release rate and exposure time across several wall types. The magnitude of the effect depends on the wall type. Walls with and more synthetic fuels and foams have less of an impact than those with more natural materials. In addition the use of synthetic wall construction materials such as foam insulation and plastic siding is more hazardous than natural products for both small and large ignition sources including sources such as gas grills.

6.5.5. Analysis of Receptacles

To evaluate the effect of electrical receptacles experiment 12 and experiment 13 had receptacles, i.e. outlets, on the back wall. In Figure 6. 46 and Figure 6.47 fire can be seen exiting out of the back wall through the receptacles. This suggests that the receptacles can contribute to the penetration of an exterior fire to the interior. These two experiments were the only two experiments with significant flaming exiting out of the back wall. There were other experiments with large areas of discoloration indicating heat damage, but the flame did not penetrate through, since there was no hole in the wall for the flame to exit. The gypsum board provides an effective fire barrier when not compromised by penetrations for purposes such as electrical or plumbing. Therefore the walls themselves are unlikely to be the method of penetration from the exterior. Instead, other parts of the wall that make the wall more vulnerable to penetration, such as receptacles or possibly windows, are likely to be the cause of exterior to interior fire spread.

Table 6. 98: Type and Material for Experiments 12 and 13

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Exp 12	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, Spray Polyurethane Foam	1/2" Gypsum Board
Exp 13	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 6. 46: Image of Fire out of Back Wall of Experiment 12

Figure 6. 47: Image of Fire out of Back Wall of Experiment 13

6.6. Most Hazardous Wall Assemblies

6.6.1. Wall Assemblies with Fastest Growing Fires

In the 28 wall burn experiments, only ten experiments (Exps. 1, 4, 5, 6, 7, 8, 9, 10, 12, and 13) had flames that reached the top of the wall in less than 2 min. Every single one of those experiments had vinyl siding, and all but one of the experiments had either polystyrene or polyisocyanurate sheathing. The only experiment that had flame reach the top of the wall with plywood sheathing was Experiment 1, where the burner heat release rate was 150 kW. This shows that in terms of the growth of the fire, both the siding and the sheathing play an important role, and that the combination of vinyl siding and polystyrene (or polyisocyanurate) lead to fires that grow very quickly when exposed to a large enough fire source.

6.6.2. Wall Assemblies with Highest Peak Heat Release Rates

In the 28 wall burn experiments, only eight experiments (Exps. 4, 8, 9, 11, 12, 18, 21, and 24) had a peak heat release rate above 1000 kW. Seven of the eight experiments had vinyl siding and polystyrene sheathing. In addition, in those seven experiments there was another layer of material that could get involved. That additional layer included either spray foam, closed cell foam, or open cell foam insulation, or it included thicker siding (i.e. polypropylene shingle siding). Experiment 21 was the only experiment with a large heat release rate that did not have vinyl siding. However, the experiment did have polystyrene sheathing and the involvement of the sheathing supplied enough heat to get the wood lap siding involved. Again, this shows the increased hazard of polystyrene sheathing, but also shows that the addition of foam wall cavity insulation can lead to more severe fires compared with those with fiberglass insulation

6.6.3. Wall assemblies with Largest Total Heat Released

In the 28 wall burn experiments, only five experiments (Exps. 11, 13, 18, 21, and 28) released more than 700 MJ of heat. The main outlier in that group is Experiment 28, which to release more than 700 MJ required 300 kW burner heat release rate and manual opening of the wall to the ambient environment. Experiments 11 and 13 both had spray polyurethane foam, which shows the large fuel load of that type of wall cavity insulation. Experiment 18 had polypropylene shingle siding, which shows the increased fuel load of polypropylene shingle siding compared with double 4" vinly siding. And finally, Experiment 21 had wood lap siding, which shows that if wood lap siding is exposed to a large enough fire for a long enough time and begins to get invovled, the fire can grow large enough to release a large amount of heat.

7. Eave Experiments

7.1. Experimental Description

Three separate wall and eave assemblies were subjected to similar 100 KW exposure fires under the oxygen consumption calorimeter at Underwriters Laboratories facilities in Northbrook, Illinois. These scenarios were designed to expand upon the data from the 28 experiments with 8 ft. by 8 ft. wall burns, and to examine the effect of a larger burn area on the flame spread. Additionally, the experiments allow analysis of the flame spread from the exterior to the eaves and then into the attic. The speed at which this occurs determines the potential hazard that the fire department will arrive to. For each experiment, the wall was 16 ft. tall and 16 ft. wide, and incorporated side walls and corners at each end with 8 ft. side walls running continuously up to the roof line. A section of truss attic was constructed on the walls with an eave that projected from the front of the structure. Three different wall configurations were chosen from the wall fire experiments. First, a 2 by 4 wood framed wall insulated with fiberglass insulation, sheathed with plywood and sided with vinyl siding. Second, a 2 by 6 wood framed wall insulated with fiberglass insulation, sheathed with polystyrene rigid foam board and sided with vinyl siding. Third, a 2 by 6 wood framed wall insulated with spray foam insulation, sheathed with polystyrene rigid foam board and sided with vinyl siding. Measurements of temperature, heat release rate, heat flux, video, thermal imaging and flow velocity into the eaves were made to examine the flame spread and fire behavior of the system. See appendix B, for construction drawings of each eave experiment.

7.2. Instrumentation

The experiments were conducted using the oxygen consumption calorimeter at Underwriters Laboratories facilities in Northbrook, Illinois. The experiments were performed in a 50 by 50 ft. test cell with a 25 ft. hood to measure the heat release rate. In the test cell four inlet ducts provide air to the room and are located 5 ft. above the floor to minimize induced drafts within the room.

For each of the experiments, the heat source was a line burner with dimensions 39 in. wide, 4 in. thick, and 16 in. high. A picture of the propane flow controller and burner can be seen in Figure 6. 5 and Figure 6. 6. The burner was set at 100 kW for every experiment, and the actual heat release rate of the burner fell within $\pm$10% of the targeted heat release rate.

Heat flux measurements were made 8 ft. from the exterior wall at heights of 4 ft. and 12 ft. and 14 ft. from the exterior wall at heights of 4 ft. and 12 ft. Temperatures were recorded under the siding and halfway in the depth of the wall. Gas velocity was recorded with 3 bi-directional probes at the eave line spaced equally across the face of the test set up. Video thermal imaging of the front surface and rear surface of the wall was taken during the experiments. The instrumentation of the experiments is shown in Figure 7.1.

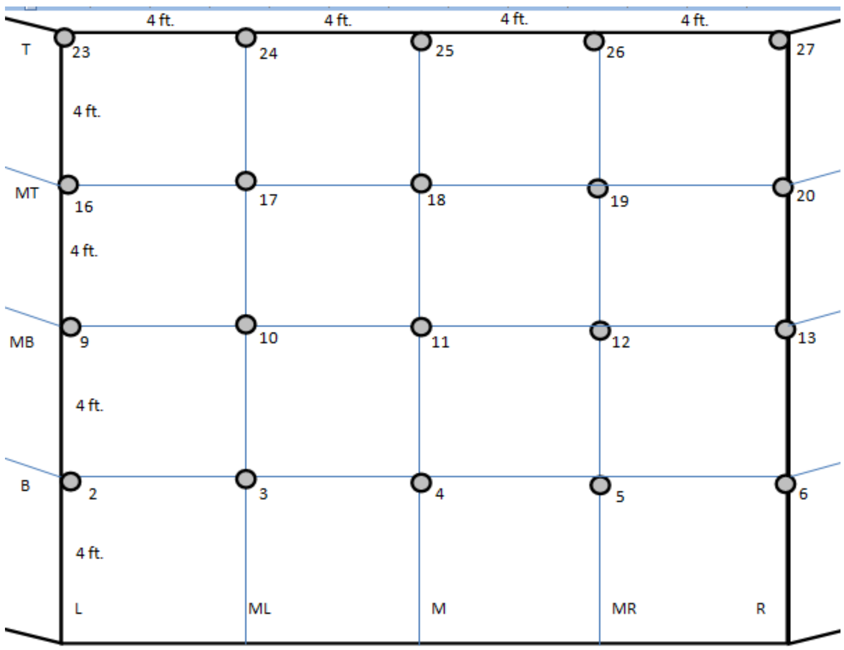


Figure 7. 1: Location of Thermocouples for Wall and Eave Burn Experiments

7.3. Eave Experiment Results

Eave Experiment 1

The layout of the wall and materials used for each layer of the exterior wall are specified in Table 7. 1. The attic insulation is the same as the wall insulation and lies on the ceiling in the attic. A front view and rear view of the wall and attic structure is shown in Figure 7. 2 and Figure 7. 3. The burner heat release rate (HRR) was 100 kW for Experiment 1 while the burner was on. Photos from Experiment 1 are displayed in Table 7. 2. A timeline of the events within Experiment 1, matching with the photos in Table 7. 2, is shown in Table 7. 3. Heat release rate data, heat flux data, temperature, and flow velocity data from Experiment 1 are shown in appendix H figures H.1-H.13.

Table 7. 1: Wall Type and Material for Experiment 1

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 1	Double 4" Vinyl Siding	Weather-Resistant Barrier	1/2" Plywood Sheathing	2x4, R-13 KFI w/ IVB	1/2" Gypsum Board

Figure 7. 2: Front View of Eave Structure for Experiment 1

Figure 7. 3: Rear View of Eave Structure for Experiment 1

Table 7. 2: Eave Experiment 1 Pictures

 00:00	 00:10
 02:00	 03:15
 04:00	 06:00

 07:00	 15:00
 17:00	 17:30
 19:00	
 26:00	 26:40

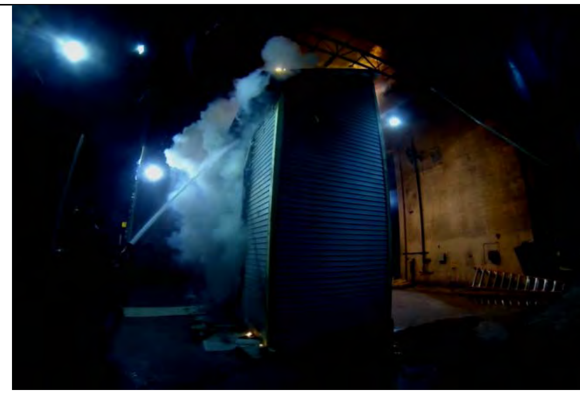
	
27:00	27:05

Table 7. 3: Eave Experiment 1 Timeline

Time (mm:ss)	Description
00:00	Start of the Experiment
00:10	Burner is turned on and heat release rate reaches 100 kW
02:00	Smoke is visible and the vinyl siding is involved in the fire
03:15	Flame has spread to halfway up the wall
04:00	Smoke and hot gases impinging on the eaves damaging the materials covering the eaves
06:00	Most of the material covering the eaves has fallen off, flames reach the top of the wall
07:00	Fire recedes back down, only the outer parts of the vinyl siding are burning
15:00	Fire starts to grow again vertically along the plywood sheathing
17:00	Flame again reaches the top of the wall, spreading vertically along the plywood sheathing
17:30	Part of one of the trusses in the attic catches fire
19:00	Fire dies back down again, burning in the eave is almost completely diminished
24:40	Flames visible in attic space
26:00	Fire again spreads to the top of the wall from the plywood sheathing
26:40	Attic is fully involved in the fire, large amounts of flame exiting out through the eaves
27:00	Flames exiting out through the eaves and the back of the attic
27:05	Fire is suppressed and experiment is over

Eave Experiment 2

The layout of the wall and materials used for each layer of the exterior wall are specified in Table 7. 4. The attic insulation is the same as the wall insulation and lies on the ceiling in the attic. A front view and rear view of the wall and attic structure is shown in Figure 7. 4 and Figure 7. 5. The burner heat release rate (HRR) was 100 kW for Experiment 2 while the burner was on. Photos from Experiment 2 are displayed in Table 7. 4. A timeline of the events within Experiment 2, matching with the photos in Table 7. 4, is shown in Table 7. 6. Heat release rate data, heat flux data, temperature, and flow velocity data from Eave Experiment 2 are shown in appendix H figures H.14-H26.

Table 7. 4: Wall Type and Material for Eave Experiment 2

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 8	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, R-19 KFI w/ IVB	1/2" Gypsum Board

Figure 7. 4: Front View of Eave Structure for Experiment 2

Figure 7. 5: Rear View of Eave Structure for Experiment 2

Table 7. 5: Eave Experiment 2 Pictures

 00:00	 00:10
	

01:00	01:30
	
02:01	02:20
	
02:45	03:00

Table 7. 6: Eave Experiment 2 Timeline

Time (mm:ss)	Description
00:00	Start of the Experiment
00:10	Burner turned on, set at heat release rate of 100 kW
01:00	Smoke begins to show, flame starts spreading up the vinyl siding
01:30	Flame is more than halfway up the wall, large amounts of smoke entering the attic
02:01	Flames reach the top of the wall and enter into the attic through the eaves, no smoke exiting the back of the attic yet
02:20	Fire in the attic, large amounts of smoke exiting out the back of the attic
02:45	Flames exiting out the back of the attic, flames are also visible along the length of the eaves
03:00	Fire suppressed and experiment terminated

Eave Experiment 3

The layout of the wall and materials used for each layer of the exterior wall are specified in Table 7. 7. The attic insulation is the same as the wall insulation, and, in this case, is applied to the underside of the roof. A front view and rear view of the wall and attic structure is shown in Figure 7.6 and Figure 7. 7. The burner heat release rate (HRR) was 100 kW for Experiment 3 while the burner was on. Photos from Experiment 3 are displayed in Table 7. 8. A timeline of the events within Experiment 3, matching with the photos in Table 7. 8, is shown in Table 7. 9. Heat release rate data, heat flux data, temperature, and flow velocity data from Eave Experiment 3 are shown in appendix H, figures H.27-H.39.

Table 7. 7: Wall Type and Material for Eave Experiment 3

Wall Type	Siding	Additional Material	Sheathing	Insulation	Back Wall
Wall 9	Double 4" Vinyl Siding	Weather-Resistant Barrier	1" R-5 EPS Insulation Board	2x6, Spray Polyurethane Foam	1/2" Gypsum Board

Figure 7. 6: Front View of Eave Structure for Experiment 3

Figure 7. 7: Rear View of Eave Structure for Experiment 3 before drywall application

Table 7. 8: Eave Experiment 3 Pictures

 00:00	 00:10

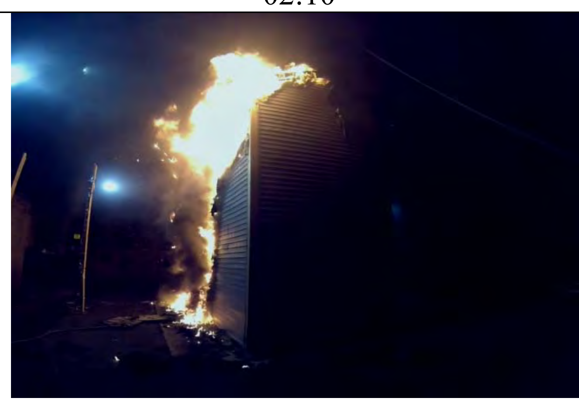

01:00


01:30


02:00


02:10


02:50


04:00


06:00


08:00

10:00

12:00

14:00

15:40

Table 7. 9: Eave Experiment 3 Timeline

Time (mm:ss)	Description
00:00	Start of the Experiment
00:10	Burner is turned on and set to a heat release rate of 100 kW
01:00	Smoke is visible, vinyl siding begins to burn
01:30	Flame reaches halfway up the wall, large amounts of smoke and hot gases impinge on the material covering the eaves
02:00	Flames reach top of the wall, large amounts of smoke and hot gases collecting at the eaves
02:10	Eaves get involved in fire
02:50	Fire spreading up the side of the roof
04:00	Fire has spread to the side of the roof, the wall and eaves are fully involved
06:00	Eaves are still fully involved, parts of the wall in the center have burned up, the fire on the wall is spreading horizontally outwards from the center
08:00	Eaves still fully involved, flames have spread farther out and are nearing the edge of the wall, flame from the wall has diminished
10:00	Eaves still fully involved, clear damage to vinyl siding at the top of the side of the structure
10:24	Flames visible in the eave space
12:00	Attic still fully involved though producing less flame and more smoke
14:00	Attic fire still well involved but has died down in severity, and flames have reached the edge of the wall on the wall's front surface. Almost all of the vinyl siding of the front wall has burned off
15:40	Fire is suppressed and the experiment is over

7.4. Eave Experiment Analysis

Table 7. 10 compares the peak heat release rate, peak heat flux, and the times the peaks occur, as well as the total heat released and the time to a heat release rate larger than 5 MW. Experiment 2 was the fastest gowing fire, reaching the highest peak heat release rate and being the fastest to reach its peak heat release rate while also being the quickest to exceed 5 MW. Experiment 3 also grew quickly, reaching a heat release rate of 5 MW 3 min. and 23 s after ignition. Experiment 1 was a much slower growing fire, taking more than 27 minutes to exceed 5 MW. This data is consistent with the wall burns in showing the increased hazard for rapid fire progression of polystyrene compared to plywood sheathing. The polystyrene becomes involved in the fire much faster, which allows the fire to spread up the wall and into the eaves and supplies enough heat to raise the temperature in the attic and ignite the attic materials (both structural members and insulation in the case of Experiment 3). Experiment 3 had the largest amount of total heat released as well as having the highest peak heat flux. It is difficult to compare this to Experiment 2 though because Experiment 2 was extinguished shortly after reaching its peak heat release rate, whereas Experiment 3 sustained a high heat release for a long period of time without exceeding 10 MW and requiring the fire to be extinguished to protect the calorimeter.

The difference between the heat release rate of Experiment 3 and Experiment 2 suggests that the spray polyurethane foam gets involved in the fire, but it also provides a barrier to the attic space slowing the transition to a structure fire through the eaves.

The larger heat flux in experiment 3 could stem from the spray polyurethane foam on the exterior wall becoming involved, which would emit radiation with a larger view factor, due to lateral flame spread along the eave line, than does the combustion products released in the attic in Experiment 2, of which a large portion exit out the back of the attic. The images of the fires (Figure 7. 8 and Figure 7. 9) from the two experiments supports this theory as the intensity of the flame visible to the heat flux gauge is larger in Experiment 3. The sustained large heat release rate may also play a role in the large peak heat flux seen in Experiment 3.

Table 7. 10: Comparison of Eave Experiment Results

Experiment	Attic Flame Penetration	Peak HRR (MW)	Time of Peak HRR (mm:ss)	Peak HF (kW/m^2)	Time of Peak HF	Time to HRR > 5 MW
1	24:40	11.4	27:50	9.2	30:50	27:34
2	2:01	13.5	02:30	13.6	2:55	2:12
3	10:24	10.4	16:05	33.2	3:35	2:43

Figure 7. 8: Eave Experiment 2 Fire

Figure 7. 9: Eave Experiment 3 Fire

Flame Spread

One area of interest in the wall and eave experiments was to determine how the different wall materials affected the flame spread. This included both the vertical spread up the wall and into the attic, the horizontal spread of the fire along the wall, and the spread of the fire deeper into the wall and into the wall cavity insulation. To determine the flame spread, the measured temperature data was used, with the time for the thermocouple to reach a value of 200°C signalling the time when flame had spread to the location of that thermocouple. Table 7. 11 through Table 7. 19 show the flame spread under the siding, in the wall cavity, and in the eaves and attic for Experiments 1, 2, and 3. N/A means the flame never spread to that location.

Table 7. 11: Eave Experiment 1 Under Siding Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Top	N/A	31:38	N/A	N/A	N/A
Middle Top	N/A	09:15	07:18	N/A	N/A
Middle Bottom	N/A	N/A	07:28	N/A	N/A
Bottom	N/A	N/A	N/A	N/A	N/A

Table 7. 12: Eave Experiment 1 Wall Cavity Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Top	N/A	N/A	N/A	N/A	N/A
Middle Top	N/A	N/A	30:36	N/A	N/A
Middle Bottom	N/A	N/A	25:52	N/A	N/A
Bottom	N/A	N/A	23:47	N/A	N/A

Table 7. 13: Eave Experiment 1 Attic and Eave Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Eave	09:39	08:12	09:57	09:38	20:56
Back Attic	30:35	30:34	30:32	30:36	30:41

Table 7. 11 through Table 7. 13 show that in Experiment 1 the flame along the wall takes a significant amount of time to spread vertically up the wall and barely spreads horizontally along the wall. The flame does reach the eave line approximately 9 minutes after ignition, but based upon the time the flame takes to get into the back of the attic, it is evident that the flame grows to the eave line but then dies back down on the wall. Additionally, based upon the wall cavity flame spread data, the fire takes a long time to penetrate into the wall cavity after the flame initially reaches that height under the siding. This is due to the plywood sheathing and fiberglass insulation, both of which take a long time to get involved in the fire and do not burn quickly when compared to the other wall systems tested.

Table 7. 14: Eave Experiment 2 Under Siding Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Top	N/A	03:25	01:51	N/A	N/A
Middle Top	N/A	N/A	01:50	N/A	N/A
Middle Bottom	N/A	N/A	02:01	N/A	N/A
Bottom	N/A	N/A	01:56	N/A	N/A

Table 7. 15: Eave Experiment 2 Wall Cavity Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Top	N/A	N/A	02:23	N/A	N/A
Middle Top	N/A	N/A	02:27	N/A	N/A
Middle Bottom	N/A	N/A	N/A	N/A	N/A
Bottom	N/A	N/A	N/A	N/A	N/A

Table 7. 16: Eave Experiment 2 Attic and Eave Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Eave	02:40	02:23	02:24	02:27	02:33
Back Attic	02:51	02:40	02:41	02:40	02:53

Table 7. 14 through Table 7. 16 show that the addition of polystyrene sheathing greatly increases the rate of vertical flame spread along the wall. The fire reaches the eave line in a third of the time it took to reach the eave line in Experiment 1 and it reaches the back of the attic in less than a tenth of the time it took in Experiment 1. It is important to note that in Experiment 2, the time difference between the flame reaching the eave line and the flame reaching the back of the attic is around 15 seconds. So, once the combustibles in the eave got involved, the fire was large enough to quickly spread to the rest of the attic. The flame also quickly spread into the wall cavity near the top center of the wall. However, in this experiment there was again very little horizontal flame spread along the wall.

Table 7. 17: Eave Experiment 3 Under Siding Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Top	03:59	02:58	02:04	03:04	03:45
Middle Top	04:49	03:06	02:00	04:16	13:42
Middle Bottom	06:18	03:41	01:57	07:16	13:33
Bottom	05:53	03:40	01:40	09:27	14:41

Table 7. 18: Eave Experiment 3 Wall Cavity Flame Spread

	Left	Middle Left	Middle	Middle Right	Right
Top	04:27	04:09	03:20	04:20	04:57
Middle Top	04:59	03:48	03:18	05:31	07:56
Middle Bottom	08:28	04:35	02:58	07:59	12:59
Bottom	06:25	04:50	03:05	10:48	N/A

	Left	Middle Left	Middle	Middle Right	Right
Eave	02:15	02:10	02:03	02:09	02:19
Back Attic	13:37	13:21	13:12	14:54	15:44

Table 7. 19: Eave Experiment 3 Attic and Eave Flame Spread

Table 7. 17 through Table 7. 19 show that the vertical flame spread rate was even greater than in Experiment 2, and was likely due to the presence of spray polyurethane foam getting involved in the fire along with the polystyrene sheathing. The biggest difference between the flame spread in Experiment 3 and the other experiments is the horizontal spread along the wall. Due to the presence of spray polyurethane foam in the wall cavity and the large amount of radiation onto the wall from the flames protruding out of the eave line, the fire did spread horizontally along the entire width of the wall. Another thing to note is the large time difference between the involvement of the eave line and the back of the attic. This large time difference exists because the spray polyurethane foam blocks the hot gases from entering into the attic and so instead those flames flow out of the eave line. It is not until the foam is burned away that the temperatures at the back of the attic indicate flames reaching that point.

The attic space of the structure became involved as the flames spread up the surface vertically and through the eaves in all three experiments. Due to the different materials and construction the transition from an exterior fire to a structure fire occurred on very different time scales.

Figure 7. 10: Vinyl Eave Vents

Eave experiment 1 took over 24 minutes to transition from the bases of the test set up to the flames in the attic space. The flame spread rate up the wall surface was the driving factor as initially the flames spread up the vinyl siding but as that melted and fell away the flames returned to the burner. The higher ignition temperature of the plywood along with the development of a char layer slowed the growth up the wall surface. Once the flames reached the eave line the vinyl eaves (Figure 7. 10) melted away along with the plastic baffles (Figure 7. 11) and provided a direct path for flames to spread into the attic space. See Table 7. 2 for visuals of the flame spread.

Figure 7. 11: Plastic Ventilation Baffles

Flames entered the attic space in eave experiment 2 occurred at 1:51 into the experiment due to the rapid flame spread up the surface of the wall. The present of vinyl eaves (Figure 7. 10) and plastic baffles (Figure 7. 11) which melted out quickly due to the heat from below provided no resistance to the spread of flames into the attic space. The additional fuel from the polystyrene insulation board and direct flame impingement on the sheathing of the roof resulted in the attic space becoming fully involved in under 20 seconds. Figure 7. 12 through Figure 7. 16 show the rapid progression of flames in the attic space.

Figure 7. 12: Eave Exp 1 02:01

Figure 7. 13 Eave Exp 1 02:05

Figure 7. 14: Eave Exp 1 02:10

Figure 7. 15: Eave Exp 1 02:15

Figure 7. 16: Eave Exp 1 02:20

The transition to structure fire in experiment 3 took significantly longer than eave experiment 2 but not as long as eave experiment 1. This occurred due to the construction of the eave and attic space. Unlike experiment 2 the attic space in experiment 3 was part of the conditioned space of the structure with the spray foam providing the insulation barrier in the exterior wall and on the roof of the attic. To ensure energy efficiency the spray foam was also placed in the eaves to provide a continuous insulation system (Figure 7. 17). Flames entered the attic space at 10:23 only after they had spread vertically up the wall and the spray foam in burned away.

Figure 7. 17: Spray Foam Insulation in Eave Line

8. Full-Scale Attic Fire Experiments

Four residential structures were constructed in the large fire laboratory to evaluate the fire dynamics and suppression effectiveness of 4 different fire suppression tactics in both ventilated and unventilated attic structures. The intent of the experiments was to quantify the effectiveness of the most common fire service suppression tactics for attic fires along with evaluate potential tactics. Both interior and exterior tactics were evaluated for their ability to reduce temperatures in attics both pre and post flash over conditions.

8.1. Experimental Setup

The four full scale attics test structures incorporated a light weight truss roof system with an 8 ft. space below simulating the living space in a home. The structures measured 30 ft. by 36 ft. with 6-12 pitched roofs constructed with wood plywood sheathing, ridge vent, gable vents and eave vents (Figure 8. 1 through Figure 8. 8). Shingles were provided on the ridge vent and 4 ft. down each side of the peak for all fixtures with the exception of the test fixture used in experiment 1. The attic was separated from the space below with a layer of ½ in. gypsum wall board and two layers of 6” fiberglass bat insulation. Attic access hatches measuring 2 ft. by 4 ft. were used to gain access to the attic space for instrumentation however were closed off with a ½ in. sheet of gypsum wall board and no insulation during tests. The space below was finished with ½ in. gypsum wall board to provide an enclosure finished with tape and plaster. A single door provided access for suppression tactics and instrumentation. Each structured was used to evaluate the effectiveness of one or more fire suppression tactics for a total of 7 experiments. Construction drawings for the test fixtures can be found in Appendix C, Figures C.1-C.4.

Figure 8. 1: Rendering of experimental fixture

Figure 8. 2:Front of structure

Figure 8. 3: Rear of structure

Figure 8. 4: Eave construction detail (before soffit was added)

Figure 8. 5: Attic construction

Figure 8. 6: Attic insulation


Figure 8. 7: Center of attic and gable vent


Figure 8. 8: Interior of structure

8.2. Instrumentation

Instrumentation was provided to measure temperature the of the gases in the attic and space below, heat flux from the gable vents, velocity of gases from the gable vents and velocity of gases in through the front door. In eave tests the velocity was measured in through the eave vents. Video footage of the tactic being performed, attic space, interior space and exterior were recorded for each test. Instrumentation drawings can be found in Appendix E, Figures E.1-E.7.

8.3. Full Scale Attic Experiment Results

Attic Experiment 1

This experiment was intended to evaluate the fire dynamics and suppression effectiveness of an attic fire where interior operations were conducted. The suppression tactic evaluated involved breaching the attic ceiling just enough to provide access to the space with a nozzle. Eight (8) type IV commodity boxes (cardboard boxes with plastic cups) were placed on a 4 ft. x 4 ft. cement board located centered in the attic space. This experiment was the only experiment conducted without shingles over the ridge vent and 4 ft. down the roof slope. Ignition was provided by an electric match located at the center of the boxes covered with shredded paper to ensure fire spread to the commodity boxes. Figure 8. 9 and Figure 8. 10 below show the fuel load in the attic and a sample of the electric match used for ignition.

Figure 8. 9: Attic Experiment 1 Fuel Load

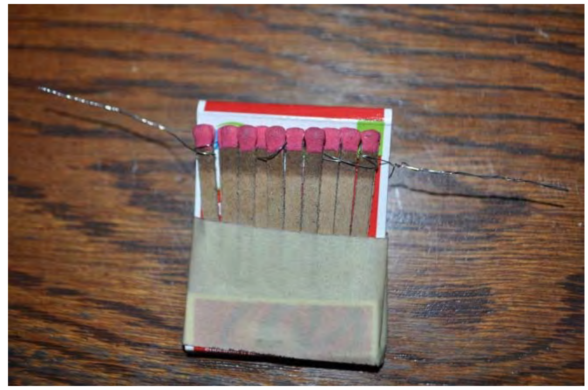


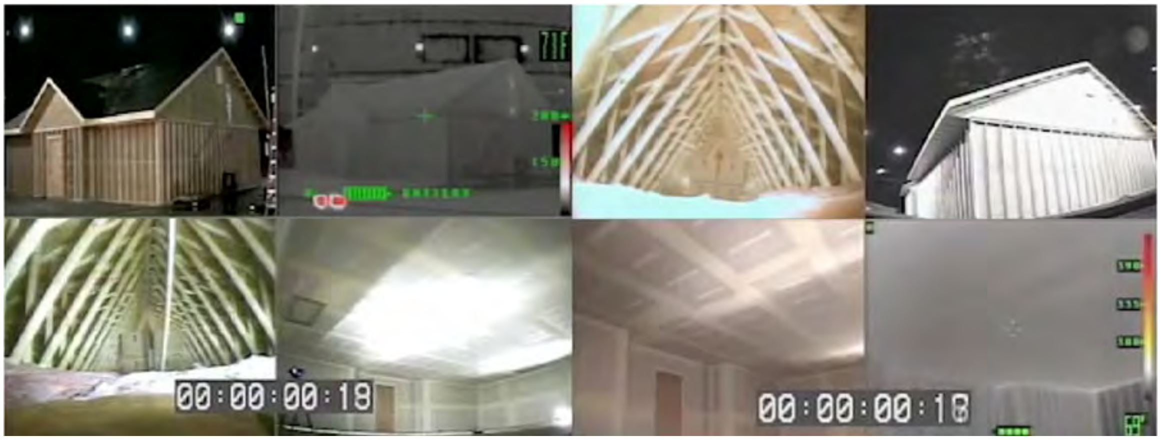
Figure 8. 10: Electric Match

The front door to the test set up was closed and ignition takes place at 00:00. After the fire grows to a relatively steady state a simulated engine crew opens the front door and uses a pike pole to punch a small hole is put in ceiling just inside the door just large enough for an automatic nozzle to fit through. An automatic nozzle set to a wide fog and supplied with 100psi flowing approximately 150gpm is placed in the hole created and turned on at 05:46. Water flows for 38 seconds or a total of approximately 95 gallons and the nozzle is removed at 06:24. The crew backs out and leaves the front door open. The crew repositions to the east gable and at 08:06 uses a straight stream for 24 seconds through the east gable with the same flow rate. At 08:53 the front eaves are pulled starting on the west side of the door and working toward the east side. Water is applied through the eaves at 09:06 starting in the same location and working west using a straight stream at 100psi flowing 150gpm. While water is flowing through the front east eaves the west eaves are removed at 09:15. At 09:33 the line is repositioned to the west eaves and water is applied using the straight stream pattern at the same flow rate. Water is applied though the rear eaves at 11:31 using a safety line for which pressure/flow were not monitored. The ceiling collapses at 11:47. After 12:00 the majority of the flames have been extinguished, video and data continue until 12:45. Table 8. 2 shows images of the experiment at each of the events steps described in Table 8. 1. All data gathered during the experiment can be found in Appendix I, Figures I.1-I.11.

Table 8. 1– Attic Experiment 1 Event List

Event	Time
Ignition	00:00
Fog Stream through Small Hole Below - On	05:46
Fog Stream through Small Hole Below - Off	06:24
1 Minute Following Water Application	07:24
Straight Stream East Gable	08:06
Eaves Pulled	08:53
Water Applied through Eaves – Side A East	09:06
Water Applied through Eaves – Side A West	09:33
Water Applied through Eaves – Side C	11:31
Ceiling Collapse	11:47

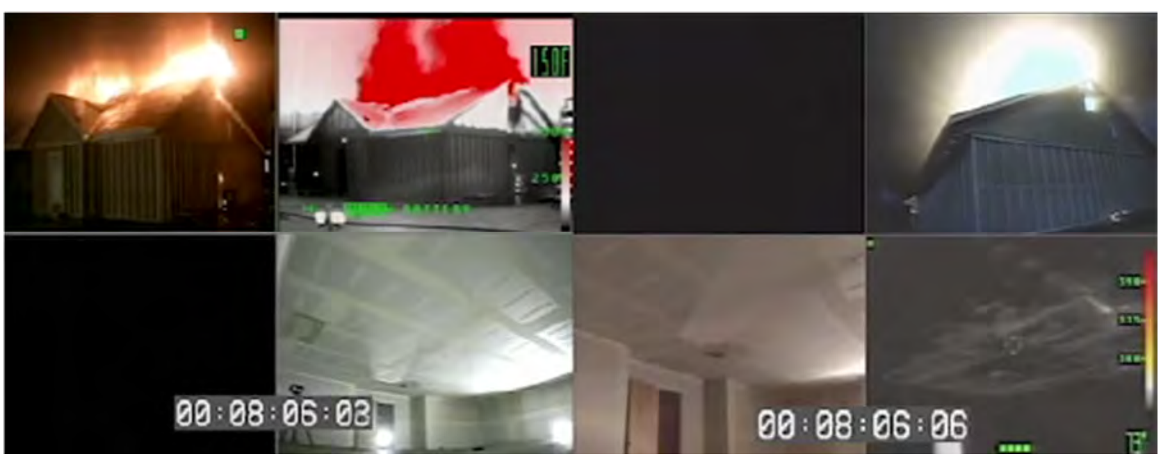
Table 8. 2: Experiment 1 - Chronological Images



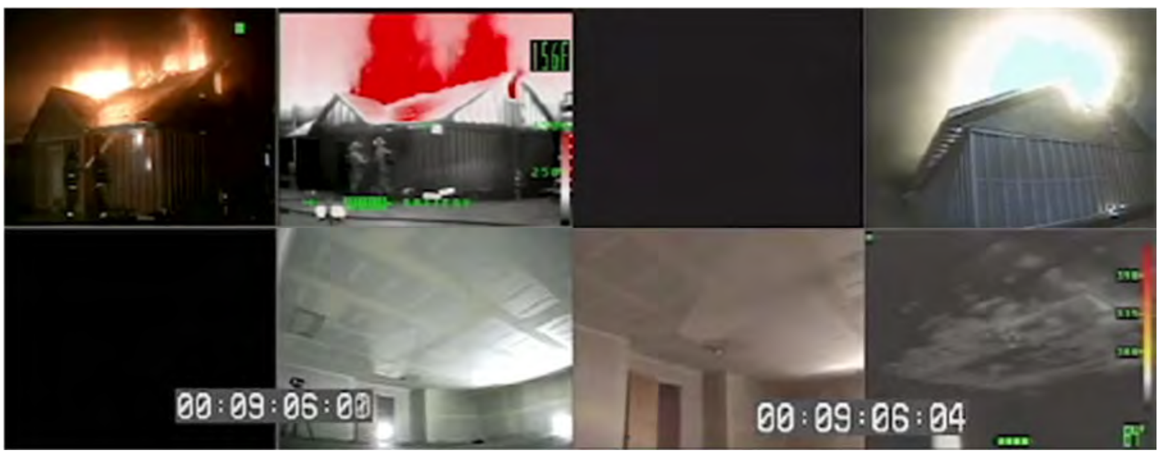


120F
00:06:24:18


159F
00:07:24:11


150F
00:08:06:03
00:08:06:06


00:08:53:08
00:08:53:10


00:09:06:00
00:09:06:04


00:09:33:08
00:09:33:10


00:11:31:10
00:11:31:14


00:11:47:12
00:11:47:15

Attic Experiment 2A

This experiment was intended to study the fire dynamics and suppression effectiveness when a large is created below the fire to apply water while the attic is intact. Two (2) type IV commodity boxes were placed on a 4 ft. x 4 ft. cement board located centered in the attic space. Ignition was provided by an electric match located at the center of the boxes covered with shredded paper to ensure fire spread to the commodity boxes. Figure 8. 11 shows the fuel load for this experiment.

Figure 8. 11: Attic Experiment Two Box Fuel Load

At 00:00 ignition occurred. The fire was permitted to grow to a ventilation-limited state. At 12:00 a simulated engine crew opened the front door and made an approximately 8 ft. x 8 ft. attic access hole just inside the door to the structure. The conditions were monitored for two minutes. Water was applied at 15:07 for 20 seconds using a straight stream followed by a fog stream. The nozzle was supplied with 100psi flowing approximately 150gpm. After the application of water conditions were monitored and after 30 minutes the temperatures were steadily decreasing and the experiment ended. Table 8. 4 shows images of the experiment at each of the events described in Table 8. 3. All data gathered during this experiment can be found in Appendix I, Figures I.12-I.26.

Table 8. 3– Attic Experiment 2A Event List

Event	Time
Ignition	00:00
Door Opened & 8ft. x 8ft. Attic Access Hole	12:00
1 Minute after access hole	13:07
2 Minutes after access hole	14:07
10 Seconds water from below (Straight Stream & Fog)	16:07
1 Minute after water application	17:17
2 Minutes after water application	19:17
5 Minutes after water application	22:17
9 Minutes after water application	26:17

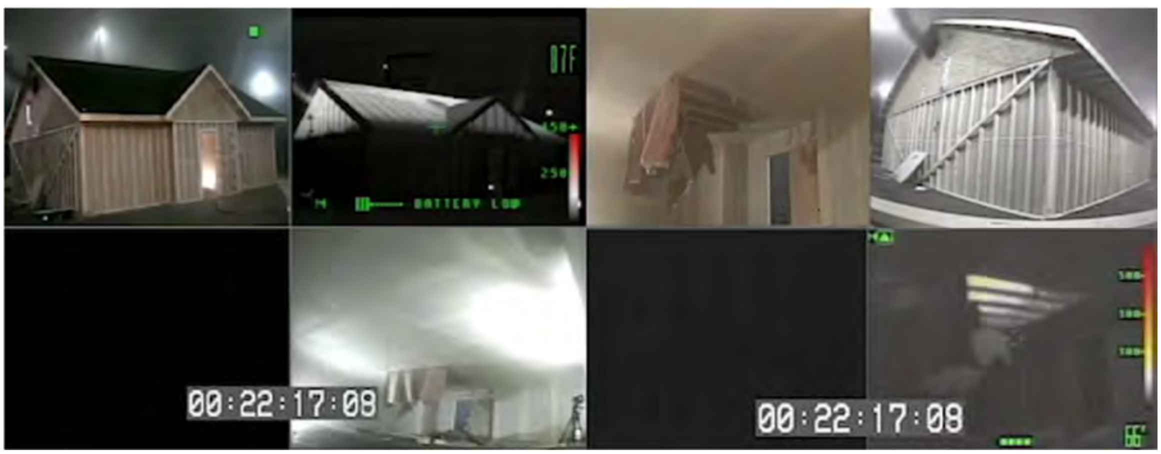
Table 8. 4: Experiment 2A Chronological Images

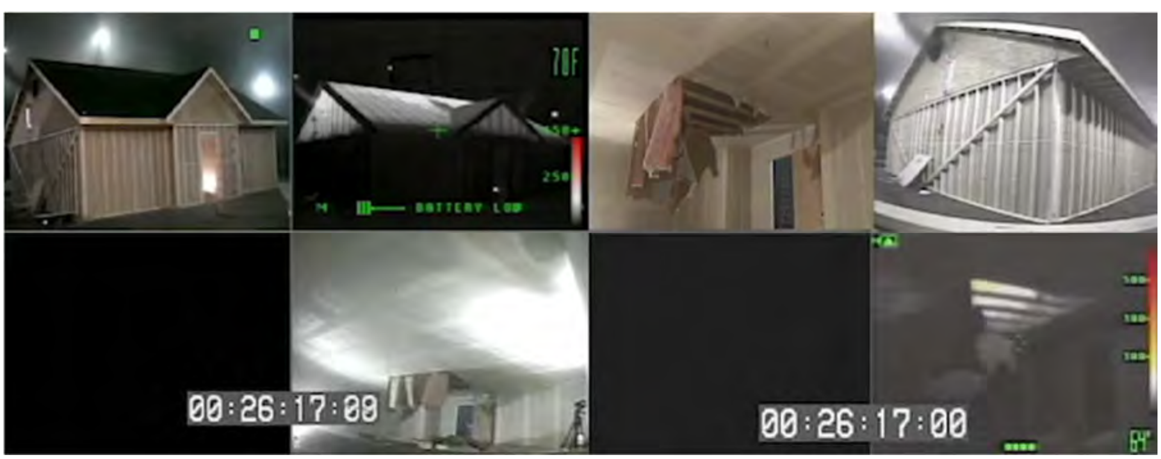

BATTERY LOW
00:14:07:03
00:14:07:04


BATTERY LOW
00:16:07:17


BATTERY LOW
00:17:17:13


00:19:17:16


00:22:17:08
00:22:17:08


00:26:17:00

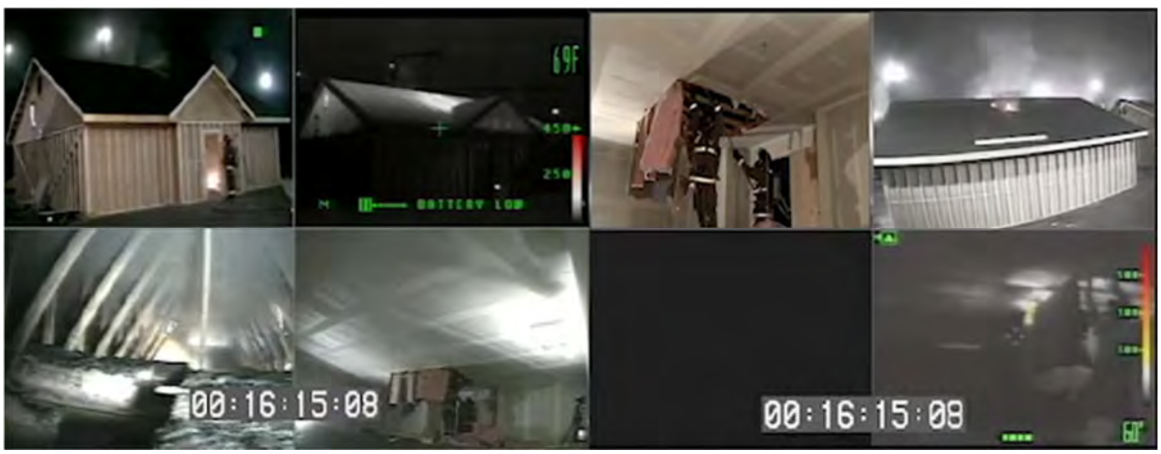
Attic Experiment 2B

A continuation of experiment 2A this experiment was intended to evaluate the fire dynamics and suppression effectiveness of interior operations where a large hole is made below and water applied into a vented or burned through attic. Two (2) type IV commodity boxes placed just inside the 8ft. x 8ft. attic access hole and an approximate 4ft. x 4ft. ventilation hole was opened centerline on the side 'C' roof to simulate a ventilated or burned through attic. Ignition was provided with an electronic match show in Figure 8. 11 placed between the commodity boxes and covered with shredded paper. Ignition occurred at 00:00 and the fire was permitted to grow. Due to the moisture from the earlier water application two (2) additional commodity boxes were added at 16:15 to provide the required fuel load to dry out the wood surfaces and permit flashover of the attic space. The attic approached flashover at 19:30. Water was applied with a fog nozzle supplied with 100 psi flowing 150gpm for 15 seconds at 20:35. The effect was evaluated and followed up with 23 seconds of straight stream supplied with 100psi at 150gpm at 22:32. Extinguishment was initiated at 25:10 via the eaves. Table 8. 6 shows the experiment images at each of the events described in Table 8. 5. All data for this experiment is shown in Appendix I.

Table 8. 5– Attic Experiment 2B Event List

Event	Time
Ignition	00:00
2 Commodity Boxes Added	16:15
3 Minutes After Boxes Added	19:15
Attic space approaches Flashover	19:30
15 Seconds of Fog	20:35
1 Minute after water application	21:50
23 Seconds of Straight Stream	22:32
1 Minute after water application	23:55
Water through Front Soffits (Extinguishment)	25:10

Table 8. 6: Attic Experiment 2B Chronological Images



70F
BATTERY LOW
00:19:30:22
00:19:30:23

172F
BATTERY LOW
00:20:35:26
00:20:35:22

116F
BATTERY LOW
00:21:50:08
00:21:50:04


BATTERY LOW
00:22:32:07
00:22:32:03


BATTERY LOW
00:23:55:12
00:23:55:08


BATTERY LOW
00:25:10:18
00:25:10:14

Attic Experiment 3A

This experiment was intended to evaluate the fire dynamics and suppression effectiveness of an exterior water application through the gable vent on an intact attic. Two (2) type IV commodity boxes were placed on a 4 ft. x 4 ft. cement board located centered in the attic space. Ignition was provided by an electric match located at the center of the boxes covered with shredded paper to ensure fire spread to the commodity boxes. Figure 8. 11 shows the fuel load for this experiment. Ignition occurred at 00:00 and the fire was permitted to grow. At approximately 07:45 the fire becomes ventilation-limited. Water is applied through the side ‘B’ gable at 12:02 via a combination nozzle set to straight stream supplied with 100psi flowing 150gpm. The effects of the water application are evaluated for approximately 2 minutes. At 13:59 the experiment is transitioned to 3B. Table 8. 8 shows the experiment images at each of the events described in Table 8. 7. All data for this experiment is shown in Appendix I, Figures I.42-I.57.

Table 8. 7– Attic Experiment 3A Event List

Event	Time
Ignition	00:00
Temperature Decrease in Attic Space	07:45
20 Seconds of Water West Gable	12:02
Transitioned to Experiment 3B	13:59

Table 8. 8: Attic Experiment 3 Chronological Images


00:07:45:10
00:07:45:08


00:12:02:28
00:12:02:28


00:13:59:13
00:13:59:08

Attic Experiment 3B

Experiment 3B is a continuation of experiment 3A, intended to evaluate the fire dynamics and suppression effectiveness of water application through the gable vent of a ventilated or burned through attic space. The experiment begins at 00:00 after the conclusion of experiment 3A. A 4 aft. x 4 ft. roof vent is opened on the 'C' side at 1:03. At 5:51 flames are visible from the side 'C' roof ventilation hole and side 'D' gable. Water is applied from the side 'B' gable using the same combination nozzle and pressure/flow from before for 20 seconds at 8:27. The water application effect is monitored for a little over 1 minute. At 9:46 the experiment is concluded. Table 8. 10 shows the experiment images at each of the events described in Table 8. 9. All data for this experiment is shown in Appendix I, Figures I.58-I.71.

Table 8. 9: Attic Experiment 3B Event List

Event	Time
Experiment Begins from Experiment 3A (14:00)	0:00
4 ft. x 4 ft. Attic Vent Open	1:04
Flames from Vent & East Gable	5:51
20 Seconds of Water West Gable	8:27
Experiment Concluded	9:46

Table 8. 10: Attic Experiment 3B Chronological Images


Tactic Time 01:04
00:15:04:20
00:15:04:20


Tactic Time 05:51
00:19:51:11
00:19:51:08


Tactic Time 08:27
00:22:28:00
00:22:27:28


Tactic Time 09:46
00:23:46:00
00:23:46:00

Attic Experiment 4A

This experiment was intended to investigate the fire dynamics and suppression effectiveness of water application through the eaves into an intact attic fire. Two (2) type IV commodity boxes were placed on a 4 ft. x 4 ft. cement board located centered in the attic space. Ignition was provided by an electric match located at the center of the boxes covered with shredded paper to ensure fire spread to the commodity boxes. Figure 8. 11 shows the fuel load for this experiment. Ignition occurred at 00:00 and the fire was permitted to grow. At approximately 08:00 the fire becomes ventilation-limited. The side 'A' East eaves are removed at 12:00, followed by water application through them at 12:17 with a combination nozzle set to straight stream supplied with 100psi flowing 150gpm. The side 'A' West eaves are removed at 12:20 followed by water application through them at 12:39 using the same nozzle, pressure and flow. The effects of the water application are evaluated for approximately 7 minutes and 45 seconds at which time a 4 ft. x 4 ft. roof vent is opened on the 'C' side at 19:07. Conditions were evaluated for the next two minutes with further decrease in interior temperature. The experiment was stopped 1:45 after the vent hole was opened.

Table 8. 12 shows the experiment images at each of the events described in Table 8. 11. All data for this experiment is shown in Appendix I, Figures I.72-I.87.

Table 8. 11– Attic Experiment 4A Event List

Event	Time
Ignition	00:00
Temperature Decrease in Attic Space – Ventilation-limited	08:00
Side 'A' East Eaves Pulled	12:00
Water East Eaves Straight Stream – 12 Seconds	12:17
Side 'A' West Eaves Pulled	12:20
Water West Eaves Straight Stream – 12 Seconds	12:39
1 Minute After Water Application	13:51
3 Minutes After Water Application	15:51
4ft. x 4ft. Side 'C' Roof Vent Open	19:07
1 Minute After Open Vent	20:07
1:45 After Open Vent (End Experiment)	20:52

Table 8. 12: Attic Experiment 4A Chronological Images


00:12:00:03


00:12:17:10
00:12:17:10


00:12:20:23


00:12:39:19
00:12:39:20


00:13:51:06
00:13:51:08


00:15:51:09
00:15:51:10


73F
450+
250
BATTERY
00:19:07:13
00:19:07:10
66'


71F
450+
250
BATTERY
00:20:07:08
00:20:07:08
62'


71F
450+
250
BATTERY
00:20:52:06
00:20:52:06
60'

Attic Experiment 4B

This experiment was intended to evaluate the fire dynamics and suppression effectiveness of water application through the eaves on a ventilated or burned through attic. It was a continuation of experiment 4A, where the majority of the initial fuel load had been consumed and the remaining fuel could not heat adjacent surfaces enough to propagate flame spread. At the beginning of the experiment temperatures at the peak of the attic were below 150°F. Two (2) type IV commodity boxes were placed inside the East access hatch as additional fuel. Ignition was provided by an electric match located at the center of the boxes covered with shredded paper to ensure fire spread to the commodity boxes. Figure 8. 11 shows an example of the fuel load for this experiment. Ignition occurred at 00:00 and the fire was permitted to grow in the attic vented attic space. At approximately 08:15 the temperatures stabilize in the attic space representing roughly a steady state. Water is applied through the side 'A' eaves at 09:13 using a combination nozzle set to straight stream supplied with 100psi flowing 150gpm. The effects of the water application are evaluated for approximately 4 minutes where further decrease in interior temperature occurred. The test is concluded 4 minutes after water is applied.

Table 8. 14 shows the experiment images at each of the events described in Table 8. 13. All data for this experiment is shown in Appendix I, Figures I.88-I.102.

Table 8. 13– Attic Experiment 4B Event List

Event	Time
Ignition	00:00
Relatively Steady State Temperatures in Attic	08:15
Water Through Side 'A' Eaves – 12 Seconds Each Side	09:13
1 Minute after water application	10:41
3 Minutes after water application	12:41
4 Minutes after water application	13:41

Table 8. 14: Attic Experiment 4B Chronological Images


Tactic Time 09:13
00:42:13:20
00:42:13:20


Tactic Time 10:41
00:43:41:08
00:43:41:08


Tactic Time 12:41
00:45:41:08
00:45:41:08

Attic Experiment 4C

This experiment is intended to revisit suppression by gable attack and eave attack on a ventilated or burned through attic. At the conclusion of experiment 4B the majority of the initial fuel load had been consumed and the remaining fuel could not heat adjacent surfaces enough to propagate flame spread. The temperatures at the peak of the attic were below 150°F F. Two (2) type IV commodity boxes were placed inside the West access hatch as additional fuel. Ignition was provided by an electric match located at the center of the boxes covered with shredded paper to ensure fire spread to the commodity boxes. Figure 8. 11 shows an example of the fuel load for this experiment. Ignition occurred at 00:00 and the fire was permitted to grow in the attic vented attic space. As the fire progresses roll over on at the peak of the attic space can be seen in the attic camera at 03:20. At approximately 03:45 the temperatures stabilize in the attic space. The rapid increase in the fire is most likely attributed to the pre-heated fuel which due to the flashover in the earlier experiment permitted heat to transfer into the material. Water is applied through the side 'D' gable vent at 05:17 for 50 seconds using a combination nozzle set to straight stream provided with 100psi flowing 150gpm. The effects of the water application are evaluated and 10 seconds after application and temperatures in the attic space are climbing rapidly at 06:17. Water is applied through the eaves 12 seconds on the East side and 15 seconds on the west side at 06:36 using the same nozzle, pressure and flow. Temperature are monitored for an additional 3 minutes after water application and the experiment is concluded at 10:12. Table 8. 16 shows the experiment images from at each of the events described in Table 8. 15. All data for this experiment is shown in Appendix I.

Table 8. 15– Experiment 4C Event List

Event	Time
Ignition	00:01

Roll Over Seen in Attic Camera	03:20
Relatively Steady State Temperatures in Attic	03:45
Water Through Side ‘D’ Gable – 50 Seconds	05:17
10 Seconds After Water Application	06:17
Water Through Side ‘A’ Eaves – 12 Seconds East, 15 Seconds West	06:36
1 Minutes After Water Application	08:12
3 Minutes After Water Application (End Experiment)	10:12

Table 8. 16: Attic Experiment 4C – Chronological Images


Tactic Time 03:20
00:55:51:07
00:55:51:08


Tactic Time 03:45
00:56:15:17
00:56:15:18


Tactic Time 05:17
00:57:47:28
00:57:47:28


Tactic Time 06:17
00:58:47:25
00:58:47:25


Tactic Time 06:36
00:59:06:18
00:59:06:18

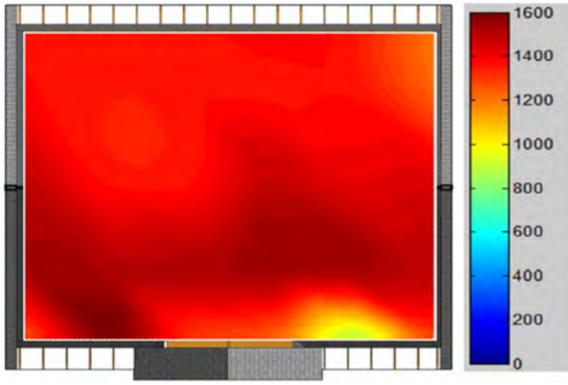

Tactic Time 08:12
01:00:43:02
01:00:43:02

8.4. Full Scale Attic Experiment Analysis

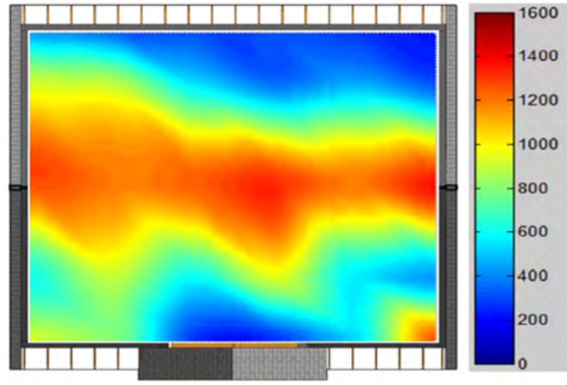
Attic Experiment 1: Fog stream below through small hole with burned through attic

In experiment 1, 5:46 after ignition, water was supplied to the attic space through a small hole in the ceiling with a fog stream nozzle with 100 psi flowing 150 gpm. The water application lasted for 38 s. Table 8. 17 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the attic space was uniformly above 1000°F and most of the attic was involved. At the end of water application the temperatures are still elevated near the peak of the attic, but significant cooling has occurred near the front and back of the structure. At 30 s after water application, temperatures have continued to decrease. However, several hot spots still remain, and it is around these hot spots that the fire begins to regrow. At 60 s after water application, most of the attic space is again above 1000°F. This water application shows that the fog stream provides gas cooling but most likely does not penetrate the gases to cool surfaces. The gas cooling contracted the gasses and brought cool air in the eaves reducing temperatures along the eave line. The presence of hot spots further indicates that the fog stream did not provide surface cooling and suppression and therefore, after the water application is ended, the fire grows and returns to conditions similar to the conditions prior to water application within 60 seconds.

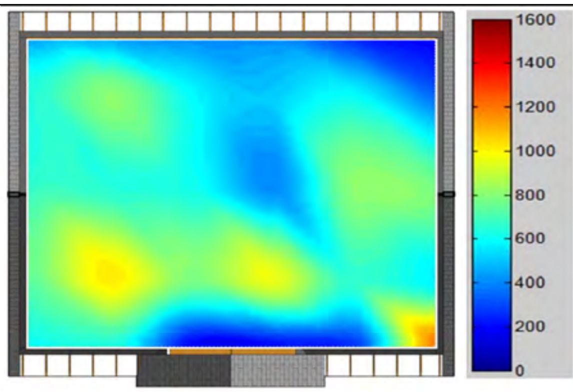
Table 8. 17: Attic Experiment 1 Heat Maps



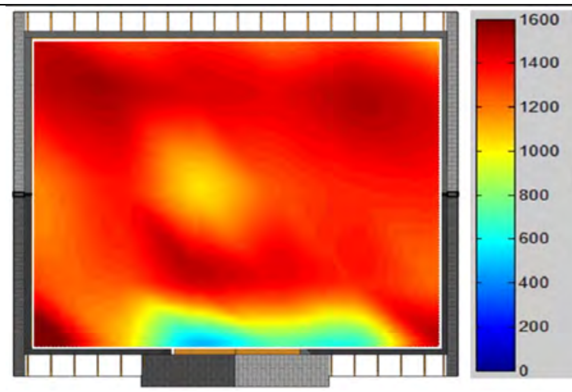
Start of Water



End of Water



30 s After Water

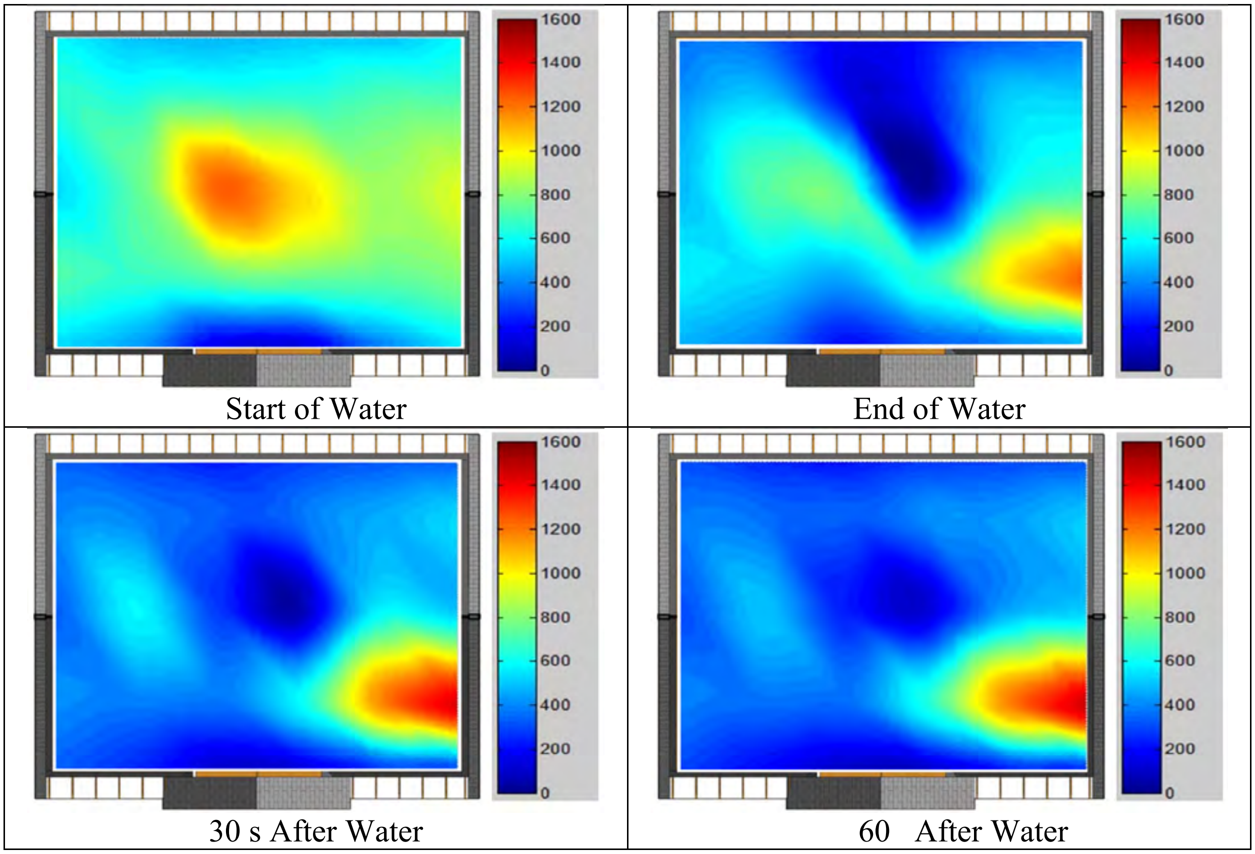


60 s After Water

Attic Experiment 2A: Fog and straight stream below through large hole with an intact attic

In experiment 2A, 16:07 after ignition, water was supplied to the attic space through a large hole in the ceiling with a combination of fog stream and straight stream nozzle with 100 psi flowing 150 gpm. The water application lasted for 10 s. Table 8. 18 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the attic space was uniformly above 600°F, with the largest temperatures near the center of the attic space centered around the ignition location and ventilation opening at around 1200°F. At the end of water application, the temperatures have cooled in the attic space, particularly in the center where the temperatures were the highest before water application. This indicates the water application where water has most likely provided surface cooling and suppression. At 30 s after water application, temperatures have continued to decrease and the only hot spot is in the front, right corner of the attic space. Conditions remain the same for the next 30 s and the fire never regrows for the rest of the experiment (See results Appendix I, Figures I.12-I.17 for full experiment attic temperatures). In contrast to the water application in Experiment 1, this water application technique most likely provided surface cooling. The water reached the surface of the burning material (the sheathing) before evaporating providing cooling and extinguishment.

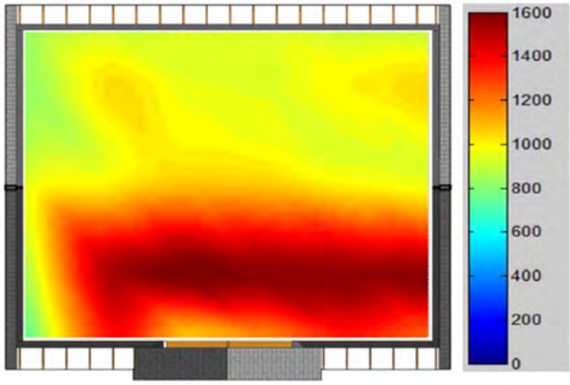
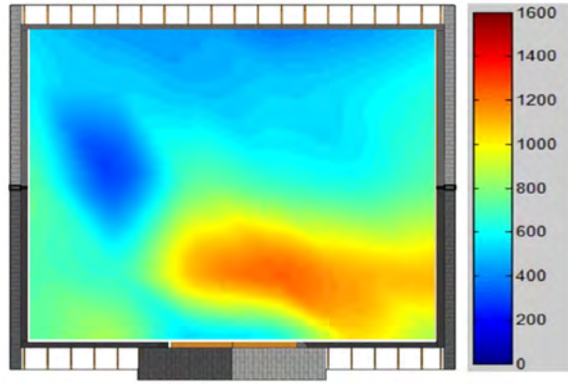
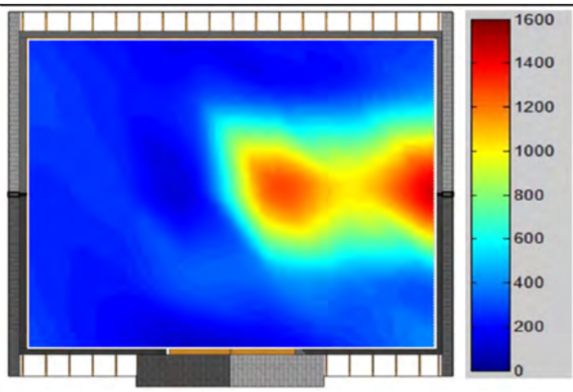
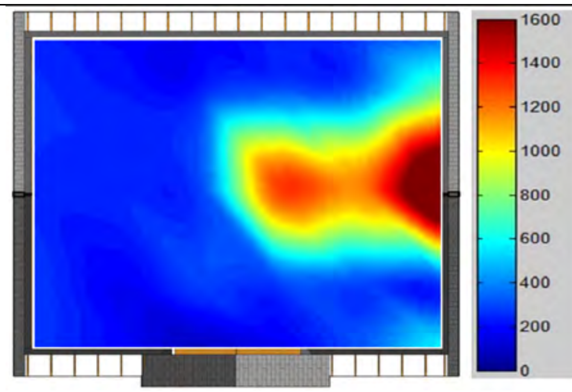
Table 8. 18: Attic Experiment 2A Heat Maps



Attic Experiment 2B: Fog stream below through large hole with attic space vented or burned through

In experiment 2B, 20:35 after ignition, water was supplied to the attic space through a large hole in the ceiling with a fog stream with 100 psi flowing 150 gpm. The water application lasted for 15 s. Table 8. 19 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the attic space was uniformly above 800°F, with the largest temperatures near the front of the attic space around 1400°F. At the end of water application, the temperatures have cooled in the attic space, with the highest temperatures still near the front of the attic space around 1200°F. At 30 s and 60 s after water application, temperatures throughout the attic space are low on the left side of the attic, but near the gable vent on the right side the temperatures are greater than 1600°F. Similar to the unvented case in experiment 2B the water goes beyond gas cooling and impacts the surfaces. The trusses in the attic prevented all surfaces from being cooled and small pockets of burning remained. The large hole below and vent above provided ideal conditions for regrowth. The fire regrew within 2 minutes on the right side of the attic (see Appendix I, Figures I.27-I.32).

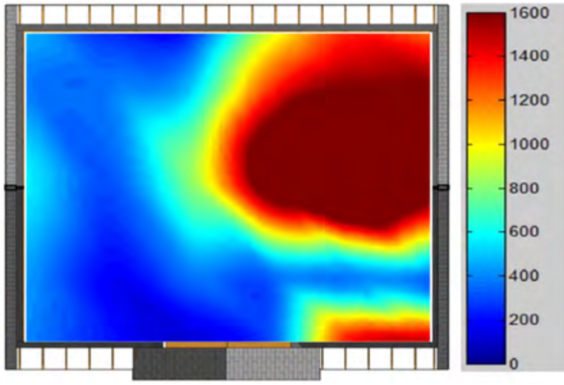
Table 8. 19: Attic Experiment 2B Fog Stream

 Start of Water	 End of Water
 30 s After Water	 60 After Water

Attic Experiment 2B: Straight stream below, large hole with attic space vented or burned through

In experiment 2B, 22:32 after ignition, water was supplied to the attic space through a large hole in the ceiling with a straight stream with 100 psi flowing 150 gpm. The water application lasted for 23 s. Table 8. 20 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the attic space was not fully involved and the fire seemed to be confined in the back right quadrant of the attic space. At the end of water application, the temperatures in the back right quadrant have significantly cooled, though temperatures above 1200°F are still observed. The fire does not recover much at 30 s and 60 s after water application, however recovers well after two minutes. Similar to the fog stream minimal surface cooling/wetting occurred as the trusses in the attic obstructed the spray and small pockets of burning remained. Regrowth occurred in 2 minutes after water application (see Appendix I, Figures I.27-I.32).

Table 8. 20: Attic Experiment 2B Heat Maps



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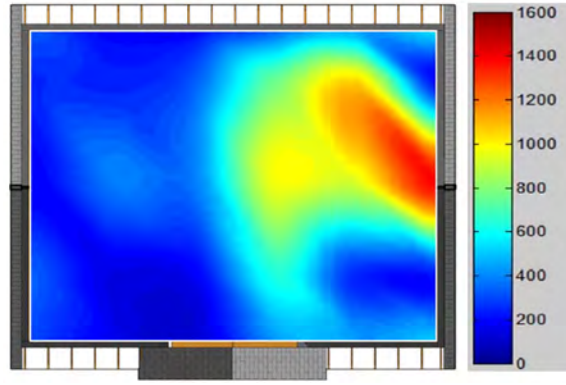
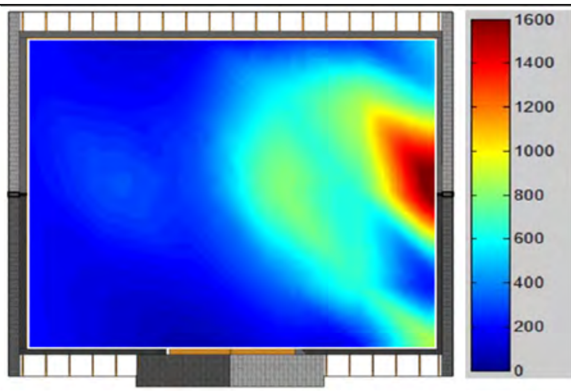
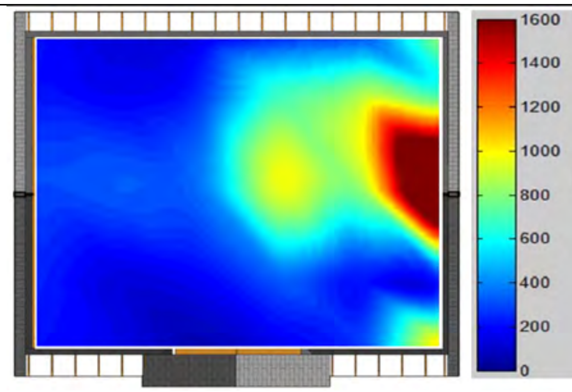


End of Water



30 s After Water

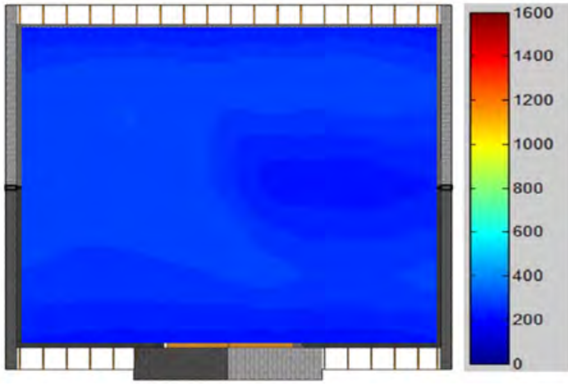


60 s After Water

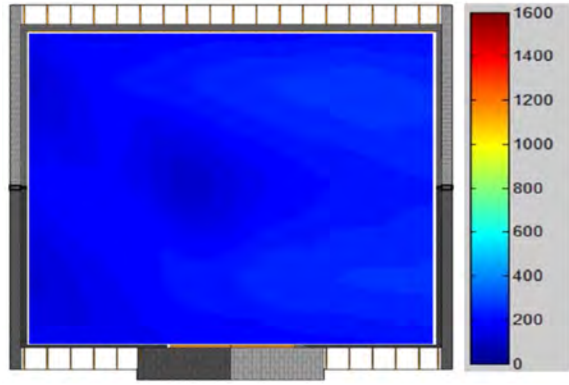
Attic Experiment 3A: Gable attack with attic space unvented

In experiment 3, 12:02 after ignition, water was supplied to the attic space through the gable vent with a straight stream with 100 psi flowing 150 gpm. The water application lasted for 20 s. Table 8. 21 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the attic space is at fairly low temperatures, with all temperatures below 400ºF. At the end of water application, the temperatures in the structure do decrease to around 200ºF. This water application was effective at cooling the attic space, but it is difficult to determine whether that is due to the low initial temperatures in the attic space or the actual effectiveness of the water application.

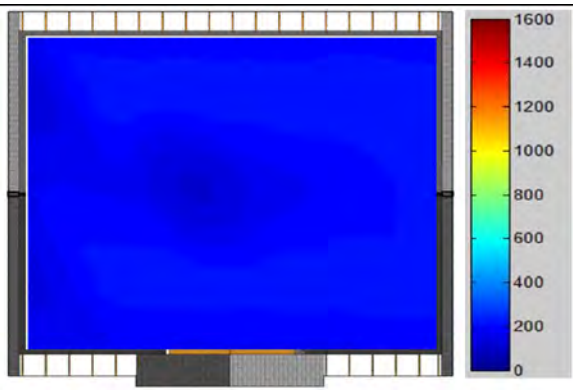
Table 8. 21: Attic Experiment 3A Heat Maps



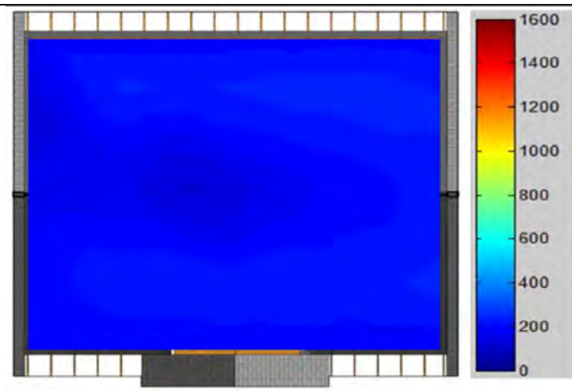
Start of Water



End of Water



30 s After Water

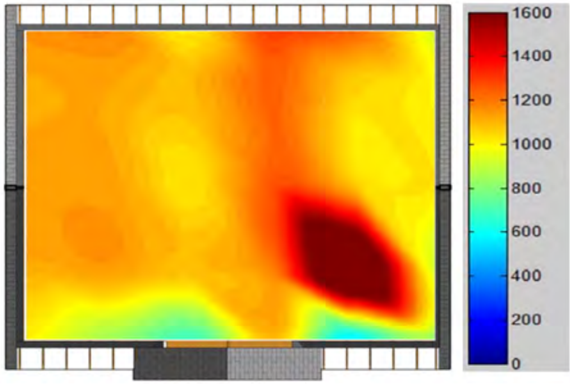
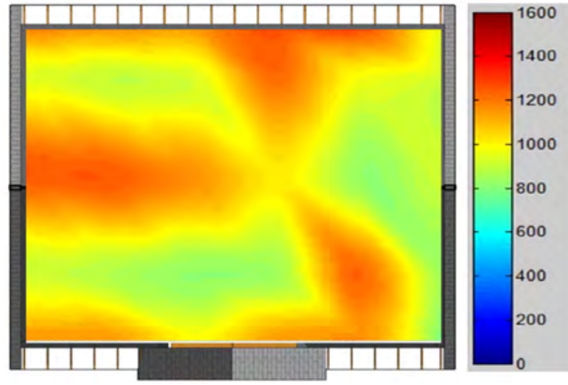
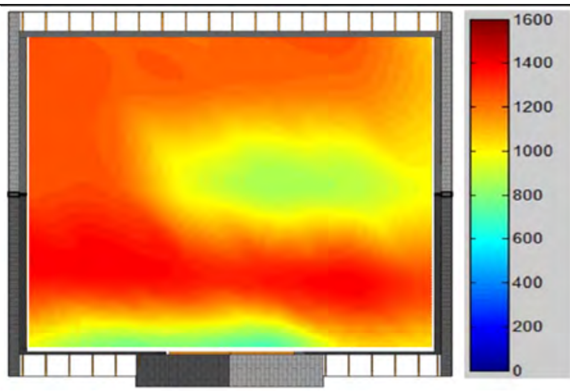
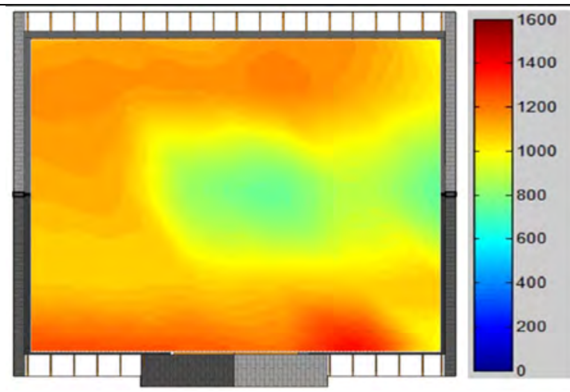


60 s After Water

Attic Experiment 3B: Gable attack with attic space vented

In experiment 3b, 22:27 after ignition, water was supplied to the attic space through the gable vent with a straight stream with 100 psi flowing 150 gpm. The water application lasted for 20 s. Table 8. 22 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the entire attic space is involved, with most temperatures above 1000°F. At the end of water application, the temperatures in the structure are pretty similar to the temperatures observed prior to water application. This water application had little impact on reducing the fire or cooling the gases in the structure. This is because of the obstructions provided by the roof trusses. As the stream entered the space it was broken up by trusses resulting changing conditions in only in one third the attic space with limited impact on the other two thirds. Regrowth occurred rapidly after application.

Table 8. 22: Attic Experiment 3A Heat Maps

 Start of Water	 End of Water
 30 s After Water	 60 s After Water

Attic Experiment 4A: Eave line attack with attic space unvented

In experiment 4A, 12:17 after ignition, water was supplied to the attic space through the eave line with a straight stream with 100 psi flowing 150 gpm. The water application lasted for 24 s. Table 8. 23 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the temperatures in the attic space are uniformly under 400ºF. At the end of water application, the temperatures in the structure decrease to being uniformly under 250ºF, except near the right gable vent where the temperature is near 400ºF. The conditions remain similar 30 s and 60 s after water application with only small temperature increases near the right gable vent. The temperatures rebound some due to the trapped heat in the unvented attic however remain under 400ºF for over 5 minutes. When ventilation is provided on the rear of the attic temperature further decrease to below 250 ºF. The eave line attack was effective at controlling the fire and improving the conditions in the attic space. The effectiveness can be attributed to the water reaching the surface of the burning material cooling and extinguishing fuel. See Appendix I, Figures I.72-I.77 for the temperature throughout the experiment.

Table 8. 23: Attic Experiment 4A Heat Maps

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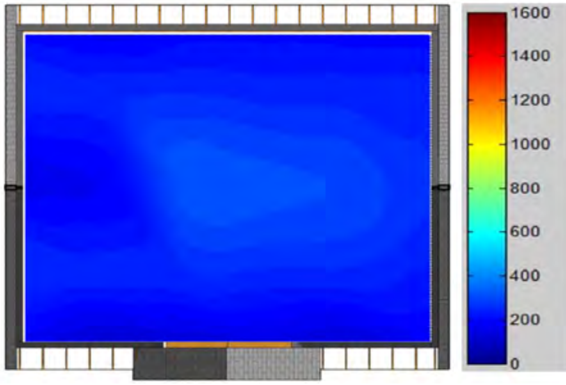
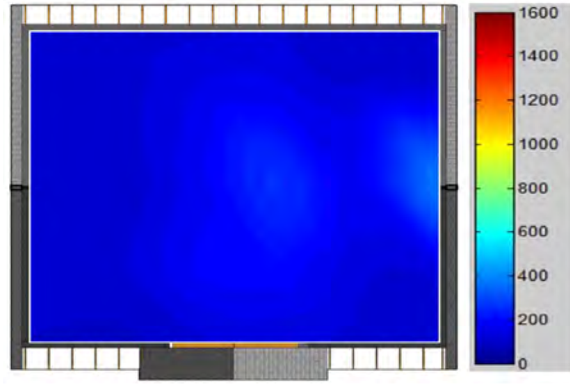
<td>

Start of Water</td>
<td>

End of Water</td>
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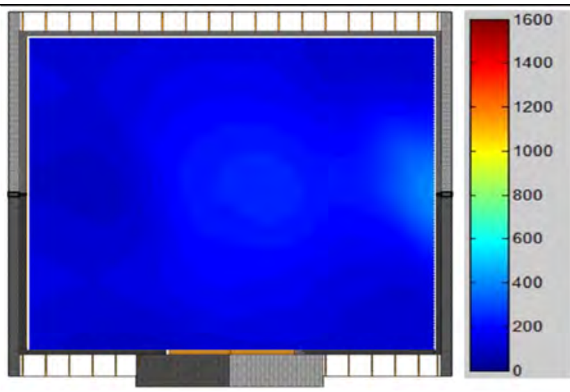
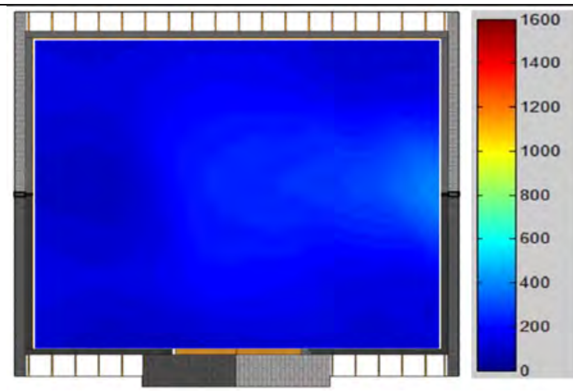
<td>

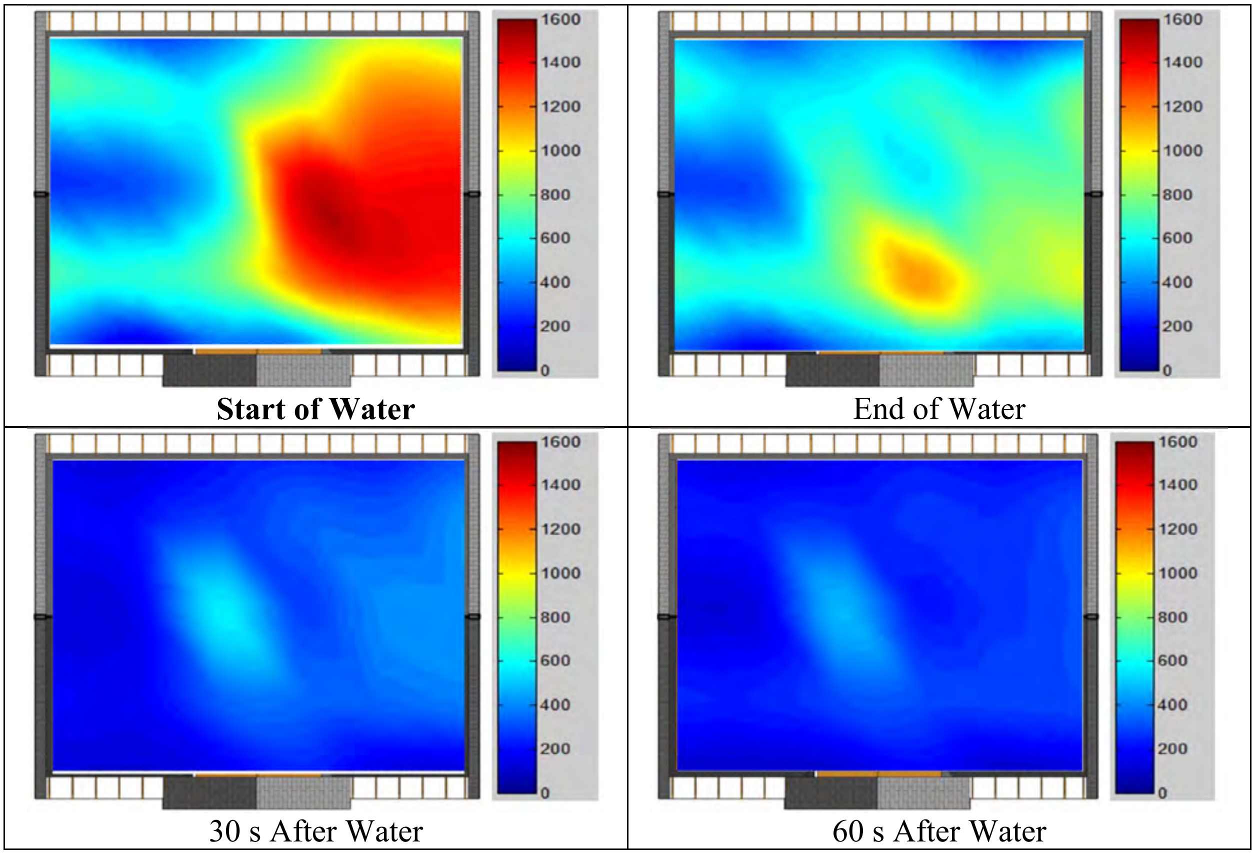
30 s After Water</td>
<td>

60 s After Water</td>
</tr>
</table>

Attic Experiment 4B: Eave line attack, vented or burned through attic.

In experiment 4B, 9:13 after ignition, water was supplied to the attic space through the eave line with a straight stream with 100 psi flowing 150 gpm. The water application lasted for 24 s. Table 8. 24 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the right side of the attic space is well involved with most the temperatures above 1000°F and the right side is much cooler with all temperatures below 800°F, most likely due to the wet sheathing from the prior experiment and the fuel source ignition near the right side of the attic. At the end of water application, the temperatures have cooled in the attic space, though there is still a large amount of area above 600°F. However, the attic space continues to cool down 30 s and 60 s after water application, with most of the attic space under 400°F at 60 s after water application. The fire never recovers. The water reached the surface of the sheathing cooling and extinguishing the majority fuel in the attic. See Appendix I.

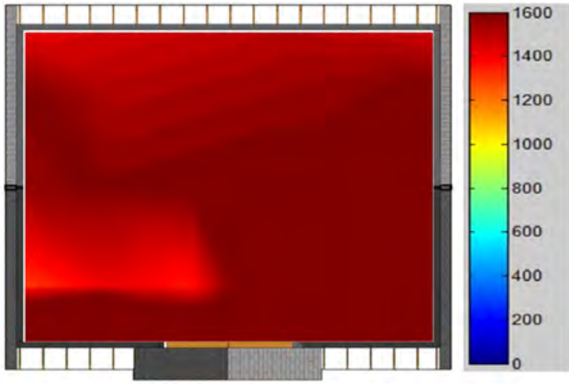
Table 8. 24: Attic Experiment 4B Heat Maps



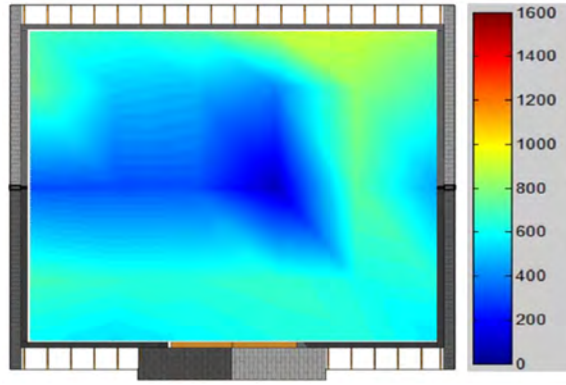
Attic Experiment 4C: Eave line attack, vented or burned through attic.

In experiment 4C, 06:36 after ignition, water was supplied to the attic space through the eave line with a straight stream with 100 psi flowing 150 gpm. The water application lasted for 27 s. Table 8. 25 shows the heat maps of the attic space before water application, at the end of water application, 30 s after water application, and 60 s after water application. From the heat maps, it is evident that prior to water application, the attic space is well involved with the temperatures above 1400°F. At the end of water application, the temperatures have cooled in the attic space, though there is still a large amount of area above 500°F. The attic space continues to cool down 30 s and 60 s after water application, with most of the attic space under 400°F at 60 s after water application. The fire never recovers. The water reached the surface of the sheathing cooling and extinguishing the majority fuel in the attic.

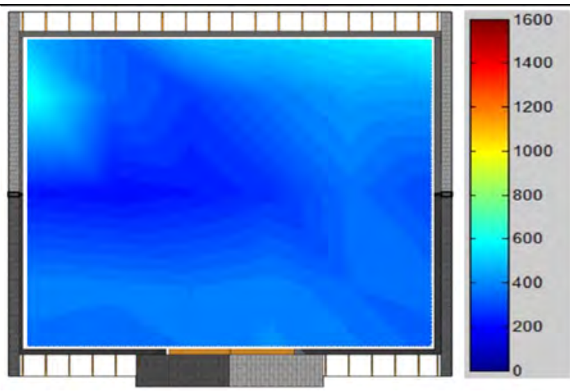
Table 8. 25: Attic Experiment 4C Heat Maps



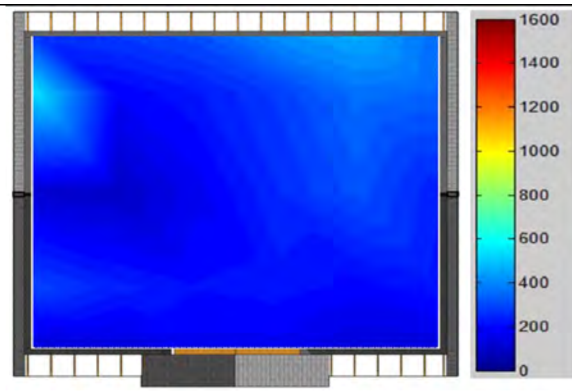
Start of Water



End of Water



30 s After Water



60 s After Water

9. Knee Wall & Attic Field Experiments

Three experiments were conducted in vacant structures scheduled for demolition to examine attic fires with knee wall construction features. Many firefighters have been injured or killed in these type of structures. The purpose of these experiments was to begin to understand the fire dynamics associated with this construction type and to examine different tactics to mitigate the hazards posed to firefighters.

9.1. Experimental Setup

Three separate experiments were conducted in Milwaukee, WI in partnership with the Milwaukee Fire Department. Three vacant structures scheduled for demolition were acquired from the city of Milwaukee for use in the testing (Figure 9. 1 through Figure 9. 3). The structures were located on North 9th street, West Burleigh St, and North 25th St. Detailed floor plans for each structure can be found in Appendix D. The experiments were designed to test different types of firefighting tactics on concealed knee wall & attic fires. The structures were instrumented to gather data on the ways in which fire spreads to and within the knee wall & attic voids during a structure fire. Various firefighting tactics were employed during each experiment to evaluate their effect on fire dynamics of knee wall & attic void space fires. Tactics implemented were exterior attack, simulated interior attack, eave attack and master stream attack. Measurements of temperature, pressure and heat flux (9th St. only), video and thermal imaging were also recorded for the experiments with the intent of quantifying the fire dynamics along with the effectiveness of the different firefighting tactics.


Figure 9. 1: North 9th St


Figure 9. 2: West Burleigh St


Figure 9. 3: North 25th St

9.2. Instrumentation

<u>Field Experiment 1 - North 9th St</u>

Instrumentation for North 9th St. includes measurements of temperature, pressure, and heat flux. Visualization of the experiment was recorded using high definition video cameras and thermal imaging. The location of the sensors and cameras are shown in Figure 9. 4 through Figure 9. 6 (more detailed drawings are in Appendix F, Figures F.1-F.4). Temperatures were measured in the half-story attic space, in the peak of the attic, and in the second story of the structure. The half-story attic space has 3 rooms and a bathroom. Thermocouple trees measuring temperature at heights of 0.5 ft., 2.5 ft., 4.5 ft., and 5.5 ft. above the floor in the 7 ft. tall space which were centered in the bedroom, center room, entrance area, and the stairwell of the half attic space. Temperatures were measured 1 ft. above the floor in both knee walls in knee wall 'B' and in knee wall 'D'. In knee wall B, temperatures were measured at seven different equally spaced locations spanning the length of the knee wall at intervals of 4 ft. 2 in. In knee wall 'D', temperatures were measured at nine different equally spaced locations spanning the length of the knee wall at intervals of 3.5 ft. In the peak of the attic, temperatures were measured 1 ft. above the floor at nine different equally spaced locations spanning the length of the peak at intervals of 3.5 ft. On the second story of the structure, thermocouple trees measuring temperatures at 1 ft., 3 ft., 5 ft., and 7 ft. above the floor in the 8 ft. tall space were centered in the bedroom and in the entrance to the stairwell. Additionally, temperatures were measured at six locations (three interior and three exterior) along the eave line over the second story bedroom window.

Six pressure measurements were made in the half story attic space and two were measured in the peak of the attic. Pressures were measured on each end of knee wall 'B' and 'D' 1 ft. above the floor, at each end of the peak of the attic 1 ft. above the half attic ceiling, and in the entrance area of the half story and the bedroom of the half story 1 ft. off the floor of the half attic. Heat flux was measured with a view horizontally and vertical from the center of the room at two in the entrance area of the half story and in the bedroom of the half story 3 ft. above the floor of the half attic space.

High definition cameras recorded video in knee wall 'B', the entrance area of the half story, the bedroom of the half story, and in the peak of the attic. Thermal imaging was recorded at the entrance to the attic viewing the knee wall. Additional high definition video and thermal imaging video of the exterior of the structure was recorded at the 'AB' corner. Additionally, a high definition video camera recorded the 'C' side of the structure.

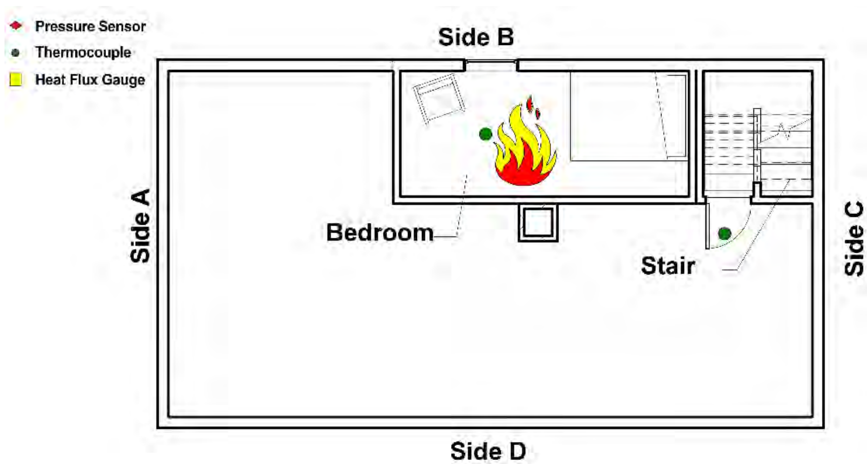


Figure 9. 4: 9th St. Second Floor Instrumentation

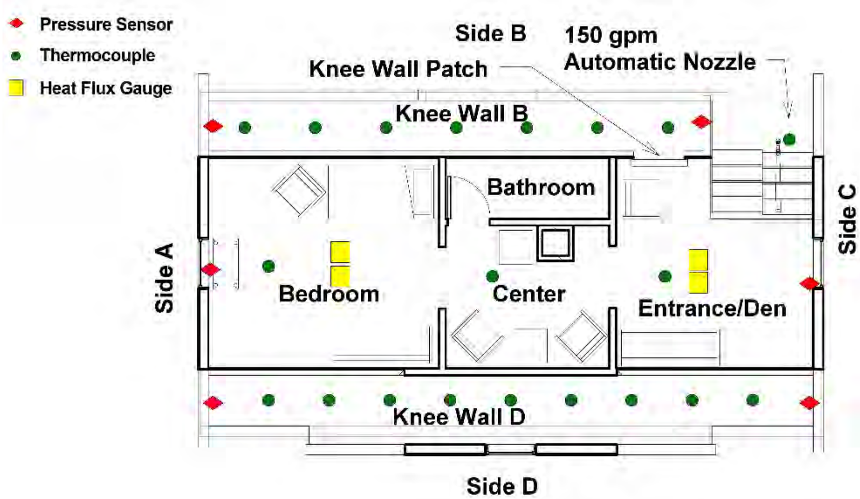


Figure 9. 5: 9th St. Second Floor Instrumentation

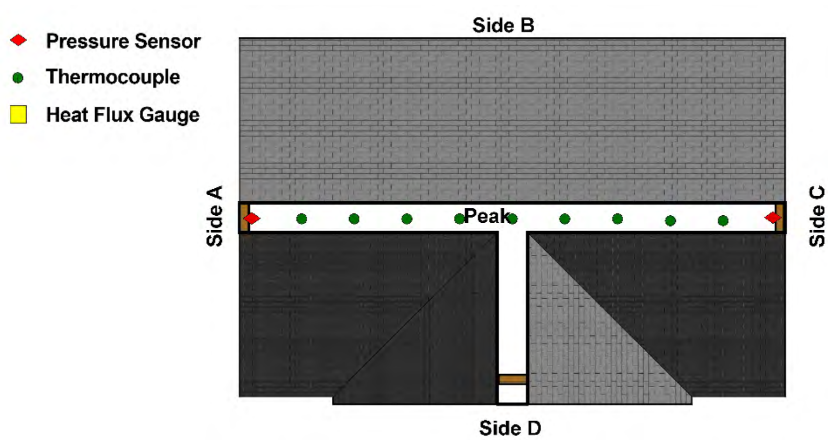


Figure 9. 6: 9th St. Roof Instrumentation

Field Experiment 2 - West Burleigh St

Instrumentation for West Burleigh St. includes measurements of temperature and pressure. Visualization of the experiment was recorded using high definition video cameras and thermal imaging. The location of the sensors and cameras are shown in Figure 9. 7 through Figure 9. 9 (more detailed drawings are in Appendix D Figures F.5-F.8.)

Temperatures were measured in the half-story attic space, in the peak of the attic, and in the second story of the structure. The half-story attic space has 3 rooms and a bathroom. Thermocouple trees measuring temperature at heights of 0.5 ft., 2.5 ft., 4.5 ft., and 5.5 ft. above the floor in the 7 ft. tall space were centered in the bedroom, center room, entrance area, and the stairwell of the half attic space. Temperatures were measured 1 ft. above the floor in both knee walls. In knee wall 'B', temperatures were measured at nine different equally spaced locations spanning the length of the knee wall at intervals of 4 Ft 8 inches. In knee wall 'D', temperatures were measured at seven different equally spaced locations spanning the length of the knee wall at intervals of 5 ft. In the peak of the attic, temperatures were measured 1 ft. above the floor at nine different equally spaced locations spanning the length of the peak 4 Ft 8 Inches. On second story of the structure thermocouple trees measuring temperatures at 1 ft., 3 ft., 5 ft., and 7 ft. above the floor in the 8 ft. tall space were centered in the bedroom and in the entrance to the stairwell. Additionally, temperatures were measured at six locations (three interior and three exterior) along the eave line over the second story bedroom window.

Six pressure measurements were made in the half story attic space and two were measured in the peak of the attic. Pressures were measured on each end of knee wall 'B' and 'D' 1 ft. above the floor, at each end of the peak of the attic 1 ft. above the half attic ceiling, and in the entrance area of the half story and the bedroom of the half story 1 ft. off the floor of the half attic.

High definition cameras recorded video in knee wall 'B', the entrance area of the half story, the bedroom of the half story, and in bedroom, which was the fire room on the second story. Thermal imaging was recorded at the entrance to the attic viewing the center room. High definition video and thermal imaging video of the exterior of the structure was recorded at the 'AB' corner. Additionally, a high definition video camera recorded the 'C' side of the structure.

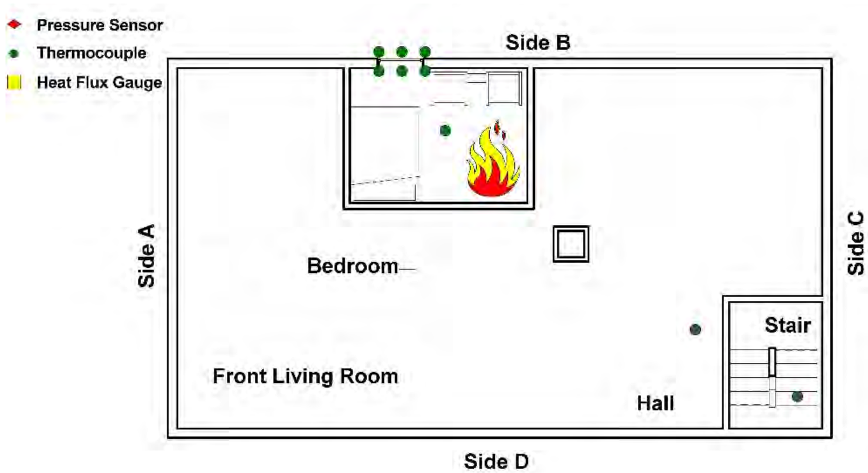


Figure 9. 7: Burleigh St. Second Floor Instrumentation

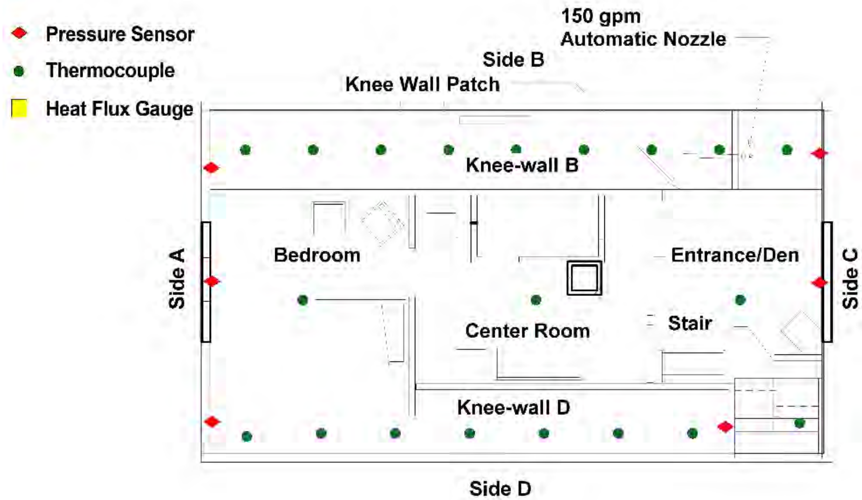


Figure 9. 8: Burleigh St. Attic Instrumentation

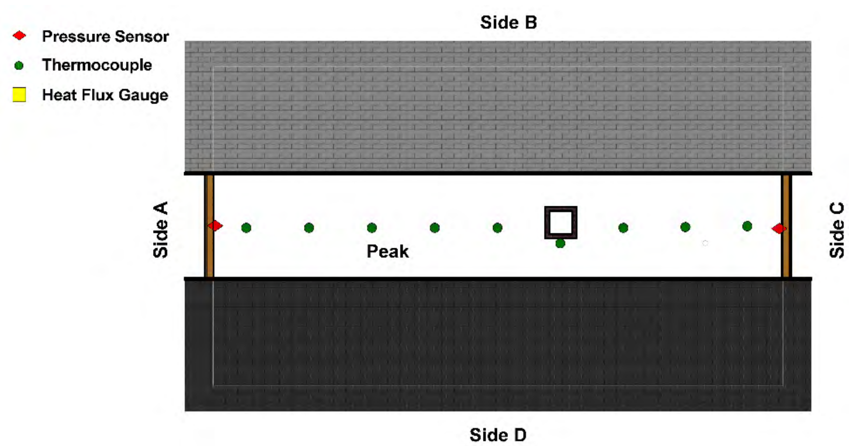


Figure 9. 9: Burleigh St. Roof Instrumentation

<u>Experiment 3 - North 25th St</u>

Instrumentation for North 25th St. includes measurements of temperature and pressure. Visualization of the experiment was recorded using high definition video cameras and thermal imaging. The location of the sensors are shown in Figure 9. 10 and Figure 9. 11 (more detailed drawings are in Appendix F, Figures F.9-F.11).

Temperatures were measured in the attic space, in the peak of the attic, in the joist bays, and along the exterior of the structure. The attic space has 5 rooms and a bathroom. Thermocouple trees measuring temperature at heights of 1 ft., 3 ft., 5 ft., and 7 ft. above the floor were centered in the bedroom 1, bedroom 2, bedroom 3, the den, the entrance area, and the stairwell. In the peak of the attic, temperatures were measured 1 ft. above the floor at nine different equally spaced locations spanning the length of the peak at intervals of 4 ft. A thermocouple was placed in the joist bays on the 'B' side of the structure in the second, fourth, and sixth joist bay from the 'C' Side. Additionally, temperatures were measured at six locations along the exterior of the structure starting at the height of the ignition source and every 2.5 ft. up the exterior wall.

Two pressure measurements were made in the attic space and two measurements were made in the peak of the attic. Pressures were measured on each end of the peak of the attic 1 ft. above the floor, and in the entrance area and bedroom 1 of the attic space 1 ft. above the floor.

High definition cameras recorded video in bedroom 1, bedroom 2, bedroom 3, and the den of the attic space. Thermal imaging was recorded in bedroom 1 of the attic space. High definition video and thermal imaging video of the exterior of the structure was recorded at the BC corner. Additionally, a high definition video camera recorded the exterior of the structure at the AB corner of the structure.

Figure 9. 10: 25th St. Attic Instrumentation

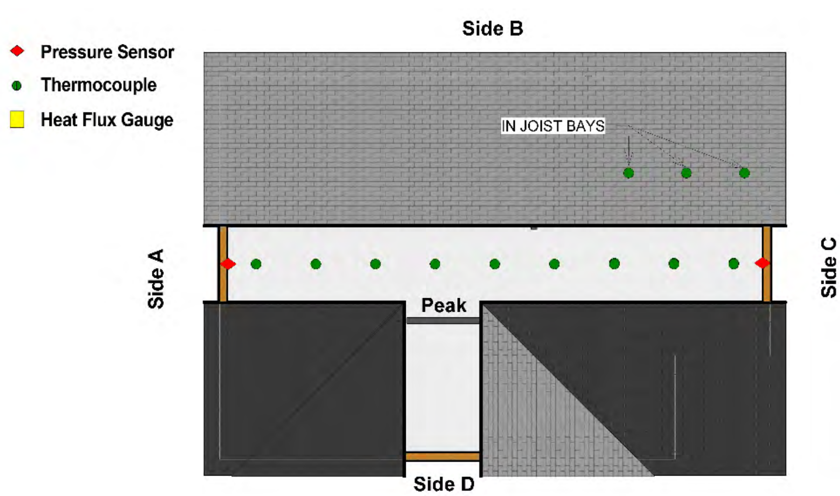


Figure 9. 11: 25th St. Attic Instrumentation

9.3. Knee Wall & Attic Field Experiment Description

<u>Experiment 1 - North 9th Street</u>

The fuel load for the ignition room was a stuffed chair, queen size bed, dresser and stuffed animals. Images of the fuel load can be found in Figure 9. 13. The finished attic space was configured with furniture as see in Figure 9.16 and Figure 9. 167. Prior to ignition the second story bedroom window was removed along with the plaster and lath from three stud bays to provide fire spread directly to the knee wall (See Figure 9. 14). The main purpose was to get the fire into the knee wall from below without focusing on how it got there so the stud bays were opened to speed up that fire spread. The bedroom was sealed from the remainder of the 2nd floor with drywall to prevent extension into the second floor. Additionally a removable patch was cut into knee wall B to simulate fire department breaching the wall (See Figure 9. 15). Ignition was provided by an electric match and occurred on a stuffed chair in the second story bedroom. During the experiment, all exterior suppression with the exception of the deck gun utilized a 150gpm combination nozzle supplied with 100 psi.


Figure 9. 12: Model of experiment layout

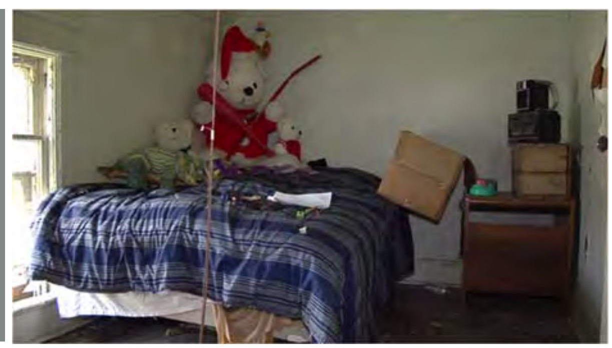


Figure 9. 13: Field Exp. 1 Attic Fuel Load


Figure 9. 14: Exp. 1 Ignition Room Wall

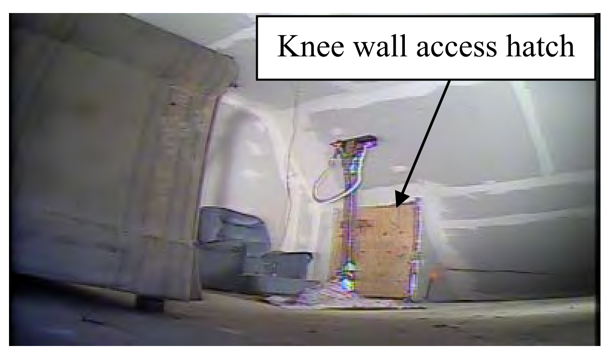


Figure 9. 15: Exp. 1 Knee Wall Access Hatch

Ignition occurs at time 00:00 (mm:ss). The fire was allowed to grow and reach steady state and at 24:05, 8s of water was supplied into the ignition room from an exterior ground attack. At

25:08, the door of the attic space was opened, and then at 25:41 and 26:30, the ‘C’ side and ‘A’ side windows were opened, respectively. The knee wall patch was opened at 27:05. Conditions were monitored for two minutes followed by 7 s of exterior water applied to the fire room at 29:00. Conditions were monitored further with exterior water applied to the fire room for 10 s at 35:58. At 39:10, the nozzle mounted in the stairwell to simulate an interior attack was turned on for 10s. At 42:36 water was applied for 30 s to all the area where there was visible fire, i.e. the exterior siding, the roof, the fire room, etc. At 51:40, the deck gun was applied to side A of the structure. Conditions were monitored while the deck gun suppressed the side ‘A’ fire. At 52:36 the Side B visible fire was suppressed using the exterior line at which time the experiment was turned over to Milwaukee Fire Department for complete suppression. Table 9. 2 below lists all actions and at what time they occurred, Table 9. 1 provides the images of all 8 camera views at the times listed.

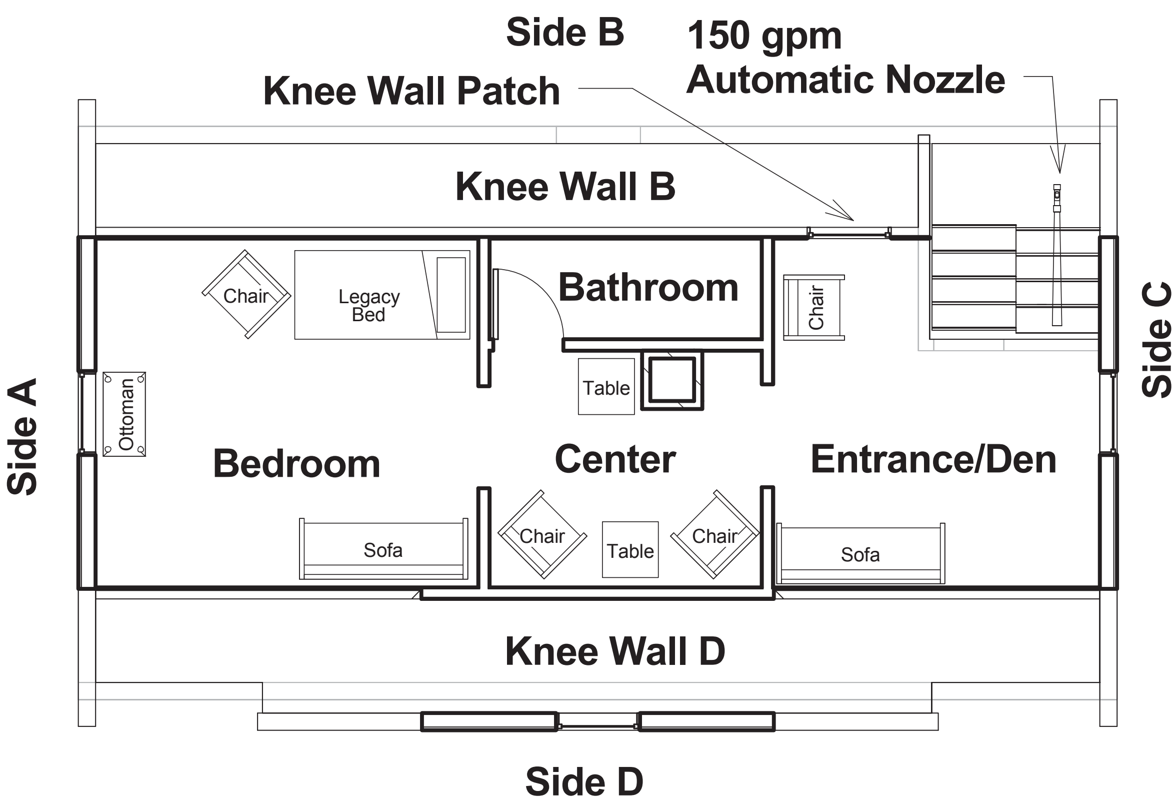


Figure 9. 16: Field Experiment 1 Attic Furniture Layout

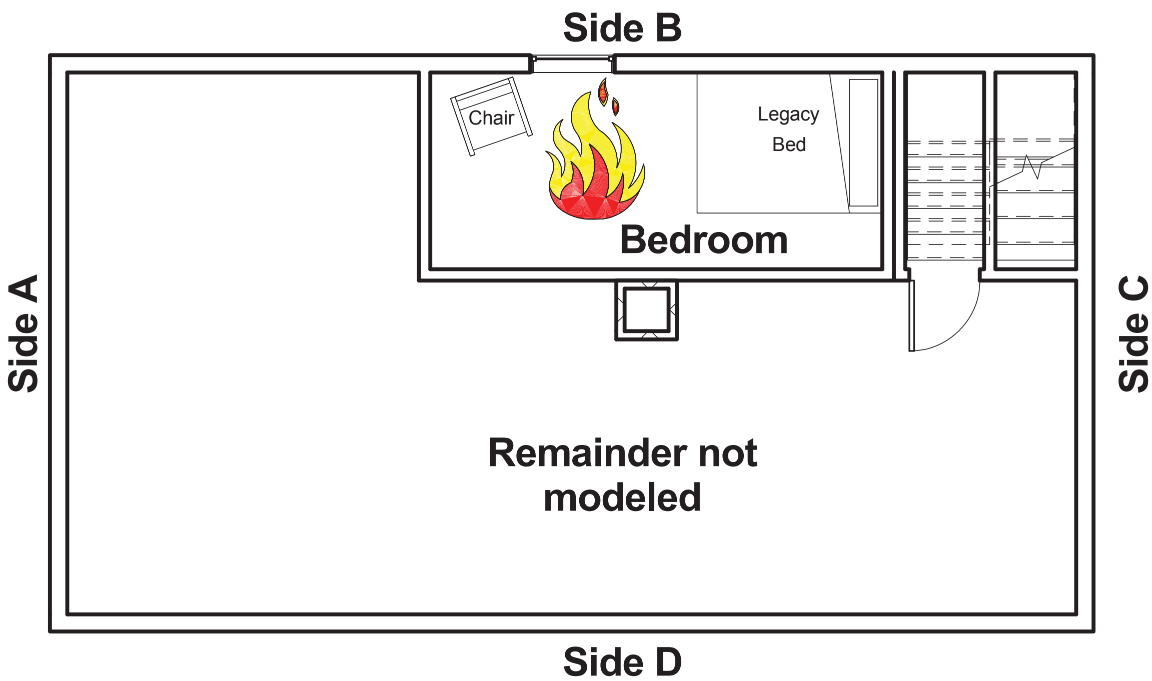
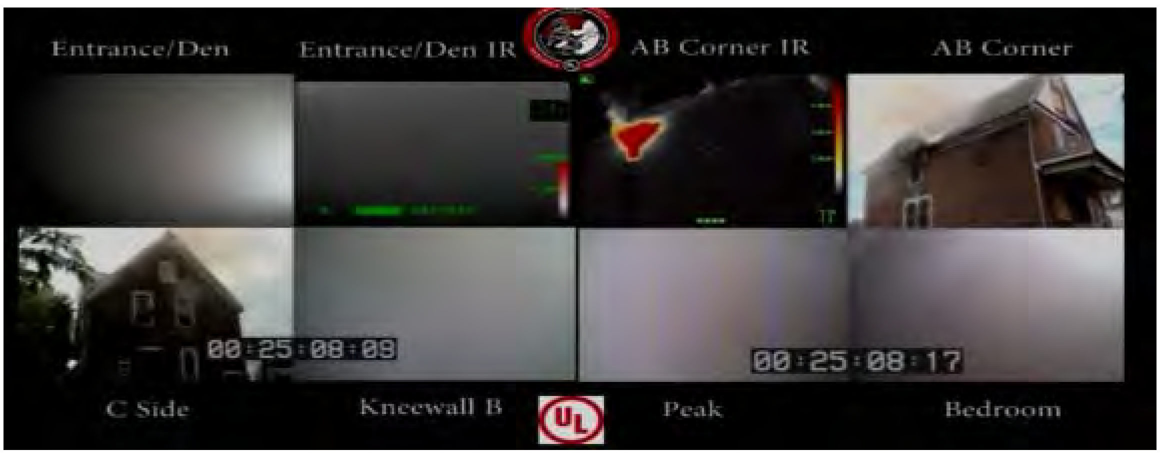


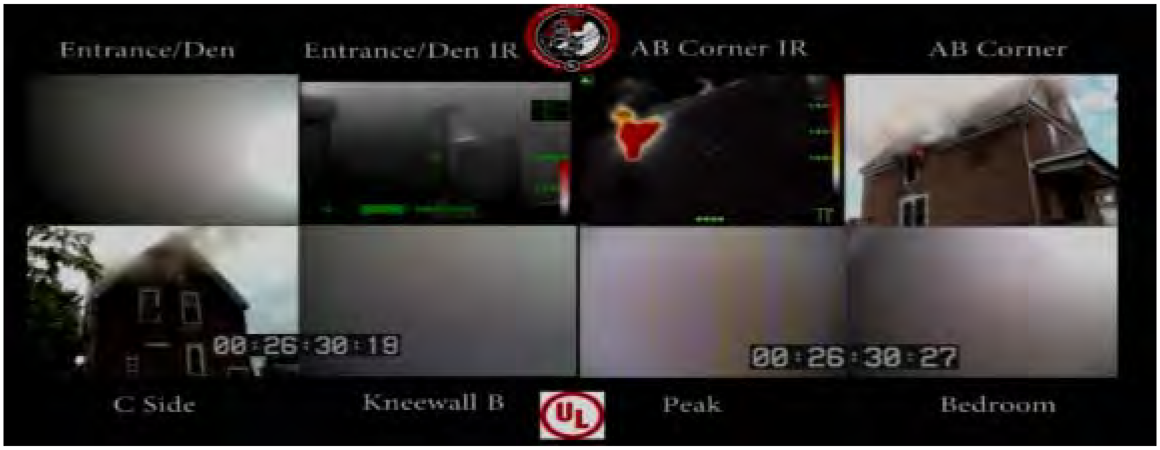
Figure 9. 17: Field Experiment 1 Ignition Room Furniture Layout

Table 9. 1: Field Experiment 1 Chronological Images


Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:24:05:10
C Side
Kneewall B
Peak
Bedroom

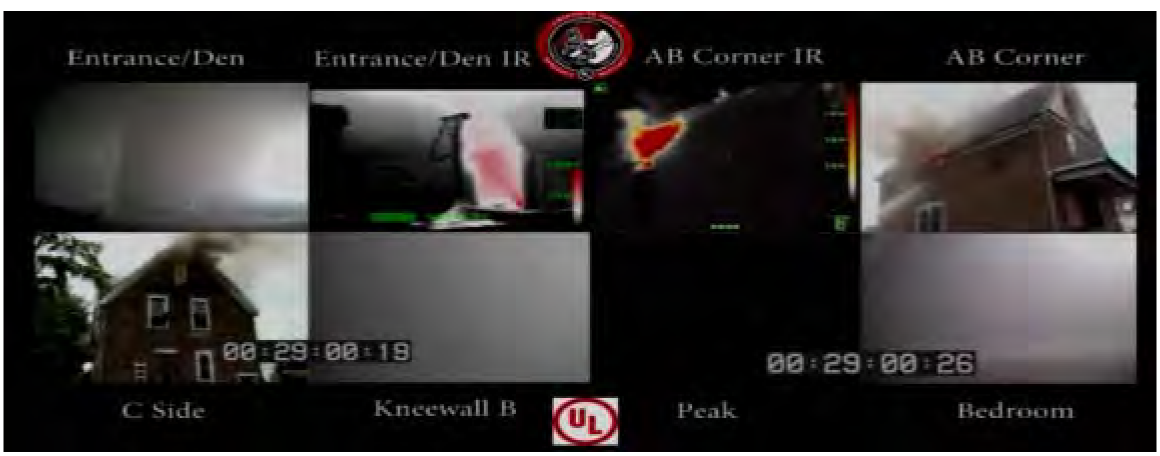

Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:25:08:09
00:25:08:17
C Side
Kneewall B
Peak
Bedroom


Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:25:42:05
C Side
Kneewall B
Peak
Bedroom

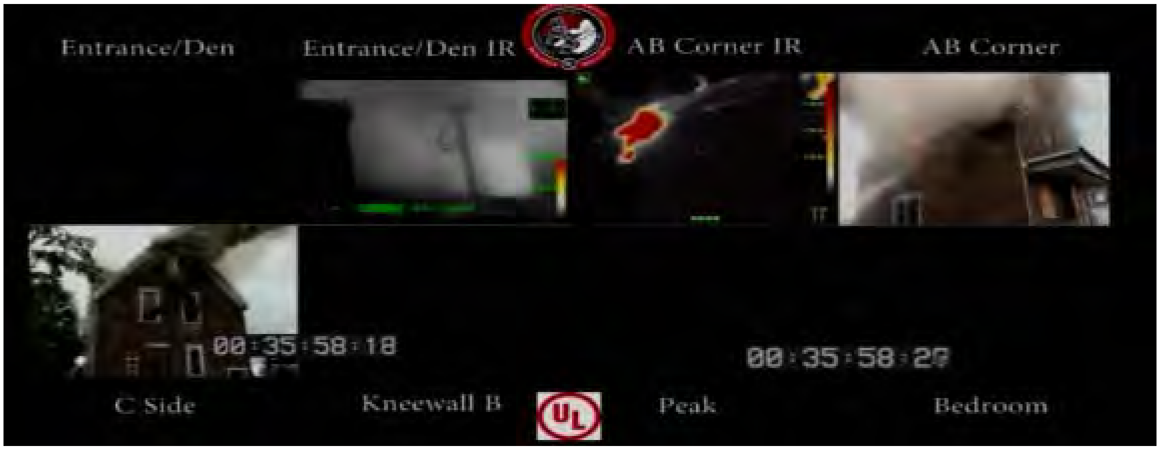


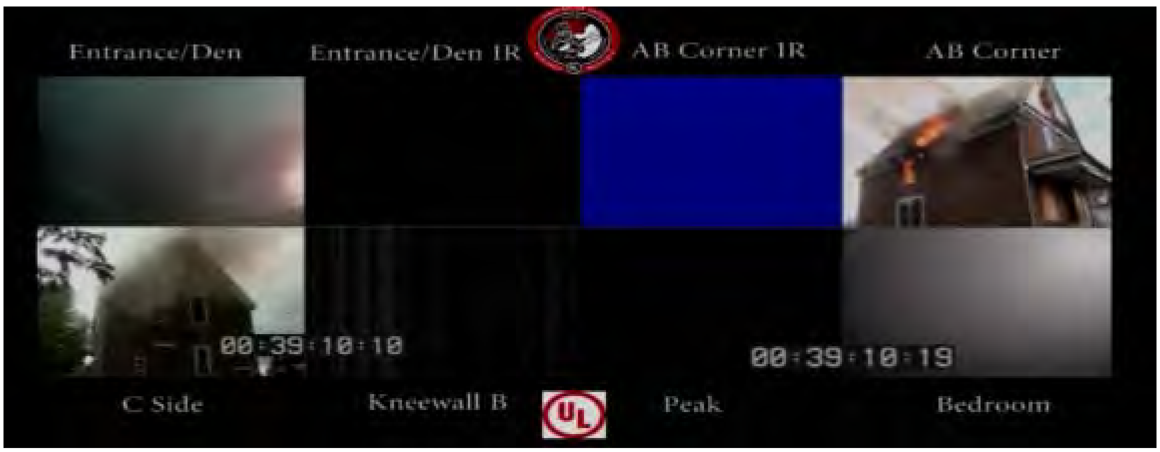
Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:26:30:19
00:26:30:27
C Side
Kneewall B
Peak
Bedroom

Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:27:05:22
00:27:06:06
C Side
Kneewall B
Peak
Bedroom

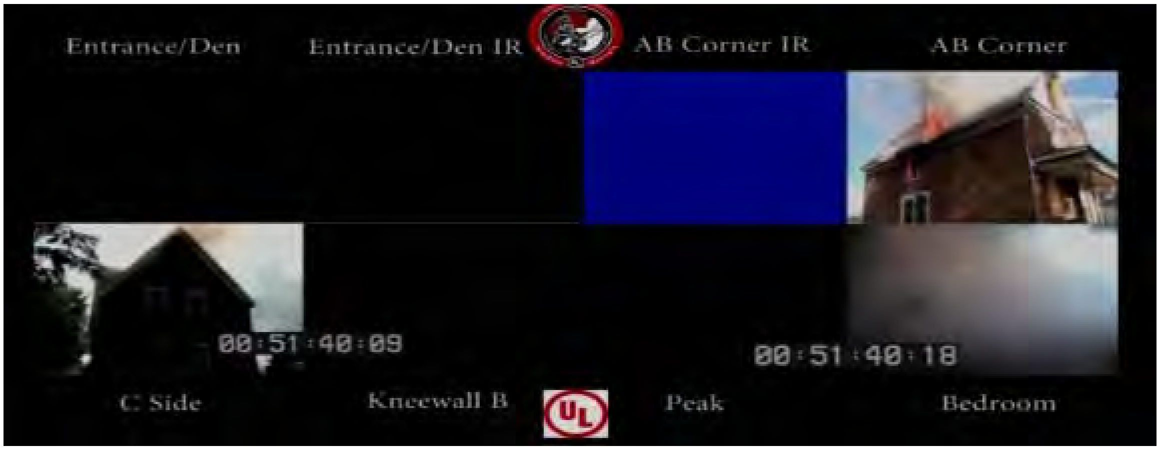


Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:29:00:19
00:29:00:26
C Side
Kneewall B
Peak
Bedroom


Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:35:58:18
00:35:58:20
C Side
Kneewall B
Peak
Bedroom


Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:39:10:10
00:39:10:19
C Side
Kneewall B
Peak
Bedroom


Entrance/Den
Entrance/Den IR
AB Corner IR
AB Corner
00:42:05:15
00:42:05:24
C Side
Kneewall B
Peak
Bedroom



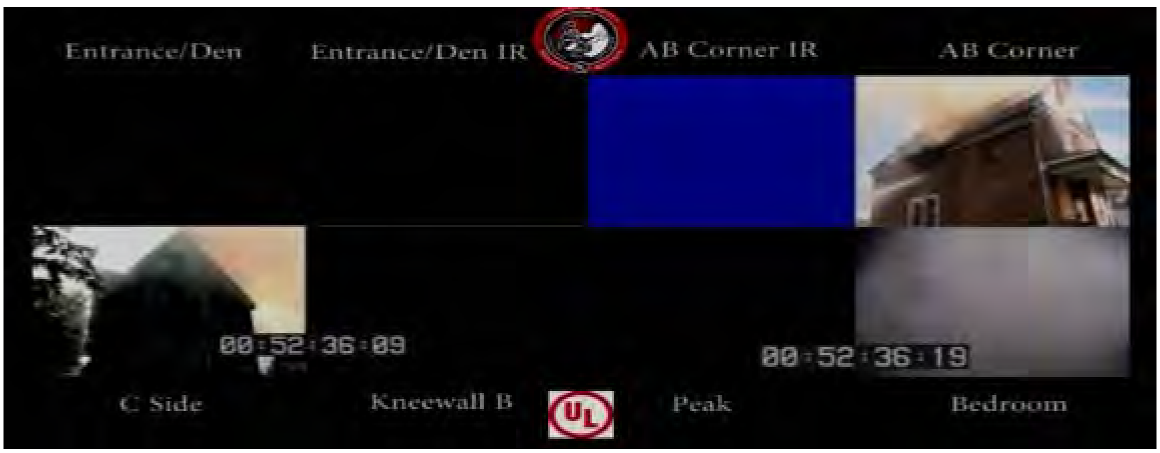


Table 9. 2: Field Experiment 1 Timeline

Time (mm:ss)	Description
00:00	Ignition
24:05	8 s of water into ignition room
25:08	Attic door opened
25:41	C side window opened
26:30	A side window opened
27:05	Knee wall patch opened
29:00	7 s of water into ignition room
35:58	10 s of water into ignition room
39:10	Interior stairwell nozzle turned on 10s
42:05	30 s of water applied to all areas where there was visible fire
51:40	Water from deck gun applied to side A

52:36	All Exterior fire suppressed from side B
55:00	Experiment turned over to Milwaukee Fire Depart for Complete Suppression

Experiment 2 - West Burleigh St

The fuel load in each of the rooms of the structure can be found in Figure 9. 22 and Figure 9. 23. Prior to ignition the second floor bedroom ceiling was removed in a 3in. x 48in. section to permit direct fire spread to the knee wall above (See Figure 9. 20). Additionally a nozzle was installed in knee wall B and a removable patch was cut into knee wall B to simulate fire department breaching the wall (See Figure 9. 21). The ignition room was isolated with drywall to prevent extension into the remainder of the second floor. Ignition was provided by an electric match and occurred on the right stuffed chair in the second story bedroom. During the experiment, all exterior suppression with the exception of the deck gun utilized a 150gpm combination nozzle supplied with 100 psi.

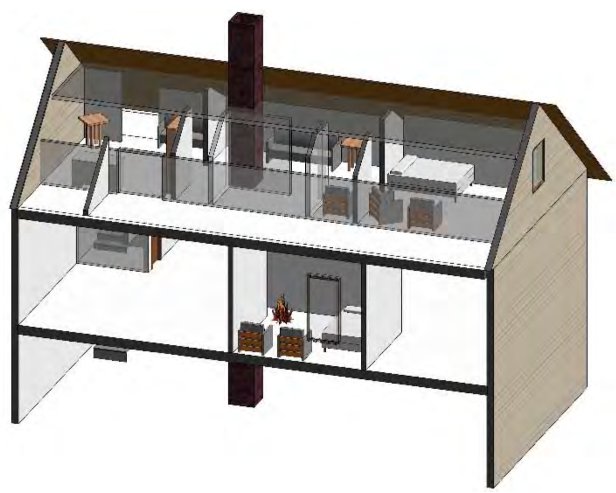


Figure 9. 18: Field Exp. 2 3D model

Figure 9. 19: Field Exp. 2 Ignition room

Figure 9. 20: Field Exp. 2 Ignition Room Wall

Figure 9. 21: Field Exp. 2 Knee Wall Access Hatch

Ignition occurs at time 00:00 (mm:ss). The fire is then allowed to grow for several minutes and reach flashover in the second story bedroom. At 09:02, water is supplied water was supplied into the ignition room from an exterior ground attack. Immediately following at 09:25 an eave attack is performed from the 'AB' corner to the 'BC' corner. The fire is allowed to grow again, and at 12:00 the attic door is opened followed at 12:30 by the 'A' side and 'C' side attic windows simultaneously. At 12:50 the knee wall B access hatch is removed. Conditions are monitored for one minute followed by an exterior attack into the second story bedroom window at 13:50. At 14:06, fire growing on the exterior siding of the B side of the structure is suppressed. The B side eaves are pulled, moving in the direction of the C side, at 17:25. A ground attack into the second story bedroom window begins at 18:45. The attack continues and moves to the fire on the exterior siding before eventually targeting the eave line on the B side. At 19:00 the experiment is brought to an end and the fire is turned over to the Milwaukee Fire Department for complete suppression. Table 9. 4 lists all actions and when they occurred. Table 9. 3 provides a snapshot of all 8 camera views for each action in the Table 9. 4.

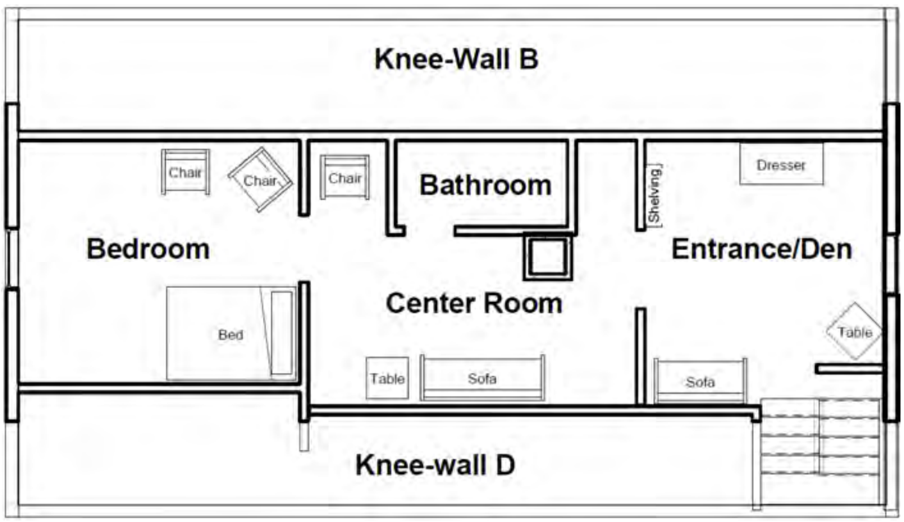


Figure 9. 22: Field Experiment 2 Attic Furniture Layout

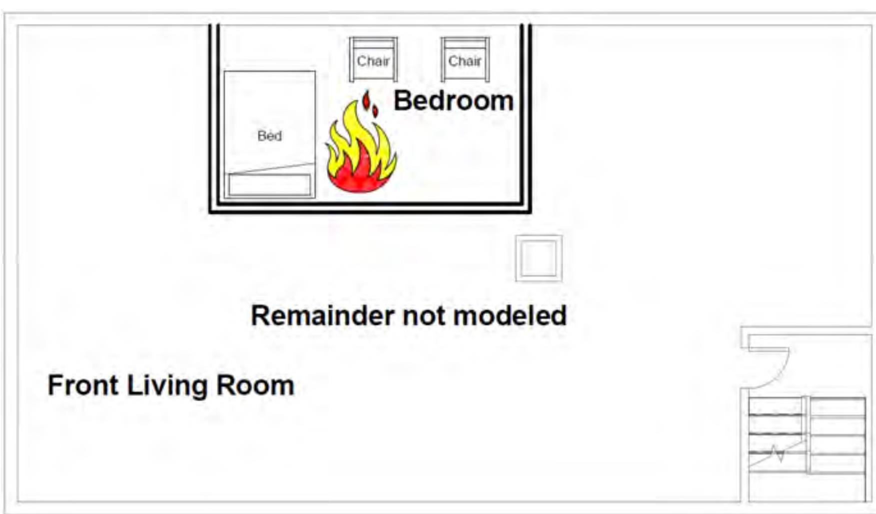


Figure 9. 23: Field Experiment 2 Ignition Room Furniture Layout

Table 9. 3: Field Experiment 2 Chronological Images

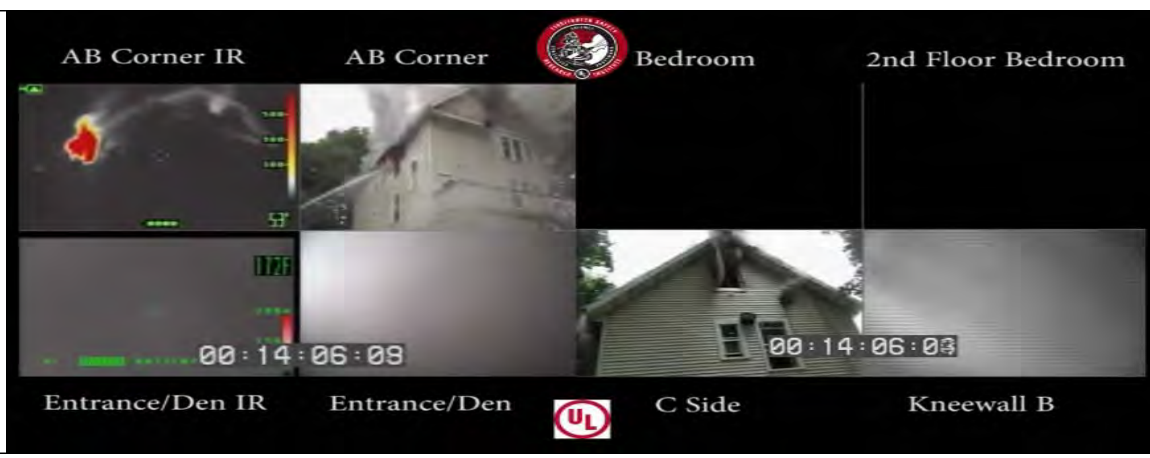

AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:12:00:05
00:12:00:28
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:12:30:22
00:12:30:13
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:12:50:18
00:12:50:12
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:13:35:25
00:13:35:20
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:13:46:23
00:13:46:18
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:14:06:08
00:14:06:03
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:17:25:20
00:17:25:16
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:18:45:23
00:18:45:18
Entrance/Den IR
Entrance/Den
C Side
Kneewall B


AB Corner IR
AB Corner
Bedroom
2nd Floor Bedroom
00:19:00:25
00:19:00:20
Entrance/Den IR
Entrance/Den
C Side
Kneewall B

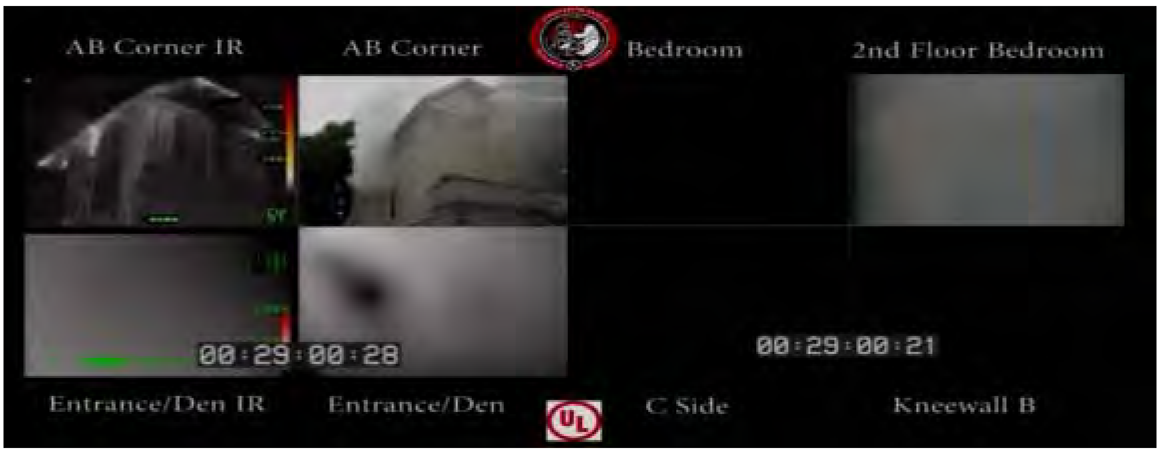


Table 9. 4: Field Experiment 2 Timeline

Time (mm:ss)	Description
00:00	Ignition at 00:00
09:02	Exterior ground attack into ignition room
09:25	Eave attack AB Corner to BC Corner
12:00	Attic Door Opened
12:30	A side and C side attic windows are opened
12:50	Knee wall access hatch opened
13:35	Knee wall Nozzle On
13:46	Exterior attack into fire room window
14:06	Exterior attack Side B Siding
17:25	Eaves pulled on B side
18:45	Exterior ground attack into fire room window and then exterior eave line attack
19:00	Experiment turned over to Milwaukee FD for suppression
26:55	Tower attack added into A side attic window
29:00	End Data Acquisition

Experiment 3 - North 25th Street

The fuel load in each of the rooms of the structure can be found in Figure 9. 24. Prior to ignition a 4ft. x 4ft. vertical vent was cut near the peak of the roof on the B side towards the rear to simulate vertical ventilation (See Figure 9. 25). The vent was sealed with a removable cover to simulate operations during the experiment. Solid eaves were removed to provide direct access to the joist bays. All insulation in the joist bays was removed to provide direct access to the peak void space. The first ignition was provided by an electric match and occurred in a trash can pressed against the exterior of the B side of the structure (See Figure 9. 26). The trash can, a 64 gallon wheeled trash bin consistent with those used in the City of Milwaukee, was filled with construction debris to the top of the can. During the experiment, all exterior suppression with the exception of the deck gun utilized a 150gpm combination nozzle supplied with 100 psi.

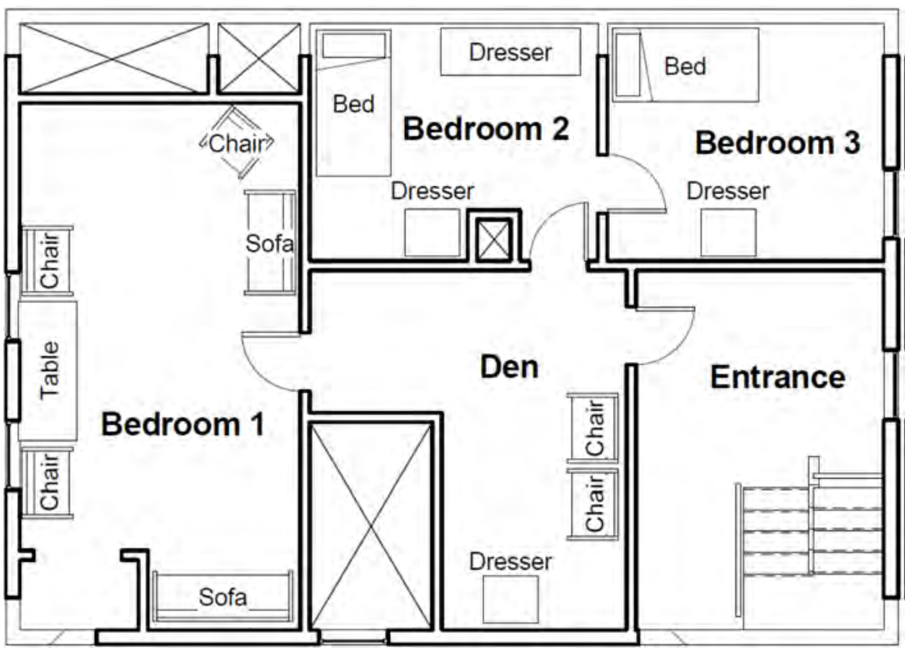


Figure 9. 24: Field Experiment 3 Attic Furniture Layout

Figure 9. 25: Field Experiment 3 Removable Vertical Vent

Figure 9. 26: Field Experiment 3 Ignition Configuration

The first ignition occurs at time 00:00 (mm:ss). The fire is then allowed to grow up the exterior of the structure, into the peak of the attic until the peak of the attic reached steady state. At 09:30, an exterior ground attack along the eave line occurs. The eave line attack does an effective job of suppressing the fire, and in order for the fire to begin to grow again in the peak of the attic, a second ignition along the exterior of the B side of the structure is required. This ignition again occurred in a trash can, and the ignition source was burning material raked over from the first ignition location to the second ignition location at 18:30. The fire was then allowed to grow again, and at 21:30 an interior opening was created on the ceiling of the attic. At 22:10, the nozzle installed on the interior to simulate and interior attack, was turned on flowing 150gpm at 100 psi. The roof vent on the B side of the structure was opened at 22:50. Another interior attack through the ceiling opening occurred at 23:20. The exterior fire on the B side of the structure was suppressed at 24:00. At 24:36, a third interior attack through the ceiling opening occurred, and then at 25:35 an exterior ground attack along the B side eave line occurred. Fire began to spread along the exterior of the C side of the structure and this fire was suppressed at 27:10. The A side gable was removed allowing for tower attacks flowing 1000 gpm into the attic space through the A side gable at 35:35, and 42:00. The experiment is terminated at 43:00. Table 9. 6 lists all actions and when they occurred. Table 9. 5 provides a snapshot of all 8 camera views for each action in the Table 9. 6.

Table 9. 5: Field Experiment 3 Chronological Images


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:18:30:23
00:18:30:28
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:21:30:21
00:21:30:23
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:22:10:13
00:22:10:17
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:22:50:19
00:22:50:23
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:23:20:25
00:23:20:29
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:24:00:21
00:24:00:25
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:24:36:19
00:24:36:21
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:25:35:21
00:25:35:24
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:27:10:27
00:27:11:00
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:30:10:19
00:30:10:18
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:35:35:19
00:35:35:21
BC Corner IR
BC Corner
Den
Bedroom 2


Entrance
AD Corner
Bedroom 1
Bedroom 1 IR
00:42:00:22
00:42:00:25
BC Corner IR
BC Corner
Den
Bedroom 2

Table 9. 6: Field Experiment 3 Timeline

Time (mm:ss)	Description
00:00	Ignition on exterior side of the house
09:30	Eave Attack from Side B window to BC Corner
18:30	2nd ignition along exterior side of the house
21:30	Interior attic ceiling opened
22:10	Interior attic attack through ceiling opening
22:50	Vent opened on the roof
23:20	Interior attic attack through ceiling opening
24:00	Suppression of exterior wall fire
24:36	Interior attic attack through ceiling opening
25:35	Exterior ground attack along eave line
27:10	Suppression of exterior fire on C side
30:10	A side gable removed
35:35	Tower attack through A side gable
42:00	Tower attack through A side gable

9.4. Knee Wall & Attic Field Experiment Analysis

Experiment 1 - North 9th Street

Initial Fire Growth

The second floor bedroom in experiment 1 was furnished with a modern chair, a legacy bed and various stuffed animals. Due to the legacy fuel mattress the growth within the room occurred over 12 minutes and 57 seconds at which point temperatures exceeded 1112°F from floor to ceiling indicating the ignition room had transitioned to flashover (Appendix J Figure J.25). It took 21 minutes and 55 seconds to see temperatures increase over 500°F in the knee wall B space directly above the bedroom.

Fire Service Intervention

The first fire service intervention was performed at 24 minutes and 5 seconds into the experiment by directing an exterior stream flowing 150gpm into the 2nd floor bedroom window off the ceiling for 8 seconds. Temperatures within the second floor bedroom were reduced and there was a very small effect on the, knee wall and peak. The living spaces on the half attic floor showed no change and remained at levels prior to water application around between 135°F and 129°F (See Figure 9. 27).

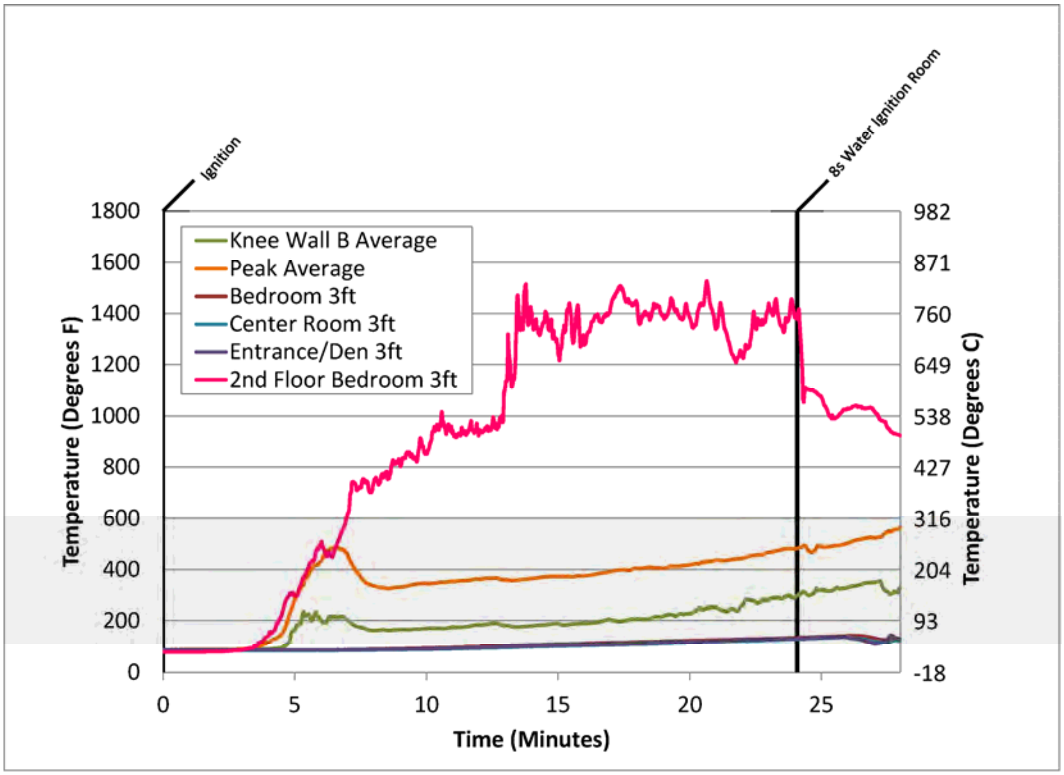


Figure 9. 27: Experiment 1 Transitional Attack Effect

After the application of water from the exterior ventilation was provided to simulate an interior attack crew entering the attic space from the second floor. The attic door was opened followed approximately 30 seconds later by opening the ‘C’ Side window as the crew passed it. It was estimated it would take the crew 30 seconds to reach the ‘A’ Side of the attic at which time the window was opened. Assuming the crew found no fire or heat, the knee wall was opened near the stairs to simulate a crew behind the original crew entering and searching for fire. The effects can be seen in Figure 9. 28**.** Fire growth before the knee wall patch was opened remained steady in the knee wall and peak, after opening the knee wall patch fire growth was accelerated to flashover temperatures in the knee wall and over 350^{o}F in the living spaces. The peak, being above the neutral plane of any ventilation with a finite exhaust area, maintained the slow temperature increase until it became stead as the knee wall reached flashover temperatures.

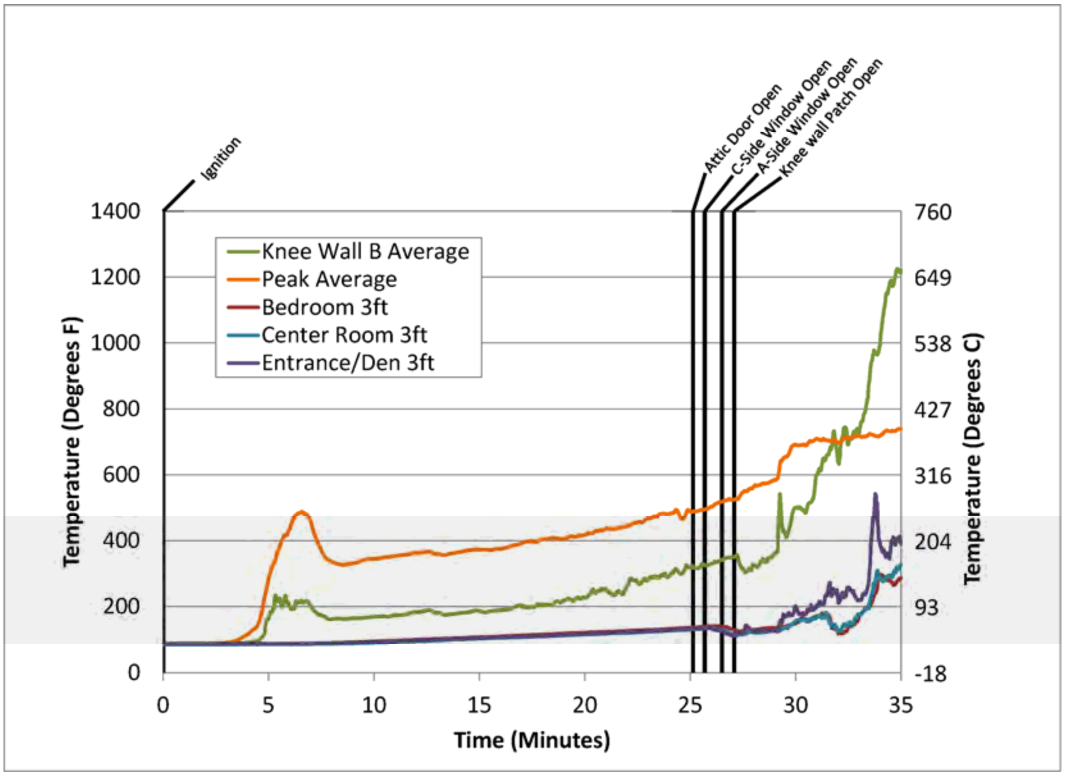


Figure 9. 28: Experiment 1 – Ventilation Operations.

Suppression operations were simulated in the stairwell via a remotely activated automatic nozzle flowing 150gpm for 10 seconds. This had no suppression effect on temperatures throughout living space and knee wall. This is most likely due to the source of the fire not being controlled and providing energy which is not reduced by cooling from surface cooling/extinguishment. The hand line was followed 1 minute and 30 seconds later with a 10 second 1000gpm burst from a smooth bore apparatus mounted master stream on side 'A' through the side 'A' gable. Temperatures reduced in the front two rooms of the living space to below 200°F, but with limited water reaching the Entrance/Den temperature were only reduced to below 800°F. No water reached the knee wall and thus temperatures remained steady. Temperatures in the center room and entrance/den rebounded within 1 minute and 30 seconds of application. In the same time period the front bedroom climbed to 400°F. The master stream application was followed by suppressing all visible fire on the 'B' side of the structure. This took temperature in the knee wall space from 1600°F to 800°F the peak from 1000°F to 450°F and the living spaces all to below 400°F. Temperatures remained below 600°F for two minutes before beginning to increase again in the living spaces. The peak and knee wall increased to pre water application temperatures in the same period of time. The effectiveness of each tactic can be seen in Figure 9. 29.

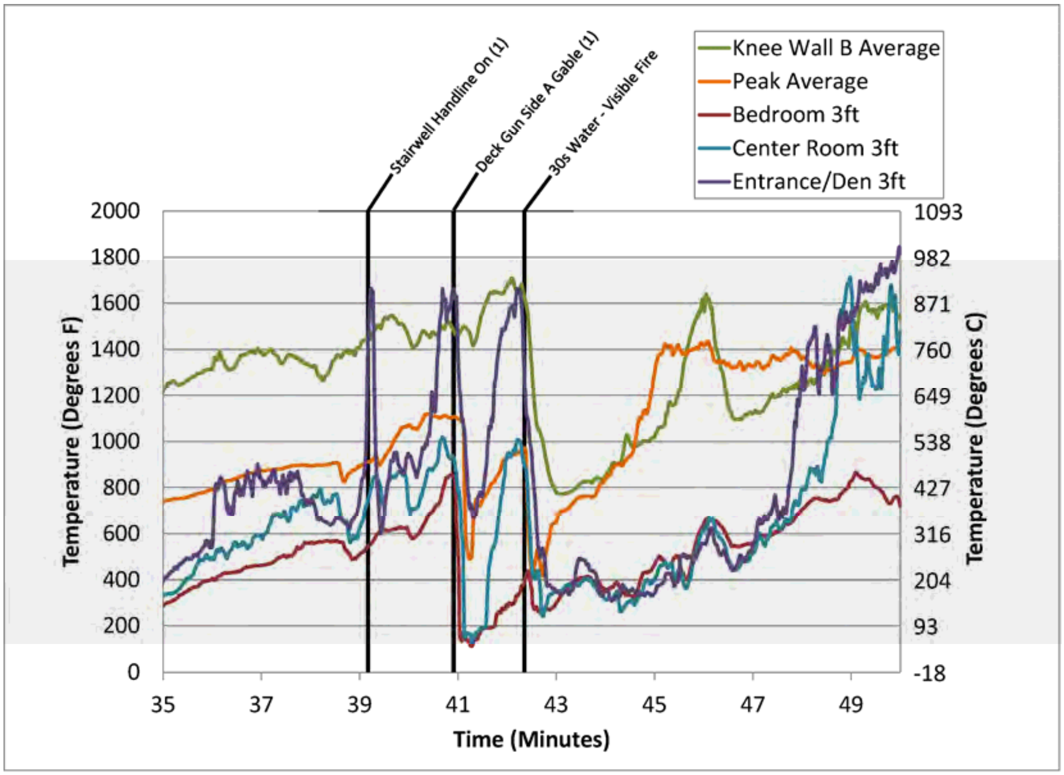


Figure 9. 29: Experiment 1 – Water Suppression Effectiveness

Experiment 2 – West Burleigh Street

Initial Fire Growth

The second floor bedroom in experiment 2 was furnished with a two modern foam chairs, a modern queen size foam mattress and various stuffed animals. With modern furnishings and a large tall window opening the room temperatures exceeded 1200°F from floor to ceiling at 6 minutes and 20 second after ignition, indicating the ignition room had transitioned to flashover (Appendix J Figure J.49). It took 6 minutes and 15 seconds for the temperatures to peak in the knee wall on the B at approximately 1400°F side and then become ventilation-limited and reduce to just over 600°F at 7 minutes and 15 seconds.

Fire Service Intervention

The first fire service intervention was performed at 9 minutes into the experiment where an exterior transitional attack using a 150gpm automatic nozzle from the ground level through the second floor bedroom window. The nozzle set to straight stream was directed off the ceiling for 10 seconds. Temperatures in the 2nd floor bedroom reduced from over 1300°F to below 600°F however regrew rapidly to over 900°F as the eave attack was performed. The hose line was than directed across the side 'B' eaves starting at side 'A' and walking toward side 'C'. The eave attack further reduced the temperatures in the 2nd Floor Bedroom from above 900°F to just above 400°F for 30 seconds before regrowth occurred. The eave attack had an effect on the bedroom due to the penetrations from the bedroom into the knee wall. The side 'B' yard was located 2 ½ stories below the eave line, this vertical distance along with the presence of the vinyl soffit coverings caused limited water to flow into the eaves. With little water penetration the eave attack only had a minor effect on the temperatures within the knee wall and had no effect on the temperature is the peak. Much of the vinyl soffit stayed in place after the eave attack with the exception of the area near the fire compartment where the soffit melted and fell away. Figure 9. 30 shows the initial growth and effect of the exterior suppression on the rooms within the structure. Within 2 minutes of the water application temperatures returned to at or above pre water application temperatures.

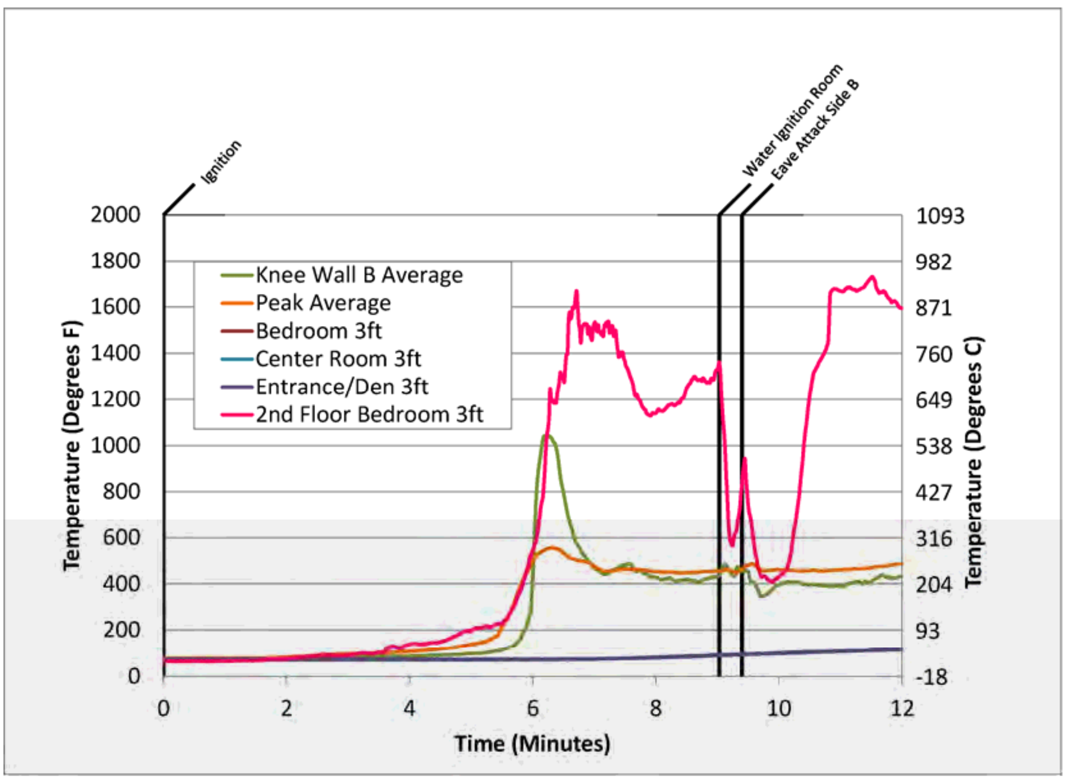


Figure 9. 30: Experiment 2 - Transitional Attack & Eave Attack

After the application of water from the exterior a simulated interior attack was conducted by opening the attic door at 12 minutes into the experiment. This was followed by the attic windows on both the 'A' side and 'C' side at 12 minutes and 30 seconds. Twenty seconds later the knee wall patch was opened simulated checking for fire in the knee wall at the top of the stairs. Conditions were monitored for 30 seconds with no noticeable change in conditions in the living space.

Water was then applied via a 150gpm automatic nozzle set to straight stream, located in the knee wall installed to simulate applying water horizontally down the center of the knee wall. Turning on the knee wall nozzle caused the average temperature in the knee wall to increase (Figure 9. 31). When individual thermocouples are reviewed the water had an impact on temperatures at the far side of the attic by reducing them below 200°F at end of the knee wall remote from the nozzle as seen in Figure 9. 32, TC's 15-18. TC – 20 at the center of the knee wall has temperatures reduced from over 900°F to below 500°F. Moving toward the nozzle located at TC-23 the temperatures increase from approximately 700°F to approximately 2000°F. The knee wall line flowed for 58 seconds, after 32 seconds the water begins to have an impact on the average knee wall temperature. The temperature is reduced until the line is turned off at which time temperatures rebound for approximately 1 minute then become ventilation-limited. After the knee wall becomes ventilation-limited, temperatures dropped until they reach approximately 600°F. As the fire slowly burns larger openings allowing more oxygen in the temperatures slowly grow to the temperature pre water application at 1 minute and 30 seconds after the line was turned off.

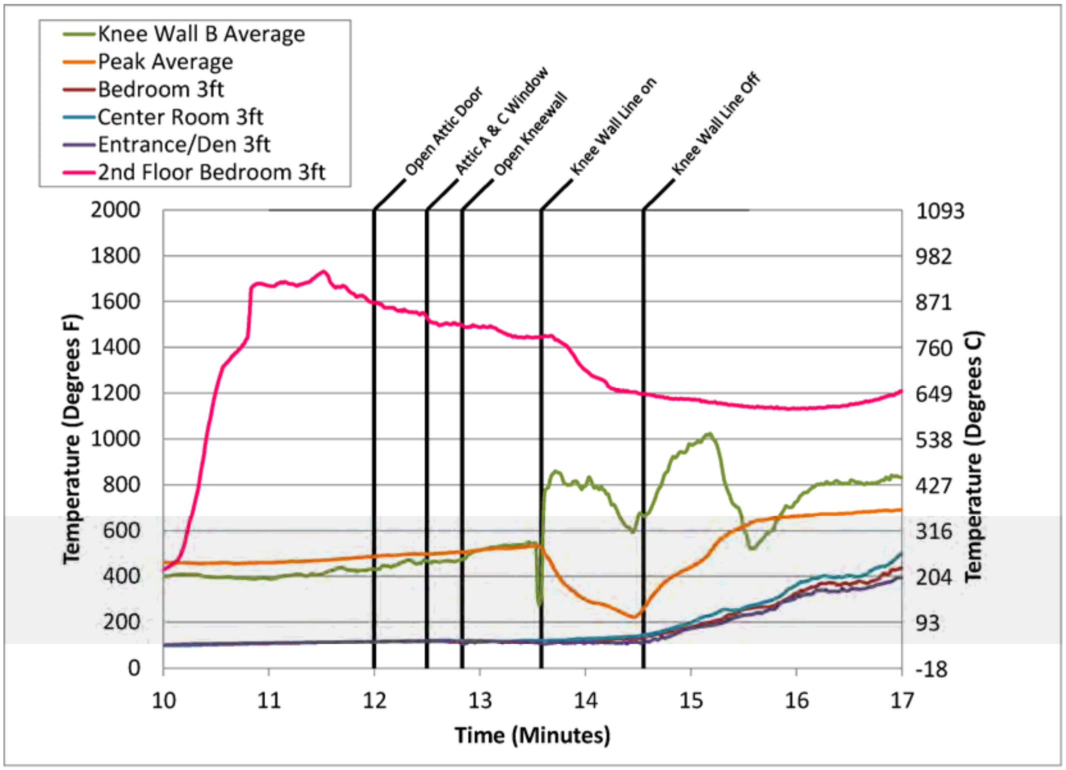


Figure 9. 31: Experiment 2 – Interior Fire Service Interventions

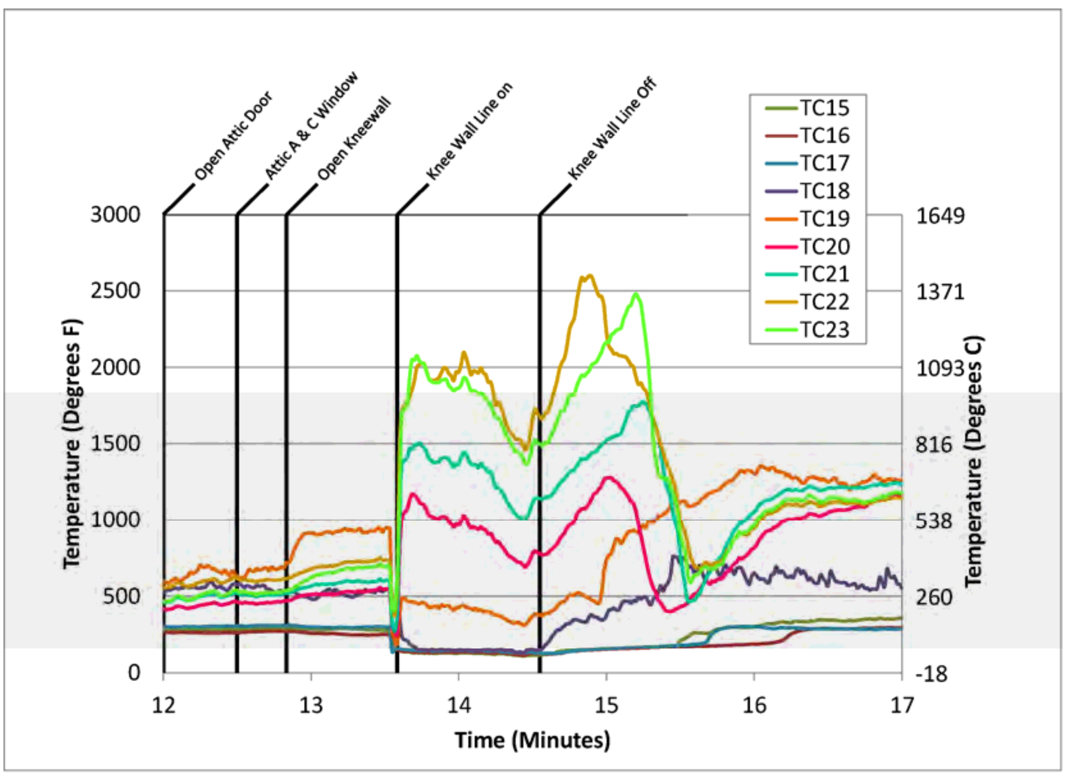


Figure 9. 32: Experiment 2 - Effect of Knee Wall Line on Knee Wall Temperatures

The increase in temperature when the line was turned on indicates an increase in burning near the nozzle may have occurred. This could be potentially due to the air entrainment from the nozzle. The high velocity water spray may have created a venture effect from the entrance/den to the knee wall as illustrated in Figure 9. 33. The increase in available oxygen increased the burning rate near the nozzle.

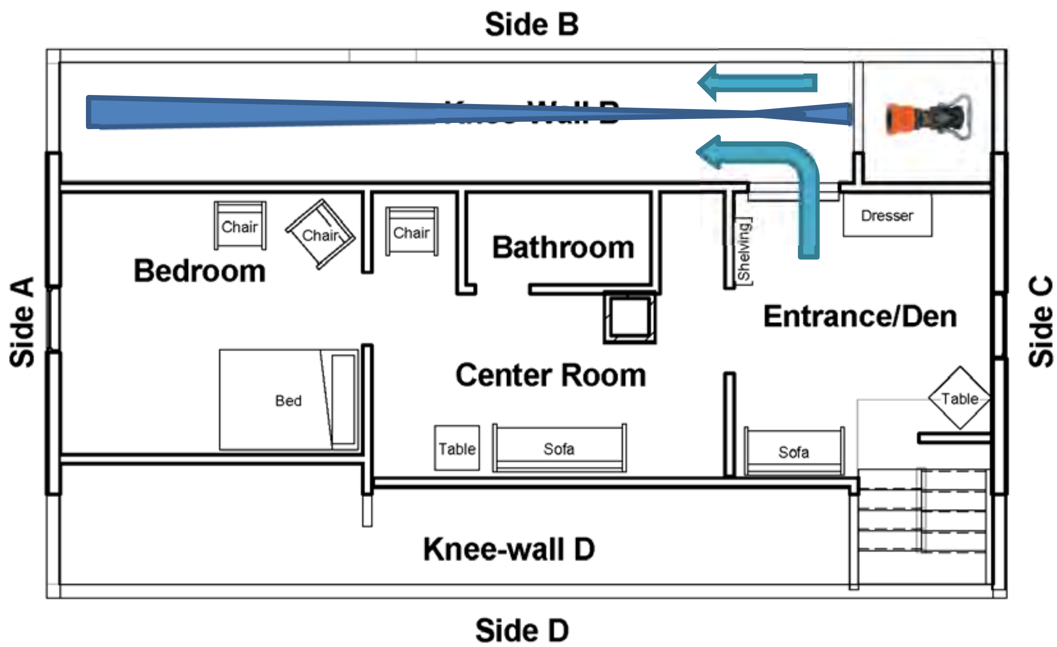


Figure 9. 33: Knee Wall Venturi Effect

After interior Suppression was completed an additional attempt at the eave attack was conducted. Instead of using the nozzle to attempt to remove the vinyl soffit a pike pole and extension ladder were used to remove the entire soffit line. As seen in Figure 9. 34, removing the eaves allowed more air into the knee wall and peak, increasing the burning rate and temperatures in both spaces. Water was applied via a transitional attack into the 2nd floor bedroom followed closely by a sweep of the eve line. The temperatures responded quickly throughout the knee wall with reductions from over 800°F to under 400°F. The living space temperatures dropped to the same level. Indicating the attack had a significant impact on conditions in theses spaces (See Figure 9. 34).

Although water was able to penetrate the knee wall, limited impact was achieved on the peak space. Temperatures dropped because the space feeding the peak dropped however this also allowed an increase in airflow to the peak space which increased temperatures to an average of 1200°F within a minute and 30 seconds of applying water to the eave, an increase of 500°F from prior to water application.

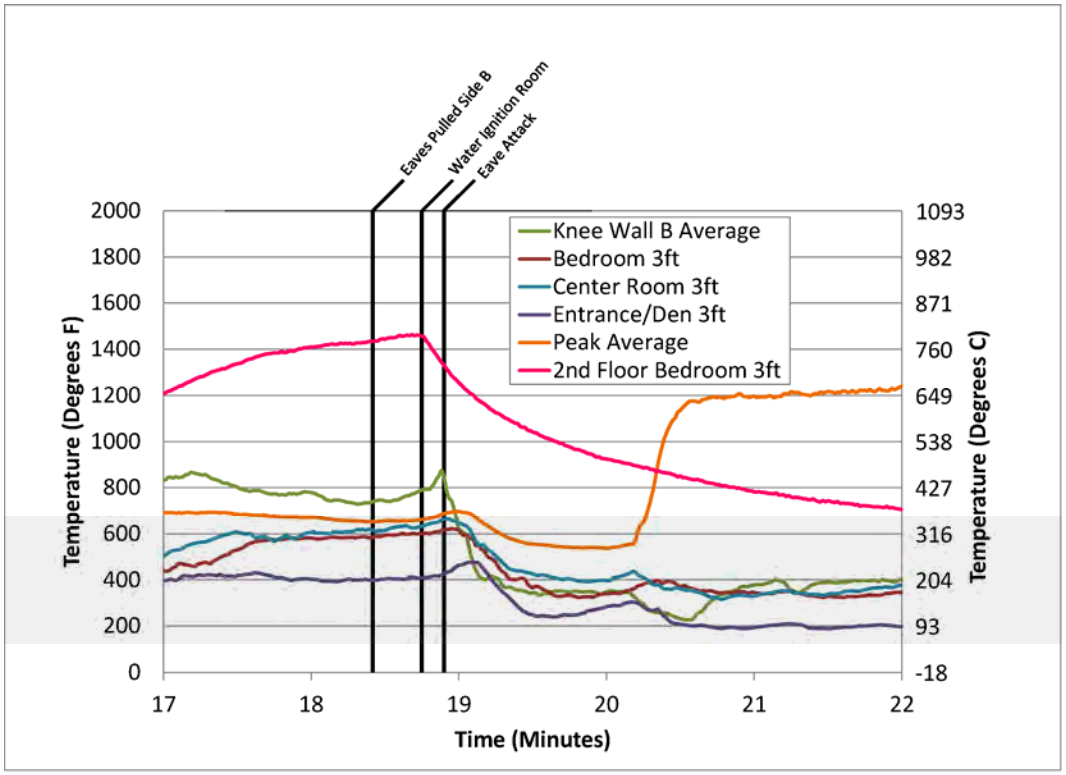


Figure 9. 34: Experiment 2 – Eave Attack Effectiveness (Soffit Removed)

Experiment 3 – North 25th Street

Initial Fire Growth

A standard size city trash can, 65 gallons, was utilized as the ignition source loaded with construction debris such as wood, paper and plastic refuse. The can was placed up against the structure and ignition was provided via an electric match (See Figure 9. 35). The fire grew up the exterior of the house and into the open eave space. The change in temperatures monitored can be seen in Figure 9. 36.

Figure 9. 35: Experiment 3 – North 25th Street Exterior Ignition Source

Fire Service Intervention

Initial fire service intervention by a single crew was performed on the exterior side ‘B’ of the structure. Suppression with an automatic nozzle flowing 150gpm set to straight stream was preformed along the eaves where the fire had penetrated into the joist bays. Figure 9. 37 indicates temperatures prior to the application of water in the joist bay averaged over 1200^{o}F and in the peak averaged over 550^{o}F. After the 14 seconds of water through the eaves the temperatures reduced to below 200^{o}F in both the peak and joist areas, while no increases occurred in any of the attic living spaces. Water also indirectly effected the flames in the trash can as seen in the series of images in Figure 9. 36 and the bulk of the visible fire was extinguished.

(a) 10s Before Water Application (b) 10s After Water Application

Figure 9. 36: Experiment 3 - Eave Attack Effectiveness

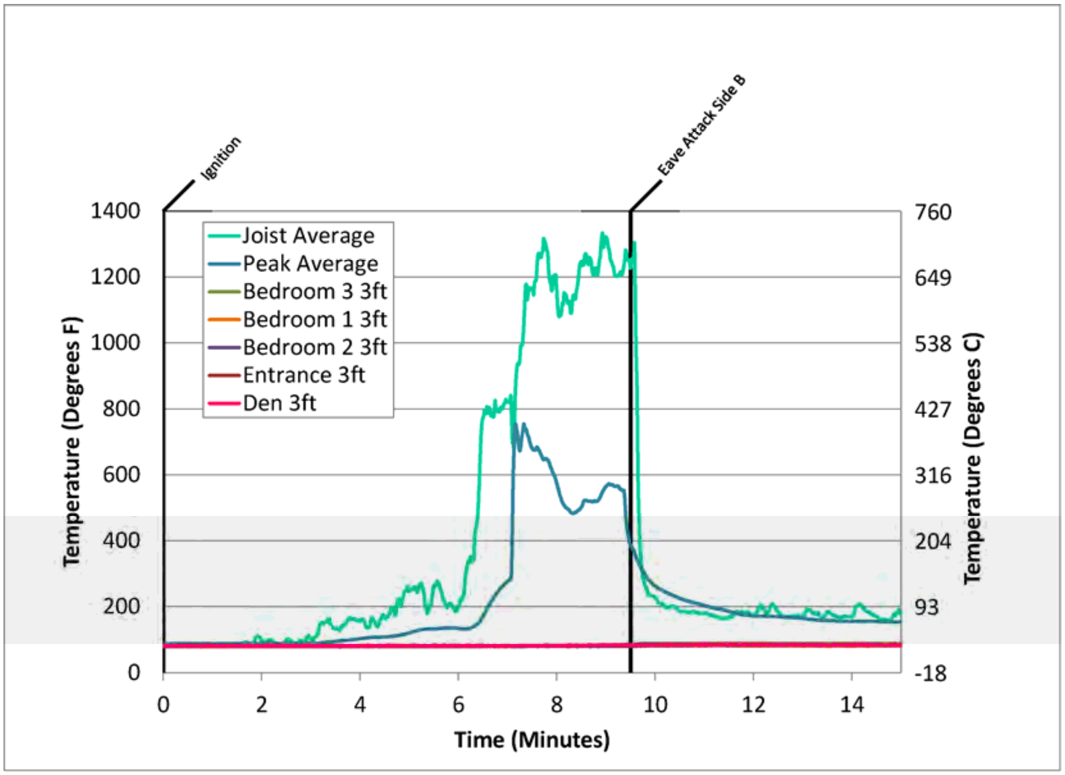


Figure 9. 37: Experiment 3 – Growth and Initial attack

After suppression the temperatures remained below 200°F for the next 8 minutes as seen in Figure 9. 38. The eave attack appeared to have controlled the growth and suppressed the bulk of the fire, wetting the surfaces and preventing re-growth. To gain more insight into the growth of exterior fires a second trash can was placed along the house and the remnants of the first can were raked over adjacent to the can, igniting the can. Depicted in Figure 9. 39a-d prior to the extension from the second trash can to the structure the attic space reached temperatures indicating flash over and the side 'C' gable vented flames.

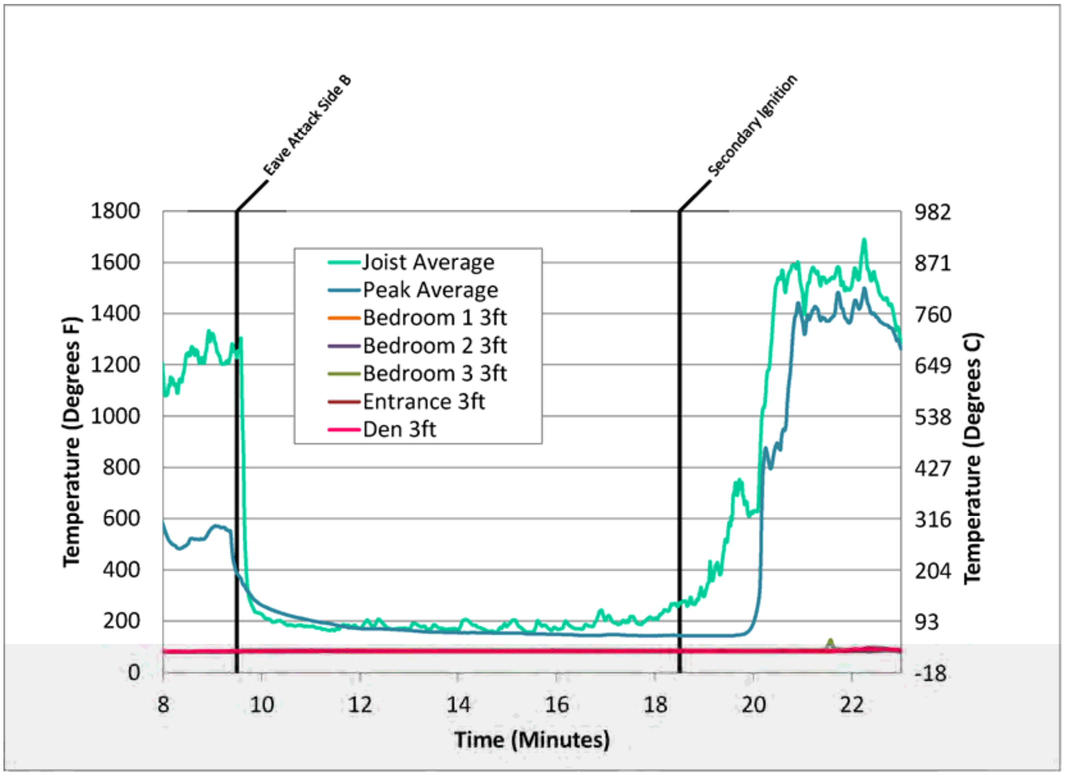


Figure 9. 38: Experiment 3 – Regrowth


(a) 19:45 (b)20:00
(c) 20:15 (d) 20:30
Figure 9. 39: Experiment 3 - Regrowth Progression 19:45-20:30

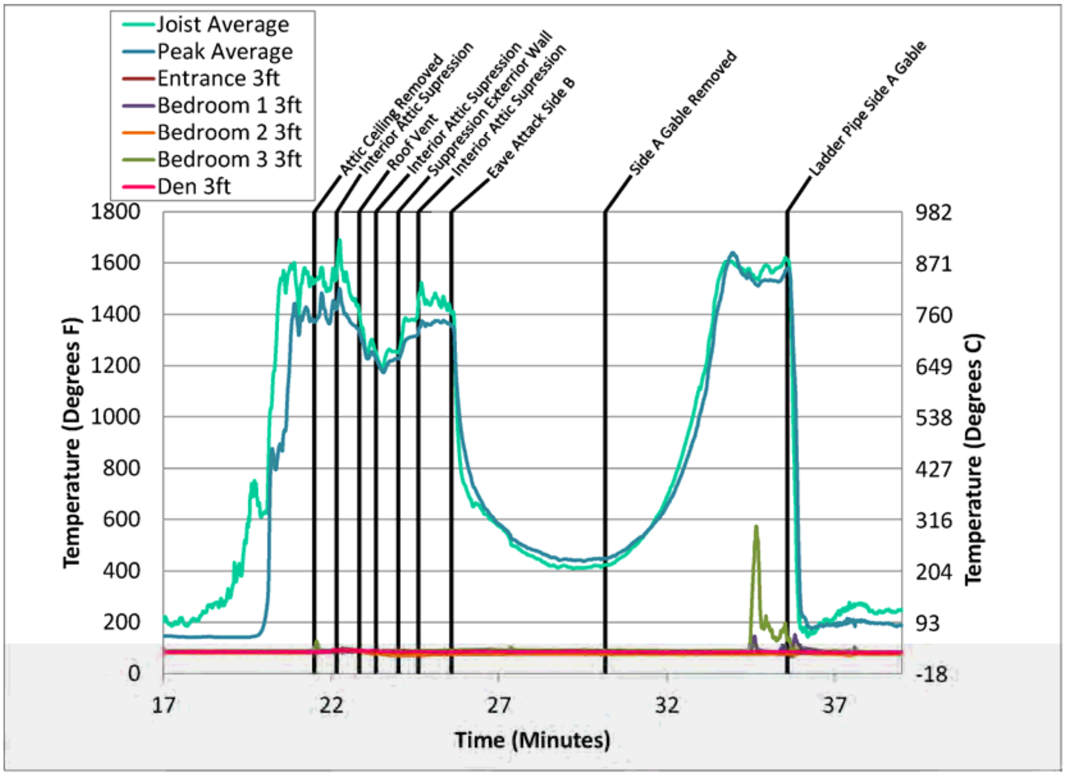


Figure 9. 40: Experiment 3 – Interior fire service intervention.

Once the peak reached flash over, interior operations were simulated by opening a 4ft x 4ft ceiling section to gain access to the peak in the side ‘A’ bedroom. As seen in Figure 9. 40 the increase ventilation below the fire had no impact on the temperatures within the attic, indicating the fire size was limited by the ability to exhaust products of combustion. This can also be seen in Figure 9. 41 a graph of the peak temperatures from side ‘A’ to side ‘C’ TC’s 15-23 respectively, where the temperatures throughout the peak remained elevated. The application of water via the 150gpm automatic nozzle set to straight stream two times had little to no impact on the temperatures within the attic. In addition no temperature rise was seen in the occupied attic spaces.

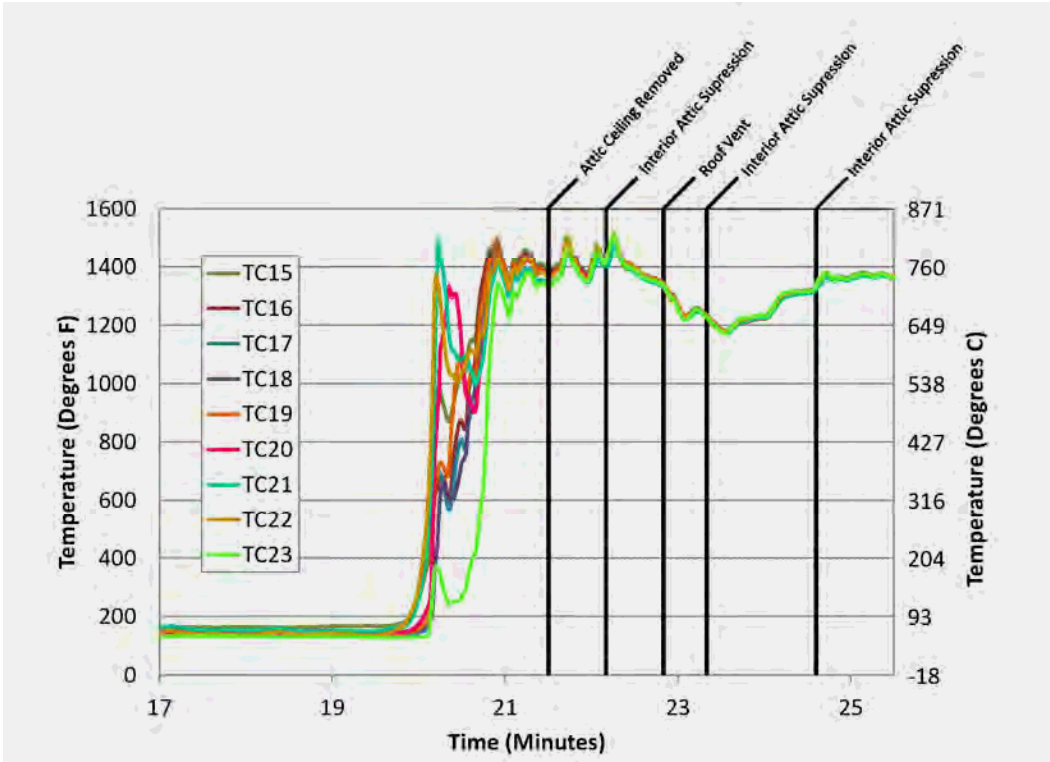


Figure 9. 41: Experiment 3 – Peak temperatures during Interior Intervention

Following the interior attack an exterior attack on side 'B' eaves was performed, which dropped temperatures within the peak and joist areas from over 1400ºF to below 500ºF. Temperatures took over 5 minutes to rebound to above previous values indicating water was able to penetrate the joist bays into the peak spaces. After regrowth the fire begun to penetrate through the separation between the joist bays and bedroom 3 as temperatures increased to over 500ºF before becoming under ventilated and decreasing. Final attic suppression was provided via a 1000gpm combination nozzle affixed to a ladder pipe. The nozzle was placed right up to the side 'A' gable and adjusted from fog to straight stream and back several times. Temperature throughout the attic, peak and finished space was reduced to below 250ºF at which time the experiment was concluded. For a graphical representation of the effects of each suppression tactic see Figure 9. 40.

10. 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. There is no silver bullet tactic for attic fires or exterior fires, these considerations are meant to increase the knowledge of the fire service and to be incorporated into training and procedures if deemed applicable. Certain sections are bold in each tactical consideration to emphasize the main points within each tactical consideration.

10.1. Increased use of plastics in exterior walls will change what you arrive to

Changes in residential wall construction methods are playing an important role in how exterior fires are initiated, as well as how they spread and extend. The potential to respond to an exterior fire that has extended into the house increases as home design and construction techniques continue to evolve. In the past, a small outside fire, or rubbish fire adjacent to a house, spread slowly if at all. Now, the same fire may quickly involve the entire side of a house and rapidly extend into the eaves and attic or to adjacent structures. Older homes commonly have brick, wood clapboard or stucco on the exterior of the structure's walls. Construction materials and the techniques used to construct homes have evolved over time and will continue to evolve. Vinyl siding was introduced in the1960's and has gained popularity since the 1970's. Today, the wood siding and vapor barrier that was once in place underneath the vinyl has been replaced with a rigid foam sheathing to increase energy efficiency in homes. The fire service must understand the potential impact these changes have on fire ground operations and safety, and evolve as well.

Figure 10. 1. Traditional Duplex with vinyl siding on left and wood siding on the right

Figure 10. 2. Modern home with energy efficient wall systems with the same look as a wood lap sided home

Figure 10. 3. Two vinyl sided wall sections with different energy efficiencies

Figure 10. 4. Two wood sided wall sections with different energy efficiencies

10.1.1. Exterior Walls Ignite More Readily

Legacy construction practices using cement based stucco and solid wood wall sidings provided a form of fire resistance to the structure, preventing or slowing even large outdoor and rubbish fires from extending into a structure. **Modern homes now commonly utilize plastic siding as the outer layer. This evolution in building materials has led to an increased ignition potential from exposure to outside fires such as mulch and grass fires, as well as fires extending from garbage and rubbish bins kept next to the structure**. The wall system experiments show that stucco, fiber cement, and wood siding would not sustain burning even after 10 minutes of exporure from a 100kW heat source. By comparison, the plastic wall sidings ignited in one minute or less and grew rapidly. A 100 kW source is equivalent to a small fire measuring approximately 2 ft wide by 2 ft deep with flames 2 feet high. This could be a mulch, grill, small trash can or plastic potted plant fire. These images show 6 different wall types after 2 minutes of exposure to the 100kW burner.

Figure 10. 5. Exp. 3 – Vinyl Siding over plywood

Figure 10. 6. Exp. 5 – Vinyl siding over polystyrene

Figure 10. 7. Exp. 14 – Wood Lap Siding

Figure 10. 8. Exp. 19 – Fiber Cement Siding

Figure 10. 9. Exp. 20 - Aluminum Siding

Figure 10. 10. Exp. 26 - Stucco Siding

10.1.2. Exterior Wall Fires Spread More Rapidly

Modern building codes place an emphasis on energy efficiency and insulation. To adhere to these more stringent requirements, manufacturers have designed materials with higher insulation values. These materials have less inherent fire resistance than the materials they replaced, and have flame spread characteristics that can lead to more rapid fire spread into the structure. **These new materials also have much higher energy release rates. All of this combines to change the way fires grow and spread on the exterior of a structure.**

Ignition and flame spread experiments indicate that the use of plywood as a sheathing material prevented rapid fire growth when compared to rigid foam board. Even when the plastic siding ignited and burned rapidly, the underlying plywood sheathing resisted sustained ignition for up to 20 minutes. When rigid foam board replaced the plywood sheathing, the foam ignited almost immediately and spread up a two story structure in under two minutes. The high heat release rate quickly drove fire into the attic space.

Adding more combustible sheathing and siding has the potential to replicate the fire spread problem associated with balloon frame construction. Firefighters will tell you that if you have a fire in the basement of a balloon frame structure then you need to quickly check conditions in the attic. With modern exterior construction, a fire in the basement (or on any floor) that exits the window and ignites the exterior wall, may travel rapidly up the wall and into the attic, mimicking the void space fire spread found in balloon frames. Fire extension via the exterior to exposed parts of a building may become as, or more common than, interior fire spread through the voids.

Figure 10. 11. Flame spread 2 minutes after ignition of a polypropylene shingle sided wall over polystyrene sheathing

Figure 10. 12. Flame spread 2 minutes after ignition of a wood lap sided wall over polystyrene sheathing

10.1.3. Exterior Fires can easily become Structure Fires Prior to Arrival

Modern attic construction is designed to produce natural ventilation that reduces moisture and heat buildup in the attic space. Solid wood eave and soffit construction has largely been replaced by vinyl soffits with built in ventilation openings to allow circulation of air. These openings provide the opportunity for direct flame spread from an exterior fire into the attic space. This process accelerates as the plastic soffits melt and fall away. Other eave construction practices, such as aluminum or solid wood with smaller air vents, also allow for fire penetration, though at a slower rate. If air can pass through, so can fire gases. This direct flame spread potential, along with the rapid ignition and flame spread found to occur within modern wall construction, combine to increase the exterior fire hazard. **Fires adjacent to modern exterior wall construction have the potential to transition to structure fires within two minutes of ignition.** This is well before most fire department intervention times. Heat sources larger than 100 kW such as fires involving vehicles, decks, porches, larger trash cans or fires extending out of windows from the interior can spread into the attic in less than two minutes.

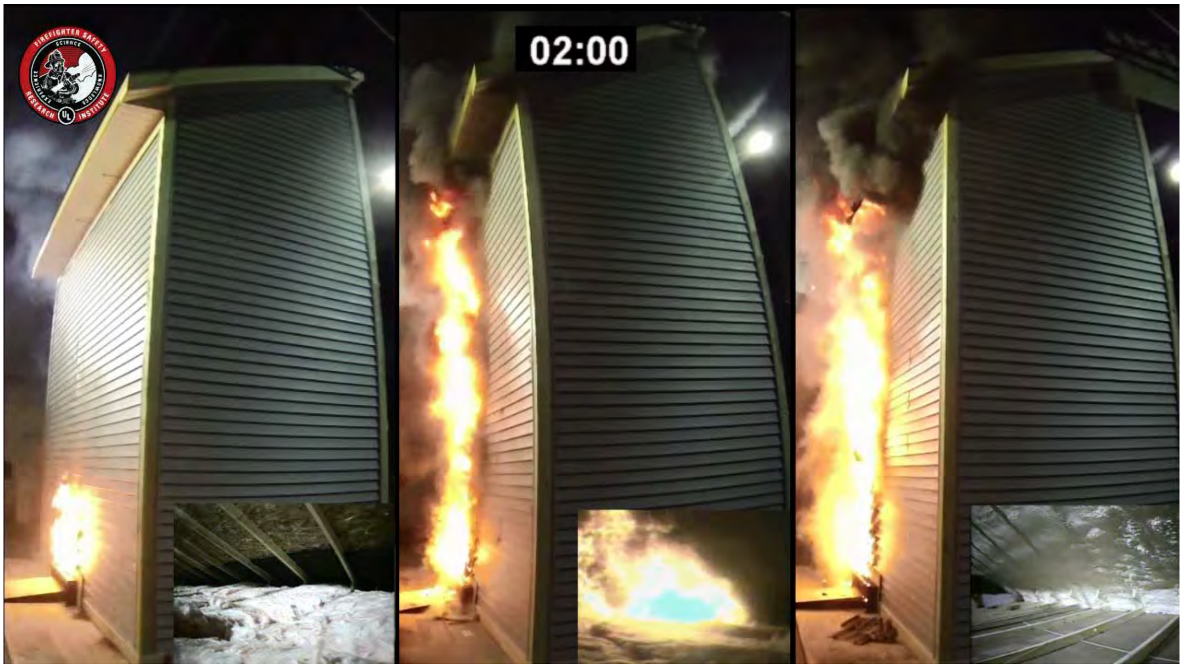


Figure 10. 13. Wall and Eave experiment as Vinyl Siding/Polystyrene Sheathing/Fiberglass Insulation system transitions to an attic fire (2 minutes after ignition)

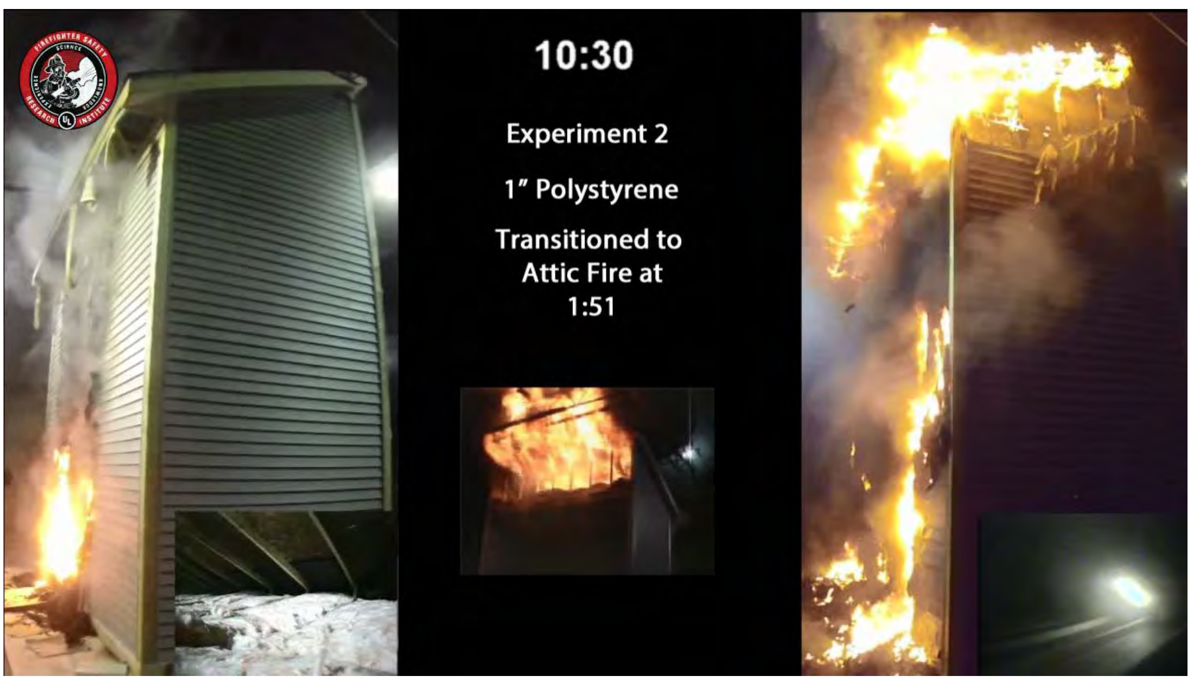


Figure 10. 14. Wall and Eave experiment as Vinyl Siding/Polystyrene Sheathing/Spray Foam Insulation system transitions to an attic fire (10 minutes 30 seconds after ignition)

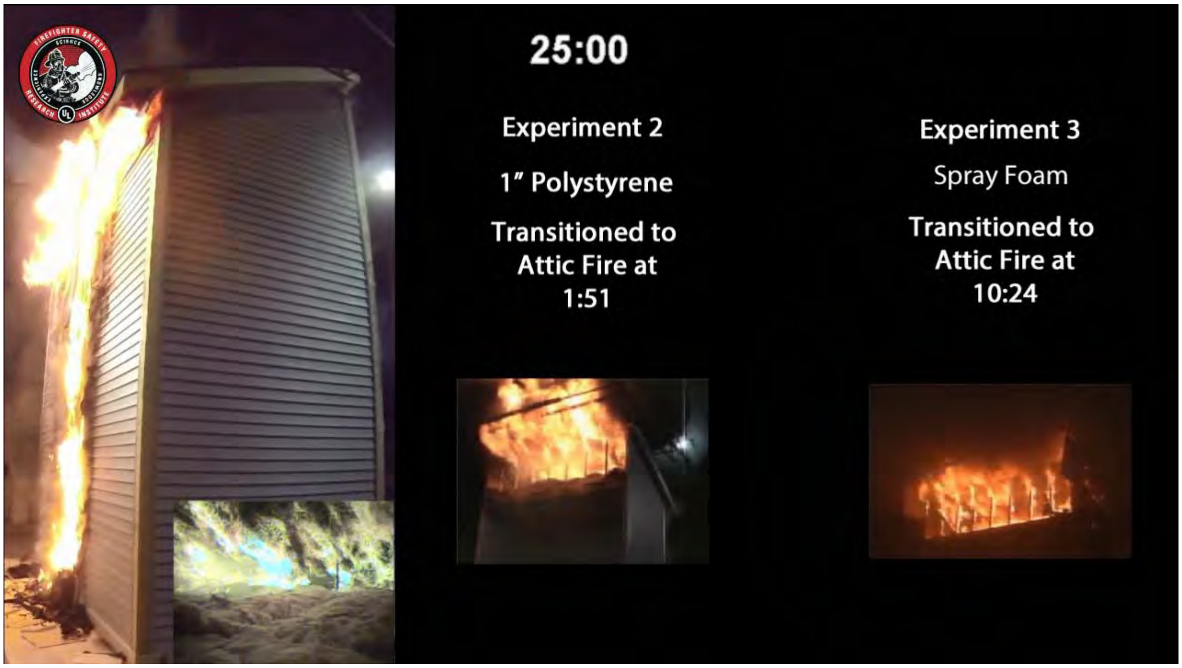


Figure 10. 15. Wall and Eave experiment as Vinyl Siding/OSB Sheathing/Fiberglass Insulation system transitions to an attic fire (25 minutes after ignition)

10.1.4. Exposure to Adjacent Structures Occurs Prior to Arrival

The introduction of spray foam insulation into the attic space of residential homes has transitioned what was once an unconditioned space (that is, one that is neither heated nor cooled) into a conditioned space. This approach has proved to be more energy efficient and therefore more cost effective. With the attic part of the conditioned space, there is no longer the need for air circulation in the attic to prevent moisture accumulation. As a result, when spray foam is used, there is usually a return to solid eaves and soffits which resist the spread of fire into the attic space.

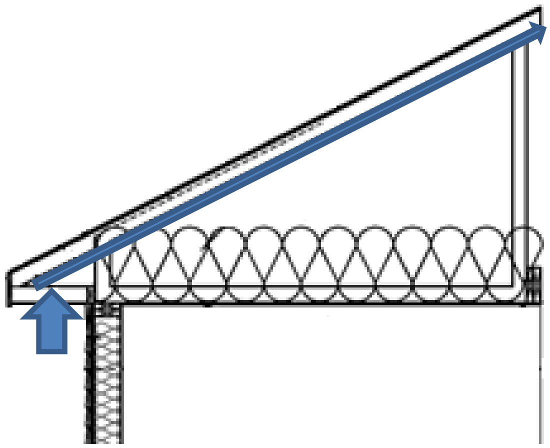


Figure 10. 16:Attic ventilated from eave to peak

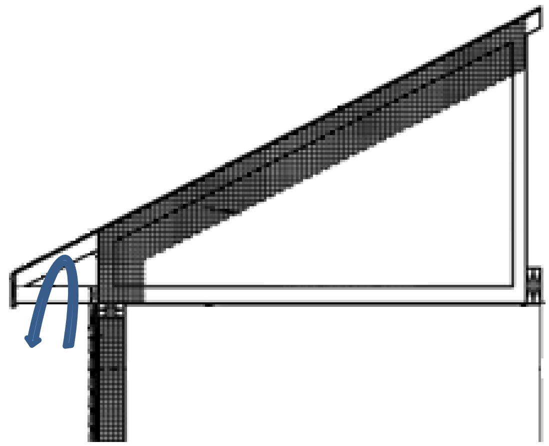


Figure 10. 17: Unventilated attic space

Figure 10. 18. View of vented attic from the attic

Figure 10. 19. View of unvented attic construction eaves

With the two story wall configuration used in the tests, fire exposure to a surface opposite the test wall was minimal during the fire's spread up the wall. However, when the fire reached the eave line, exposing the attic and involving the eaves and soffits, heat flux measurements of radiant energy at the wall opposite indicated a significant increase in exposure fire potential. **Therefore, the projection of the flames out of the eaves and the additional fuel load at the eave/soffit line combine to increase the radiant energy directed at any adjacent structures, increasing the exposure threat.** In scenarios where the wall and roof voids are filled with spray foam insulation, this effect is even more pronounced since there is more fuel available than with other insulation and sheathing combinations such as plywood over fiberglass batts or even foam board over fiberglass batts.

Figure 10. 20. Burning at eave line with vented attic (Experiment 1)

Figure 10. 21. Burning at eave line with the unvented attic (Experiment 3)

10.2. If the fire starts on the outside, start fighting it from the outside.

In newer subdivisions, zoning changes have allowed builders to construct houses with less open space between them. Thus, the exposure fire problem that has been part of the urban landscape for generations is finding its way to the suburbs and beyond. In addition, modern building materials and construction practices are allowing for the accelerated spread of exterior fires to both the interior of the original exposure as well as from one building to another. Simply put, modern building exteriors have more fuel with higher heat release rates than their legacy predecessors. Therefore, **rapid water application to knock down the exterior fire is a critical part of any attempt to control not only the fire's spread to adjacent structures but also the fire's migration into the interior of an exposed building.**

Figure 10. 22. Fire extending from a trash can into the eaves during a field experiment in Milwaukee, WI.

Figure 10. 23. Water applied to extinguish the exterior fire and flow into the eaves before interior operations were commenced.

If the source of the fire is not suppressed, it will continue to supply heat energy to the fire developing on the interior, worsening conditions on the inside and in many cases making it impossible for the interior crews to maintain or advance their positions. The incident reports listed below detail cases where failure to address the exterior fire that was continually exposing the interior crews, contributed to the injury and death of firefighters operating inside the structure

- Prince William County Department of Fire and Rescue, Line of Duty Death (LODD) Report for Technician I Kyle Robert Wilson http://www.pwcgov.org/government/dept/FR/Pages/Technician-I-Kyle-Wilson-LODD-Report.aspx, "Career Fire Fighter Dies in Wind Driven Residential Structure Fire." Fire Fighter Fatality Investigation Report F2207-12, National Institute for Occupational Safety and Health, May 2008. http://www.cdc.gov/niosh/fire/pdfs/face200712.pdf
- Investigative Report into the Meadowood Court Fire, Loudoun County VA https://www.youtube.com/watch?v=ihc_Lz7Yh_4
- Four Career Fire Fighters Injured While Providing Interior Exposure Protection at a Row House Fire – District of Columbia, http://www.cdc.gov/niosh/fire/reports/face200735.html

Tactics applied during these experiments demonstrate that an additional line can be deployed or the same line used to knock down the exterior fire can often be redirected to achieve a similar knock down of fire that has extended into the building. For instance, water may easily be flowed up through the eaves and onto the burning underside of the roof decking. This exterior and interior knock down permits firefighters to more quickly, effectively and safely advance on the interior fire. This could be the original hose crew with the same line repositioned, the same hose crew with a new hoseline, or an additional crew or crews.

10.3. Learn to anticipate where and how an exterior fire will migrate to the interior

Exterior wall fires may easily spread to the interior at locations other than the eaves and soffits. The spread of fire from the exterior of the structure through the wall to the interior living spaces is limited by the fire barrier provided by the gypsum wall board on the inside face of the wall. The fire resistive nature of gypsum wall board protects the interior contents and occupants of the structure during an exterior wall system fire by limiting the temperature rise on the interior side of the wall and stopping the migration of fire gases into the living space**. Any penetrations -- such as air vents, electrical receptacles, plumbing penetrations to faucets and drains, and especially windows -- provide the opportunity for fire spread into the interior of the structure.**

Figure 10. 24. Wall Experiment 13 before receptacle burn through

Figure 10. 25. Wall Experiment 13 after fire penetrates the receptacles

In all experiments where the gypsum wall board contained no penetrations, there were limited heat increases noted on the occupant side of the wall, and only slight discoloration of the drywall as an indication of thermal damage to that part of the system. Once electrical receptacles were included in the wall system, flames were noted on the interior side of the wall at the receptacle locations. This hazard is amplified when plastic receptacle boxes are used as they tend to melt away, providing a larger unrestricted opening for the fire to spread into the interior.

Leaving the interior fire barrier in place until the exterior fire can be controlled will limit the extension into the structure. Opening up the interior to look for and extinguish void fires should be delayed until the exterior fire has been controlled. Priority can then be shifted to examining compartments where the fire barrier has penetrations such as windows, doors, electrical receptacles, etc. Overhaul of the entire exposed wall will be necessary as pockets of smoldering combustion were noted in all wall systems, especially where spray foam insulation was used.

10.4. Attic fires are commonly ventilation-limited fires

The ventilation of residential attics for the purpose of limiting moisture and heat buildup is accomplished through the use of gable, eave and ridge vents. During non-fire conditions, the buoyancy created by the solar heating of the roof causes gases to rise and exhaust out of the upper openings, drawing cooler ambient air in from the lower openings. This engineered ventilation of the attic space is sufficient to prevent moisture and heat buildup during non-fire conditions. However, it is not sufficient to exhaust all of the products of combustion during an attic fire, nor can it provide a well-established attic fire with enough oxygen to free burn in a fuel controlled condition.

The fuel load in an attic consists of the rafters or trusses, the roof sheathing, combustible insulation and any combustibles stored there by the occupants. Even without the addition of stored material, the construction materials alone provide enough fuel to result in a ventilation-limited fire within the attic**. The openings provided for natural ventilation are not sufficient to maintain steady state burning and fuel limited fire behavior. The size of the fire is limited by the available oxygen and will nearly always become ventilation-limited.**

Table 1. Attic fire growth to ventilation-limited in 5 minutes. Views from inside attic and front of structure.

Ignition		
1 minute		
2 minutes		
3 minutes		
4 minutes		

5 minutes		

Maintaining ventilation-limited conditions by limiting the number of openings above the neutral plane of the fire, in this case the attic floor, will control fire growth and development. Any opening above the neutral plane, either by fire burn through or by firefighting ventilation operations, will result in fire growth similar to the growth seen during horizontal ventilation**. Controlled openings created below the neutral plane (such as through the ceiling below the attic space) will not cause immediate growth and can provide access for suppression operations.**

A small opening in the ceiling will supply some air to the attic fire, but without an outlet like open gables or a large hole in the roof, there is not a flow path through the attic sufficient enough to lead to rapid fire growth. There will be local mixing of fuel and air at the opening that will produce flaming, but this will only be able to exist <u>at</u> that opening and not throughout the attic because there is no increase in airflow throughout the attic (Figure 10. 26).

However, when several openings or a very large opening is made through the ceiling below, more mixing will occur and the fire may begin to grow rapidly, overwhelming any natural or firefighter made openings in the roof. This creates the potential for the fire to burn downward or for a pulse of hot, unburned gases that mix with air below and ignite (Figure 10. 27 and Figure 10. 28).

Variables such as the concentration of unburned fuel (smoke) in the attic, the amount of fuel burning prior to becoming ventilation-limited, the size and placement of inlets and outlets, and the length of time the fire was ventilation-limited prior to receiving oxygen, will all impact how and when conditions change. To safely execute this tactic, carefully coordinate the pulling of ceiling with early and sufficient cooling of gases and surfaces. When attacking an attic fire from the compartment below, tactics applied during the experiments demonstrate the advantage of starting with a small opening just large enough to allow the introduction of a stream for gas cooling, known as an indirect attack. Once the gasses have been cooled, the opening (or openings) can be increased and expanded to allow for more efficient wetting of surfaces and complete extinguishment.

Figure 10. 26. Burning at interior ventilation opening in the ceiling during Attic Fire Experiment 2B

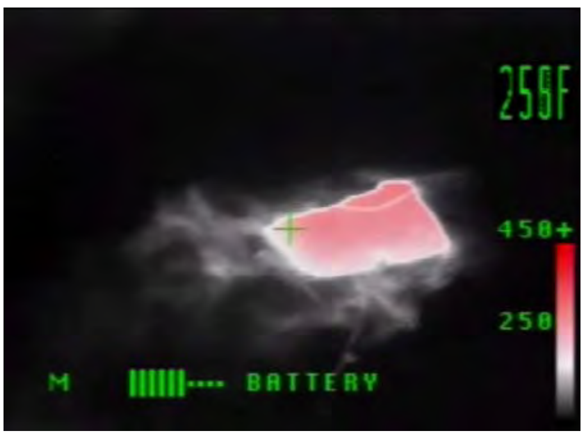


Figure 10. 27. Thermal imaging view of ceiling vent in Field Experiment 3 shortly after opening

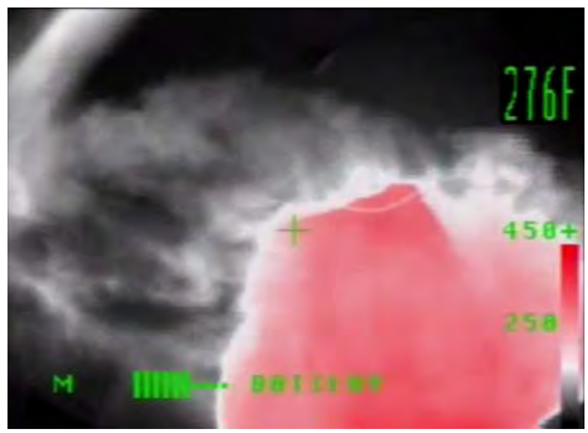


Figure 10. 28. Thermal imaging view of ceiling vent in Field Experiment 3 during pulse of heat downward into living space

10.5. Closely time or limit vertical ventilation until water is in the attic.

In every experiment, the fire growth and development was controlled by the size of the exhaust vents or a vertical ventilation opening. As the fire increased in size, the plastic gable vents commonly failed by melting away. The resulting six square feet of exhaust openings along with the replacement air supplied by the soffit vents was NOT enough to keep the fire from reaching a ventilation-limited state. In each of these cases, any of the suppression methods chosen for the experiment series (i.e. a large hole in the ceiling and water from below, water introduced into the attic through the gable ends, and water applied to the underside of the roof by way of the eaves) was successful at knocking down and limiting the size of the fire, making final suppression and overhaul relatively easy.


Figure 10. 29. Attic Fire Experiment 3 during peak temperatures in the attic with gable vents opened.


Figure 10. 30. Attic Fire Experiment 3 during peak temperatures in the attic with gable vents and roof vent opened.

The fire dynamics changed significantly when a hole in the roof was created. In some of the experiments a 4 ft. by 4 ft. hole was opened over the center of the attic. This simulated a vertical vent performed by the fire service, burn through of the sheathing by the fire, or failure of a skylight. Once the hole was opened, the products of combustion exited efficiently and a large volume of replacement air entered the attic through the eaves, gable vents, a hole in the ceiling, or combinations of all three of these. This affected the ventilation-limited fire, rapidly increasing the heat release rate. This in turn produced more energy than could be let out by the available ventilation openings. At this point, most of the burning was taking place at the vent locations in the roof, the gable ends, the eaves, and the openings created in the ceiling for suppression efforts. The fire grew at an increased rate, rapidly involving more surfaces such as trusses and the underside of the roof deck. **This relatively well vented attic fire was more difficult to control with the indirect methods applied to the unvented attic test.** This appeared to be the result of two phenomena. First, much of the steam produced by conversion followed the fire gas convection path out of the attic before the indirect attack process had full effect. Second, there were many surfaces burning at and around the ventilation openings that had to be wetted and thus cooled with direct water application in order to stop the combustion process. **This, "open up above and then attack it from below" tactic can and has been successfully used at attic fires. However, it can create a large amount of property damage and puts both civilians and firefighters at high risk during the initial stages of the operation if not timed properly.** This is due to the potential for uncontrollable fire growth, fire blow back into the occupied space, and even smoke explosions.

In the ventilated roof experiments, the suppression tactic was deliberately executed after the roof was opened and the fire accelerated in order to test and record the challenges presented when ventilation outpaces suppression. The speed at which uncoordinated attic ventilation and suppression leads to uncontrolled fire growth depends on a variety of conditions. The concentration of unburned fuel (smoke) in the attic, the amount of fuel burning prior to becoming ventilation-limited, the size and placement of inlets and outlets, and the length of time the fire was ventilation-limited prior to receiving oxygen will all impact the pace at which the conditions change. If the attic fire has not yet burned through the roof upon arrival, the responding fire department has an opportunity to control the vertical ventilation timing and thus the fire's growth. Water can be applied to the attic space through eaves or gables by removing ceiling on the interior or through any readily available or easily created opening. **Once initial water absorbs some energy, a vertical vent will assist the crews with suppression and overhaul because standard fire ground ventilation tactics will be sufficient for exhausting the smoke and fire gasses produced by the remaining fire as long as water is sufficiently applied to burning surfaces as the added air will allow the fire to recover.** While not directly tested in these experiments there are several ways to stay ahead of the fire and wet the burning surfaces such as being prepared to quickly gain access to the attic space by utilizing an attic ladder and getting a firefighter with a hoseline partially into the attic to be able to adequately see and wet burning surfaces. This allows more ceiling to be left in place which will not impede other operations such as searches.

In some situations, the products of combustion from the ventilation-limited attic fire can be forced down into the living space through openings such as light fixtures, ceiling fans, access hatches, etc., thereby reducing visibility and occupant survivability before the arrival of interior crews. In this situation, vertically ventilating ahead of suppression <u>may</u> be used to assist the crews in conducting search and rescue operations and advancing a line inside the structure. But it must be understood that the reduction in smoke in the living space does not necessarily mean a reduction in fire size in the attic. When the roof is opened, the observable effect is fire and smoke exiting the attic. What is not so readily observable is the increased air flow that follows the exiting smoke and accelerates the fire in the attic. Firefighters must also keep in mind that the flaming fire they see exiting the opening only occurs because the fuel rich smoke is thinning out as it exits the attic. The fire in the attic is still likely ventilation-limited with the potential for more rapid fire growth as more openings (particularly from below) are added. Also keep in mind lessons learned from previous vertical ventilation experiments conducted by UL. **In the absence of suppression, the positive effect of a roof opening is a very short lived phenomena. The accelerating fire will quickly overwhelm <u>all</u> openings and push back into the occupied space.** Firefighters create an access to low pressure as then enter the front door and make their way into the building. This creates a flow path that can draw the accelerating attic fire toward them, overwhelming their position.

These experiments clearly demonstrate that **increased visibility does not automatically mean a reduction in the size of the fire over your head.** Look and listen for other signs that the fire is being controlled. Understanding the fire dynamics of attic fires will assist firefighters in making better decisions on the fireground, with an emphasis on constantly monitoring conditions around them and looking for confirmation through radio reports, etc.

10.6. Plastic ridge vents can affect size-up and fire dynamics

Two common attic vents are mushroom vents and continuous ridge vents. Mushroom vents are commonly made of metal and allow fire gases to exit for the duration of the fire. They are installed on the slope of a peaked roof and the material, whether metal or plastic, flows away from the opening if the mushroom cap melts. Continuous ridge vents are nearly always made of plastic and allow fire gases to vent until they heat up. **As the vents heat, the plastic melts and collapses on the opening at the peak, creating a very effective seal.** The sealed opening (the equivalent of 10 ft^2 in these experiments) restricts air flow out of the attic, leading to a ventilation-limited fire. Thus, the true nature of the fire may be hidden during your size up. **Once the ridge vent seals, the eaves will act as both the source of air as well as the exhaust and you may notice a pulsing of smoke out of the eaves.** This is a sign that you have a ventilation-limited fire in the attic.

Figure 10. 31. Smoke coming from the ridge vent.

Figure 10. 32. Ridge vent after sealing.

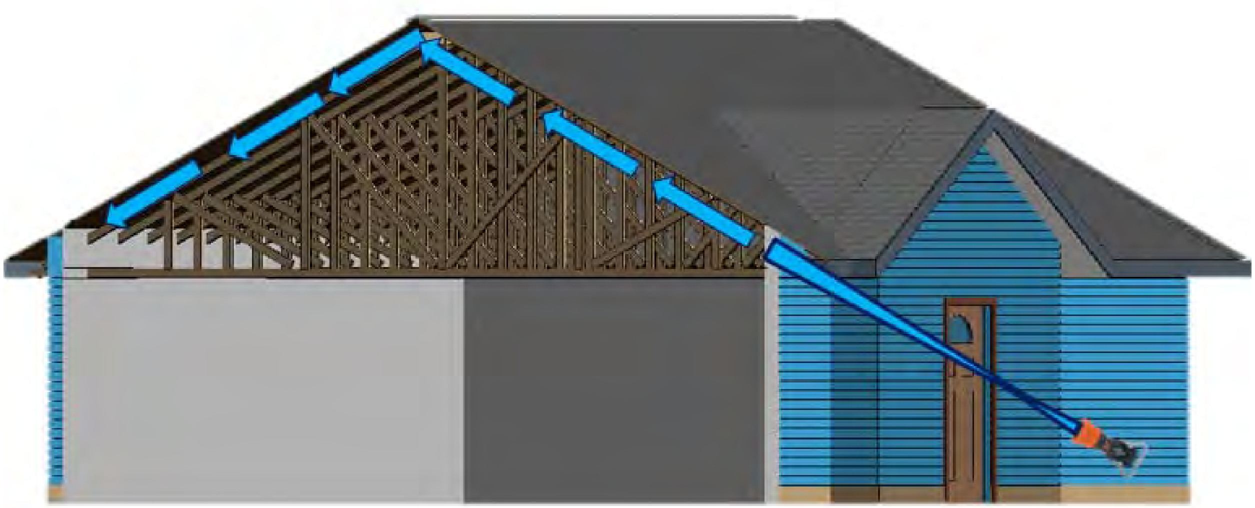
Figure 10. 33. Smoke pulsing from eaves after ridge vent sealed.

Figure 10. 34. Ridge vent after experiment.

Figure 10. 35. Section cut away after experiment to see ridge vent seal.

10.7. Wetting Sheathing with an Eave Attack Slows Attic Fire Growth

The sheathing accounts for over 50% of the exposed surface area of the construction material fuel in a typical attic. The sheathing is also in the best location to burn. Air enters at the eave line, runs along the underside of the sheathing and exits through the peak, making this an optimal place for burning. **If crews wet the sheathing, either as part of an offensive fire attack or defensively to slow fire spread to uninvolved sections of the structure, the major flame spread mechanism in the attic is eliminated until the moisture evaporates.** The other construction material fuel in the attic is the trusses. The typical truss spacing of 24 inches assisted in limiting fire spread from truss to truss. Wetting the sheathing further reduced truss to truss fire transmission. Whether or not it is already involved in fire, wetting the sheathing allows crews to ventilate or access the attic with a greatly reduced potential for rapid fire growth.



Removing the soffit and flowing water along the eave line of these structures was the most effective way to gain the upper hand on a fire that was venting through the roof. After the fire ventilates through the roof, increased air is entrained through the eaves and burning is increased. An eave attack puts water on these burning surfaces by flowing it up one side of the attic to the peak, and then running down the other side. As water wets the sheathing, it also rains down on the burning gases and other burning contents in the attic, extinguishing even more fire. In these experiments, a 1 ¾ in. handline flowing approximately 150 gpm easily had enough penetration to wet a 30 ft. by 36 ft. attic space under a 6/12 pitch roof system. Larger attics may require larger flows with more penetrating ability. Additionally, if bird blocking or other obstructions such as solid wood eaves are in place, they may need to be removed for this tactic to be effective. Careful preplanning, site visits and the ability to profile buildings in your response area will assist in the decision to make use of this tactic on the fire ground.


Figure 10. 36. Conditions at the start of eave attack during Attic Experiment 4


Figure 10. 37. Conditions at the end of eave attack during Attic Experiment 4

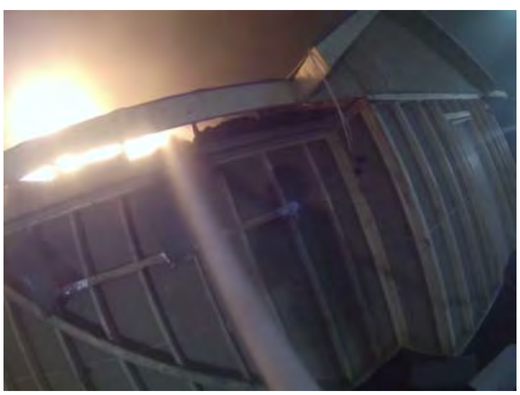


Figure 10. 38. Helmet cam view of water flow into eaves.


Figure 10. 39. View into the eaves after Attic Fire Experiment 4

10.8. Attic construction affects hose stream penetration.

The trajectory of the hose stream directed into an attic space is affected by the materials and construction practices used to build attics. In legacy construction, wood rafters were used to support the roof structure. Now, in modern construction, engineered trusses using less material support the roof structure. Both of these construction methods were found to limit the effectiveness of streams when traditional water application methods were used. Firefighters attack room and contents fires by bouncing the stream off the ceiling and raining water down on the fire. The geometry of the rafters, and especially the trusses, broke up the stream whether applied from the occupied space below or from a gable vent, severely restricting the penetration needed for this tactic to be effective in attic fires.

During the tests, only 1/3 of the attic was affected when water was applied through the gable vent, regardless of the angle of attack. When attempted from the interior, a large amount of ceiling needed to be removed in order to effectively wet all the surfaces in the attic.

The most effective water application takes into consideration the construction of the attic, using the natural channels created by the rafters or trusses to direct the water onto the vast majority of the surfaces. Application of water through open eaves along the entire eave line allows water to impact over 2/3 of the burning surfaces in the attic space. When solid eaves are encountered or an interior stream placement is chosen, the same tactical concept can be employed. The crew enters the structure and makes its way to an exterior wall that is parallel to the line of the eaves. Opening up a trough along this wall exposes the roof deck in much the same way as opening up the eaves. Alternatively, when the building layout makes the peak more readily accessible, (for instance, a building with a center hallway) a trough can be opened along the centerline of the structure immediately below the line of the peak (Figure 10. 40). Water is then directed toward the peak at as severe an angle as possible, alternately flowing water down both sides from the peak to the eaves, wetting the sheathing and raining down on the other combustible contents in the attic.

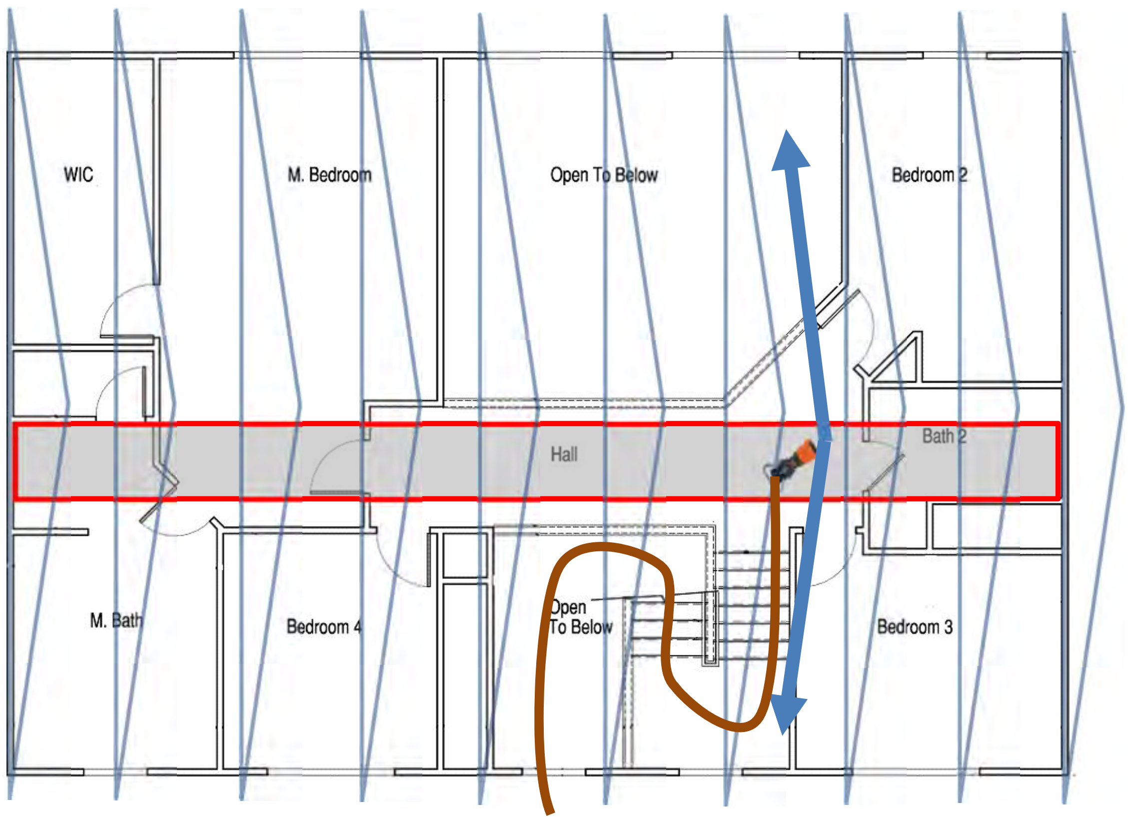


Figure 10. 40: Floor plan of a 2-story house showing where to open drywall on a center hallway layout to effectively apply water to the sheathing by flowing down each rafter bay toward the front and rear of house.

10.9. Consider flowing up instead of down with a master stream

When a fire grows in the attic space and burns through the sheathing or out of the gable ends, crews may be called out and transitioned to a defensive operation. This has commonly included putting up an aerial device and flowing water into the holes in the roof or gable ends with fire coming out of them. This tactic typically fails to put much water on the underside of the roof deck or onto any burning material or contents that are not directly beneath or in the immediate vicinity of the hole. Large portions of the roof must burn away before angles of attack are created that allow water to reach the burning materials. As an alternative, **consider using an aerial device or portable ladders and hand lines to open up the eaves and flow water into the attic** as was described in earlier tactical considerations. **This approach could result in controlling the fire enough to permit firefighting crews to transition back inside the structure to complete searches, suppression, and overhaul.**

If collapse is a concern, firefighters should not be placed in the collapse zone to accomplish this tactic. A consideration when transitioning to the interior, when large amounts of water were flowed into the attic the insulation will hold water and allow the ceiling to sag and collapse in sections. In these experiments there was fiberglass batt insulation that protected the bottom chord of the truss so collapse of the roof system did not occur but sections of gypsum board and wetted insulation did fall into the interior where crews could be operating. Not all roof systems are insulated in this manner so other roof collapse hazards could exist.

Figure 10. 41. Master stream flowing down into attic fire and not into eaves.

Figure 10. 42. Potential to flow water where fire is coming from instead of where fire is.

10.10. Knee Wall Fire Dynamics

Utilizing the upper ½ story of a structure for living space creates unique compartmentation not found on lower levels of the building (Figure 10. 43 through Figure 10. 46). The interior living space is surrounded on three sides by void spaces separated only by drywall and possibly insulation (Figure 10. 47)**. During a structure fire, it is possible for fire to enter void spaces and surround crews conducting interior operations** before they notice a rise in temperatures or see any signs of fire. Any penetration into the void space from the interior creates a flow path, allowing fire to spread into the interior and exposing the crews. This fire spread may not occur immediately following the opening of the wall or ceiling, as the void space fire is likely ventilation-limited. Thus, firefighters may breach a separation and then continue further into the structure. **Even though there is a delay between making the breach and the change in conditions, once initiated, the transition to untenable conditions in the area of operation occurs in seconds.** In Figure 10. 48 the temperatures at 3 feet in the attic increased 300 degrees in 5 seconds. When things go bad, they go bad fast.

Figure 10. 43: North 9th St attic prior to finishing

Figure 10. 44: North 9th St attic after finishing

Figure 10. 45: North 9th St from outside

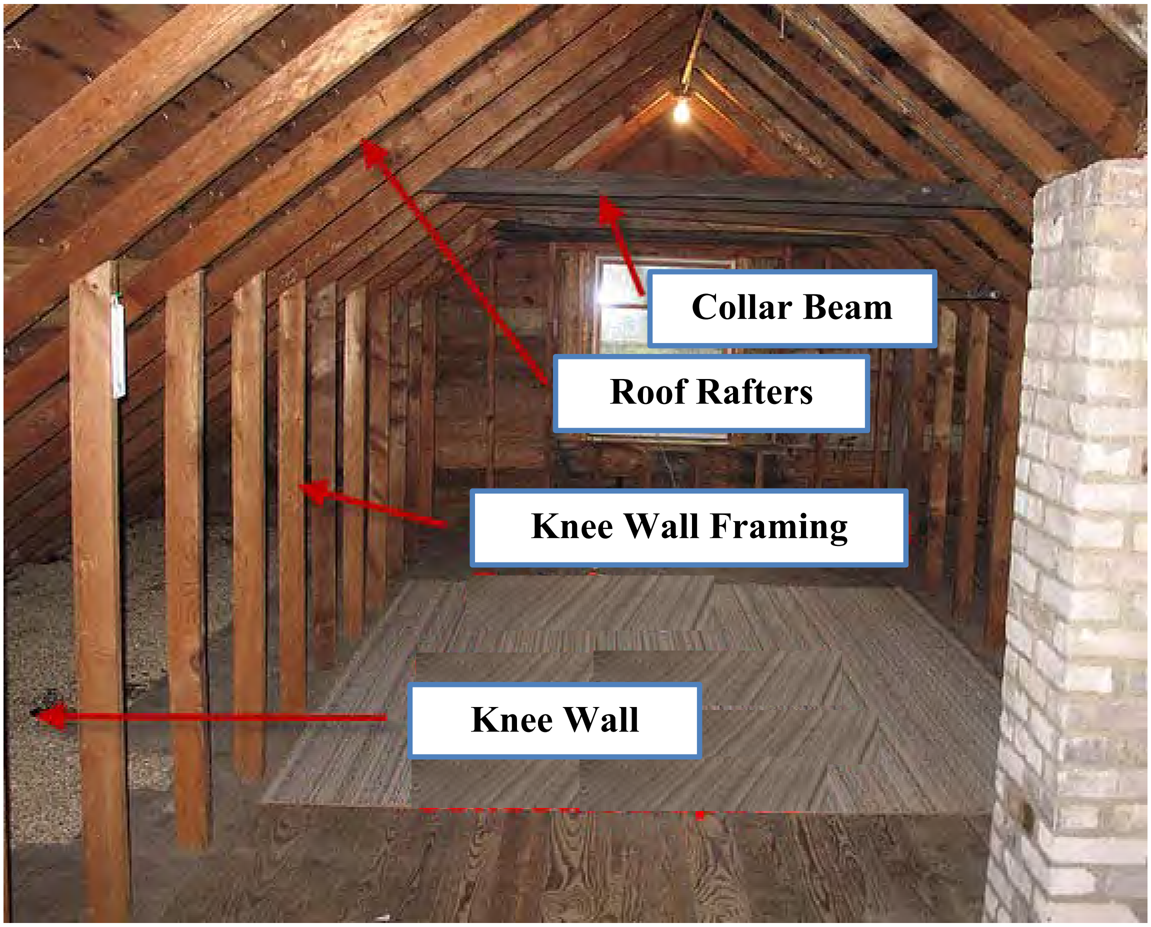


Figure 10. 46. Knee wall construction details with drywall removed.

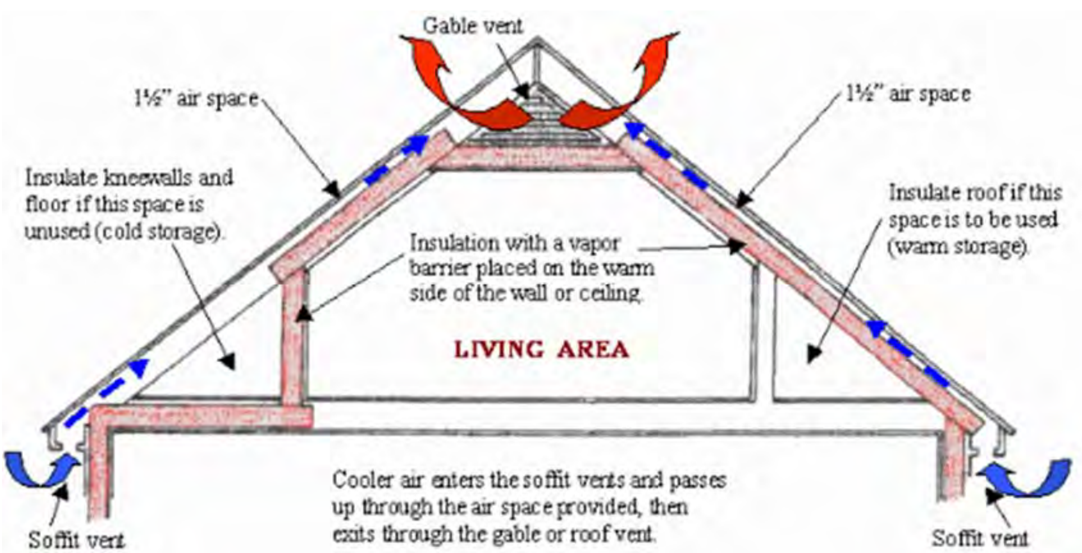


Figure 10. 47. Potential ventilation scenarios for 1/2 story structures.

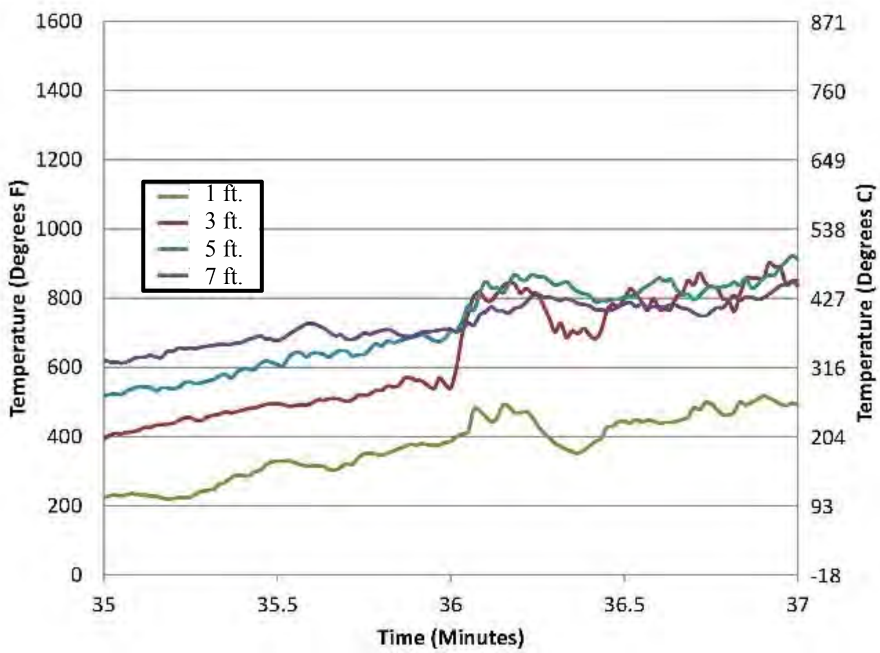


Figure 10. 48. Temperature in living space during Knee wall field experiment shows fast temperature change at 3 ft. crawling height of firefighter.

Knee wall construction often provides the potential for ideal fire growth, with air entering low at the eave line and combustion gases exiting the peak through mushroom vents, ridge vents or gable vents. The limited natural ventilation keeps the fire small and it normally becomes ventilation-limited. At the same time, the relatively large open space behind the knee wall allows for the heating of large amounts of fuel to near its ignition point. Subsequent ventilation, either by breaching the interior barrier or by venting at the roof, provides the necessary flow path to rapidly grow the fire to flashover. When the barrier between the void spaces and the occupied space fails or is breached, crews operating on the interior may find themselves trapped between the new flow path and their means of egress. Conditions will change even more rapidly if windows in the attic were opened or taken out, a common tactic employed to improve visibility and assist the crews in locating the fire and/or victims. Open windows provide even more air to mix with and ignite the rich fuel coming out of the knee walls.

In these experiments, UL replicated a scenario that has played out on many fire grounds (Figure 10. 49). The attack crew enters the attic space at the rear of the structure, chocking the doors open as they enter the attic. Then they ventilate the window at the top of the stairs in an effort to improve visibility and reduce heat in the occupied space. As smoke lifts, they work toward the front of the structure looking for victims and the source of the fire. At the front, they ventilate the front window to establish horizontal ventilation. With the hose line at the front of the attic, a firefighter in the rear of the attic near the stairs opens the knee wall to look for the fire. When this knee wall is opened, 3 flow paths are created. The previously hidden fire is connected to openings at the entrance door, the rear window, and the front window. Air from the attic enters the knee wall and mixes with the ventilation-limited fire. When the mixture is right, there will be a rapid increase in the energy produced and fire will travel along all the available flow paths endangering and possibly trapping firefighters in the attic.

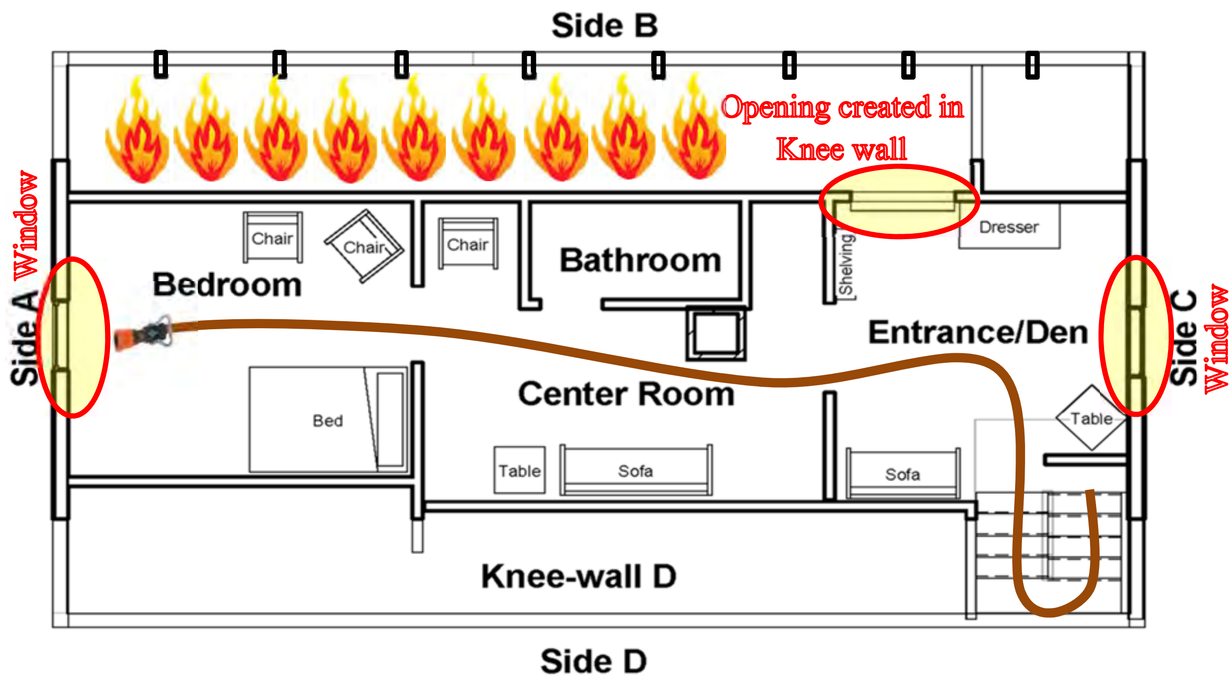


Figure 10. 49. Diagram with details about crew movement and ventilation locations

10.11. Apply water on a knee wall fire at the source and toward the direction of spread before committing to the attic.

Applying water utilizing the same path the fire took to enter the void space may be the most effective method at slowing fire growth. If the fire starts on the outside of the structure, enters the knee wall due to auto exposure through a window, or enters the knee wall through interior wall cavities (balloon flame construction as an example) controlling the source is imperative to a successful fire attack. After controlling the source fire direct water to the potential path of extension into the knee wall. This will be the eaves from an exterior fire or exposure out of the window from a room fire or the interior wall or ceiling cavities from a room fire. **Water application to the knee wall will not be effective until the source below it is controlled with direct water application to the source.** Once the source fire is controlled, crews can more readily and safely gain access to the void spaces, extinguishing any active fire in the void and wetting all exposed surfaces. This will prevent regrowth of the fire. Attempting to initiate fire control only through a breach into the knee wall, or before the source fire is effectively controlled, can place the attack crew in the flow path of a fire. If they cannot effectively reach the source from their position, they will be pinned down as the fire continues to spread and grow in the interconnected voids, eventually breaking out around or even behind them.

Figure 10. 50. Fire on second floor with extension into the knee wall. Water should be flowed to extinguish the room (from inside or outside) and then flow into the eaves (from inside or outside) before accessing the attic.

Figure 10. 51. Fire on outside with extension into the attic. Water should be flowed to extinguish the exterior fire and then flow into the eaves before accessing the attic.

10.12. Interior operations on knee wall fires

Knee wall construction creates interconnected void spaces where the wooden structural members provide a relatively large surface area of exposed fuel along with air flow conducive to spreading fire (Figure 10. 52). The experiments demonstrated that getting effective stream reach and penetration inside a knee wall and other attic voids is hindered in much the same way as are streams applied into open attics through gable ends or from the floor below (Figure 10. 53). In both cases, structural members effectively broke up the stream before it could successfully penetrate the fire area. The experiments also demonstrated that water should initially be applied into the knee walls at multiple locations through small holes, in order to suppress the burning gases, before large sections of the knee wall are opened for complete extinguishment. This tactic will maximize the benefit of energy absorption through steam conversion while minimizing the spread of fire along the flow path created by the openings made for the nozzle. Once the gases are suppressed or cooled, focus on getting water into the rafter bays where air moving from the eave line to the peak will sustain and accelerate the remaining fire. This is similar to the concept that makes the eave attack successful; the sheathing is where the air and fuel come together most effectively, so this is where suppression efforts should be focused. Don't wait to see fire in a knee wall before you apply water to the void space or the surfaces. **Tests have demonstrated that the most effective way to get a handle on knee wall fires is to control the source fire, cool the gasses prior to making large breaches in the barrier, and <u>then</u> aggressively open the knee walls to complete extinguishment, focusing on wetting the underside of the roof decking.**

Figure 10. 52. Knee wall access showing difficulty of flowing water past the rafters.

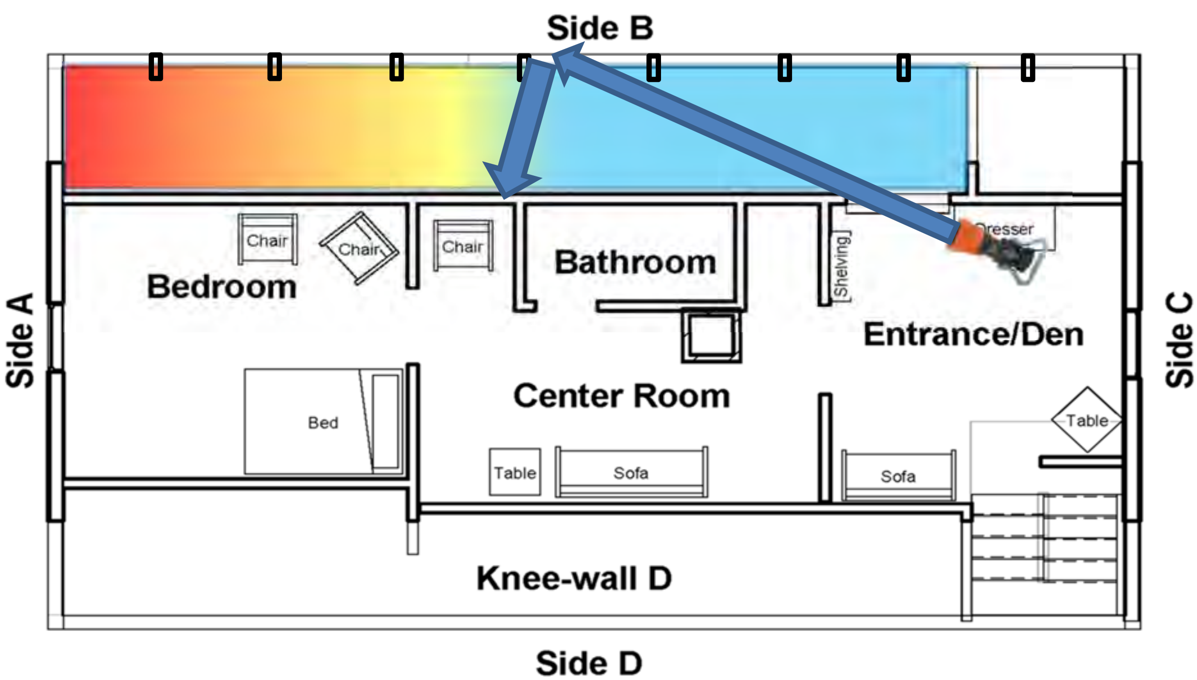


Figure 10. 53. Diagram showing deflection of water flow and inability to penetrate full length of the knee wall.

11. Future Research Needs:

11.1. Exterior Fire Spread

Although this project encompassed 28 separate wall ignition tests and 3 flame spread tests the work was only effective at developing some generalizations about ignition and flame spread on the exterior of residential structures. Additional work is needed to fully quantify the ignition of exterior walls and resulting flame spread potential. The configurations of siding, sheathing, and insulation are numerous and this study only compared a fraction of the options. More work is needed to look at the vast ignition sources against the wall construction types. Specific areas of interest are mulch fires where a smoldering may cause an exterior fire siding fire and heat flux from an adjacent structure fire.

Additionally exterior fires present a significant life safety and property hazard as they transition from the siding, up the exterior wall, into the eaves and attic space. This project looked at two different attic configurations. One with vented eaves, using plastic baffles to provide airflow to the attic space and one with spray foam insulation preventing any airflow into the attic. The transition to the attic was very different for theses construction practices. Additional eave configurations such as solid wood boards and aluminum soffits are prevalent and would also have different fire spread characteristics. A current code proposal exists for the North Carolina Residential code which would require “protected soffits”. These soffits would be required on “buildings with less than a 10 feet fire separation distance”. Protection is provided by attaching “fire retardant treated wood, 23/32 inch wood sheathing or 5/8 inch exterior grade moisture resistant gypsum board” under the vinyl or aluminum soffits. Further research is required to effectively quantify the potential for an exterior fire to enter the attic space specifically with the construction practices listed above.

Further research is needed to understand the potential for a fire on the exterior vertical surface of a home to spread to adjacent homes, specifically at what separation distance this can occur. This work is vital for firefighters who are tasked with determining the primary line placement, whether it be to the exterior, interior or adjacent structure. In addition research is needed to test the theory that fire can spread from the vertical exterior wall to the interior of an adjacent structure via radiation heat transfer through a closed window. Current incident prioritization is to deploy the line inside the adjacent exposure to stop fire spread, which may or may not be the highest priority.

11.2. Attic Suppression Tactics

Attic fires present many hazards to firefighters and due to their complexity require further study. The tactics employed for suppression in this project represent a fraction of the methods available to firefighters in applying water to an attic fire. Tactics such as aerial master stream application through a vented roof, piercing nozzle through a ceiling or bresnan distributor through the roof vent should be evaluated for suppression effectiveness in both confined and ventilated/burned through attic fires. Due to the funding of this project only a single point of water application was possible. Applying water at multiple points within the structure also could have an impact on the ability of the stream to reach the surface of the burning material. This includes applying water from below at the center line of the attic, directing a stream toward both of the load bearing walls.

This project has shown the construction of the attic has an impact on the ability to apply water to the burning surfaces. This study focused on peak truss roof attics with lay in bat insulation. This is only one type of attic construction/insulation method. The effectiveness of various suppression tactics should be evaluated for the other attic constructions to verify the findings and extend the tactical considerations to encompass more attic construction types. Specifically spray foam insulated attics where the fuel load is significantly larger and the properties of the fuel different from the truss construction evaluated.

The natural ventilation built into the construction of attic spaces has an impact on the fire behavior of the space as seen in this testing. Attics used in this work included eave vents, a ridge vent and gable vents. In construction practice not all three of these would be utilized. Future work to understand the implications of providing more natural ventilation or less natural ventilation on the behavior and growth rate of attic fires would provide firefighters with a greater understanding of the fire hazard faced during an attic fire.

11.3. Knee-Wall

Although two separate acquired structures were utilized in this project, the ability to develop more than a general understanding of the fire hazard and suppression technique effectiveness for knee-wall fires was limited. Further work on knee-wall or concealed space fires is need to aid firefighters in making tactical decisions on the suppression of these fires. Not only does this work apply to knee-walls but also to void spaces created when unique construction practices are employed. Any construction practices which creates a void space where fires could develop and spread unchecked and unnoticed will cause a hazard for firefighters. Understanding how these fires start, grow and spread will aid firefighters in their ability to effectively deploy resources to protect occupants, limit firefighter injuries and deaths. In addition their ability limit property damage would be increased by the understanding of these concealed space fires.

Many of the same suppression tactics discussed for attic fires should be evaluated in knee-wall and concealed space fires. The impact of the construction and insulation of these spaces on the fire behavior should be studied more in-depth to understand the timeline of incident priorities. Limited research exists on how opening these spaces to uncover hidden fires will affect the fires growth and spread. This project identified the rapid fire growth similar to room and content fires however it was difficult to establish a timeline for how gaining access to the space effects fire growth. Future research evaluating how the volume of the concealed space, the area of access opened and the availability of clean air to provide oxygen to the fire will effect fire growth is needed.

12. Acknowledgements:

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In addition we would like to acknowledge the Milwaukee Fire Department. The acquired structures utilized in the field experiments along with the manpower and support provided were vital. Without their tireless efforts the work on knee wall fires would not have been possible.

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:

Derek Alkonis, Battalion Chief, LA County Fire Department
John Ceriello, Captain, Fire Department of New York
James Dalton, Coordinator of Research, Chicago Fire Department
Sean DeCrane, Battalion Chief, Cleveland Fire Department
Harvey Eisner, Editor Emeritus, Firehouse Magazine
Mike Gagliano, Captain, Seattle Fire Department
Sean Gray, Firefighter, Cobb County (GA) Fire Department
Bobby Halton, Editor-in-chief, Fire Engineering Magazine
Todd Harms, Assistant Chief, Phoenix Fire Department
Ed Hartin, Chief, Central Whidbey Island Fire Rescue Department
George Healy, Deputy Chief, Fire Department of New York
Dan Madrzykowski, Fire Protection Engineer, NIST
Tim Nemmers, Firefighter, Des Moines Fire Department
Mark Nolan, Fire Chief, City of Northbrook (IL) Fire Department
P.J Norwood, Battalion Chief, East Haven (CT) Fire Department
David Rhodes, Battalion Chief, Atlanta Fire Department
Erich Roden, Battalion Chief, Milwaukee Fire Department
John Shafer, Lieutenant, Greencastle (IN) Fire Department

Tim Sendelbach, Editor-in-chief, Firehouse Magazine
Pete Van Dorpe, Assistant Chief, Algonquin-Lake in the Hills Fire Protection District
Matt Verlaque, Firefighter, Arlington County (VA) Fire Department
Chris Willis, Firefighter, Falmouth (KY) Volunteer 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.

Appendix A: Wall Construction Drawings

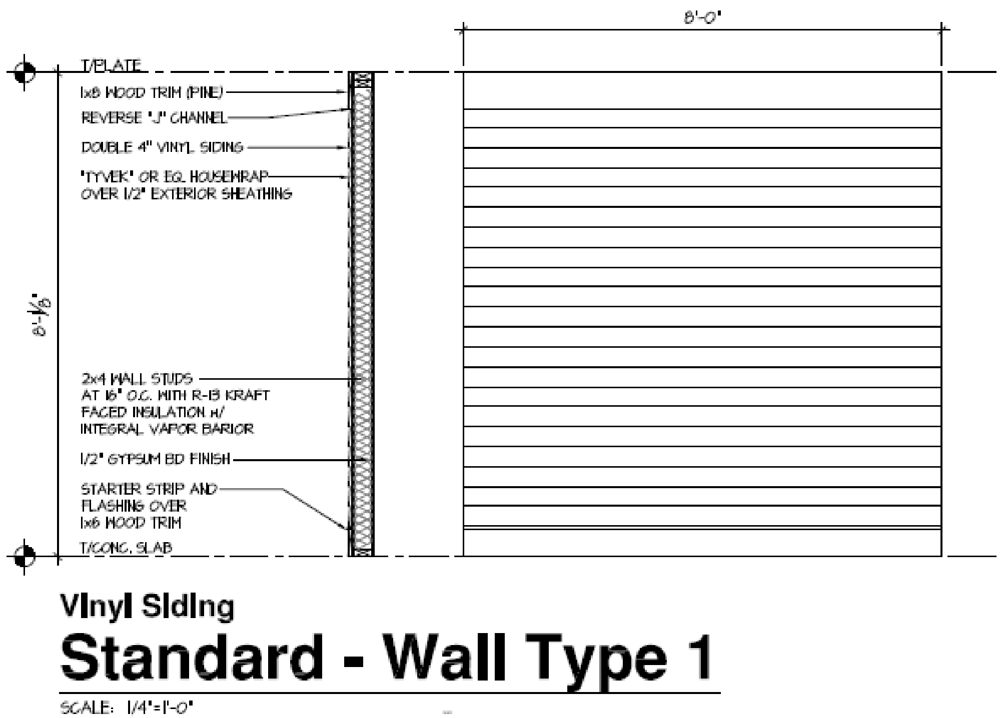


Figure A. 1: Wall Type 1 Construction Drawing

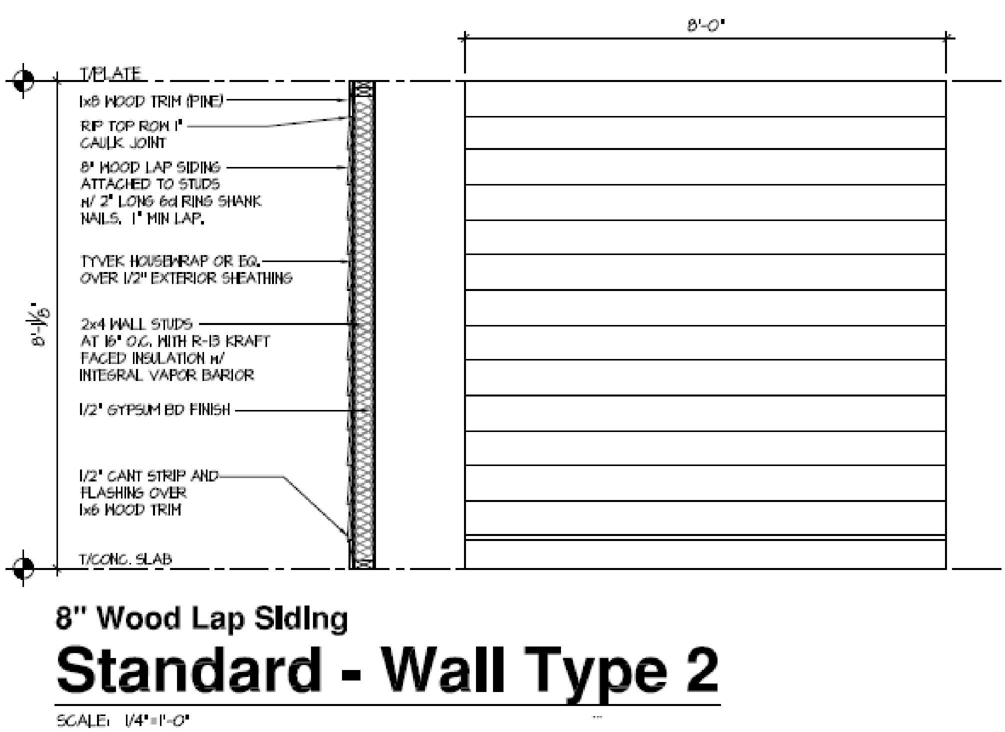


Figure A. 2: Wall Type 2 Construction Drawing

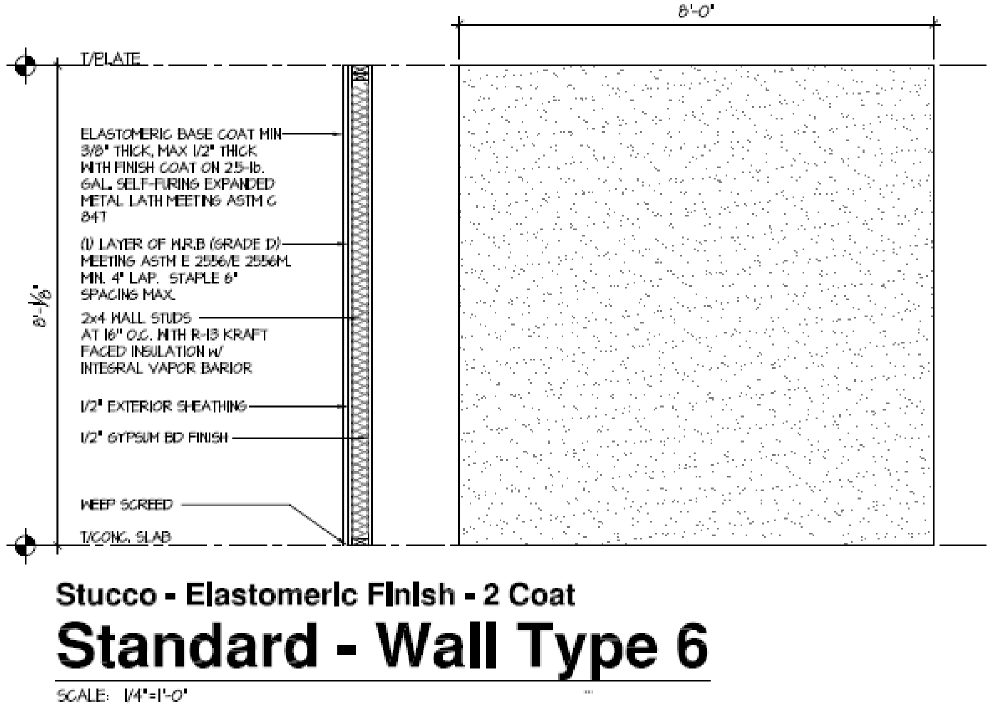


Figure A. 3: Wall Type 6 Construction Drawing

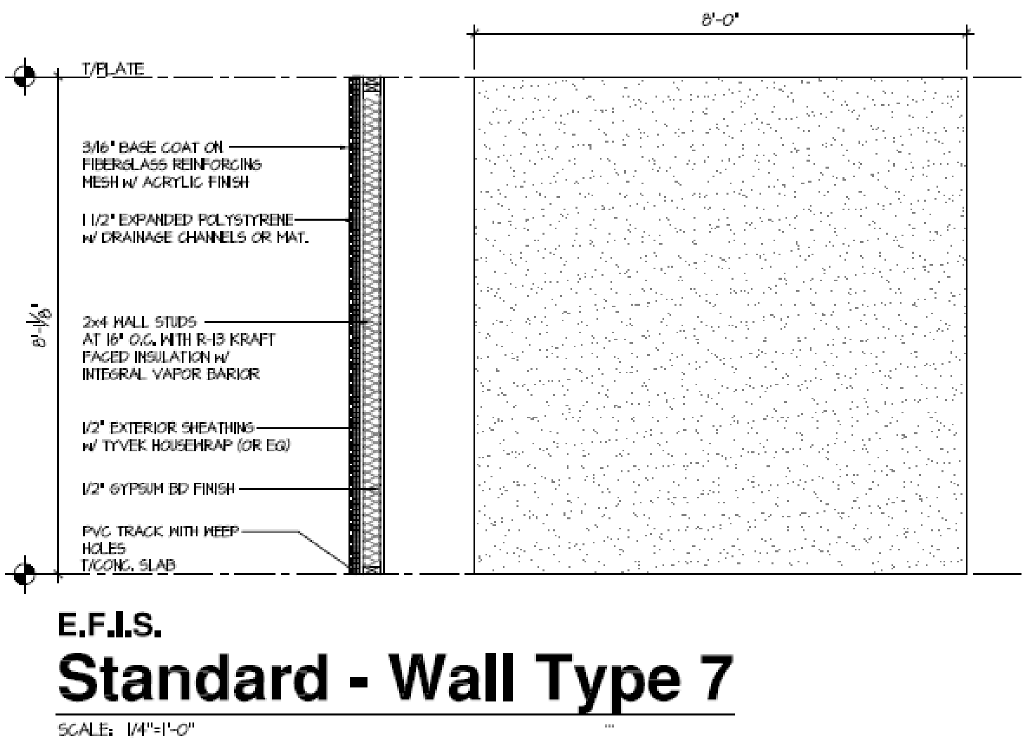


Figure A. 4: Wall Type 7 Construction Drawing

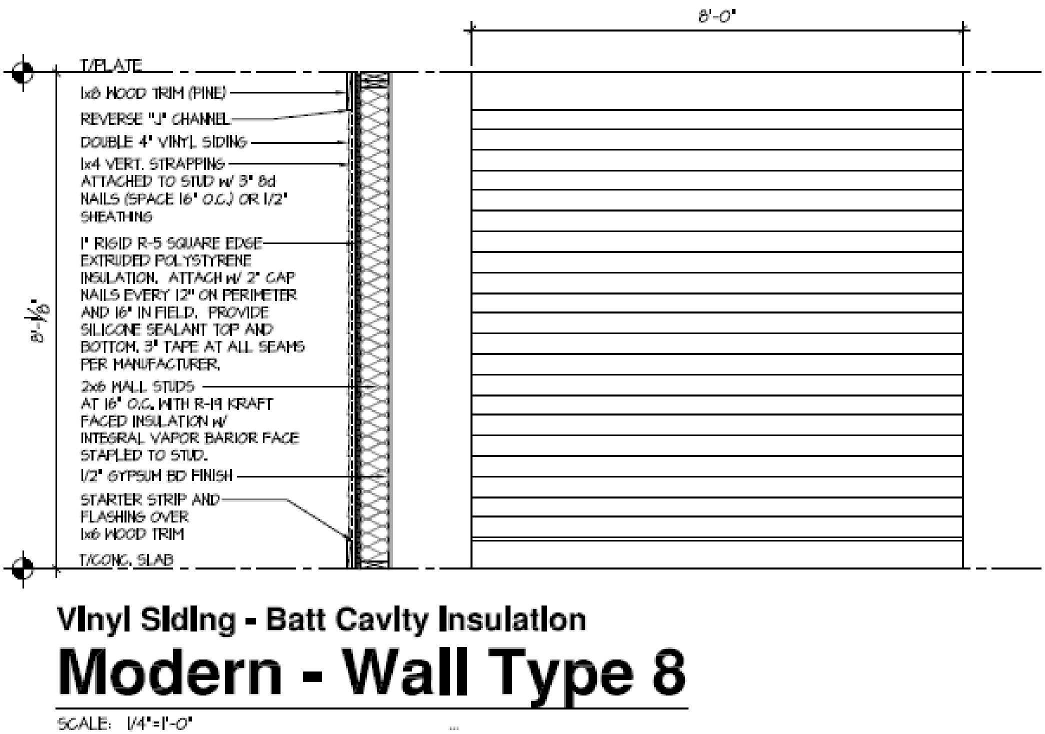


Figure A. 5: Wall Type 8 Construction Drawing

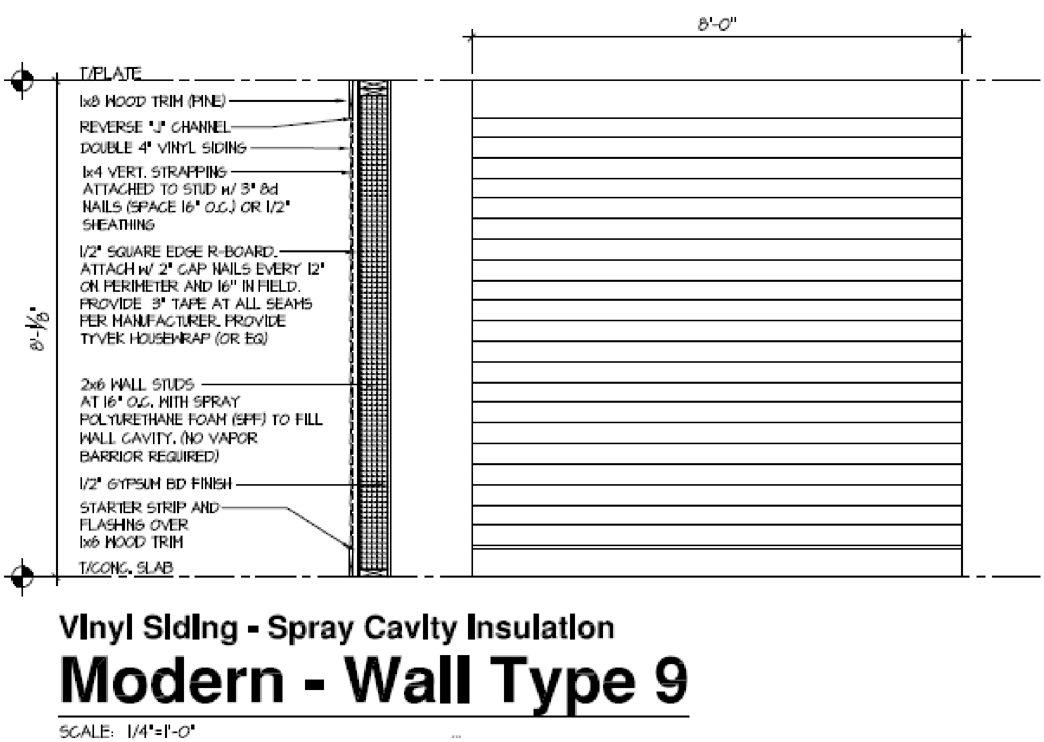


Figure A. 6: Wall Type 9 Construction Drawing

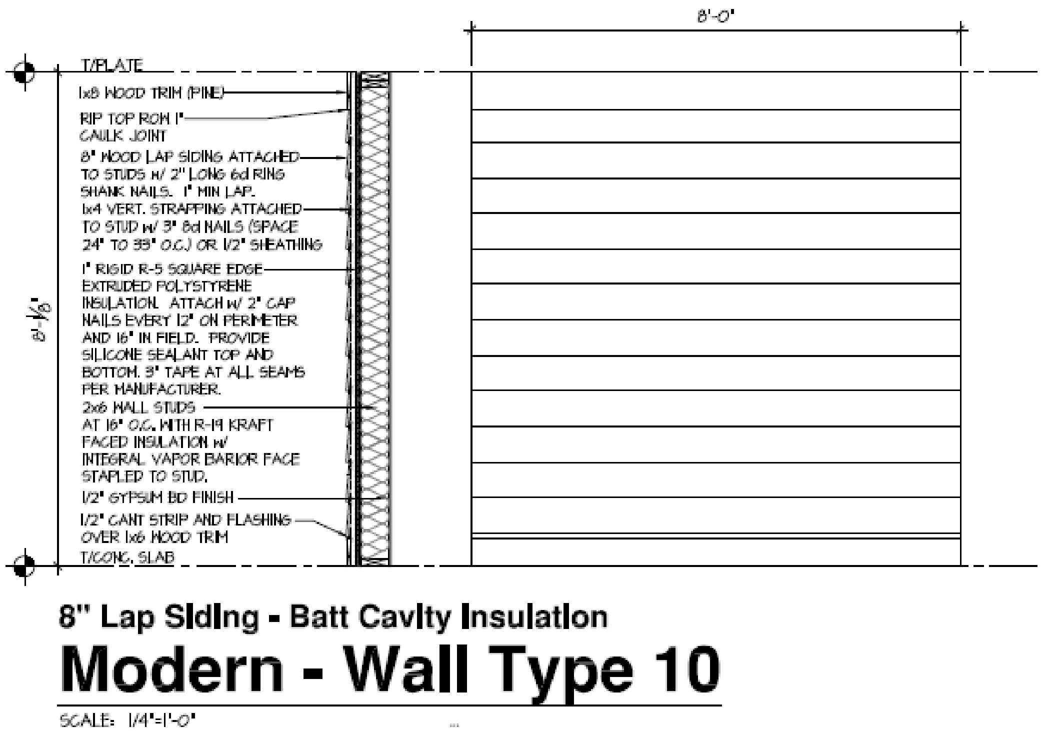


Figure A. 7: Wall Type 10 Construction Drawing

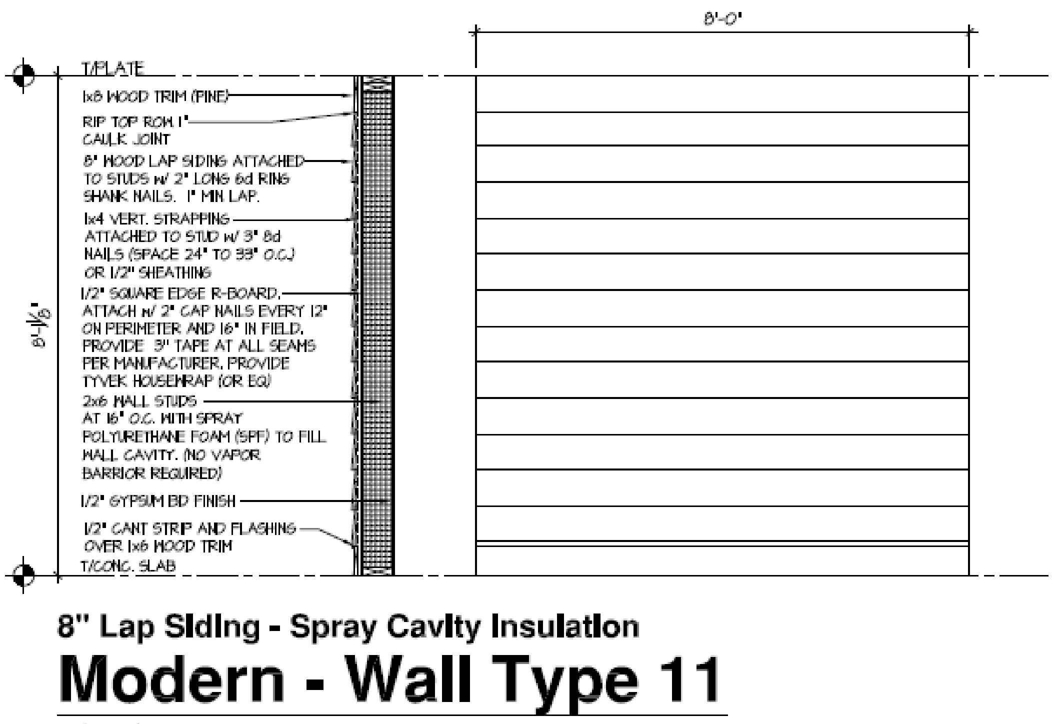


Figure A. 8: Wall Type 11 Construction Drawing

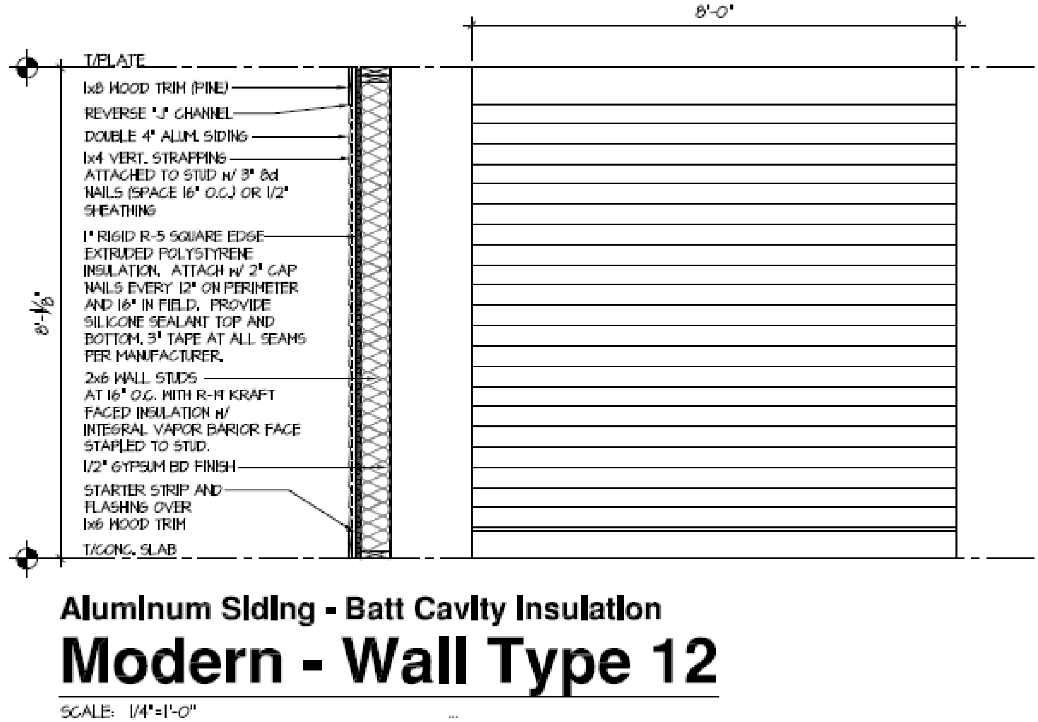


Figure A. 9: Wall Type 12 Construction Drawing

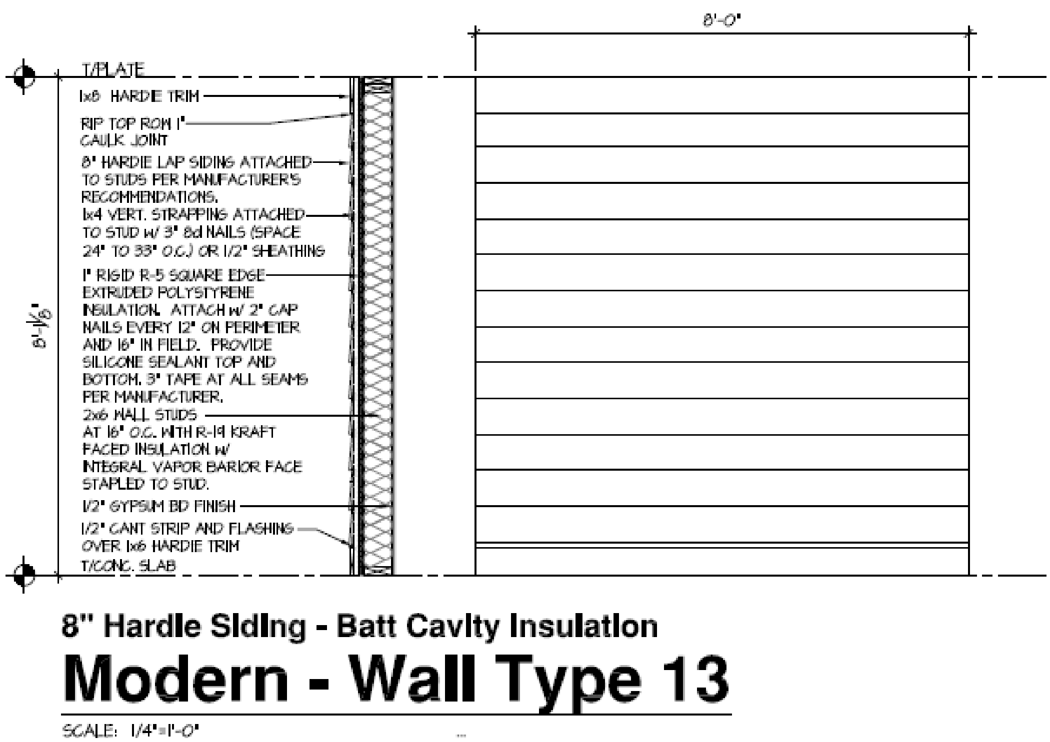


Figure A. 10: Wall Type 13 Construction Drawing

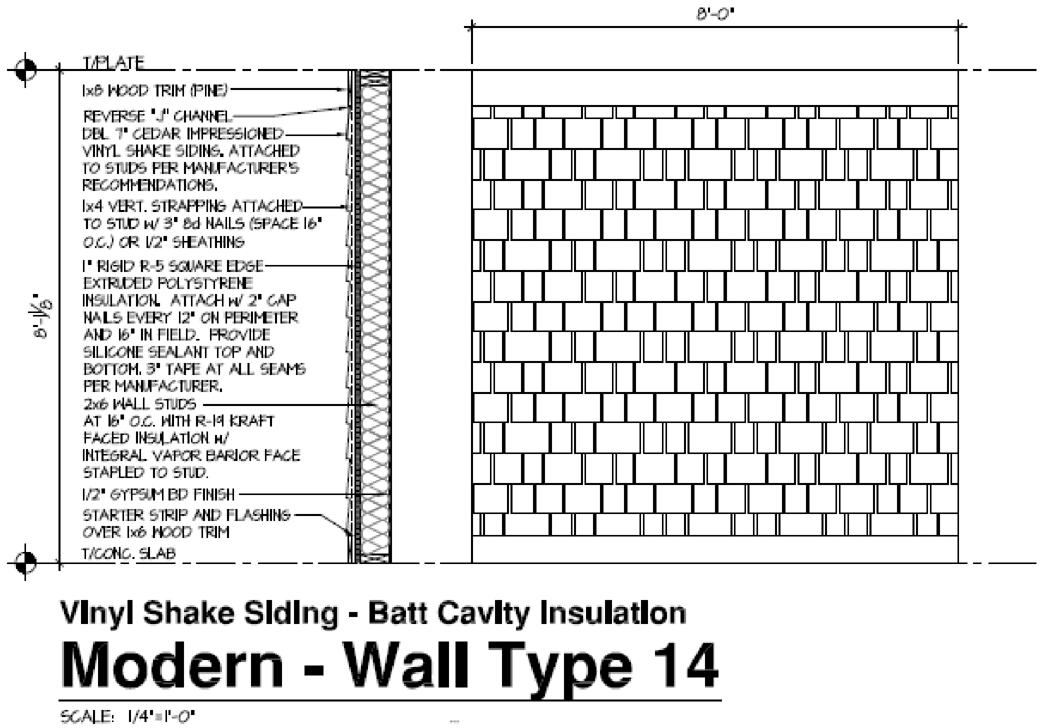


Figure A. 11: Wall Type 14 Construction Drawing

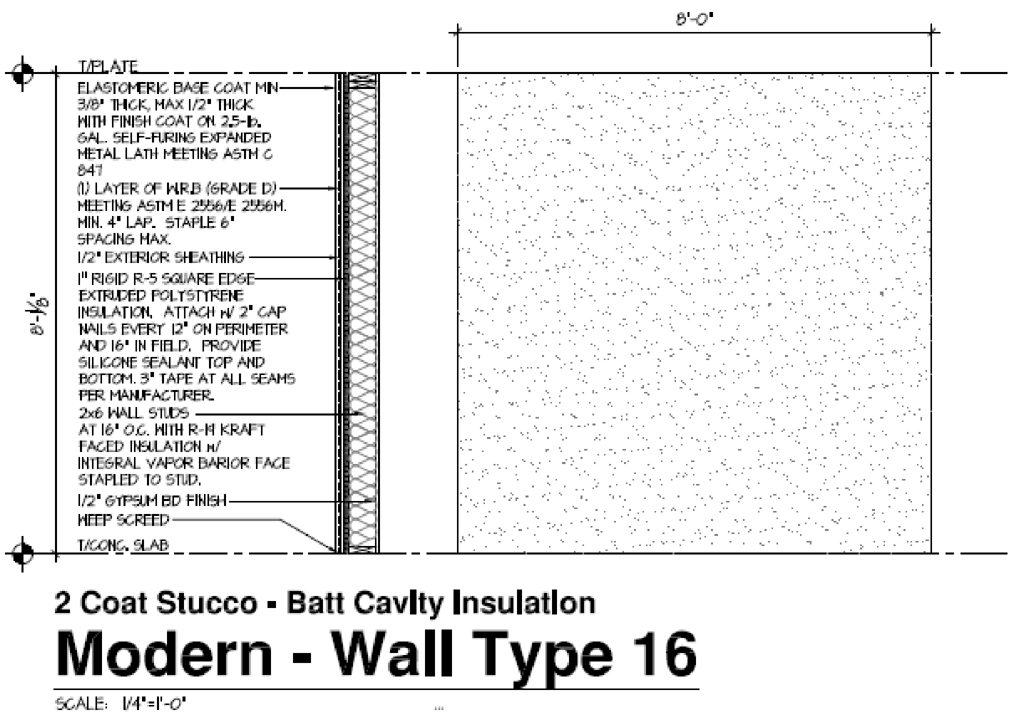


Figure A. 12: Wall Type 16 Construction Drawing

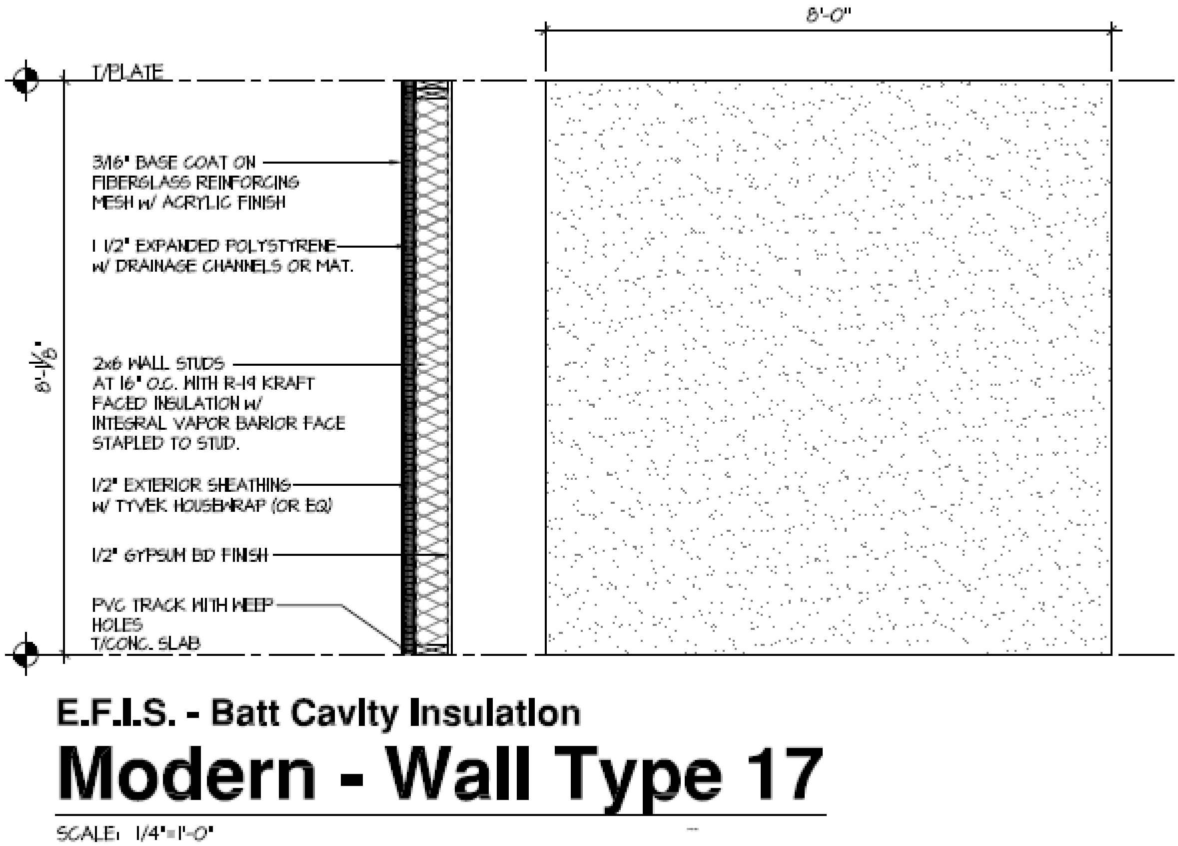


Figure A. 13: Wall Type 17 Construction Drawing

Appendix B: Eave Construction Drawings

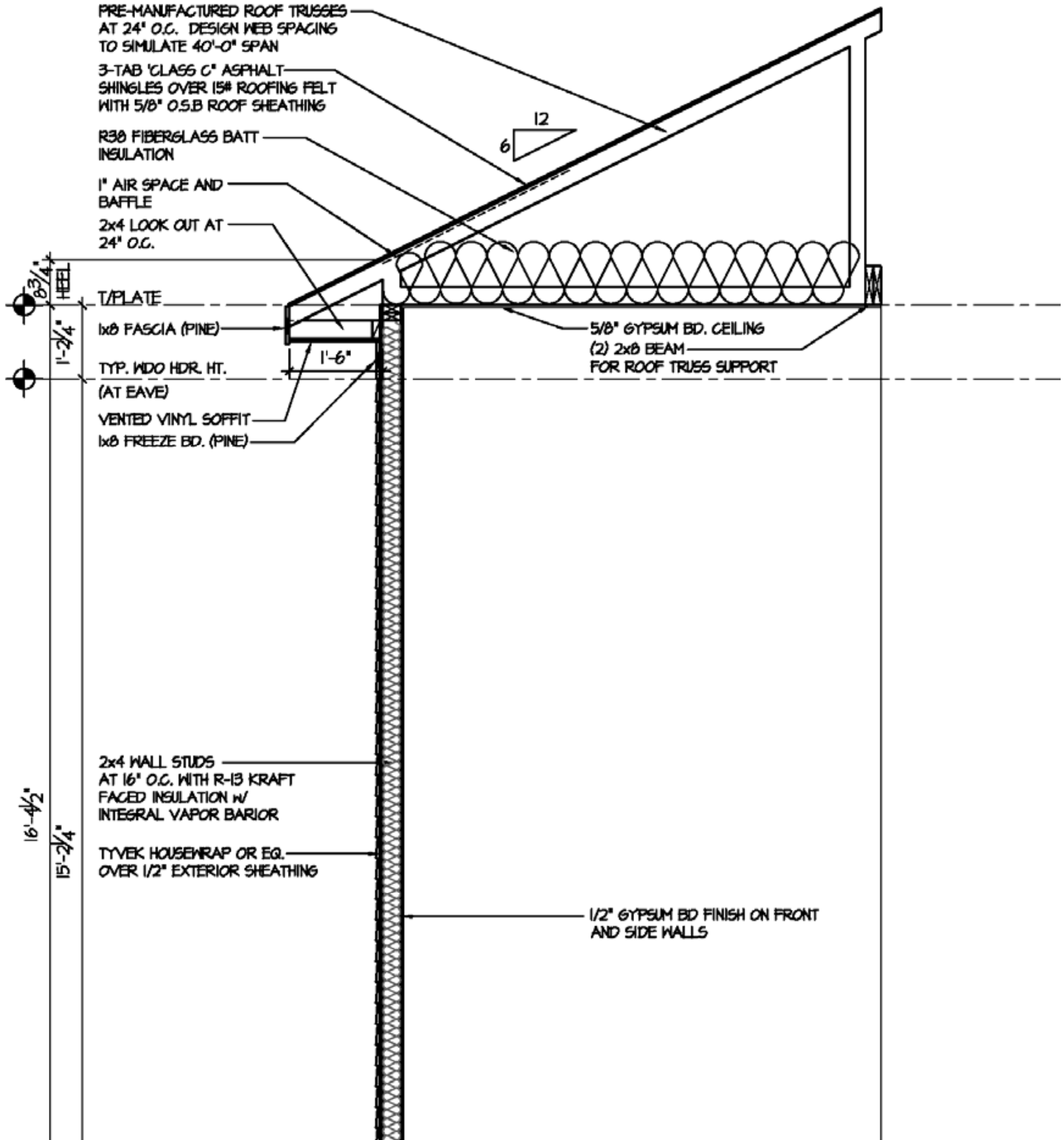
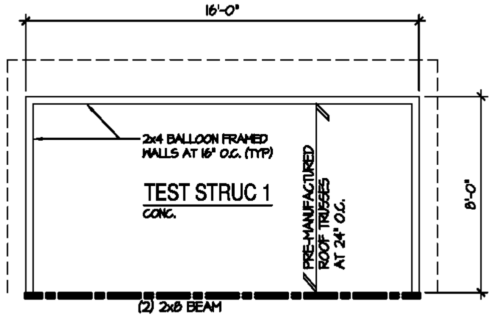


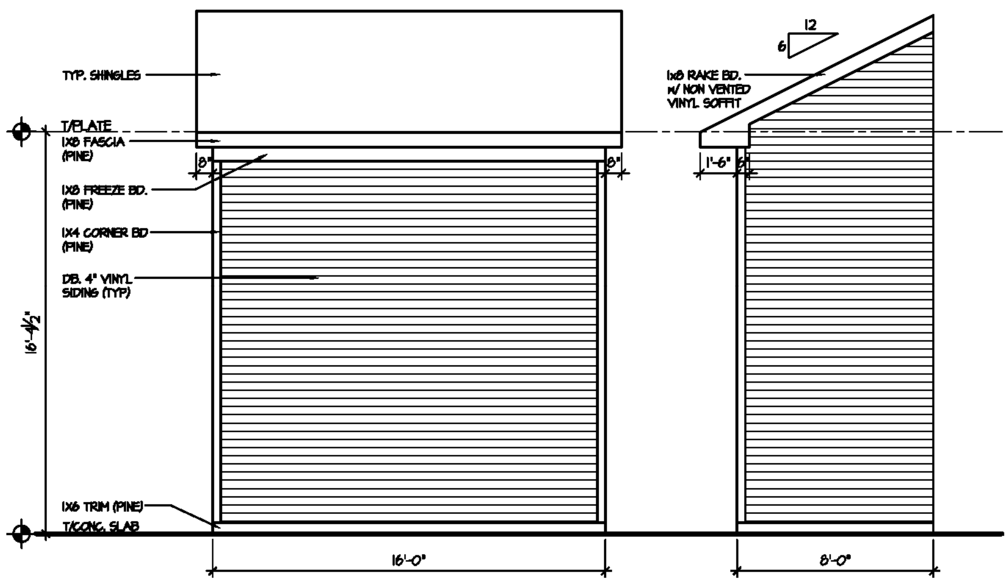
Figure B. 1: Eave Experiment 1 Section



Structure 1

Floor Plan

SCALE: 1/4"=1'-0"



Structure 1

Front and Side Elevations

SCALE: 1/4"=1'-0"

Figure B. 2: Eave Experiment 1 – Floor Plan and Elevations

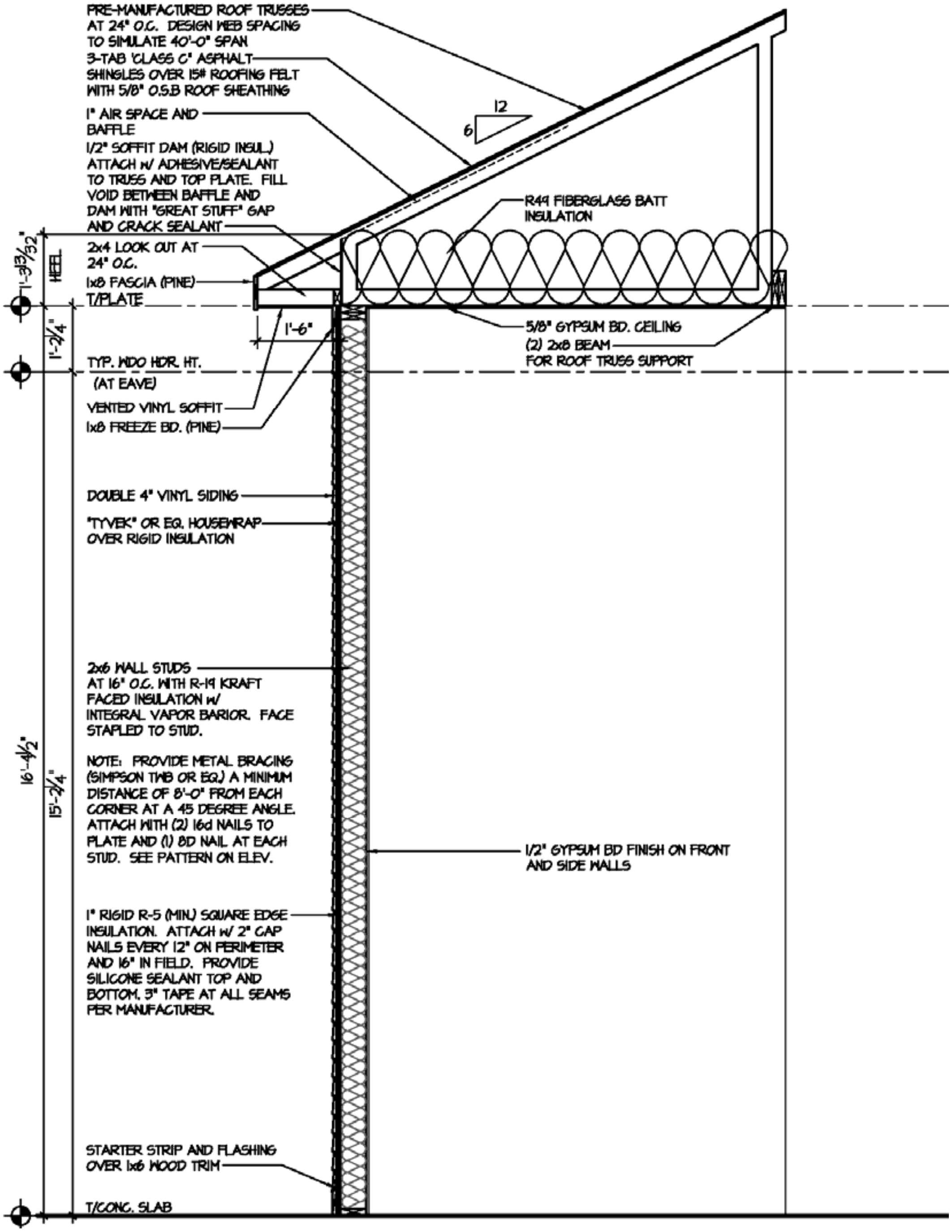
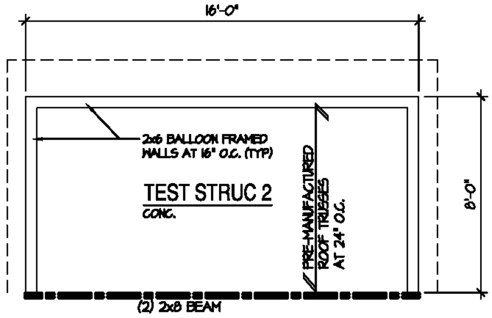


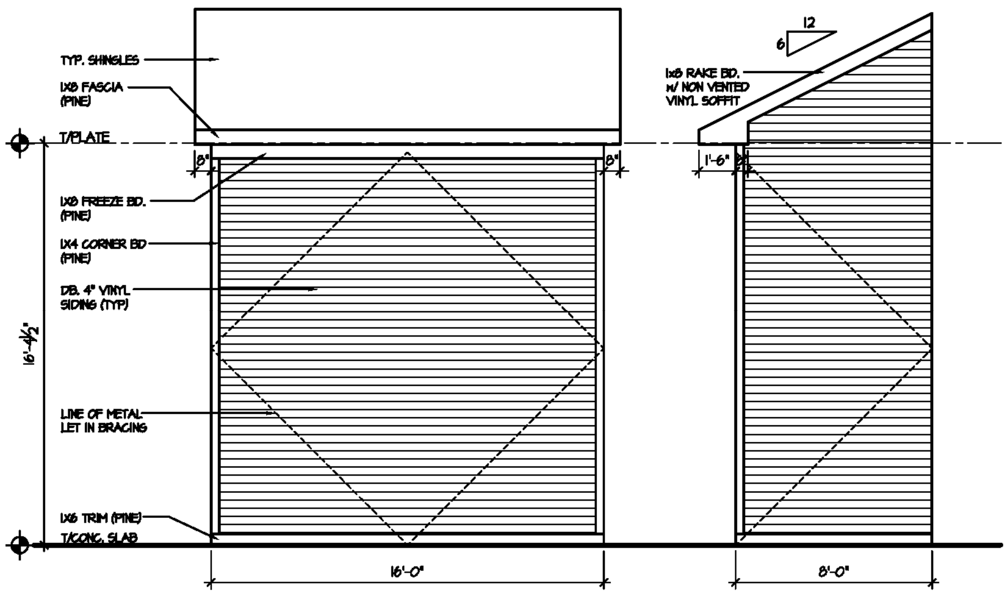
Figure B. 3: Eave Experiment 2 – Section



Structure 2

Floor Plan

SCALE: 1/4"=1'-0"



Structure 2

Front and Side Elevations

SCALE: 1/4"=1'-0"

Figure B. 4: Eave Experiment 2 – Floor Plan and Elevations

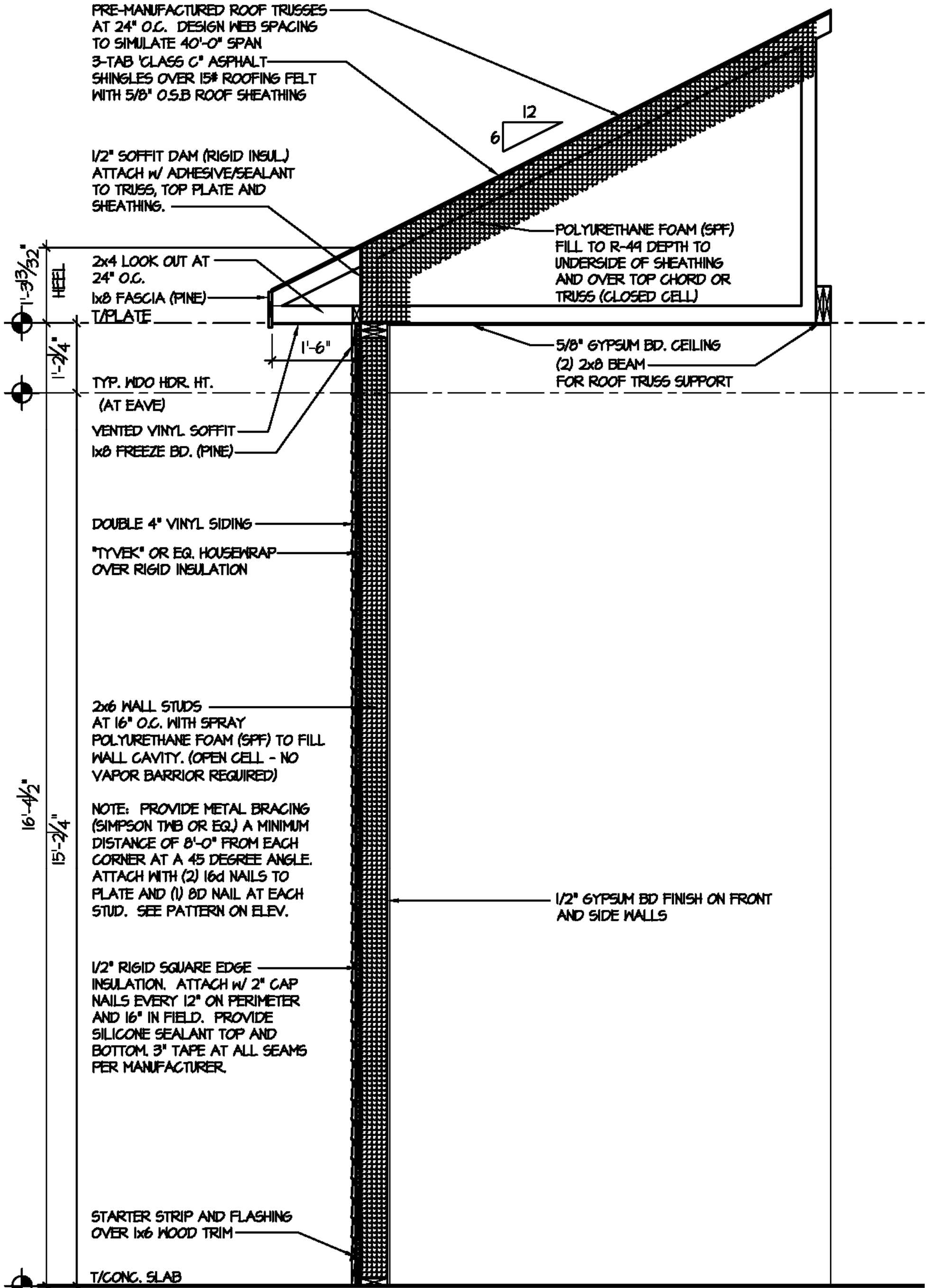
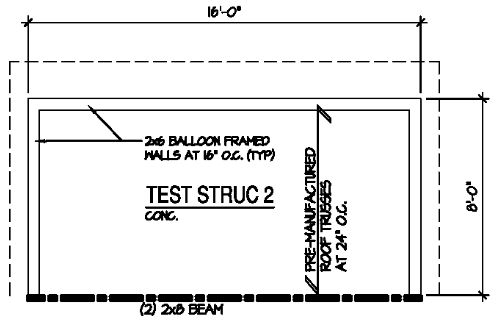


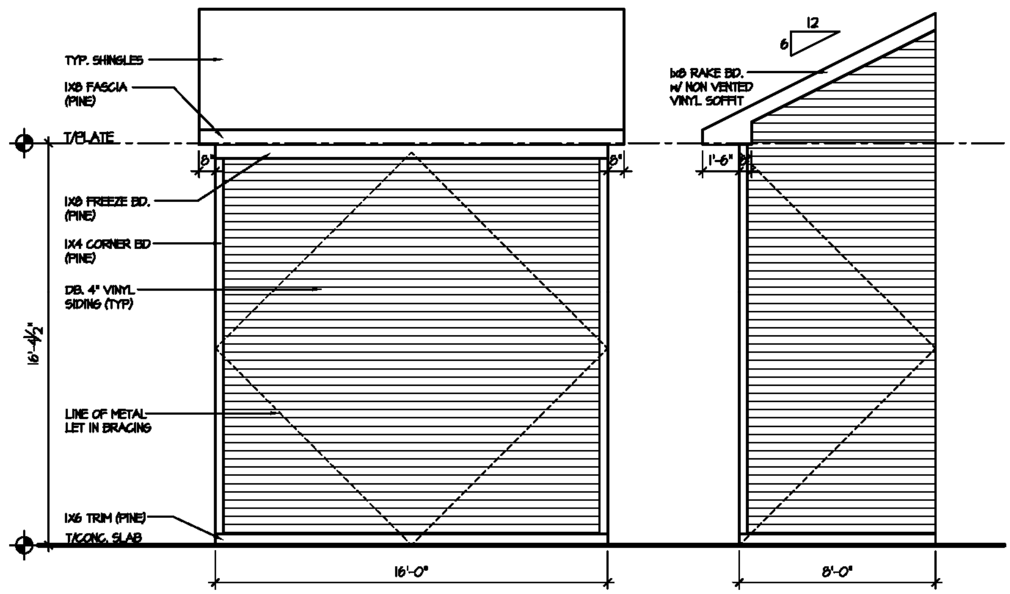
Figure B. 5: Eave Experiment 3 – Section



Structure 3

Floor Plan

SCALE: 1/4"=1'-0"



Structure 3

Front and Side Elevations

SCALE: 1/4"=1'-0"

Figure B. 6: Eave Experiment 3 – Floor Plan and Elevations

Appendix C: Full Scale Attic Construction Drawings

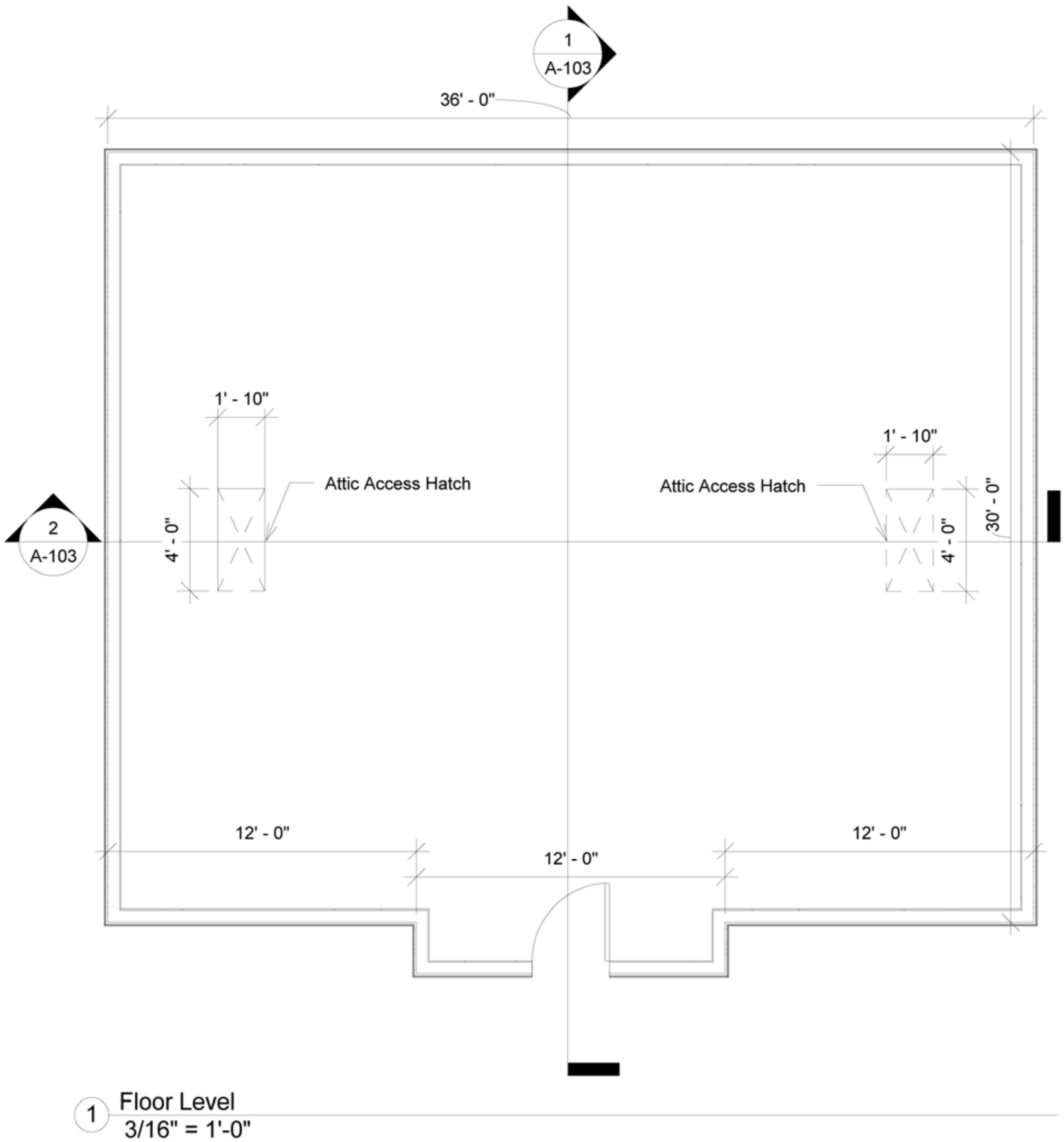


Figure C. 1: Attic Structure Floor Plan

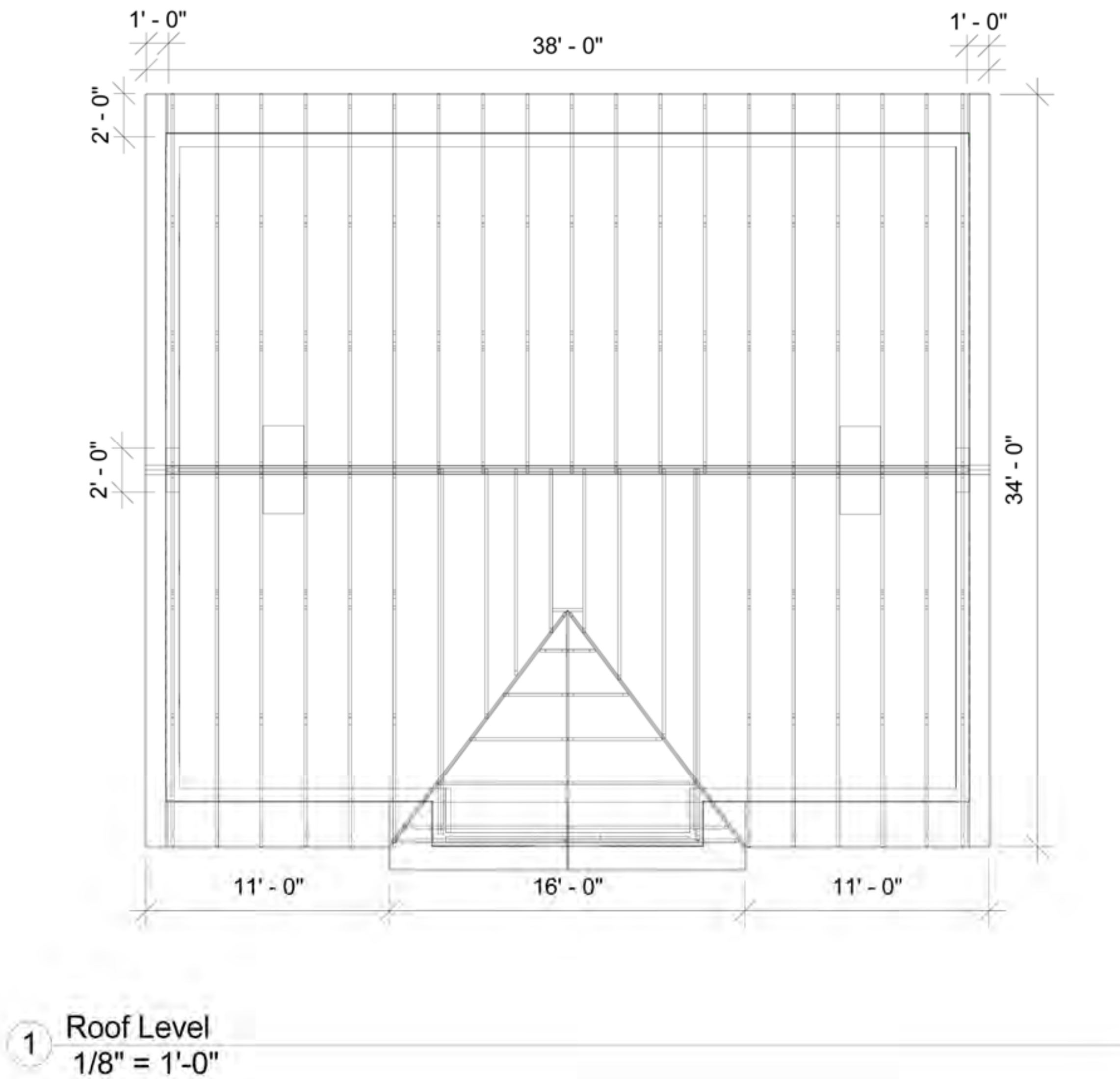
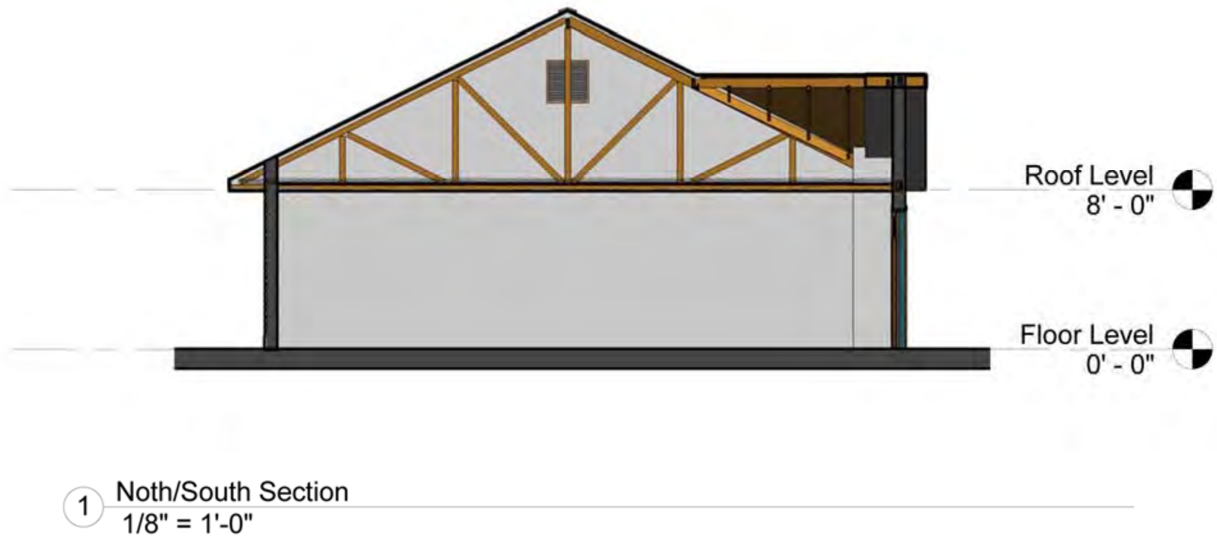


Figure C. 2: Attic Structure Roof Plan



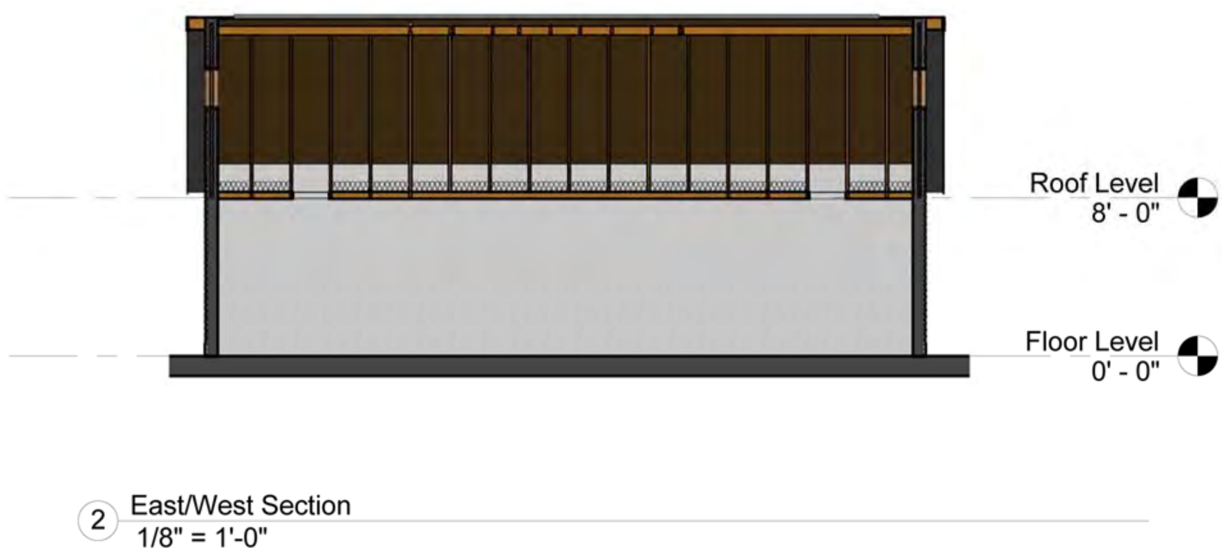


Figure C. 3: Attic Structure Sections

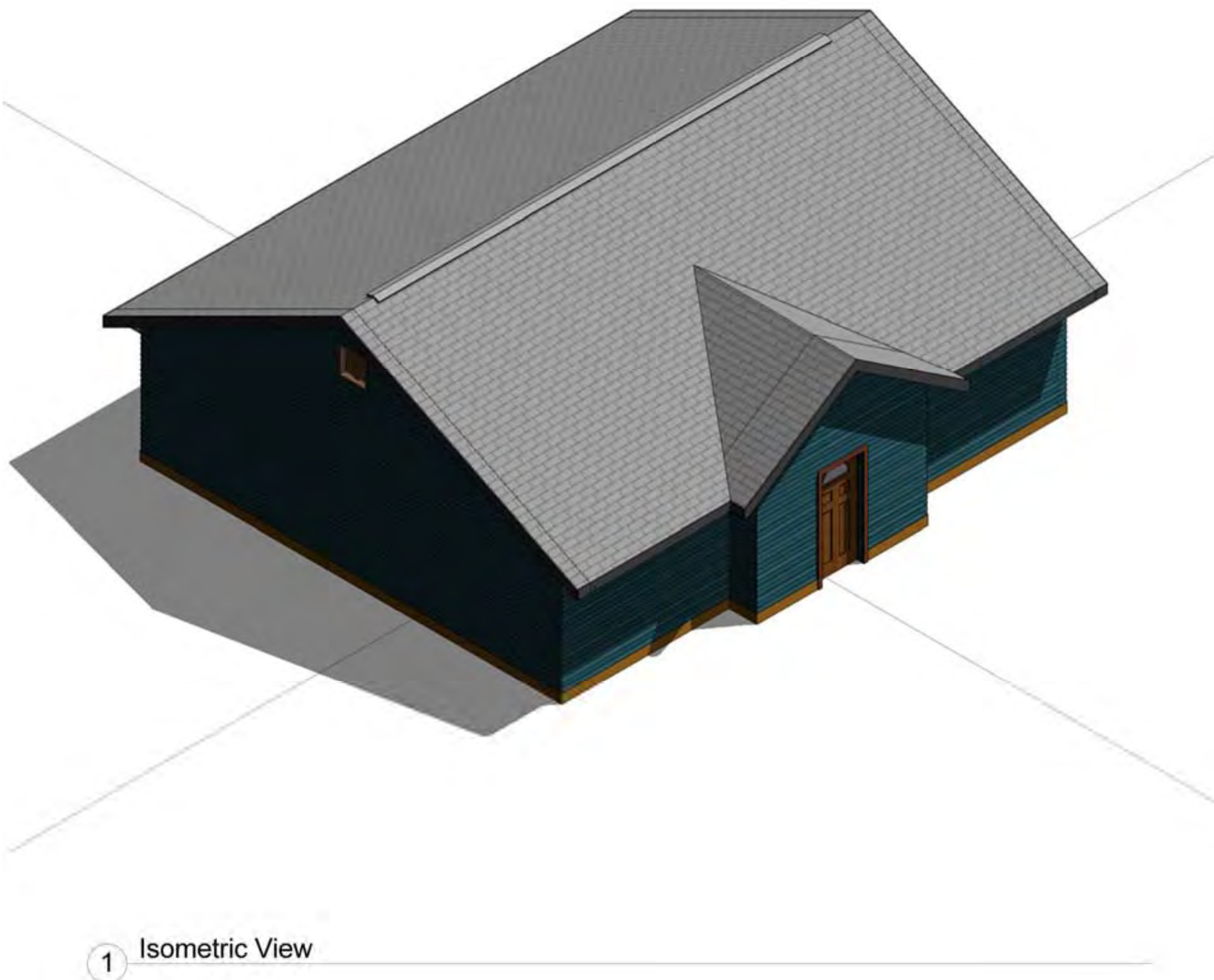


Figure C. 4: Attic Structure Isometric

Appendix D: Knee Wall & Attic Field Layout Drawings

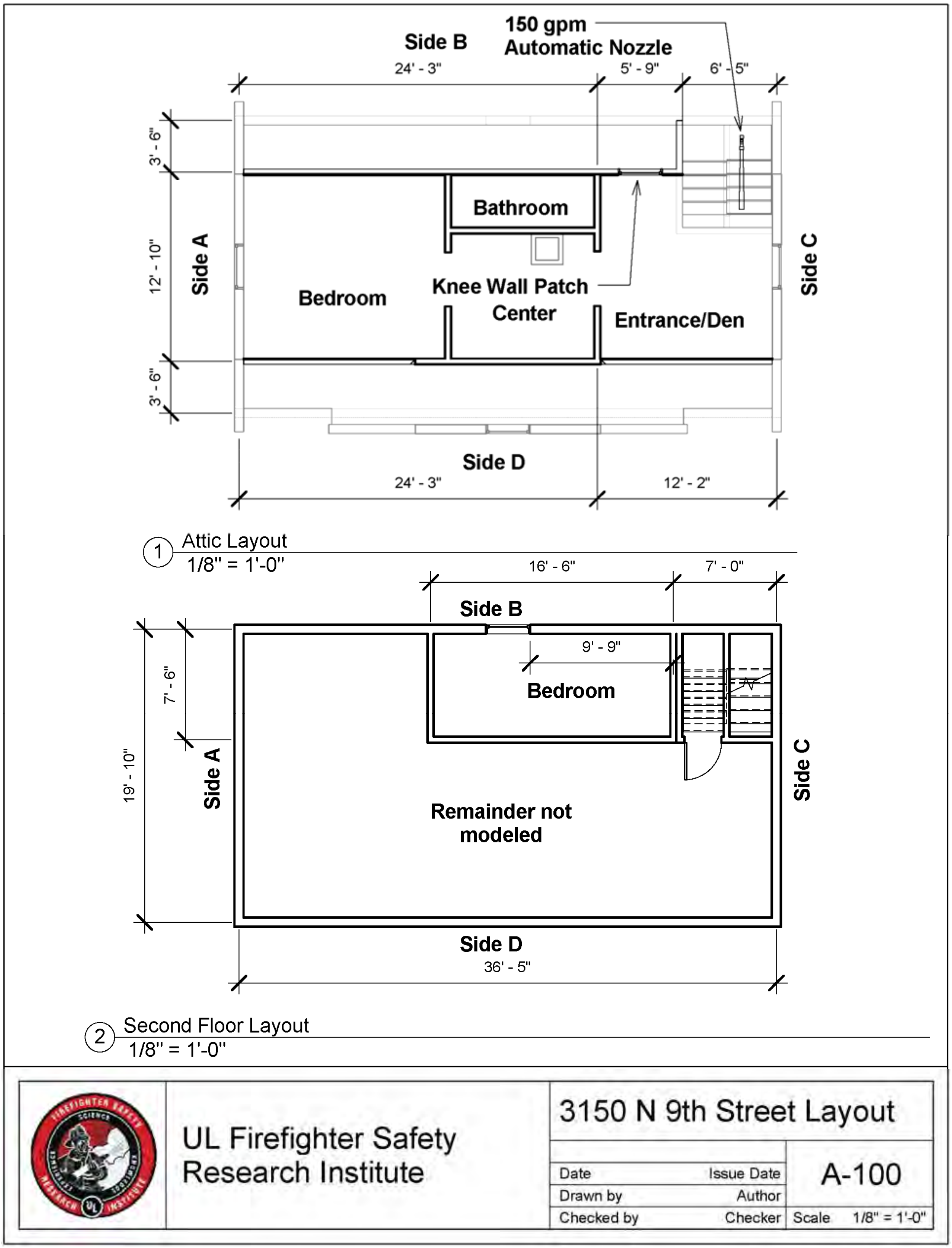


Figure D. 1: Experiment 1 – 3150 Nth 9Th Street Layout Drawing

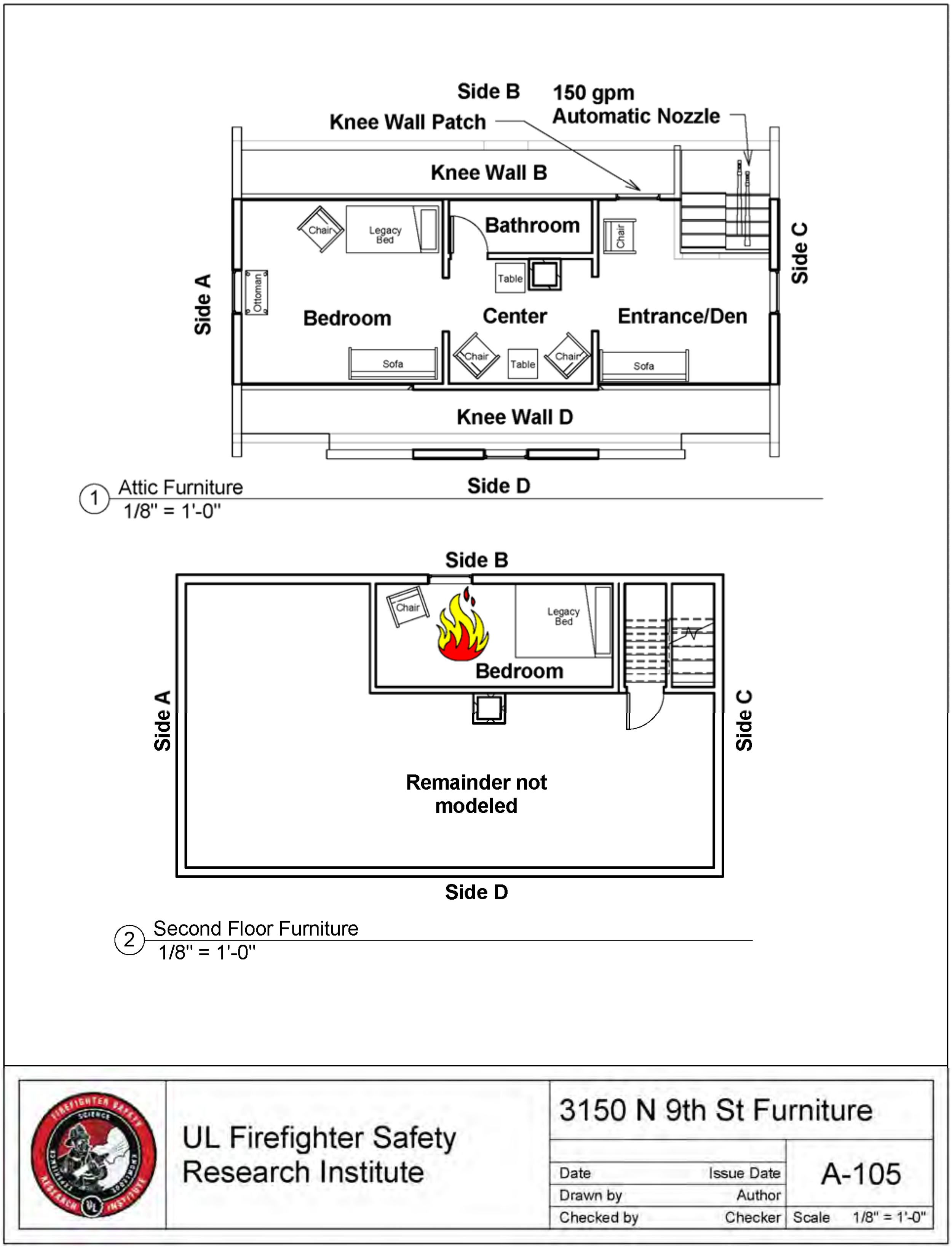


Figure D. 2: Experiment 1 – 3150 Nth 9Th Street Furniture Layout Drawing.

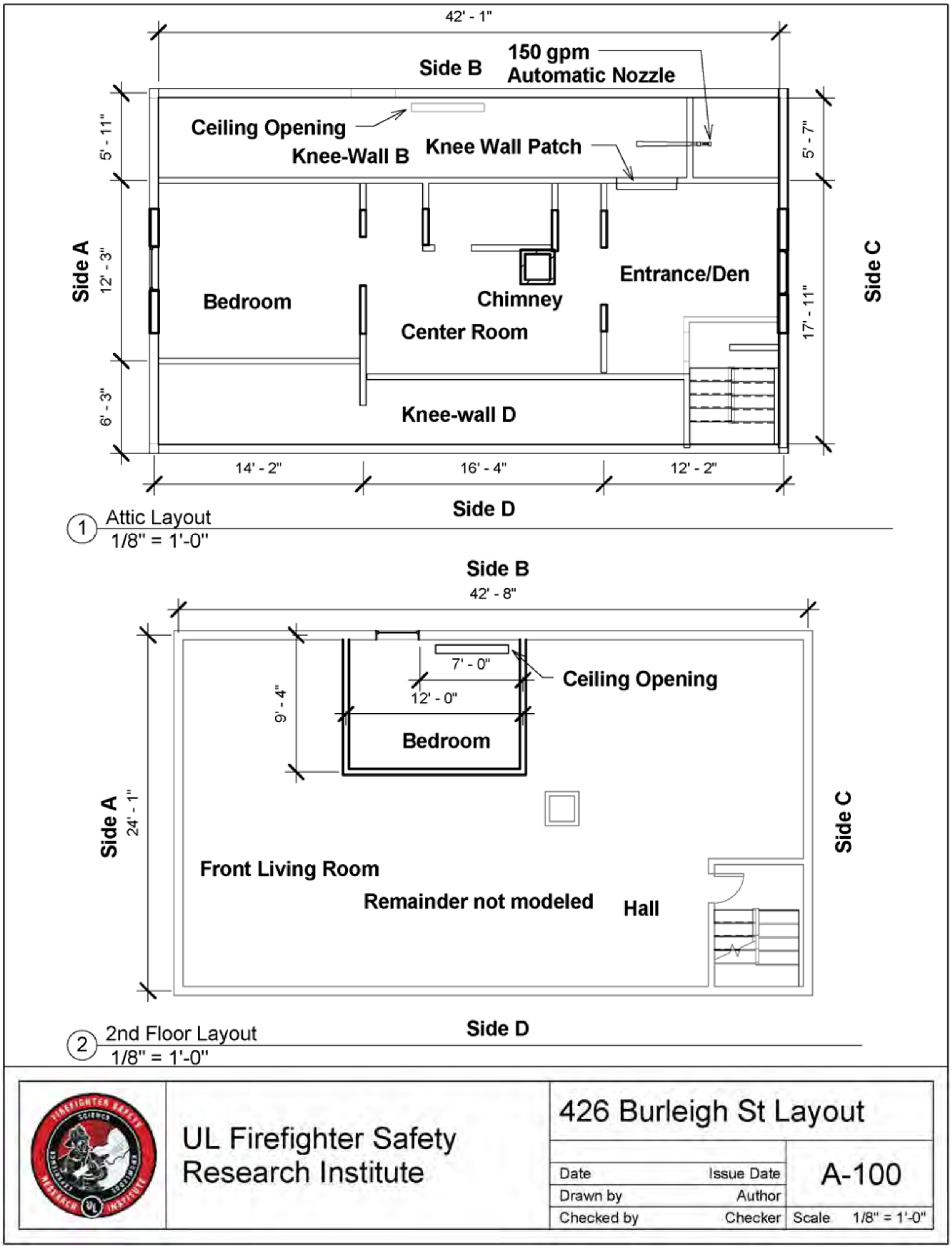


Figure D. 3: Experiment 2 – 426 Burleigh Street Layout Drawing

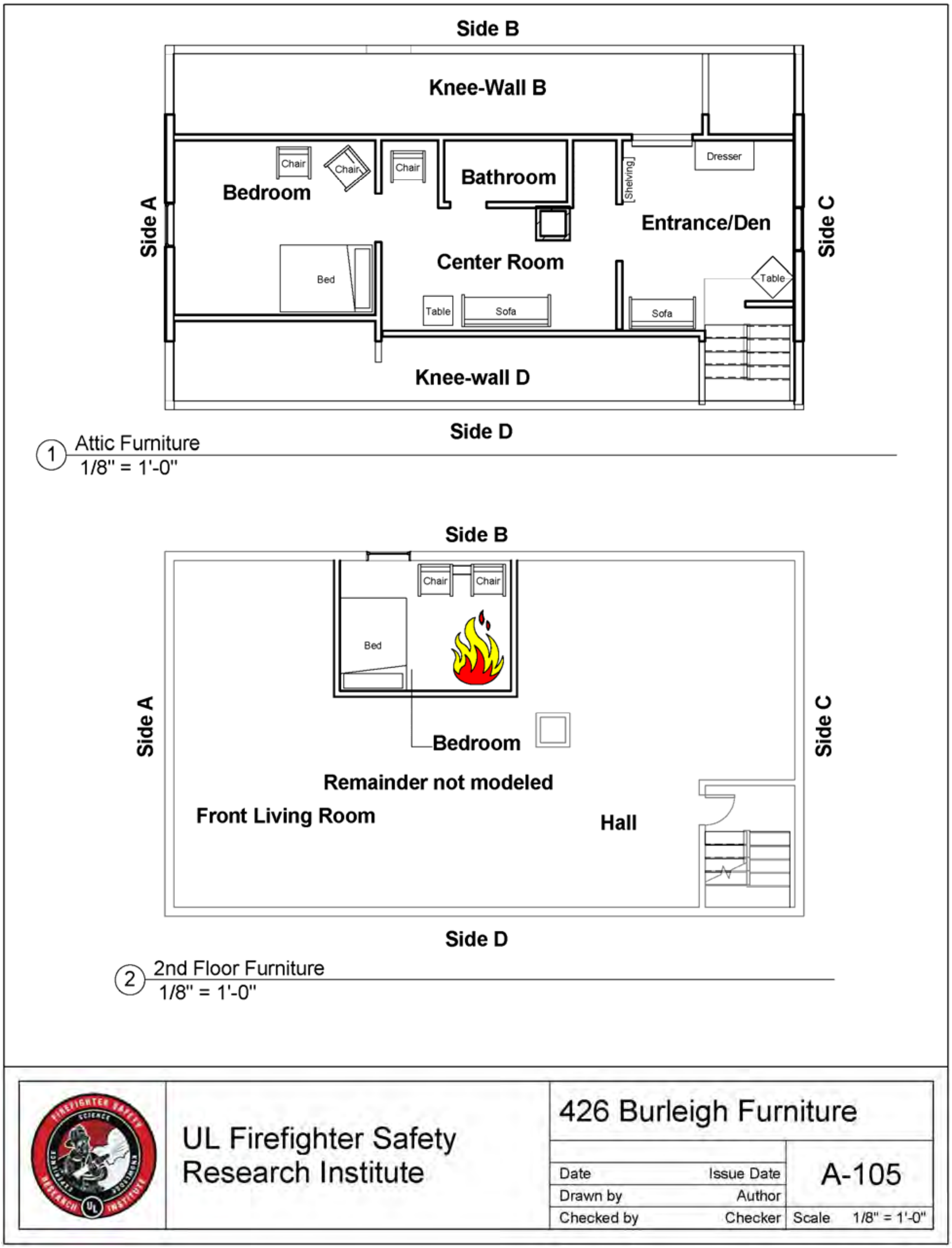


Figure D. 4: Experiment 2 – 426 Burleigh Street Furniture Layout

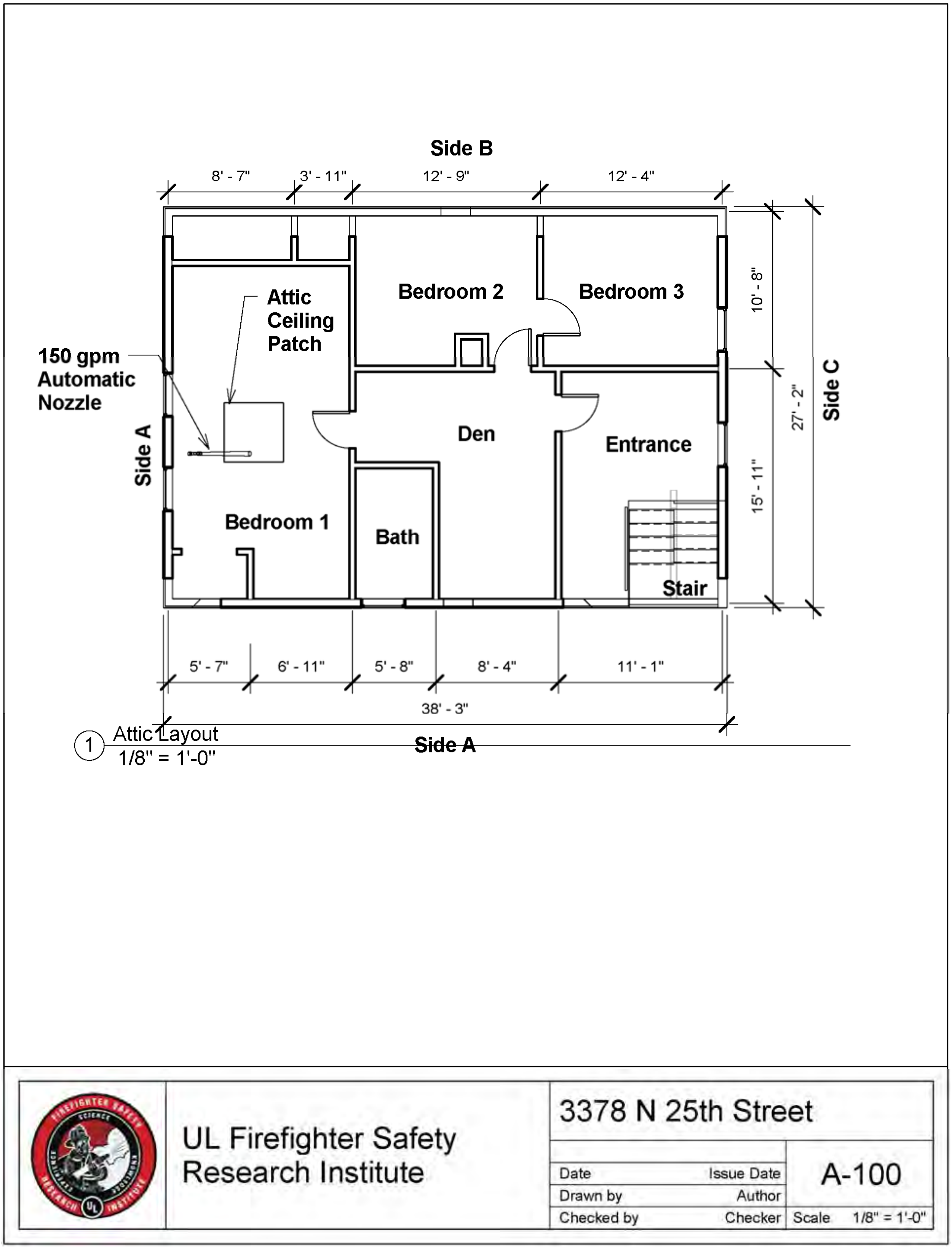


Figure D. 5: Experiment 3 – 3378 Nth 25th Street Layout Drawing

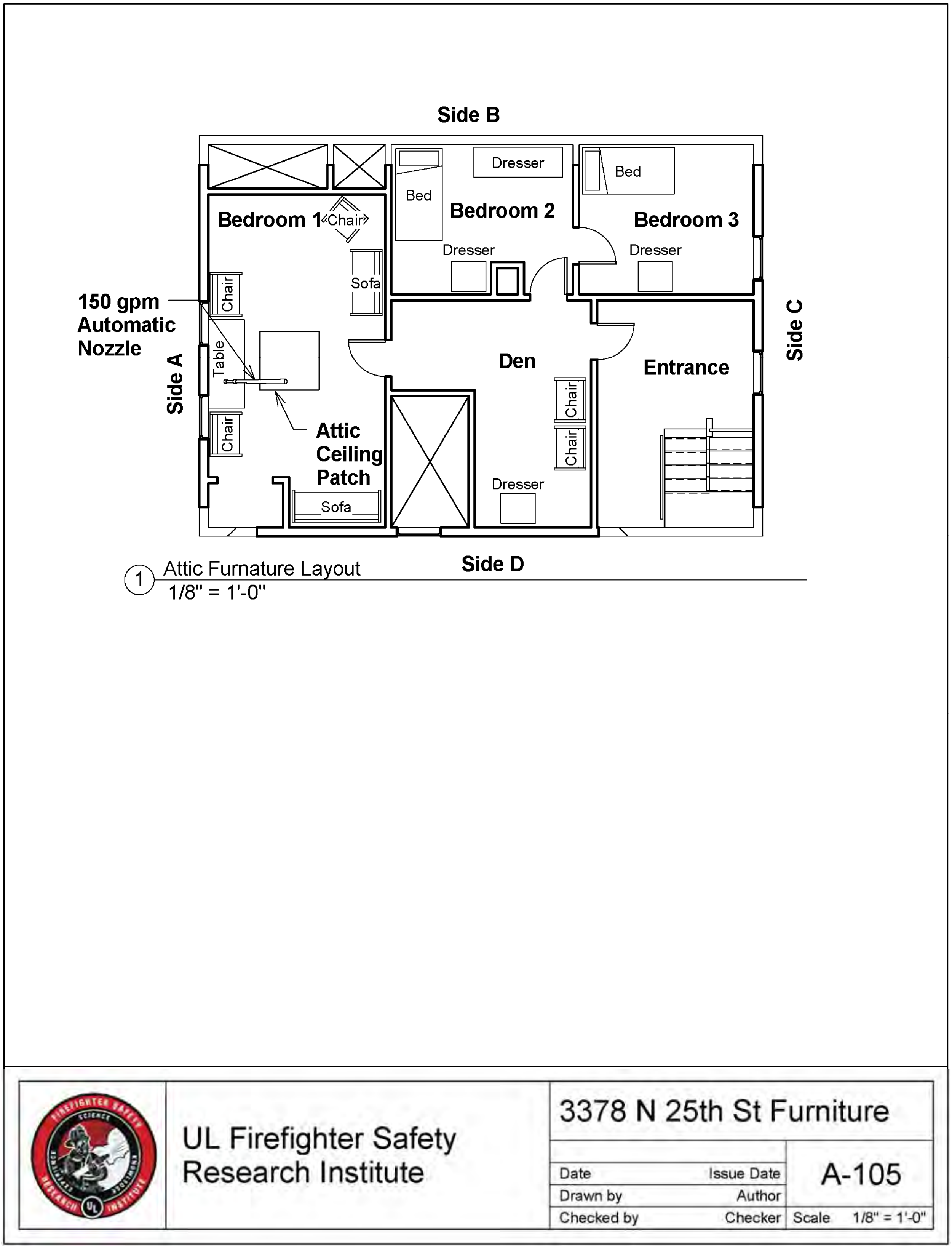


Figure D. 6: Experiment 3 – 3378 Nth 25th Street Furniture Drawing

Appendix E: Full Scale Attic Sensor Layout Drawings

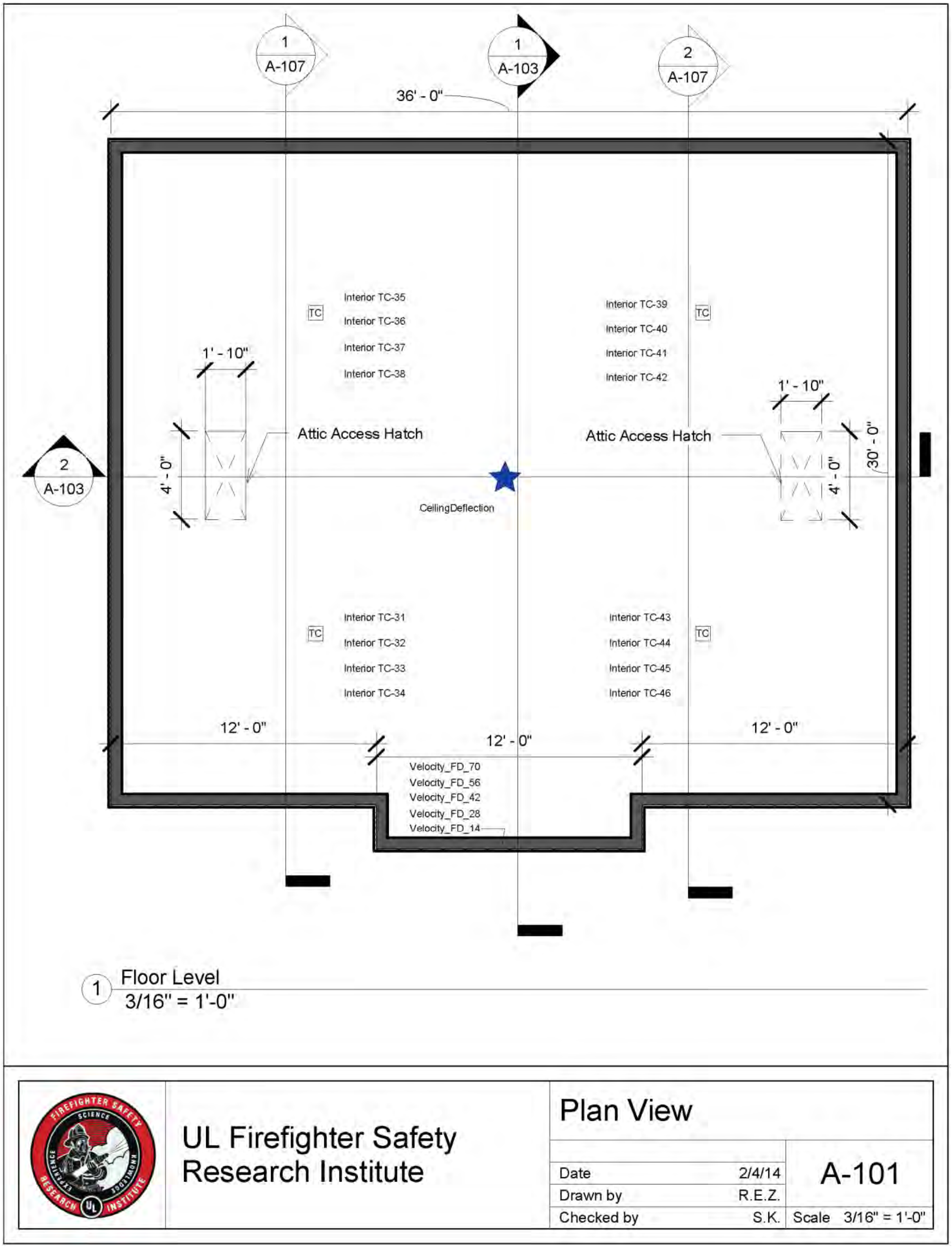


Figure E. 1: Full Scale Attic Sensor Image Plan View

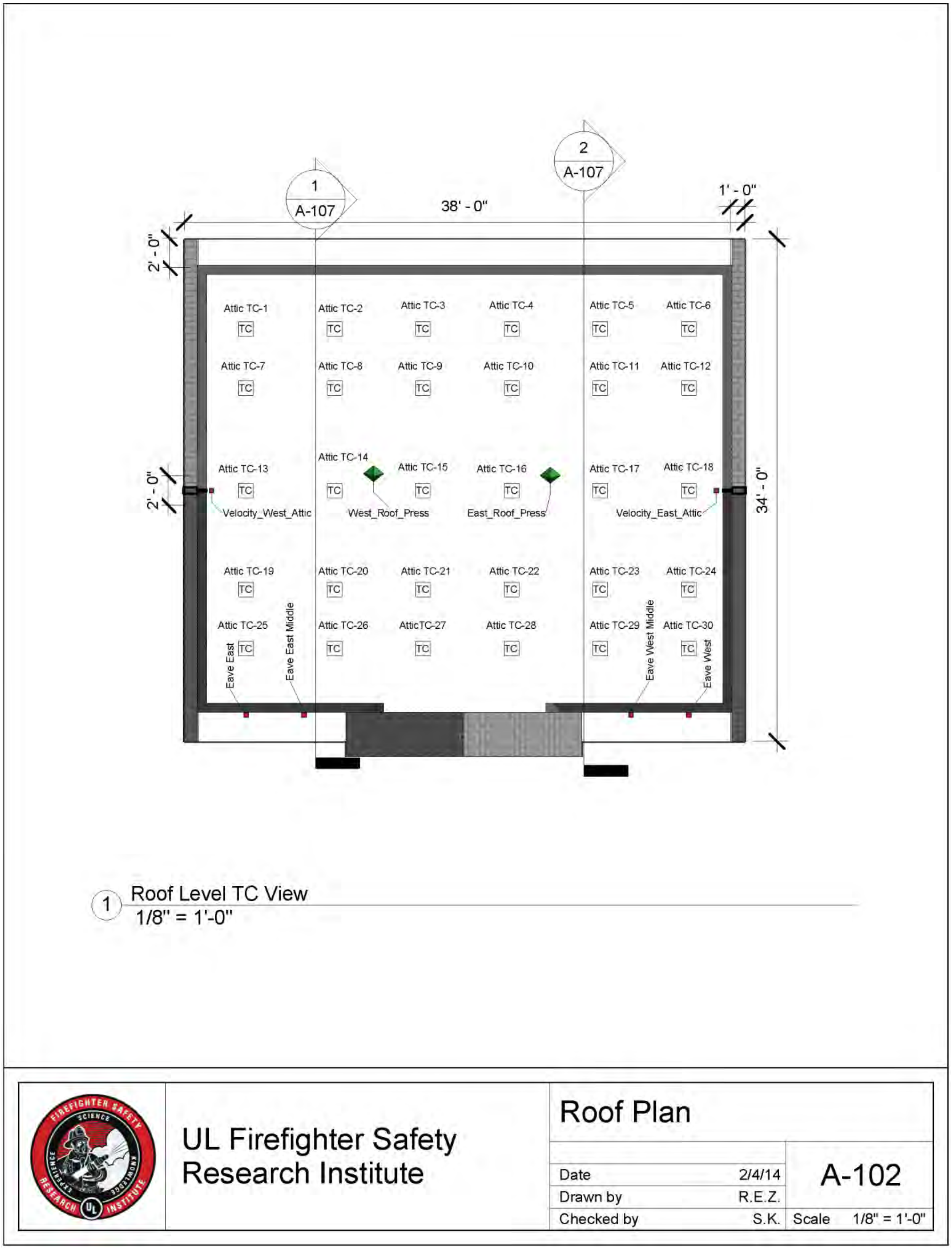


Figure E. 2: Full Scale Attic Sensor Image Roof View

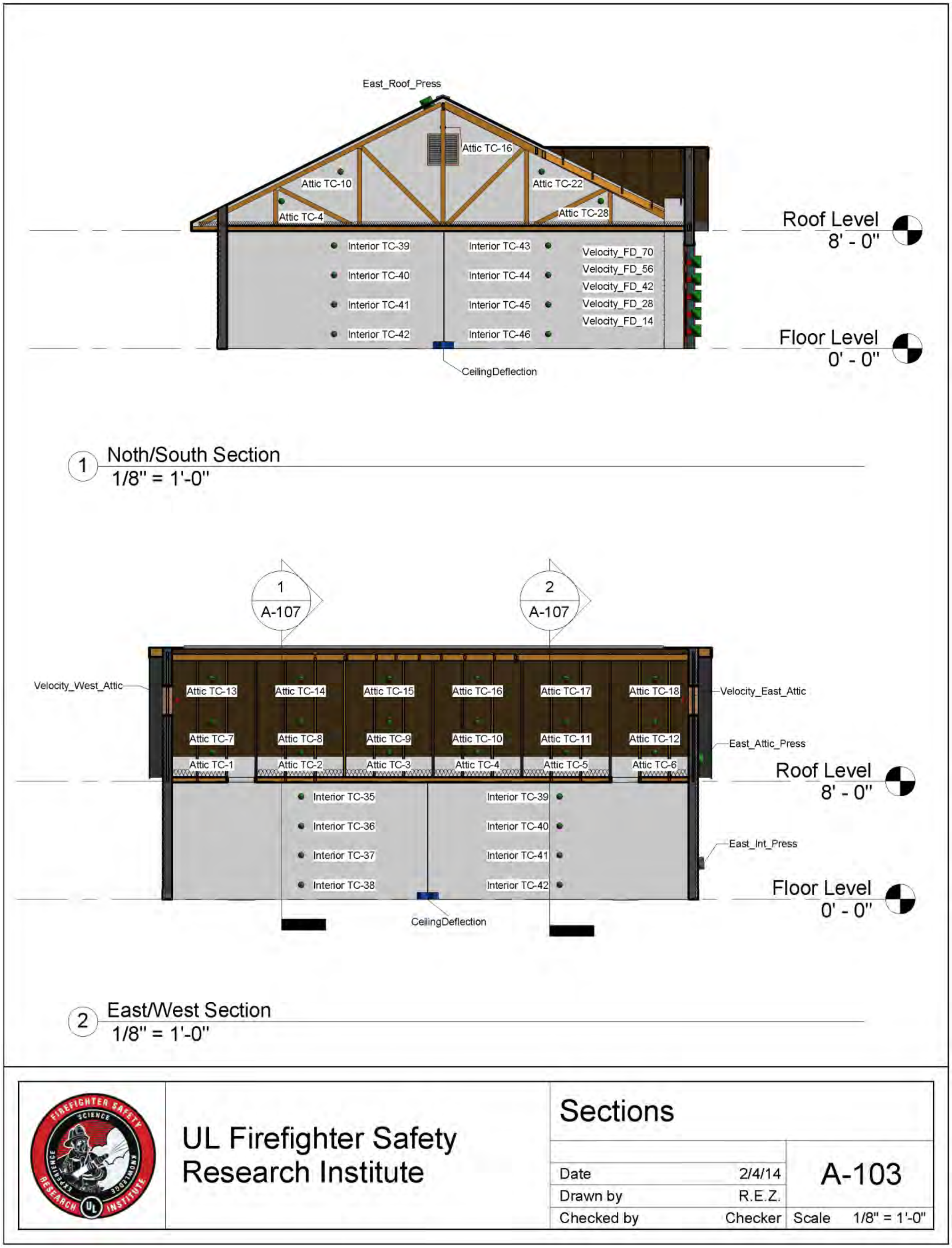


Figure E. 3: Full Scale Attic Sensor Section Views

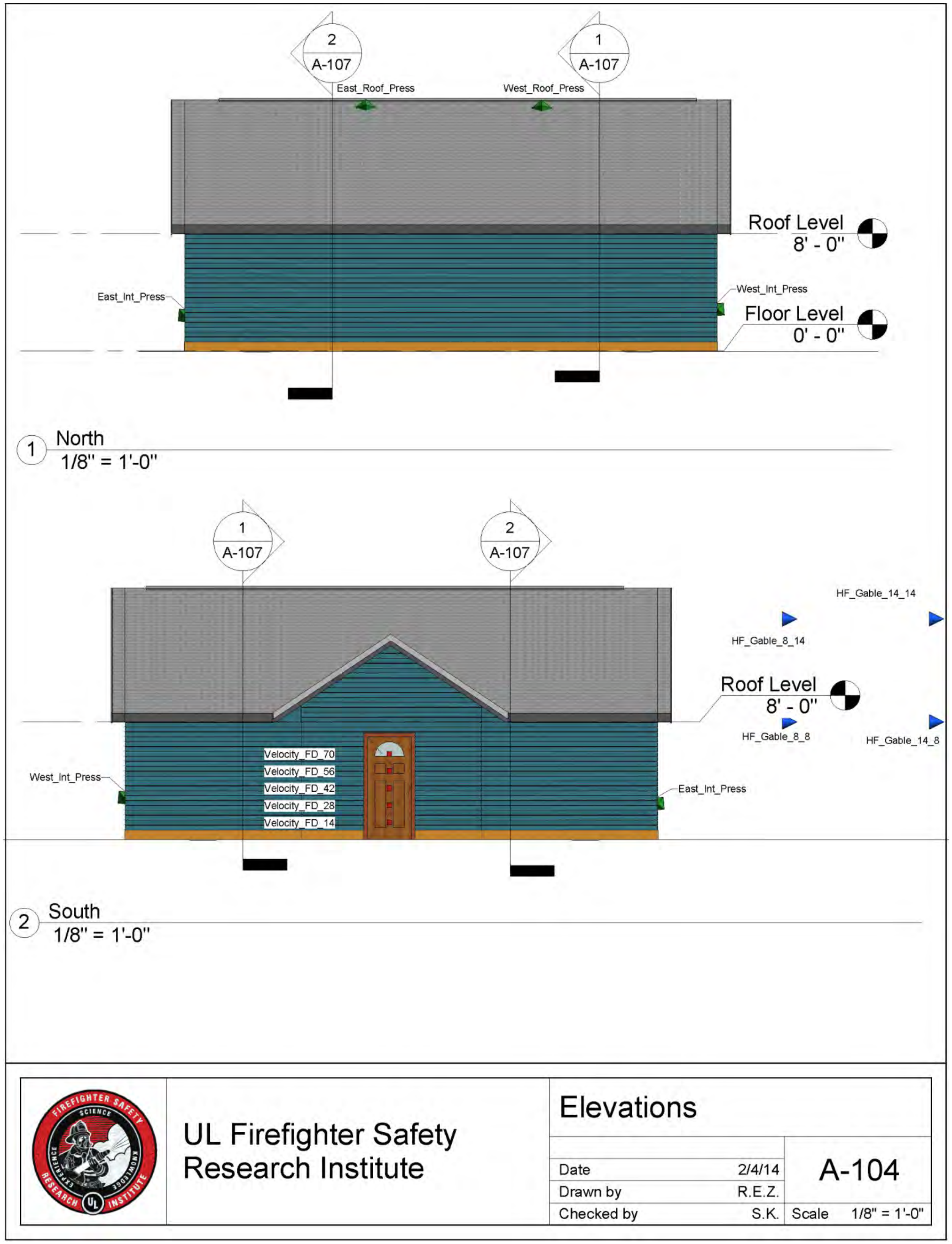


Figure E. 4: Full Scale Attic Sensor Elevation Views Front & Back

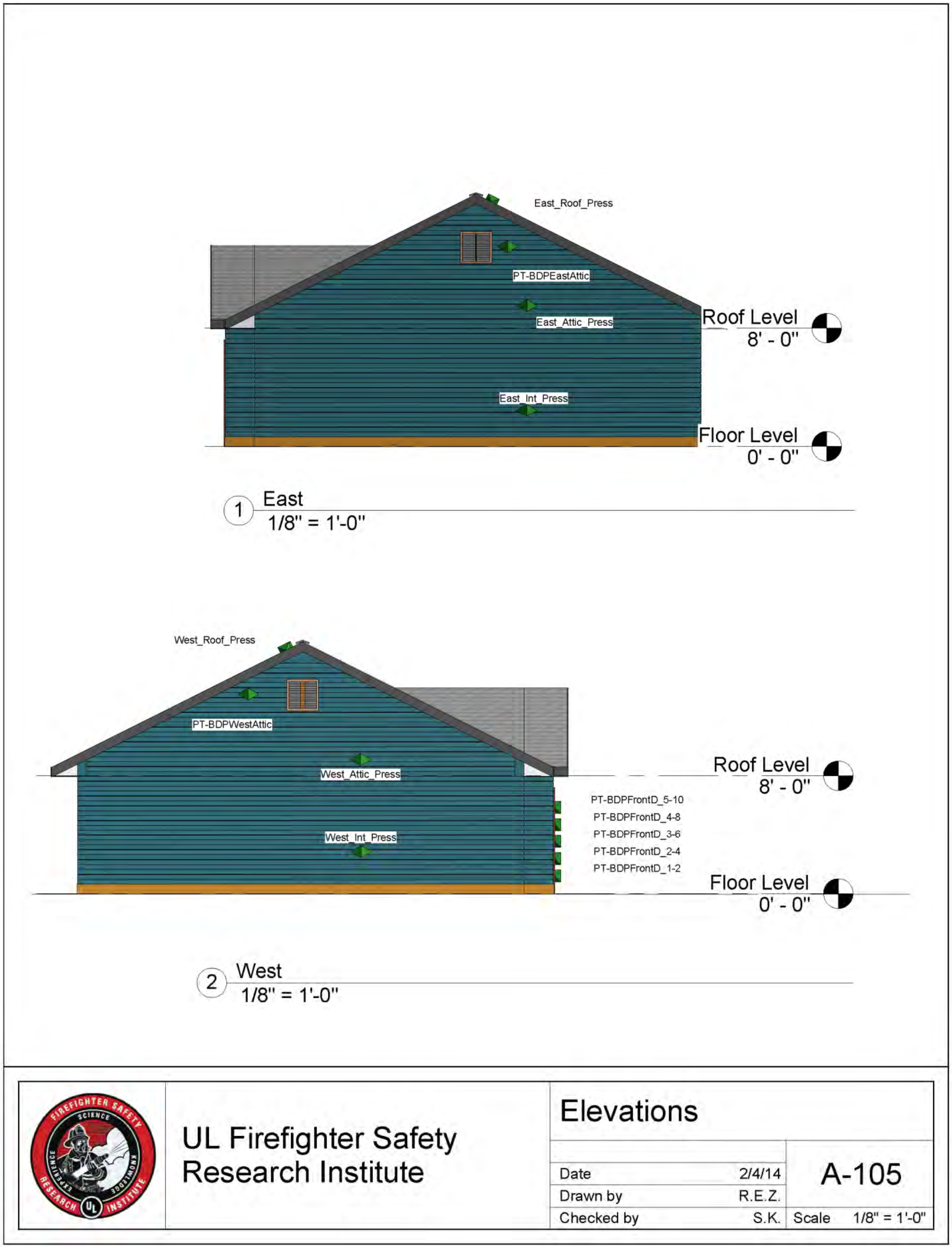


Figure E. 5: Full Scale Attic Sensor Elevation View Right & Left

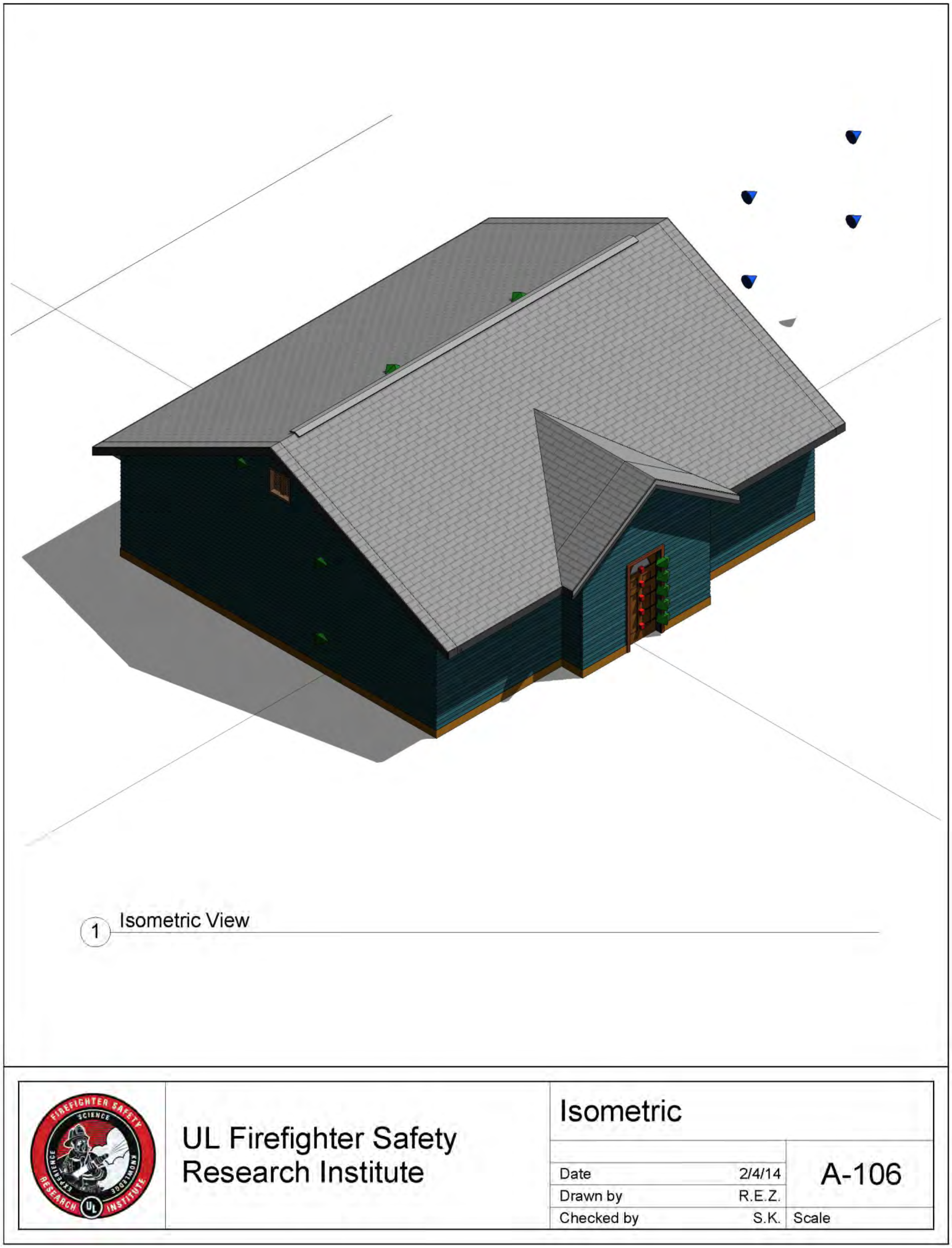
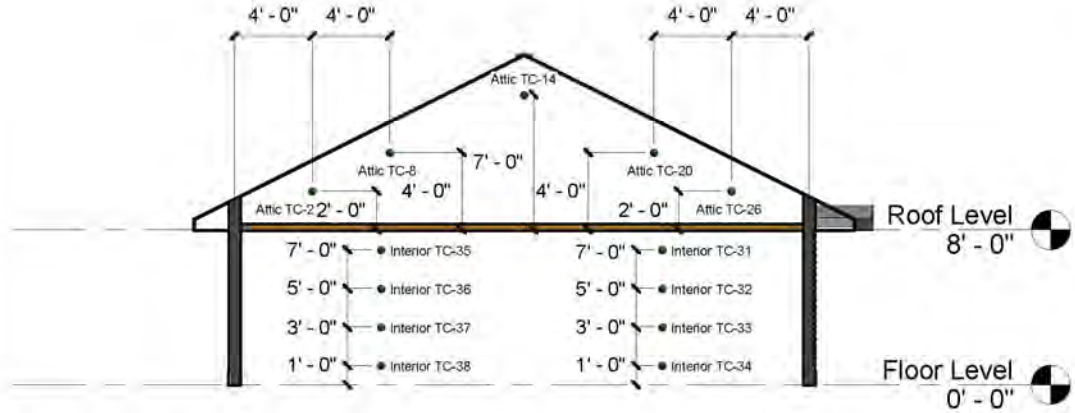
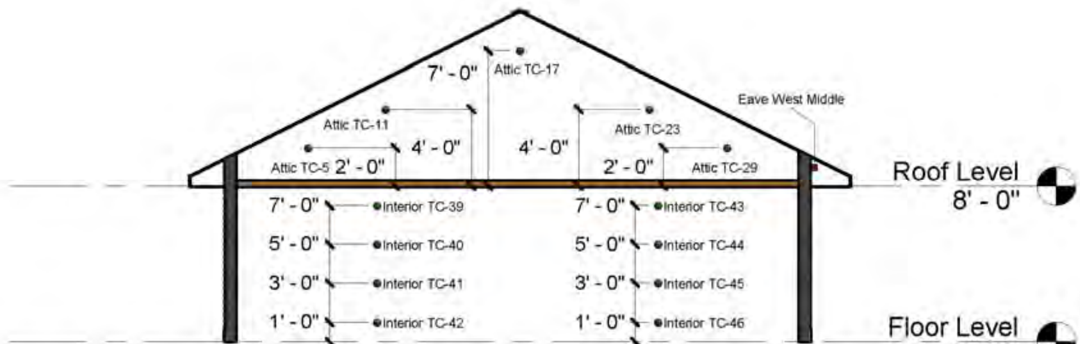


Figure E. 6: Full Scale Attic Sensor Isometric View



1 TC West Section
1/8" = 1'-0"



2 TC East Section
1/8" = 1'-0"

UL Firefighter Safety Research Institute

TC Locations

Date	2/4/14	A-107	
Drawn by	R.E.Z.		
Checked by	S.K.	Scale	1/8" = 1'-0"

Figure E. 7: Full Scale Attic Thermal Couple Sections

Appendix F: Knee Wall & Attic Field Experiment Sensor Drawings

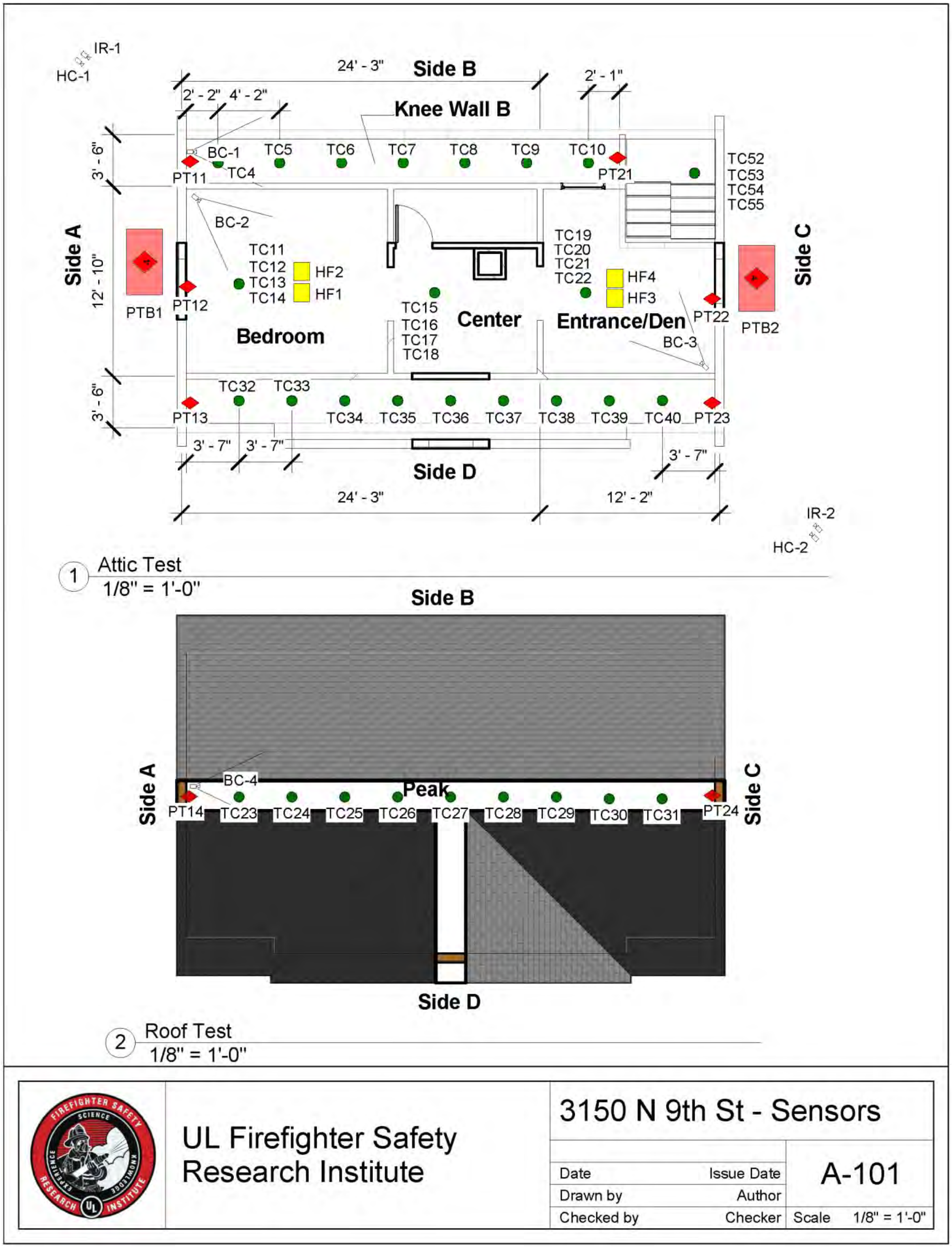


Figure F. 1: Field Experiment 1 - 3150 N 9th Street Attic & Roof Sensors

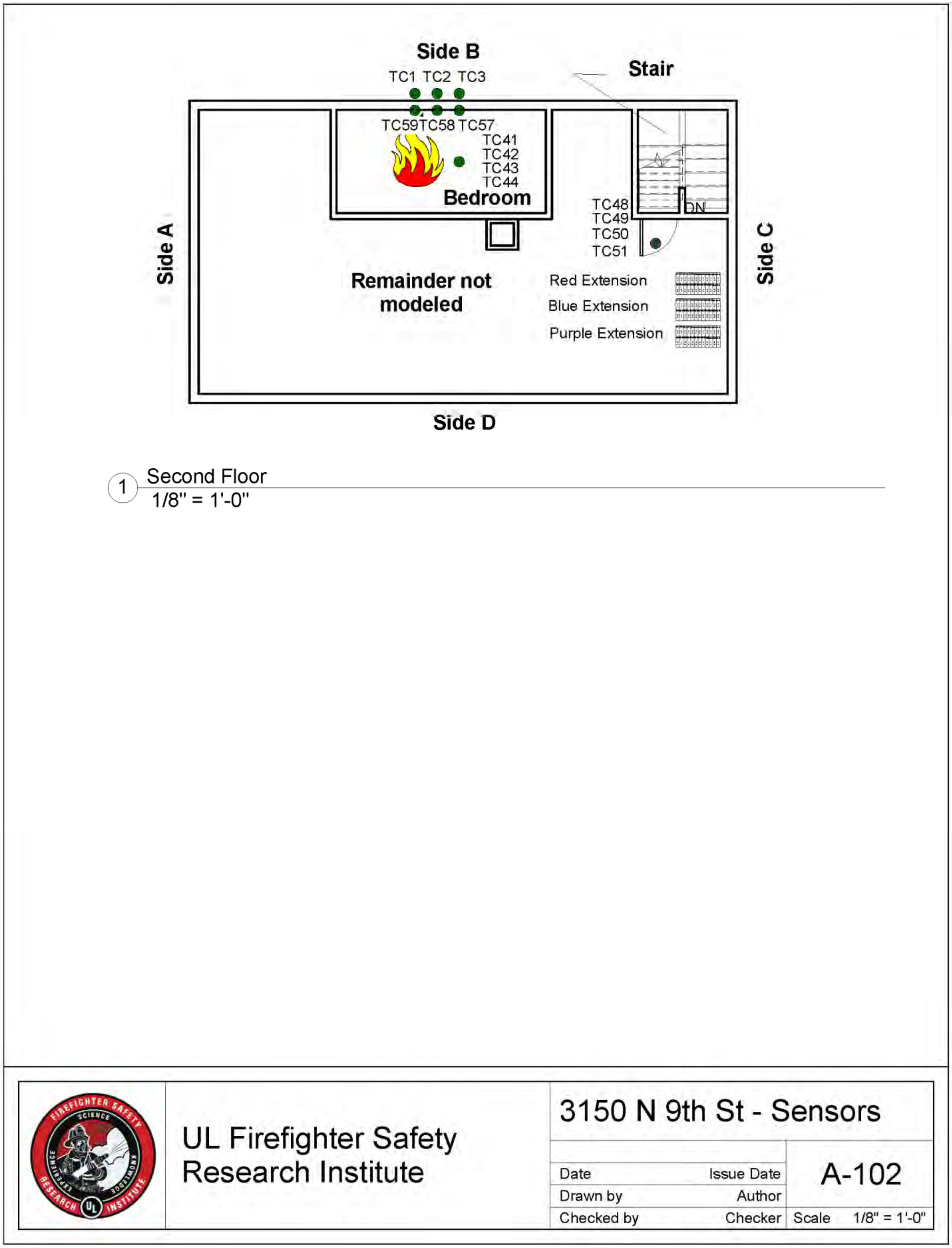


Figure F. 2: Field Experiment 1 - 3150 N 9th Street 2nd Floor Sensors

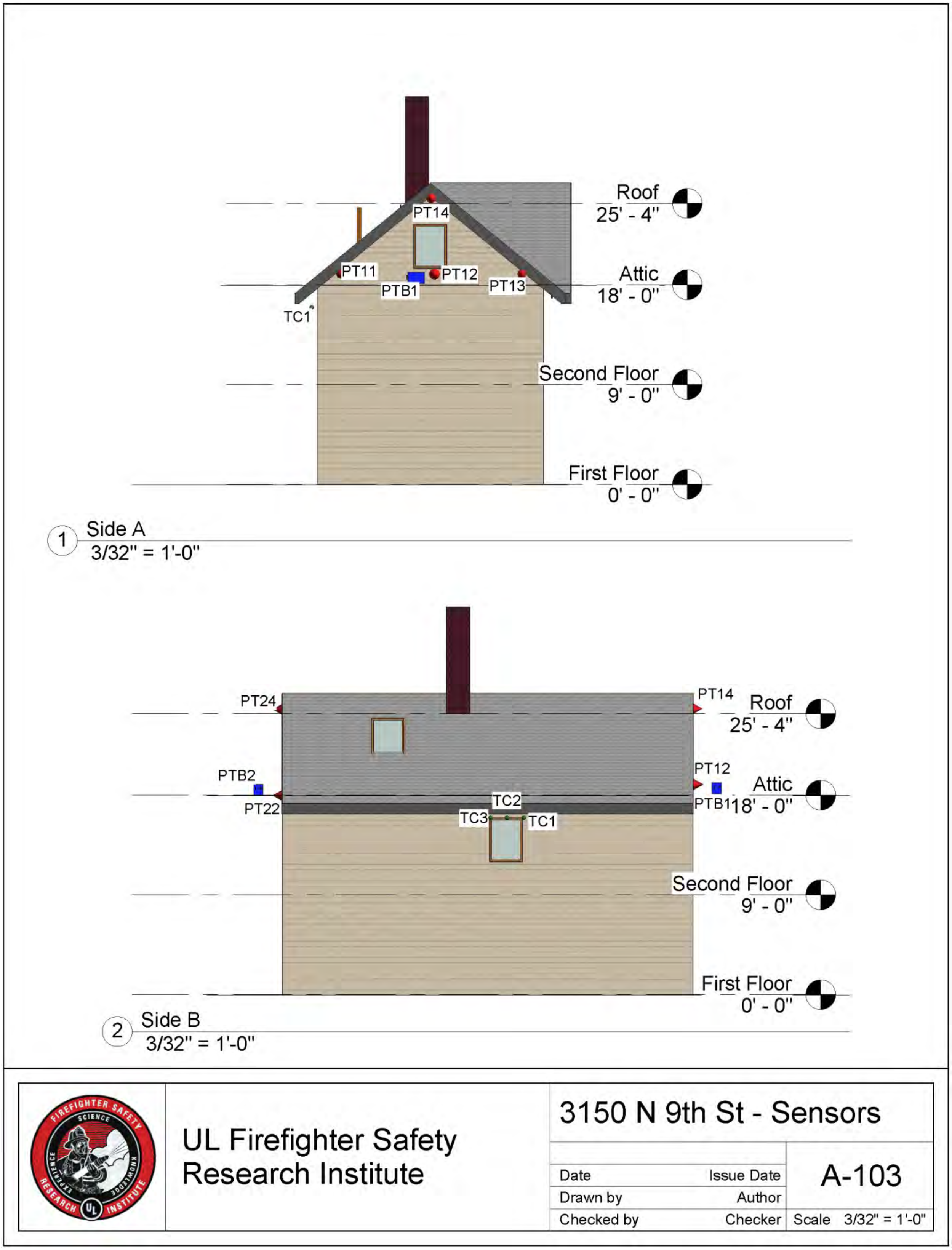
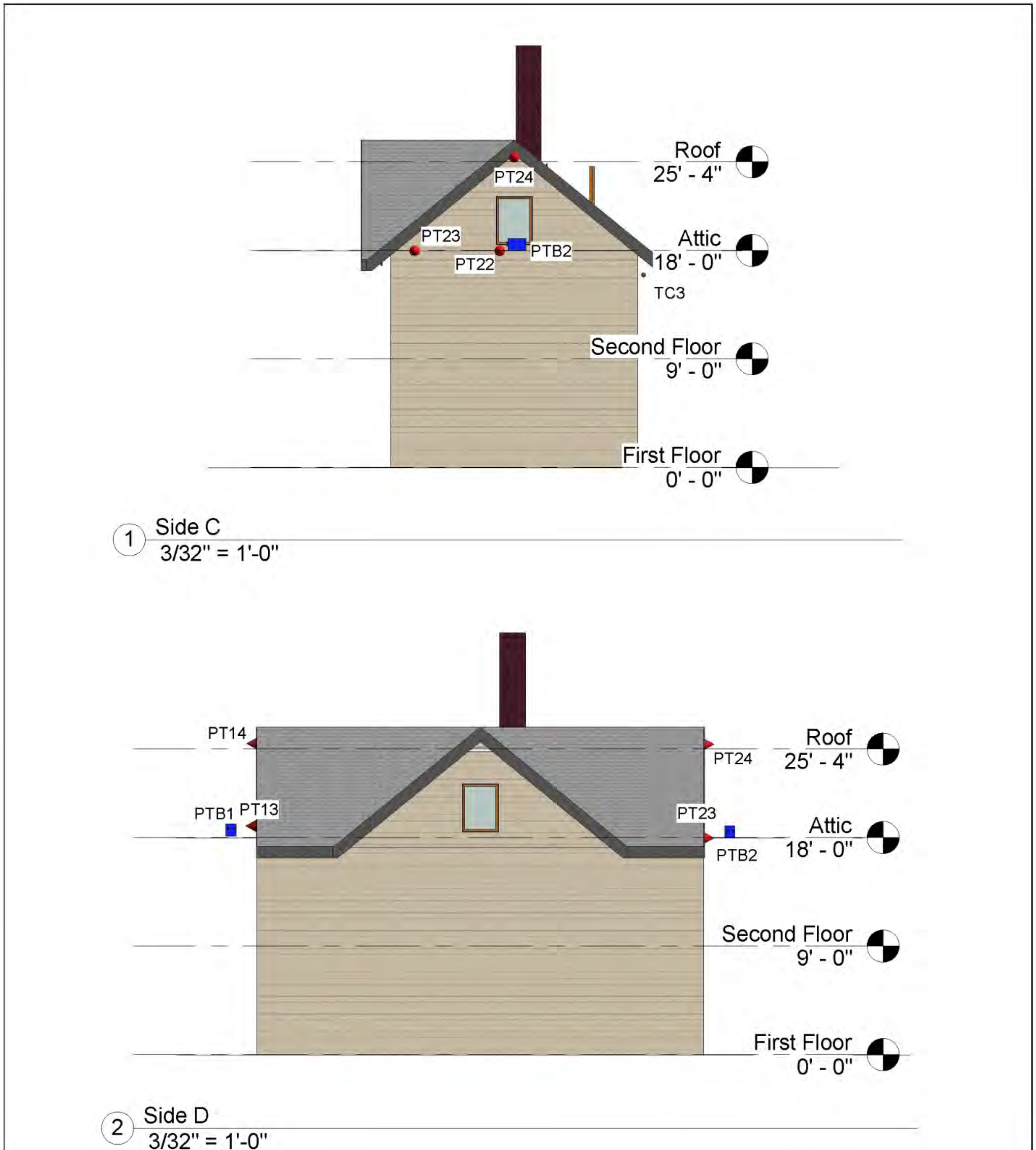


Figure F. 3: Field Experiment 1 - 3150 N 9th Street Elevation Side A & B Sensors



UL Firefighter Safety Research Institute

3150 N 9th St - Sensors

Date	Issue Date	A-104
Drawn by	Author	
Checked by	Checker	Scale 3/32" = 1'-0"

Figure F. 4: Field Experiment 1 - 3150 N 9th Street Elevation Side C & D Sensors

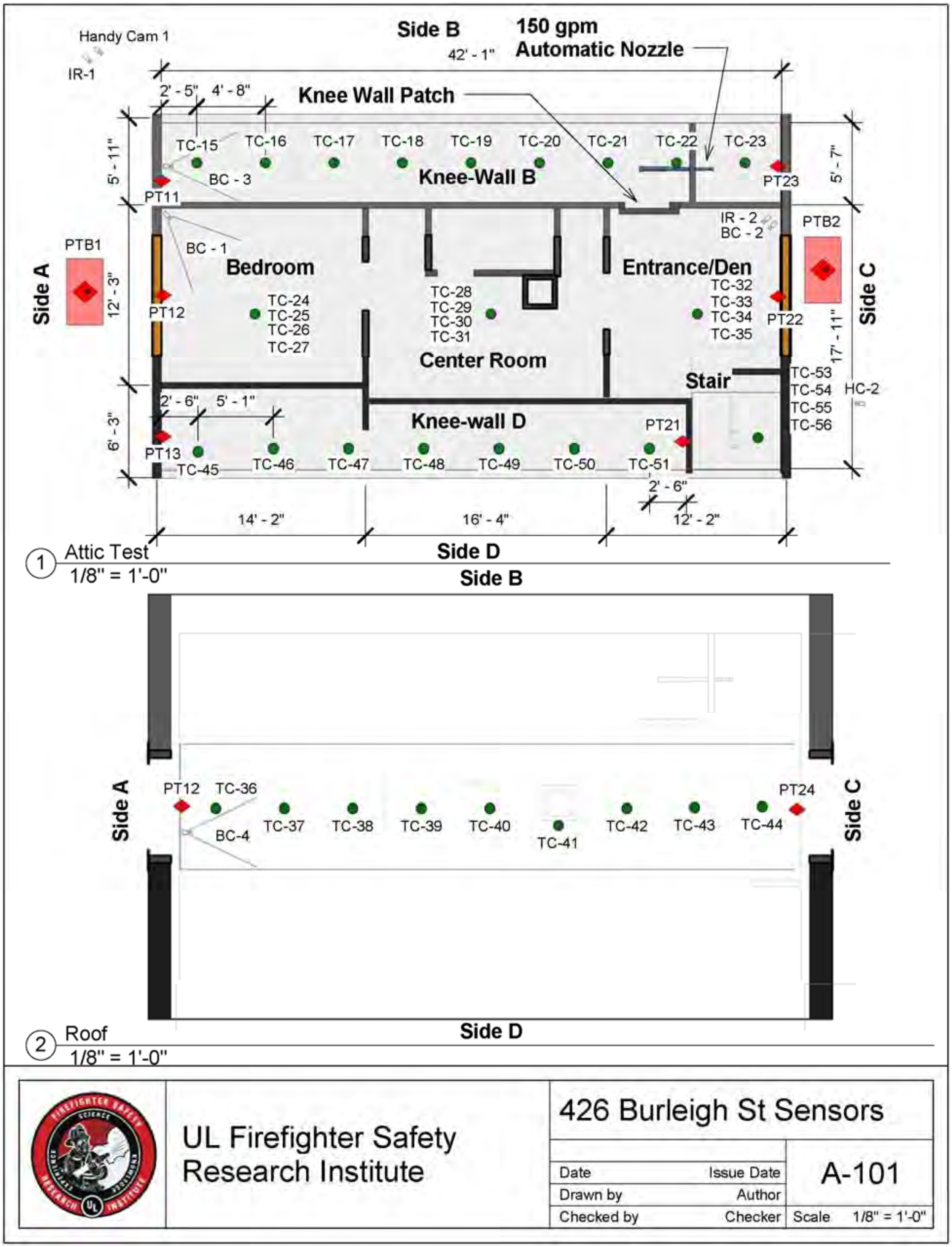


Figure F. 5: Field Experiment 2 - 426 Burleigh Street Sensors Attic Plan

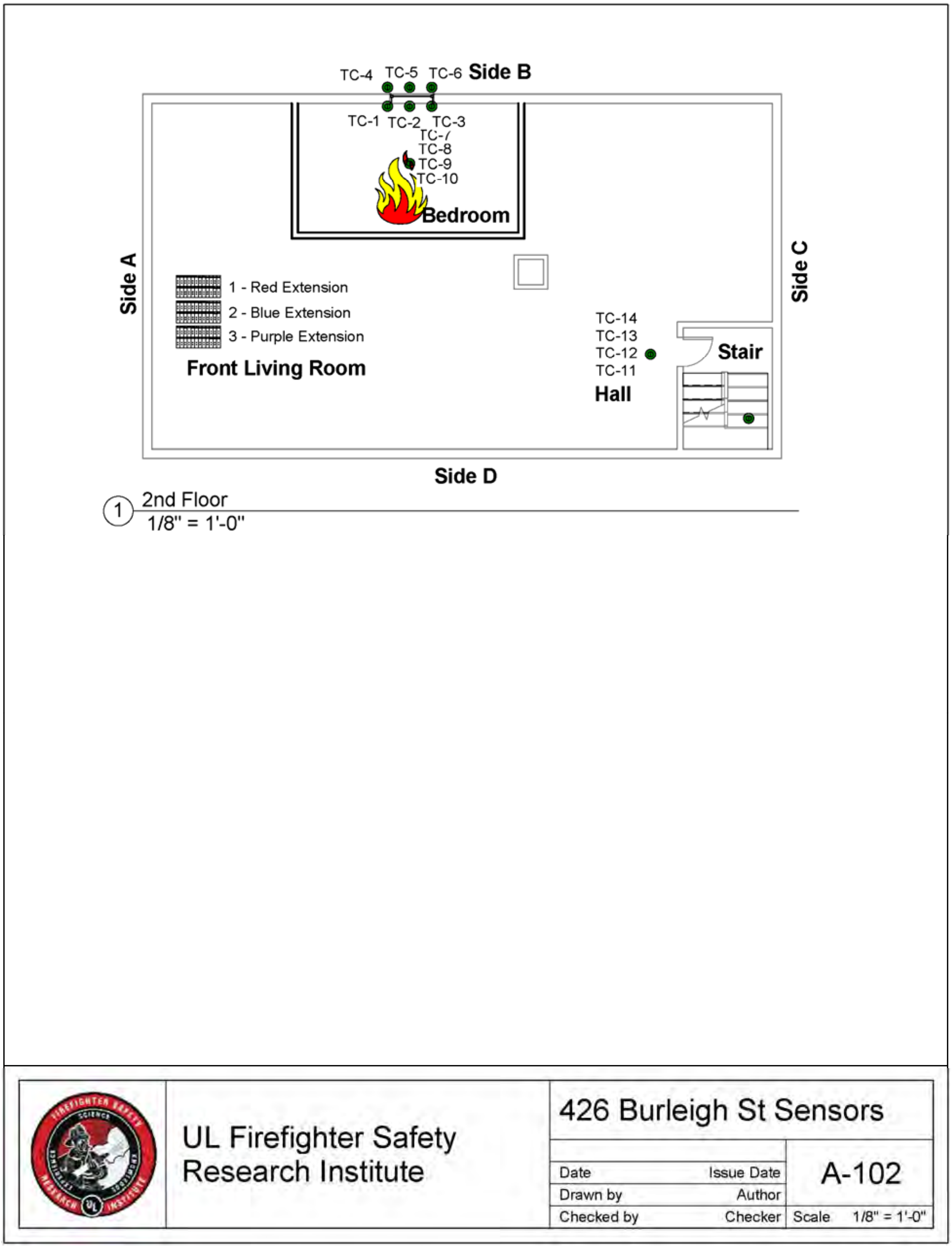


Figure F. 6: Field Experiment 2 - 426 Burleigh Street Sensors Second Floor Plan

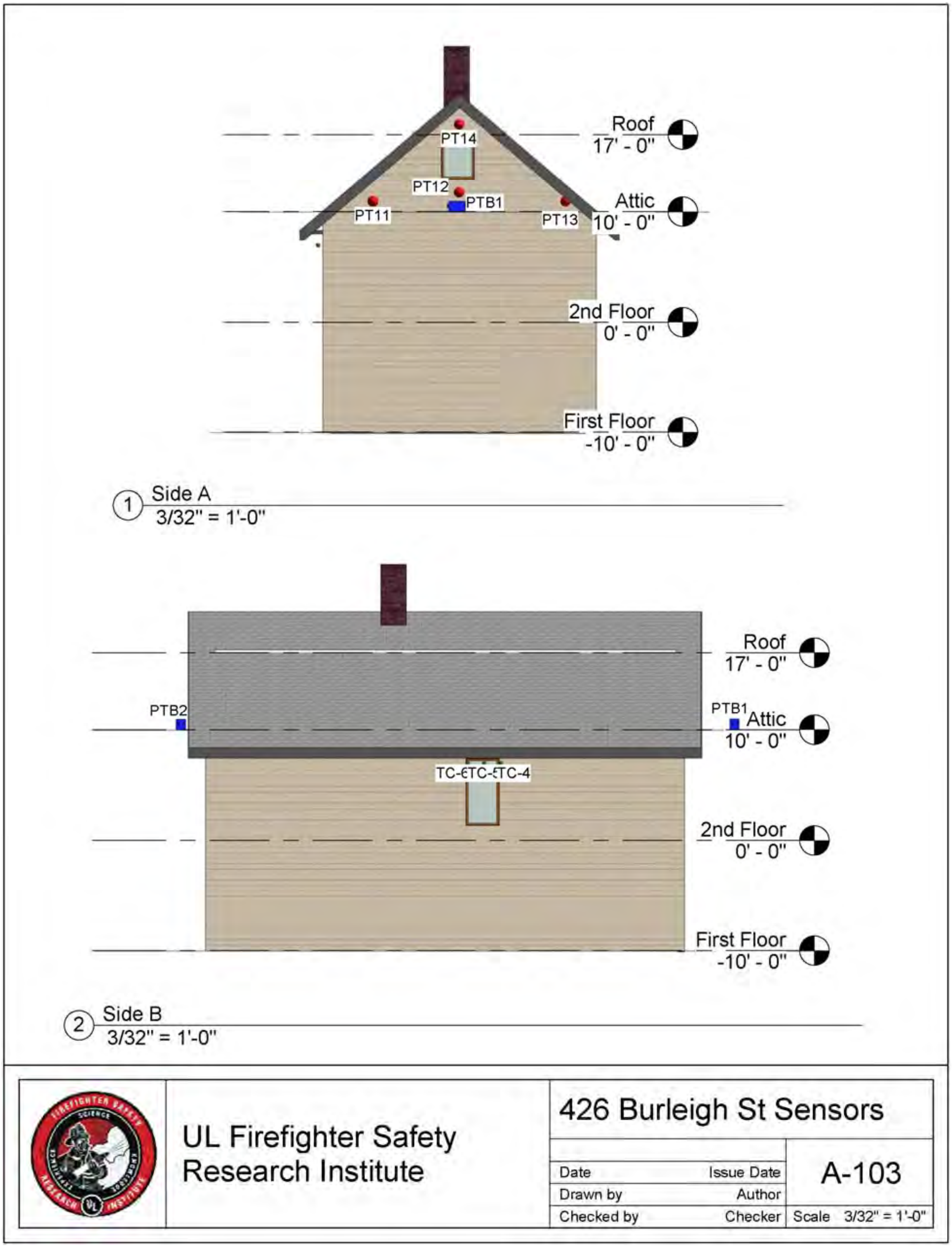


Figure F. 7: Field Experiment 2 - 426 Burleigh Street Sensors Side A & Side B Elevations

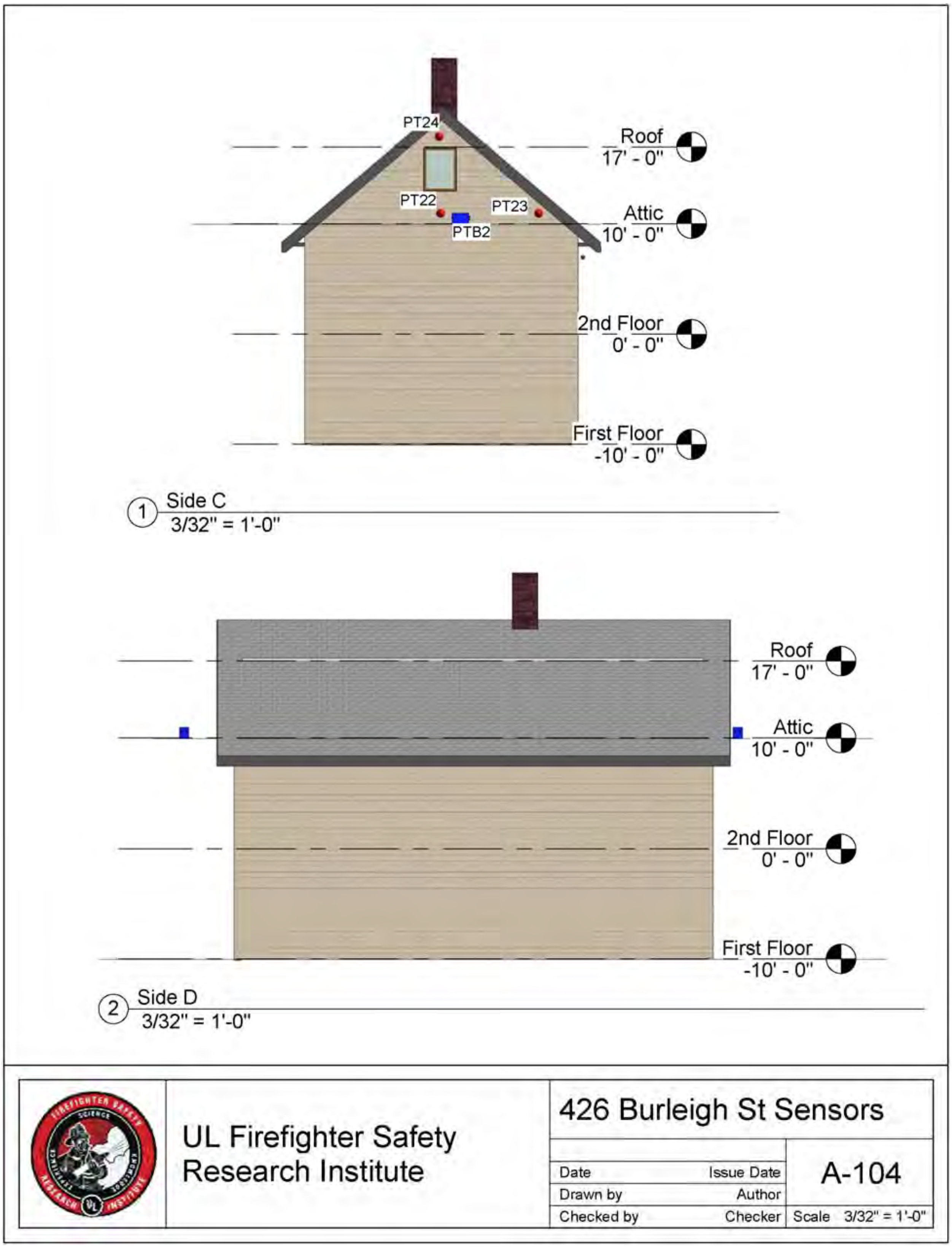


Figure F. 8: Field Experiment 2 - 426 Burleigh Street Sensors Side C & Side D Elevations

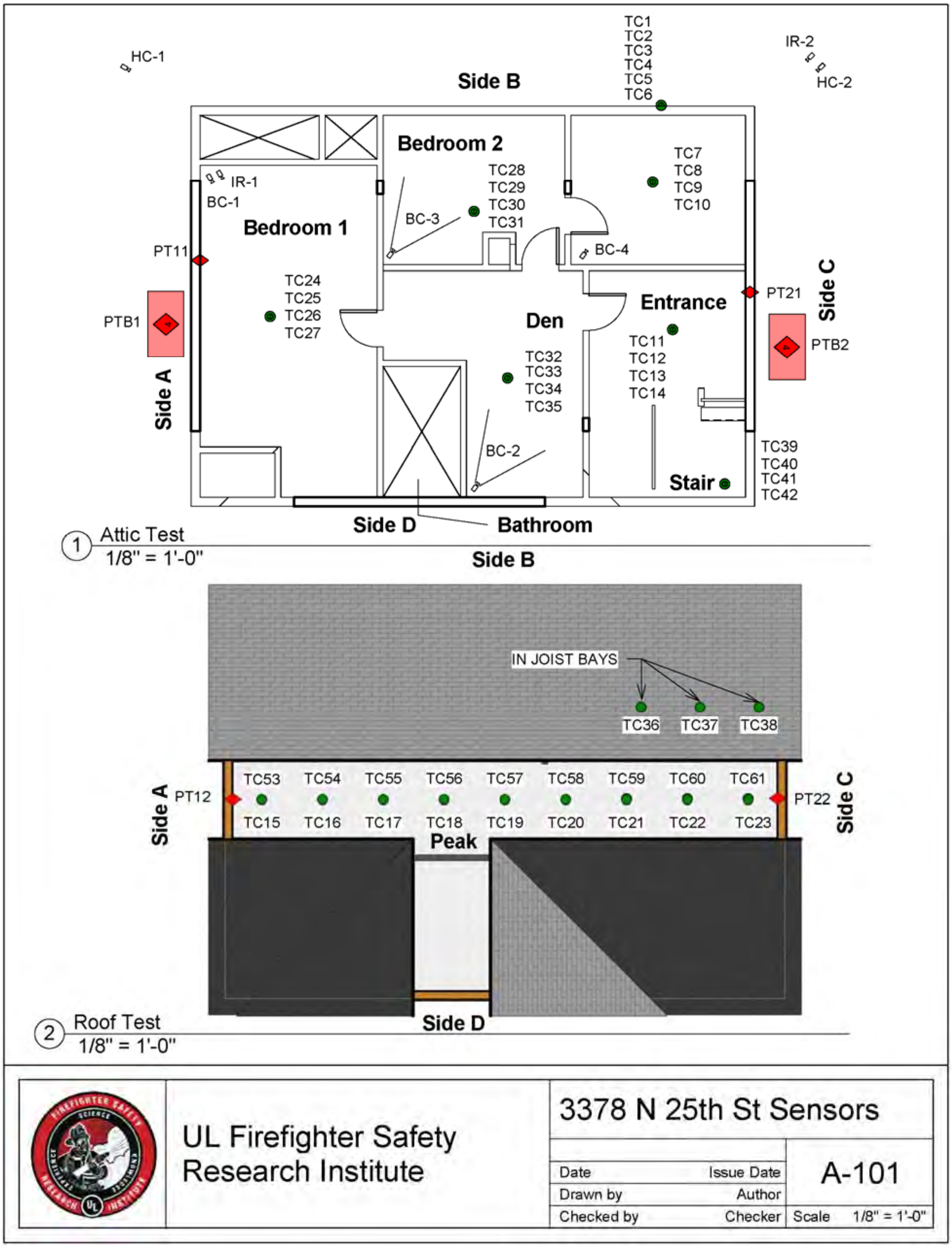


Figure F. 9: Field Experiment 3 – 3378 N 25th Street Sensors Plan View

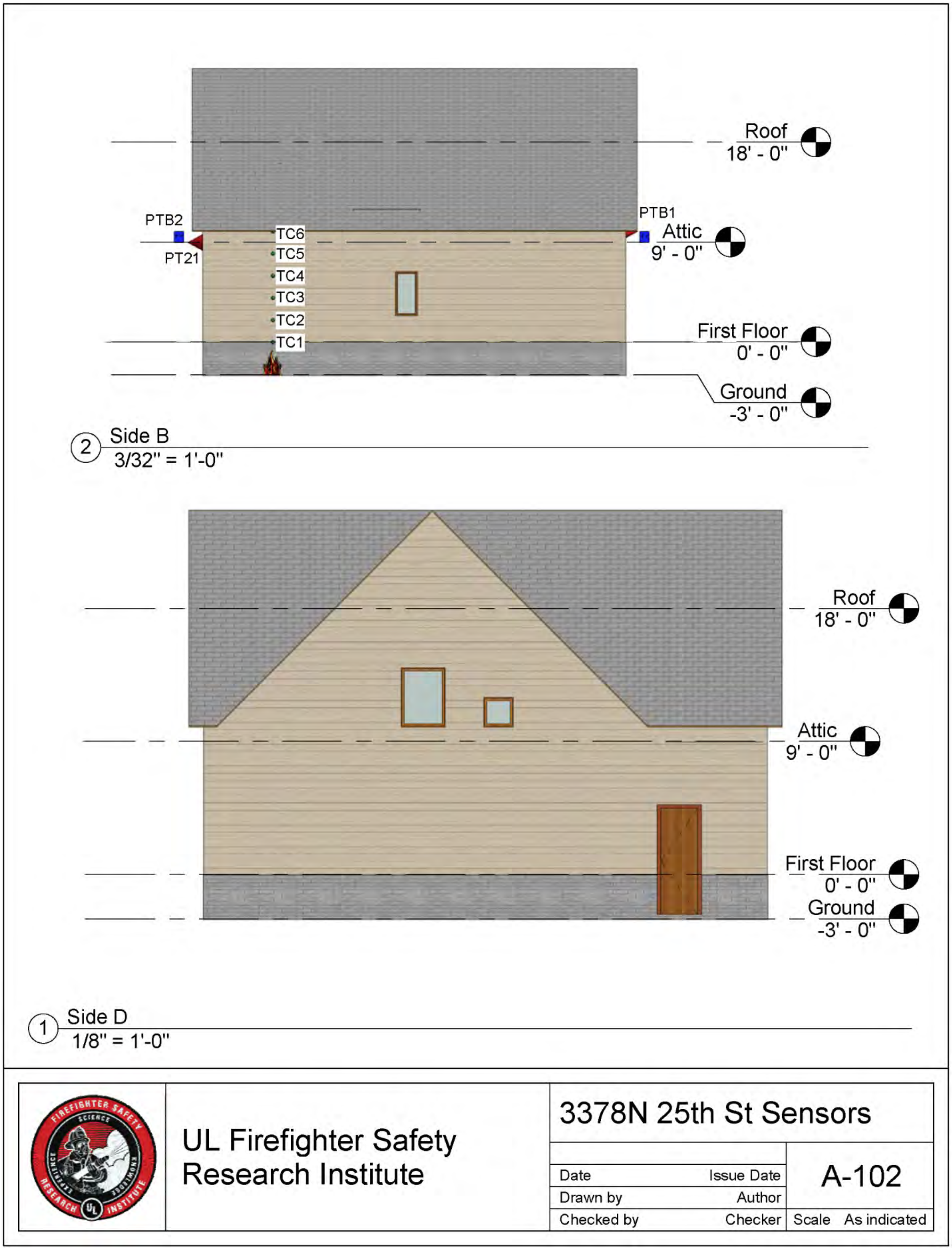


Figure F. 10: Field Experiment 3 – 3378 N 25h Street Sensors Side B & Side D Elevations

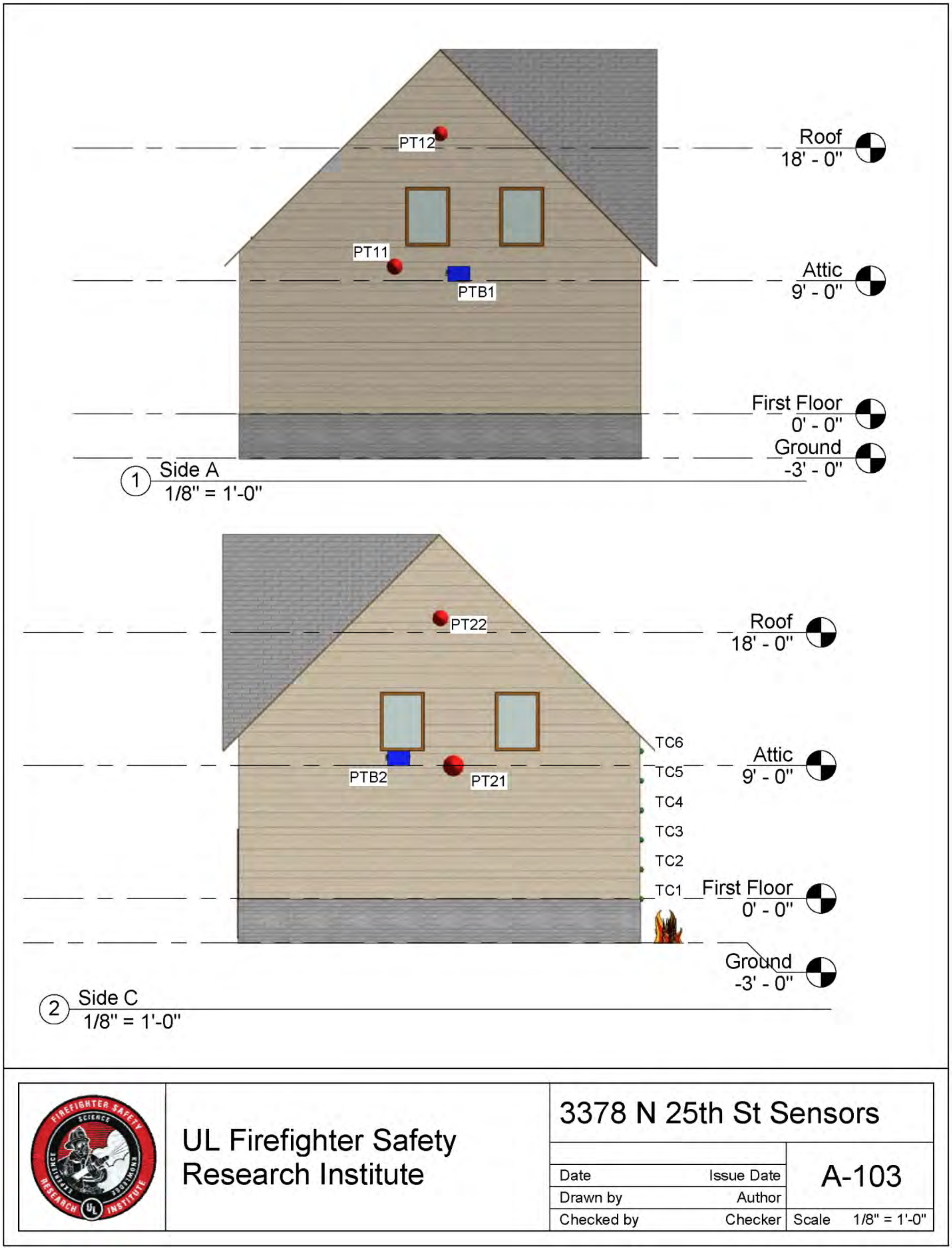


Figure F. 11: Field Experiment 3 – 3378 N 25h Street Sensors Side A & Side C Elevations

Appendix G: Wall Experiment Data

Experiment 1

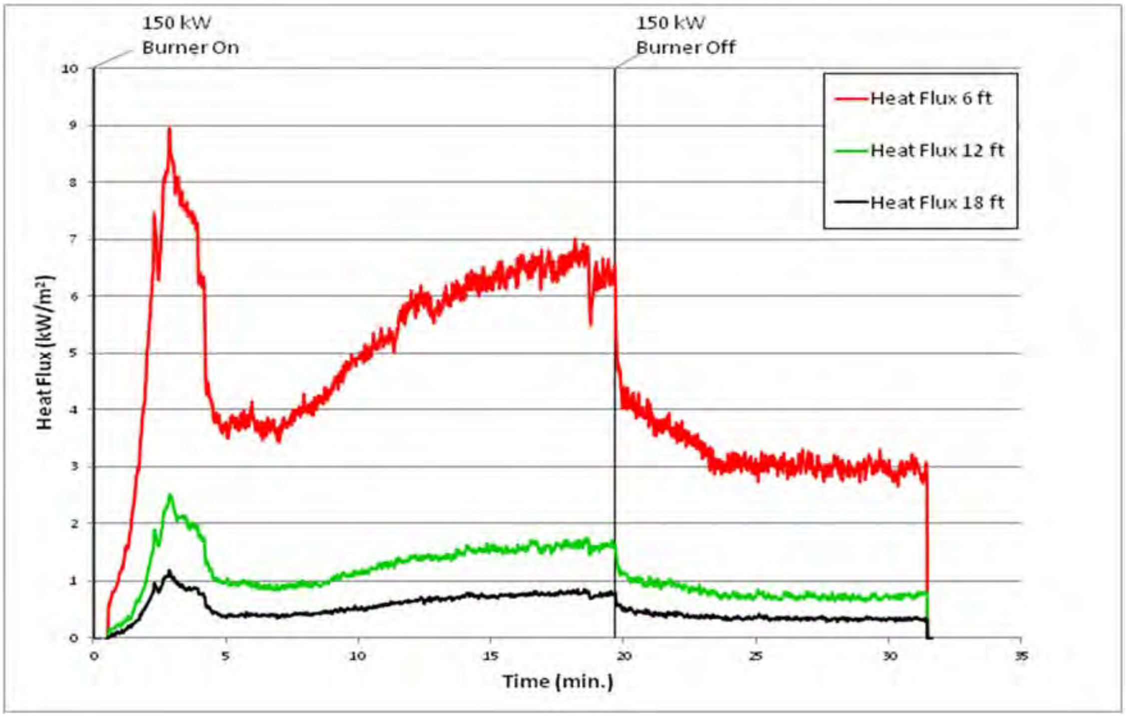


Figure G. 1: Wall Experiment 1 Heat Flux

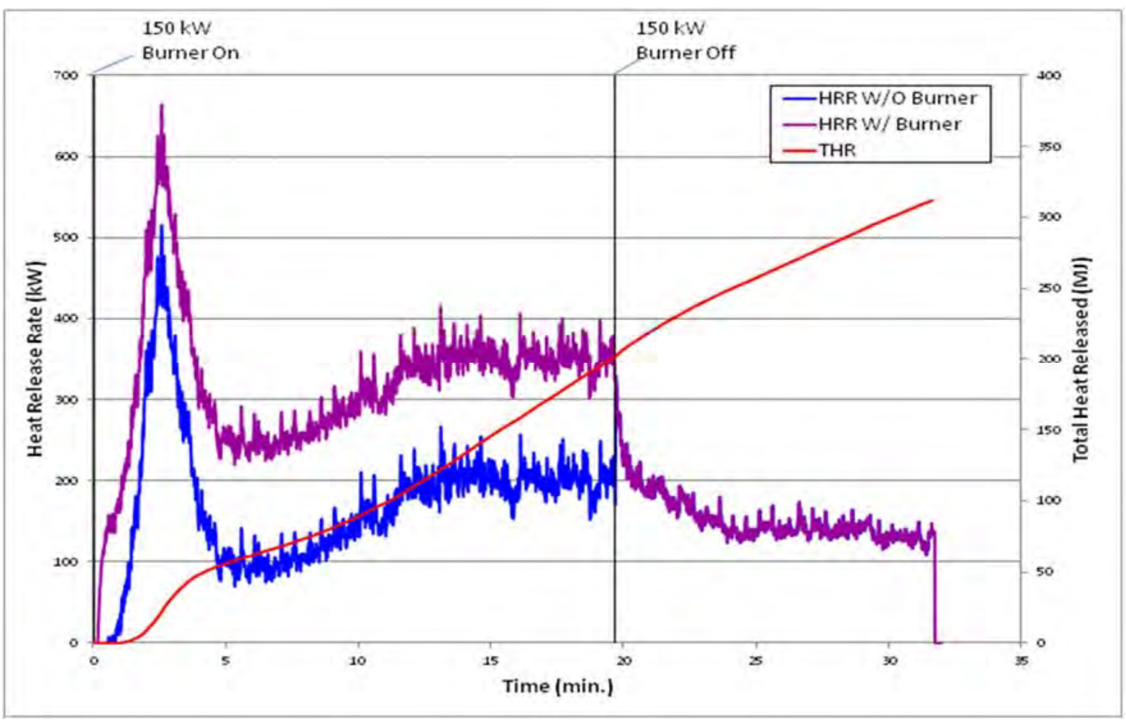


Figure G. 2: Wall Experiment 1 Heat Release Rate and Total Heat Released

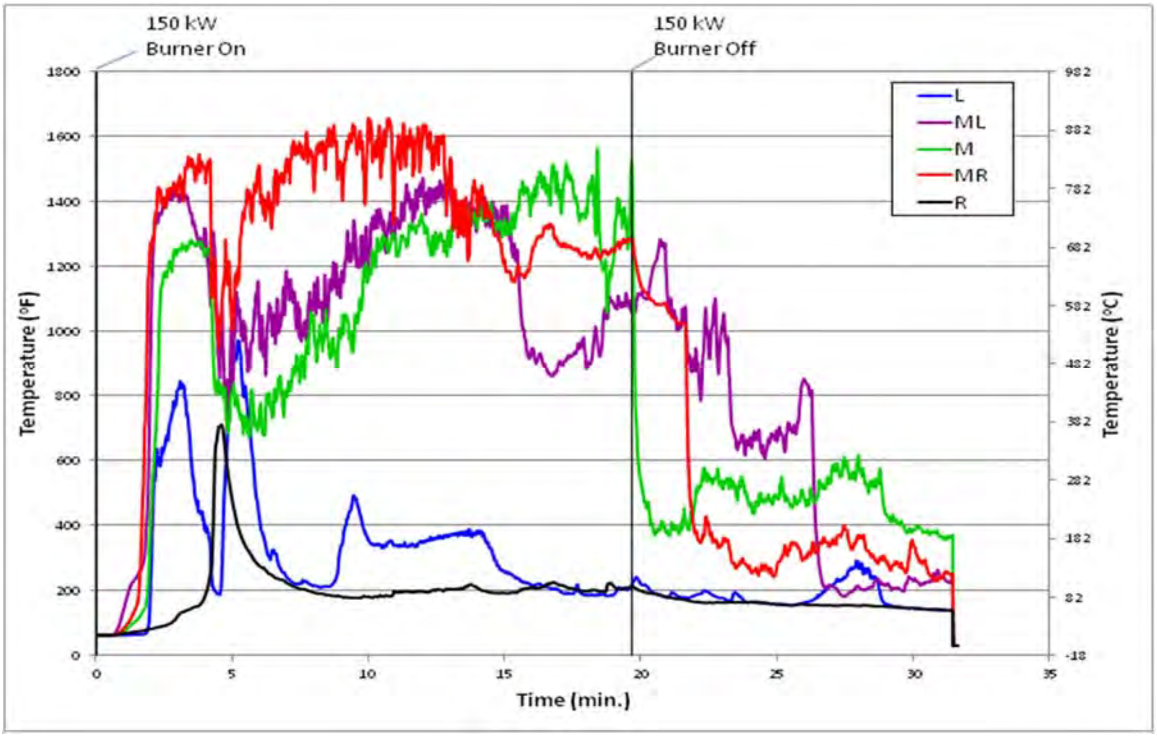


Figure G. 3: Wall Experiment 1 under Siding Horizontal Temperatures

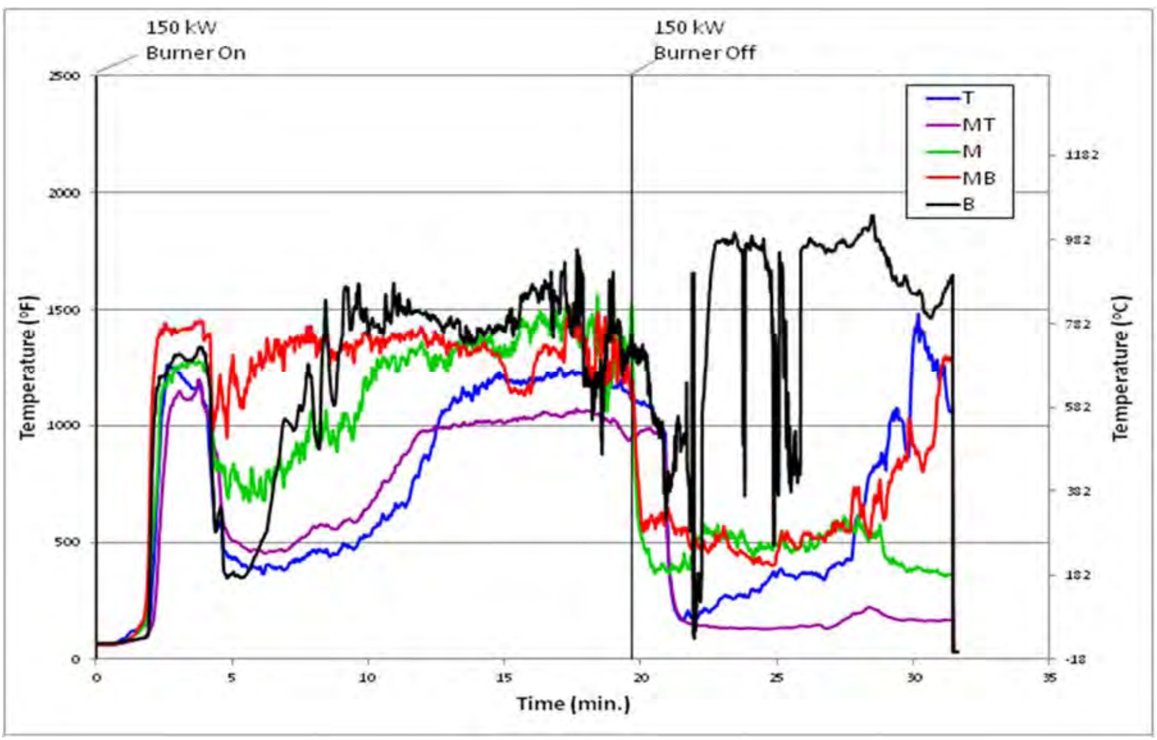


Figure G. 4: Wall Experiment 1 under Siding Vertical Temperatures

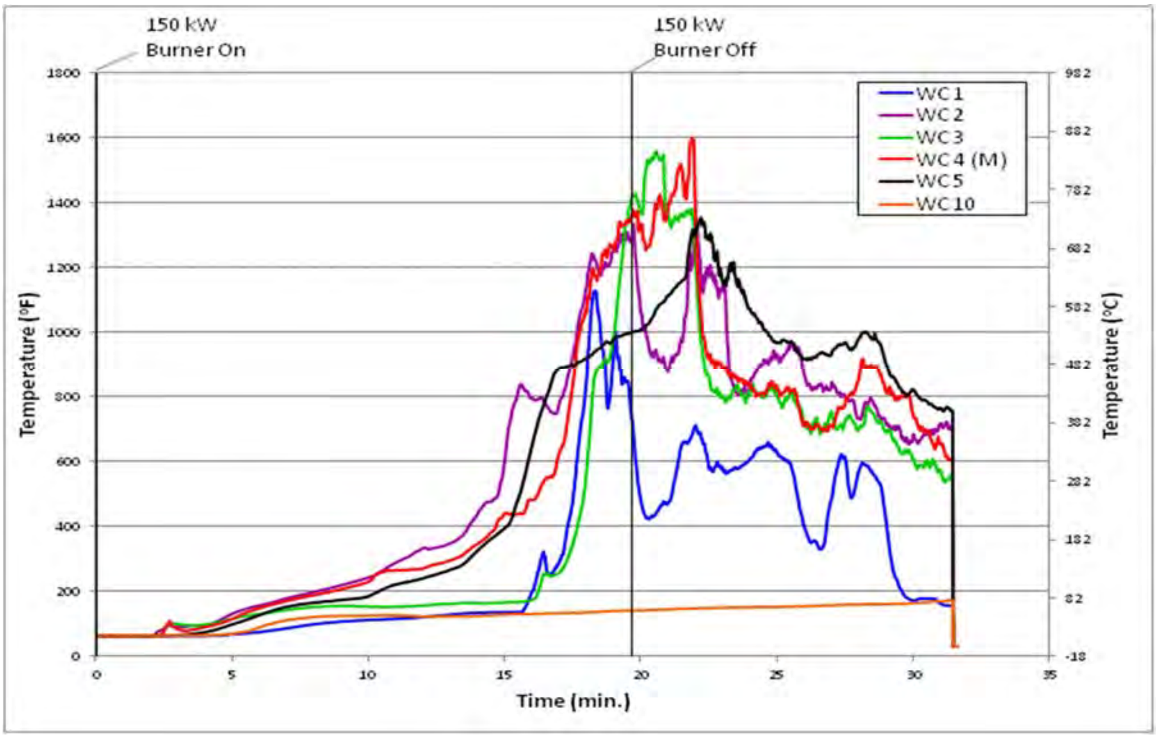


Figure G. 5: Wall Experiment 1 Wall Cavity Horizontal Temperatures

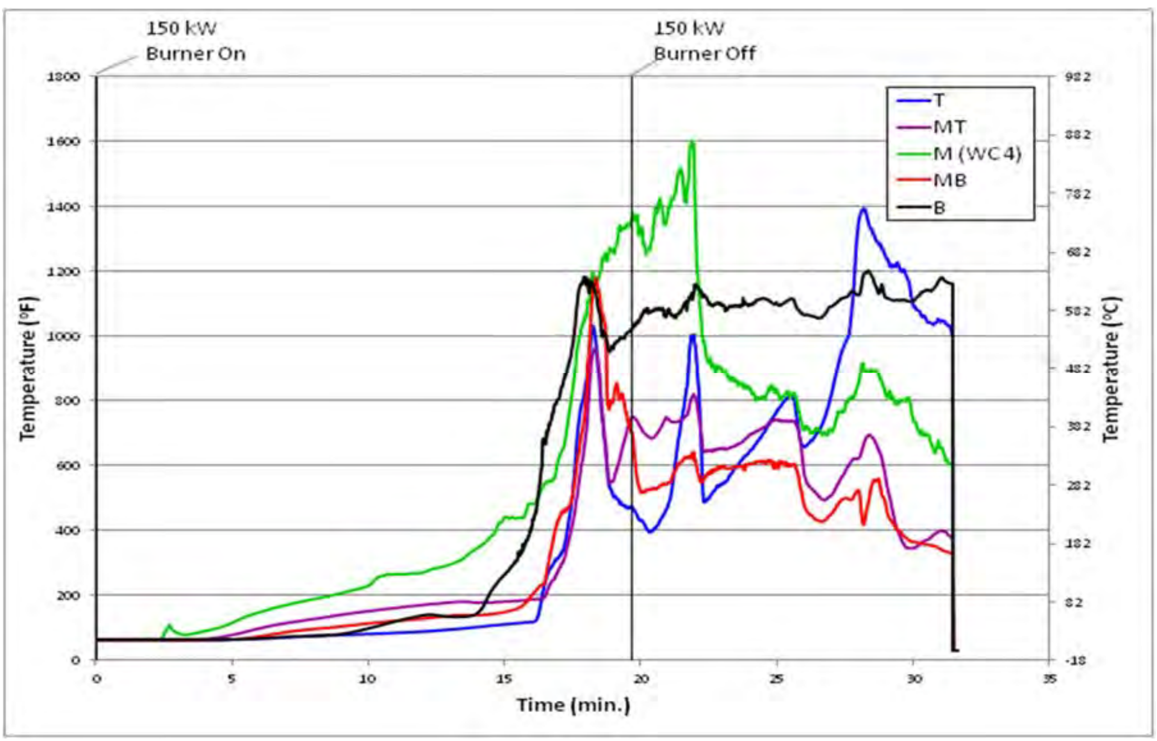


Figure G. 6: Wall Experiment 1 Wall Cavity Vertical Temperatures

Experiment 2

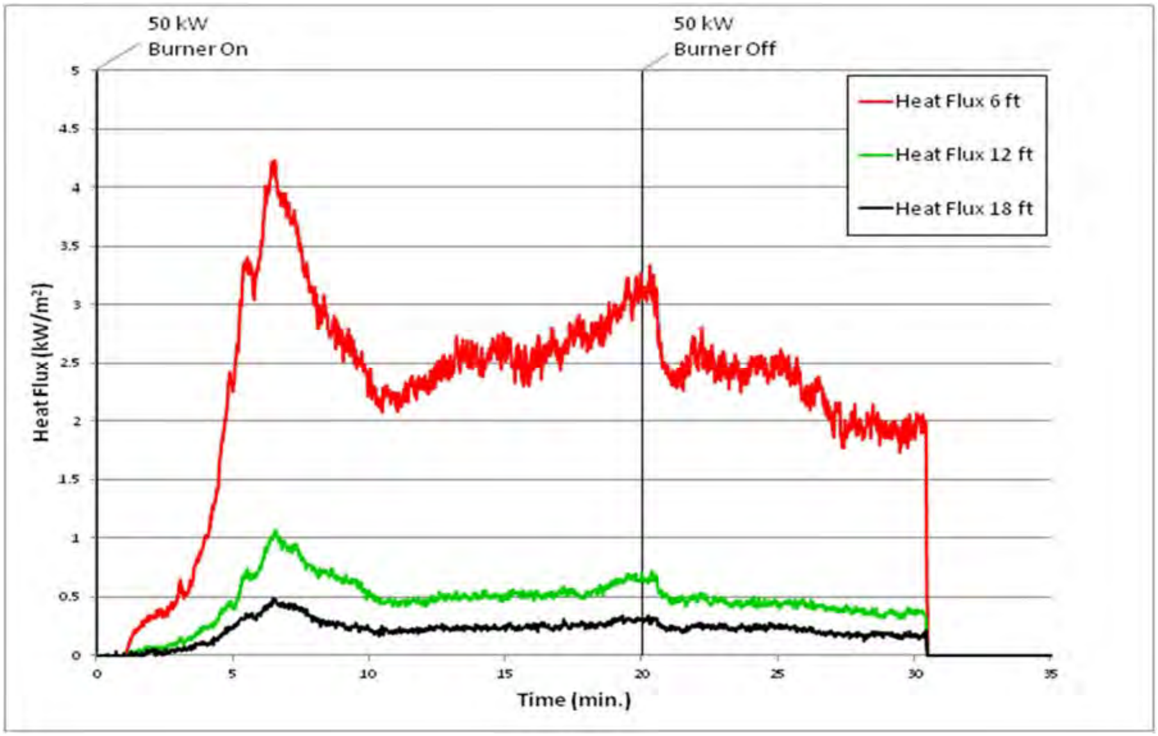


Figure G. 7: Wall Experiment 2 Heat Flux

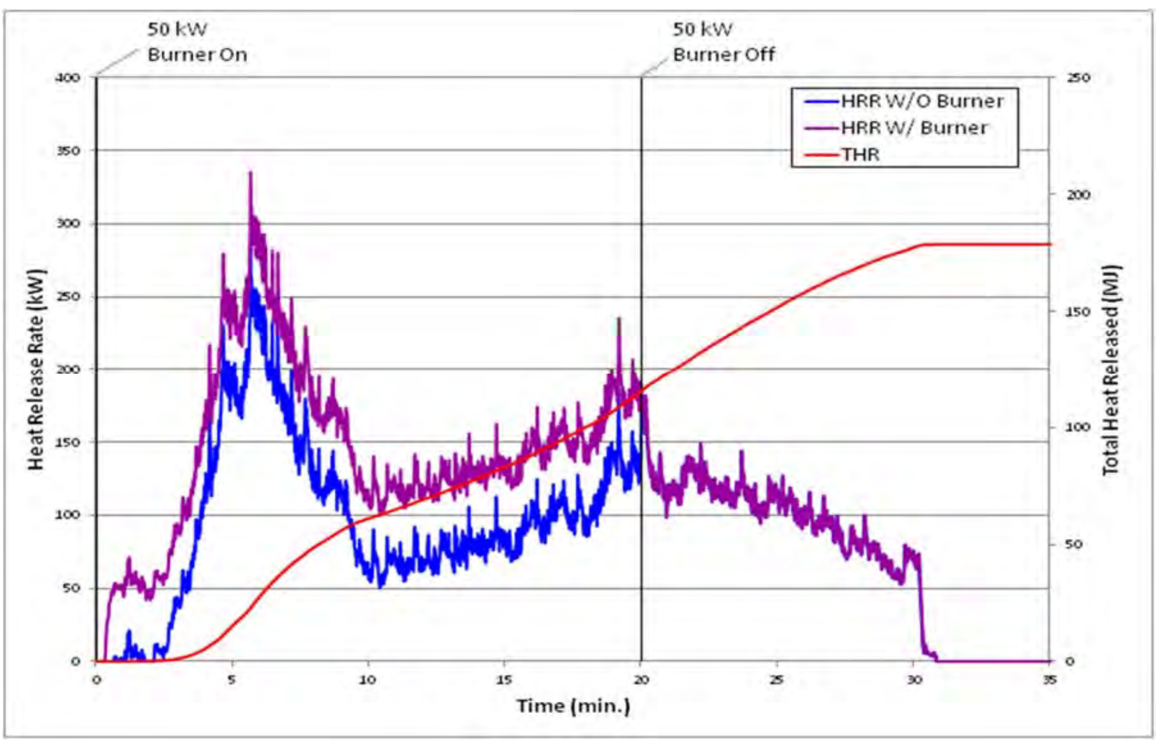


Figure G. 8: Wall Experiment 2 Heat Release Rate and Total Heat Released

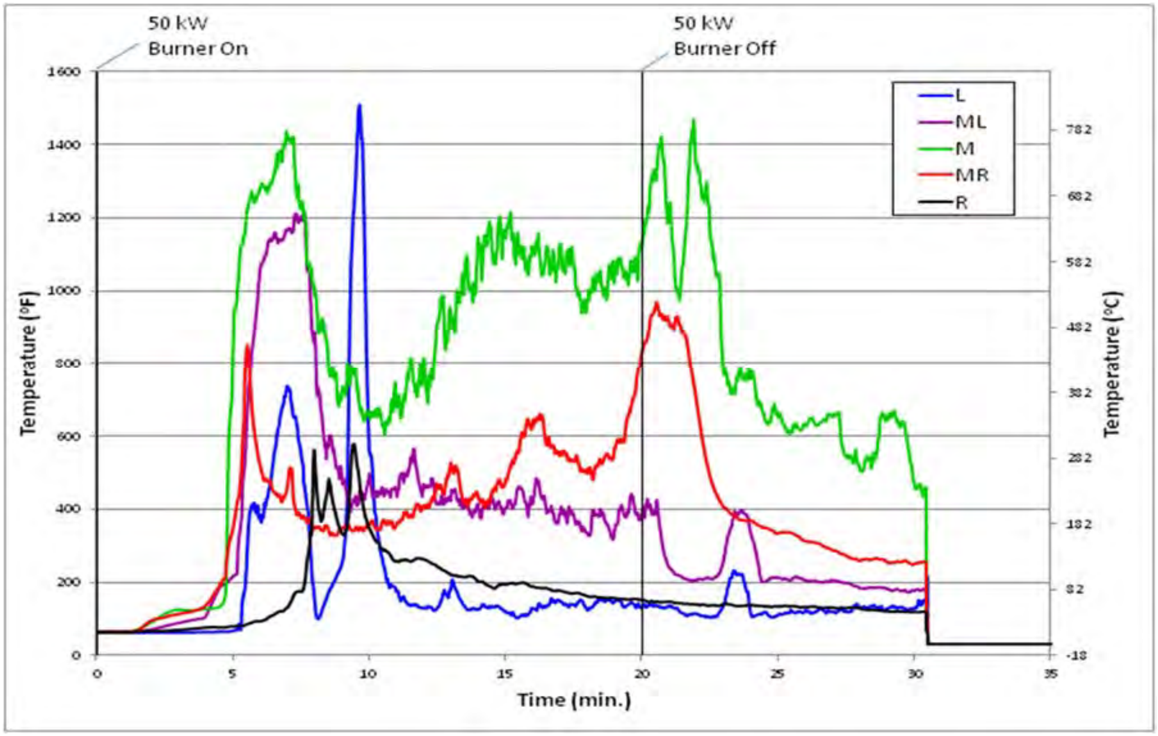


Figure G. 9: Wall Experiment 2 under Siding Horizontal Temperatures

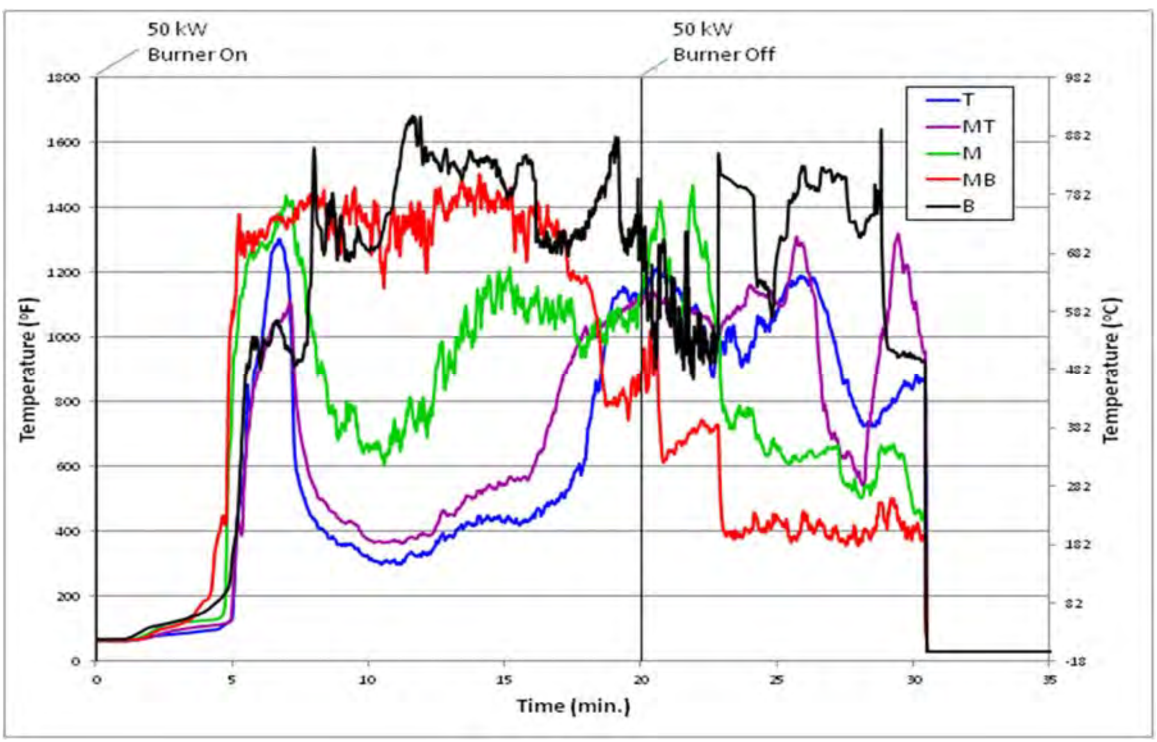


Figure G. 10: Wall Experiment 2 under Siding Vertical Temperatures

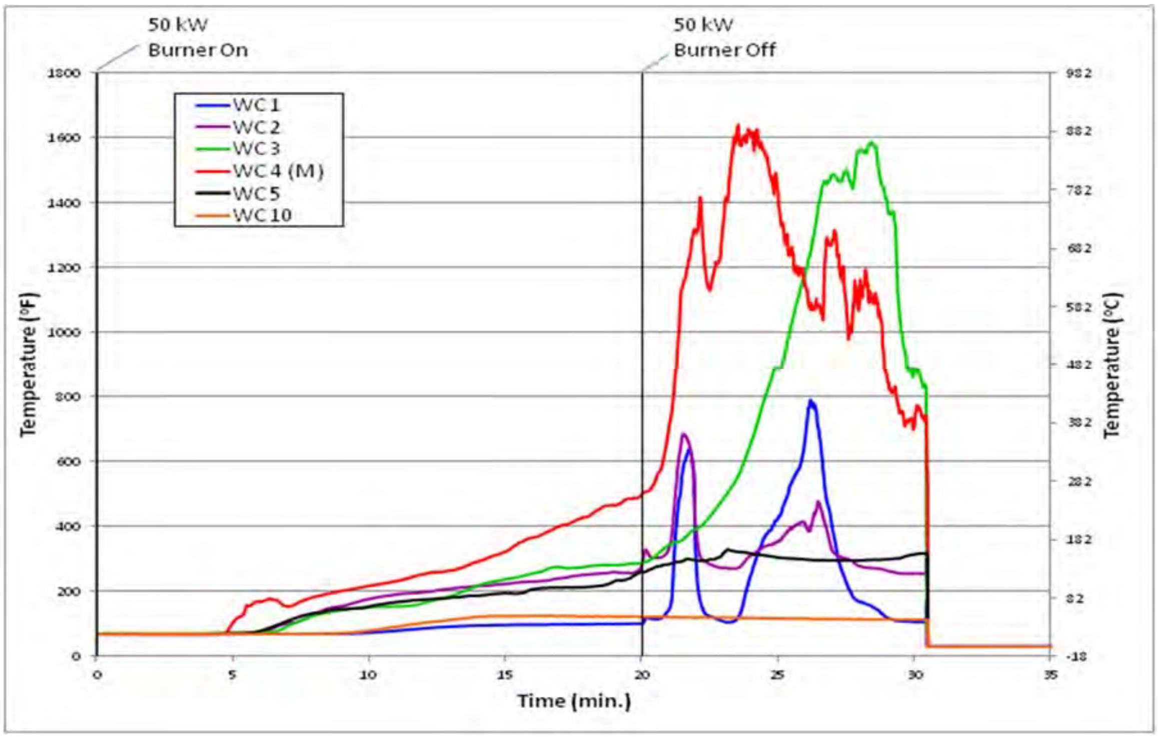


Figure G. 11: Wall Experiment 2 Wall Cavity Horizontal Temperatures

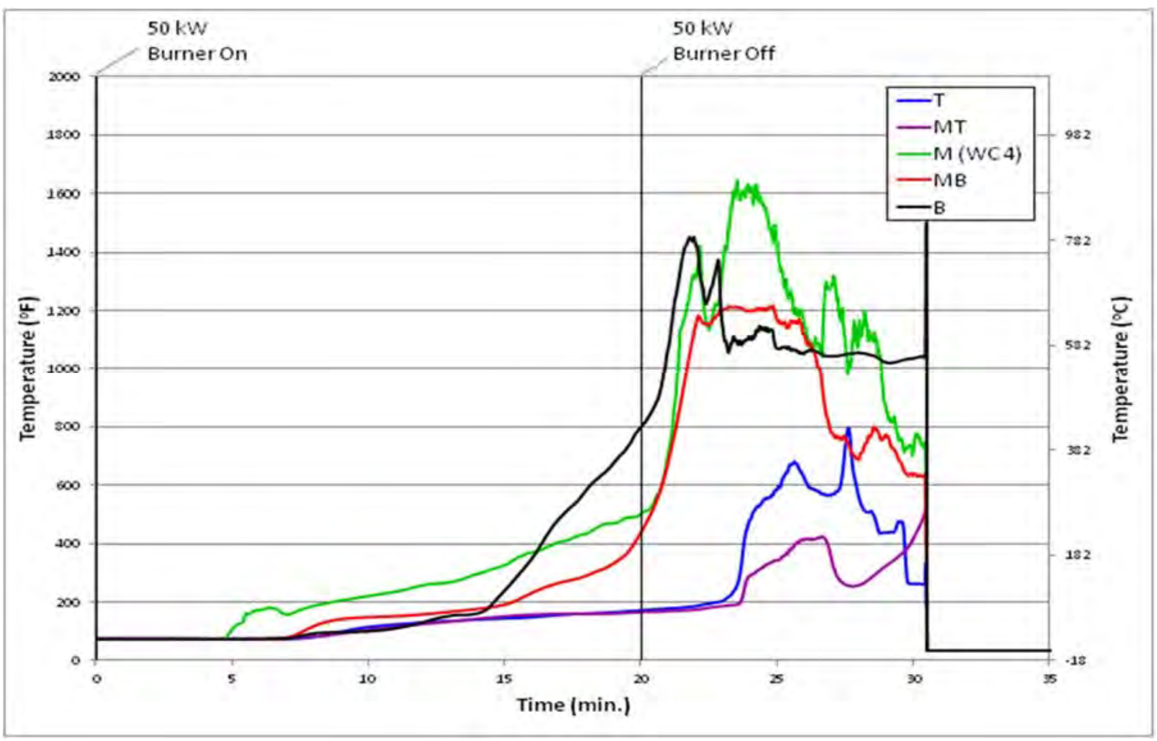


Figure G. 12: Wall Experiment 2 Wall Cavity Vertical Temperatures

Experiment 3

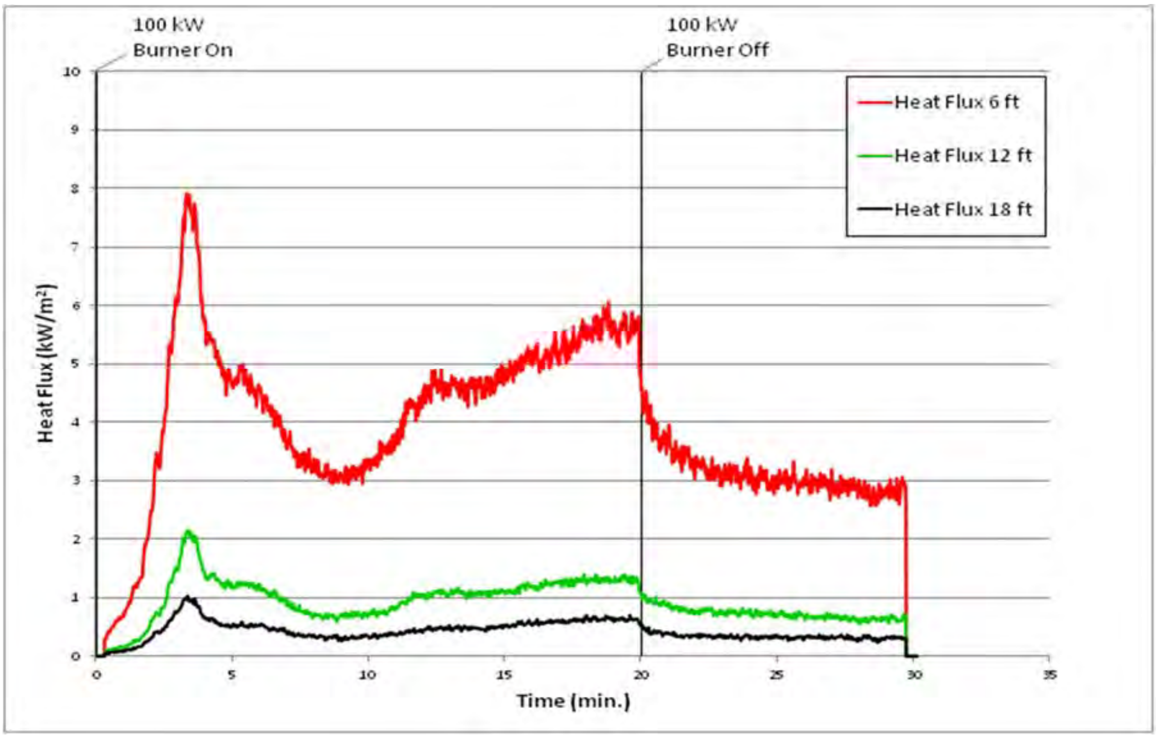


Figure G. 13: Wall Experiment 3 Heat Flux

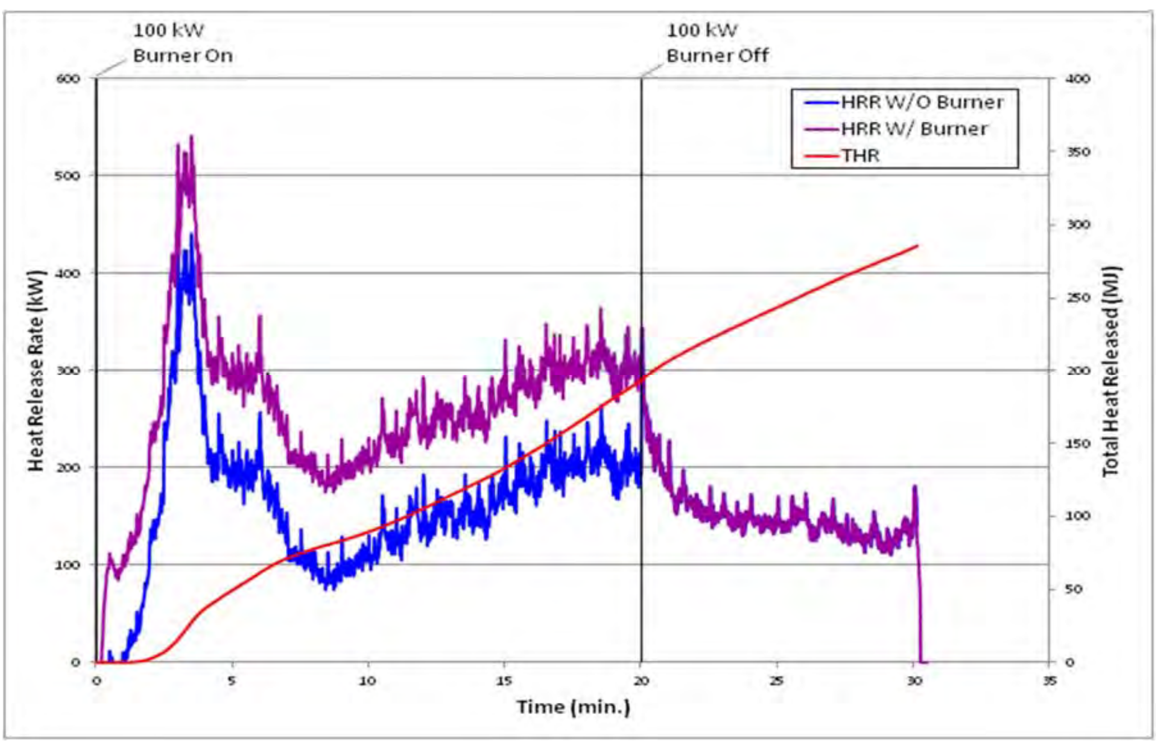


Figure G. 14: Wall Experiment 3 Heat Release Rate and Total Heat Released

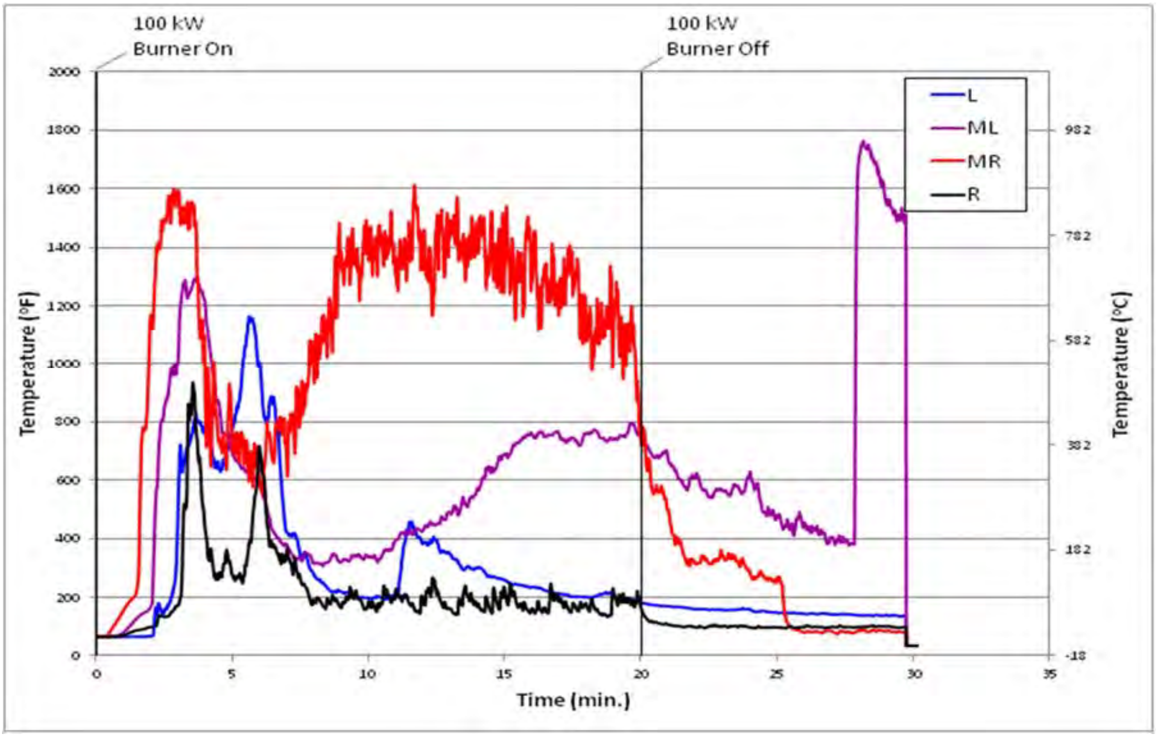


Figure G. 15: Wall Experiment 3 under Siding Horizontal Temperatures

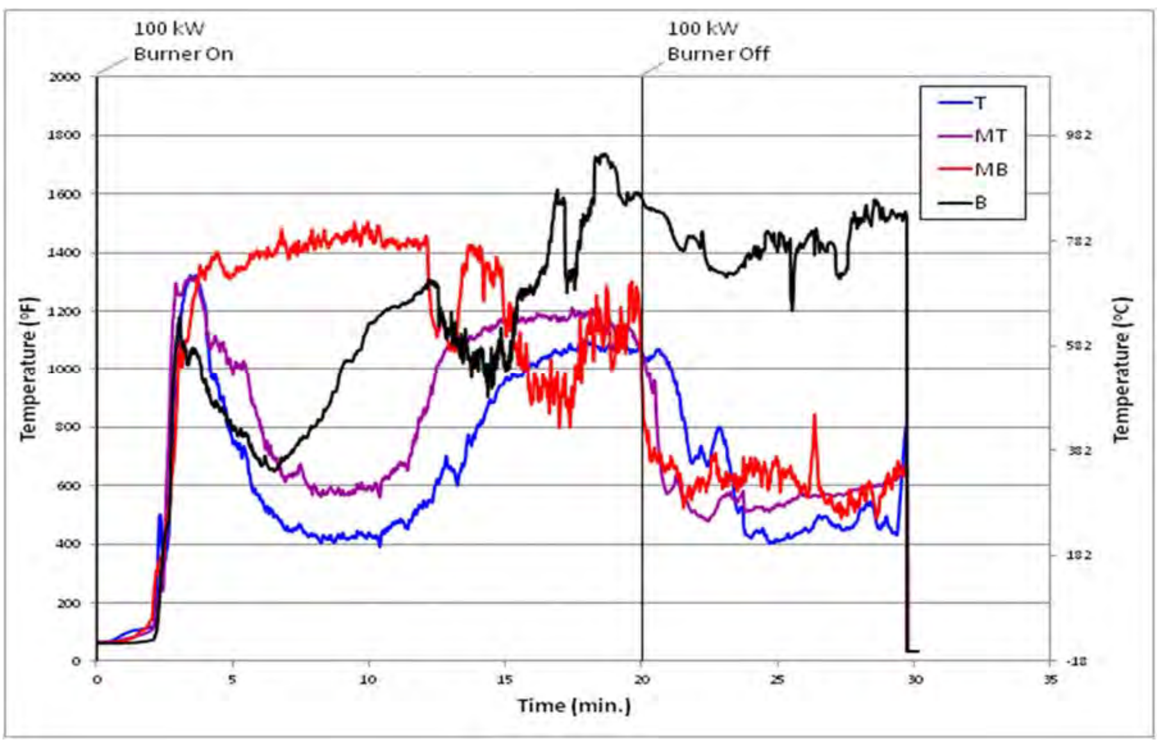


Figure G. 16: Wall Experiment 3 under Siding Vertical Temperatures

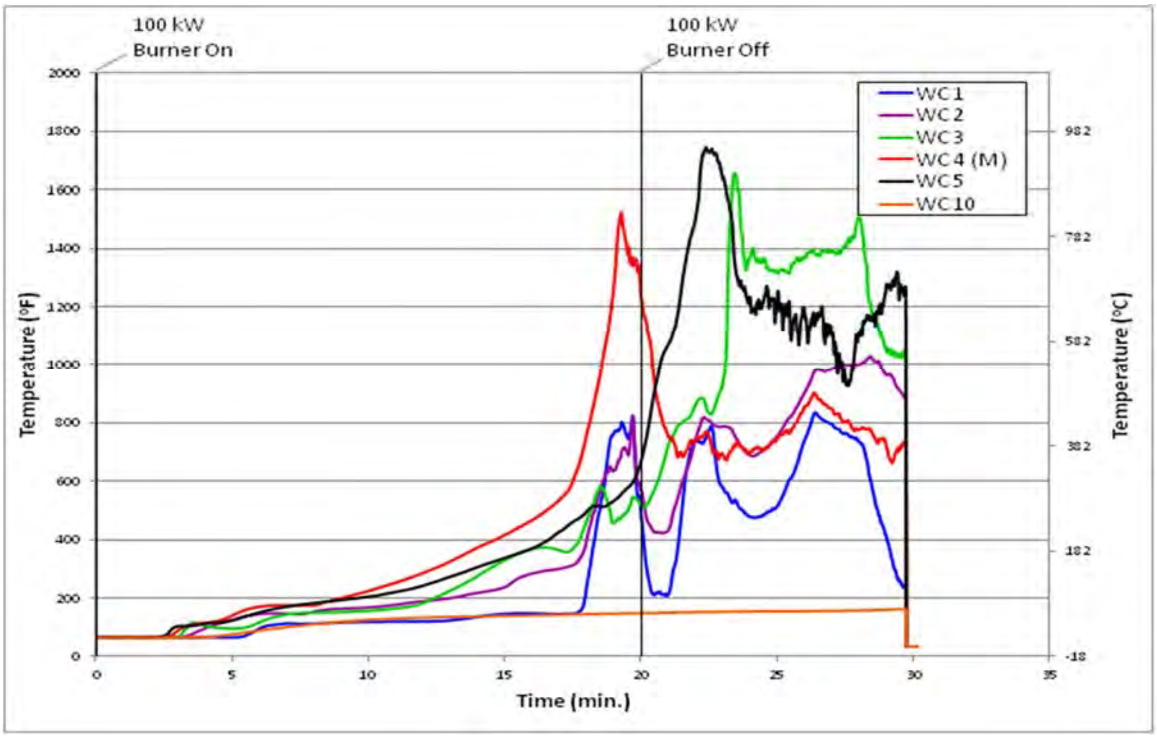


Figure G. 17: Wall Experiment 3 Wall Cavity Horizontal Temperatures

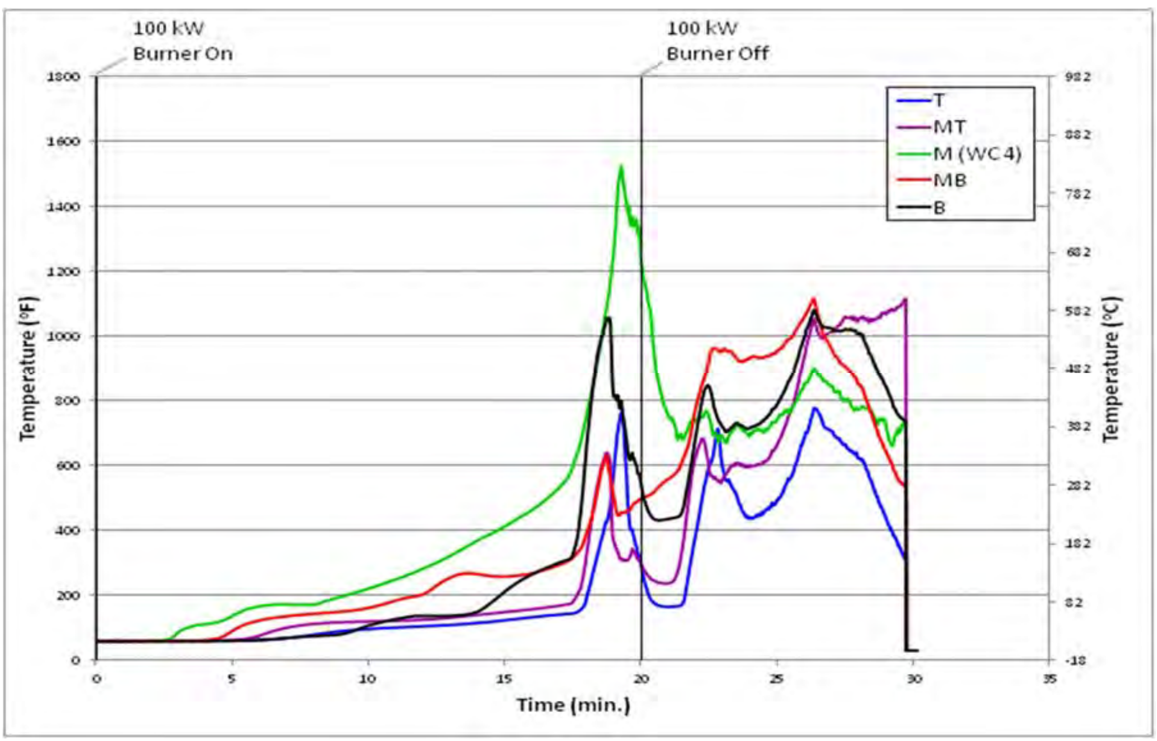


Figure G. 18: Wall Experiment 3 Wall Cavity Vertical Temperatures

Experiment 4

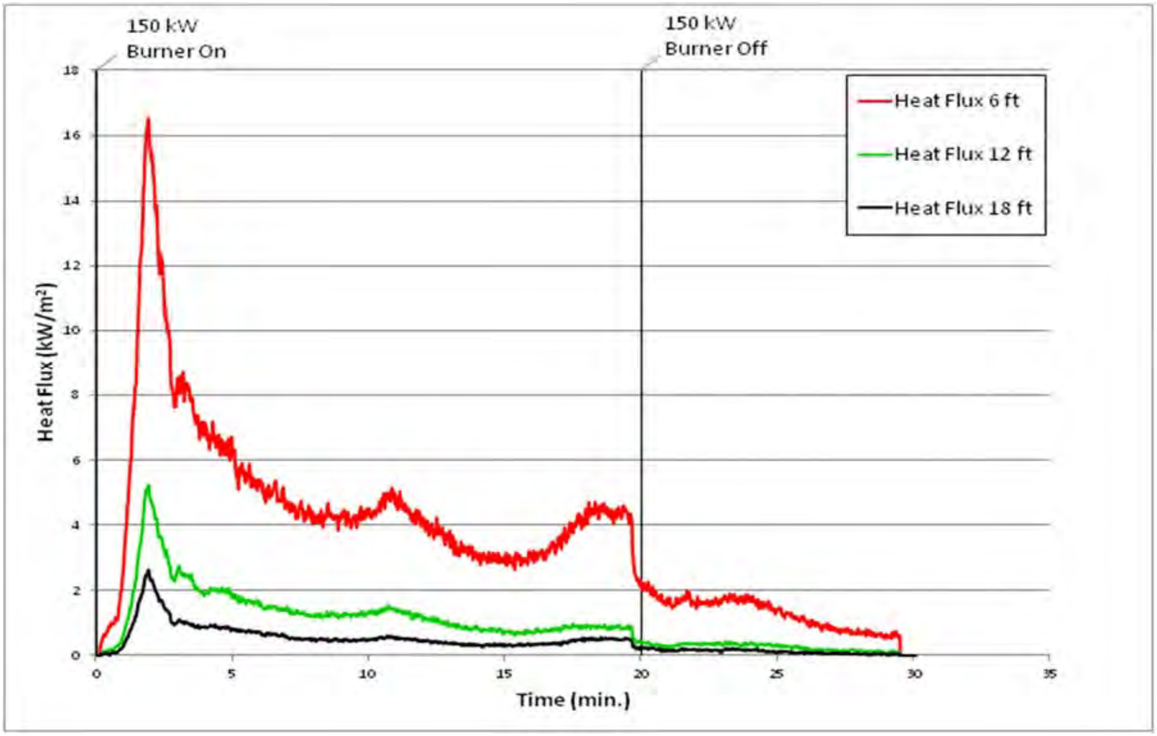


Figure G. 19: Wall Experiment 4 Heat Flux

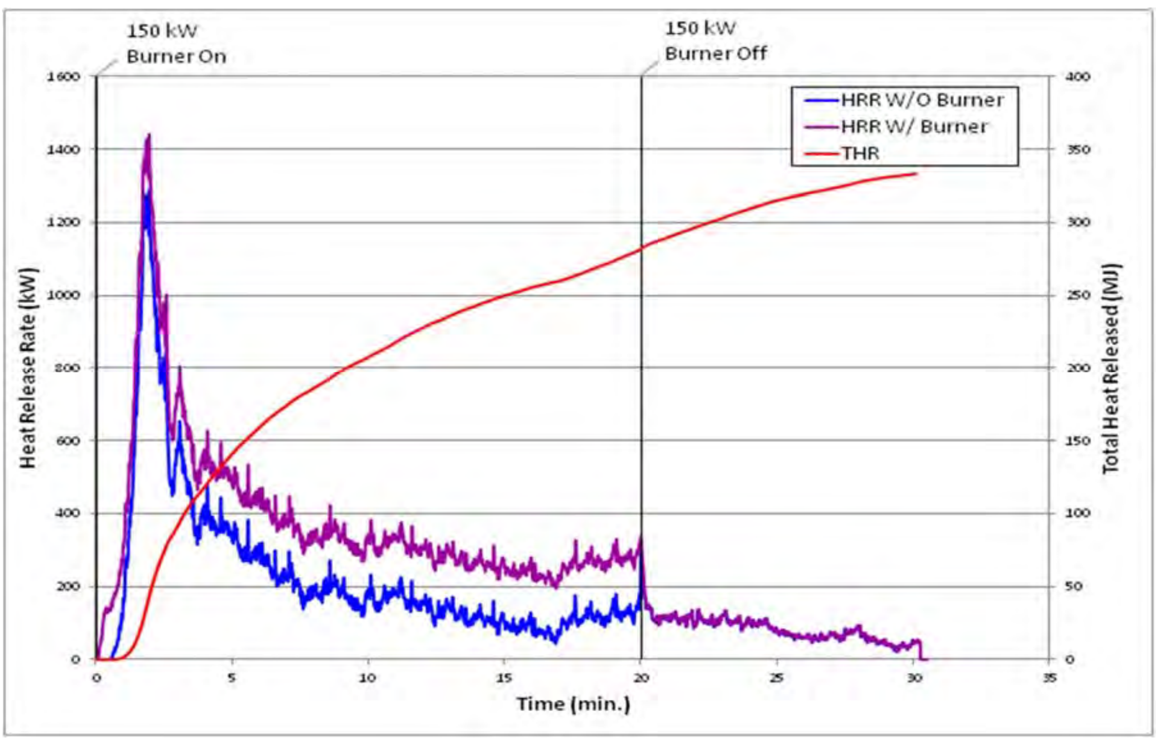


Figure G. 20: Wall Experiment 4 Heat Release Rate and Total Heat Released

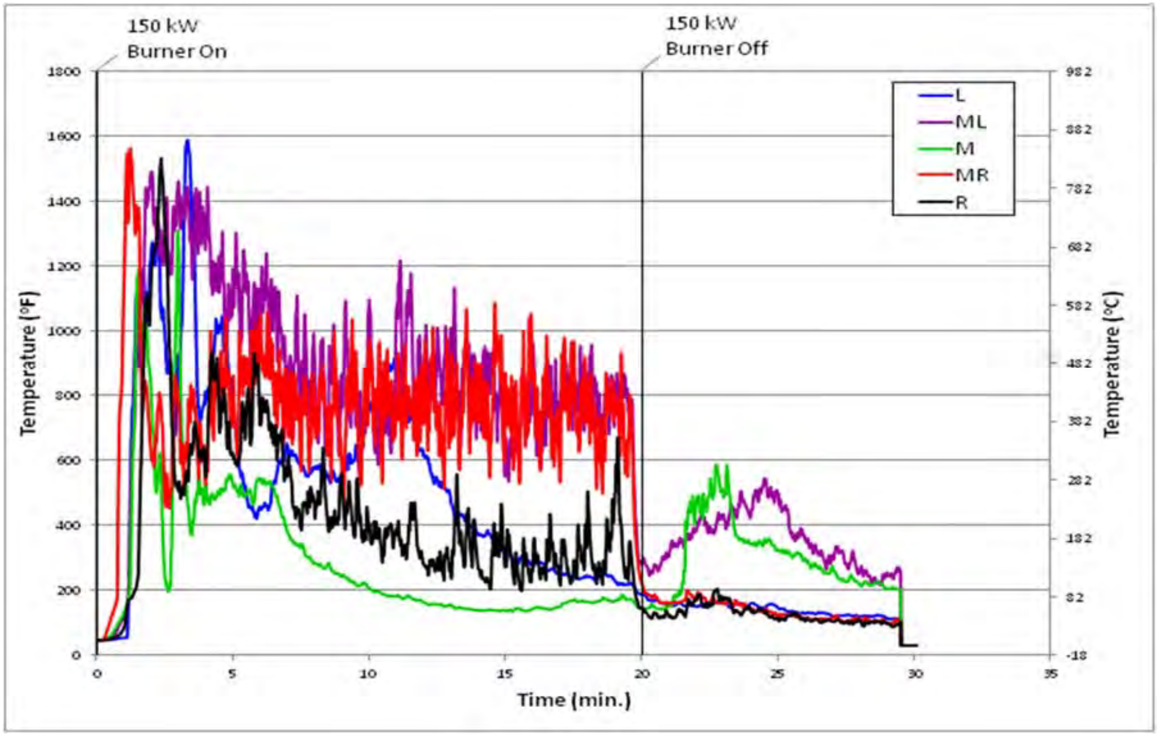


Figure G. 21: Wall Experiment 4 under Siding Horizontal Temperatures

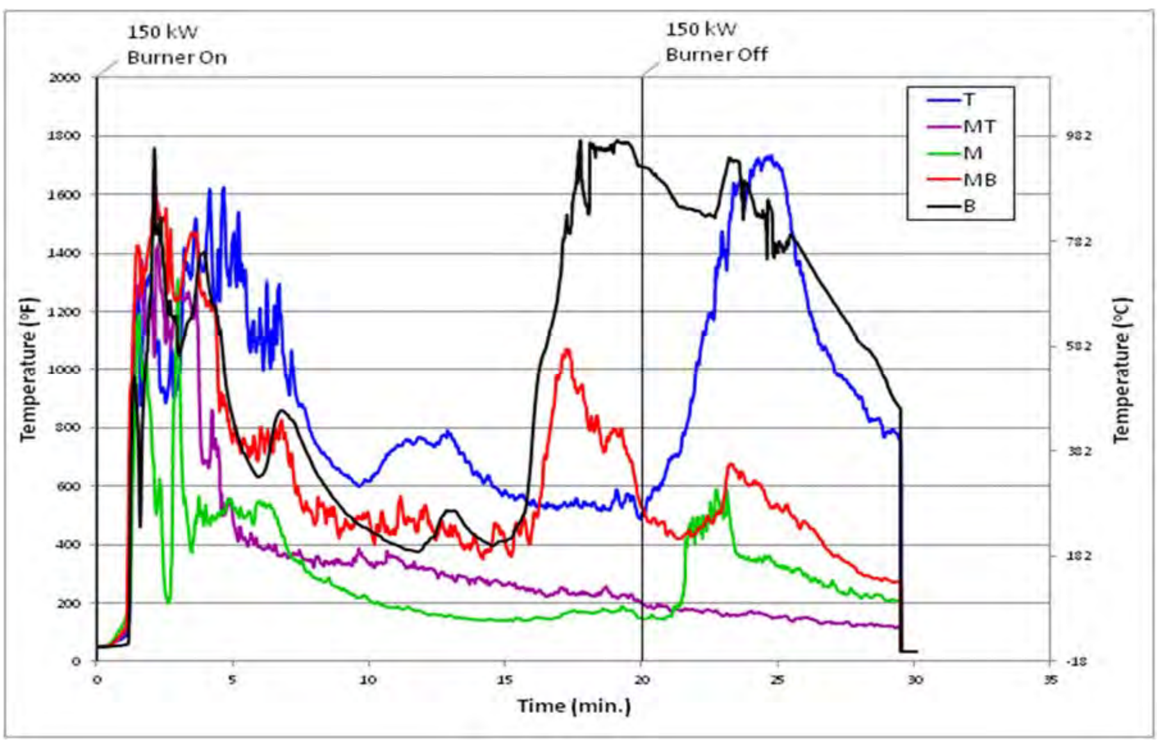


Figure G. 22: Wall Experiment 4 under Siding Vertical Temperatures

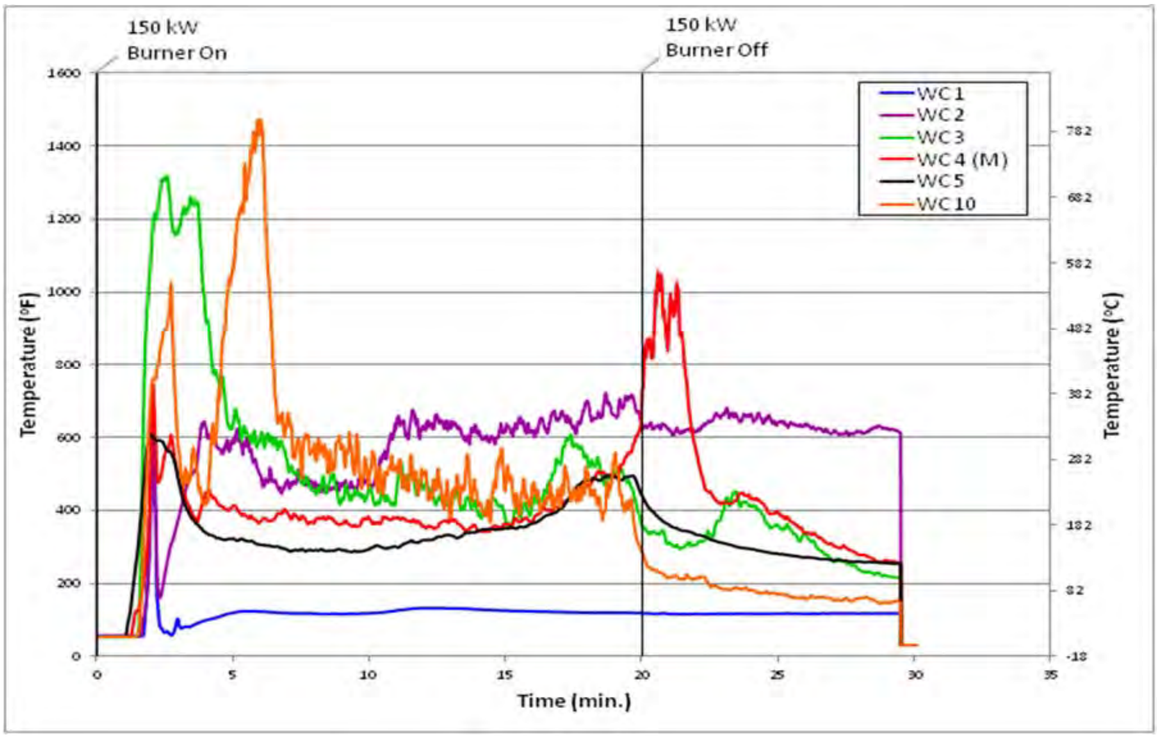


Figure G. 23: Wall Experiment 4 Wall Cavity Horizontal Temperatures

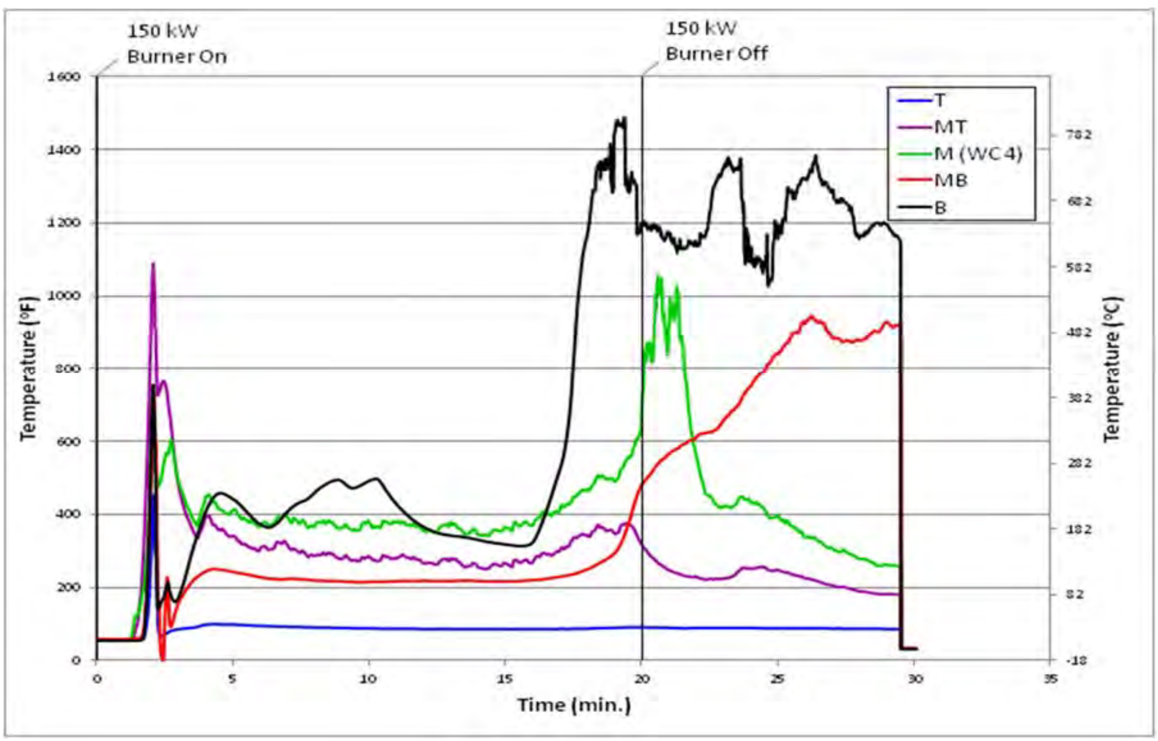


Figure G. 24: Wall Experiment 4 Wall Cavity Vertical Temperatures

Experiment 5

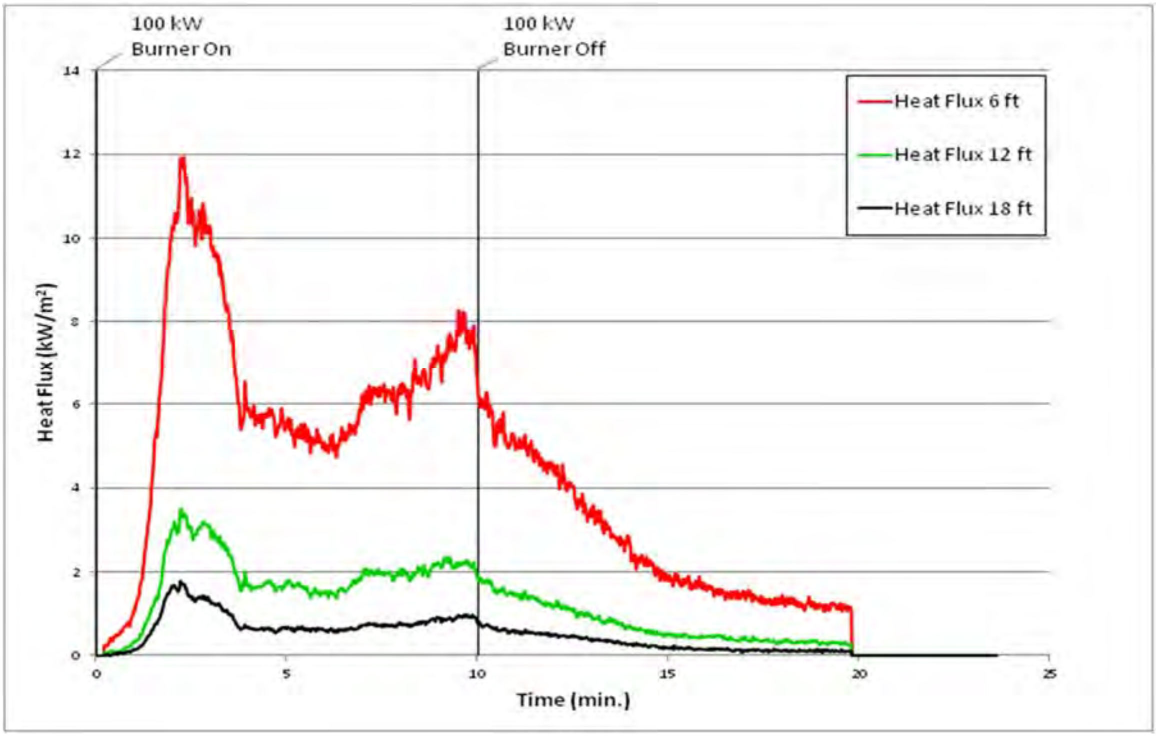


Figure G. 25: Wall Experiment 5 Heat Flux

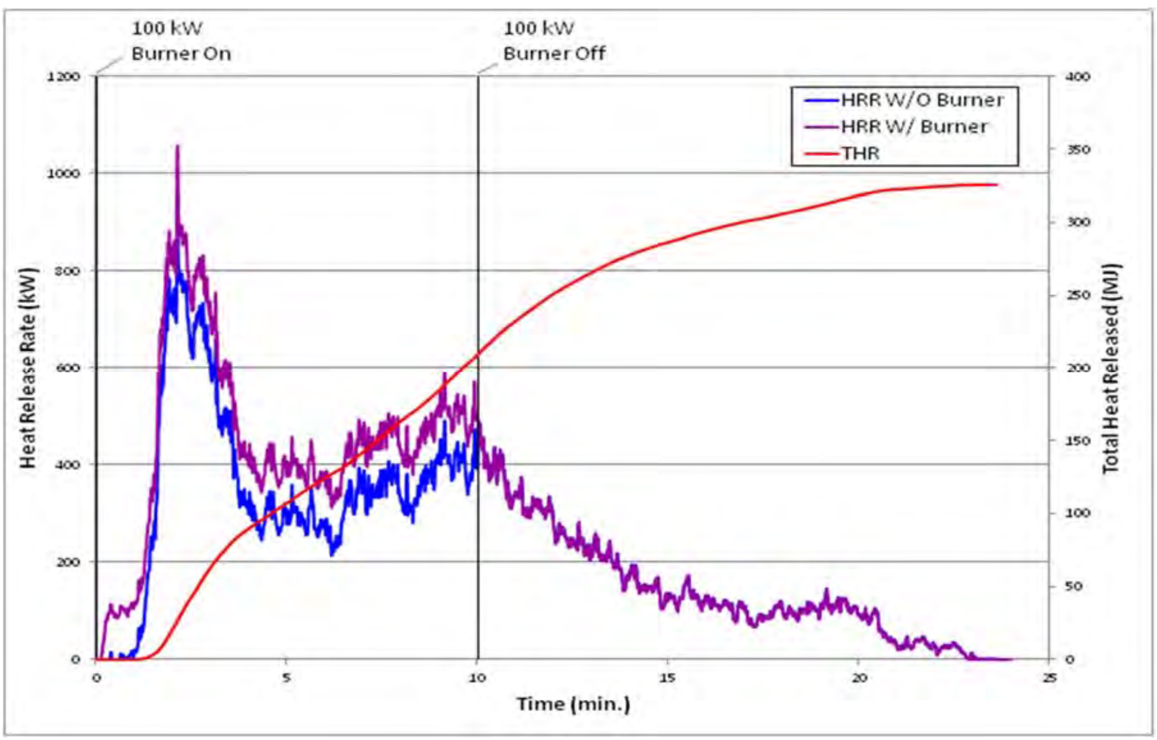


Figure G. 26: Wall Experiment 5 Heat Release Rate and Total Heat Released

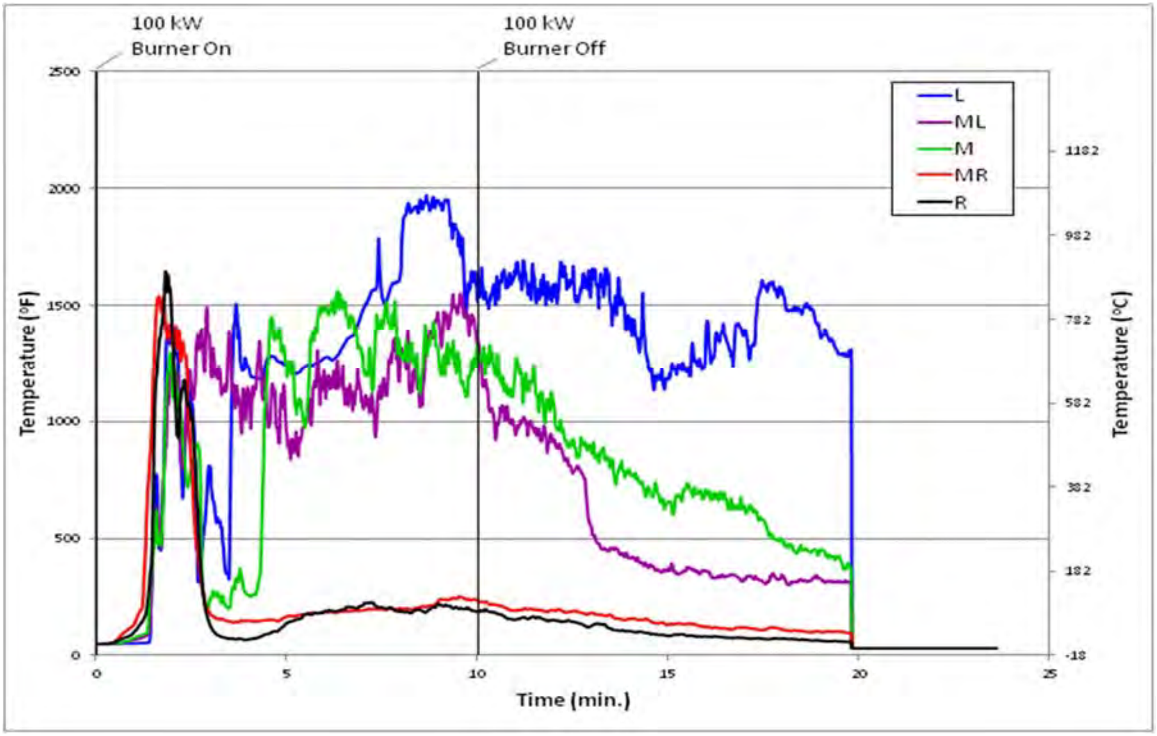


Figure G. 27: Wall Experiment 5 under Siding Horizontal Temperatures

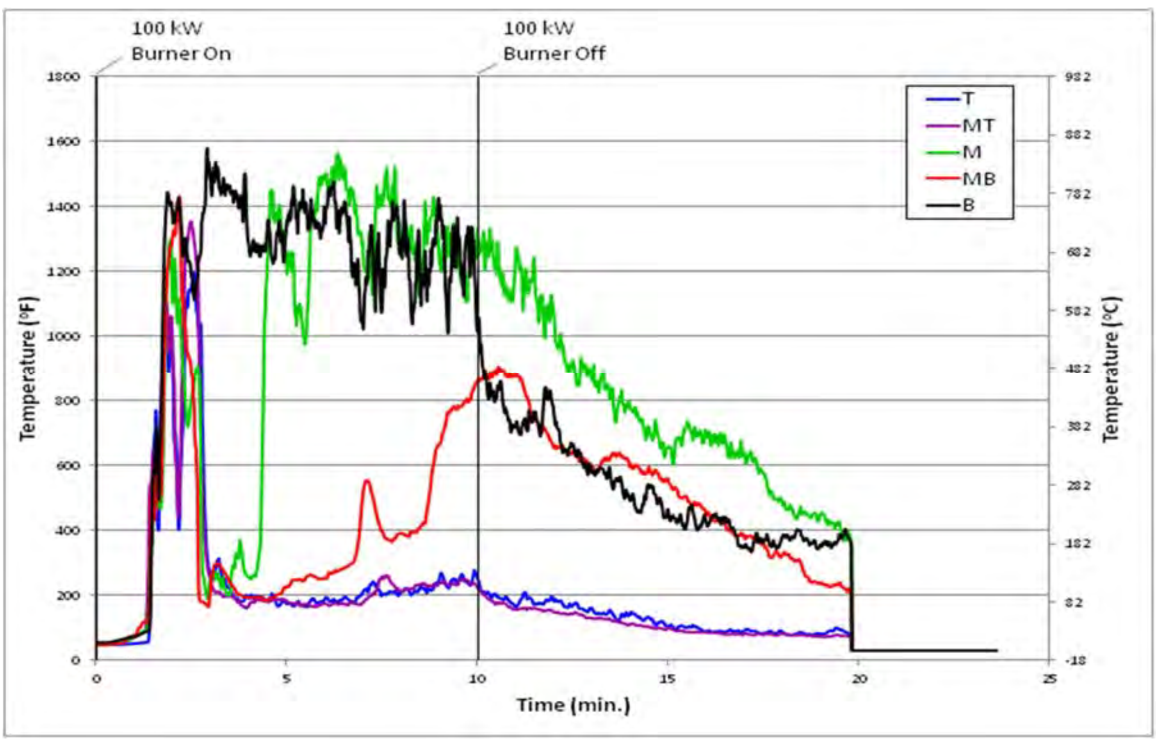


Figure G. 28: Wall Experiment 5 under Siding Vertical Temperatures

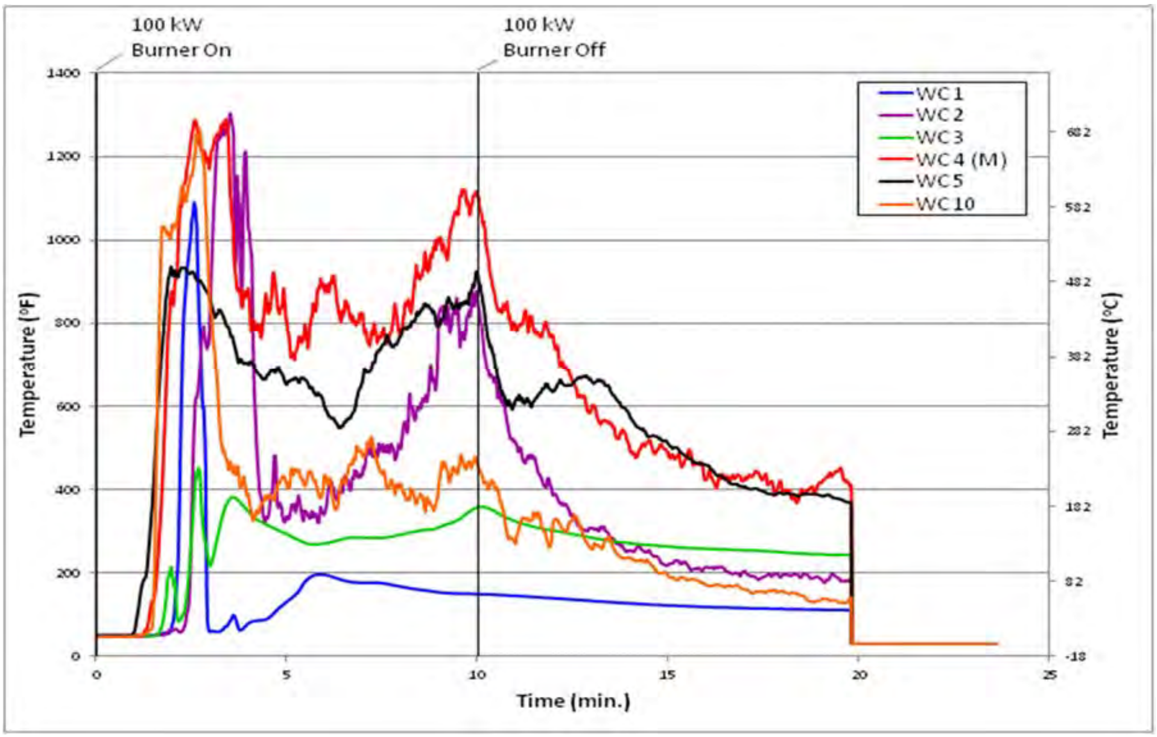


Figure G. 29: Wall Experiment 5 Wall Cavity Horizontal Temperatures

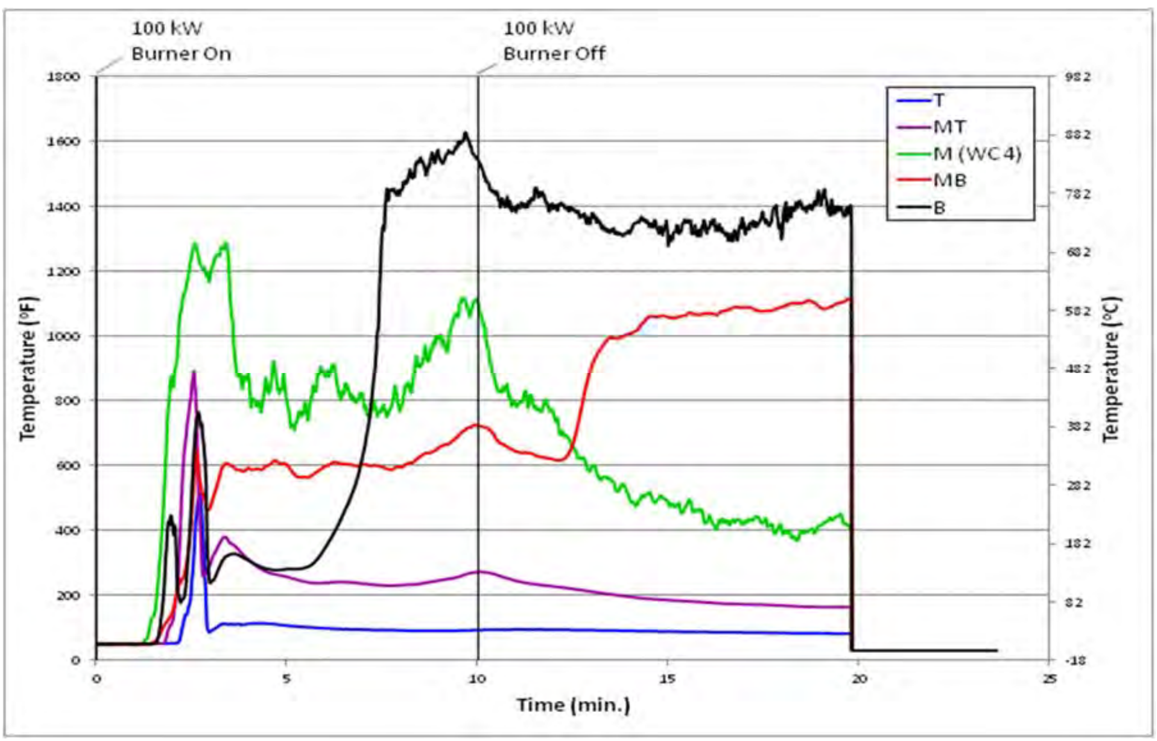


Figure G. 30: Wall Experiment 5 Wall Cavity Vertical Temperatures

Experiment 6

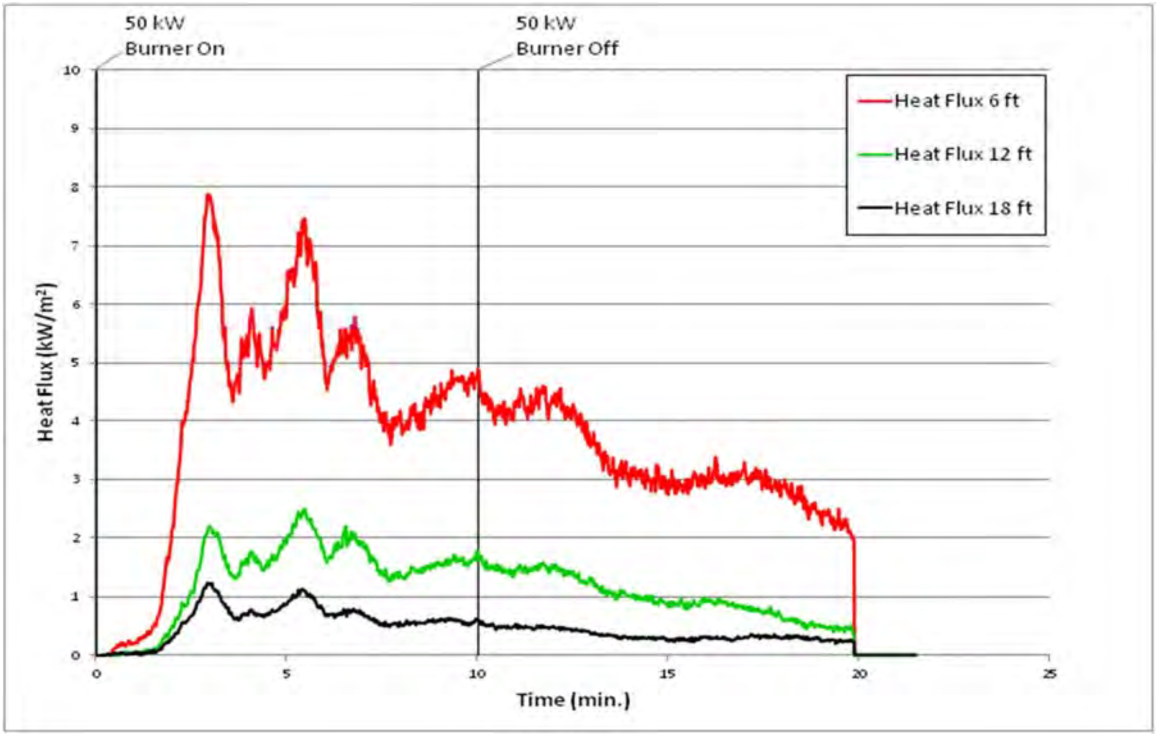


Figure G. 31: Wall Experiment 6 Heat Flux

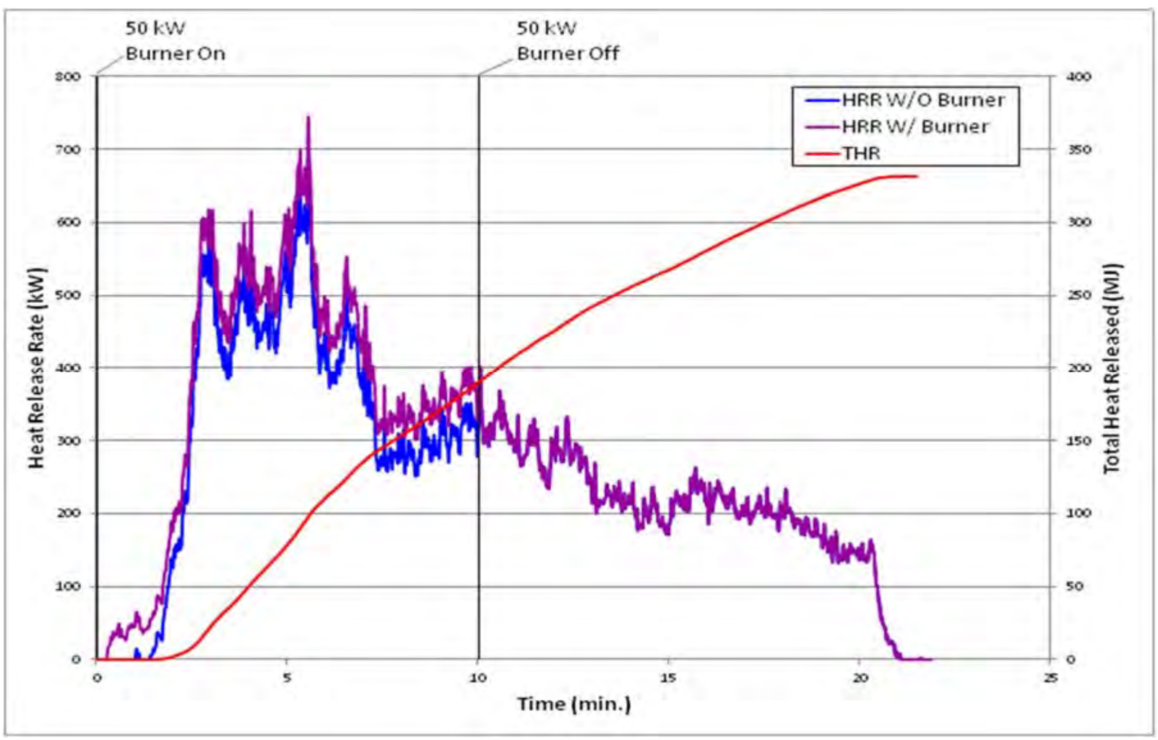


Figure G. 32: Wall Experiment 6 Heat Release Rate and Total Heat Released

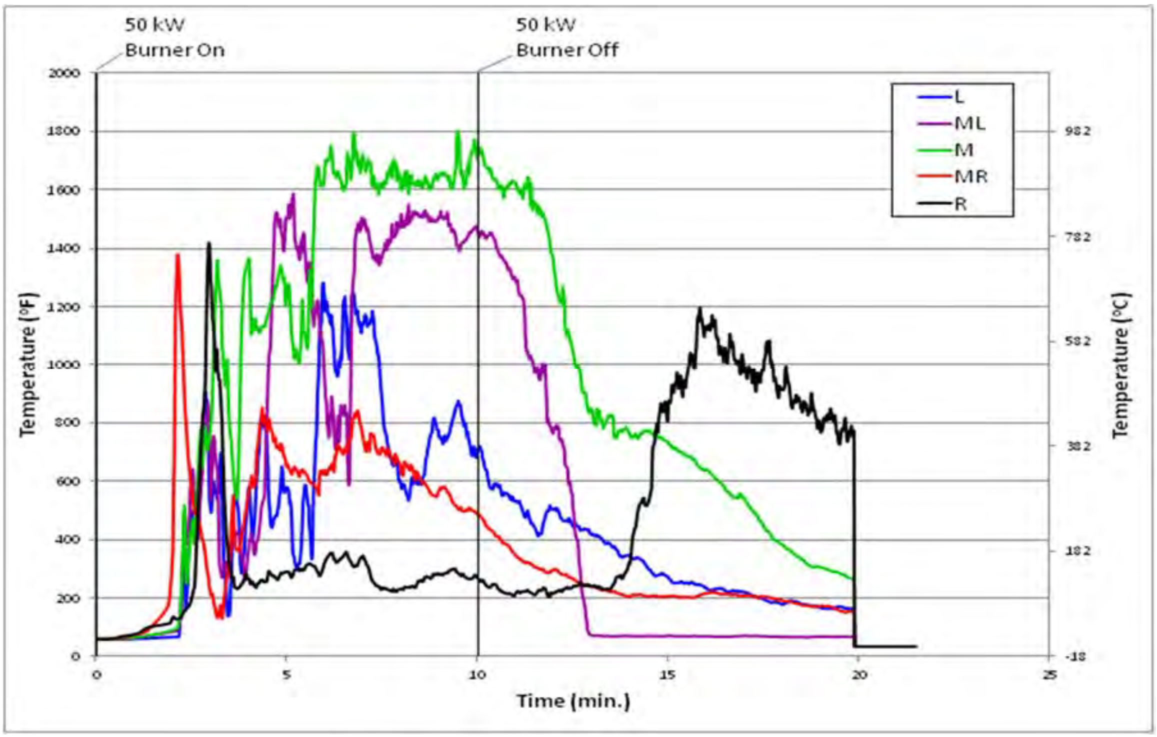


Figure G. 33: Wall Experiment 6 under Siding Horizontal Temperatures

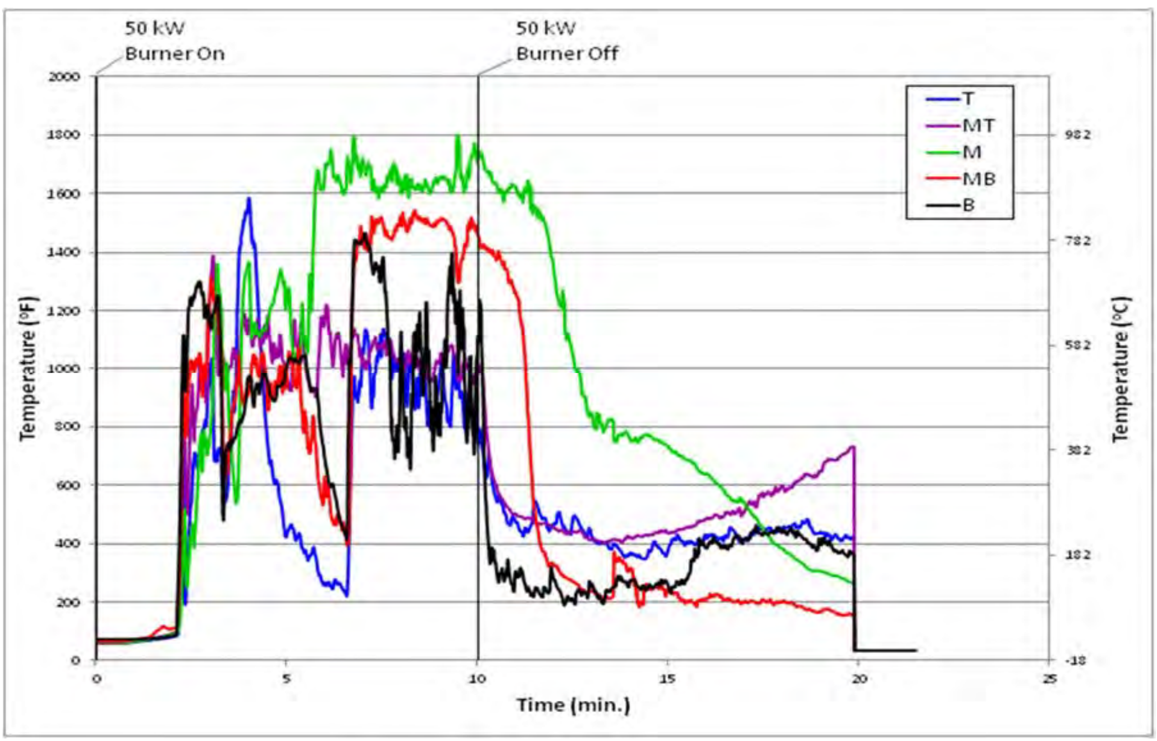


Figure G. 34: Wall Experiment 6 under Siding Vertical Temperatures

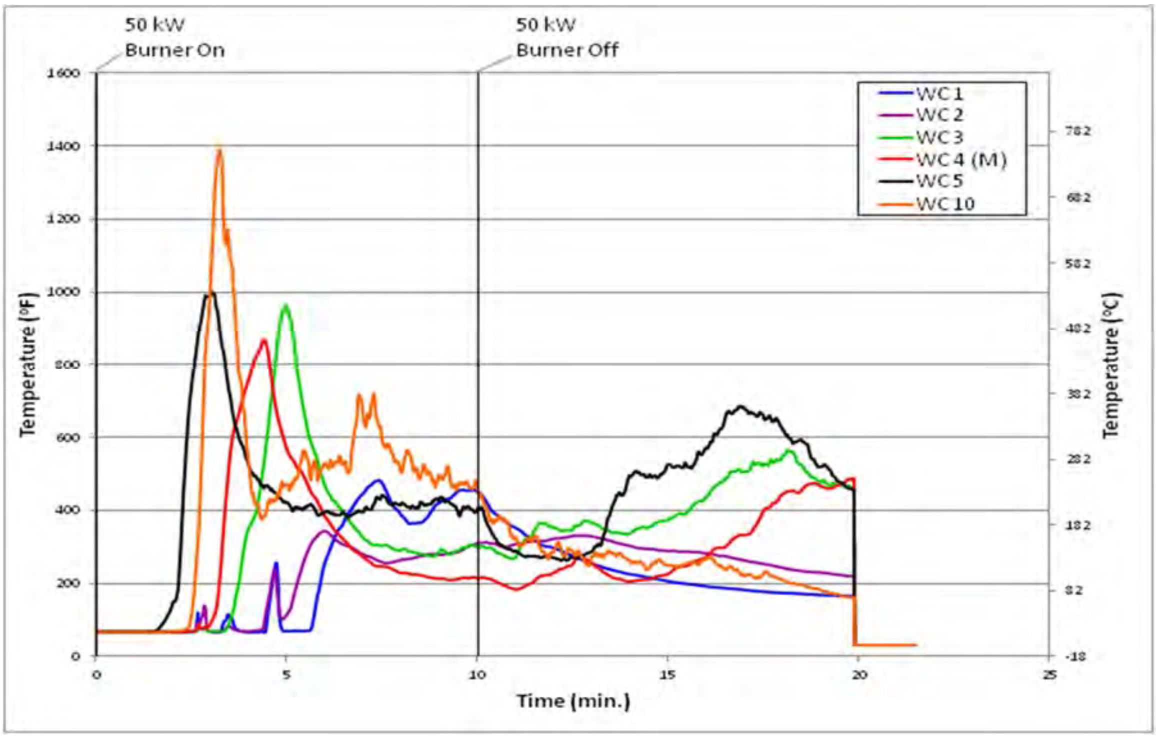


Figure G. 35: Wall Experiment 6 Wall Cavity Horizontal Temperatures

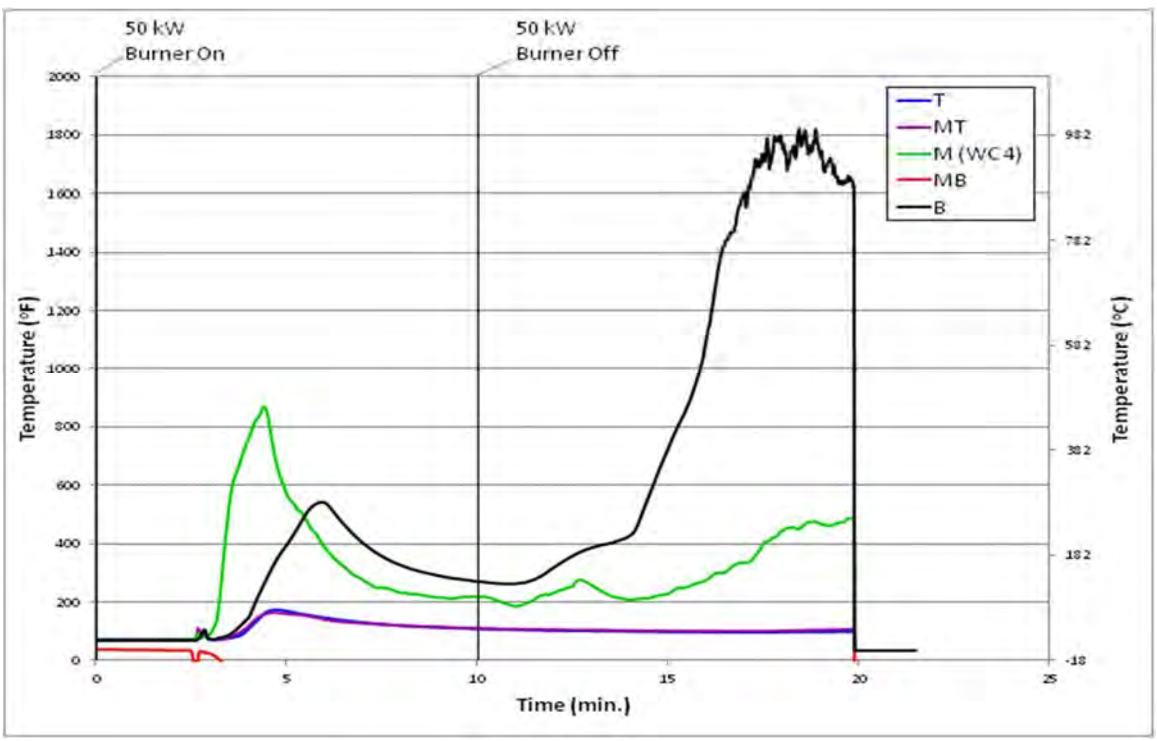


Figure G. 36: Wall Experiment 6 Wall Cavity Vertical Temperatures

Experiment 7

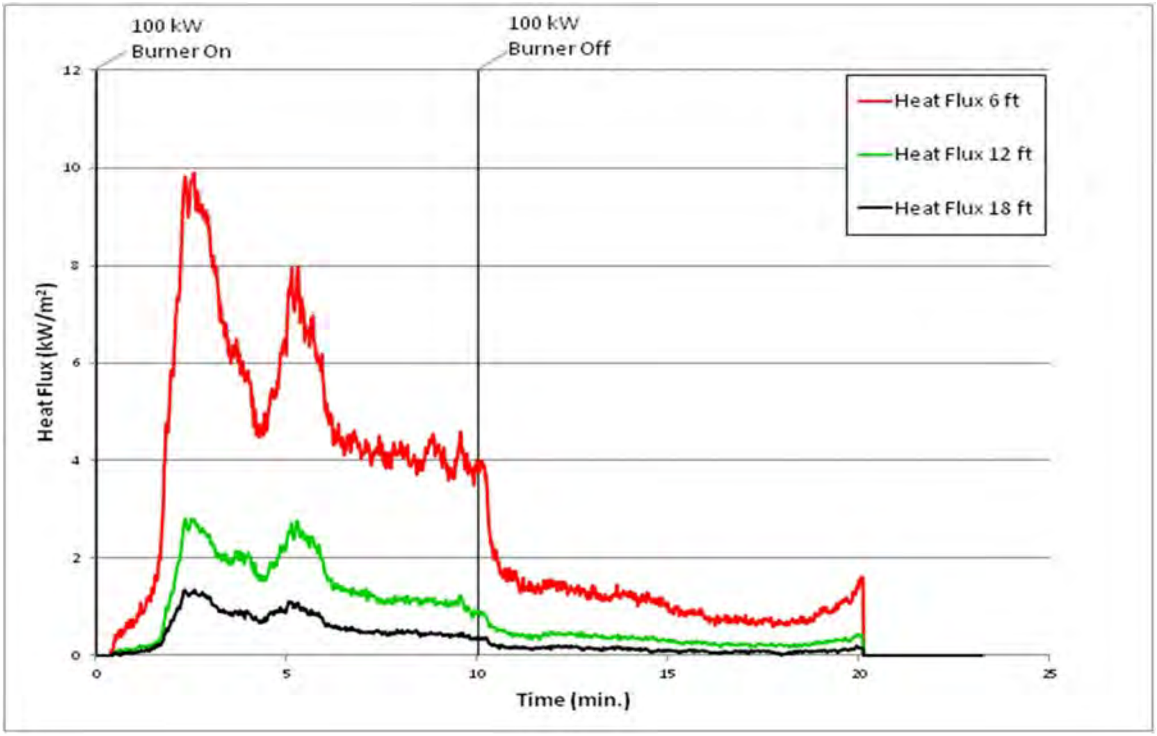


Figure G. 37: Wall Experiment 7 Heat Flux

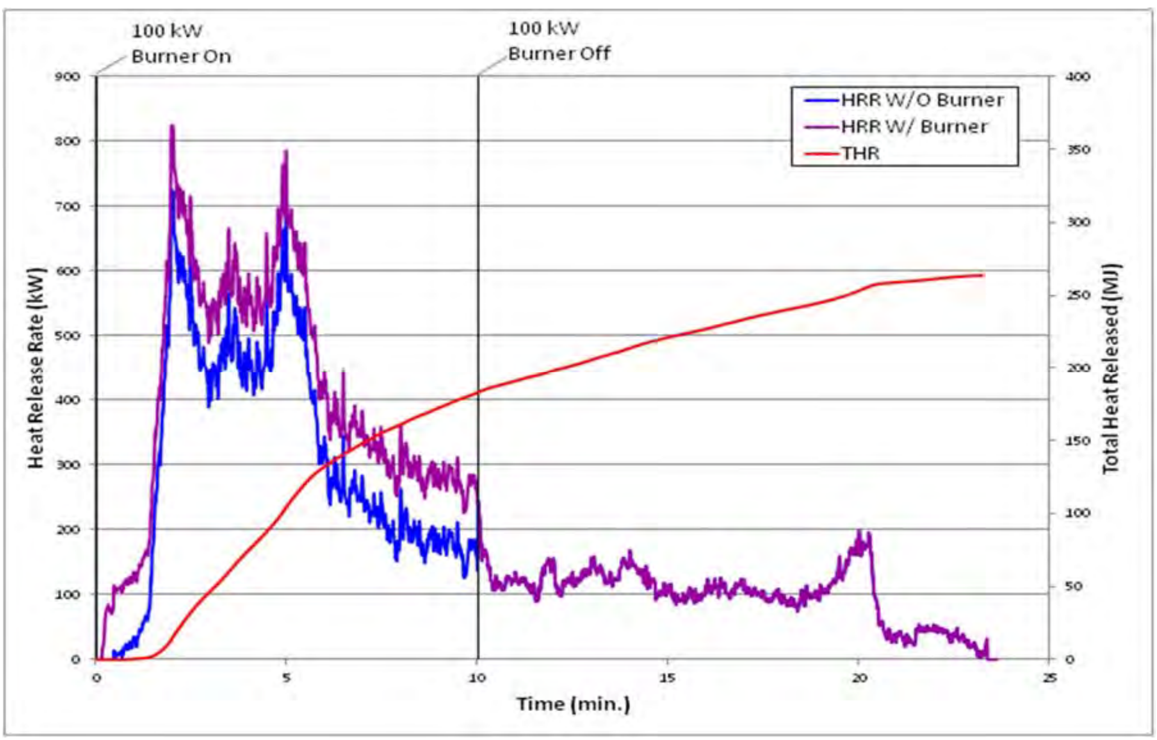


Figure G. 38: Wall Experiment 7 Heat Release Rate and Total Heat Released

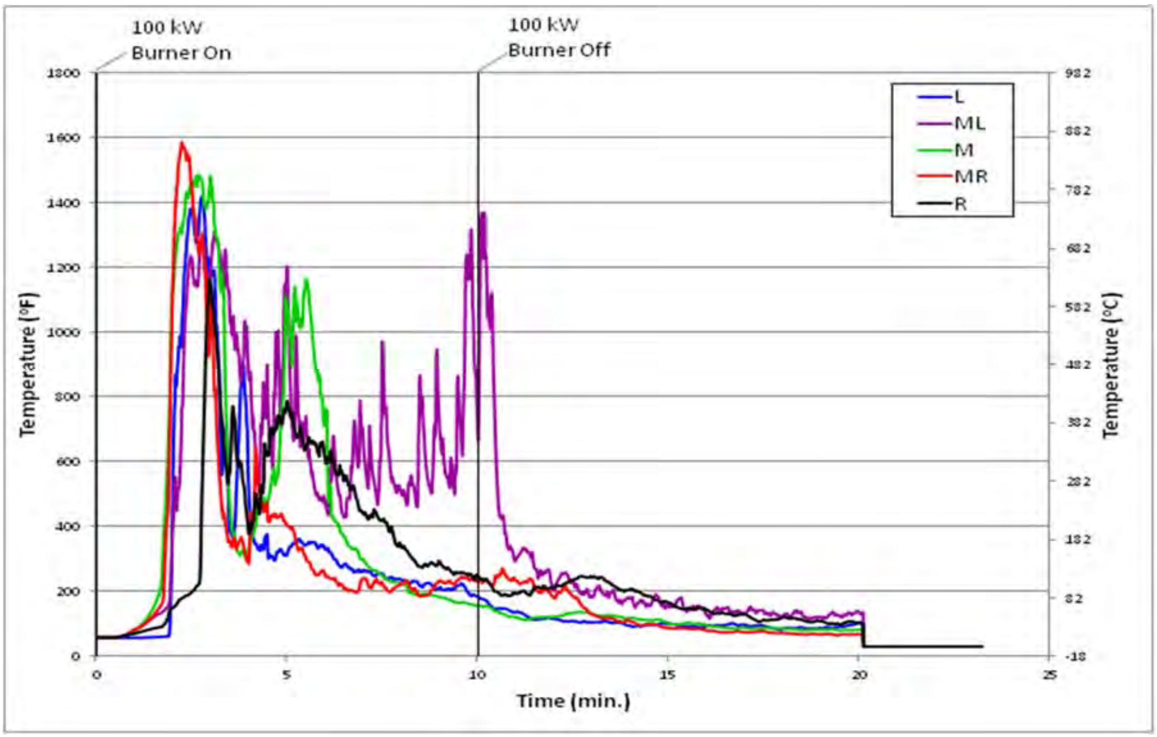


Figure G. 39: Wall Experiment 7 under Siding Horizontal Temperatures

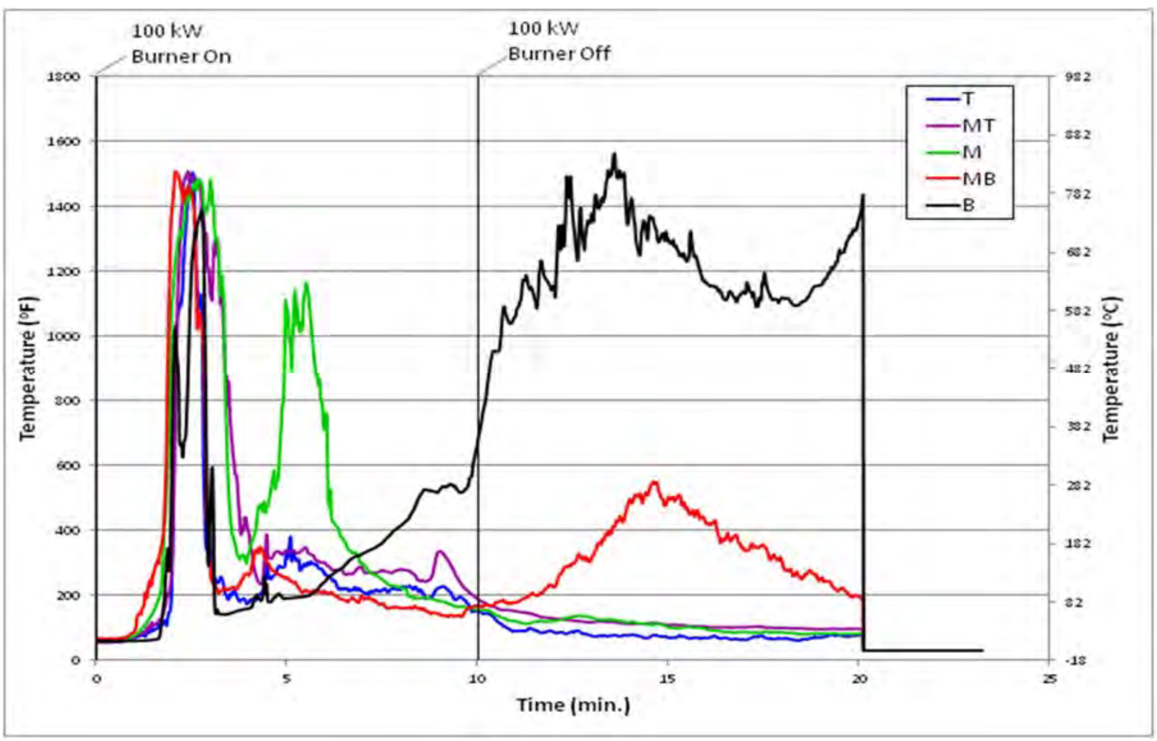


Figure G. 40: Wall Experiment 7 under Siding Vertical Temperatures

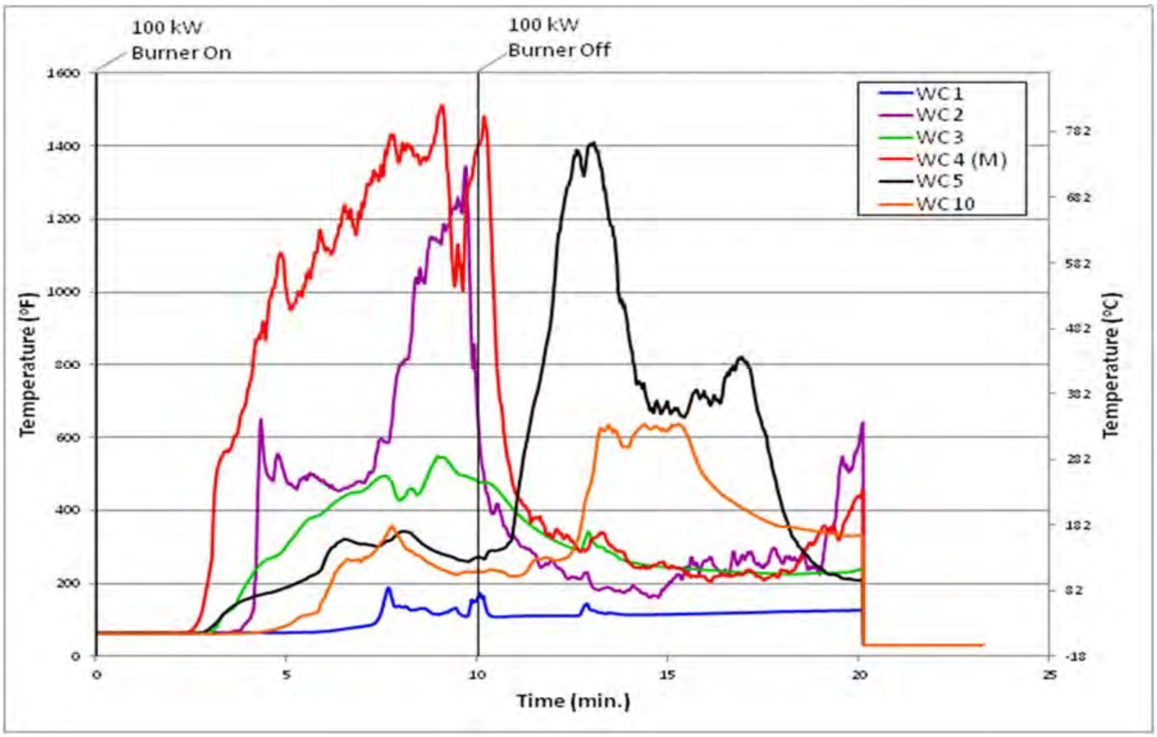


Figure G. 41: Wall Experiment 7 Wall Cavity Horizontal Temperatures

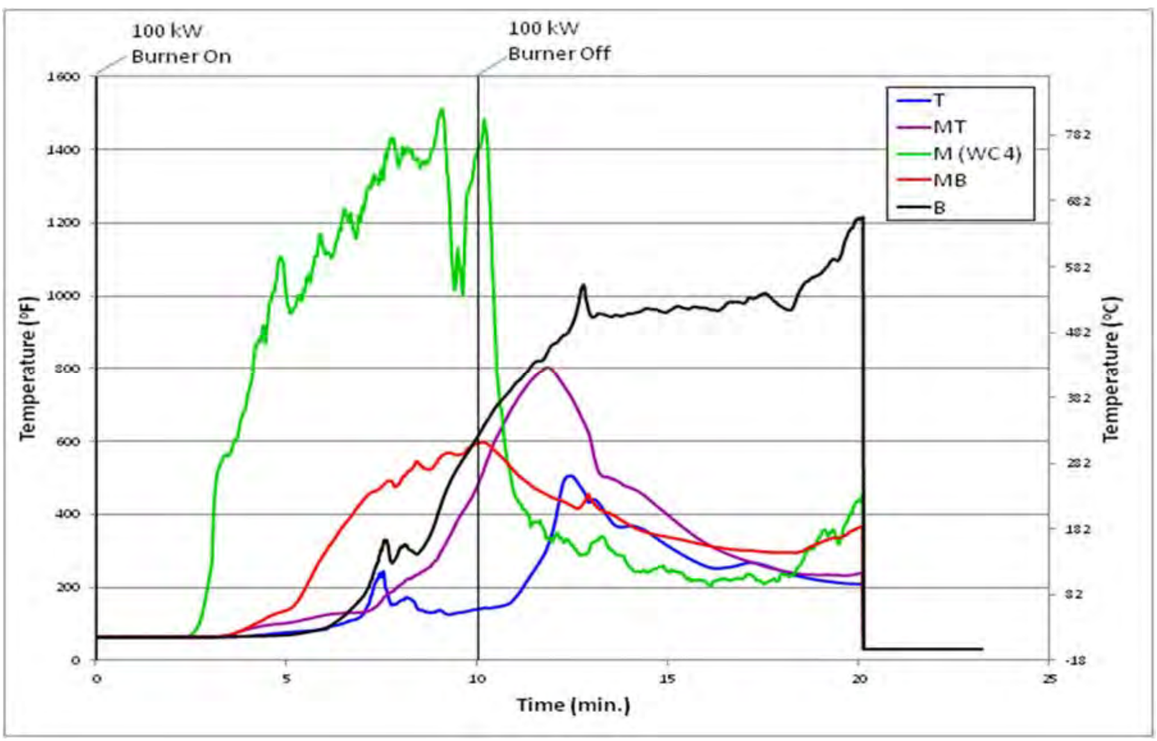


Figure G. 42: Wall Experiment 7 Wall Cavity Vertical Temperatures

Experiment 8

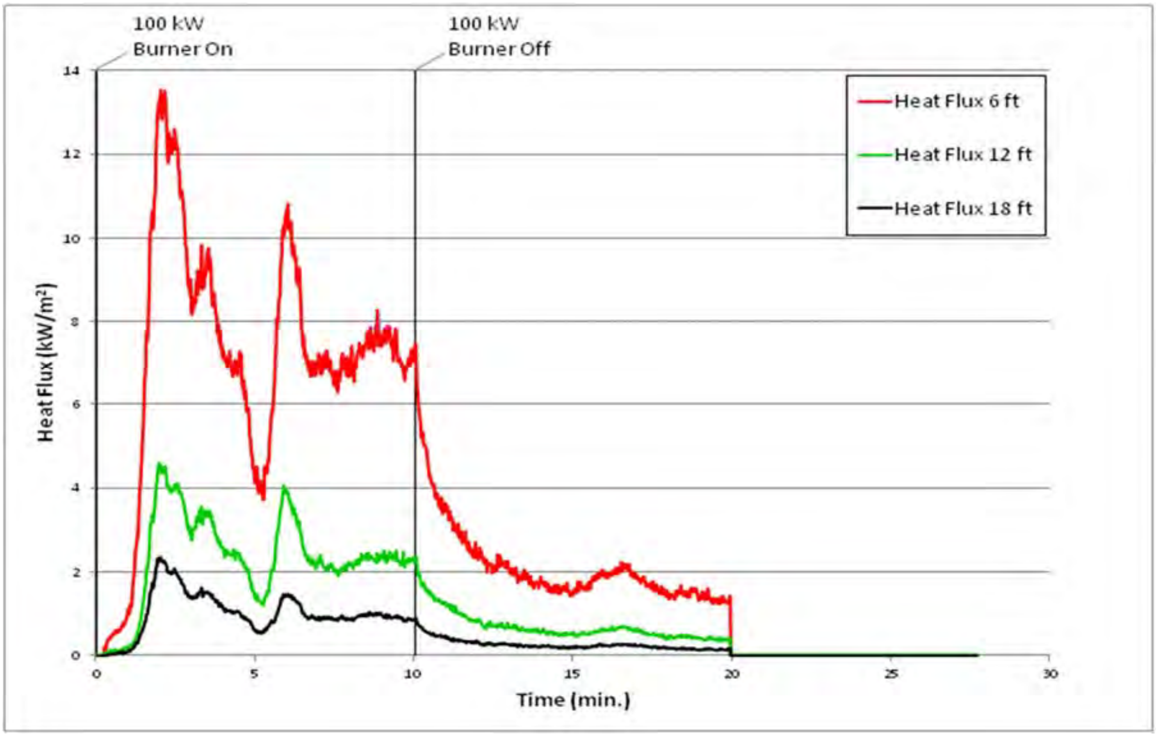


Figure G. 43: Wall Experiment 8 Heat Flux

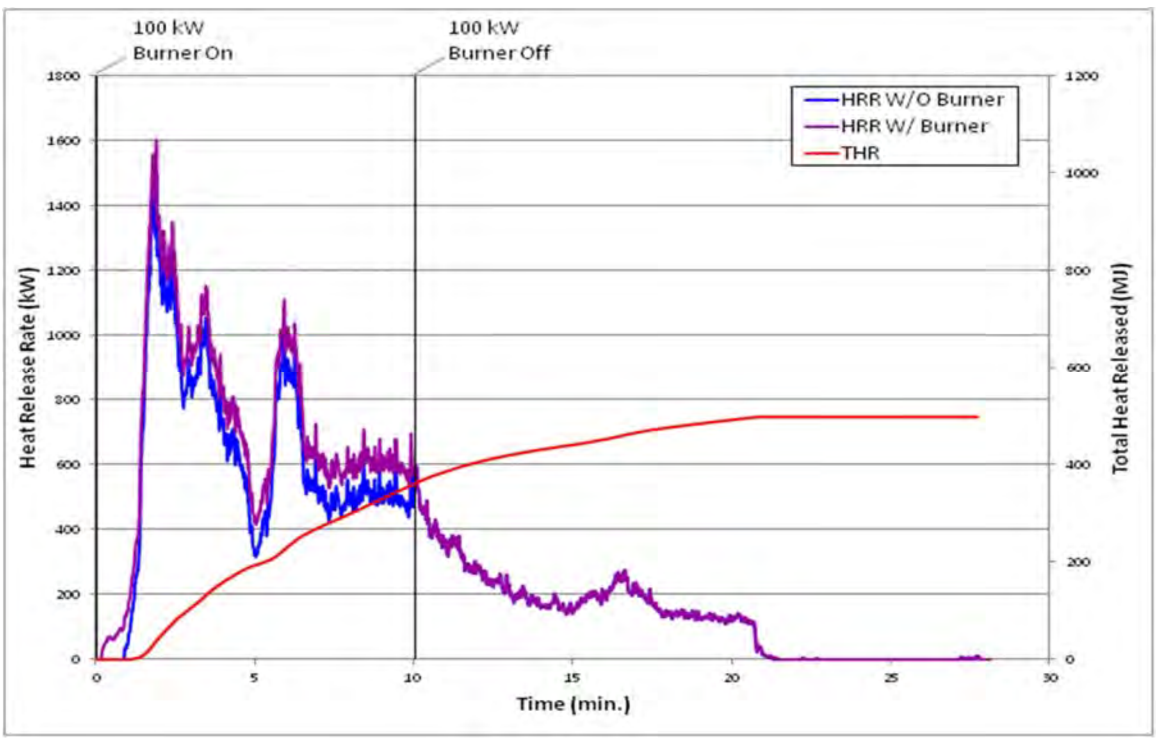


Figure G. 44: Wall Experiment 8 Heat Release Rate and Total Heat Released

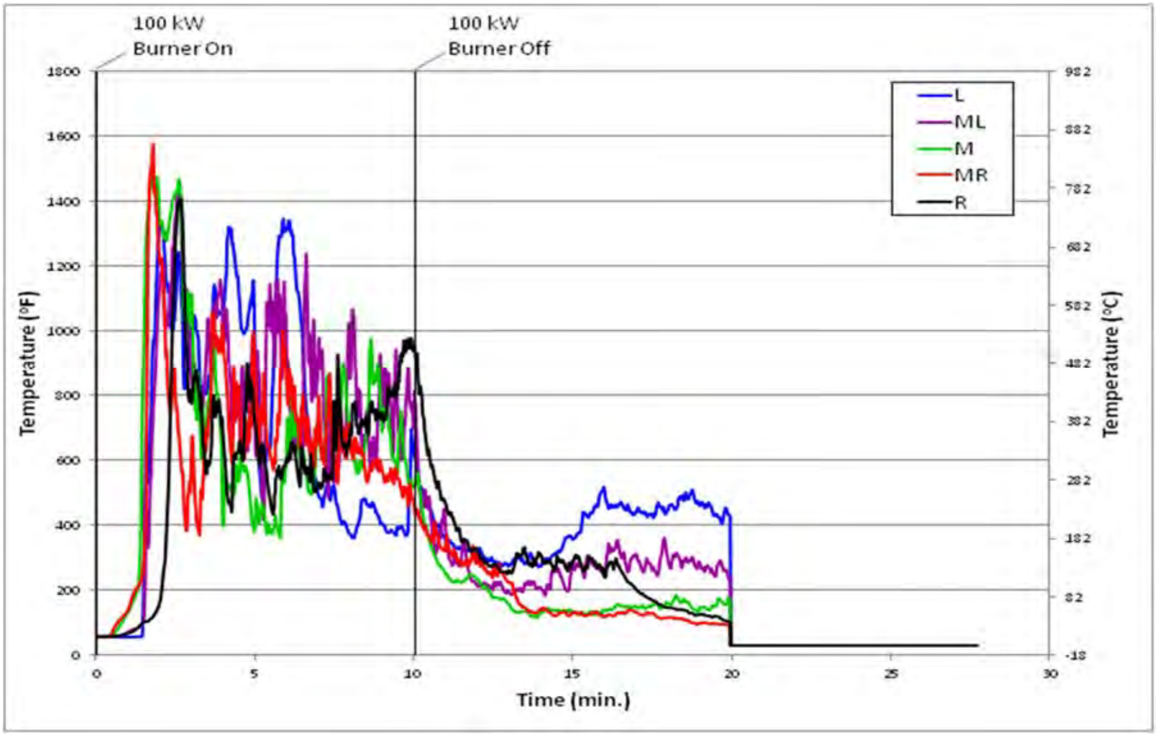


Figure G. 45: Wall Experiment 8 under Siding Horizontal Temperatures

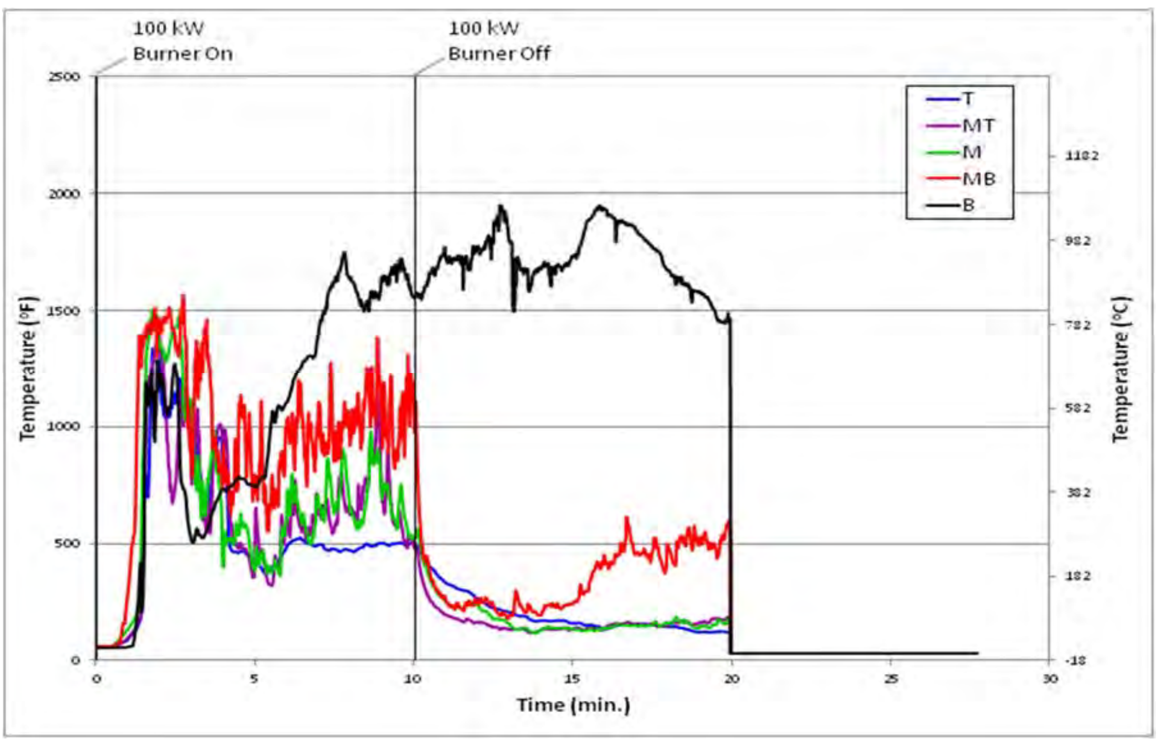


Figure G. 46: Wall Experiment 8 under Siding Vertical Temperatures

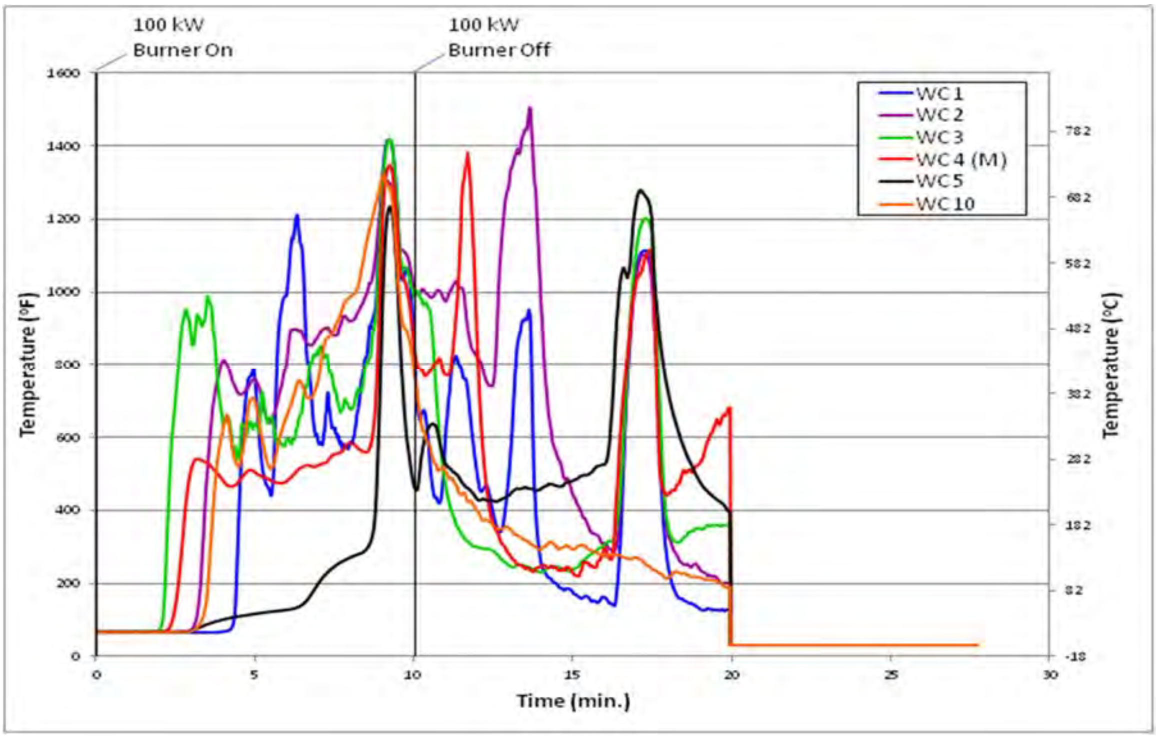


Figure G. 47: Wall Experiment 8 Wall Cavity Horizontal Temperatures

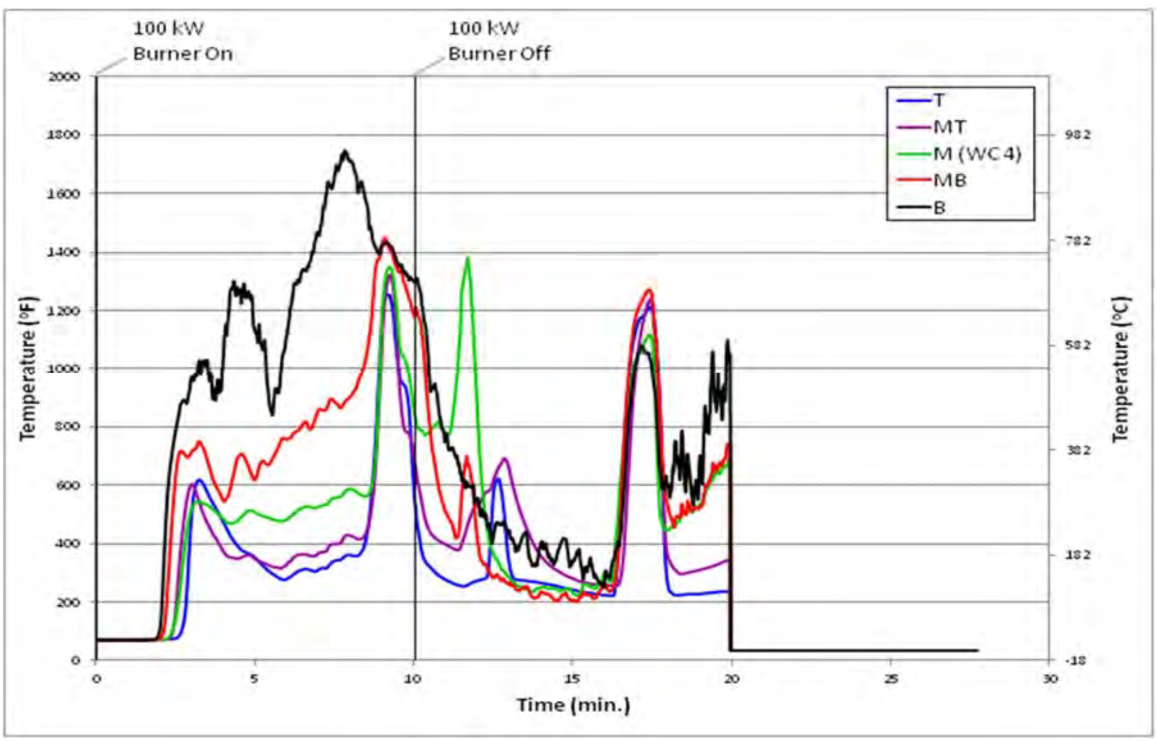


Figure G. 48: Wall Experiment 8 Wall Cavity Vertical Temperatures

Experiment 9

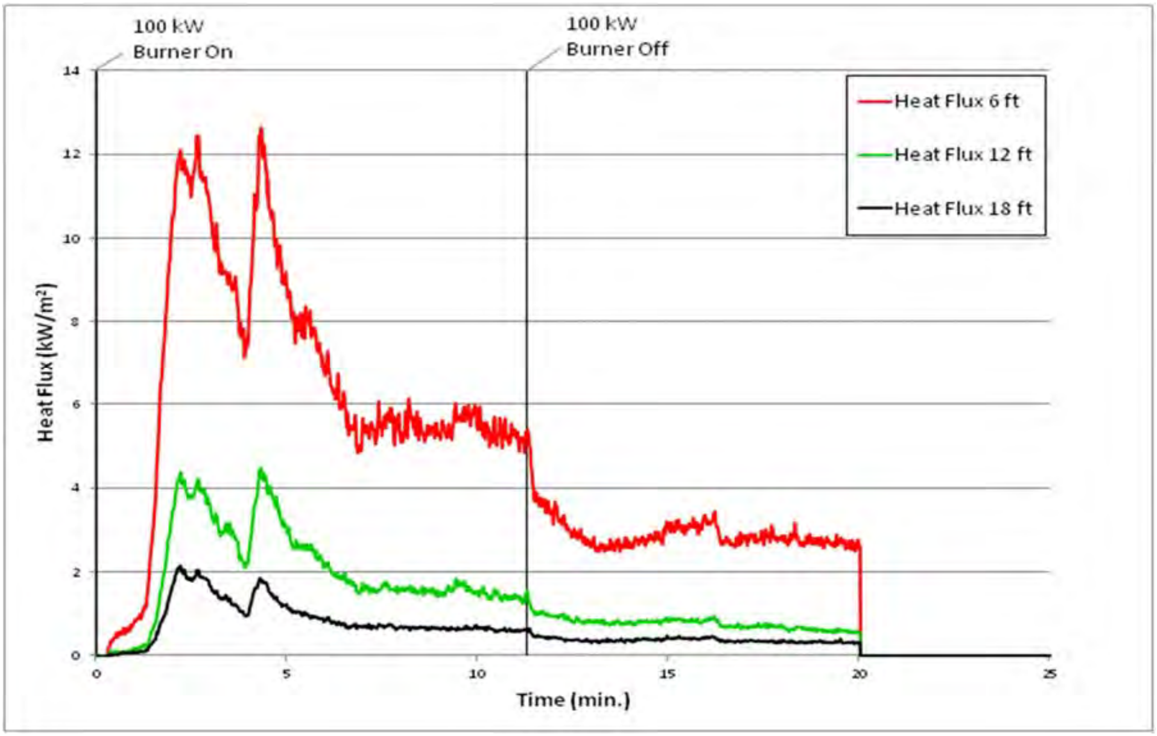


Figure G. 49: Wall Experiment 9 Heat Flux

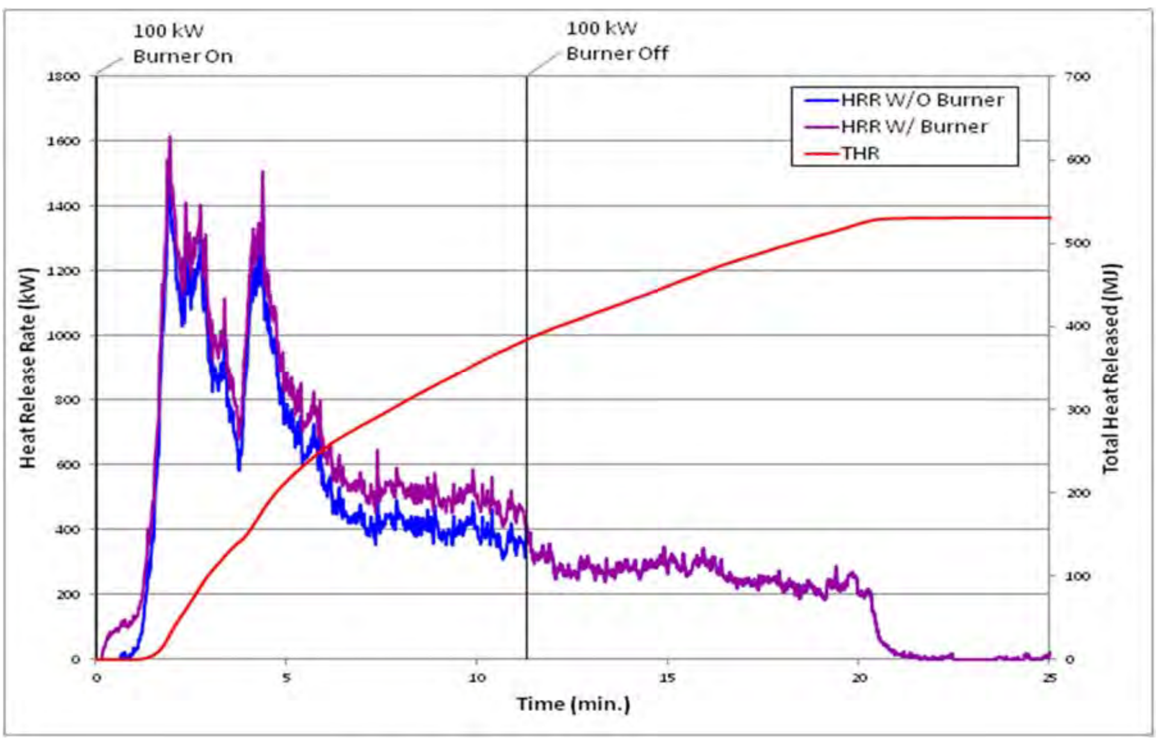


Figure G. 50: Wall Experiment 9 Heat Release Rate and Total Heat Released

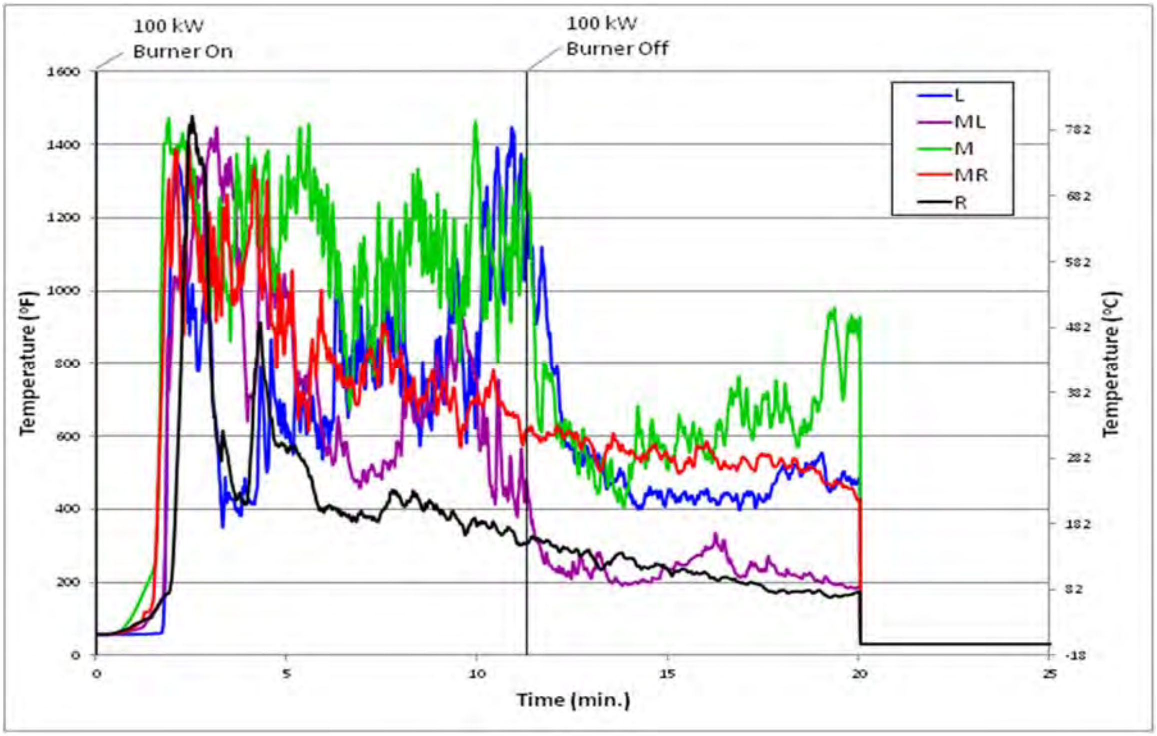


Figure G. 51: Wall Experiment 9 under Siding Horizontal Temperatures

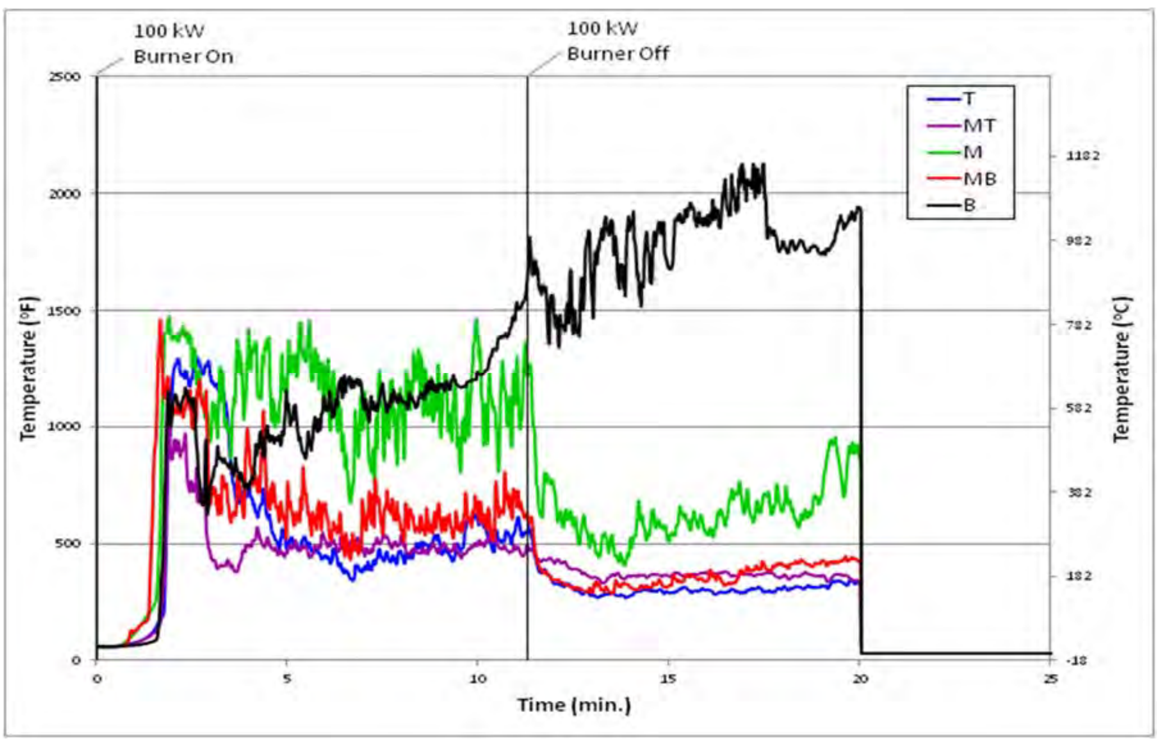


Figure G. 52: Wall Experiment 9 under Siding Vertical Temperatures

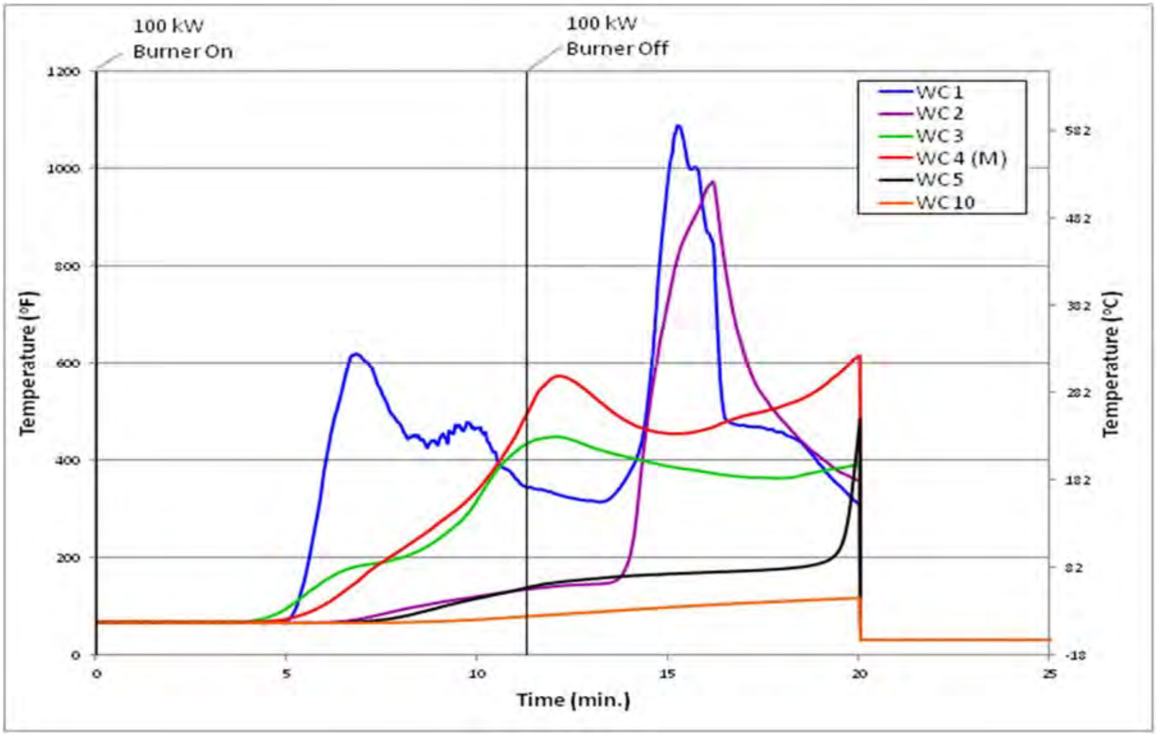


Figure G. 53: Wall Experiment 9 Wall Cavity Horizontal Temperatures

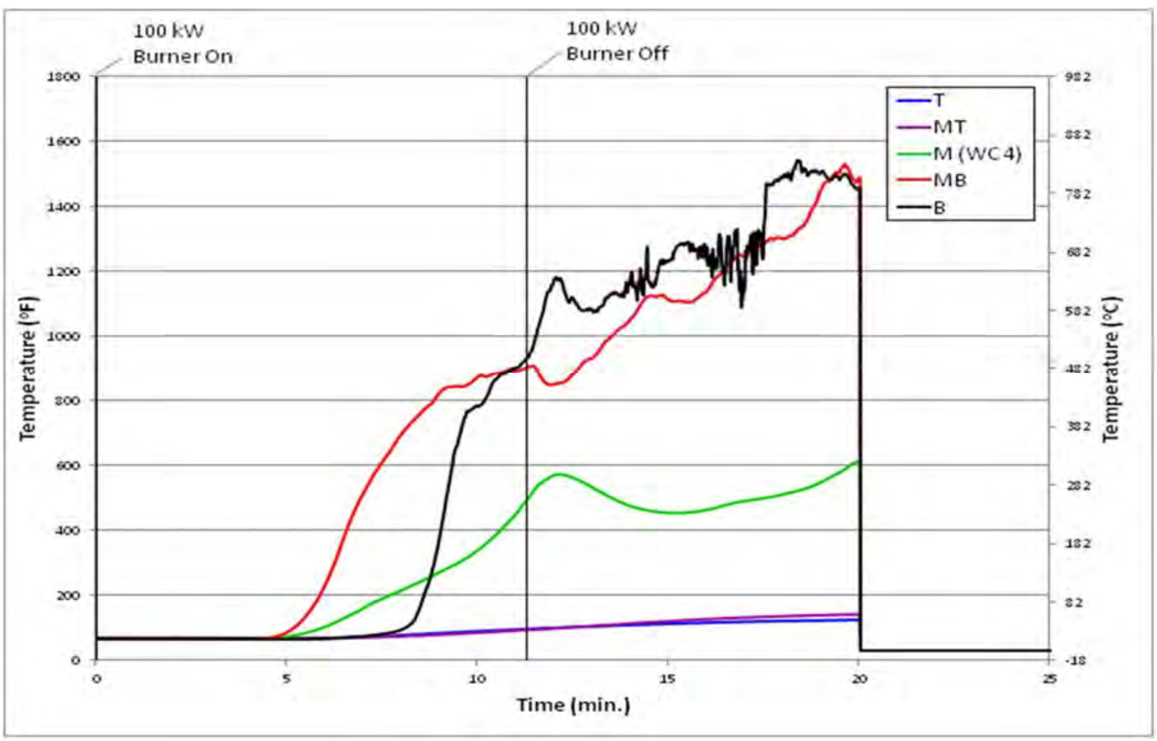


Figure G. 54: Wall Experiment 9 Wall Cavity Vertical Temperatures

Experiment 10

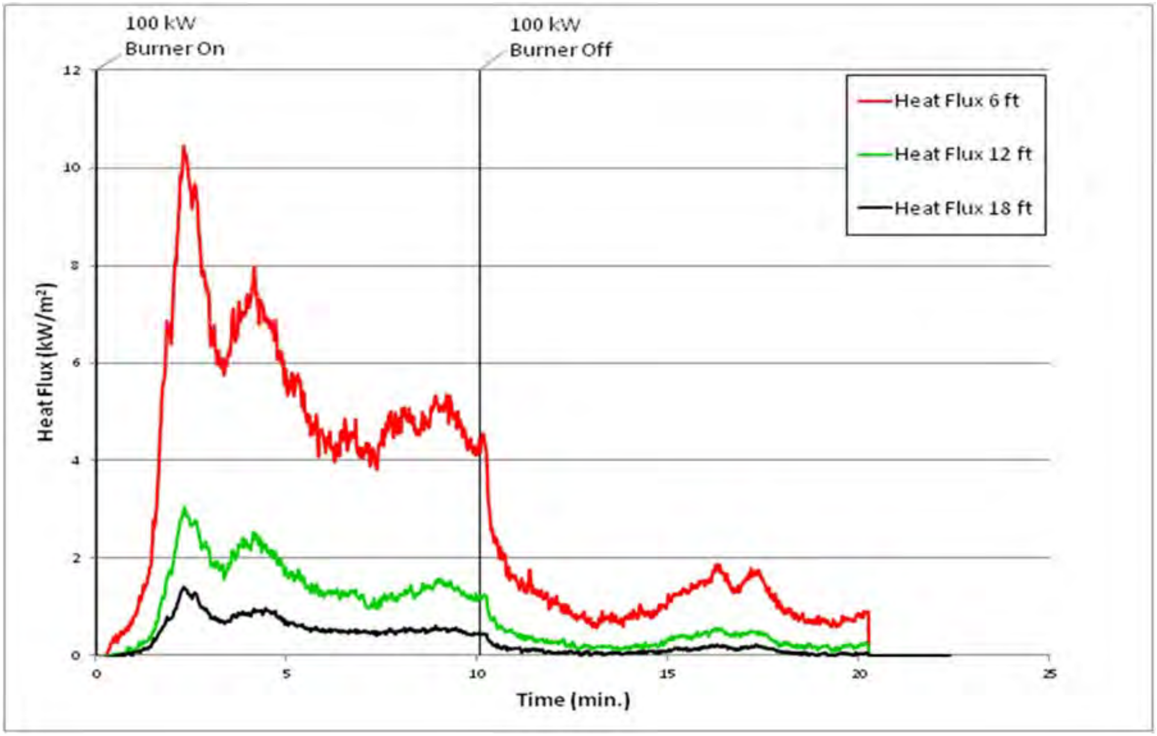


Figure G. 55: Wall Experiment 10 Heat Flux

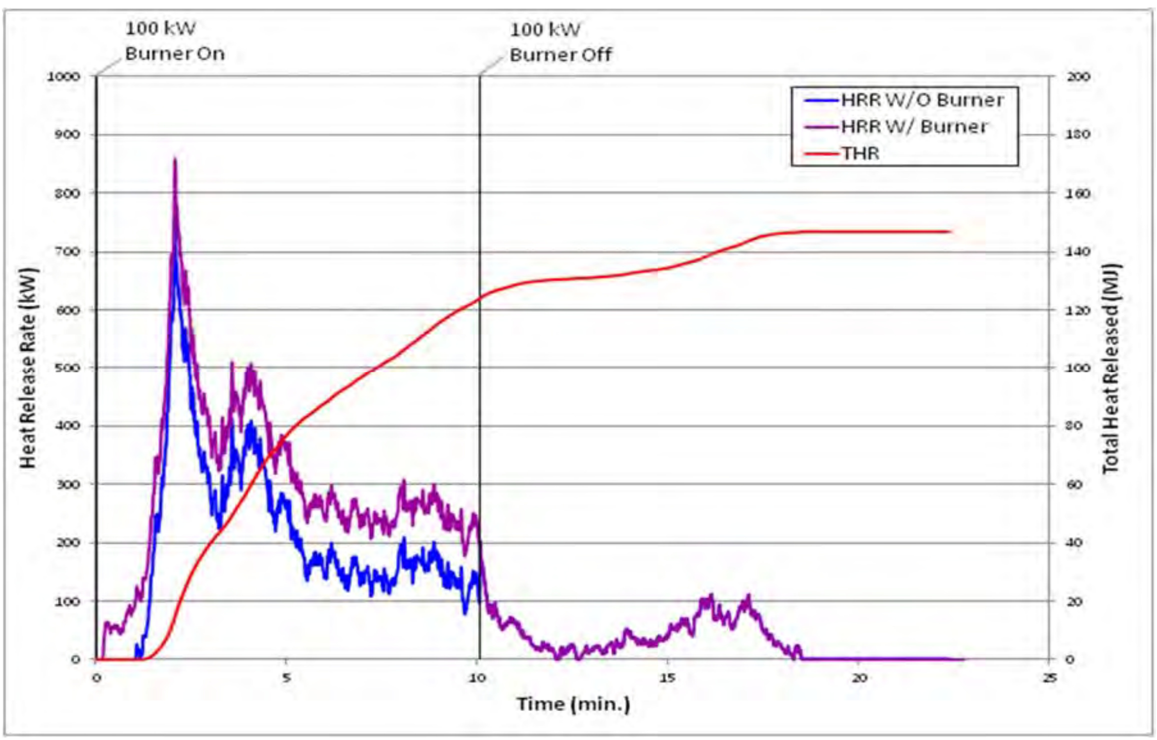


Figure G. 56: Wall Experiment 10 Heat Release Rate and Total Heat Released

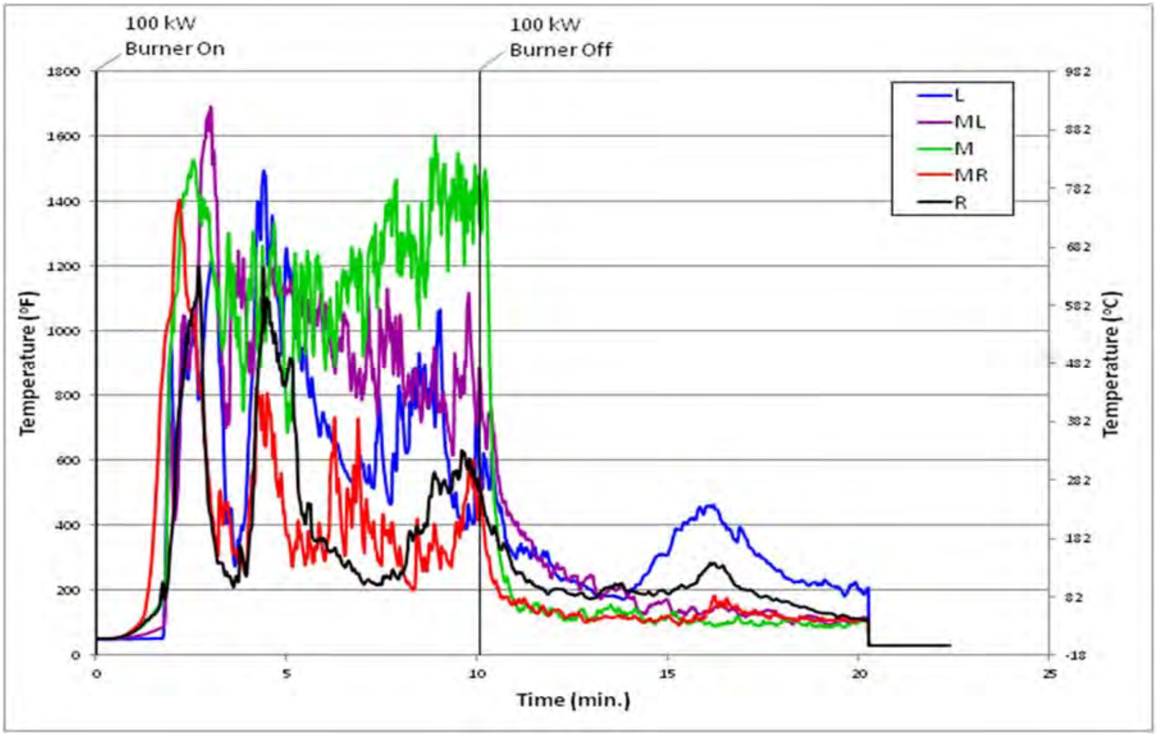


Figure G. 57: Wall Experiment 10 under Siding Horizontal Temperatures

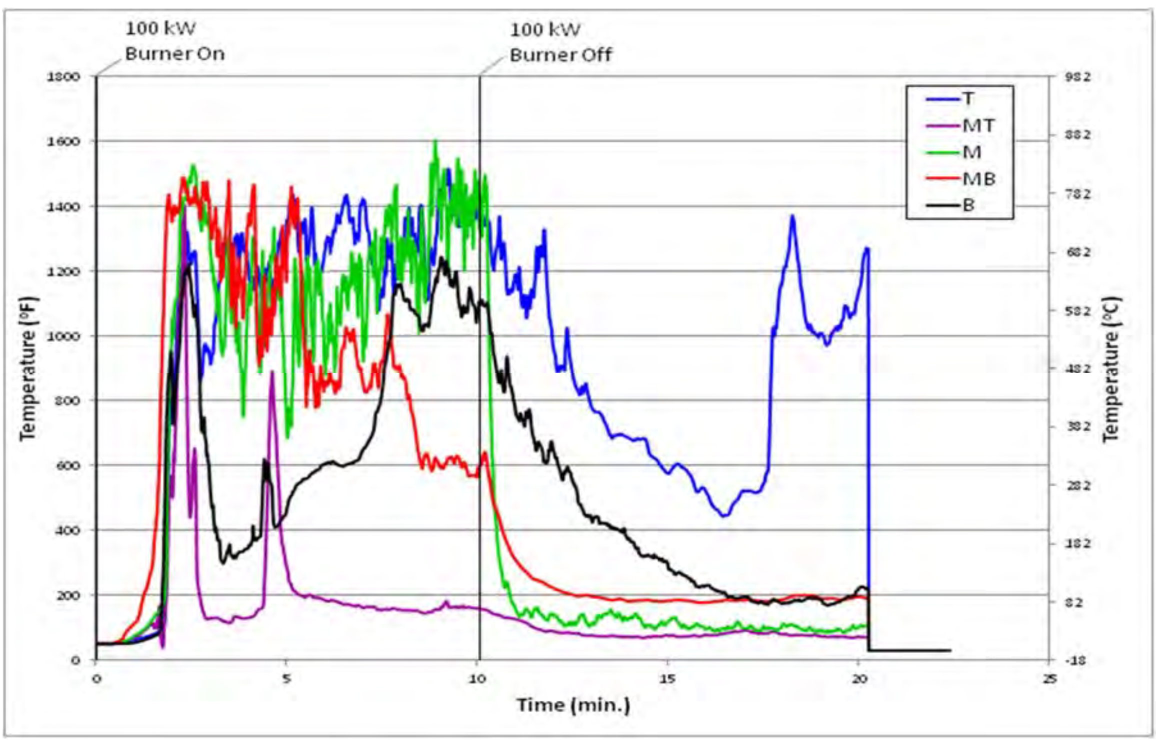


Figure G. 58: Wall Experiment 10 under Siding Vertical Temperatures

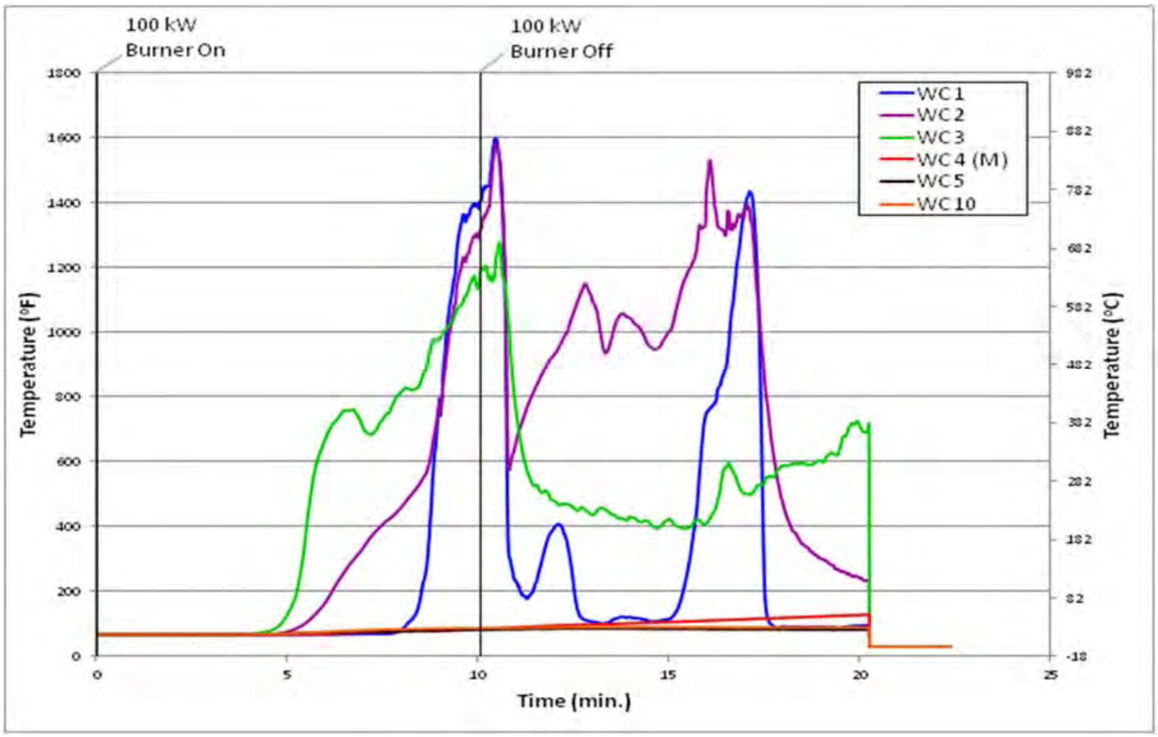


Figure G. 59: Wall Experiment 10 Wall Cavity Horizontal Temperatures

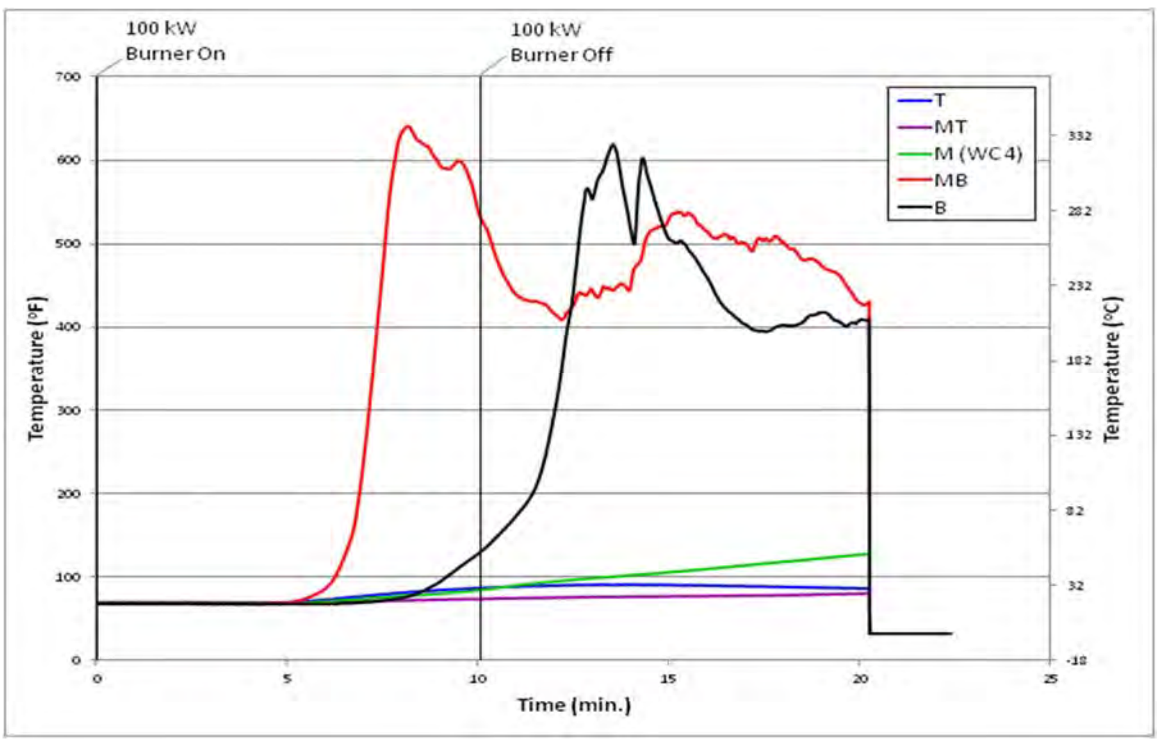


Figure G. 60: Wall Experiment 10 Wall Cavity Vertical Temperatures

Experiment 11

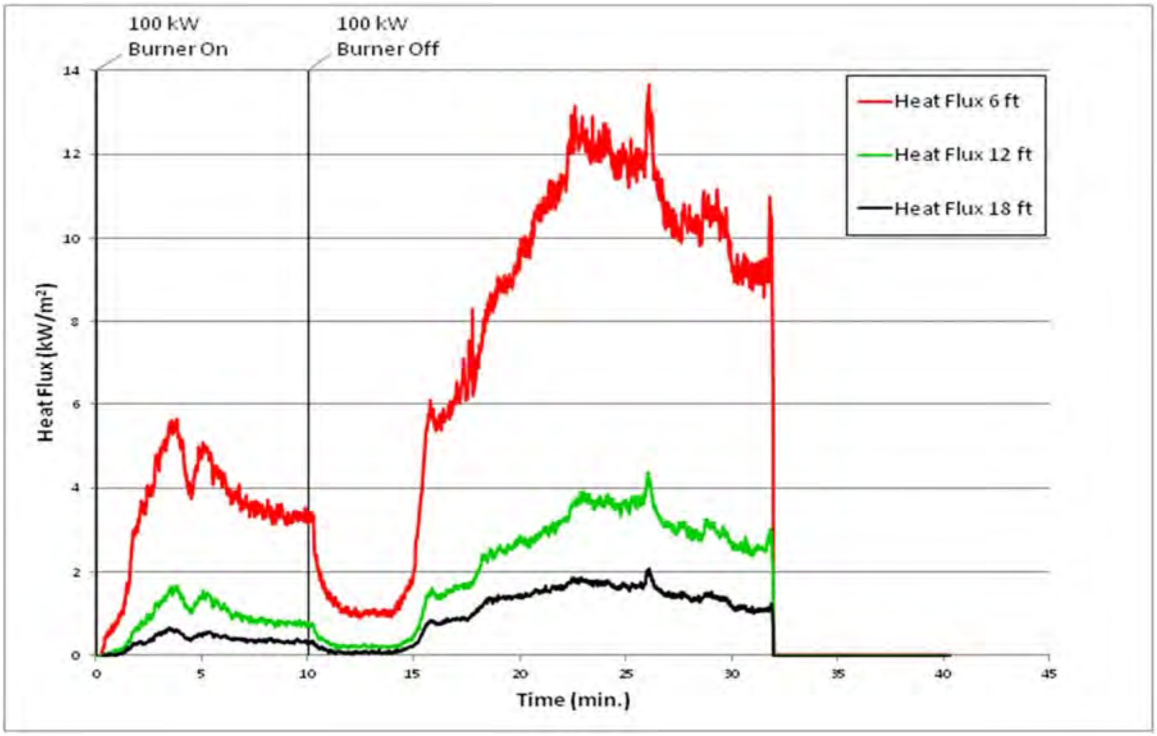


Figure G. 61: Wall Experiment 11 Heat Flux

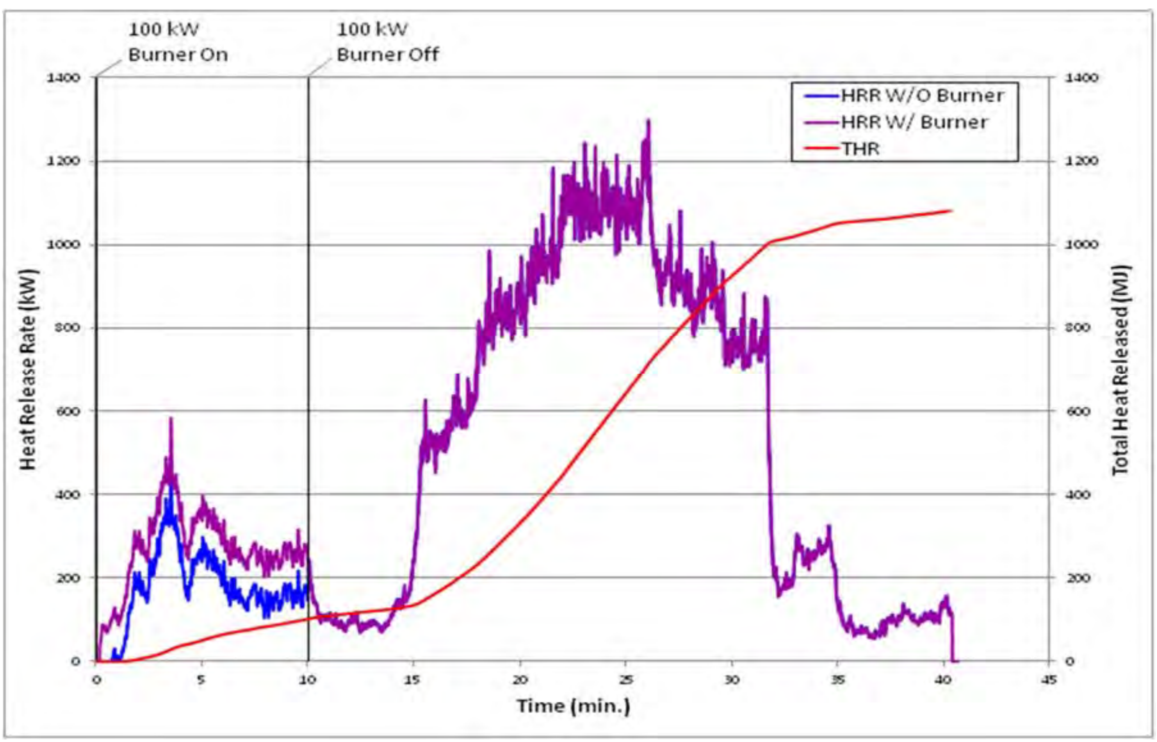


Figure G. 62: Wall Experiment 11 Heat Release Rate and Total Heat Released

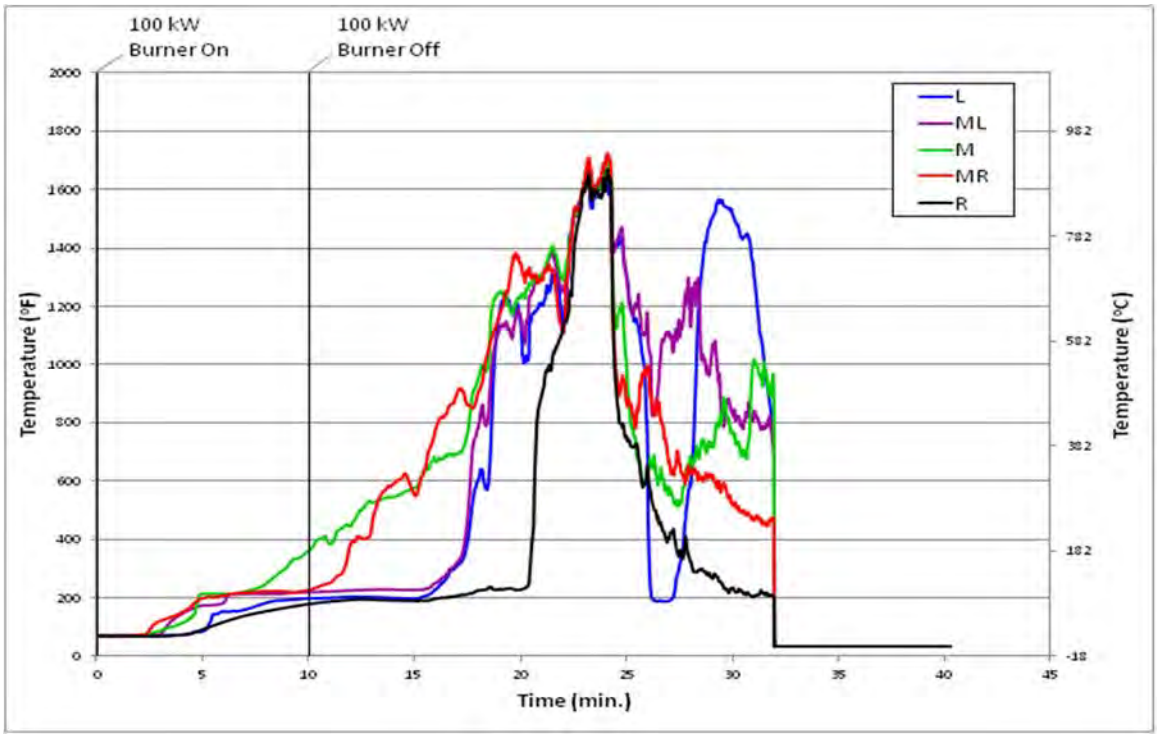


Figure G. 63: Wall Experiment 11 under Siding Horizontal Temperatures

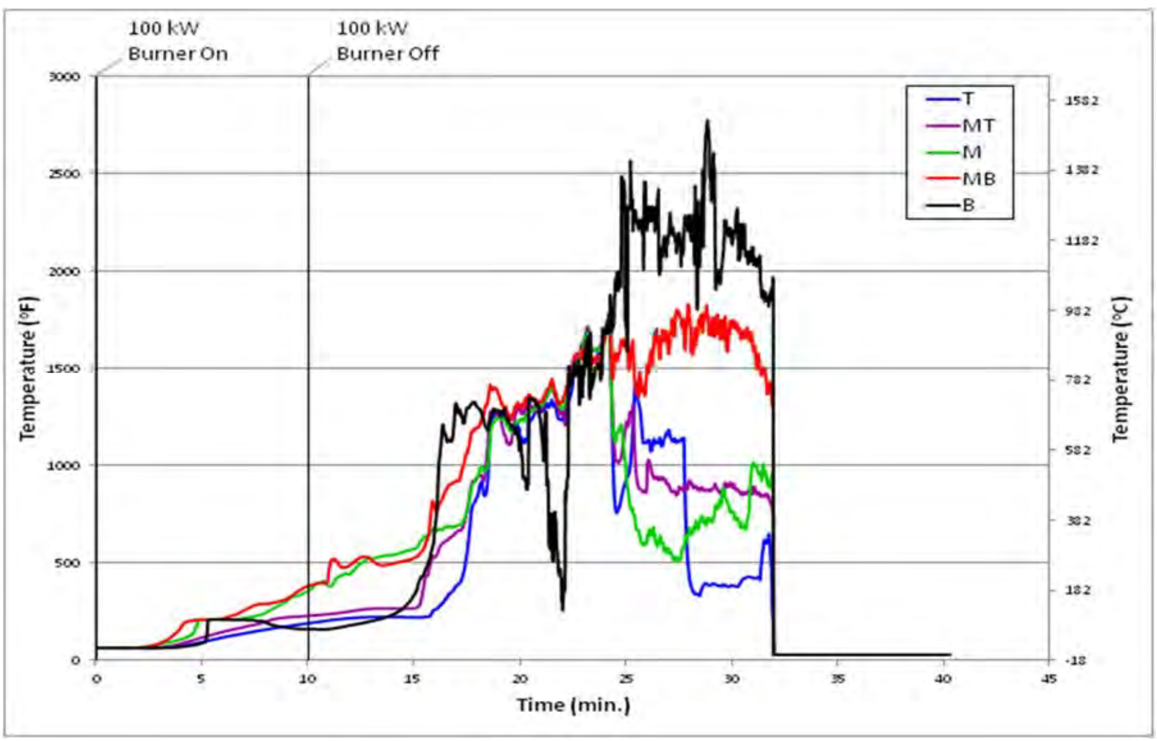


Figure G. 64: Wall Experiment 11 under Siding Vertical Temperatures

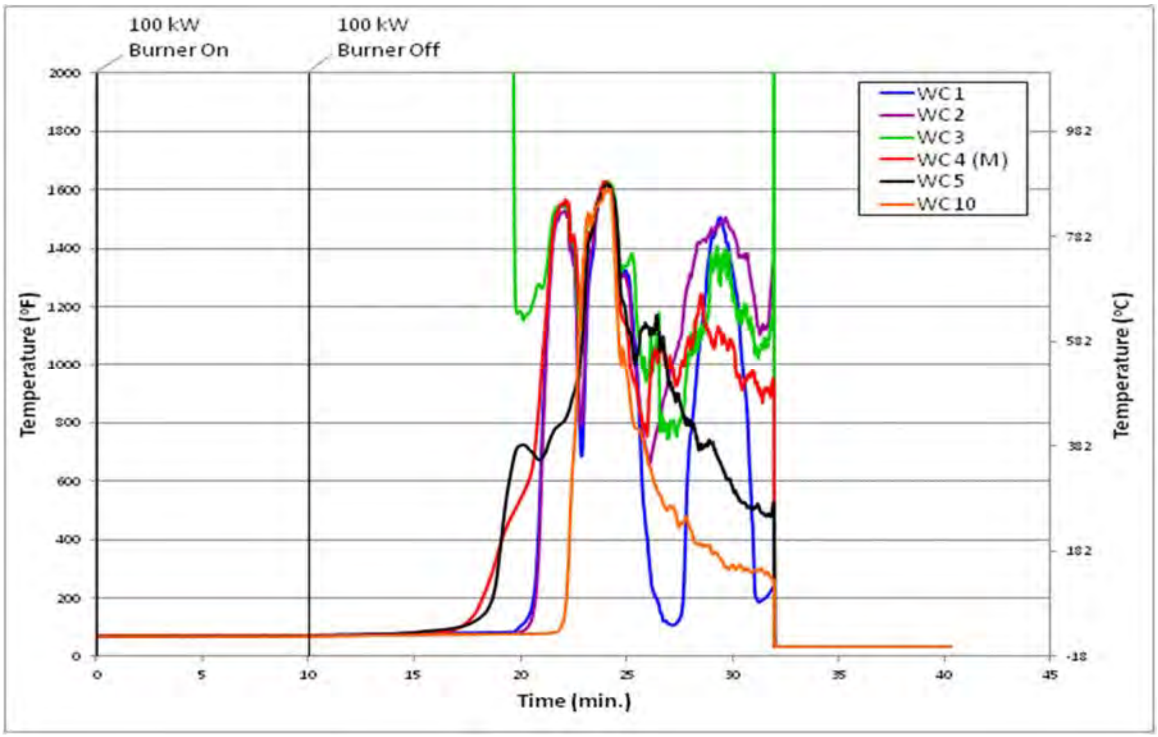


Figure G. 65: Wall Experiment 11 Wall Cavity Horizontal Temperatures

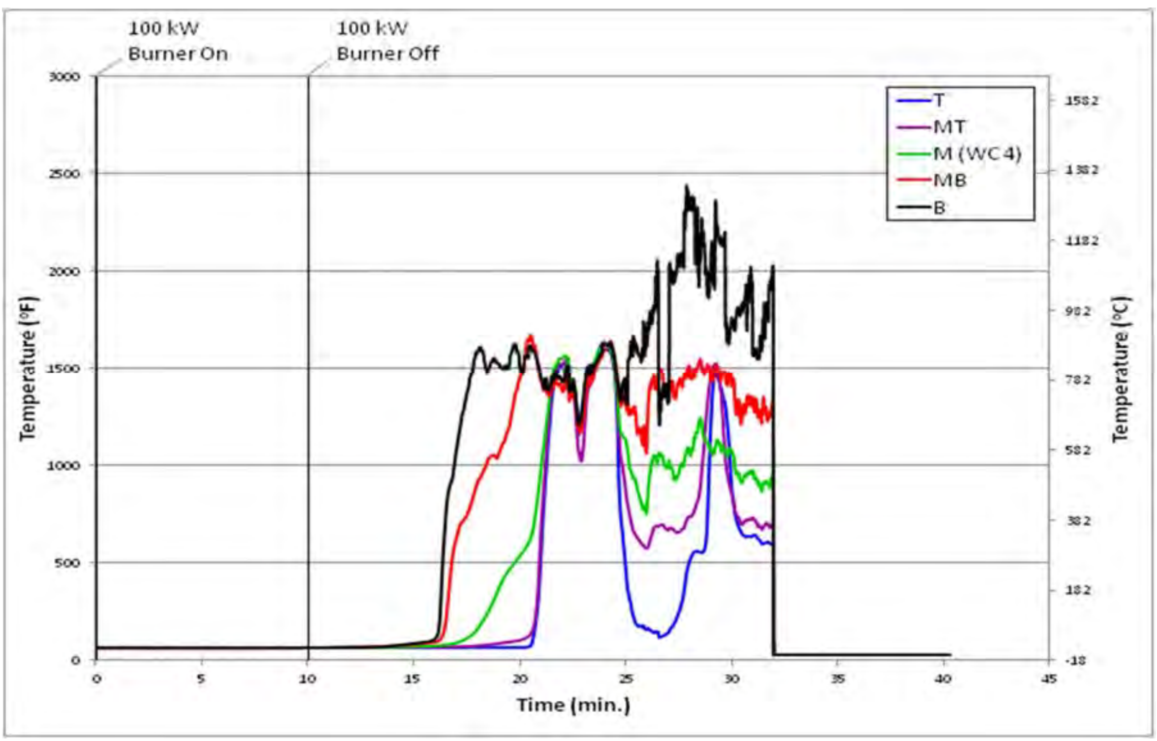


Figure G. 66: Wall Experiment 11 Wall Cavity Vertical Temperatures

Experiment 12

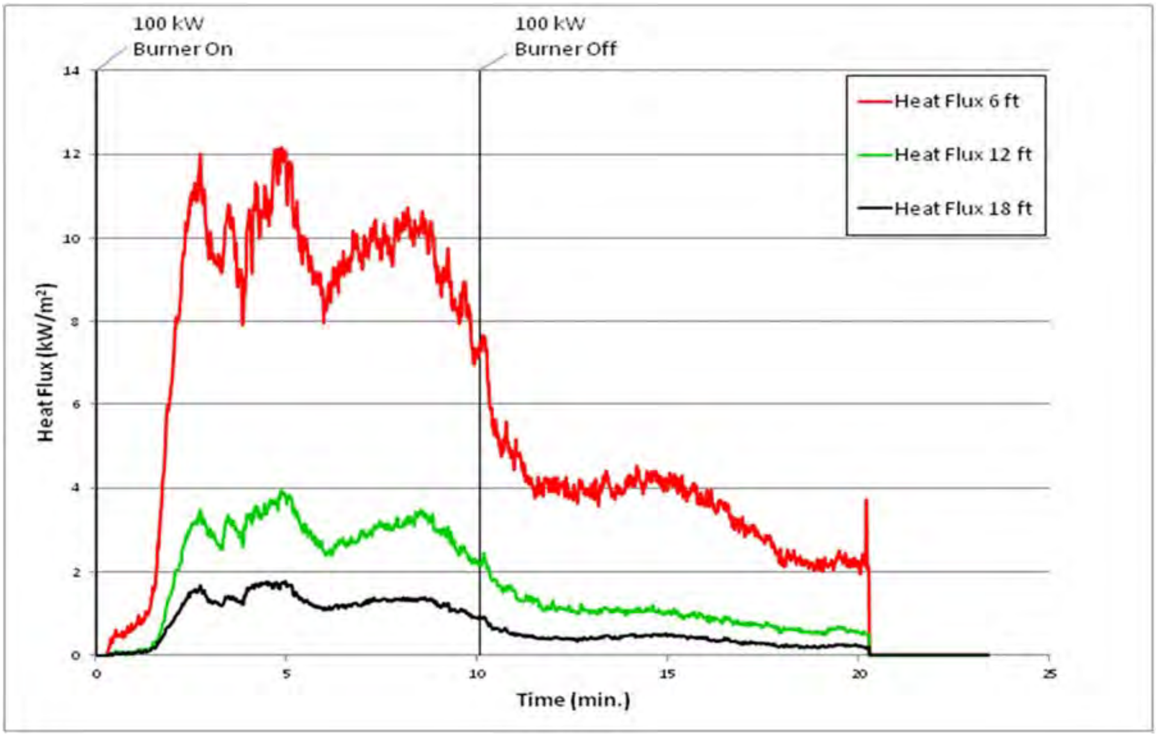


Figure G. 67: Wall Experiment 12 Heat Flux

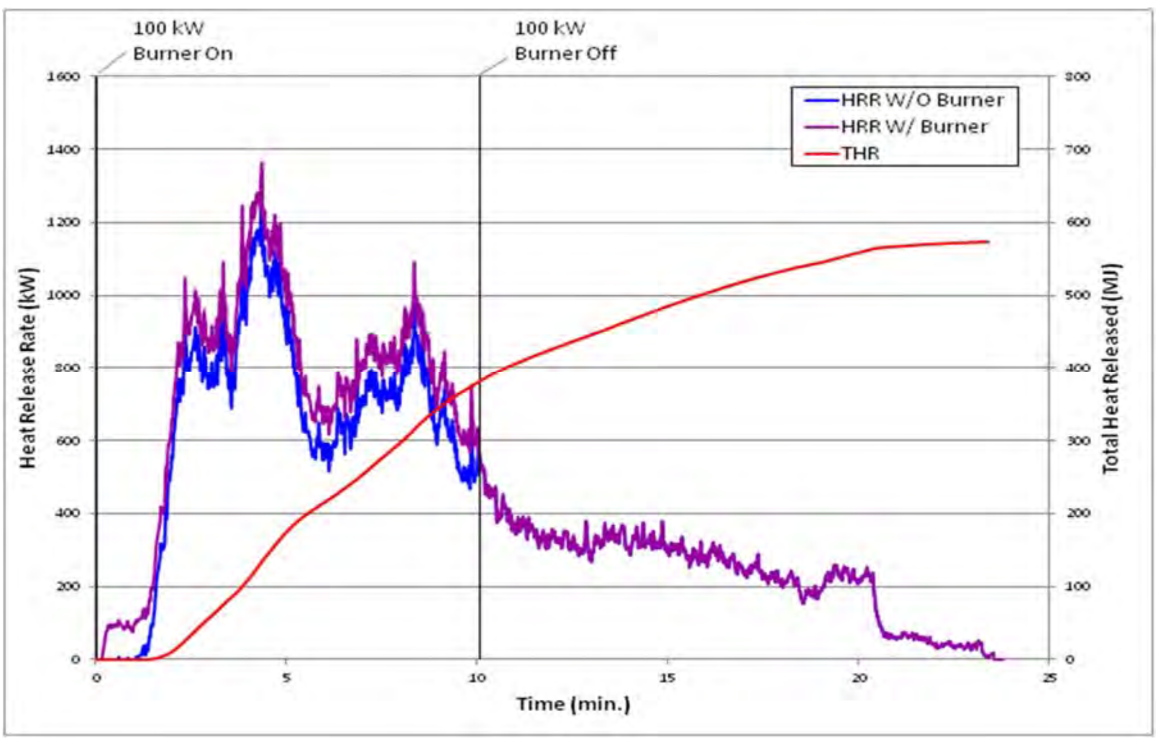


Figure G. 68: Wall Experiment 12 Heat Release Rate and Total Heat Released

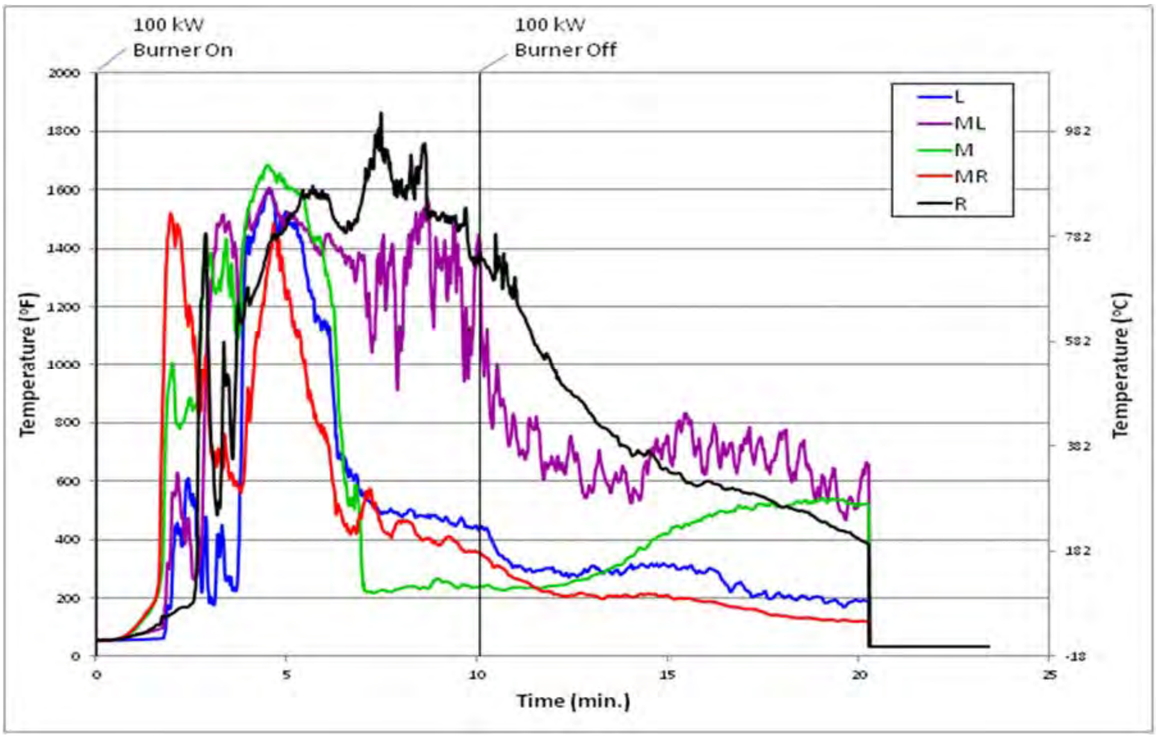


Figure G. 69: Wall Experiment 12 under Siding Horizontal Temperatures

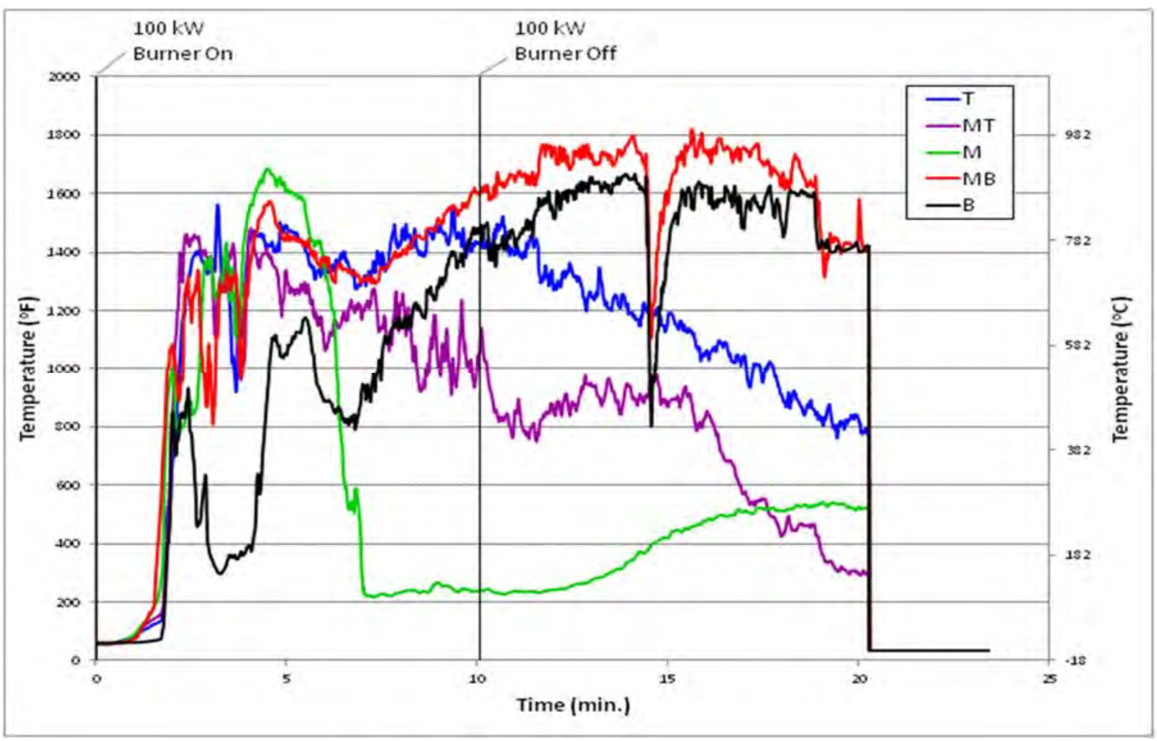


Figure G. 70: Wall Experiment 12 under Siding Vertical Temperatures

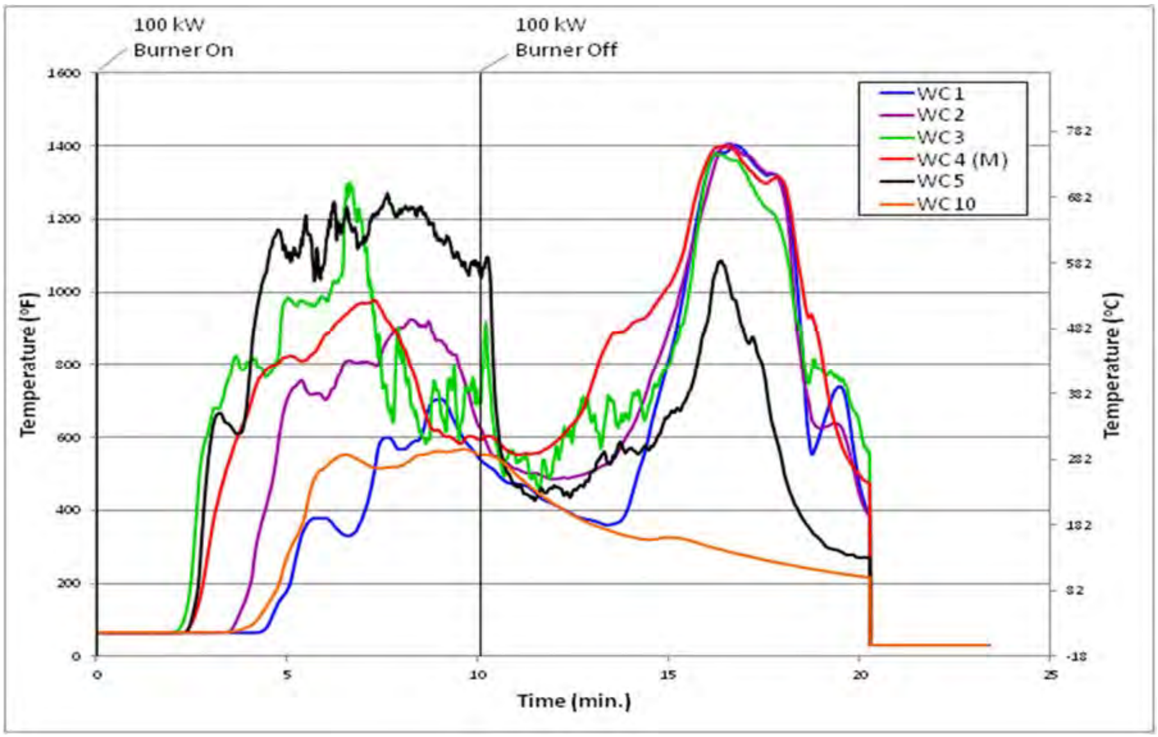


Figure G. 71: Wall Experiment 12 Wall Cavity Horizontal Temperatures

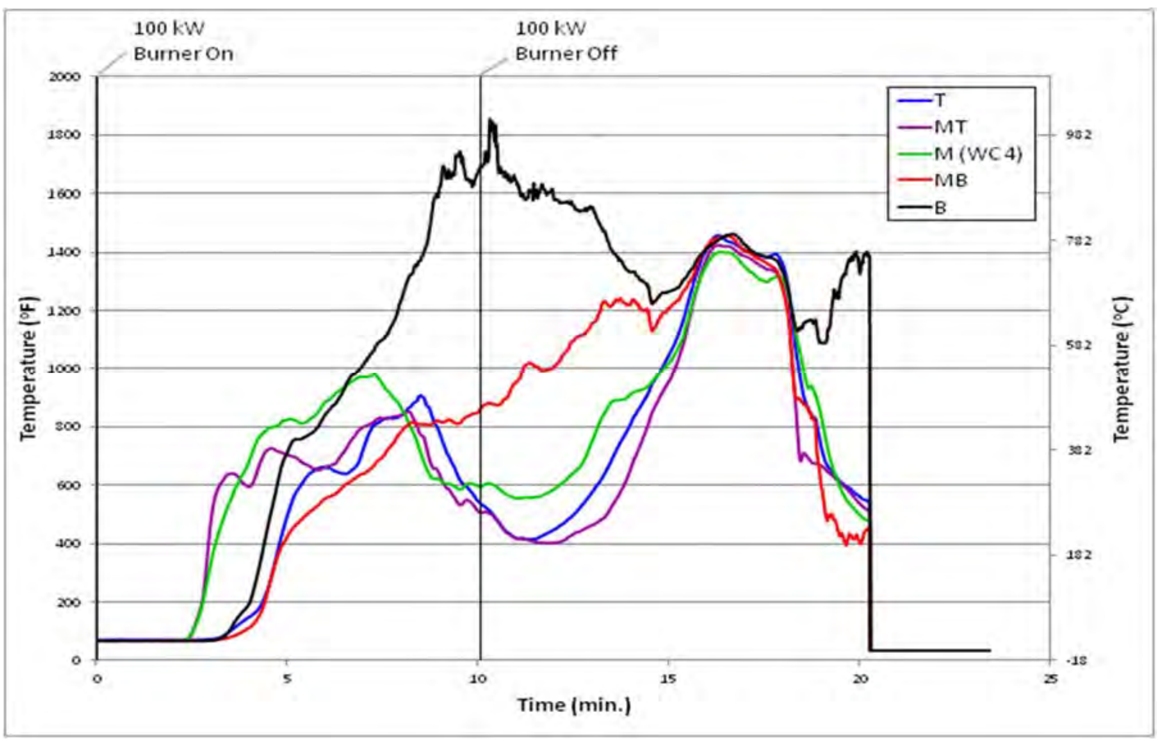


Figure G. 72: Wall Experiment 12 Wall Cavity Vertical Temperatures

Experiment 13

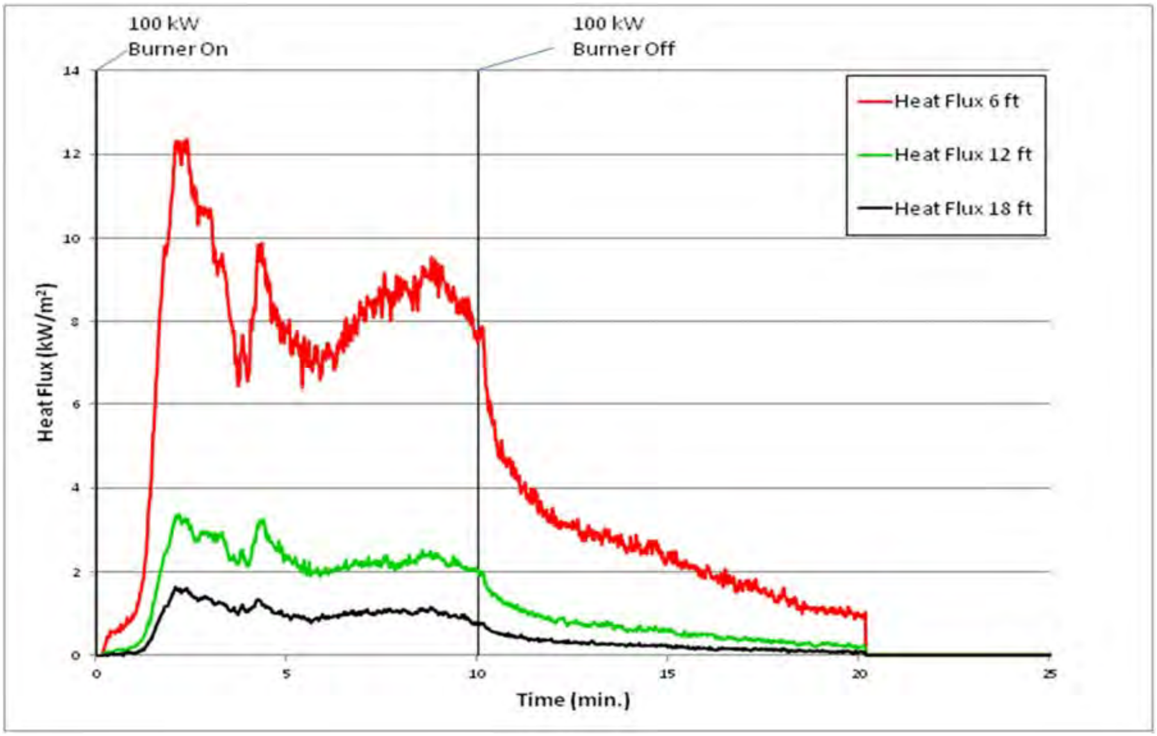


Figure G. 73: Wall Experiment 13 Heat Flux

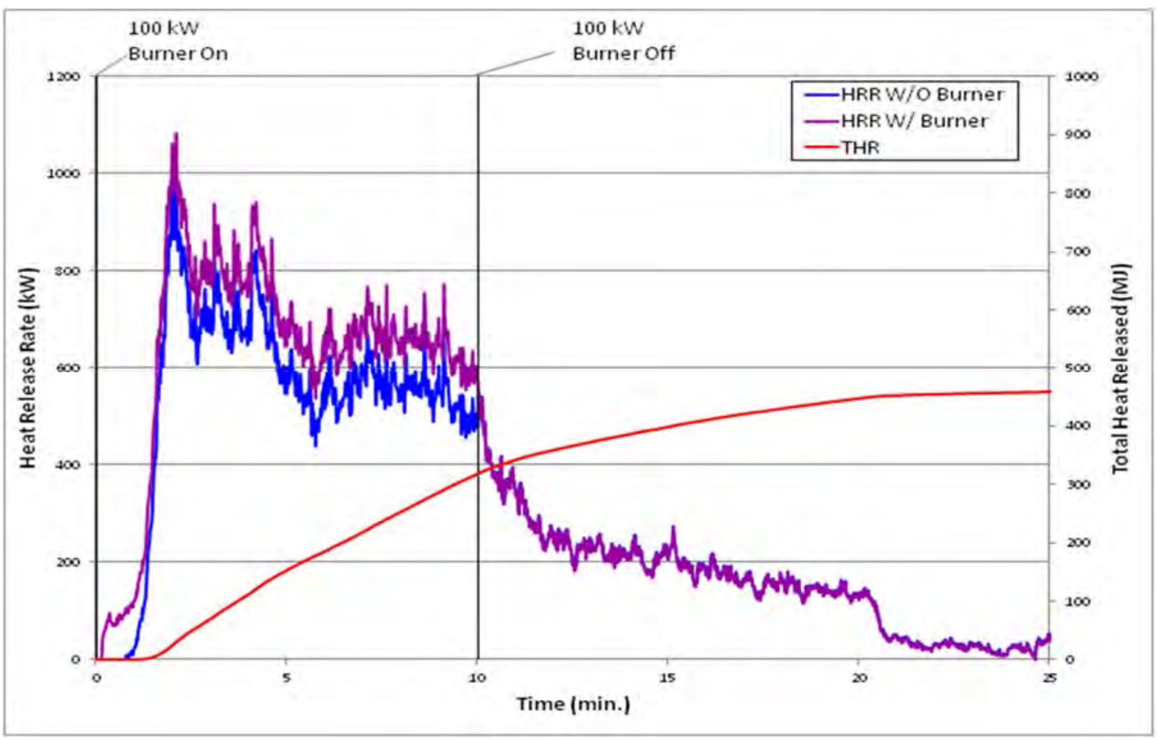


Figure G. 74: Wall Experiment 13 Heat Release Rate and Total Heat Released

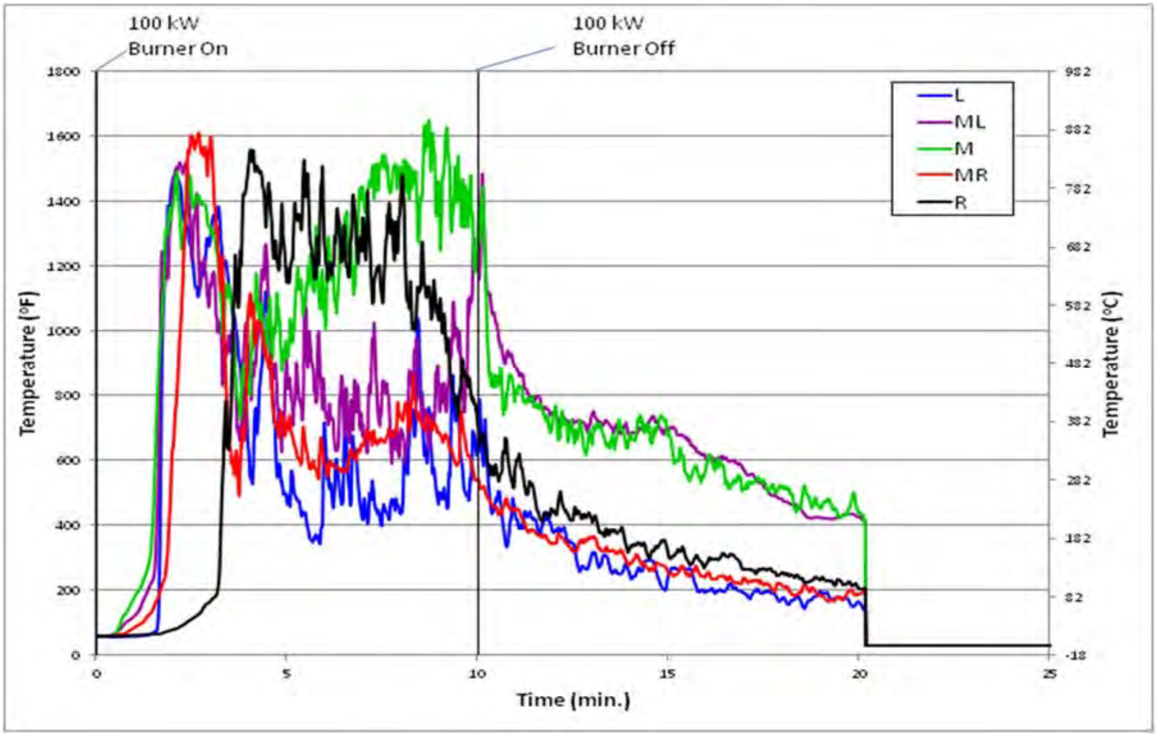


Figure G. 75: Wall Experiment 13 under Siding Horizontal Temperatures

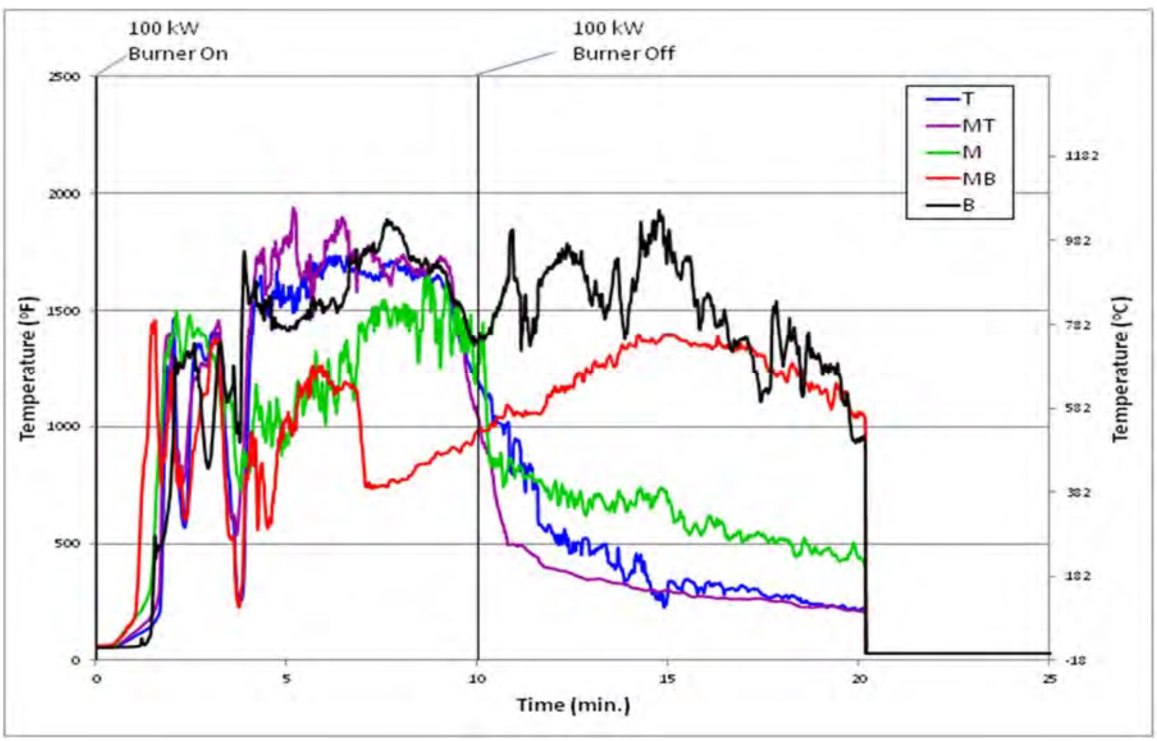


Figure G. 76: Wall Experiment 13 under Siding Vertical Temperatures

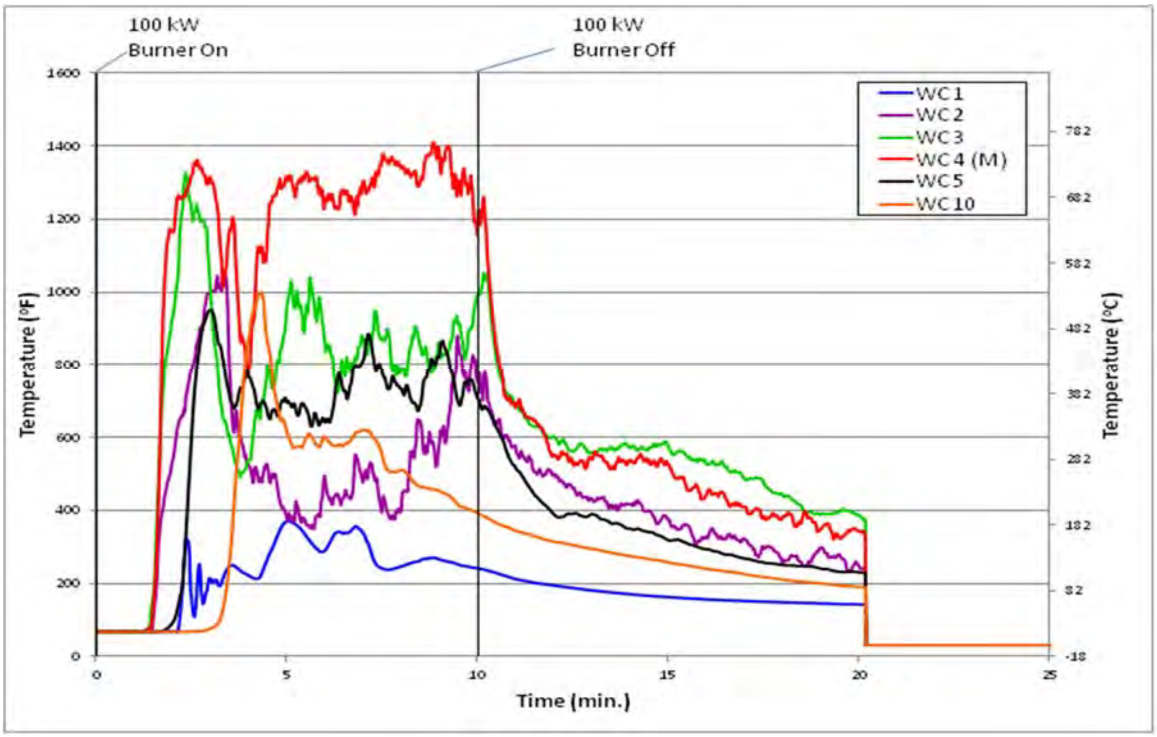


Figure G. 77: Wall Experiment 13 Wall Cavity Horizontal Temperatures

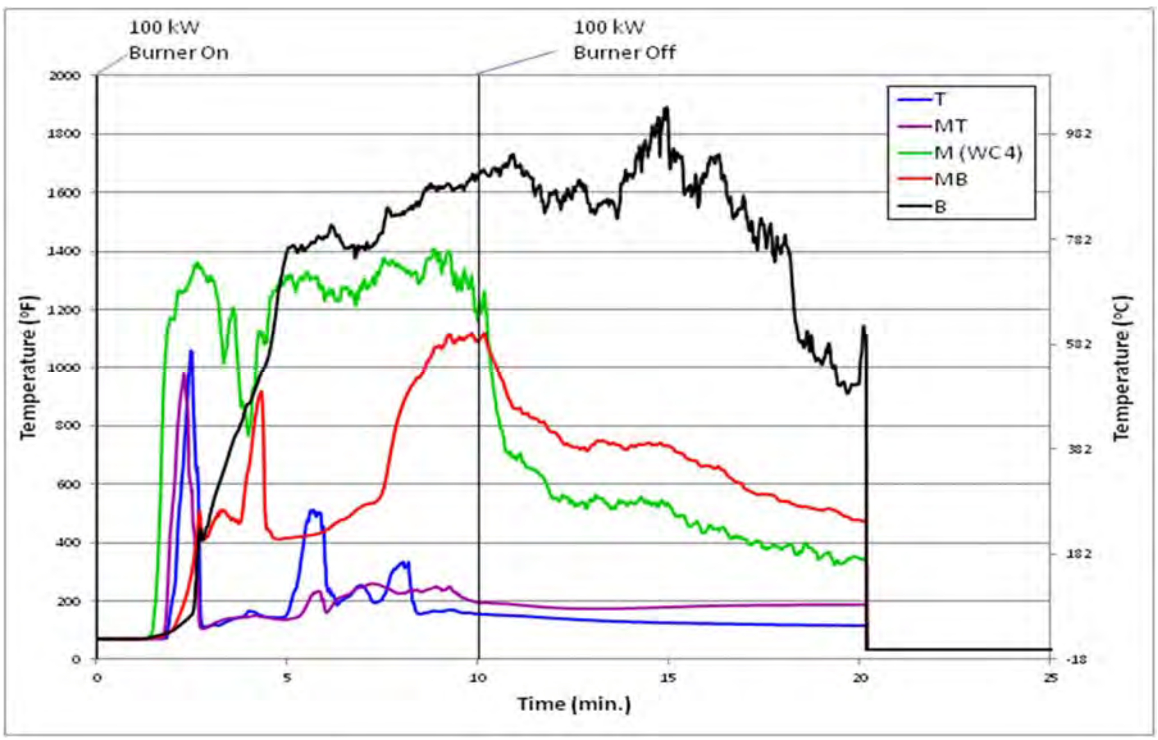


Figure G. 78: Wall Experiment 13 Wall Cavity Vertical Temperatures

Experiment 14

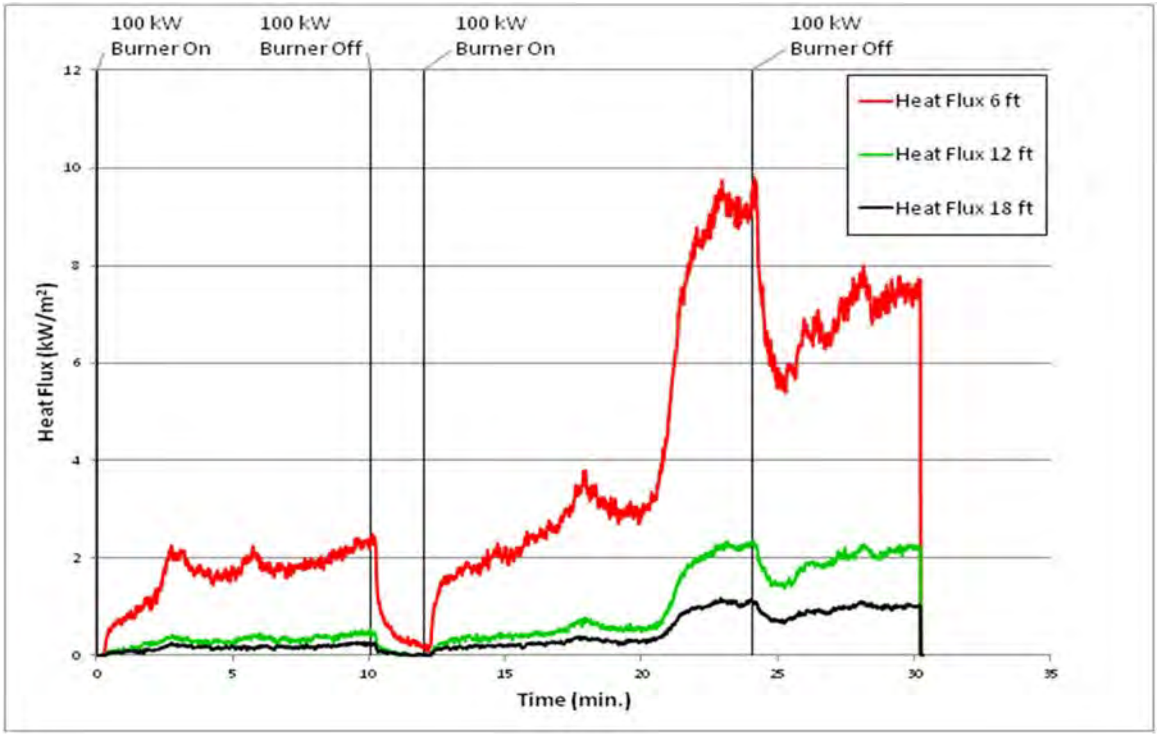


Figure G. 79: Wall Experiment 14 Heat Flux

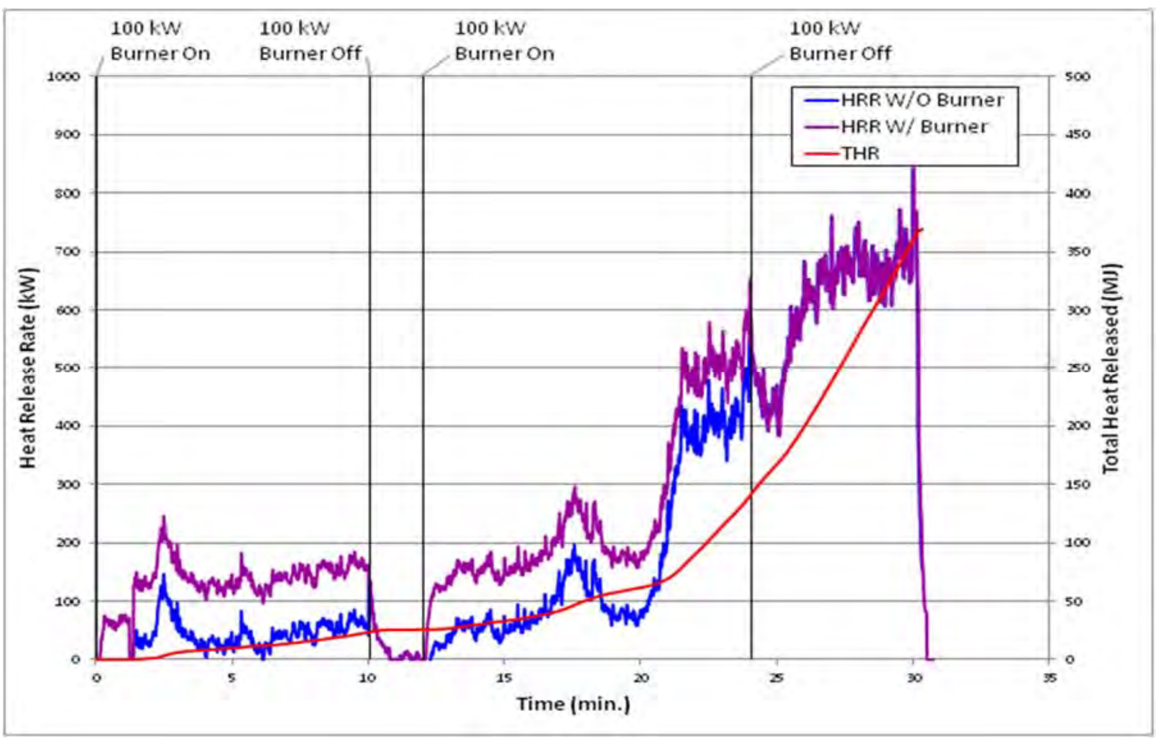


Figure G. 80: Wall Experiment 14 Heat Release Rate and Total Heat Released

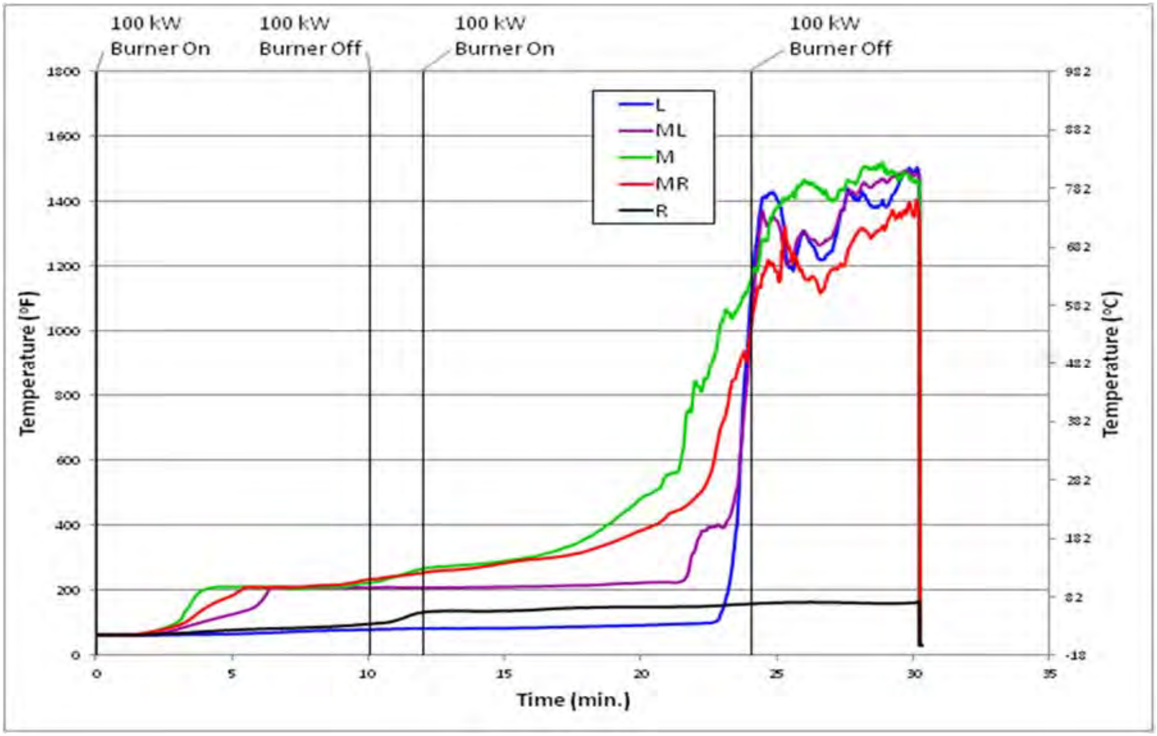


Figure G. 81: Wall Experiment 14 under Siding Horizontal Temperatures

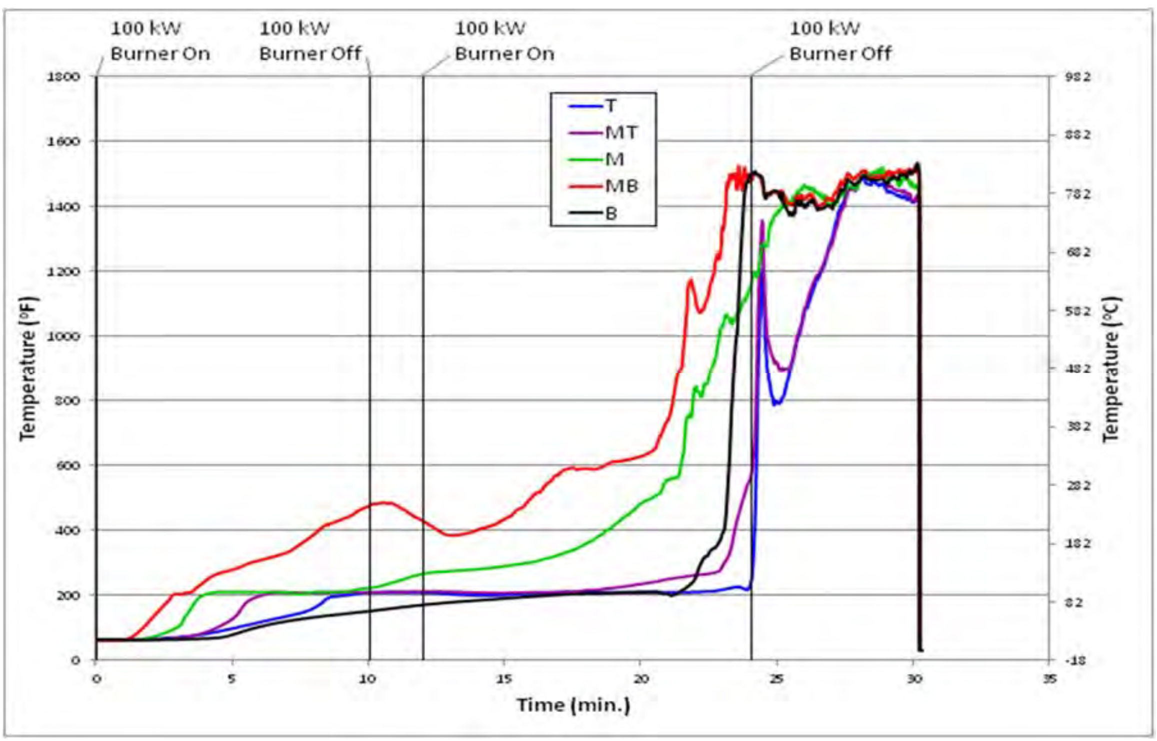


Figure G. 82: Wall Experiment 14 under Siding Vertical Temperatures

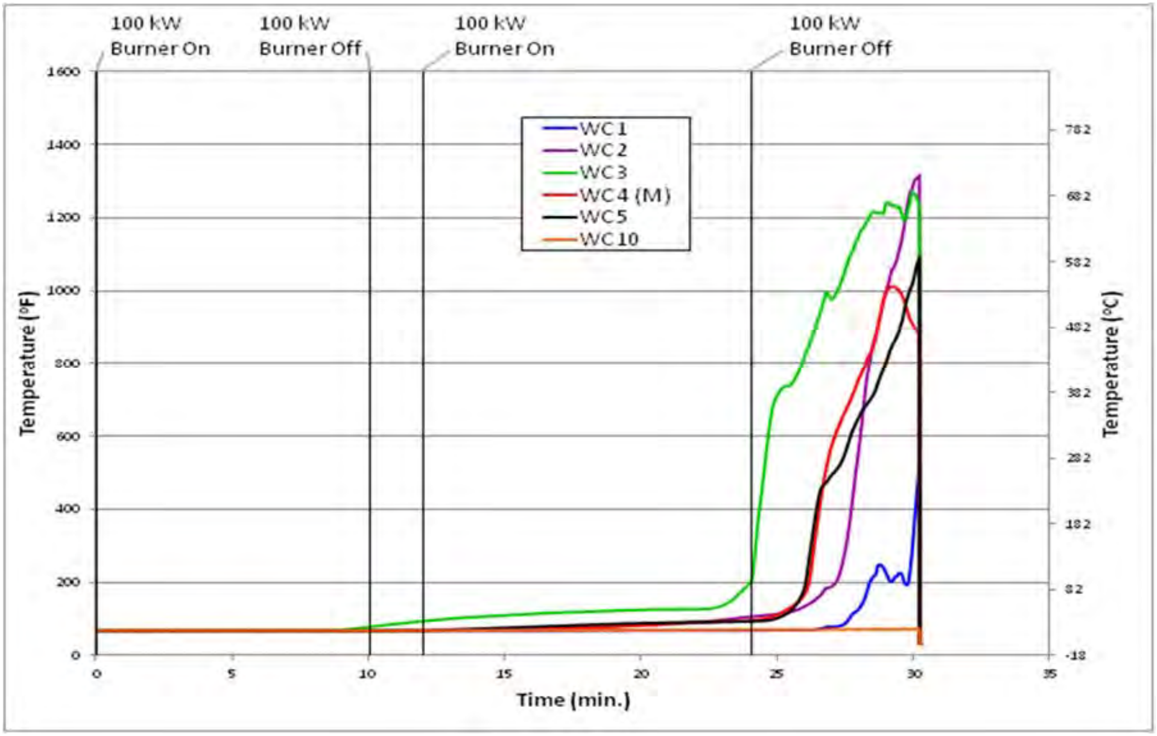


Figure G. 83: Wall Experiment 14 Wall Cavity Horizontal Temperatures

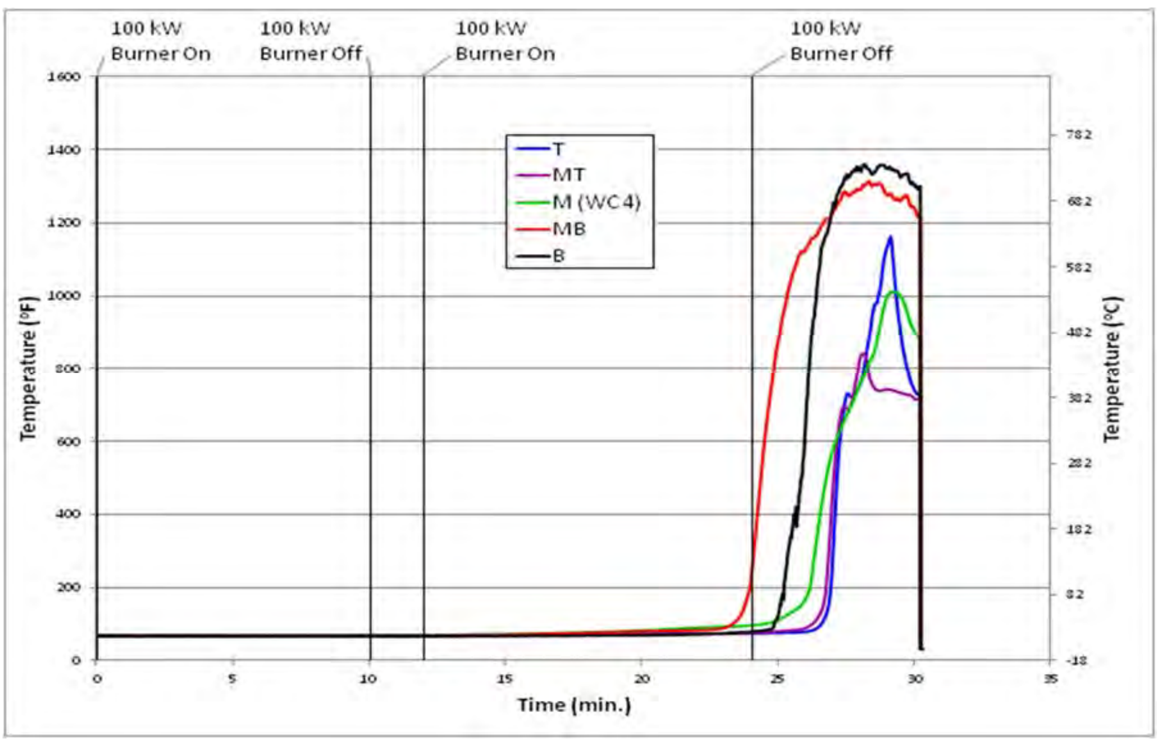


Figure G. 84: Wall Experiment 14 Wall Cavity Vertical Temperatures

Experiment 15

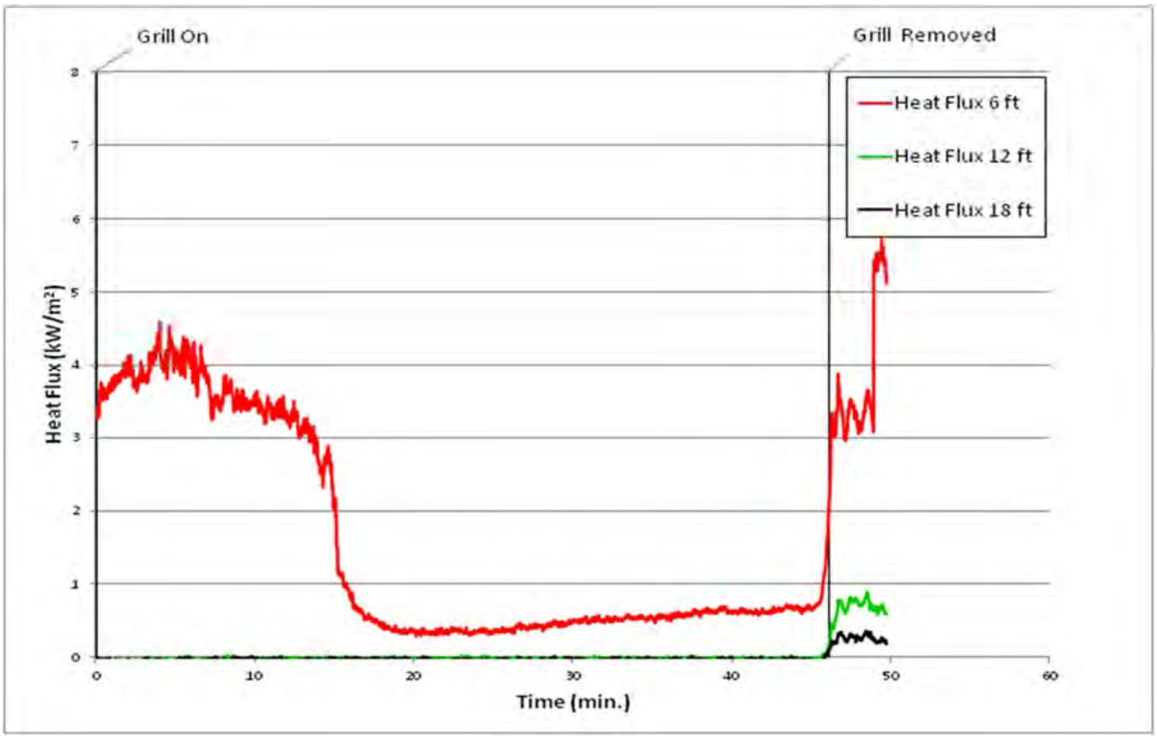


Figure G. 85: Wall Experiment 15 Heat Flux

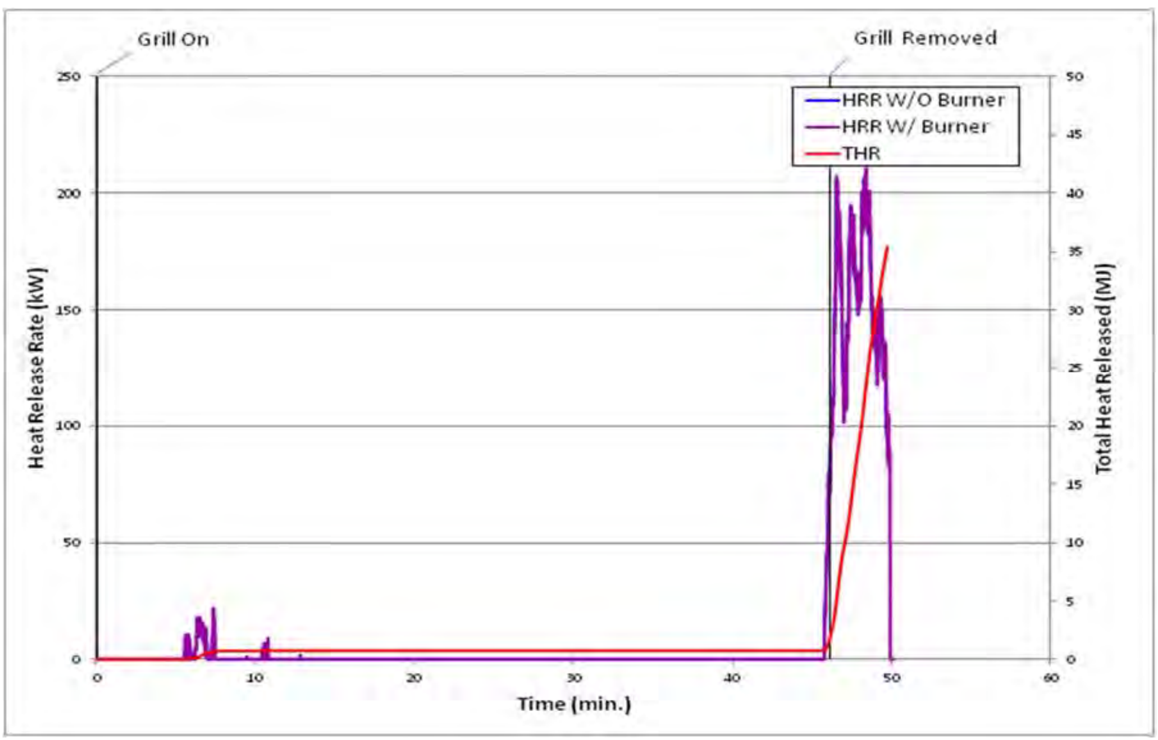


Figure G. 86: Wall Experiment 15 Heat Release Rate and Total Heat Released

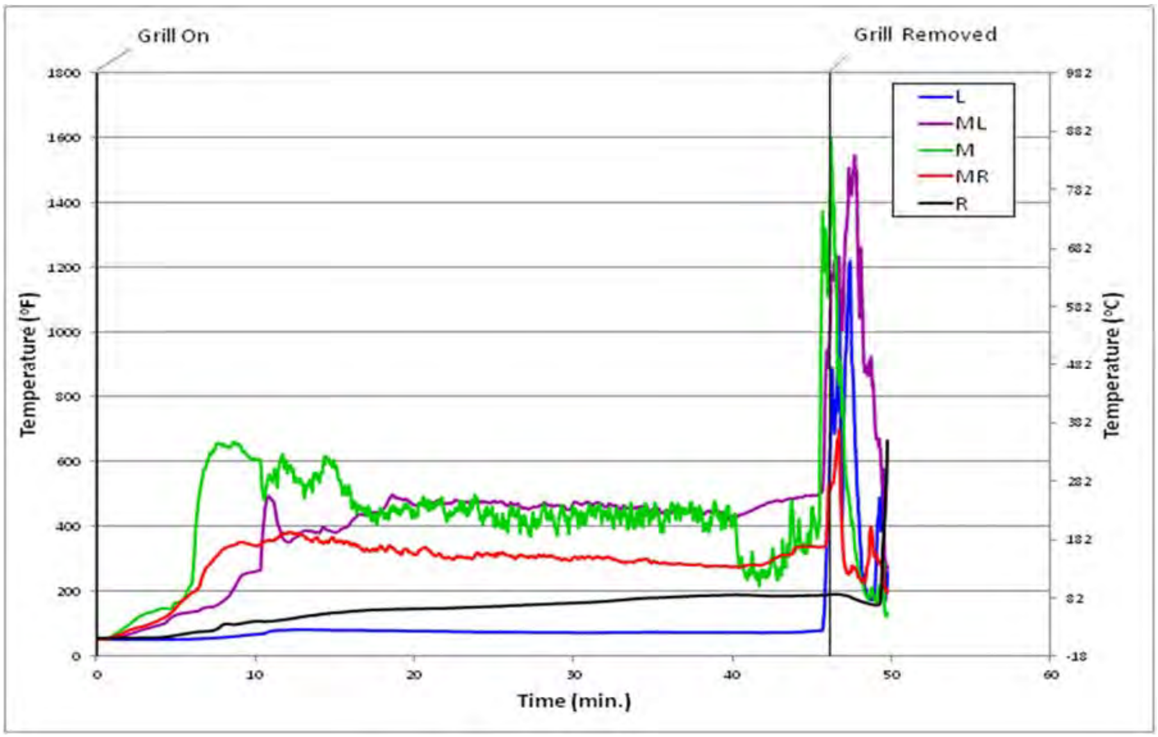


Figure G. 87: Wall Experiment 15 under Siding Horizontal Temperatures

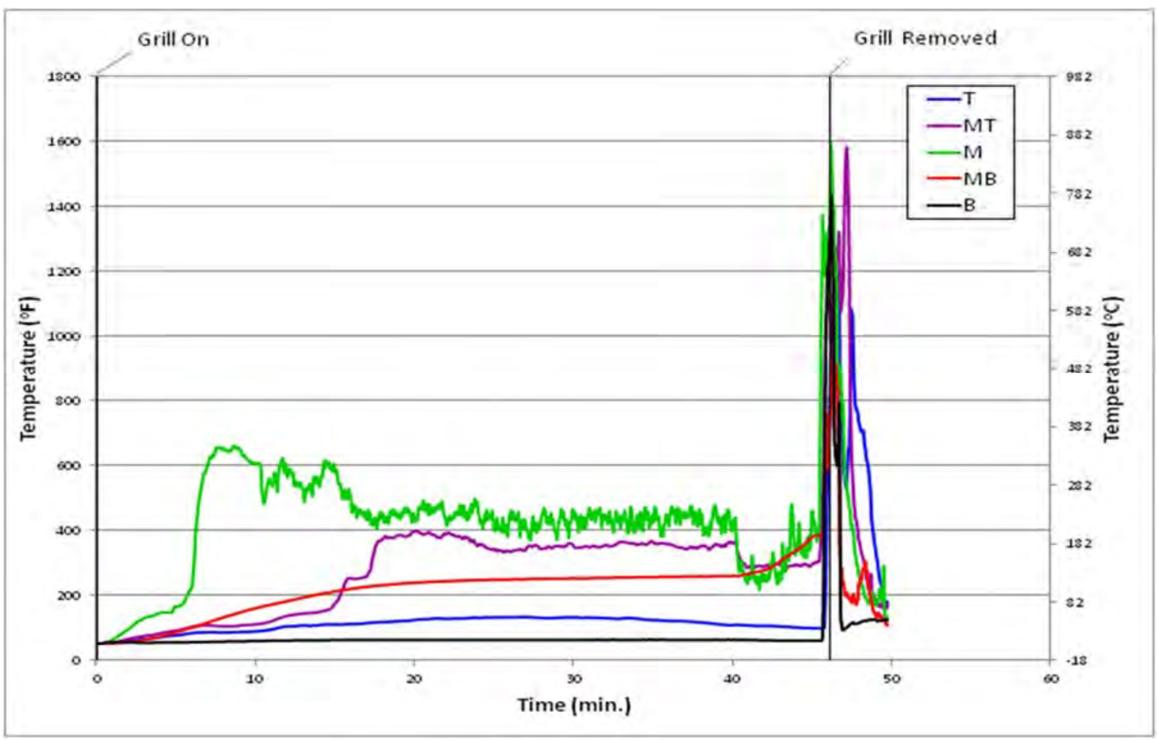


Figure G. 88: Wall Experiment 15 under Siding Vertical Temperatures

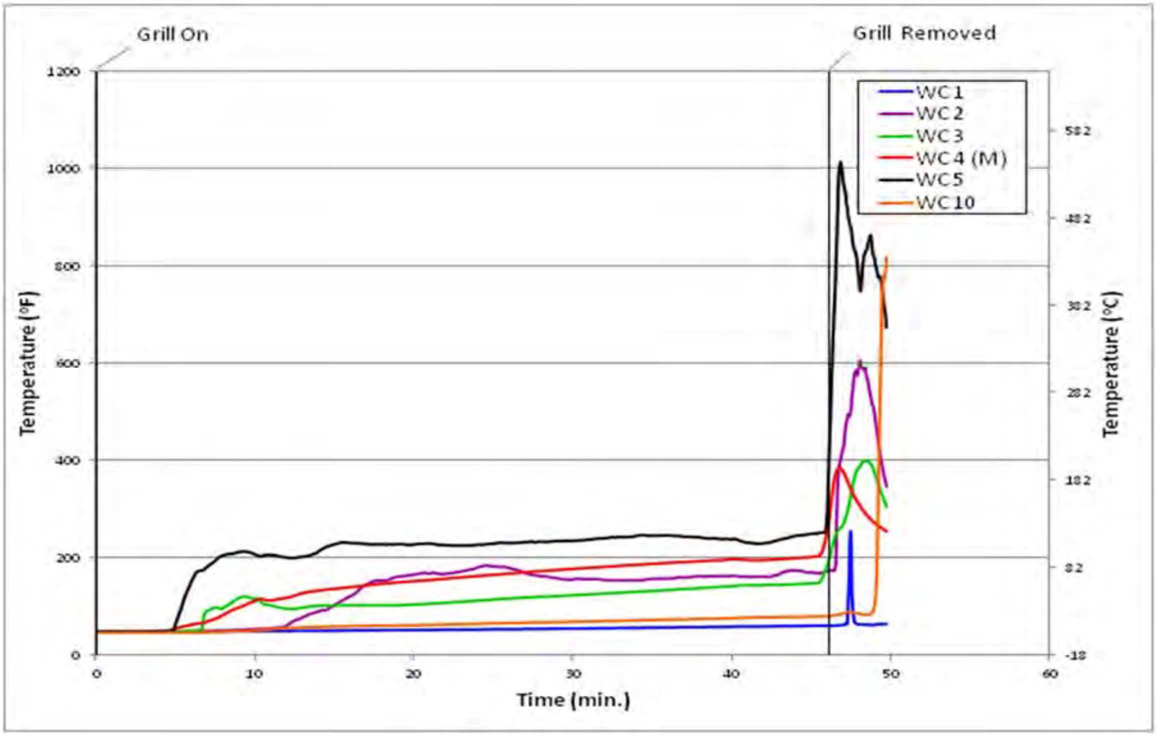


Figure G. 89: Wall Experiment 15 Wall Cavity Horizontal Temperatures

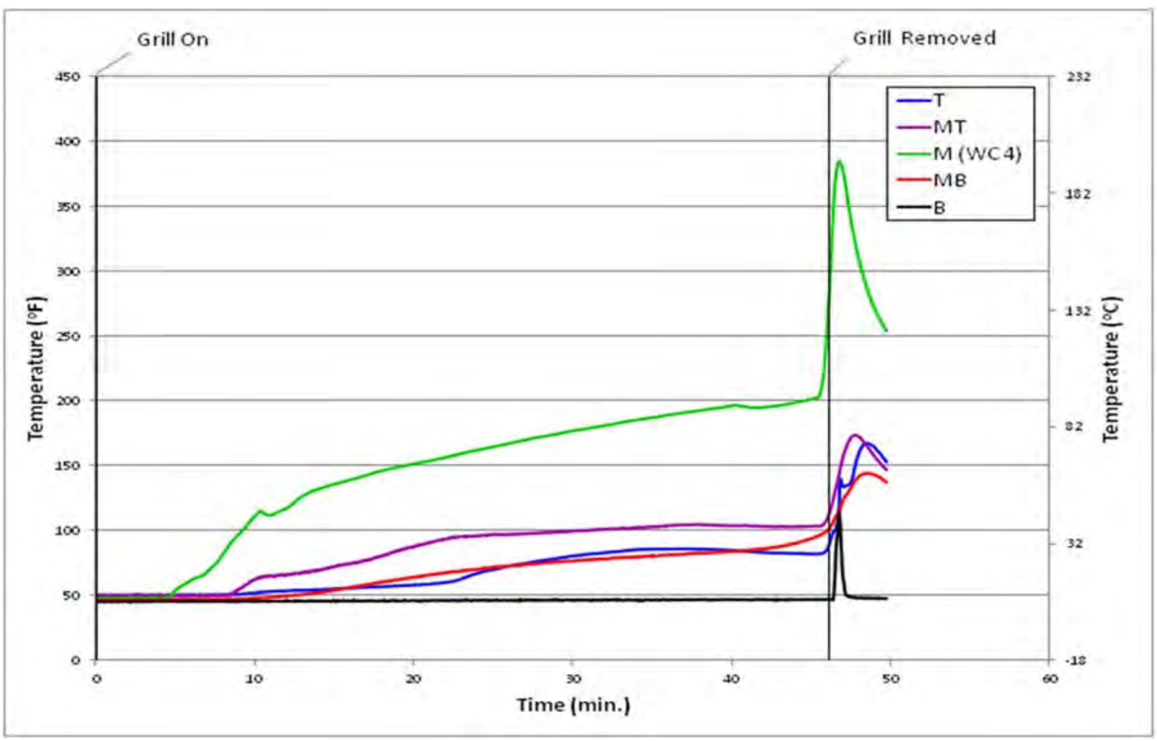


Figure G. 90: Wall Experiment 15 Wall Cavity Vertical Temperatures

Experiment 16

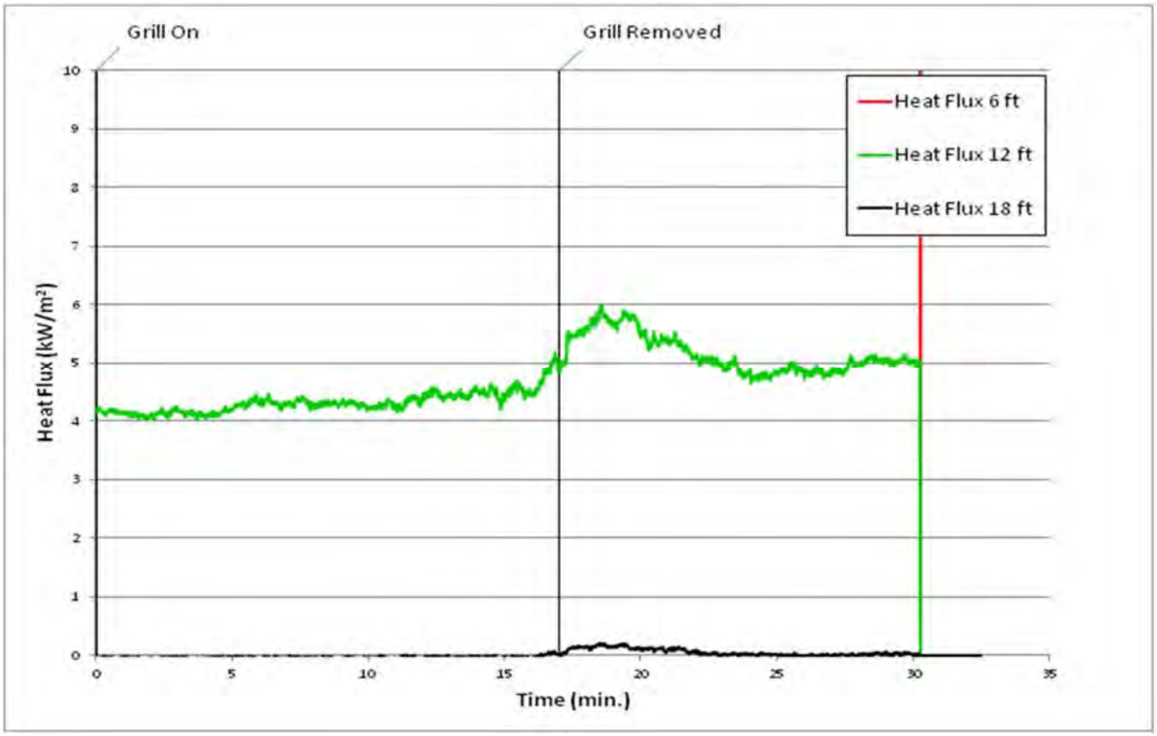


Figure G. 91: Wall Experiment 16 Heat Flux

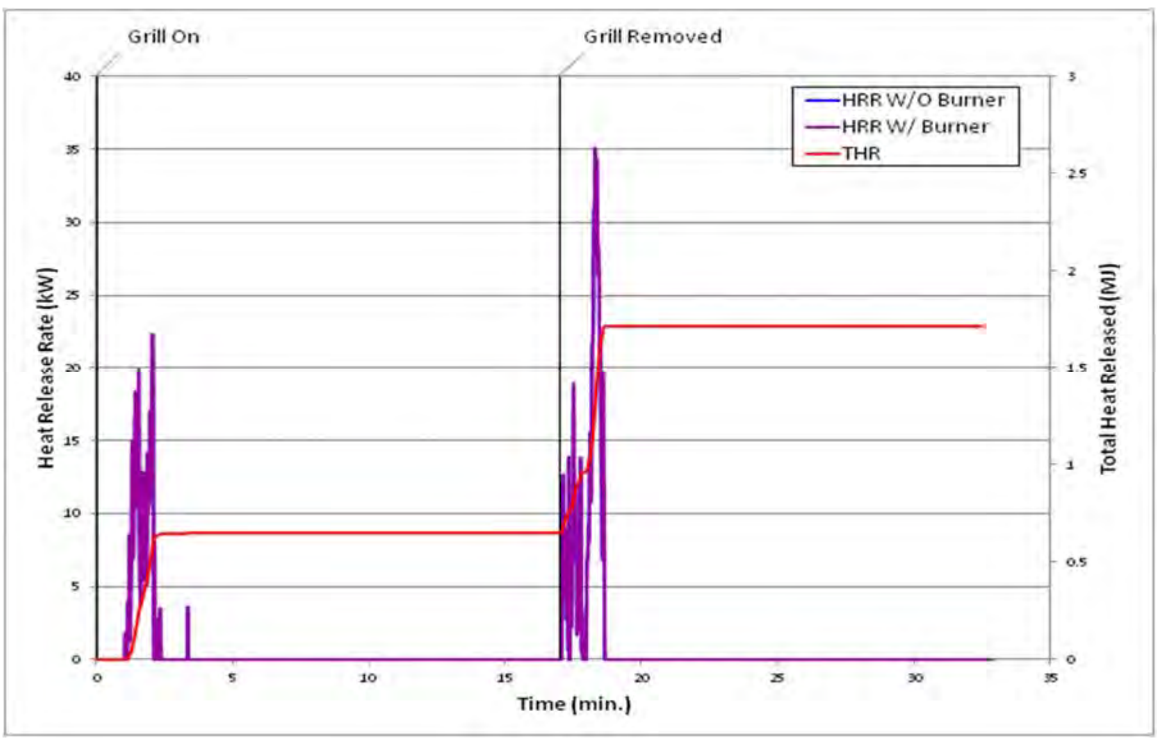


Figure G. 92: Wall Experiment 16 Heat Release Rate and Total Heat Released

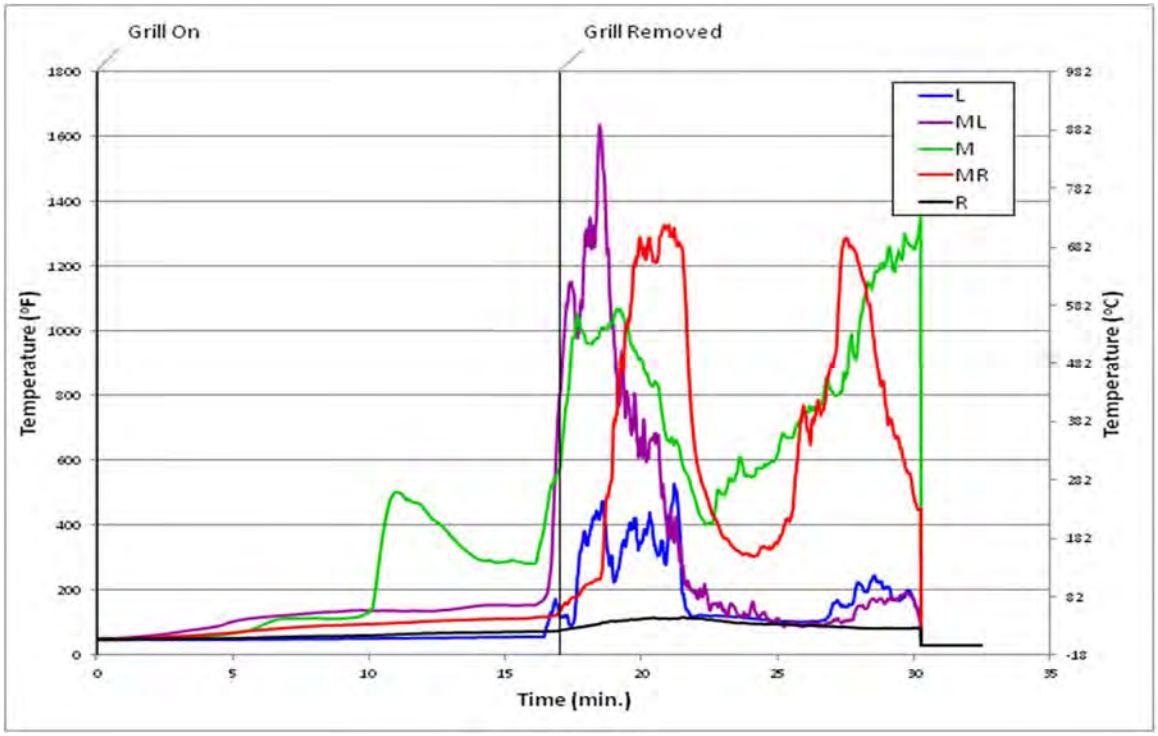


Figure G. 93: Wall Experiment 16 under Siding Horizontal Temperatures

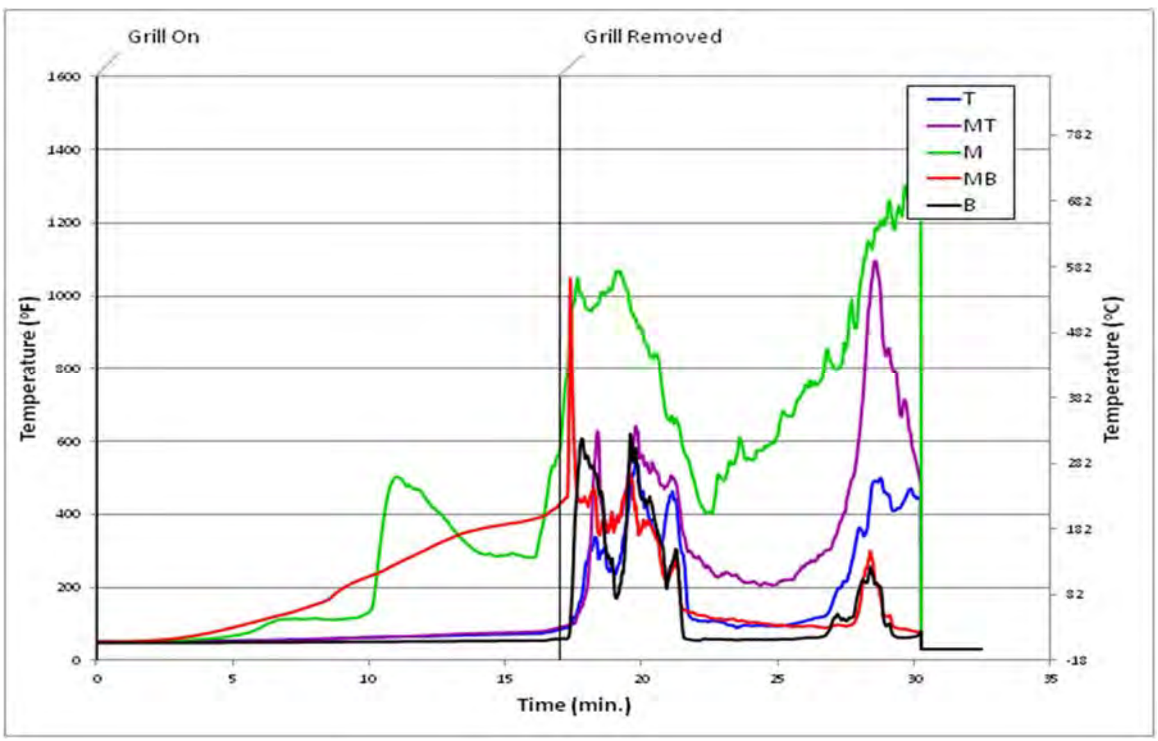


Figure G. 94: Wall Experiment 16 under Siding Vertical Temperatures

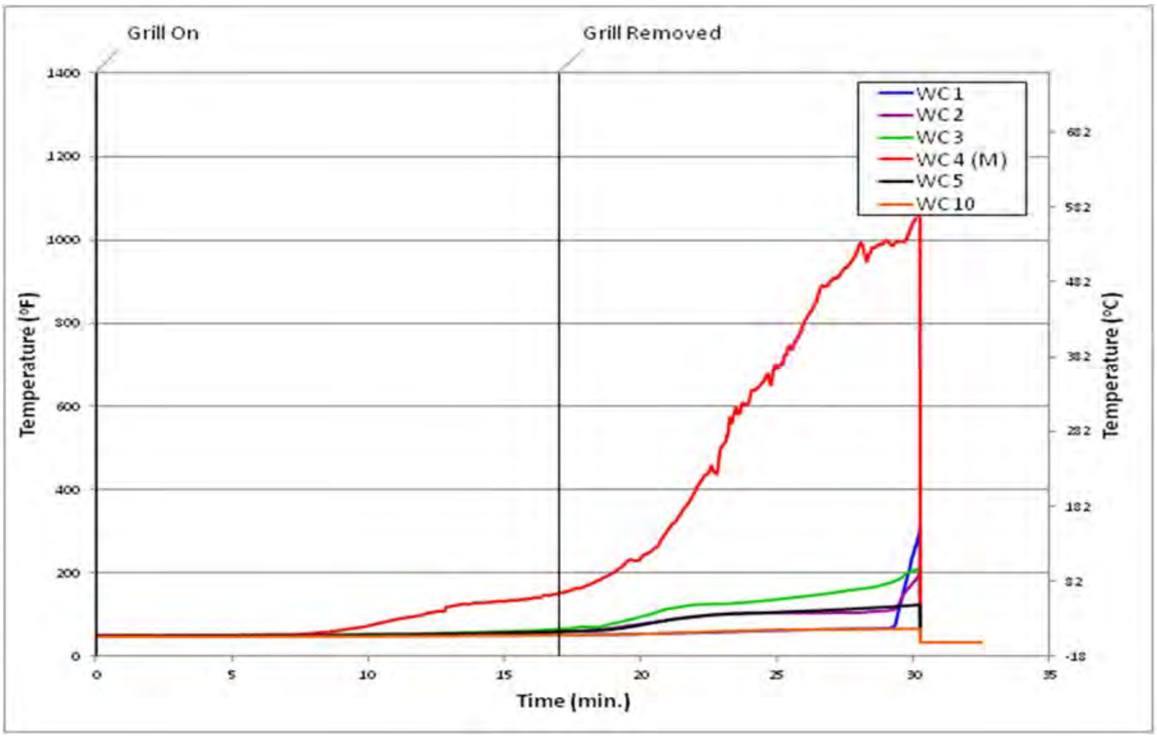


Figure G. 95: Wall Experiment 16 Wall Cavity Horizontal Temperatures

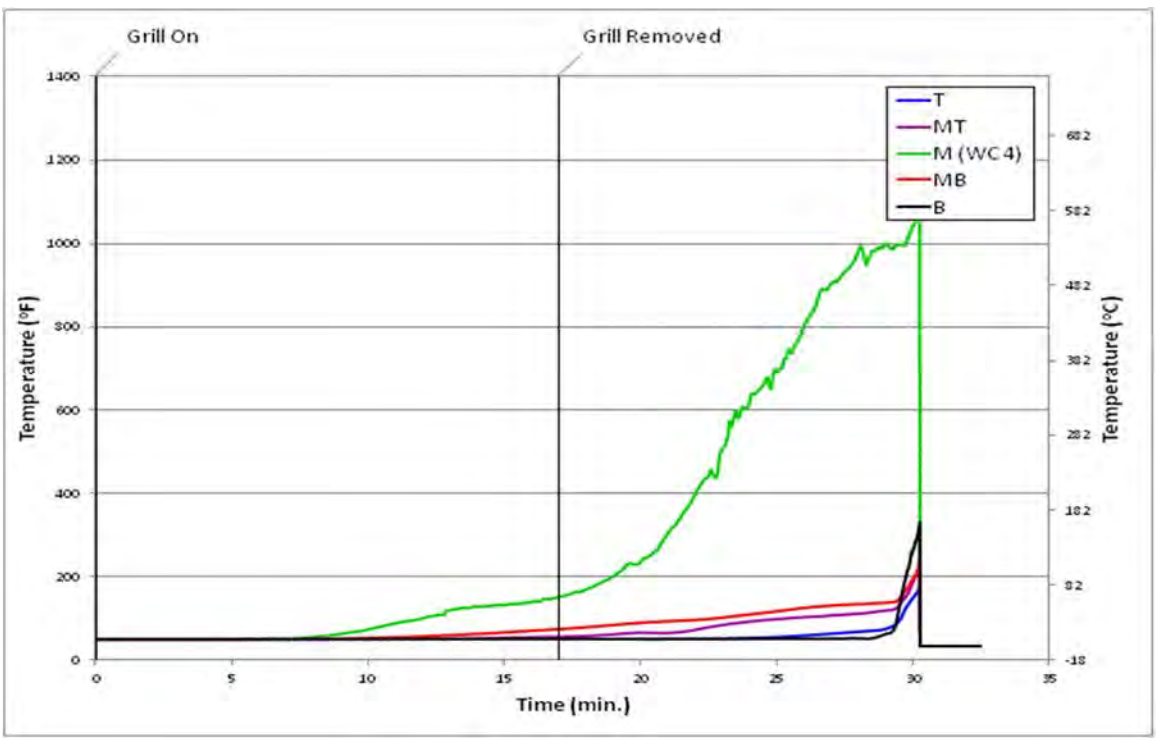


Figure G. 96: Wall Experiment 16 Wall Cavity Vertical Temperatures

Experiment 17

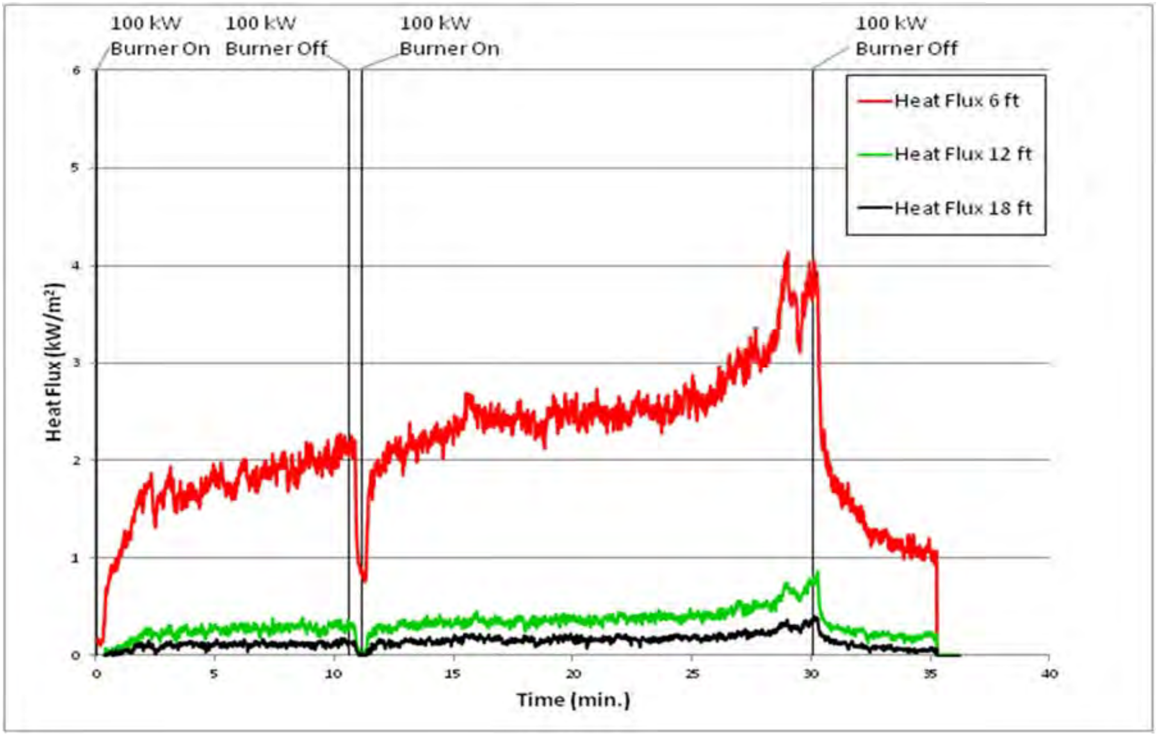


Figure G. 97: Wall Experiment 17 Heat Flux

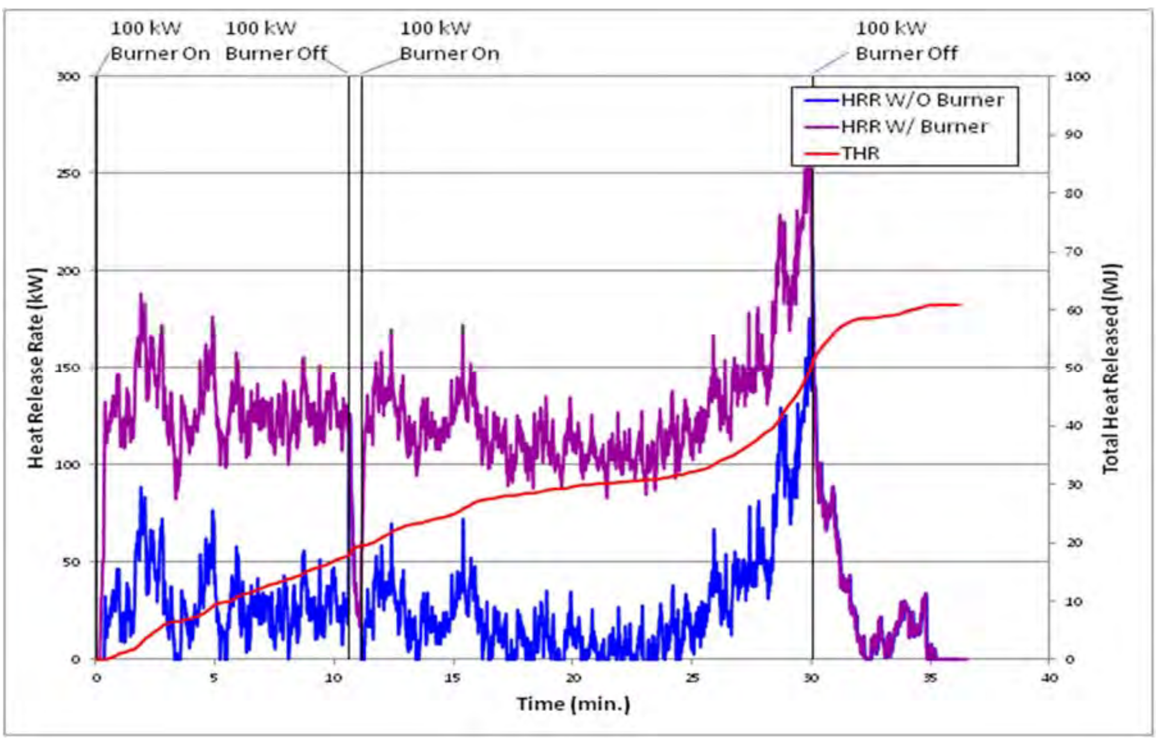


Figure G. 98: Wall Experiment 17 Heat Release Rate and Total Heat Released

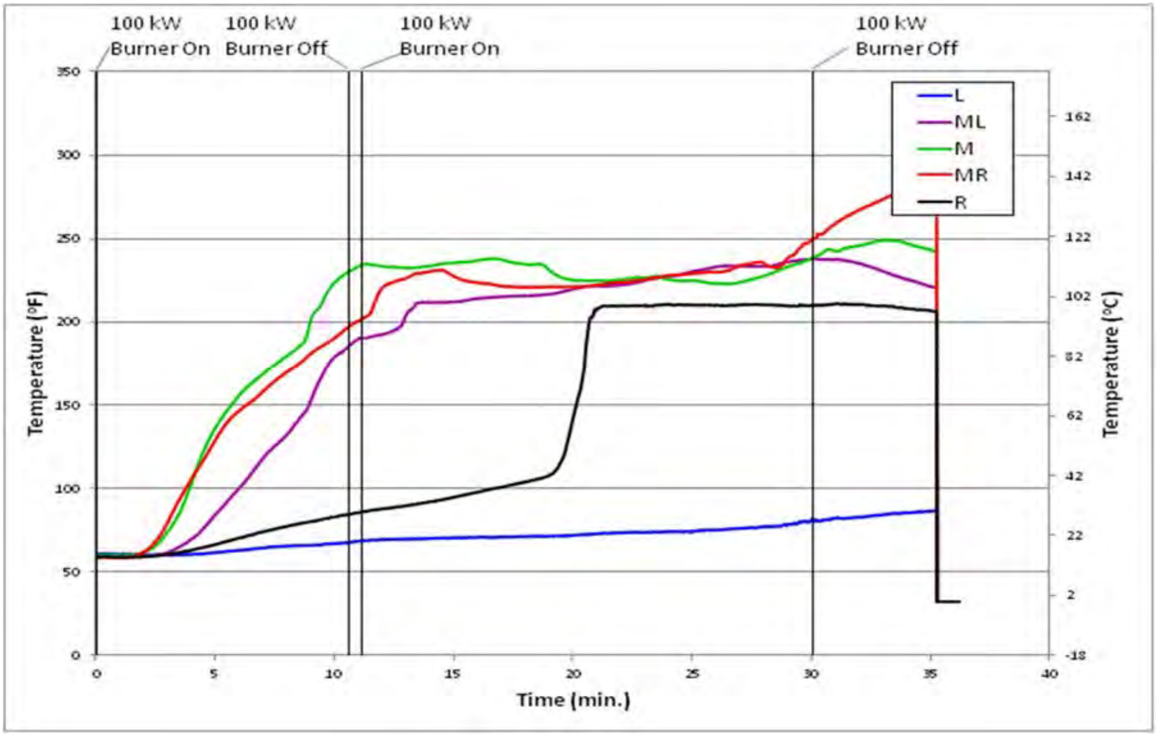


Figure G. 99: Wall Experiment 17 under Siding Horizontal Temperatures

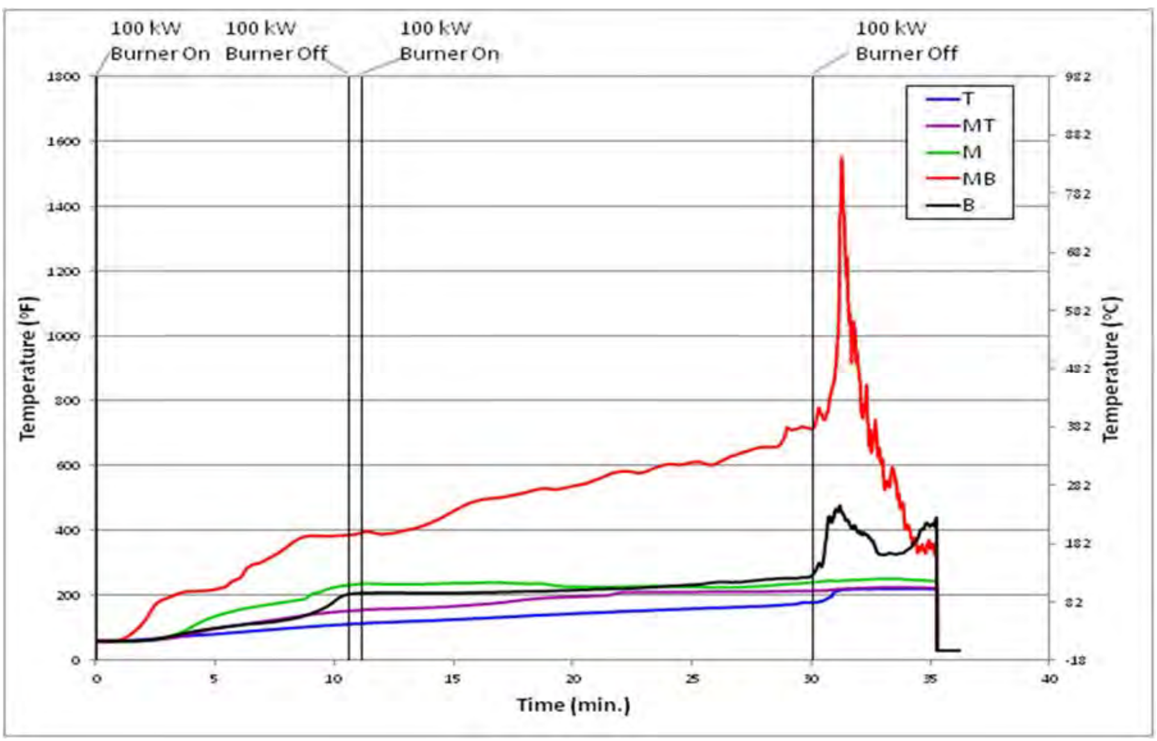


Figure G. 100: Wall Experiment 17 under Siding Vertical Temperatures

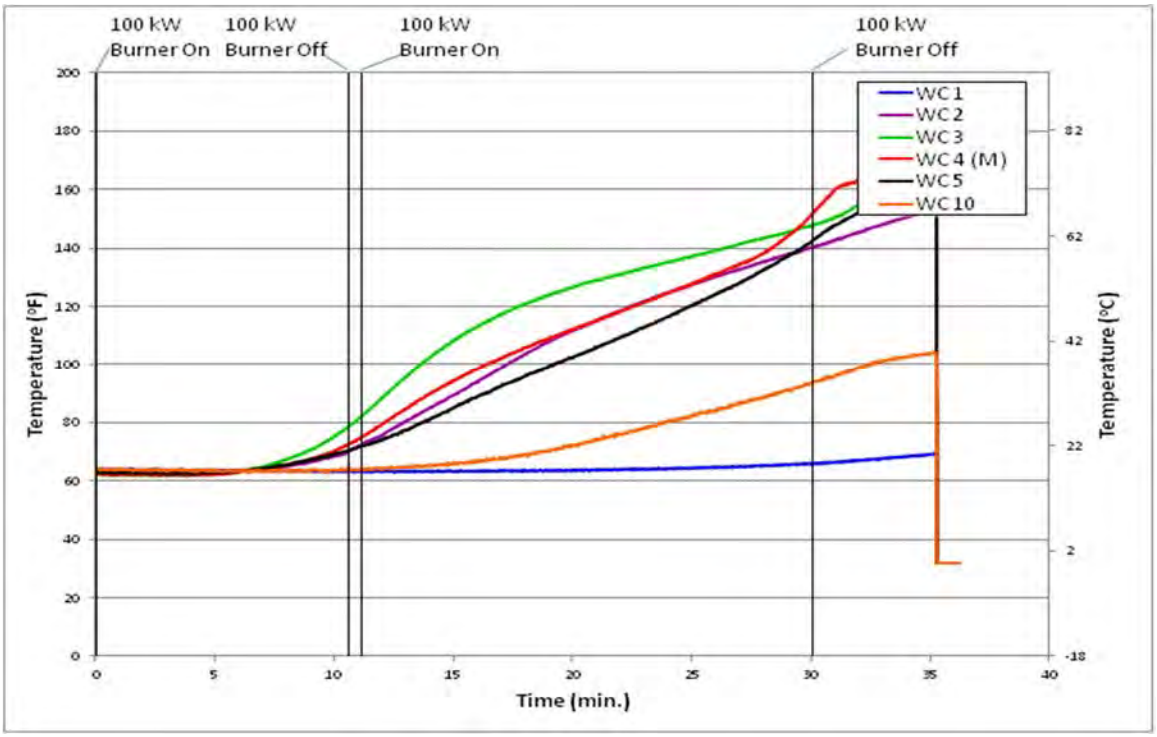


Figure G. 101: Wall Experiment 17 Wall Cavity Horizontal Temperatures

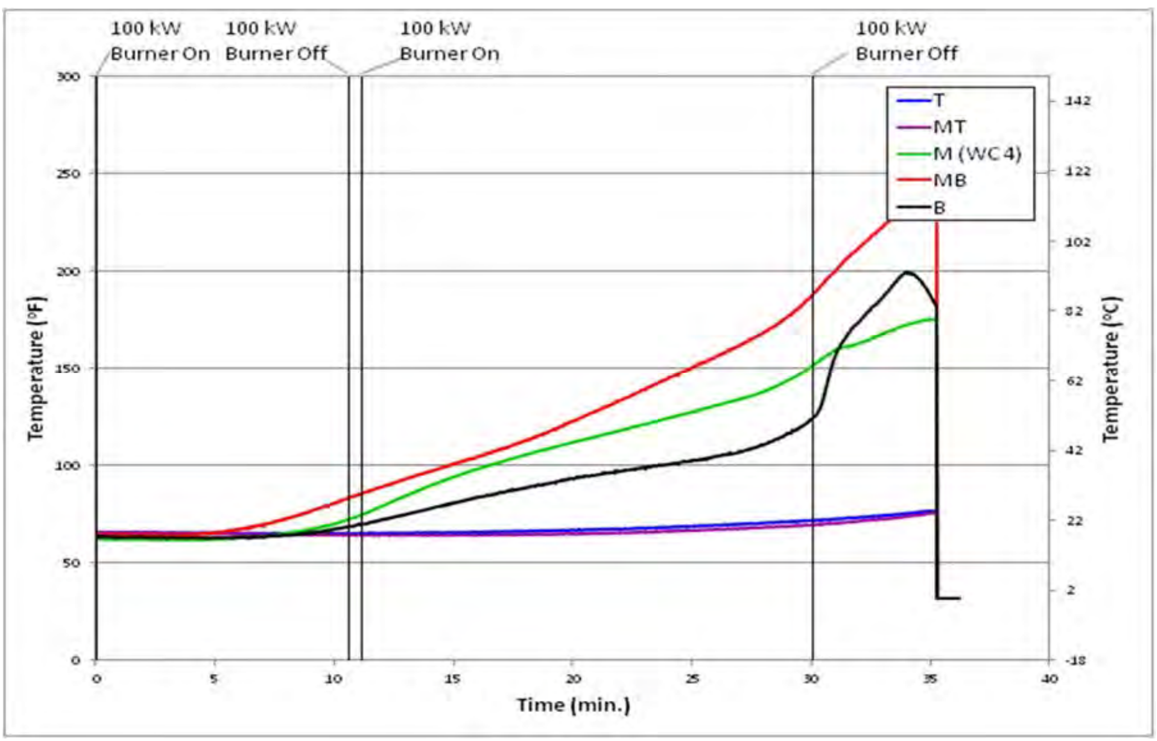


Figure G. 102: Wall Experiment 17 Wall Cavity Vertical Temperatures

Experiment 18

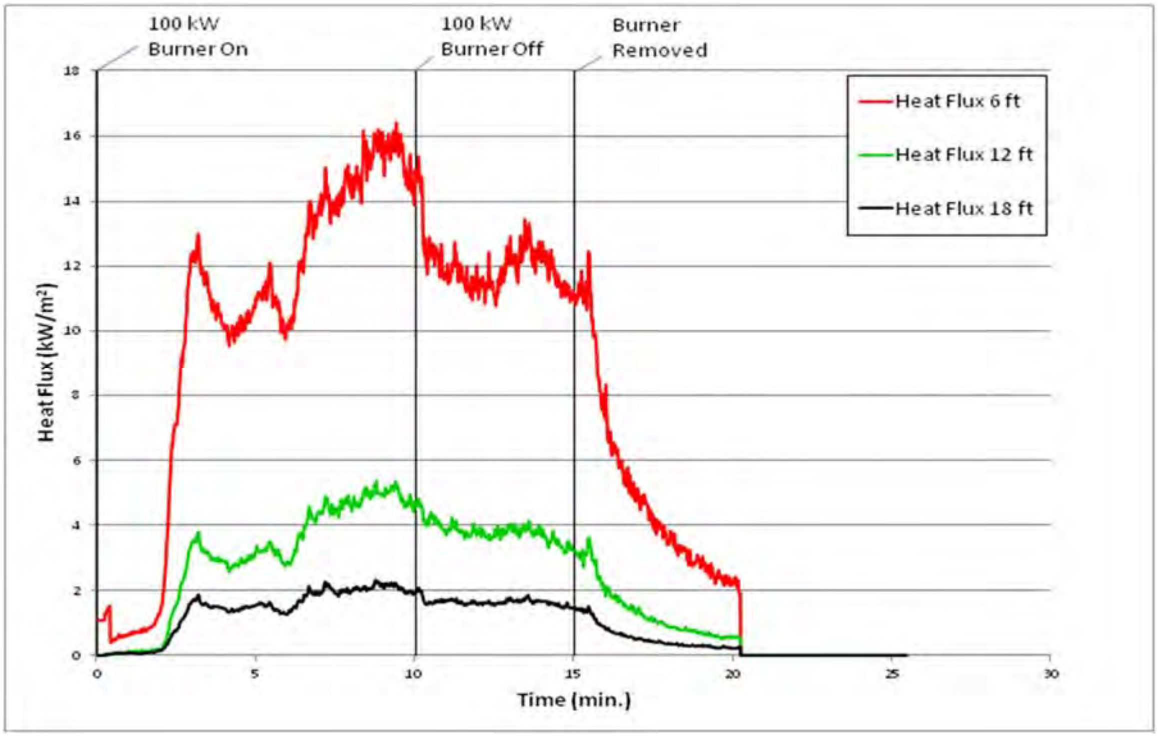


Figure G. 103: Wall Experiment 18 Heat Flux

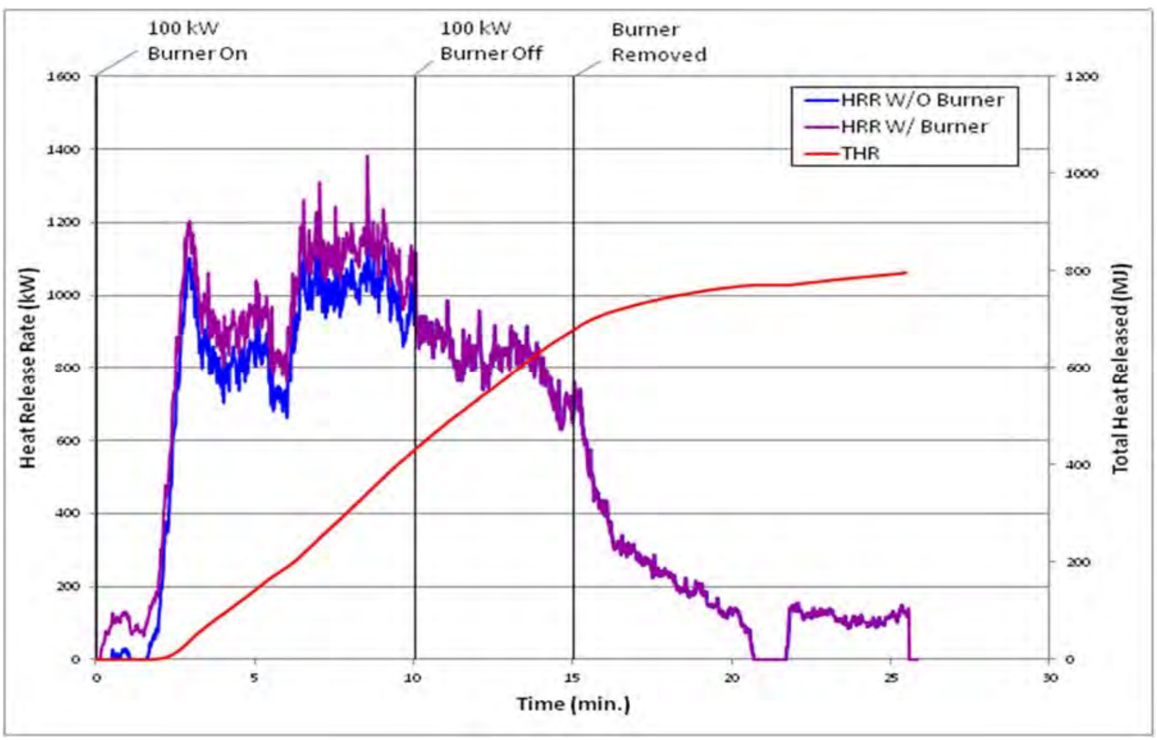


Figure G. 104: Wall Experiment 18 Heat Release Rate and Total Heat Released

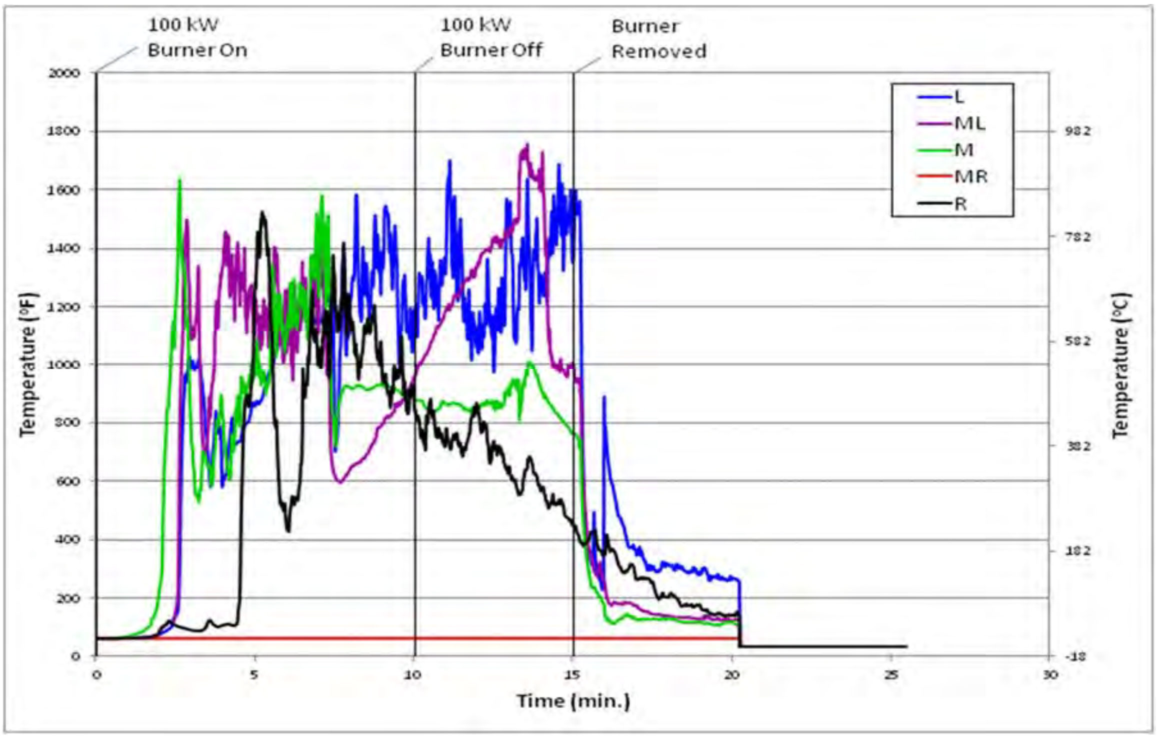


Figure G. 105: Wall Experiment 18 under Siding Horizontal Temperatures

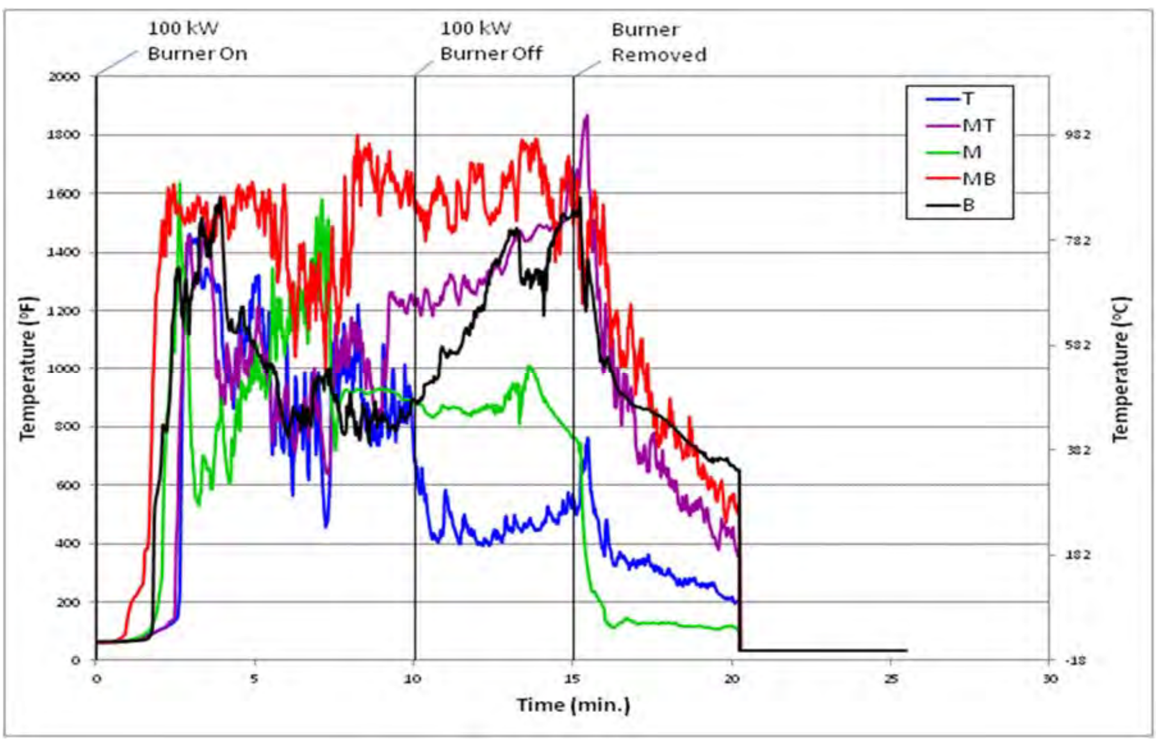


Figure G. 106: Wall Experiment 18 under Siding Vertical Temperatures

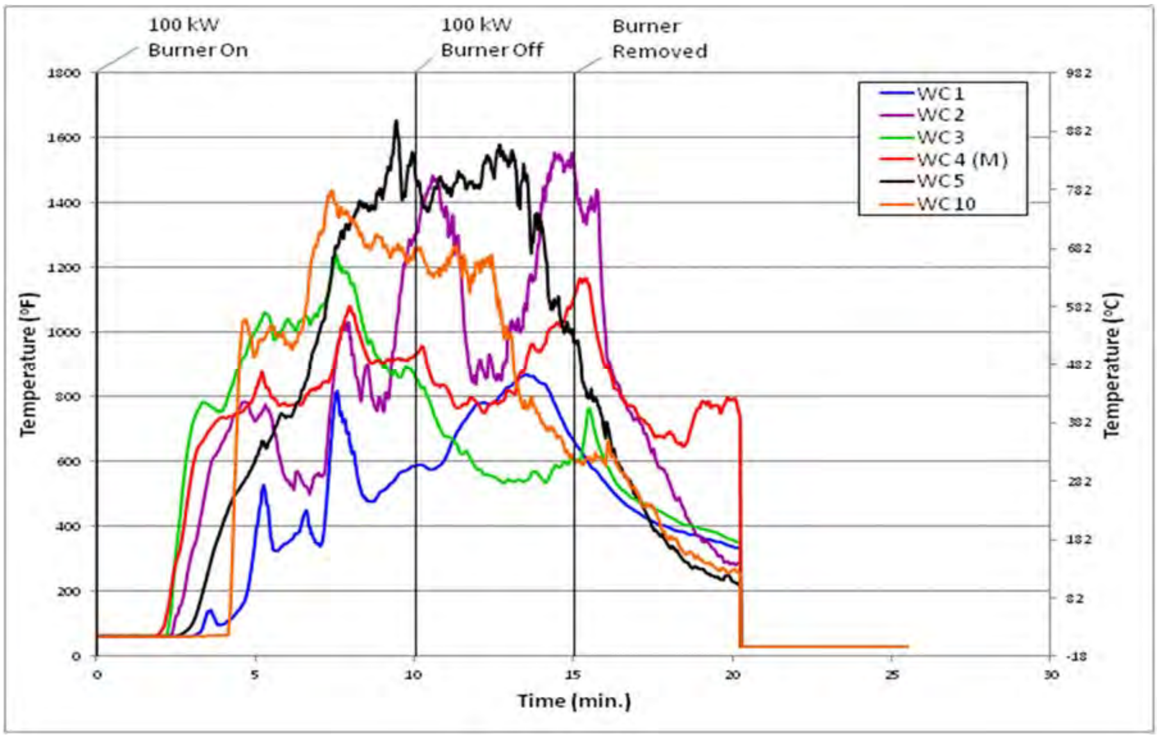


Figure G. 107: Wall Experiment 18 Wall Cavity Horizontal Temperatures

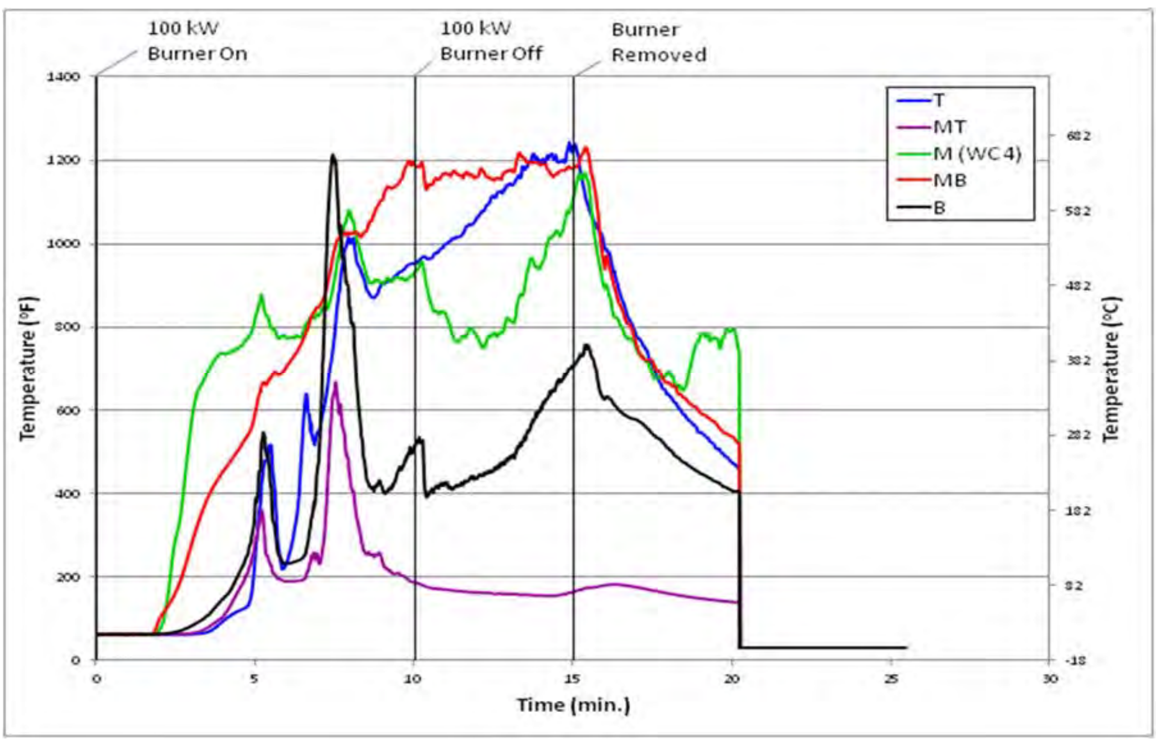


Figure G. 108: Wall Experiment 18 Wall Cavity Vertical Temperatures

Experiment 19

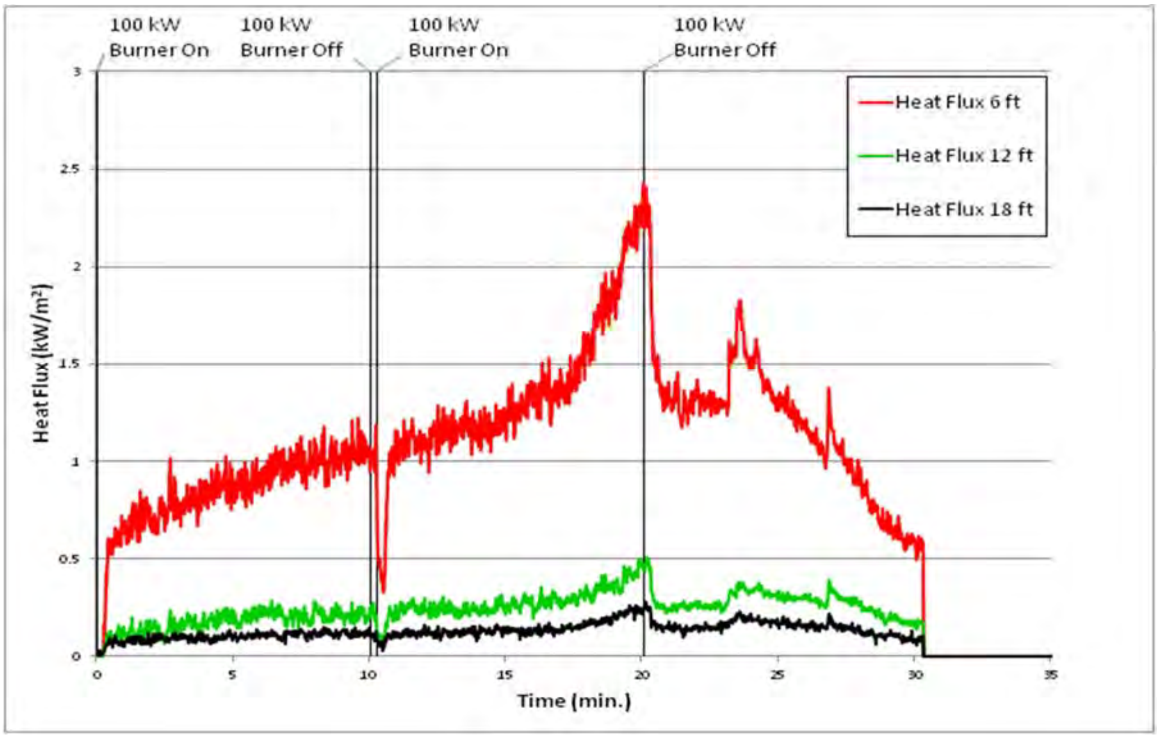


Figure G. 109: Wall Experiment 19 Heat Flux

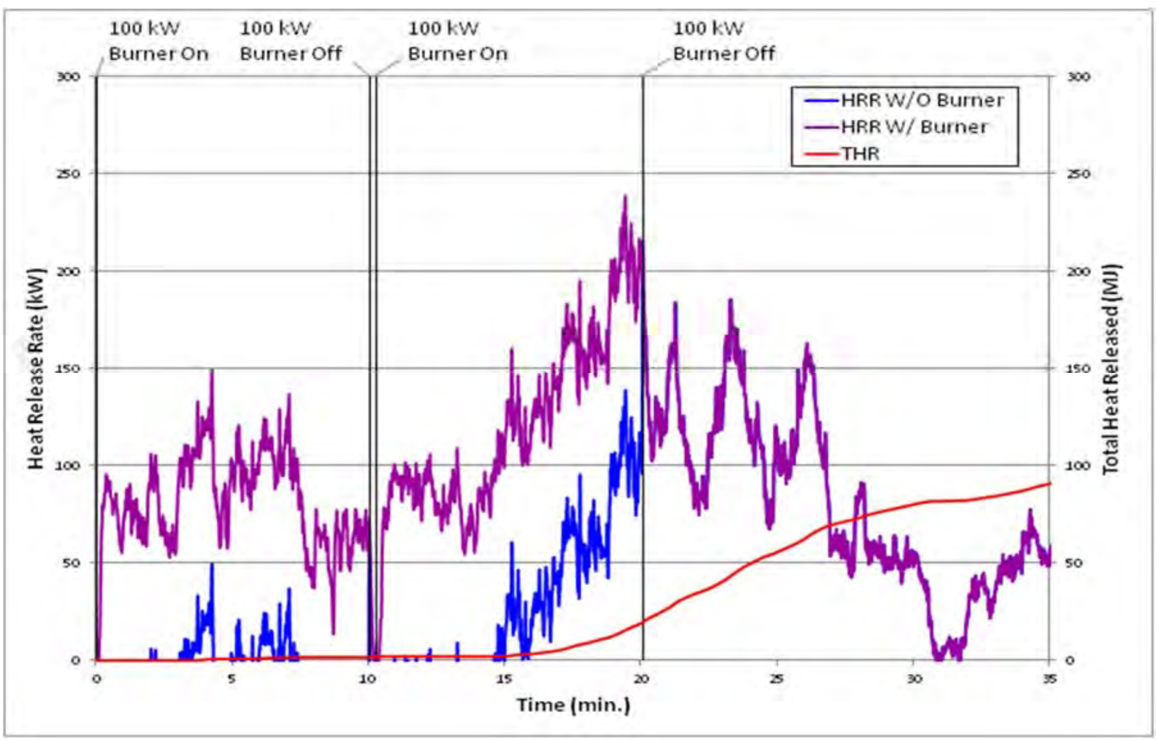


Figure G. 110: Wall Experiment 19 Heat Release Rate and Total Heat Released

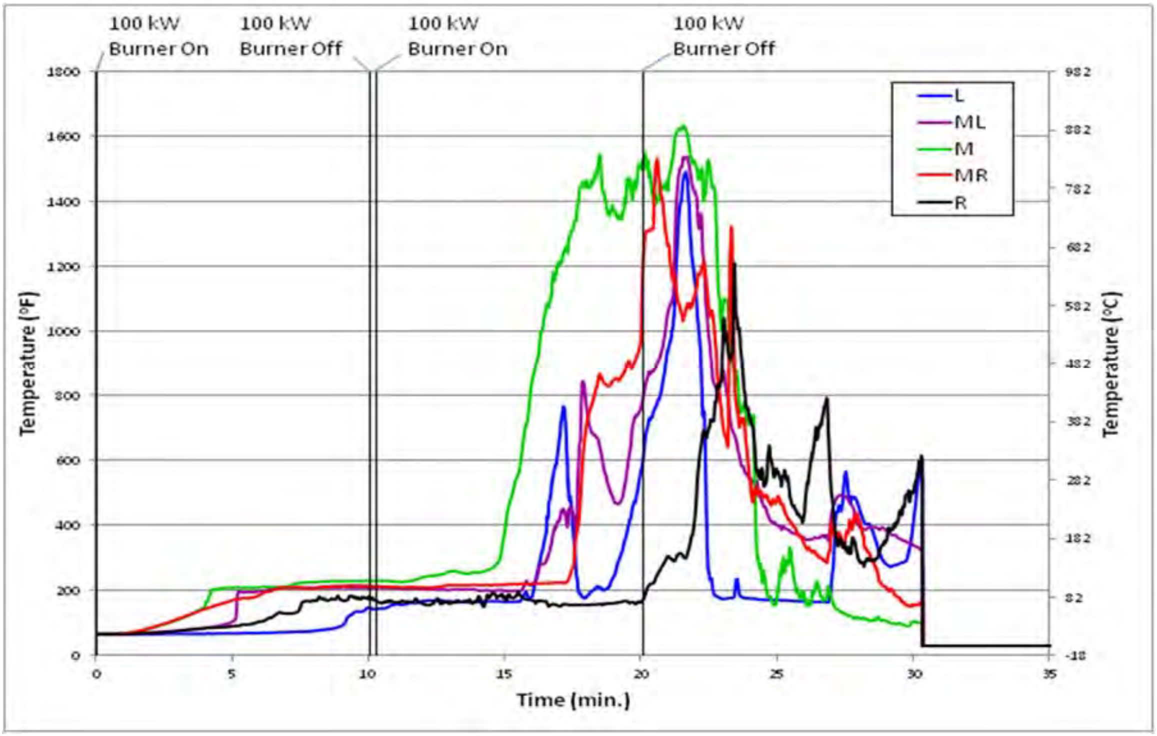


Figure G. 111: Wall Experiment 19 under Siding Horizontal Temperatures

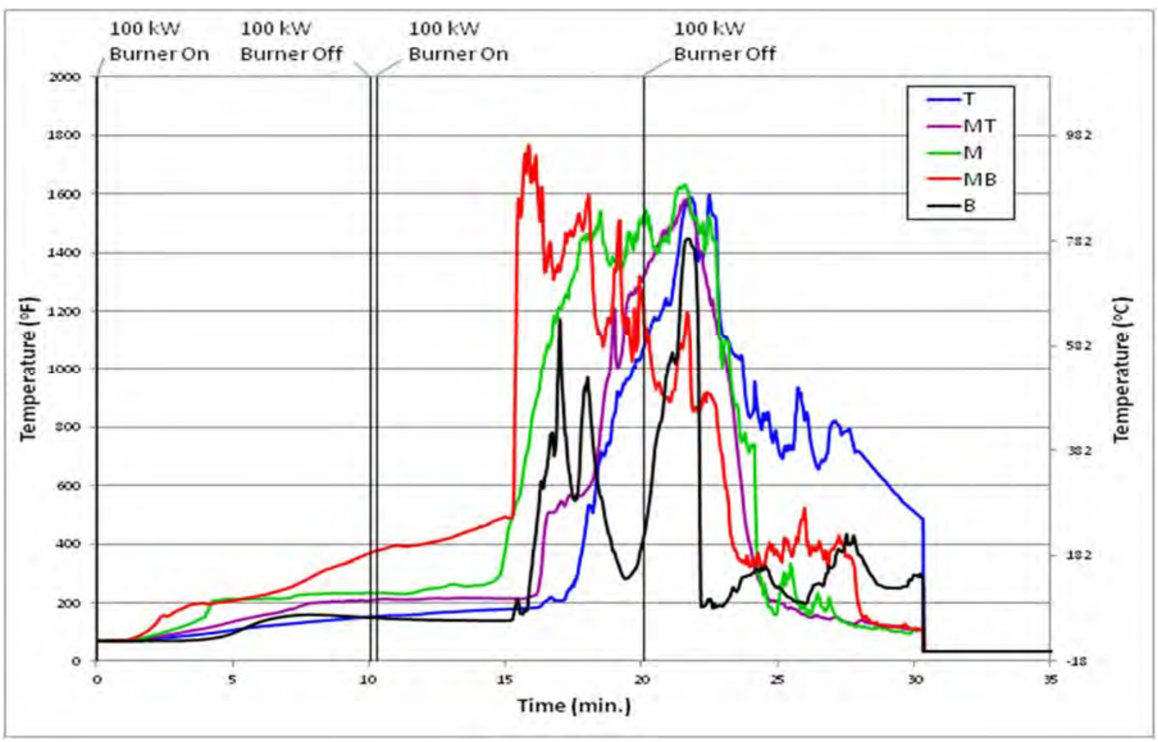


Figure G. 112: Wall Experiment 19 under Siding Vertical Temperatures

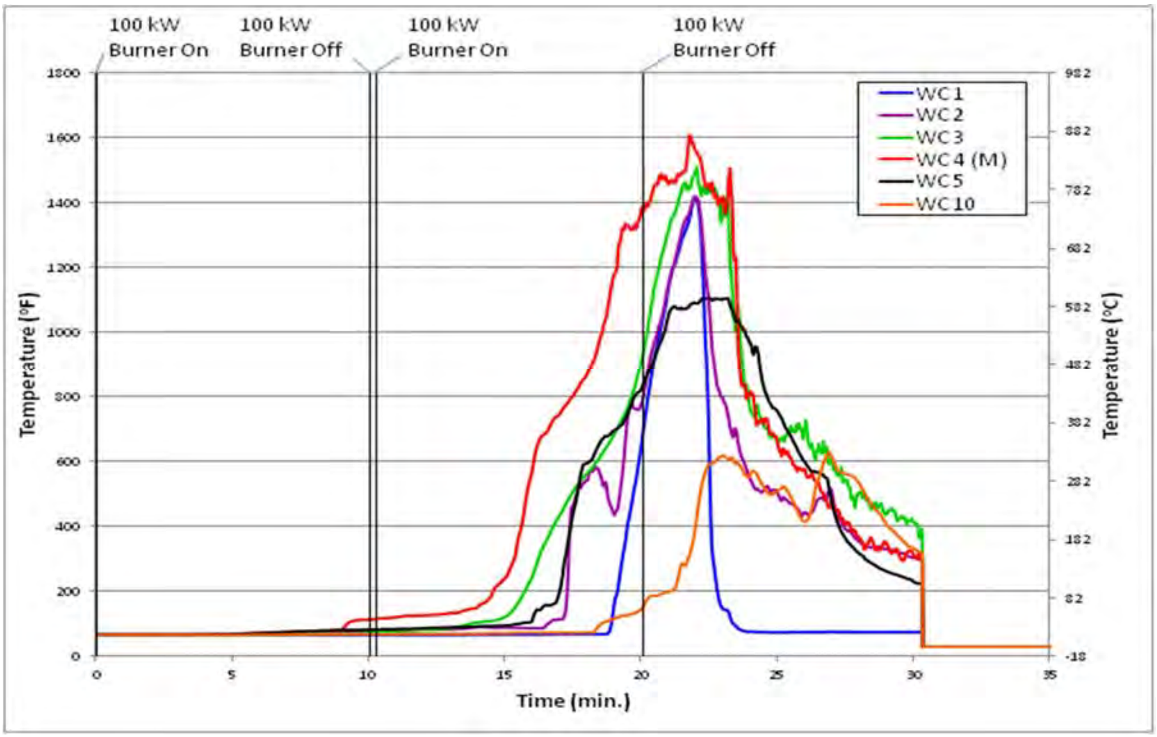


Figure G. 113: Wall Experiment 19 Wall Cavity Horizontal Temperatures

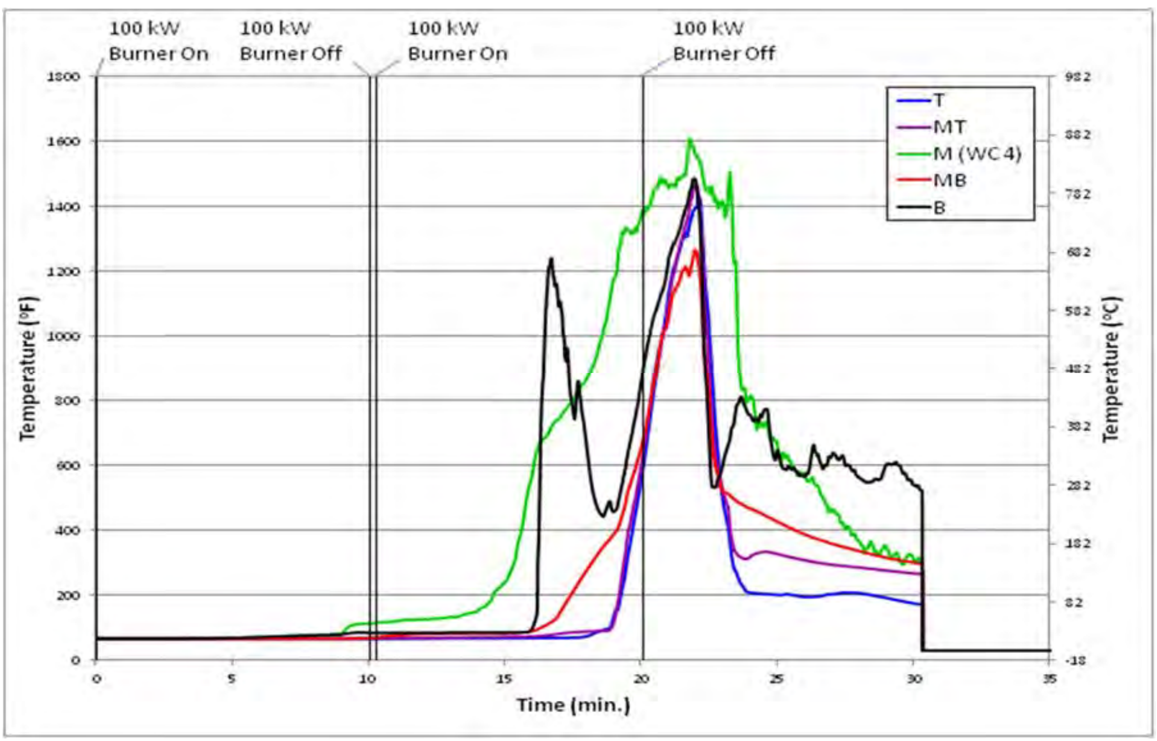


Figure G. 114: Wall Experiment 19 Wall Cavity Vertical Temperatures

Experiment 20

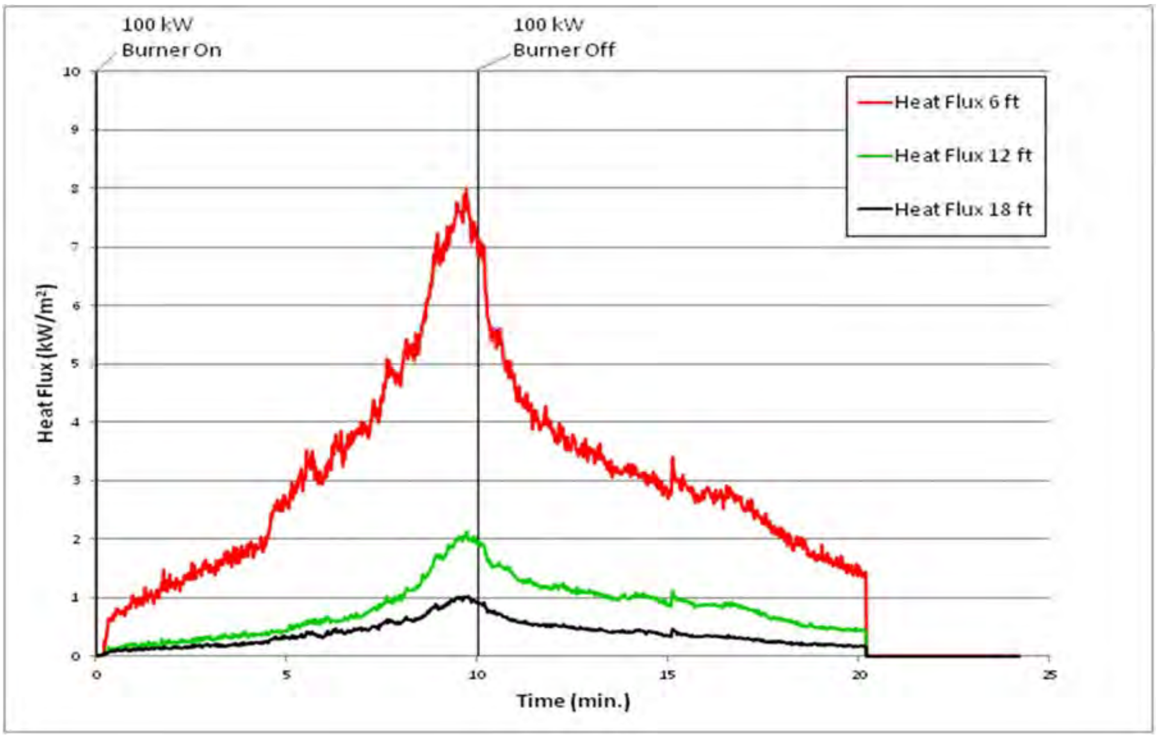


Figure G. 115: Wall Experiment 20 Heat Flux

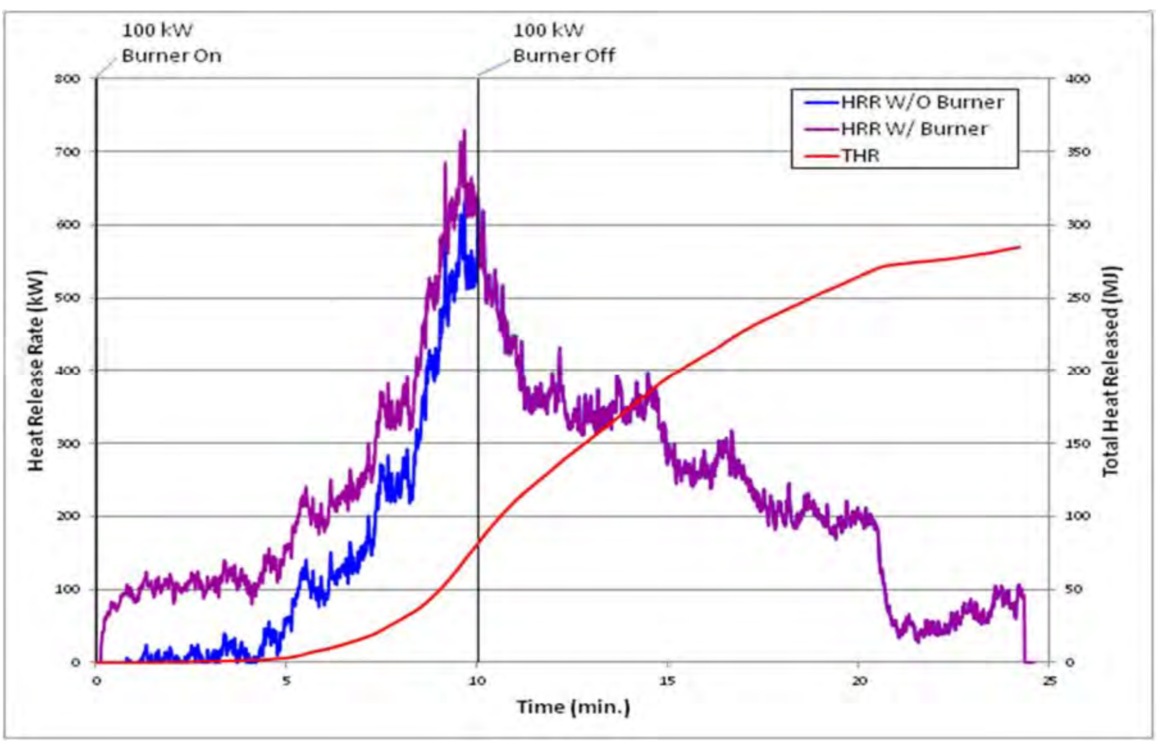


Figure G. 116: Wall Experiment 20 Heat Release Rate and Total Heat Released

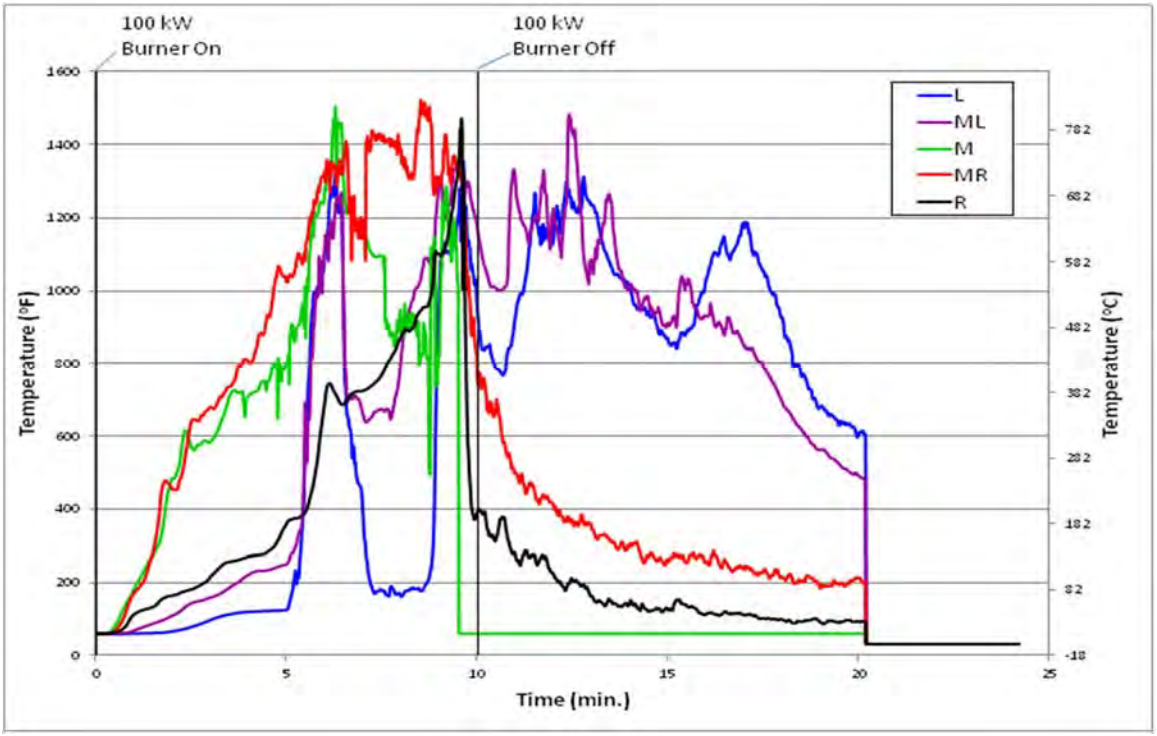


Figure G. 117: Wall Experiment 20 under Siding Horizontal Temperatures

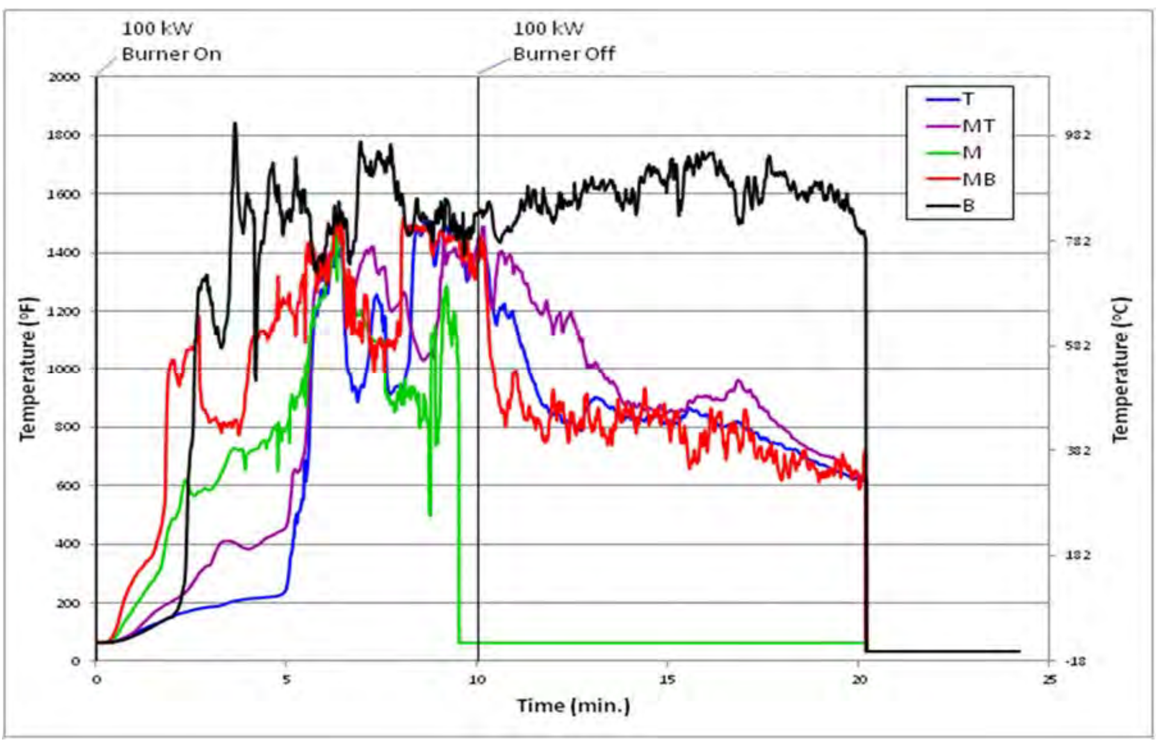


Figure G. 118: Wall Experiment 20 under Siding Vertical Temperatures

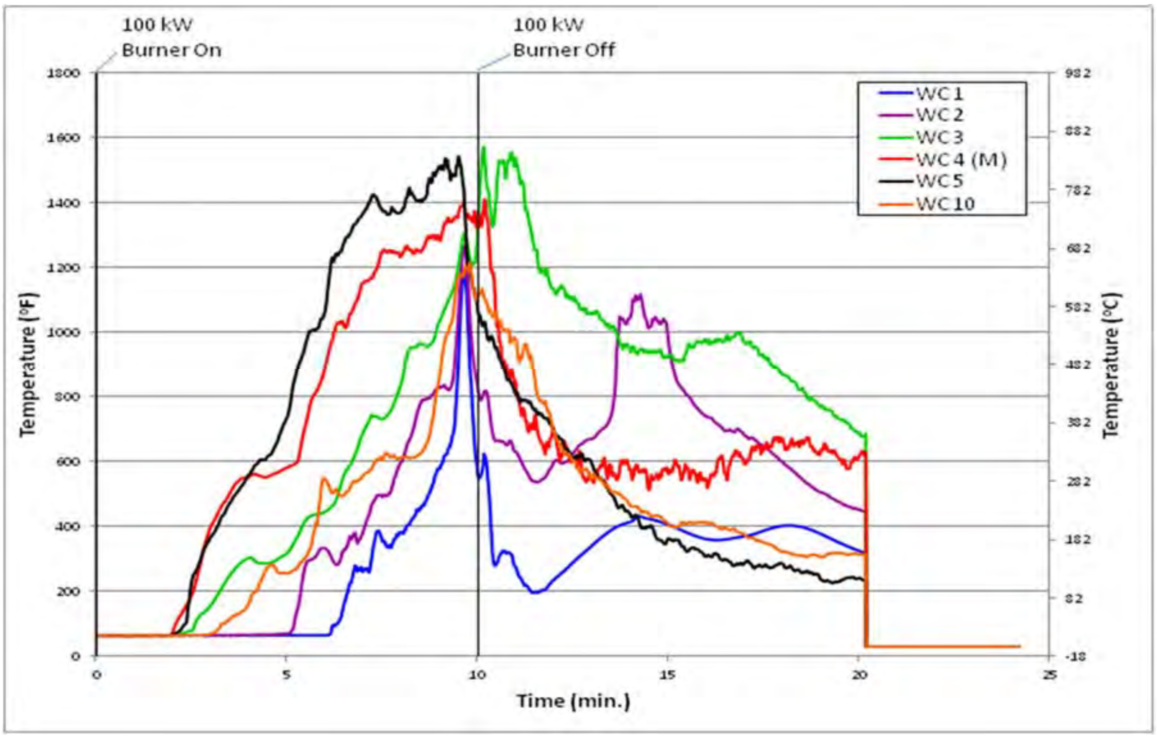


Figure G. 119: Wall Experiment 20 Wall Cavity Horizontal Temperatures

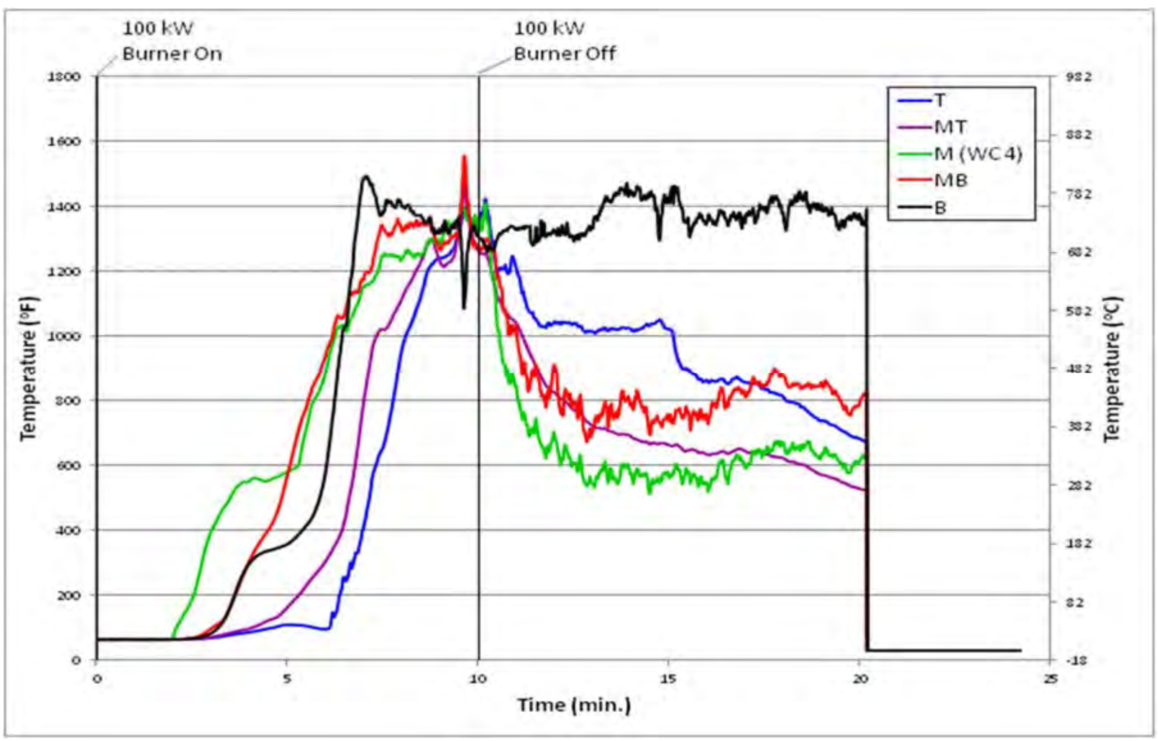


Figure G. 120: Wall Experiment 20 Wall Cavity Vertical Temperatures

Experiment 21

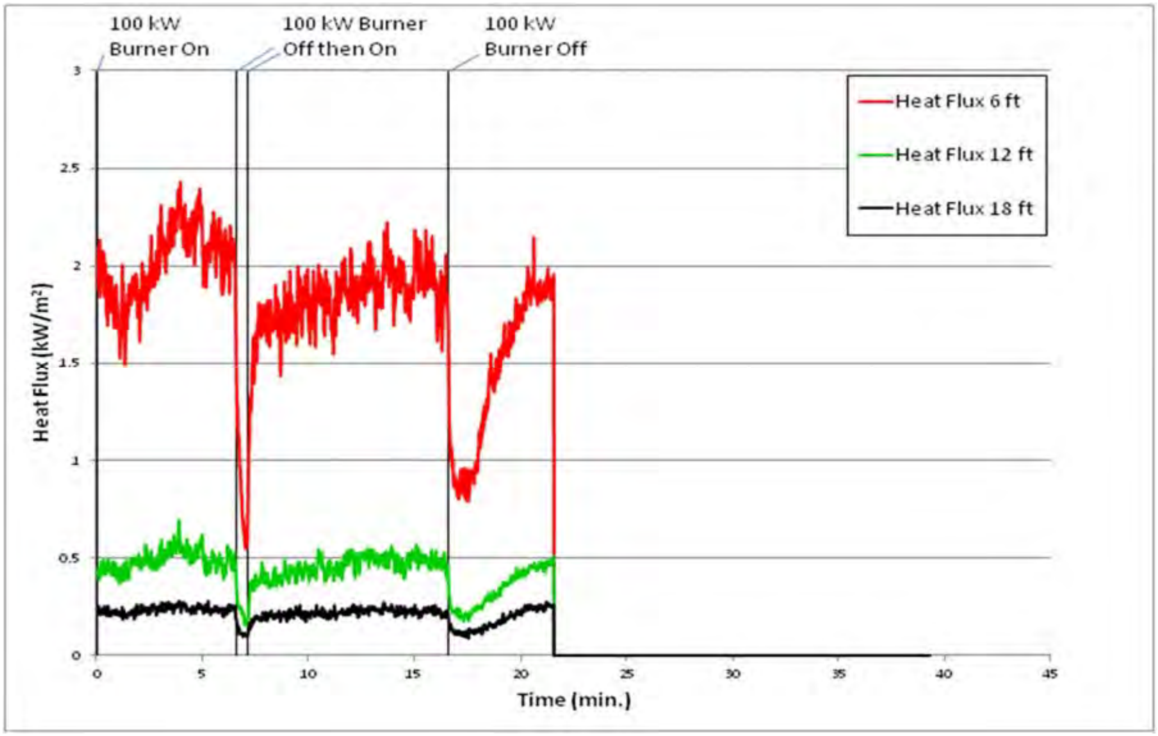


Figure G. 121: Wall Experiment 21 Heat Flux

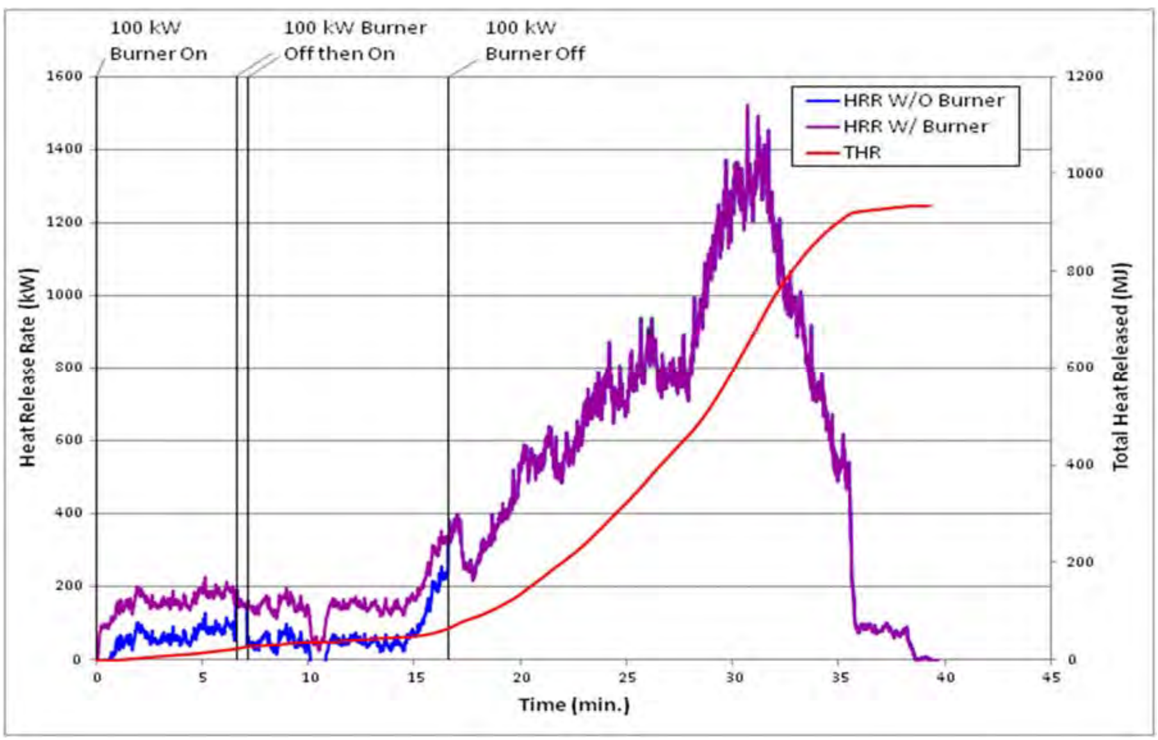


Figure G. 122: Wall Experiment 21 Heat Release Rate and Total Heat Released

Experiment 22

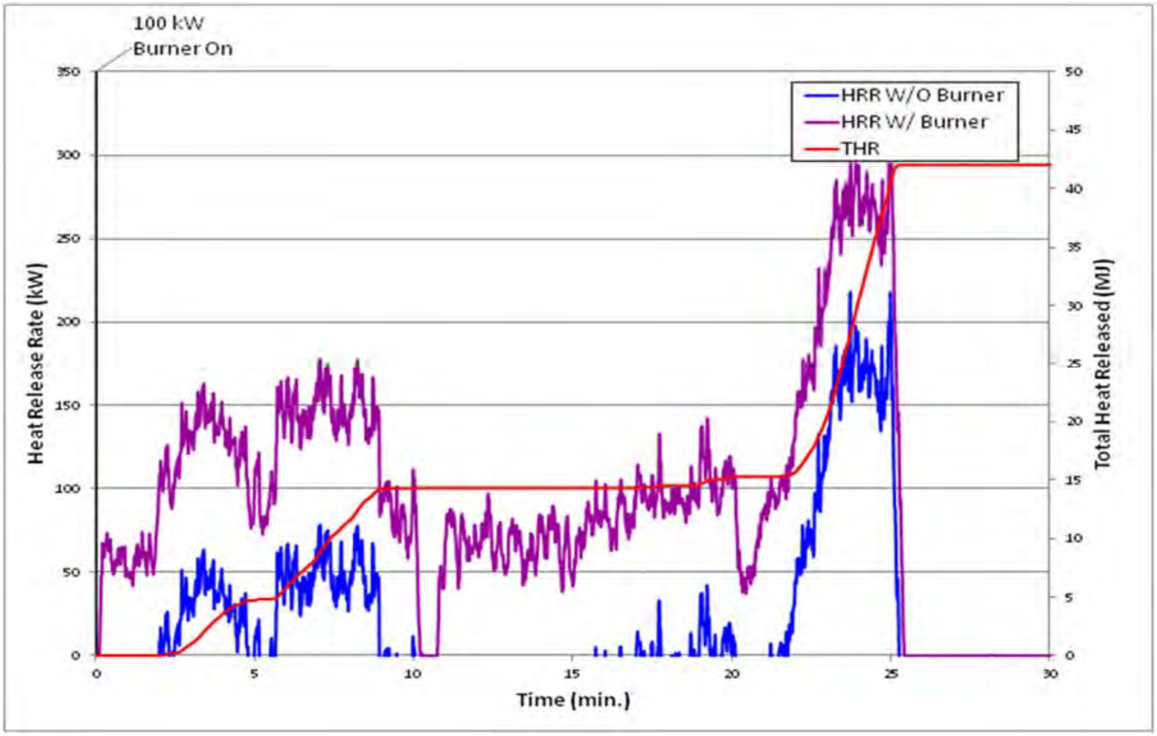


Figure G. 123: Wall Experiment 22 Heat Release Rate and Total Heat Released

Experiment 23

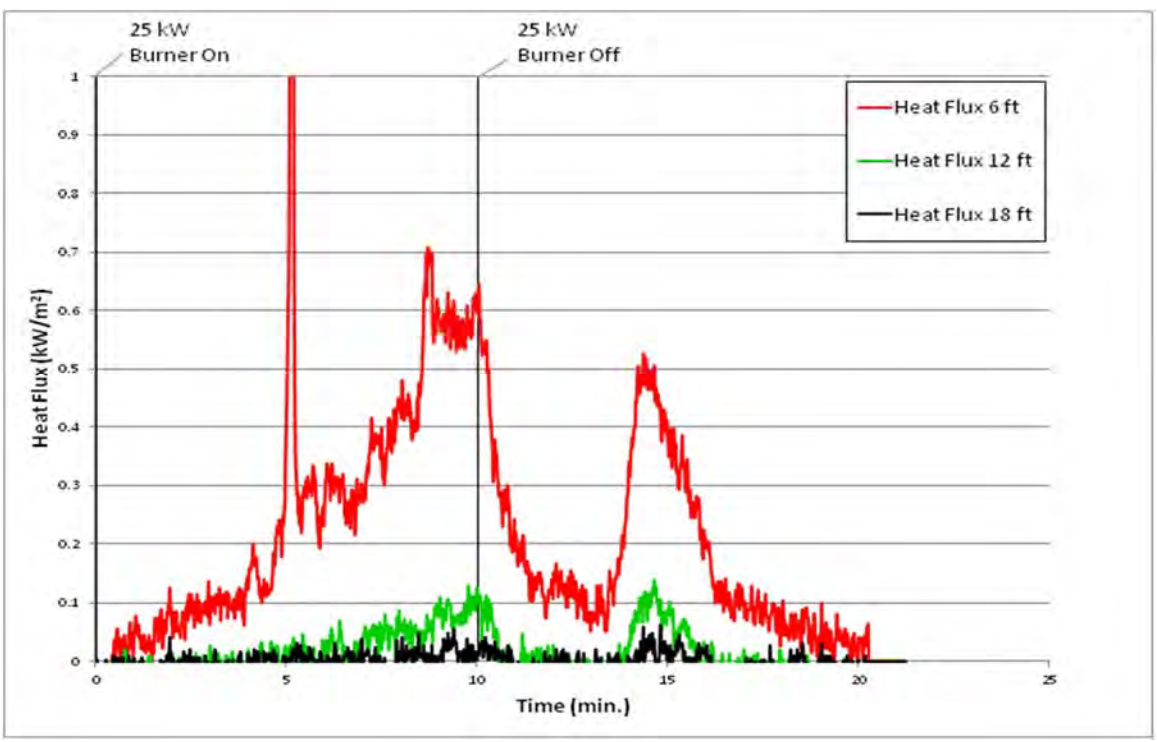


Figure G. 124: Wall Experiment 23 Heat Flux

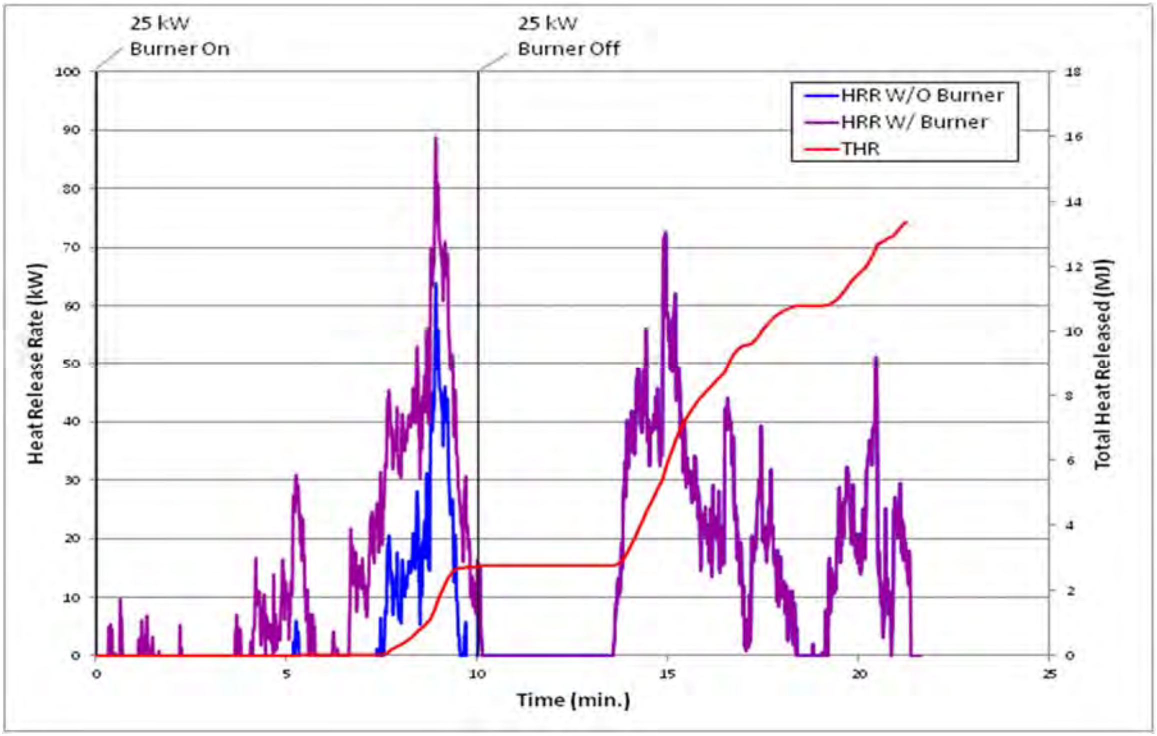


Figure G. 125: Wall Experiment 23 Heat Release Rate and Total Heat Released

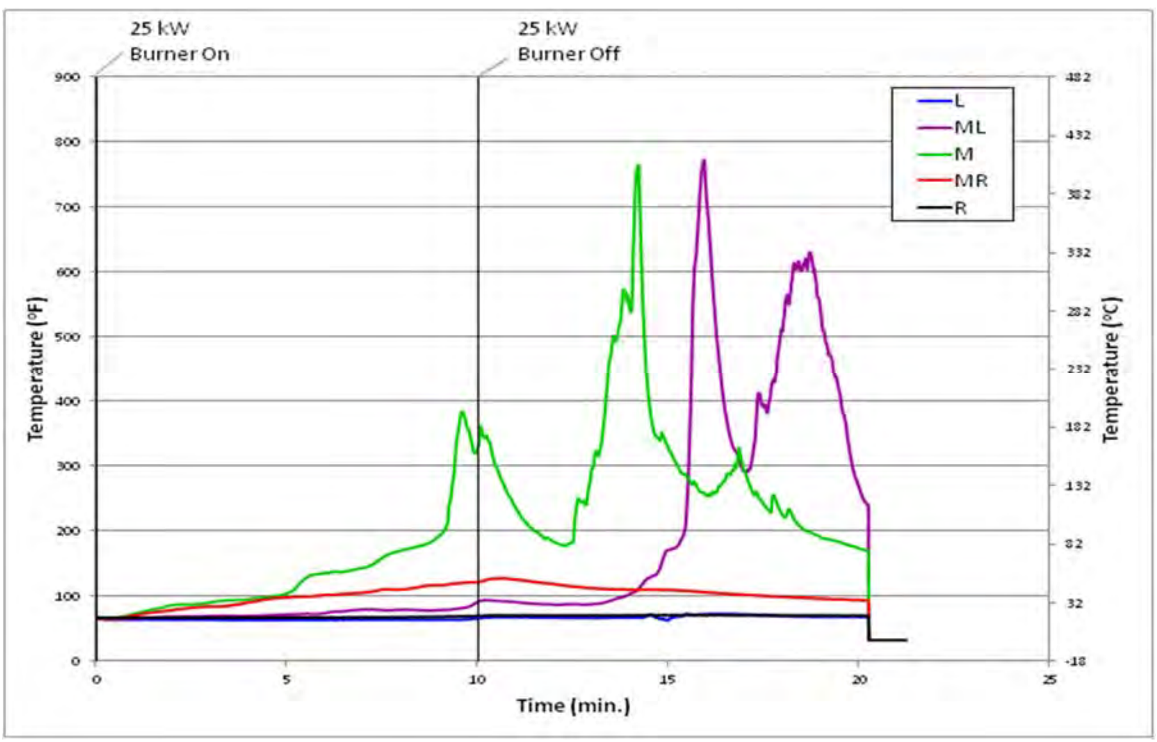


Figure G. 126: Wall Experiment 23 under Siding Horizontal Temperatures

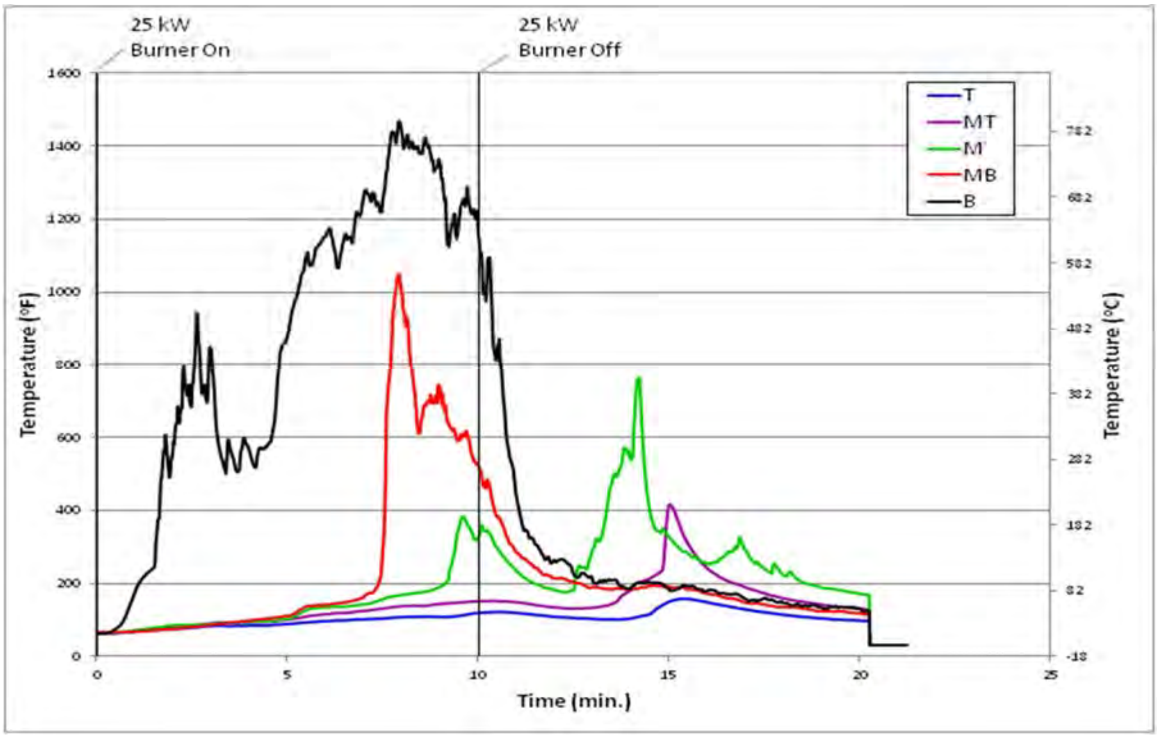


Figure G. 127: Wall Experiment 23 under Siding Vertical Temperatures

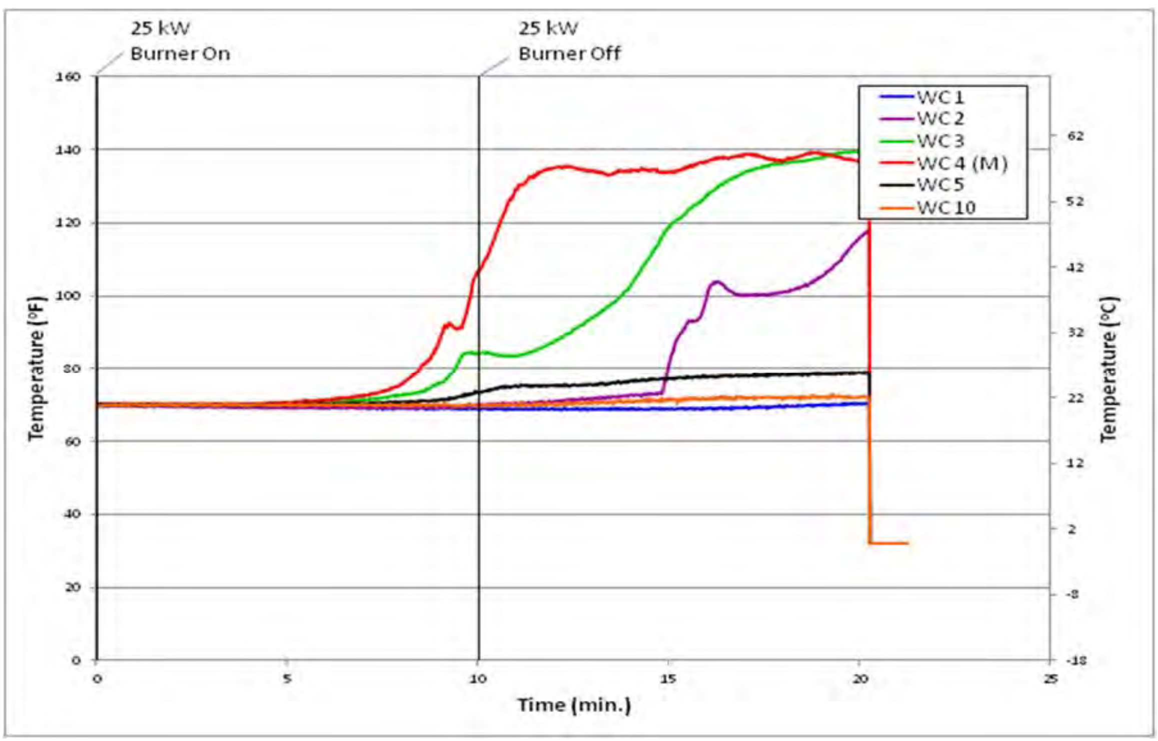


Figure G. 128: Wall Experiment 23 Wall Cavity Horizontal Temperatures

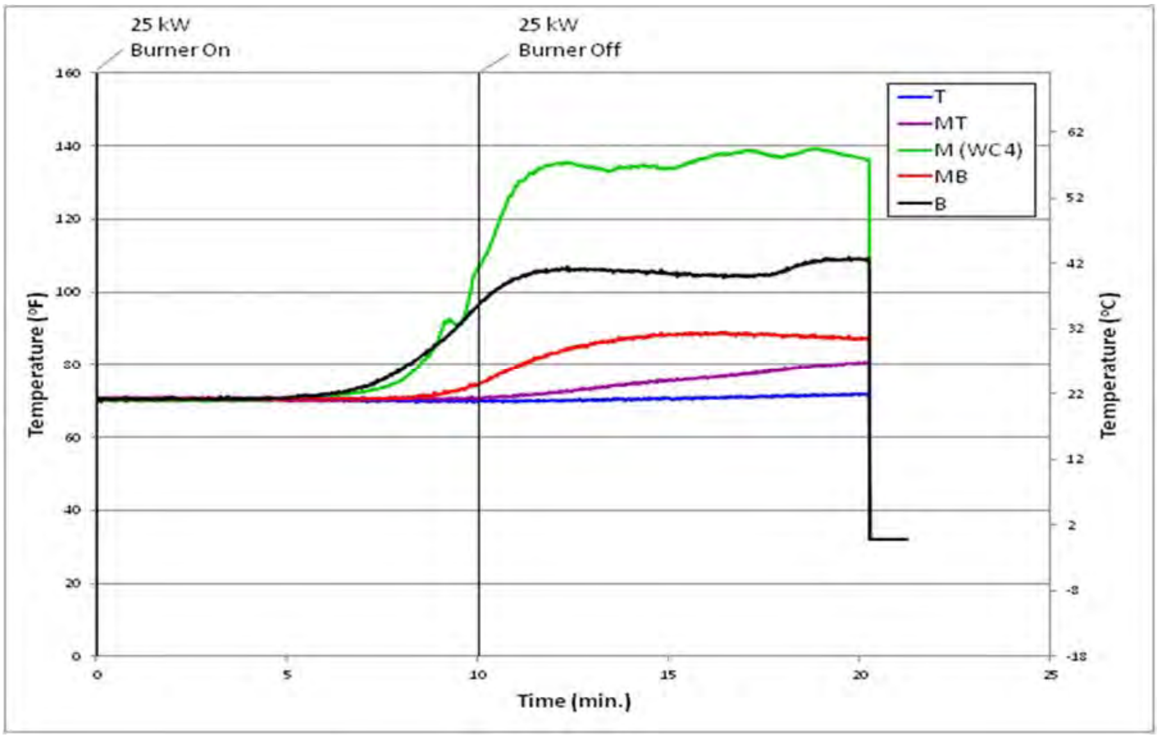


Figure G. 129: Wall Experiment 23 Wall Cavity Vertical Temperatures

Experiment 24

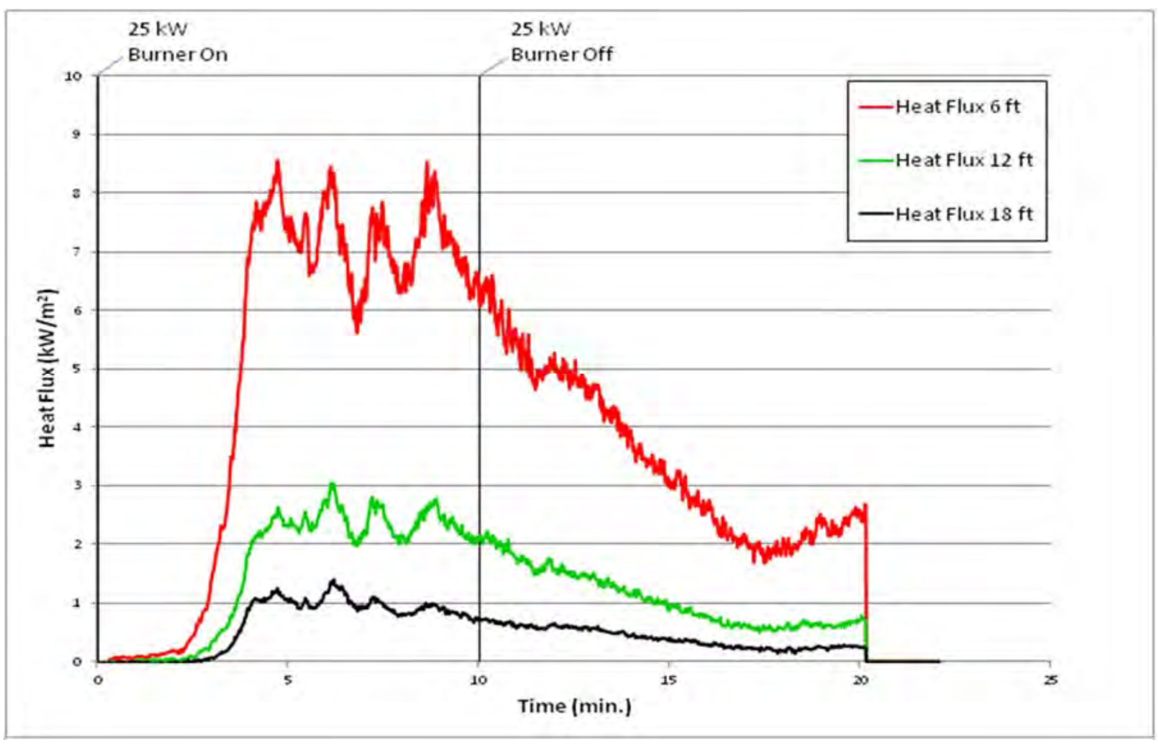


Figure G. 130: Wall Experiment 24 Heat Flux

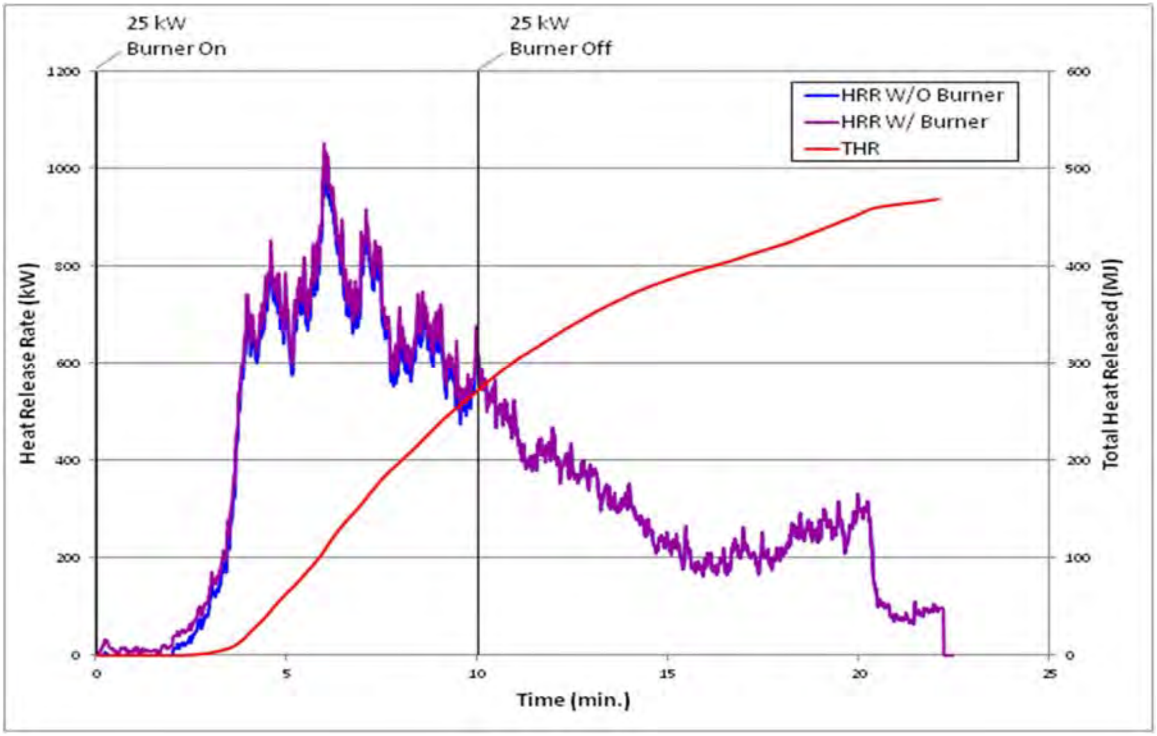


Figure G. 131: Wall Experiment 24 Heat Release Rate and Total Heat Released

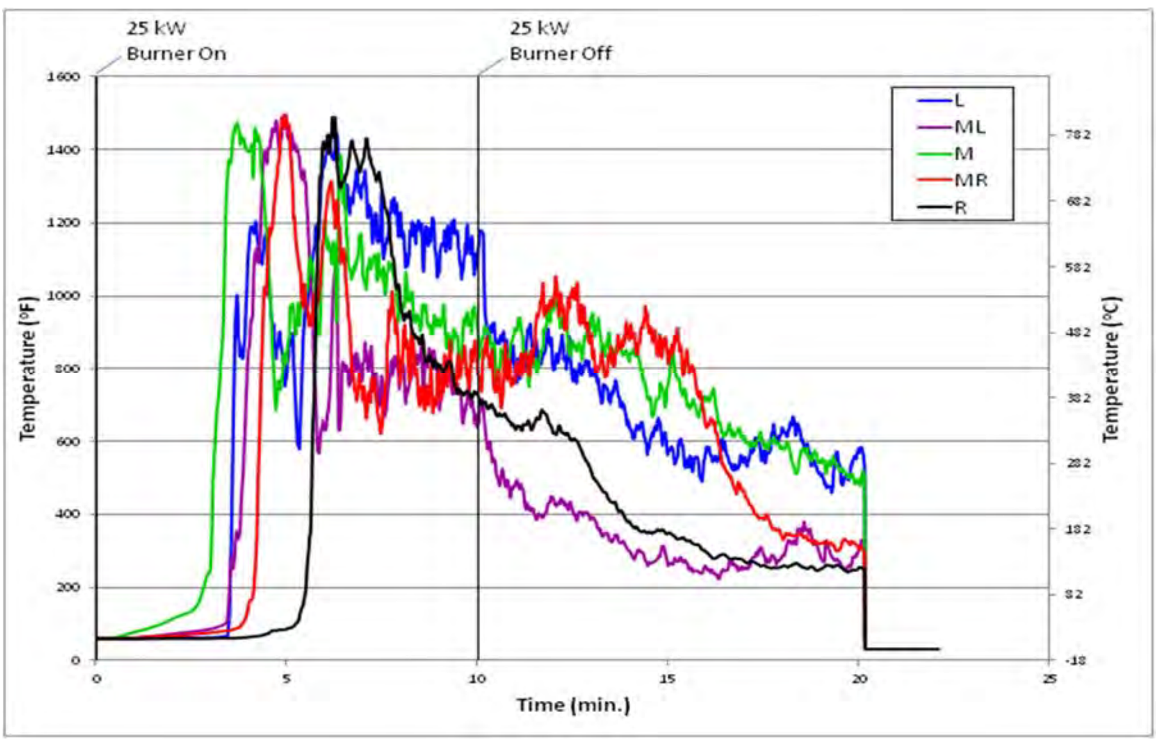


Figure G. 132: Wall Experiment 24 under Siding Horizontal Temperatures

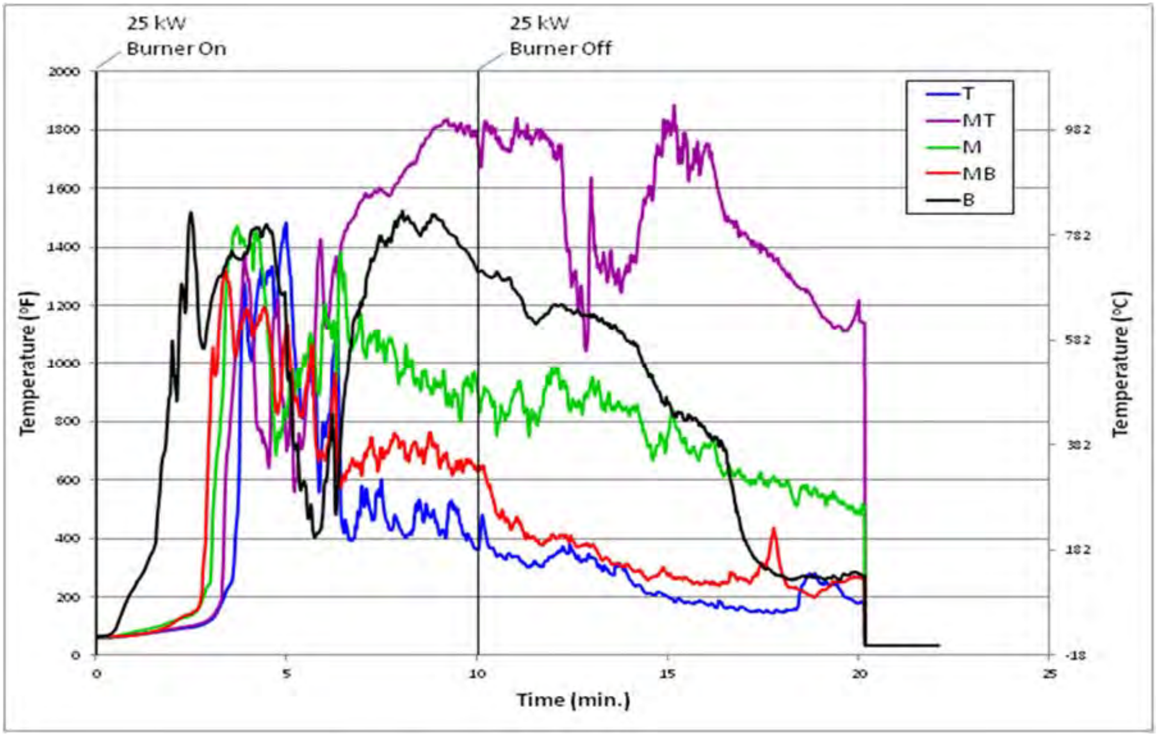


Figure G. 133: Wall Experiment 24 under Siding Vertical Temperatures

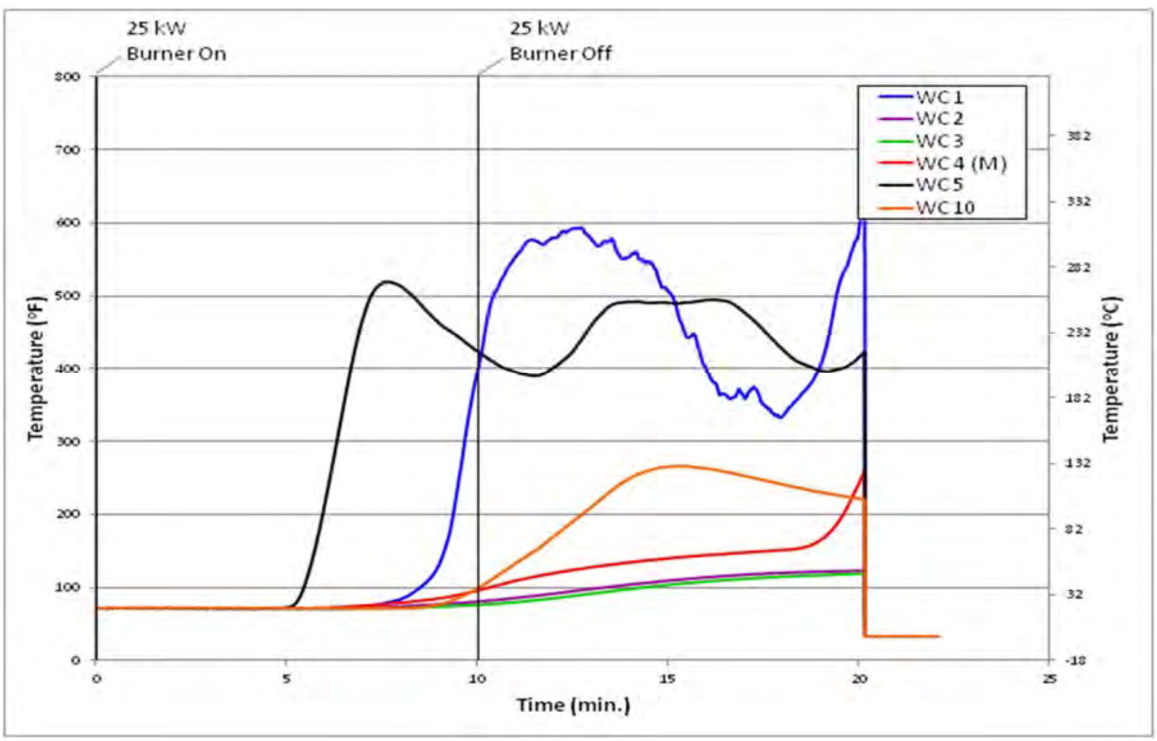


Figure G. 134: Wall Experiment 24 Wall Cavity Horizontal Temperatures

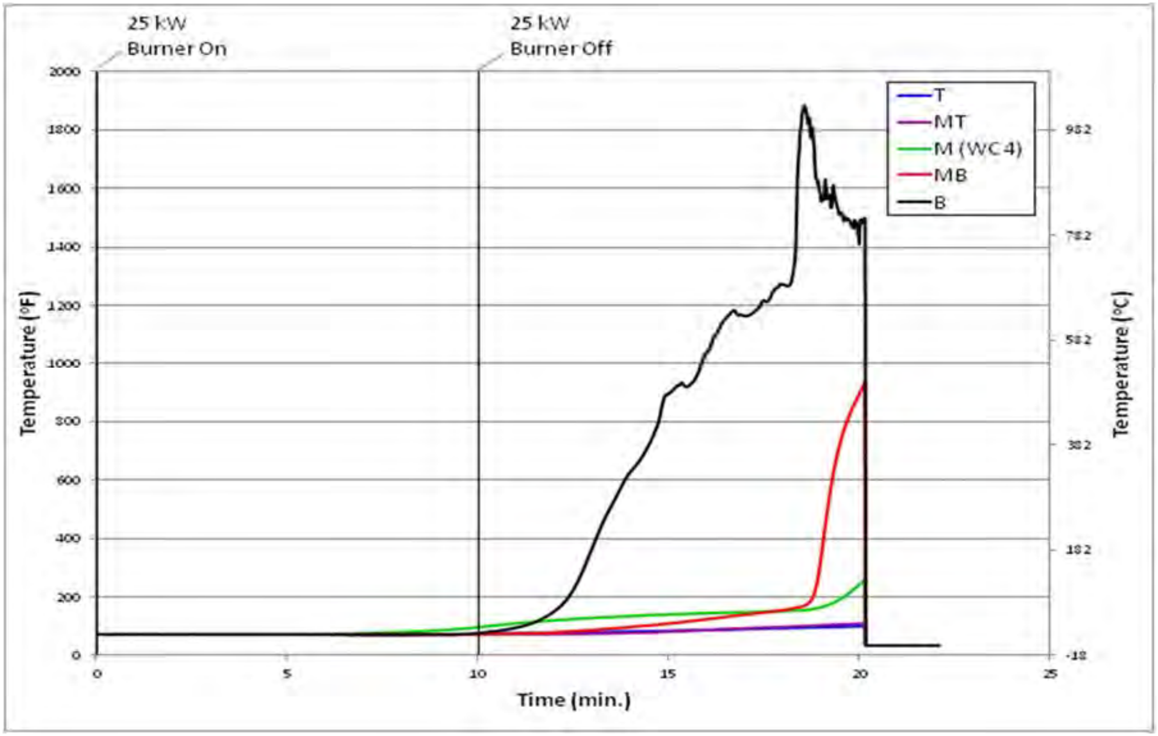


Figure G. 135: Wall Experiment 24 Wall Cavity Vertical Temperatures

Experiment 25

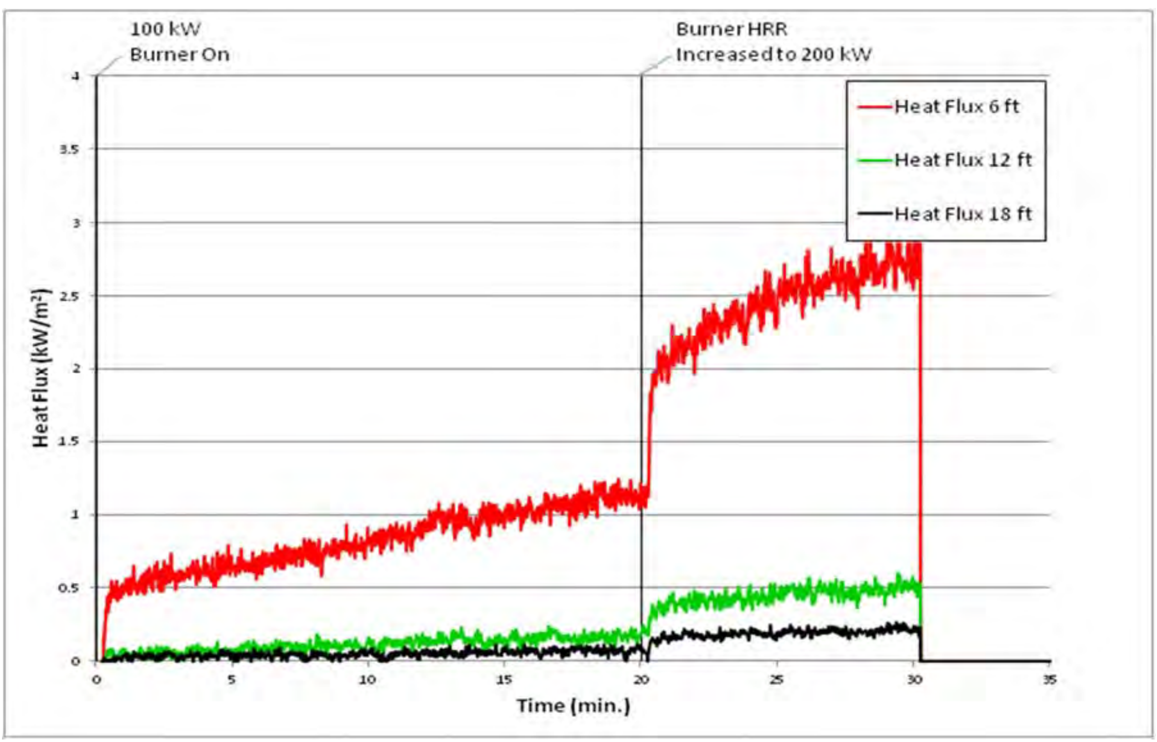


Figure G. 136: Wall Experiment 25 Heat Flux

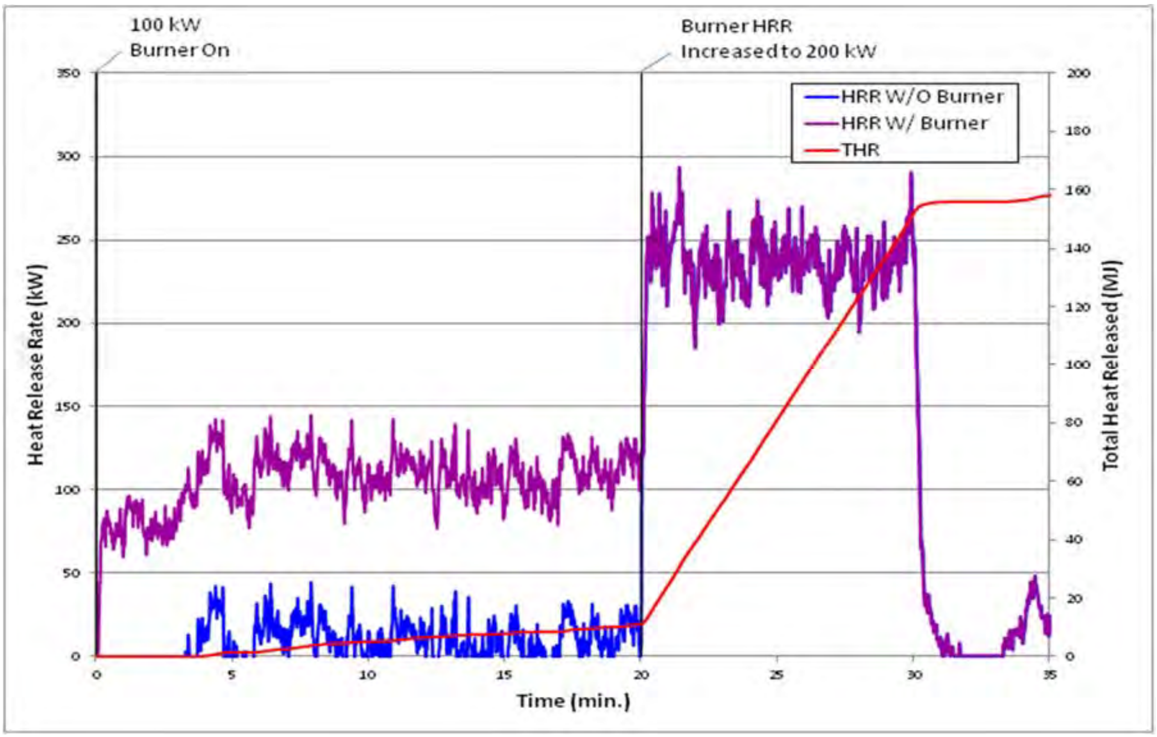


Figure G. 137: Wall Experiment 25 Heat Release Rate and Total Heat Released

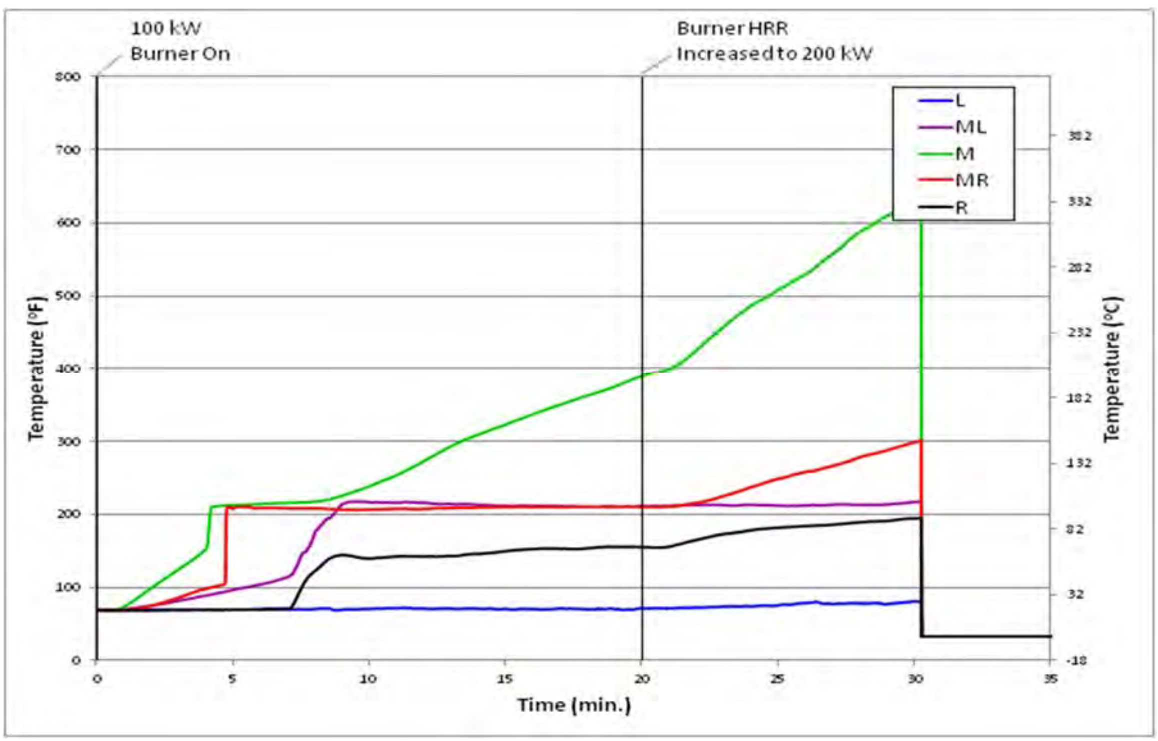


Figure G. 138: Wall Experiment 25 under Siding Horizontal Temperatures

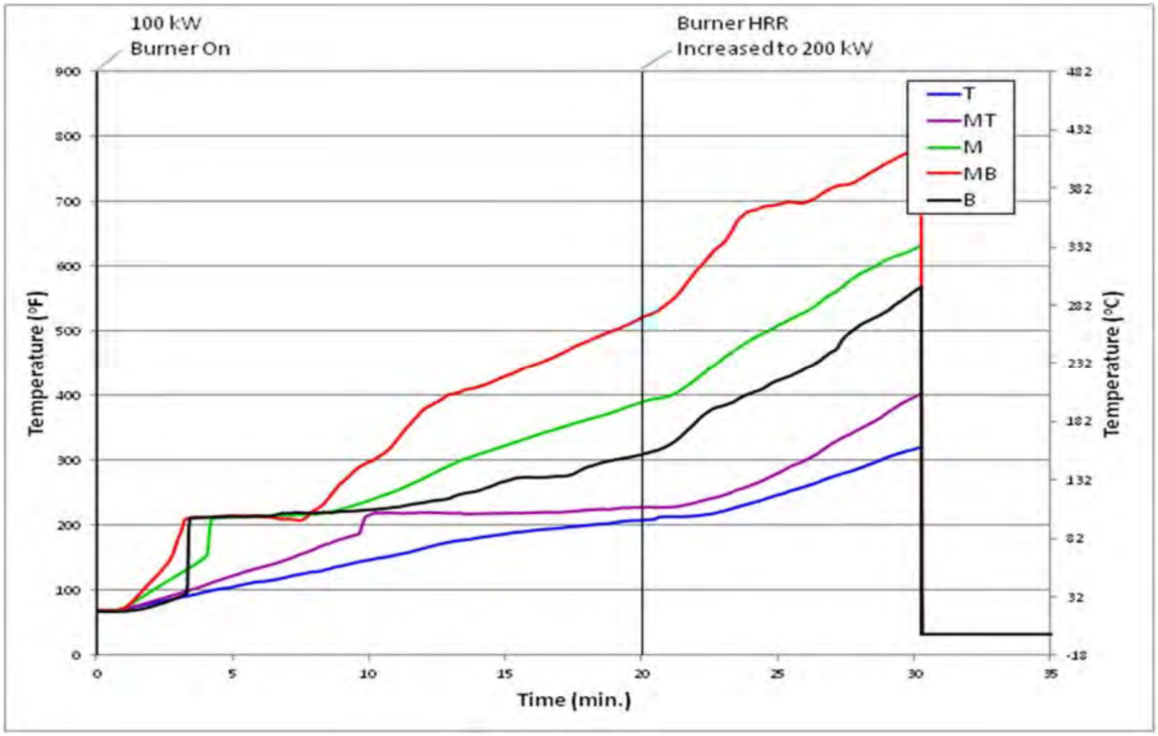


Figure G. 139: Wall Experiment 25 under Siding Vertical Temperatures

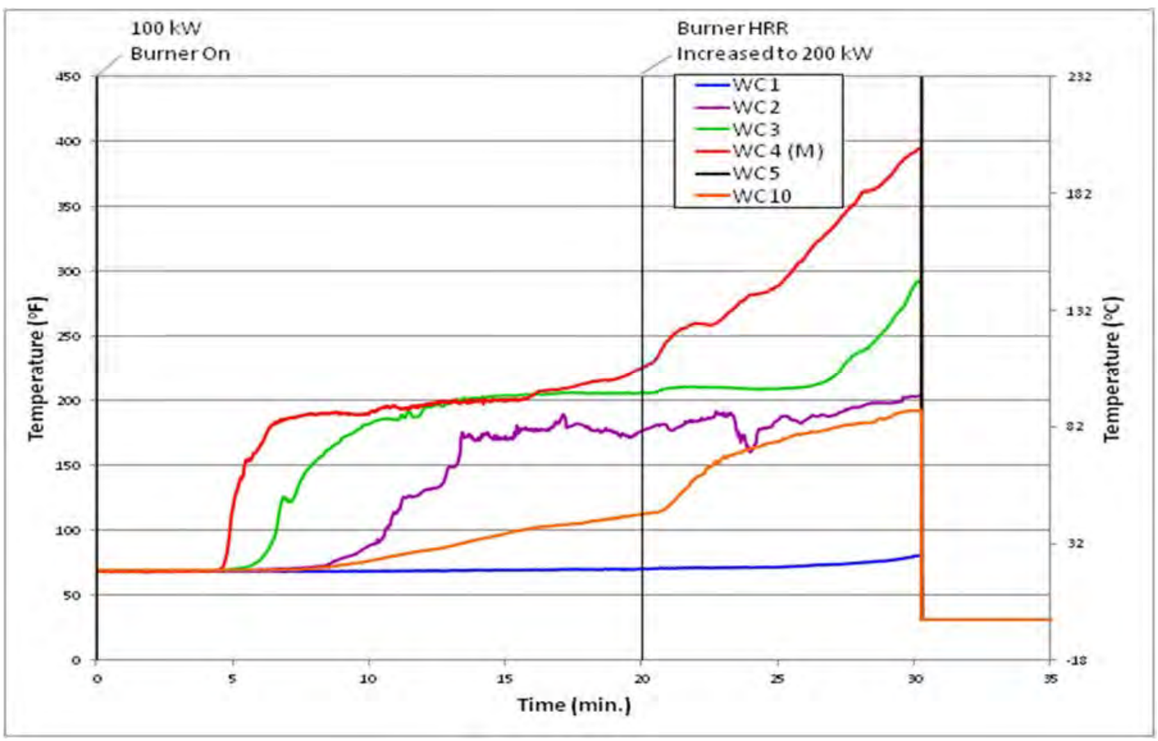


Figure G. 140: Wall Experiment 25 Wall Cavity Horizontal Temperatures

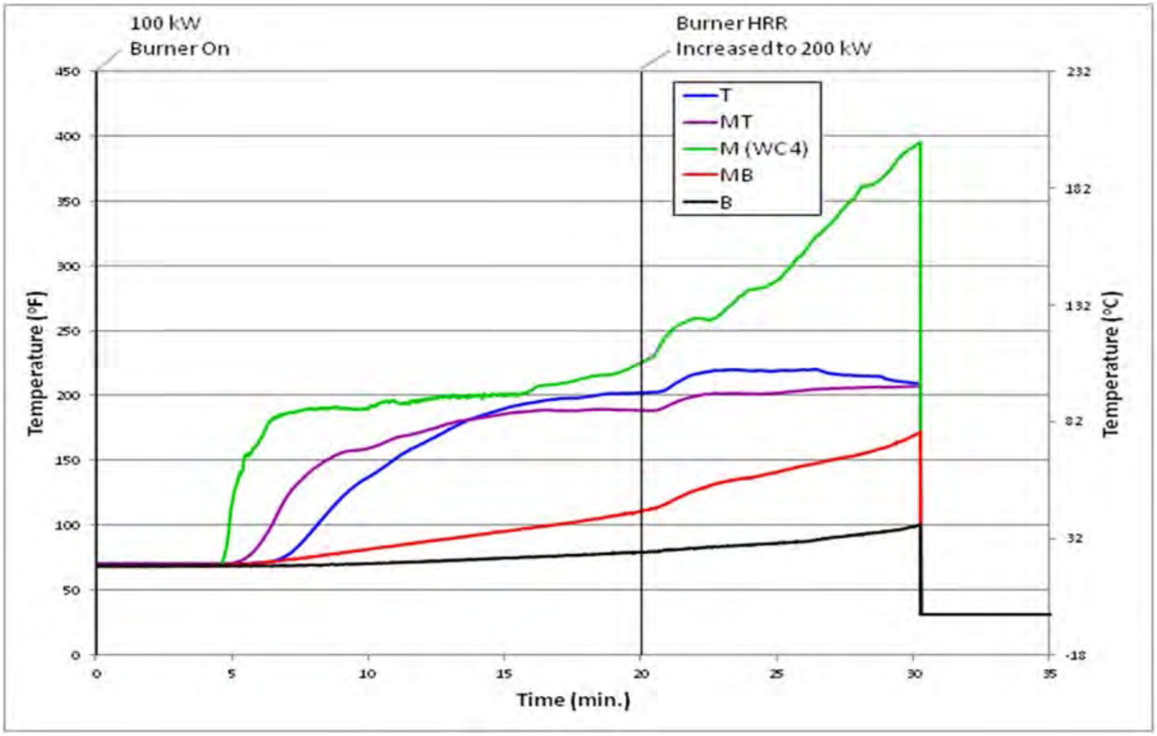


Figure G. 141: Wall Experiment 25 Wall Cavity Vertical Temperatures

Experiment 26

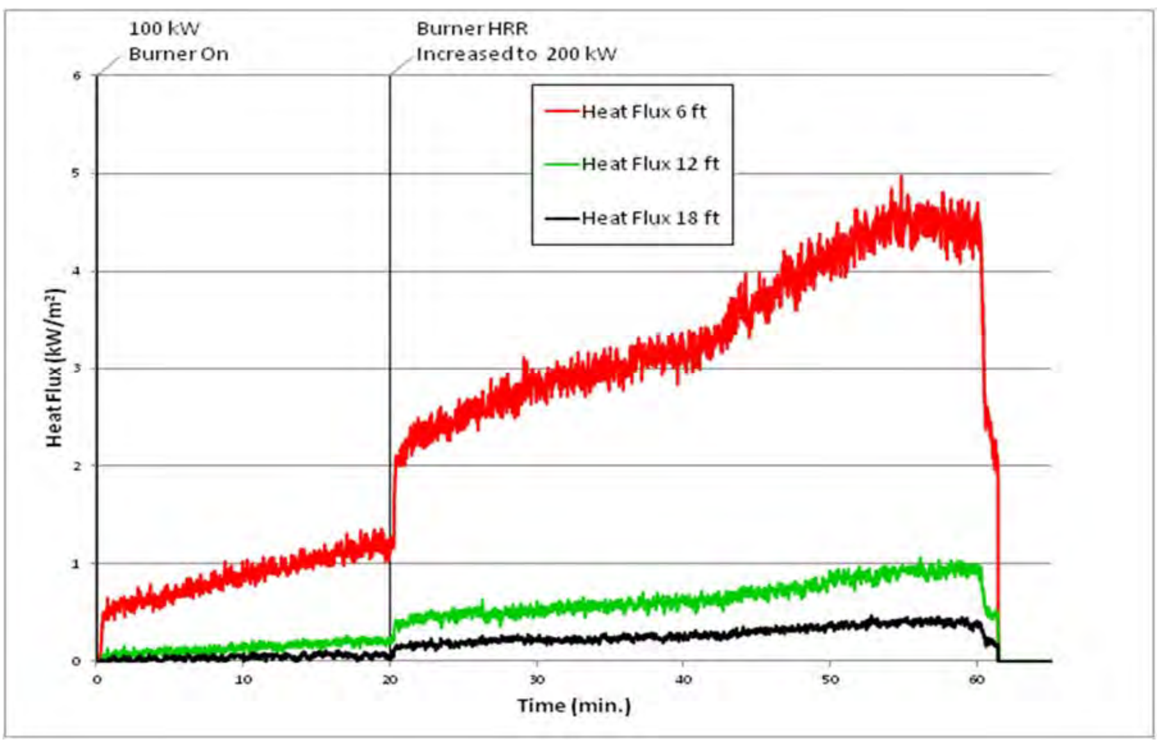


Figure G. 142: Wall Experiment 26 Heat Flux

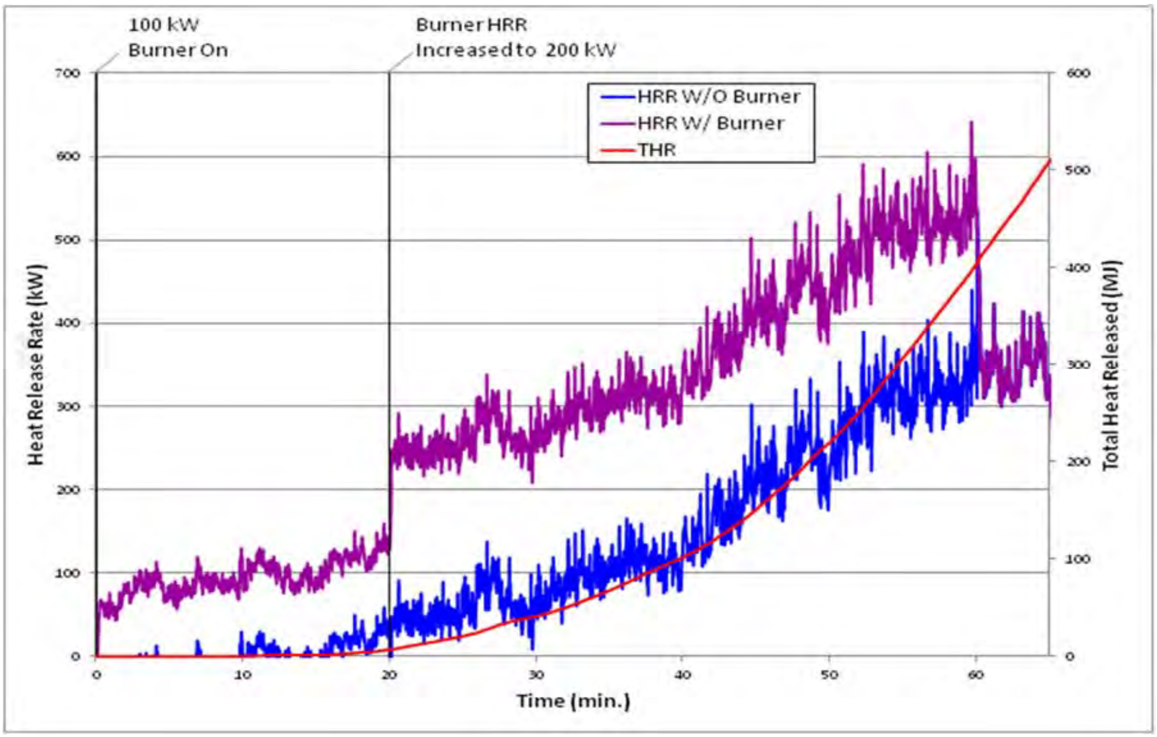


Figure G. 143: Wall Experiment 26 Heat Release Rate and Total Heat Released

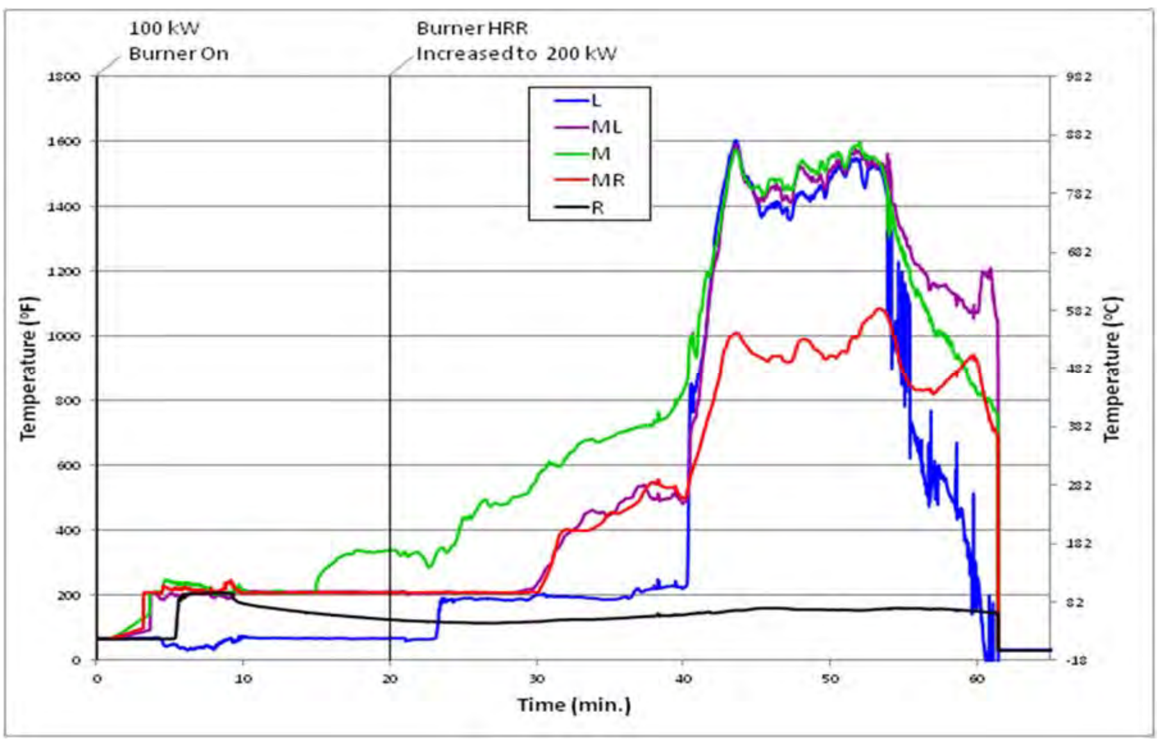


Figure G. 144: Wall Experiment 26 under Siding Horizontal Temperatures

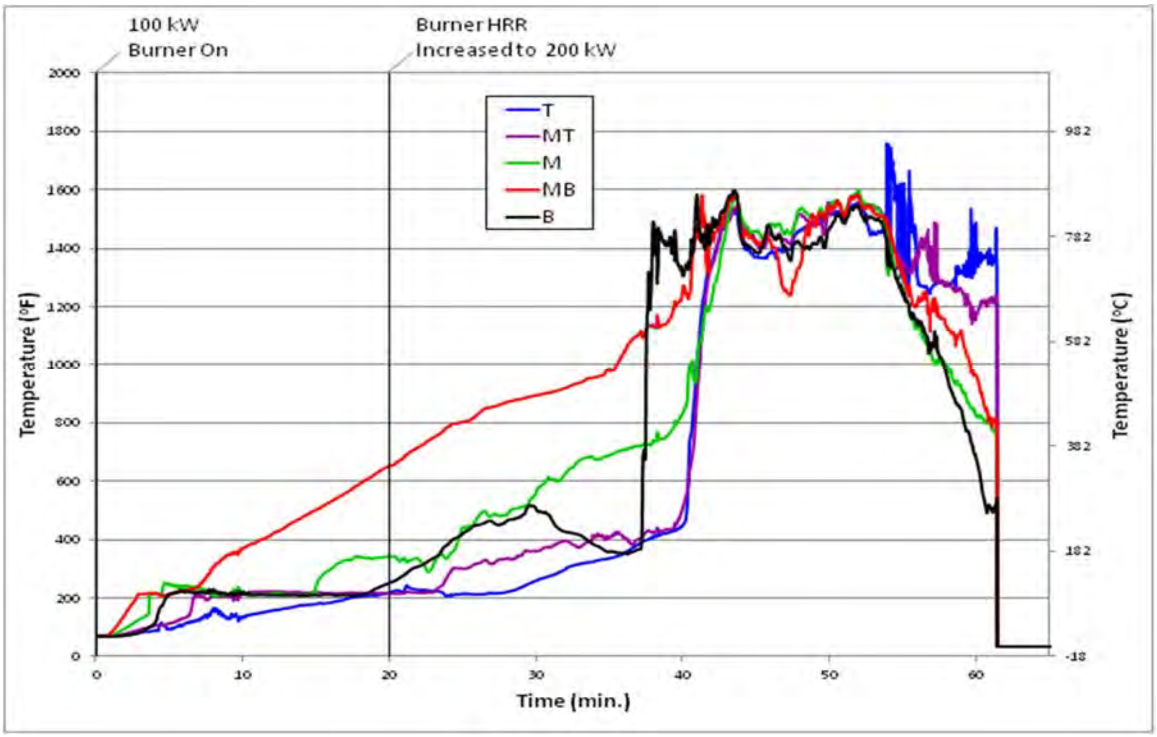


Figure G. 145: Wall Experiment 26 under Siding Vertical Temperatures

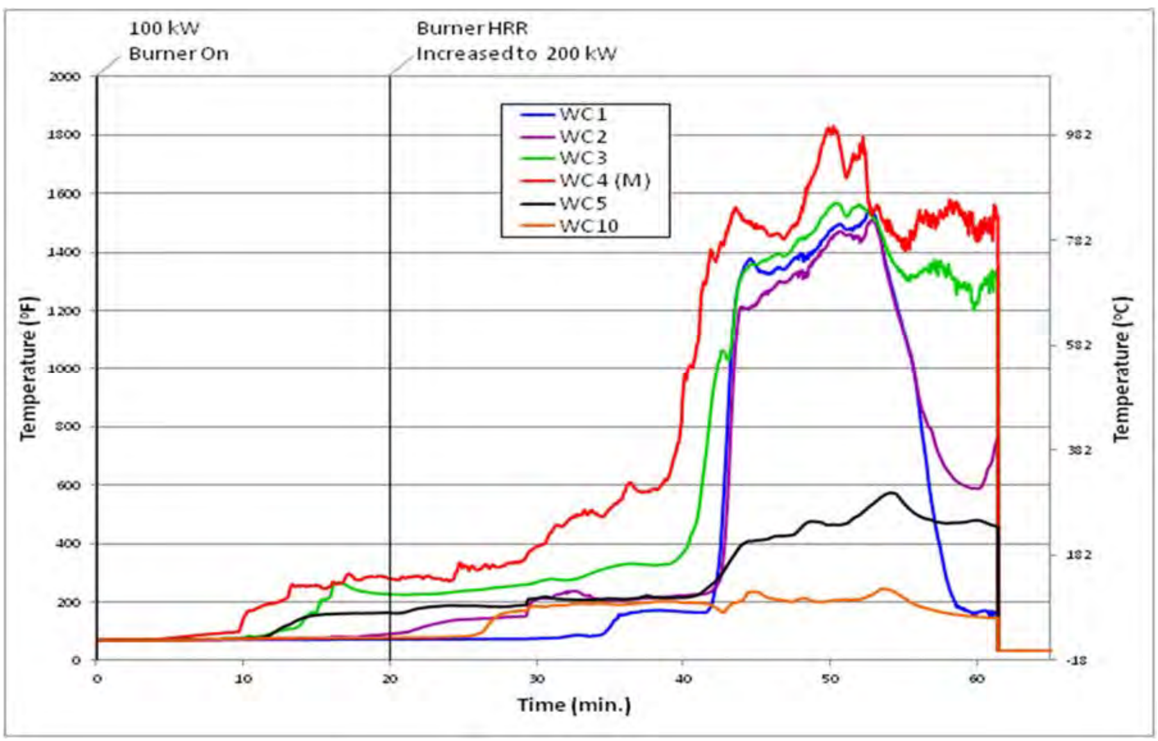


Figure G. 146: Wall Experiment 26 Wall Cavity Horizontal Temperatures

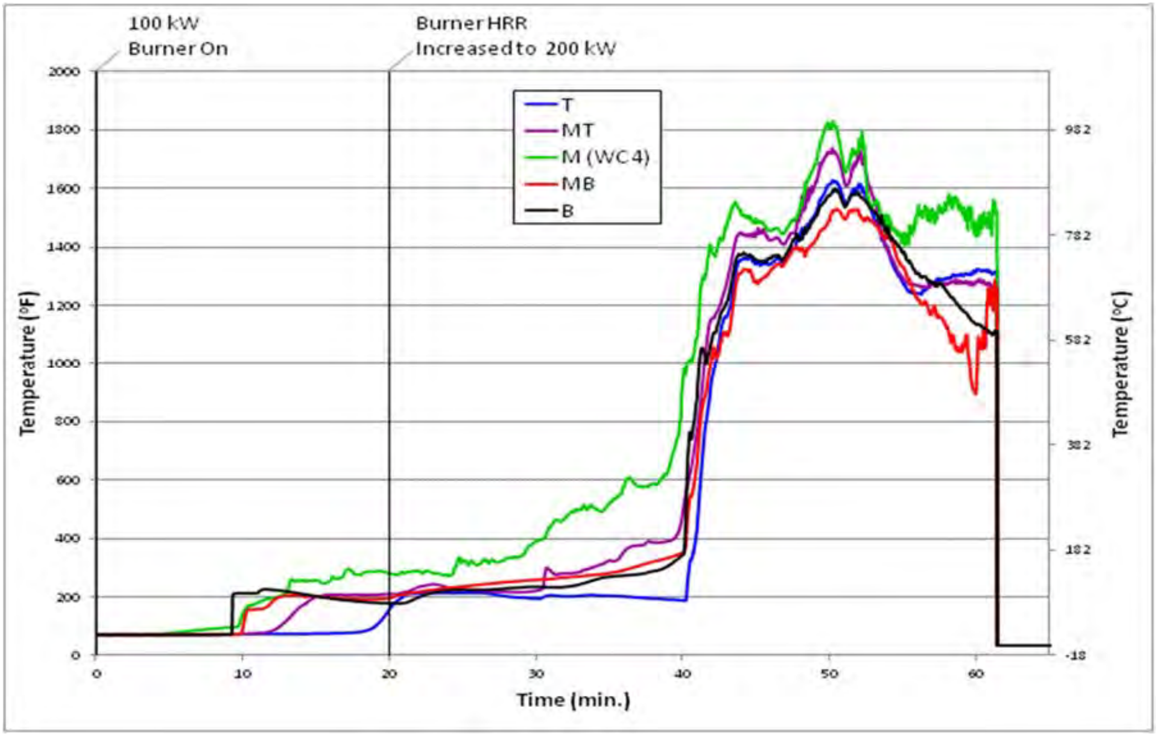


Figure G. 147: Wall Experiment 26 Wall Cavity Vertical Temperatures

Experiment 27

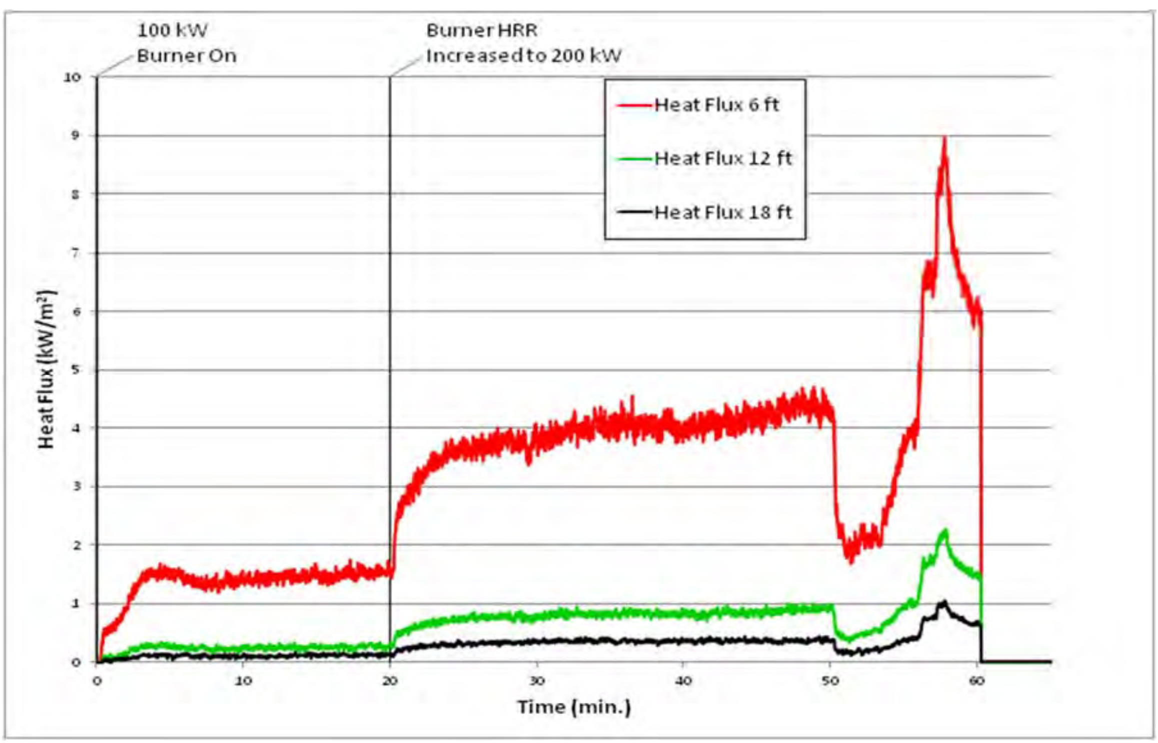


Figure G. 148: Wall Experiment 27 Heat Flux

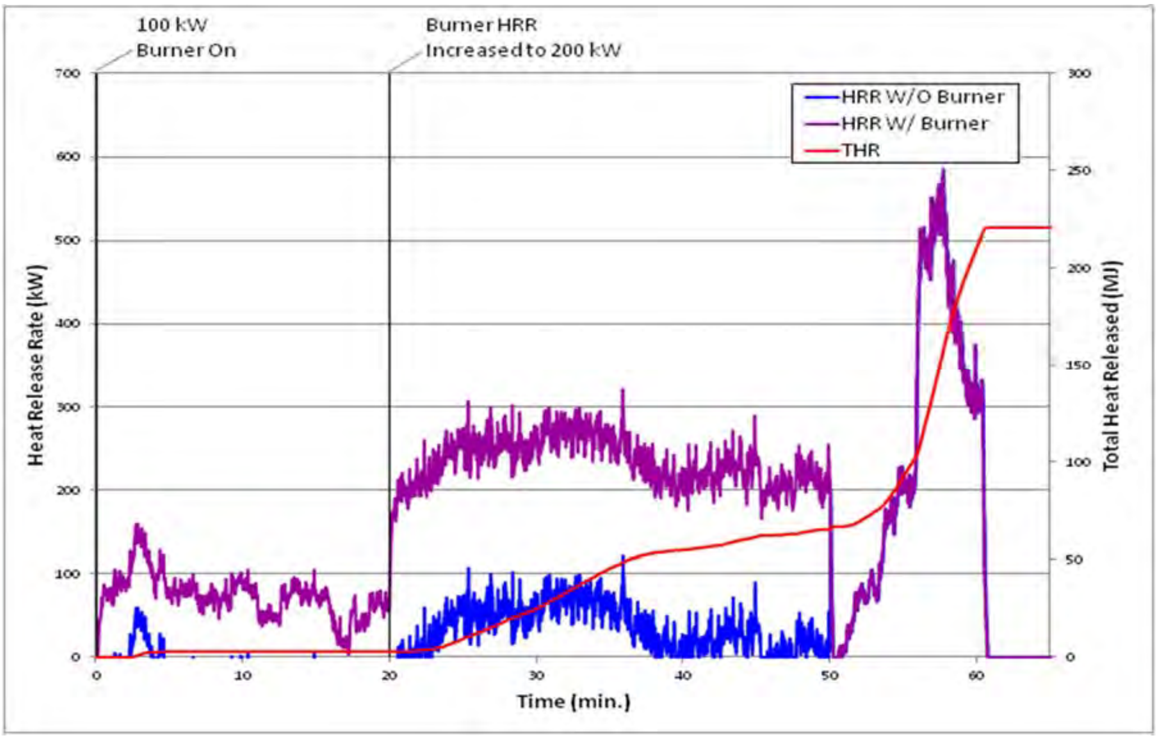


Figure G. 149: Wall Experiment 27 Heat Release Rate and Total Heat Released

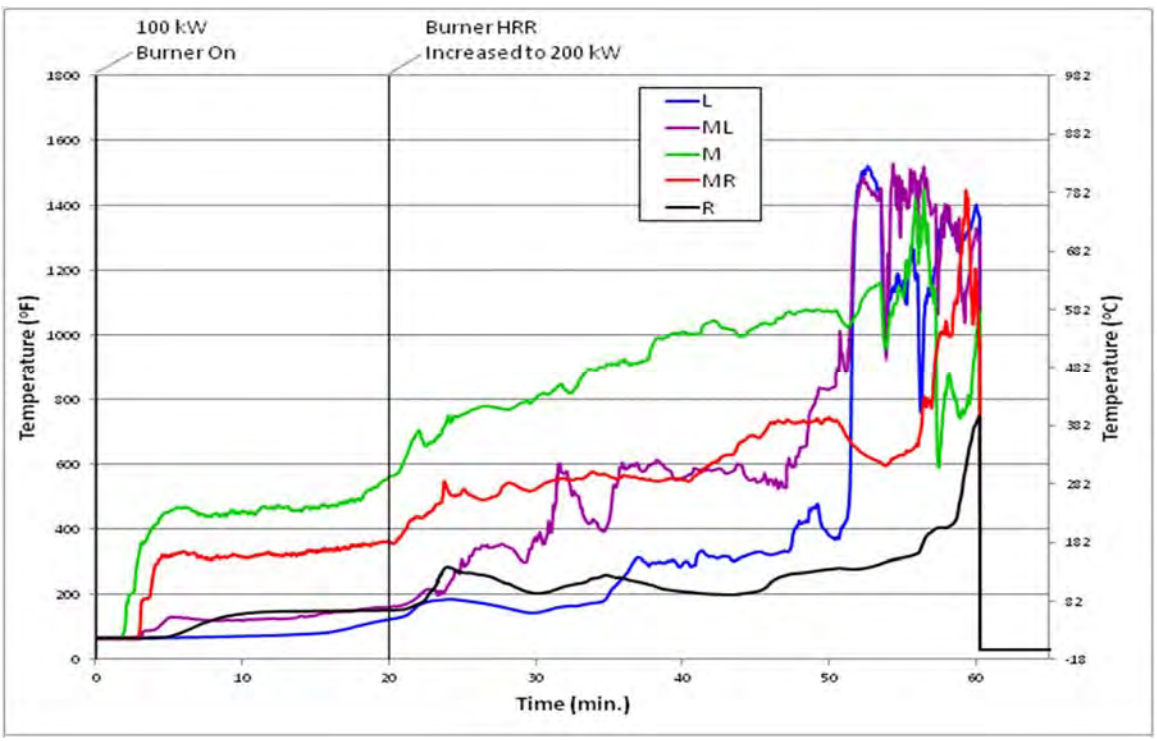


Figure G. 150: Wall Experiment 27 Under Siding Horizontal Temperatures

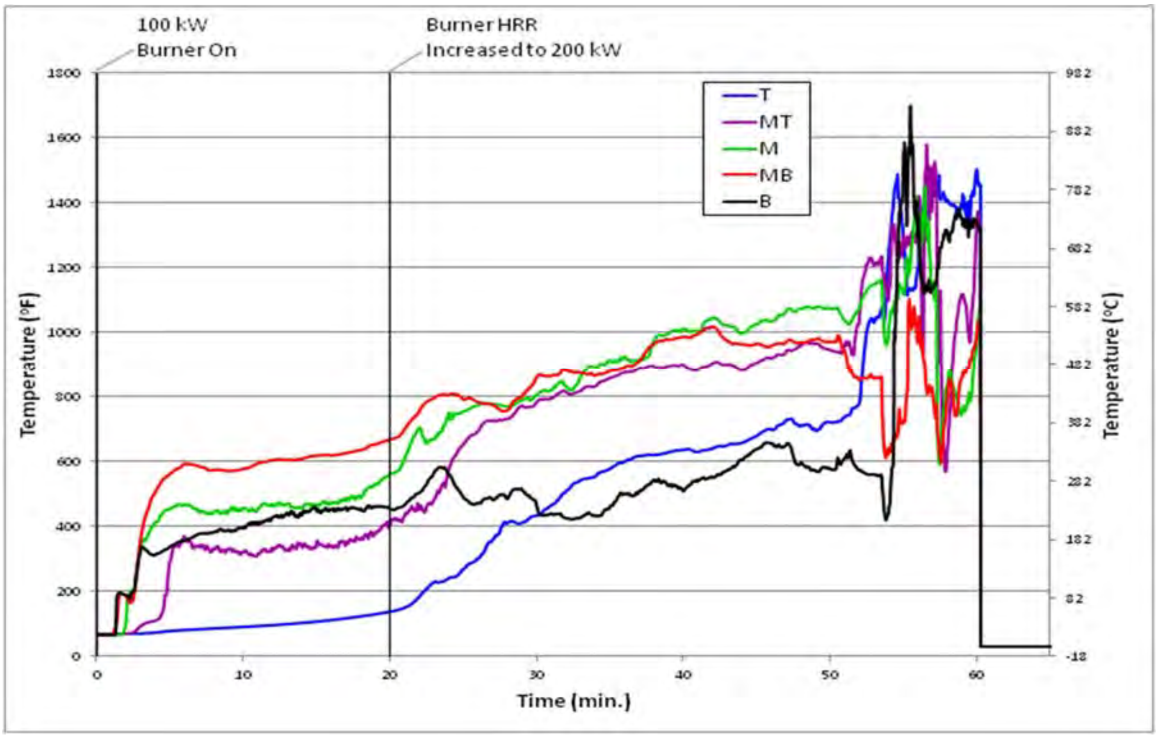


Figure G. 151: Wall Experiment 27 Under Siding Vertical Temperatures

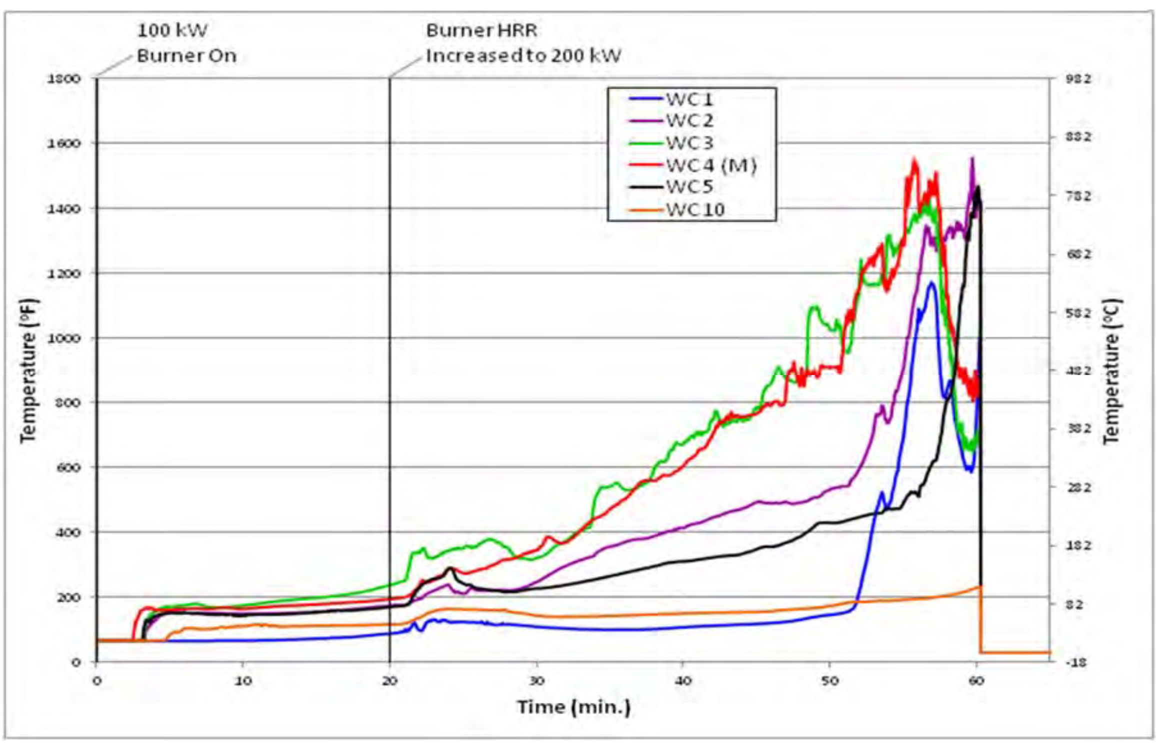


Figure G. 152: Wall Experiment 27 Wall Cavity Horizontal Temperatures

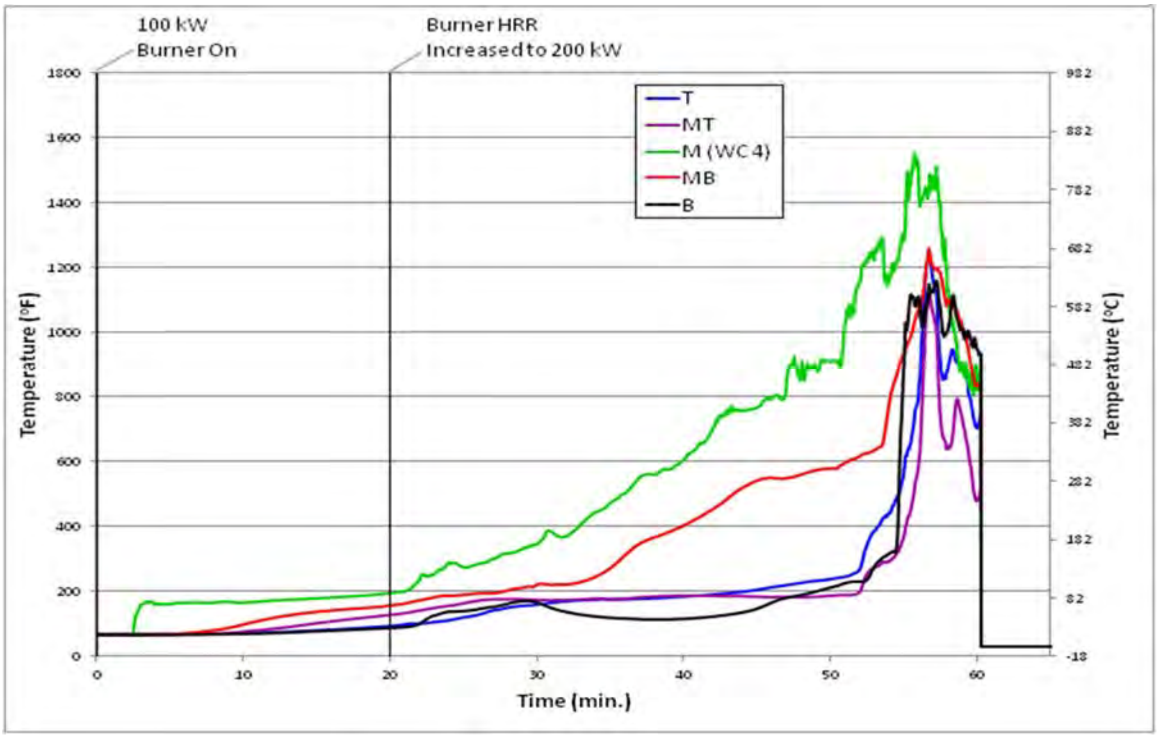


Figure G. 153: Experiment 27 Wall Cavity Vertical Temperatures

Experiment 28

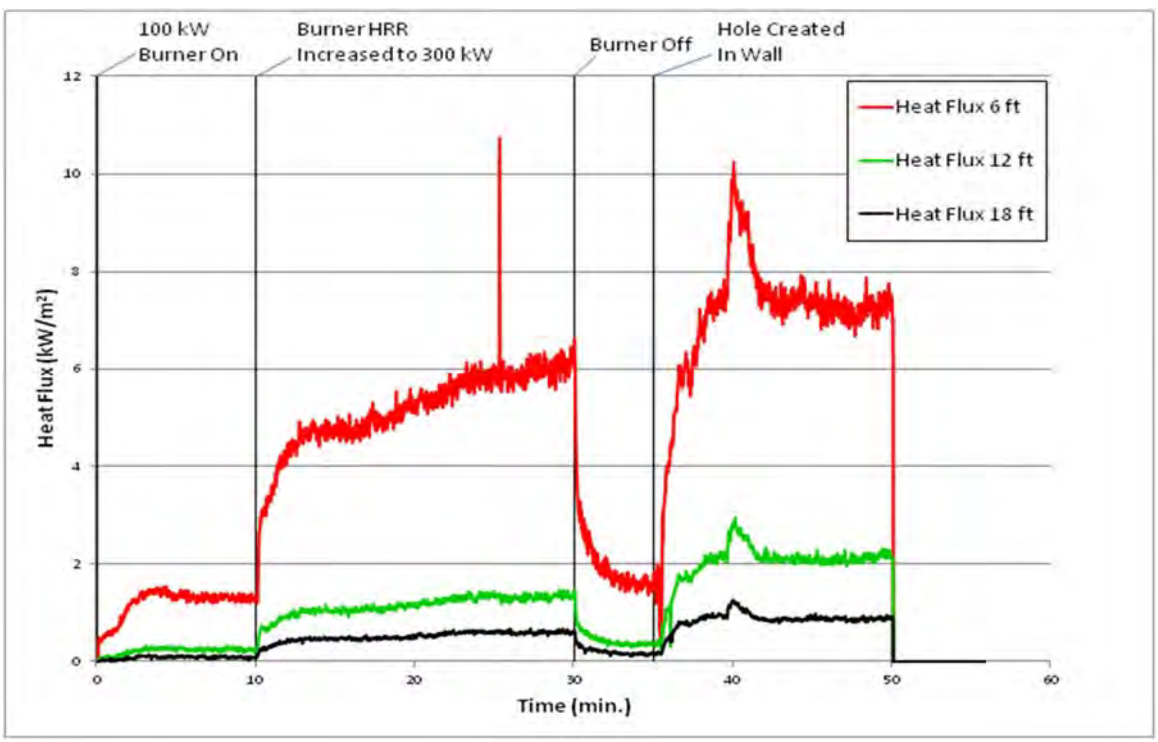


Figure G. 154: Experiment 28 Heat Flux

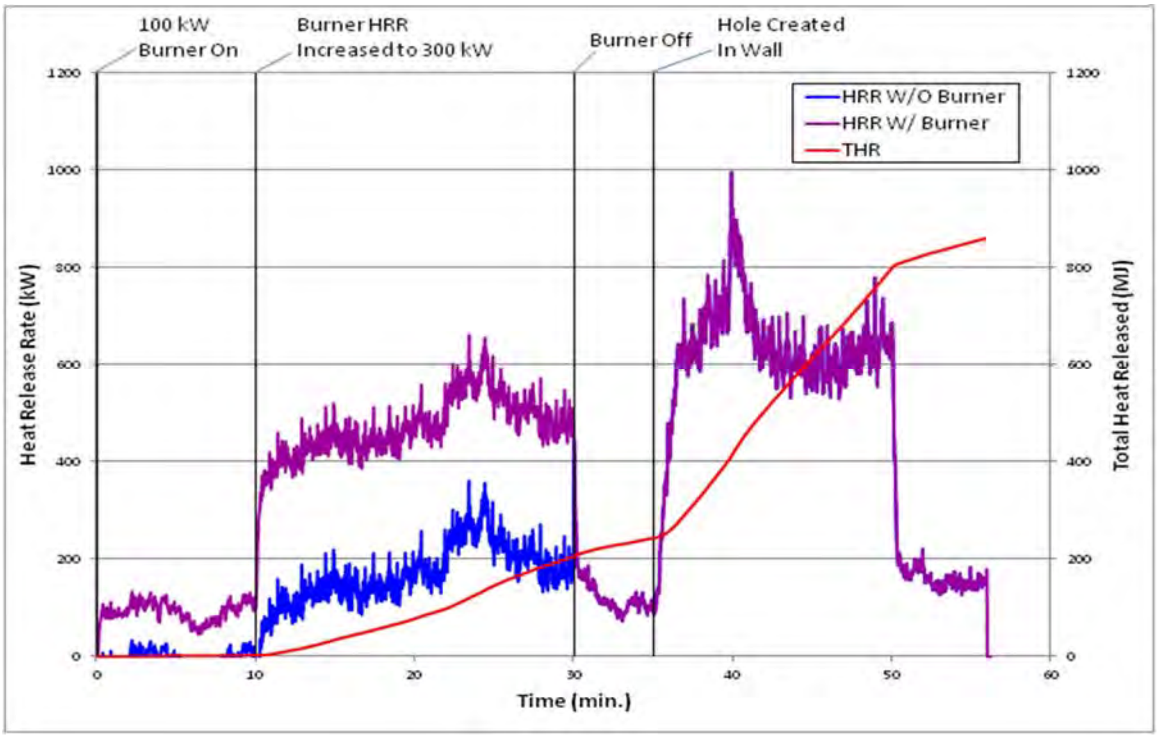


Figure G. 155: Experiment 28 Heat Release Rate and Total Heat Released

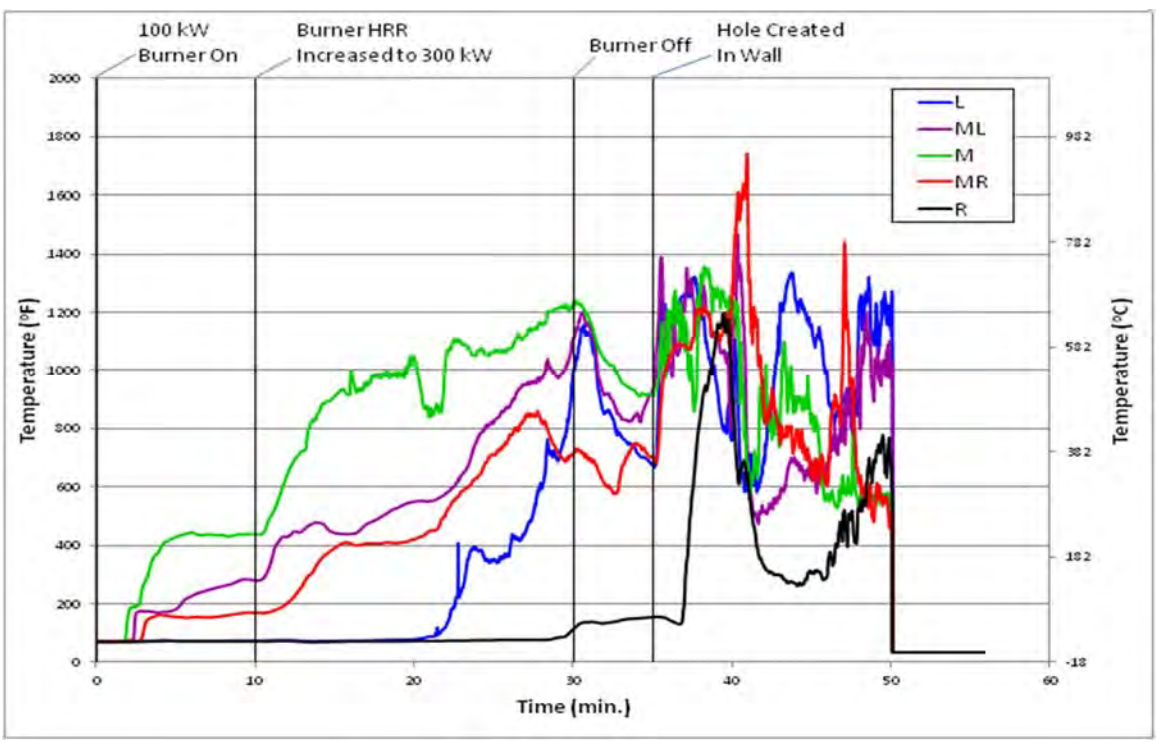


Figure G. 156: Experiment 28 Under Siding Horizontal Temperatures

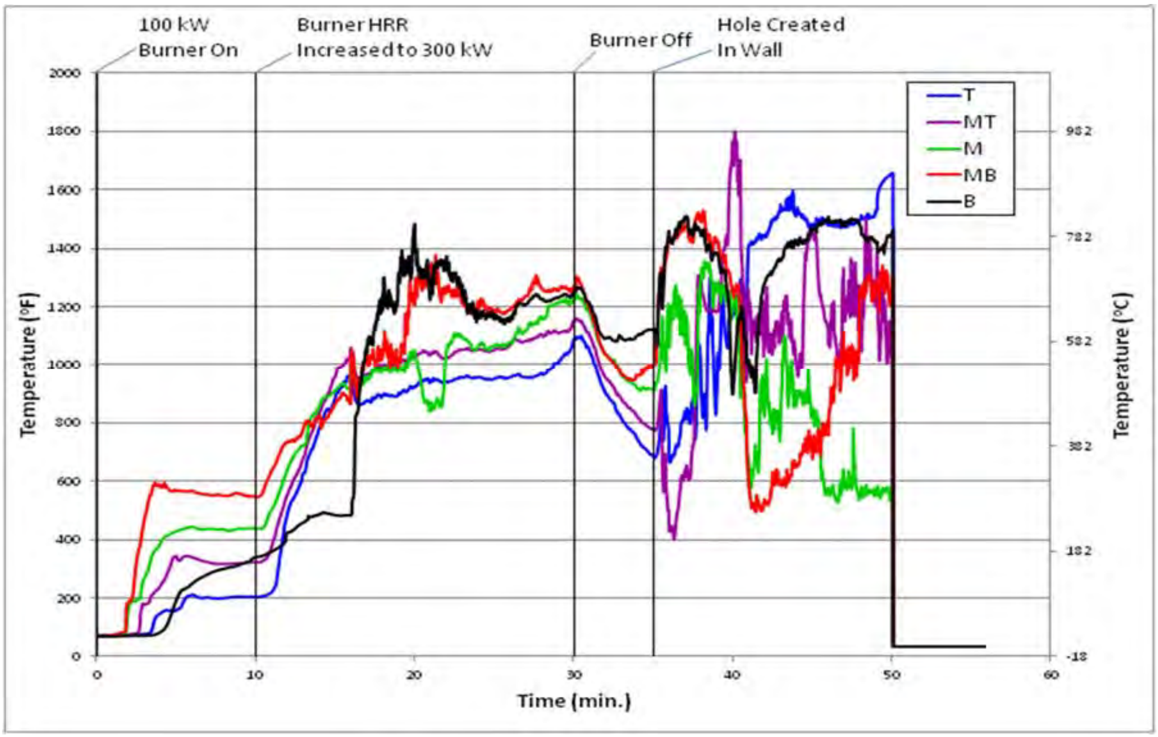


Figure G. 157: Experiment 28 Under Siding Vertical Temperatures

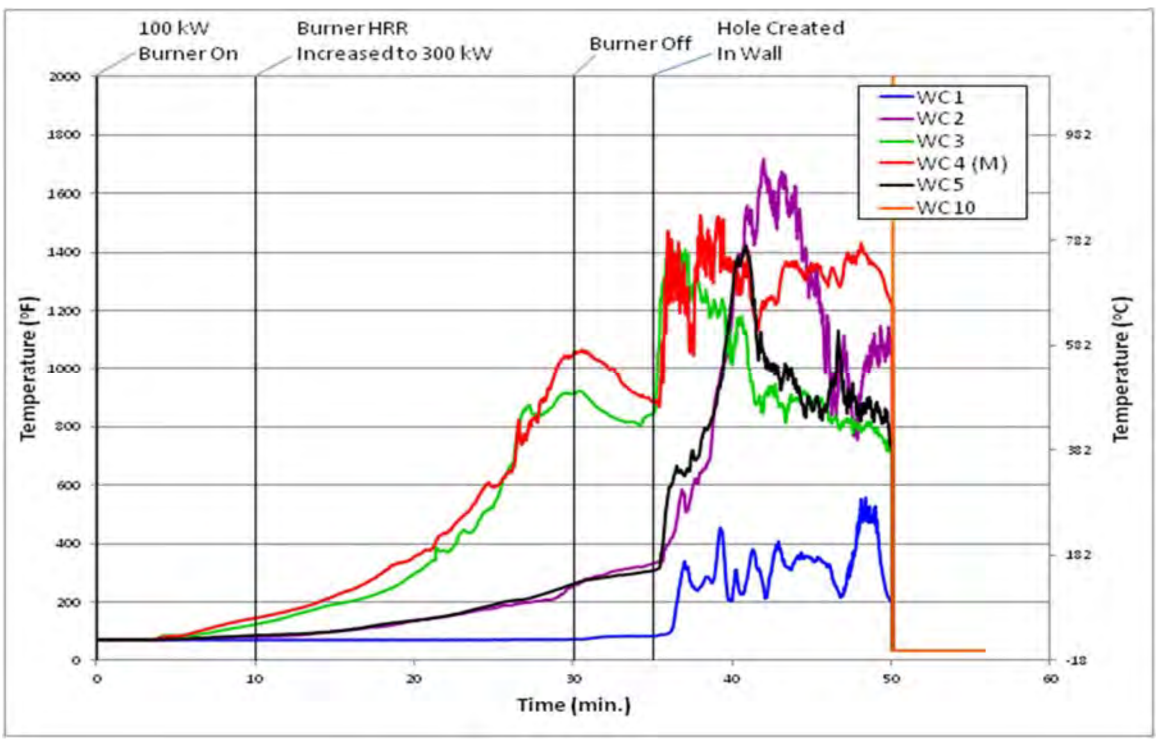


Figure G. 158: Experiment 28 Wall Cavity Horizontal Temperatures

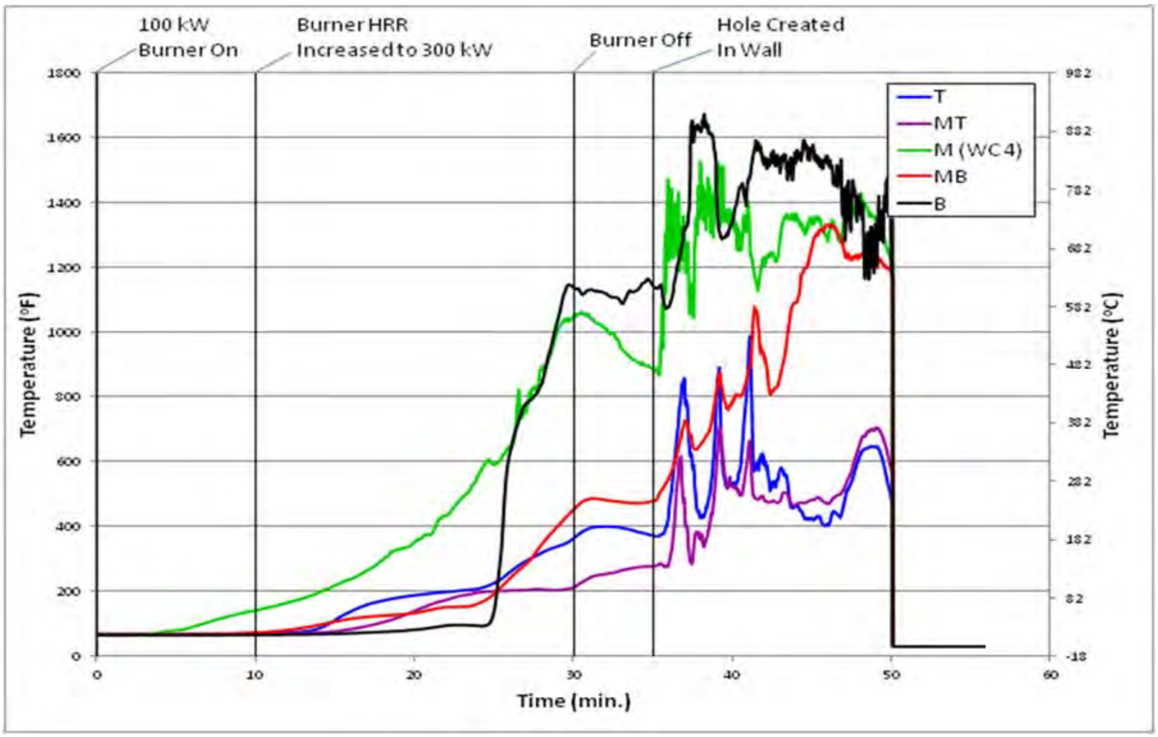


Figure G. 159: Experiment 28 Wall Cavity Vertical Temperatures

Appendix H: Eave Experiment Data

Experiment 1

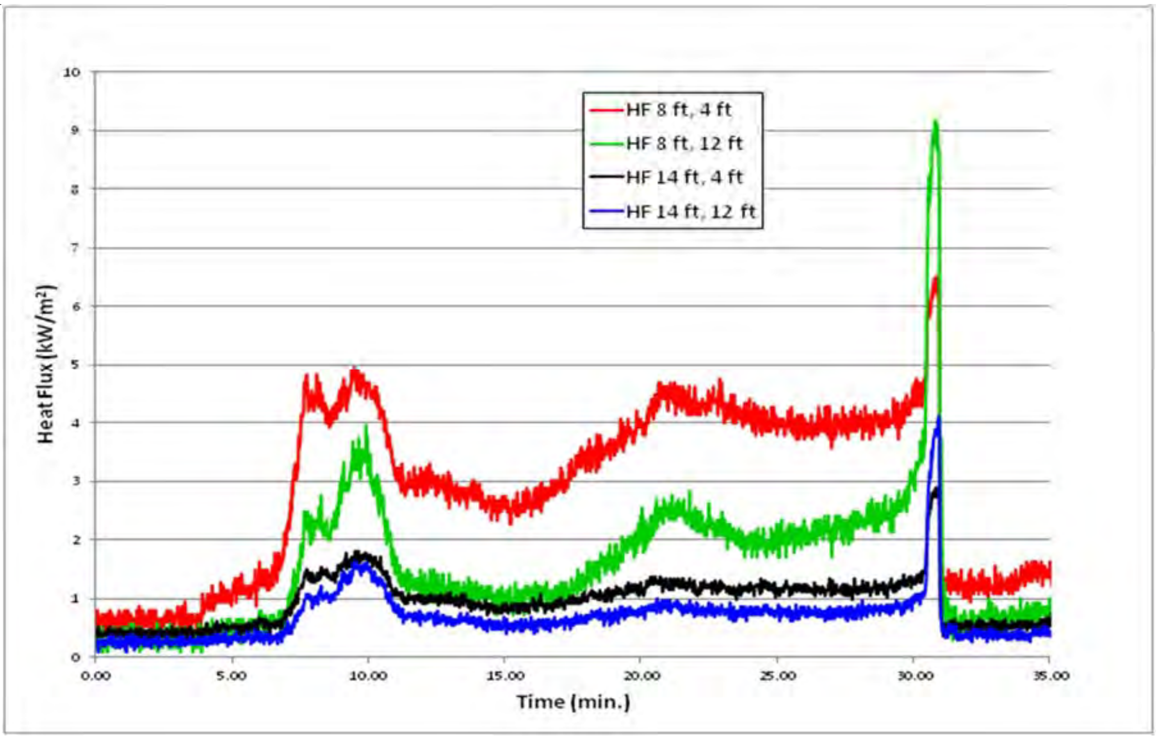


Figure H. 1: Eave Experiment 1 Heat Flux

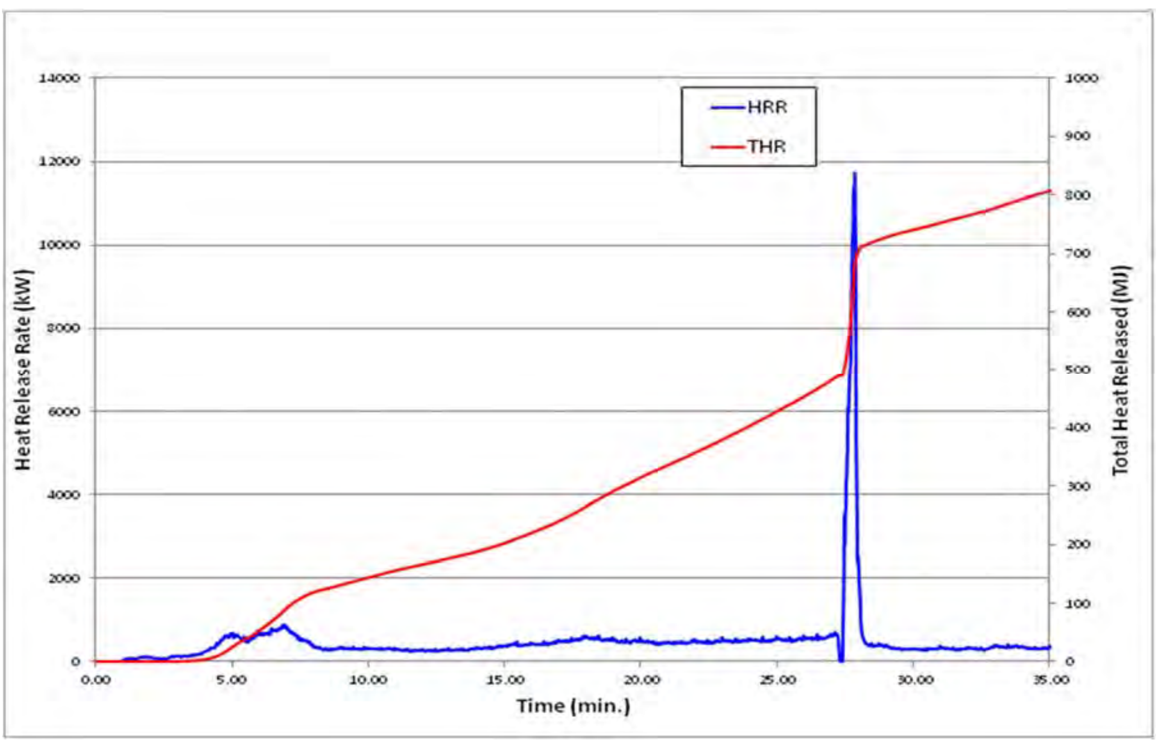


Figure H. 2: Eave Experiment 1 Heat Release Rate and Total Heat Released

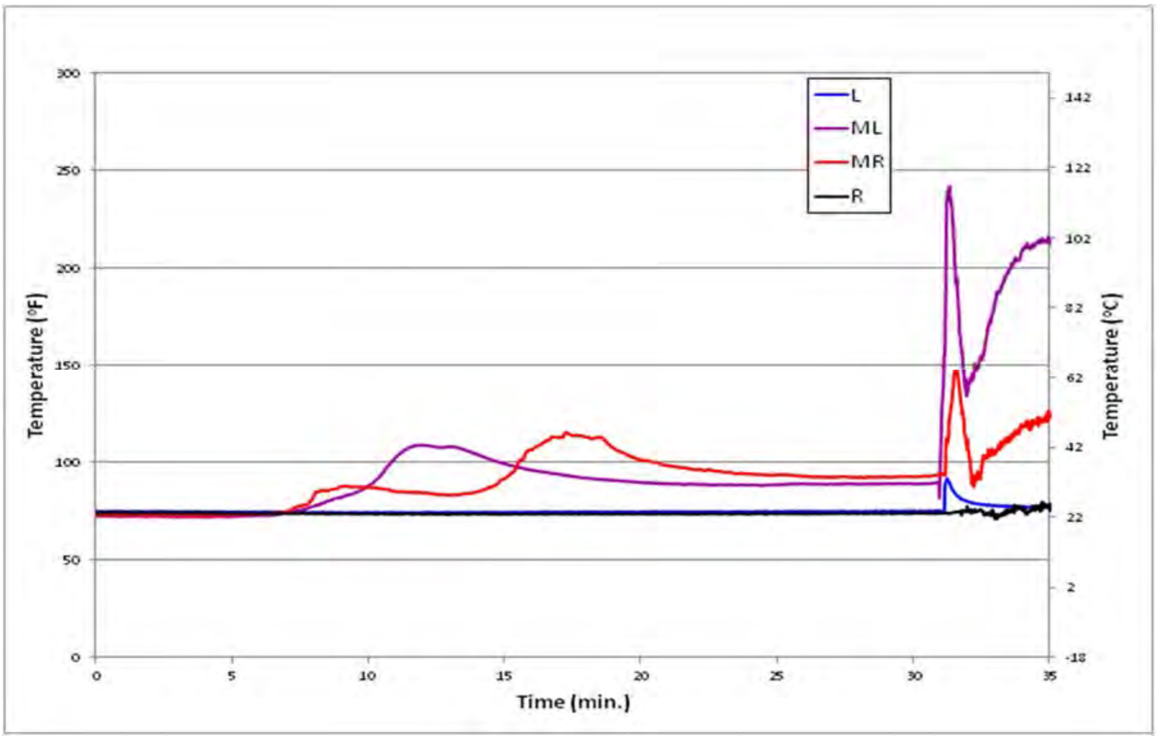


Figure H. 3: Eave Experiment 1 Bottom under Siding Temperatures

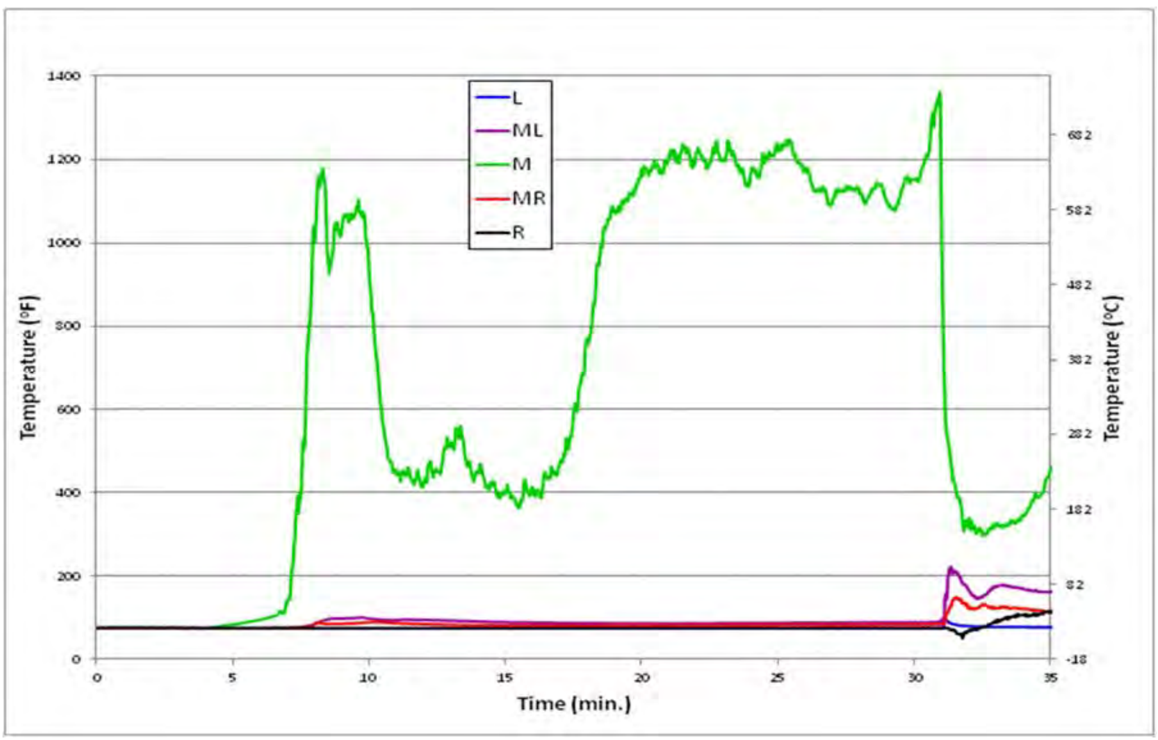


Figure H. 4: Eave Experiment 1 Middle Bottom under Siding Temperatures

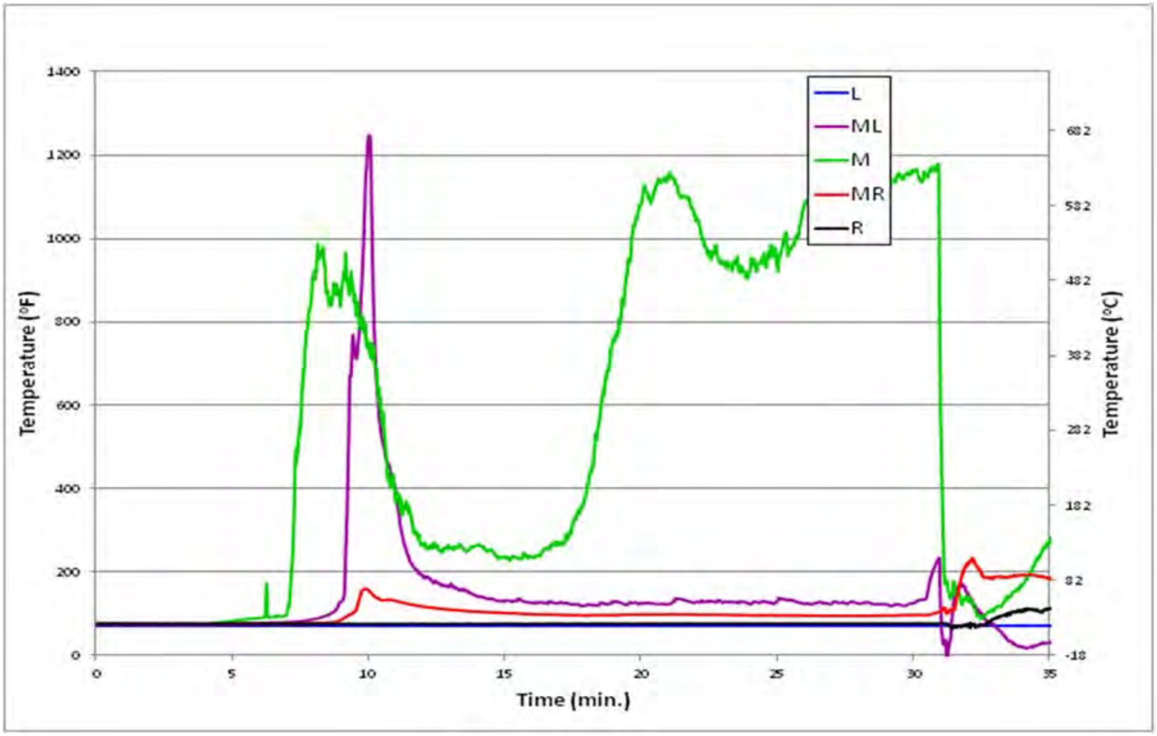


Figure H. 5: Eave Experiment 1 Middle Top under Siding Temperatures

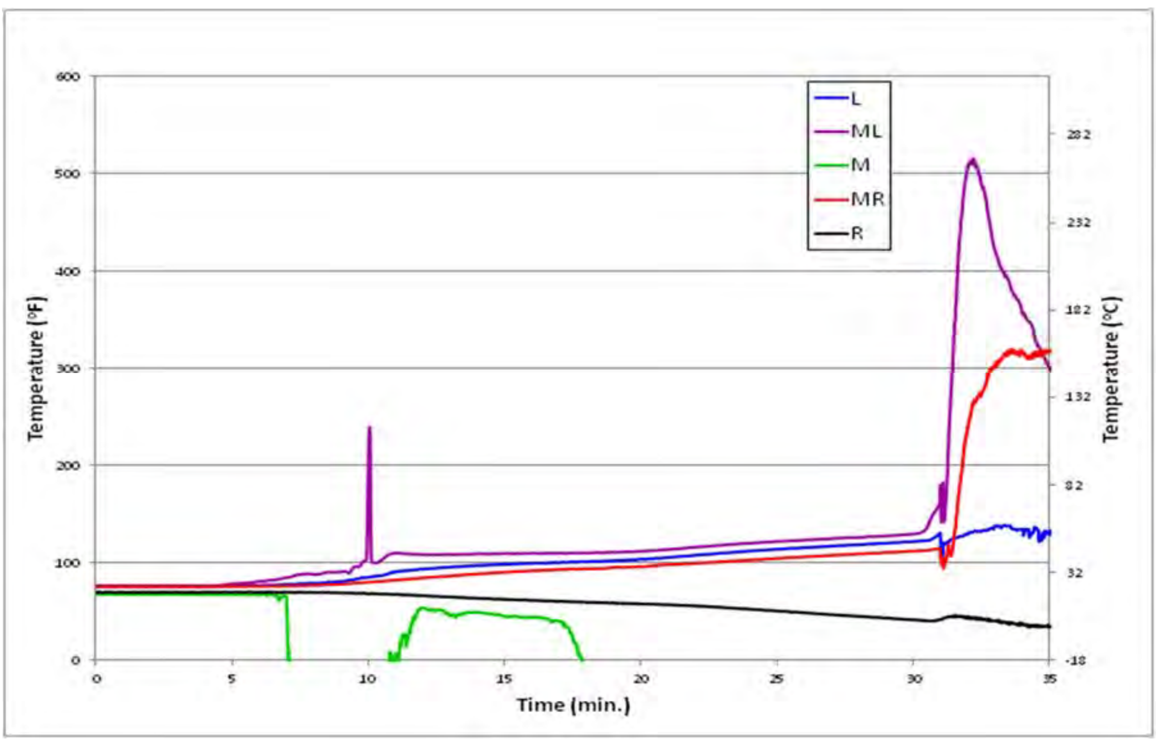


Figure H. 6: Eave Experiment 1 Top under Siding Temperatures

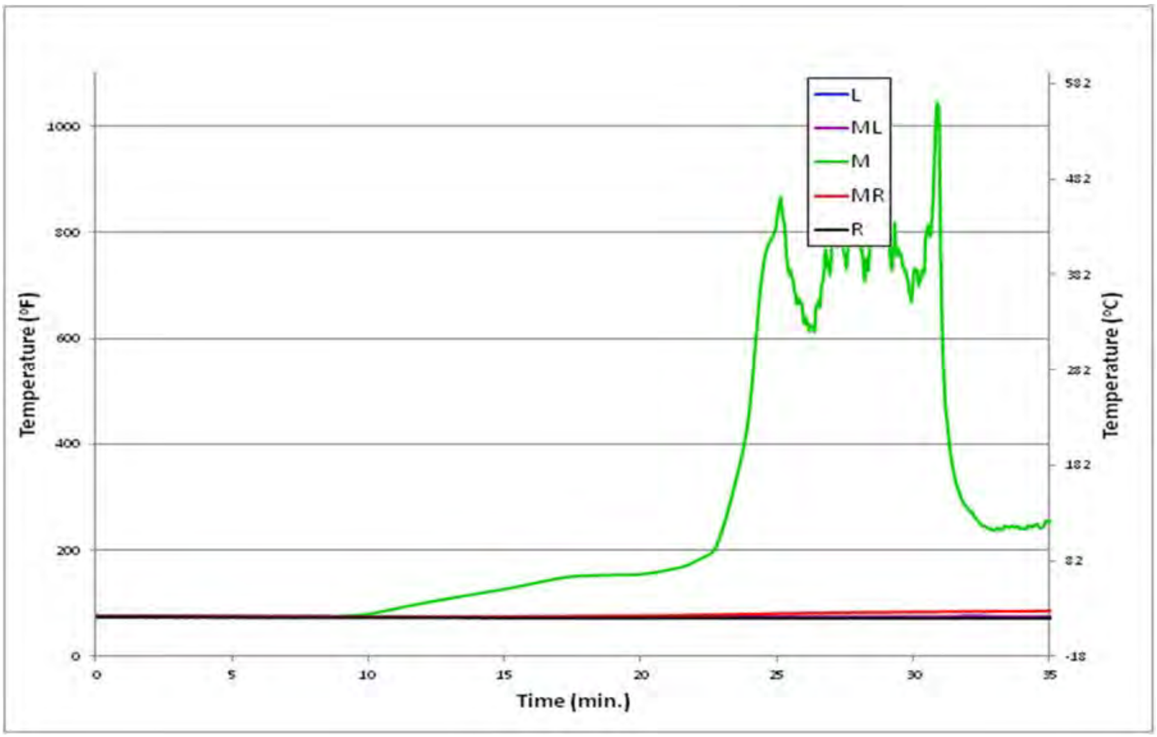


Figure H. 7: Eave Experiment 1 Bottom Wall Cavity Temperatures

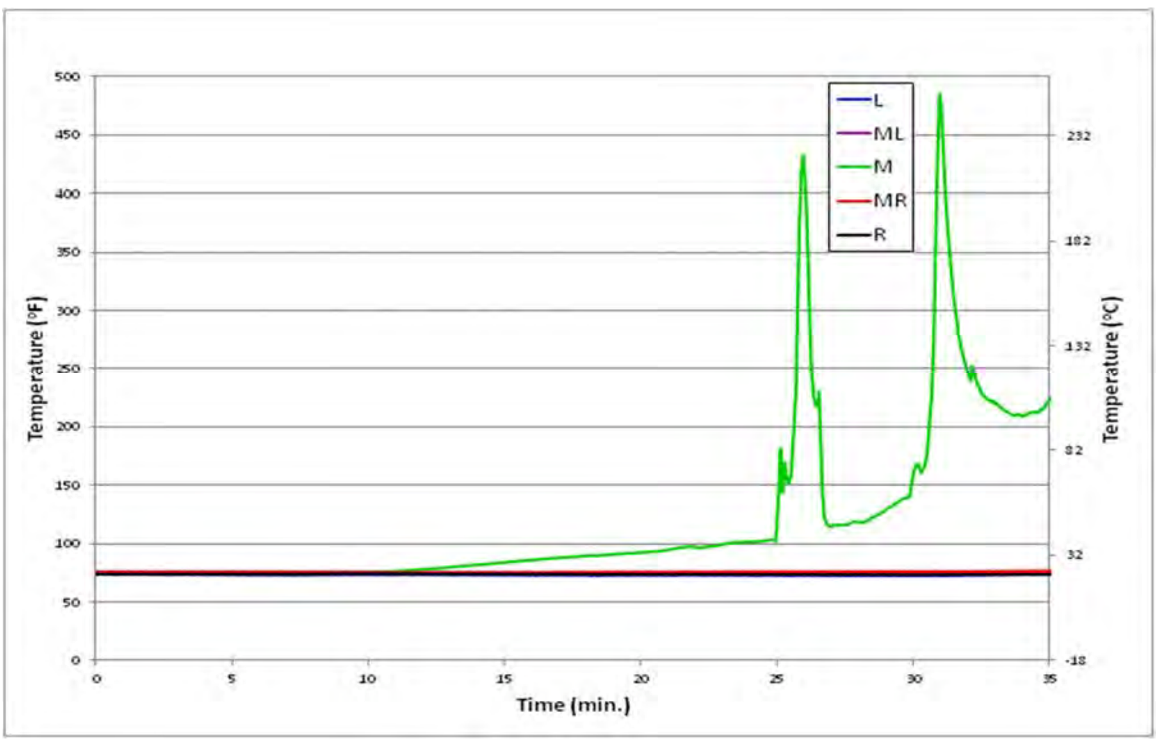


Figure H. 8: Eave Experiment 1 Middle Bottom Wall Cavity Temperatures

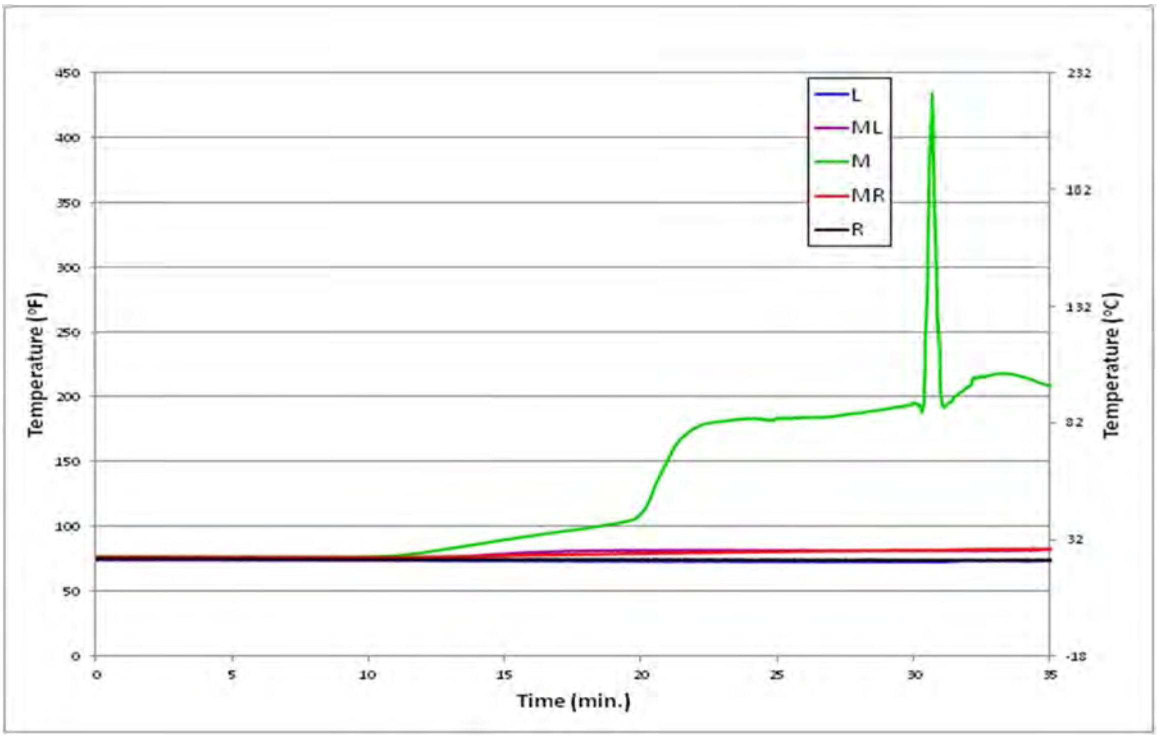


Figure H. 9: Eave Experiment 1 Middle Top Wall Cavity Temperatures

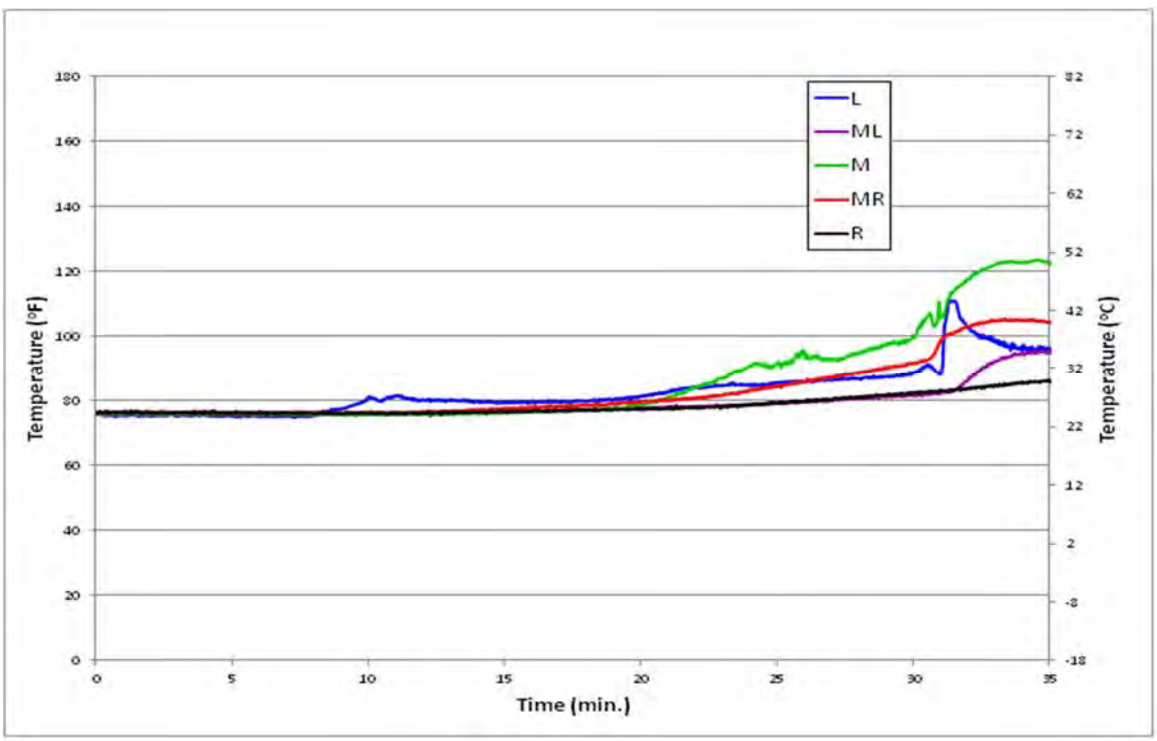


Figure H. 10: Eave Experiment 1 Top Wall Cavity Temperatures

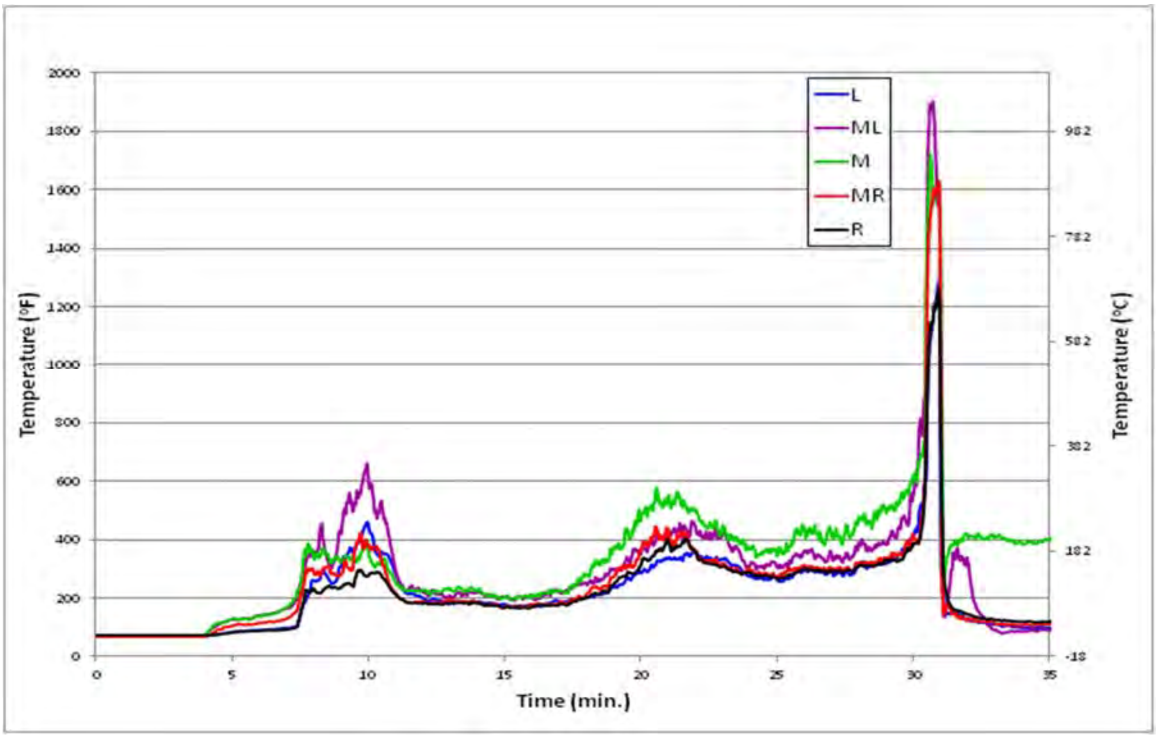


Figure H. 11: Eave Experiment 1 Eave Attic Temperatures

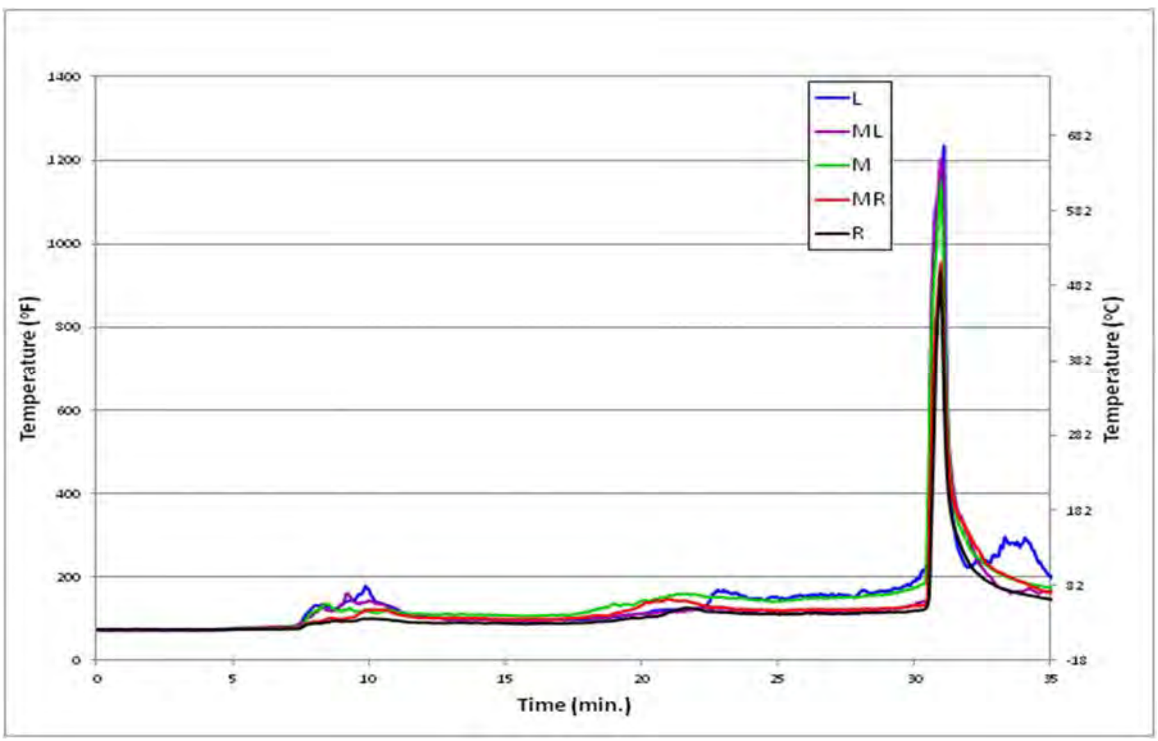


Figure H. 12: Eave Experiment 1 Back Attic Temperatures

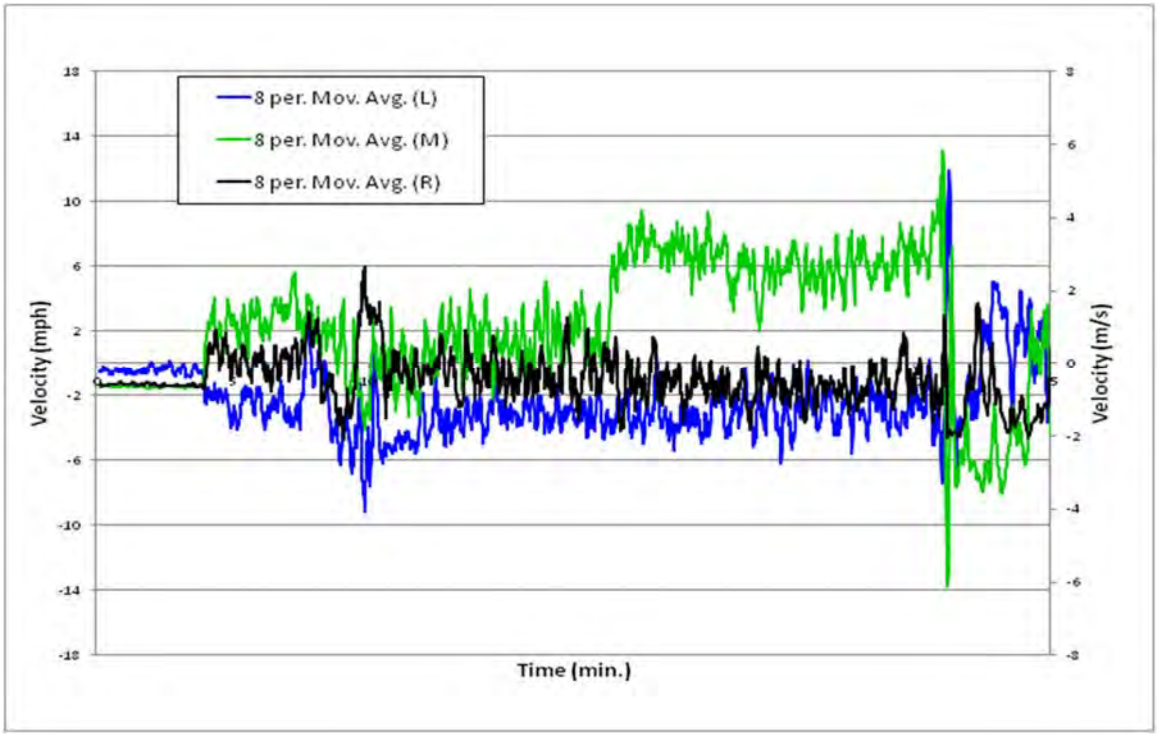


Figure H. 13: Eave Experiment 1 Eave Flow Velocity

Experiment 2

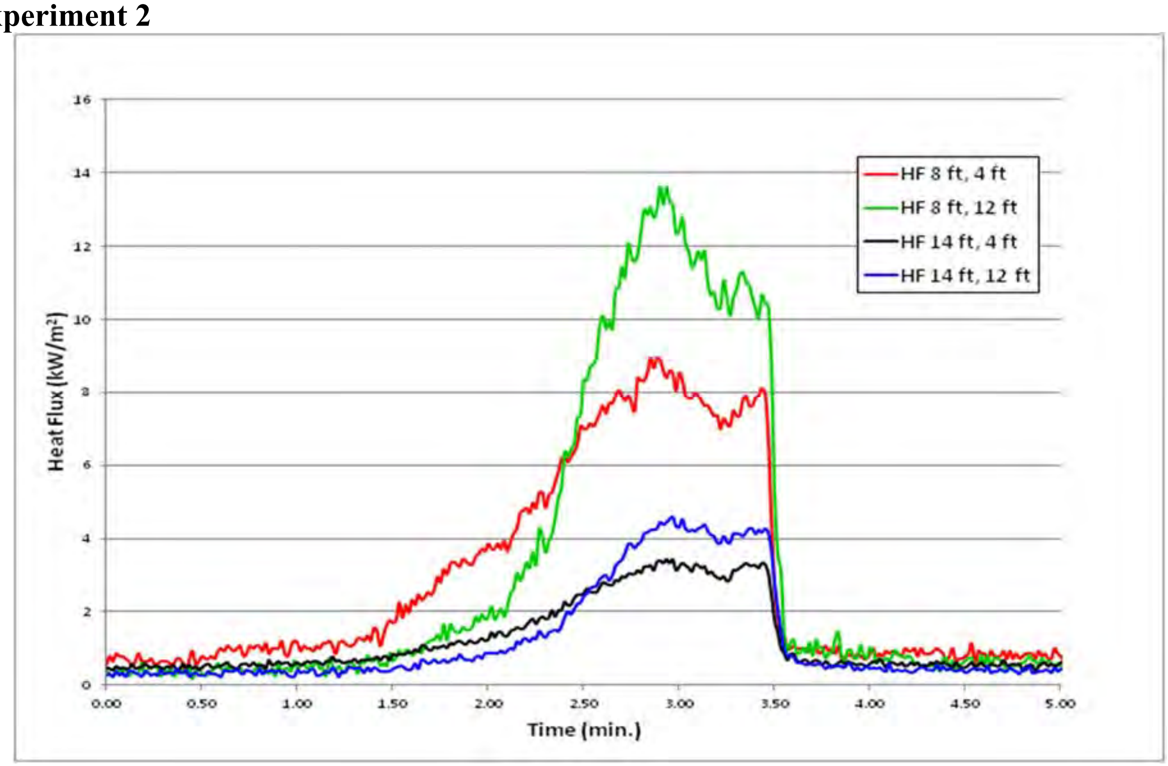


Figure H. 14: Eave Experiment 2 Heat Flux

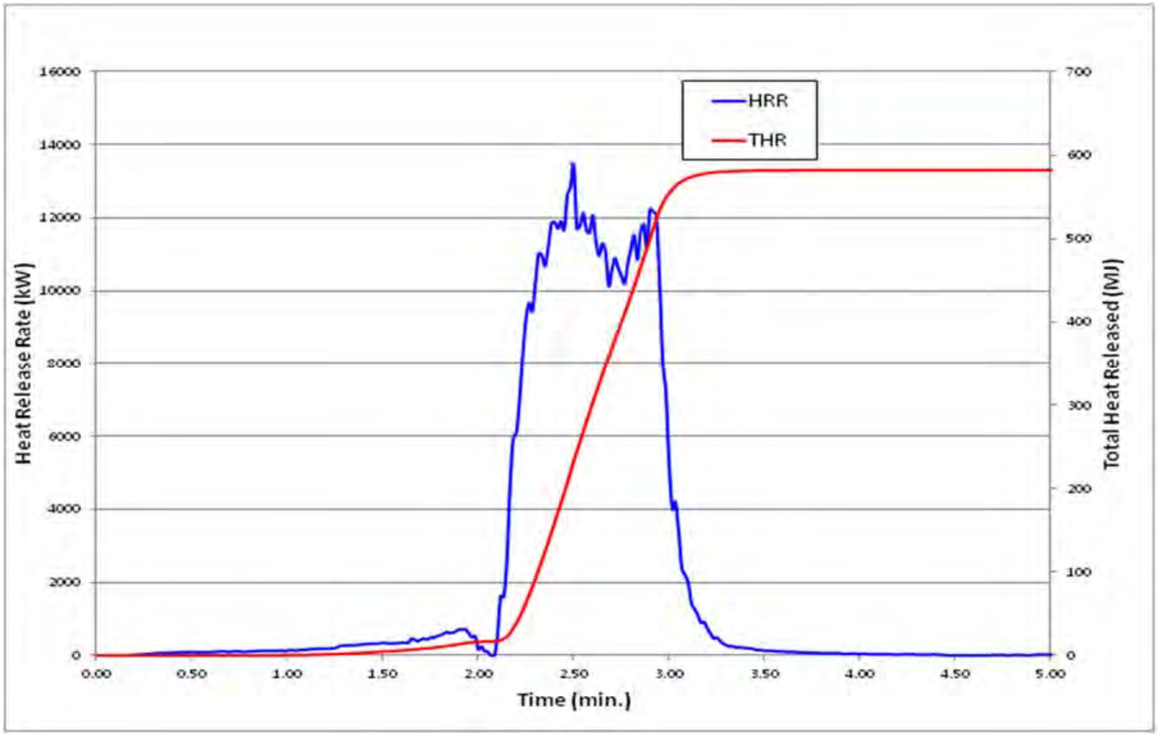


Figure H. 15: Eave Experiment 2 Heat Release Rate and Total Heat Released

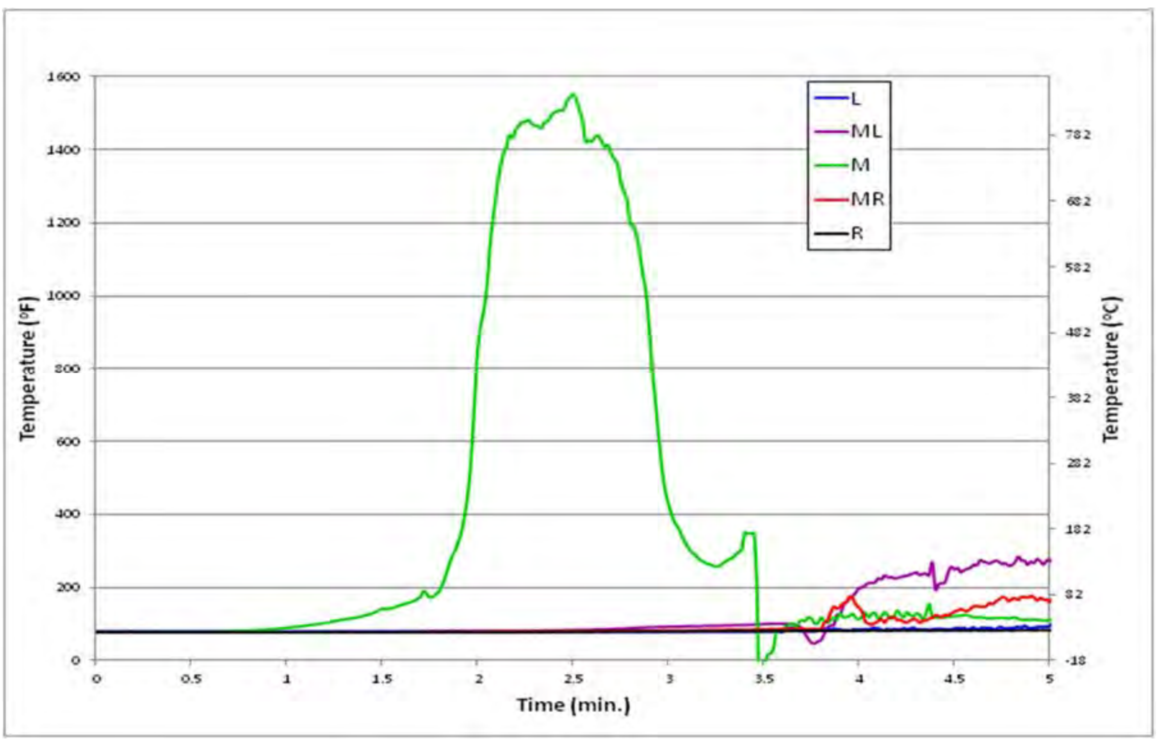


Figure H. 16: Eave Experiment 2 Bottom under Siding Temperatures

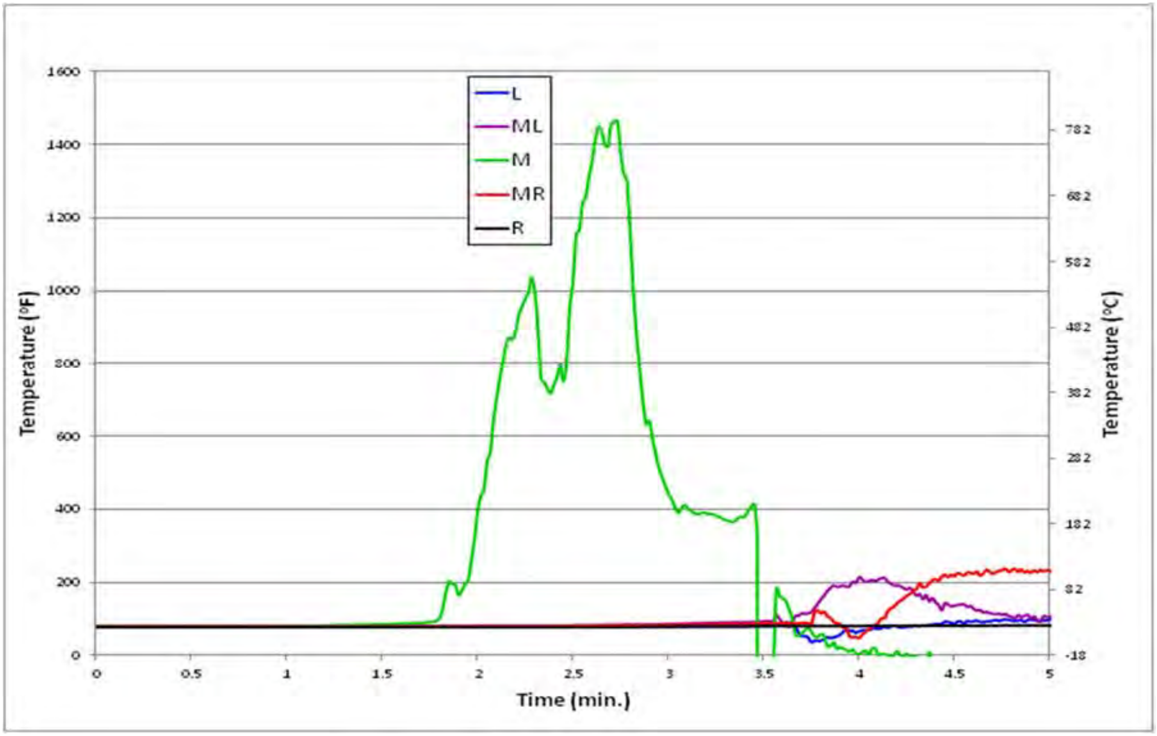


Figure H. 17: Eave Experiment 2 Middle Bottom under Siding Temperatures

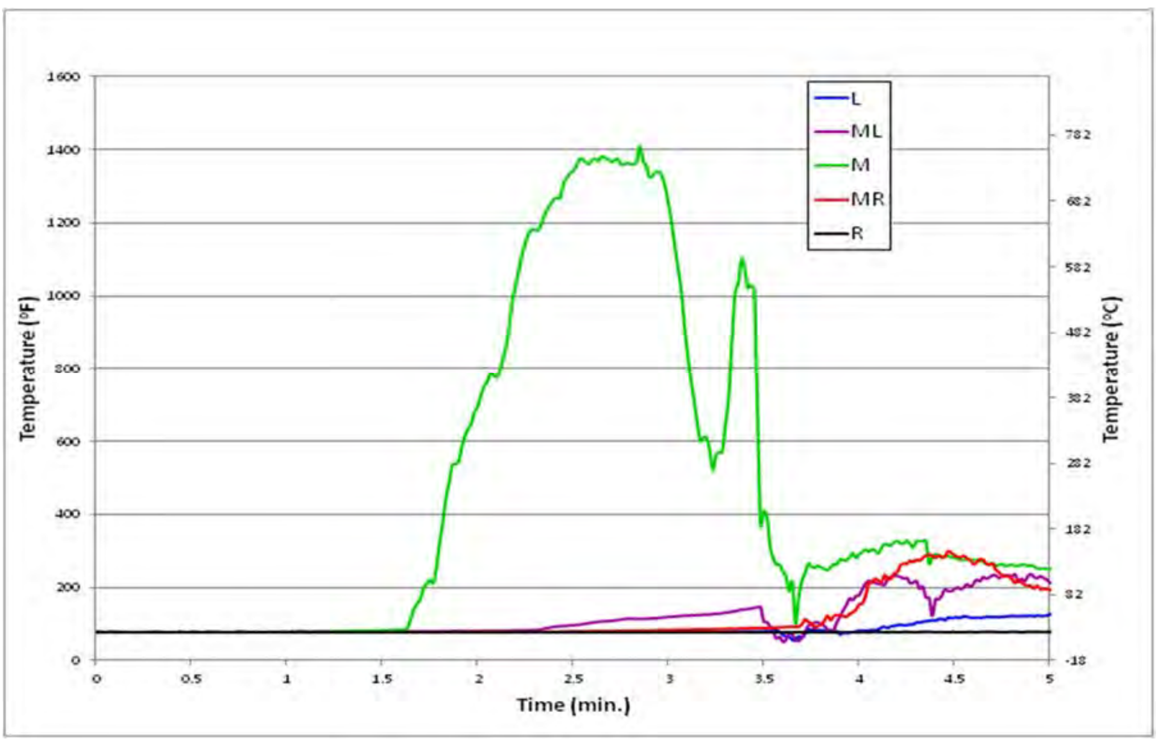


Figure H. 18: Eave Experiment 2 Middle Top under Siding Temperatures

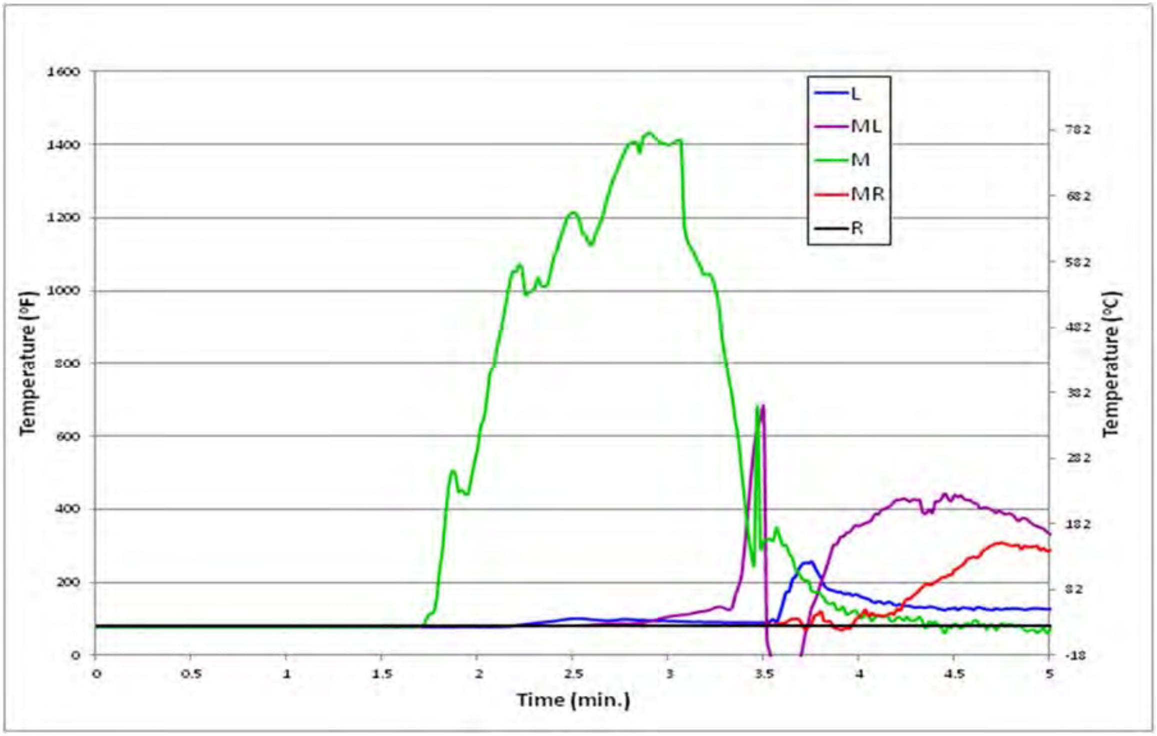


Figure H. 19: Eave Experiment 2 Top under Siding Temperatures

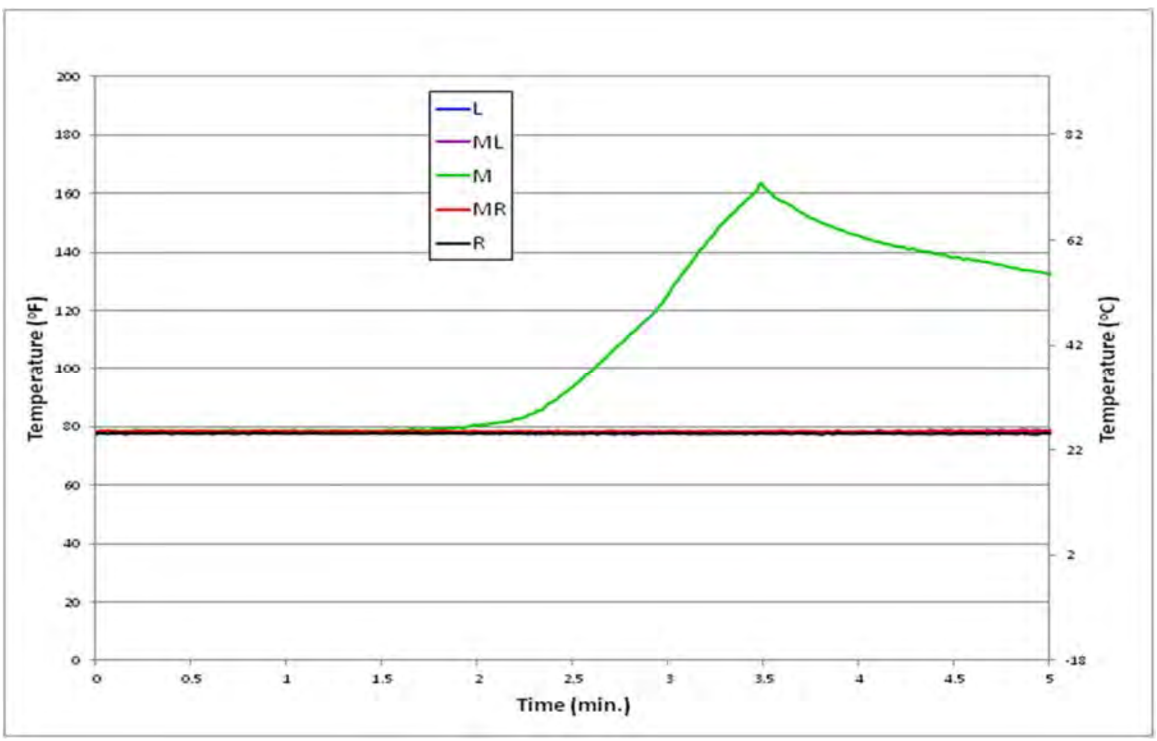


Figure H. 20: Eave Experiment 2 Bottom Wall Cavity Temperatures

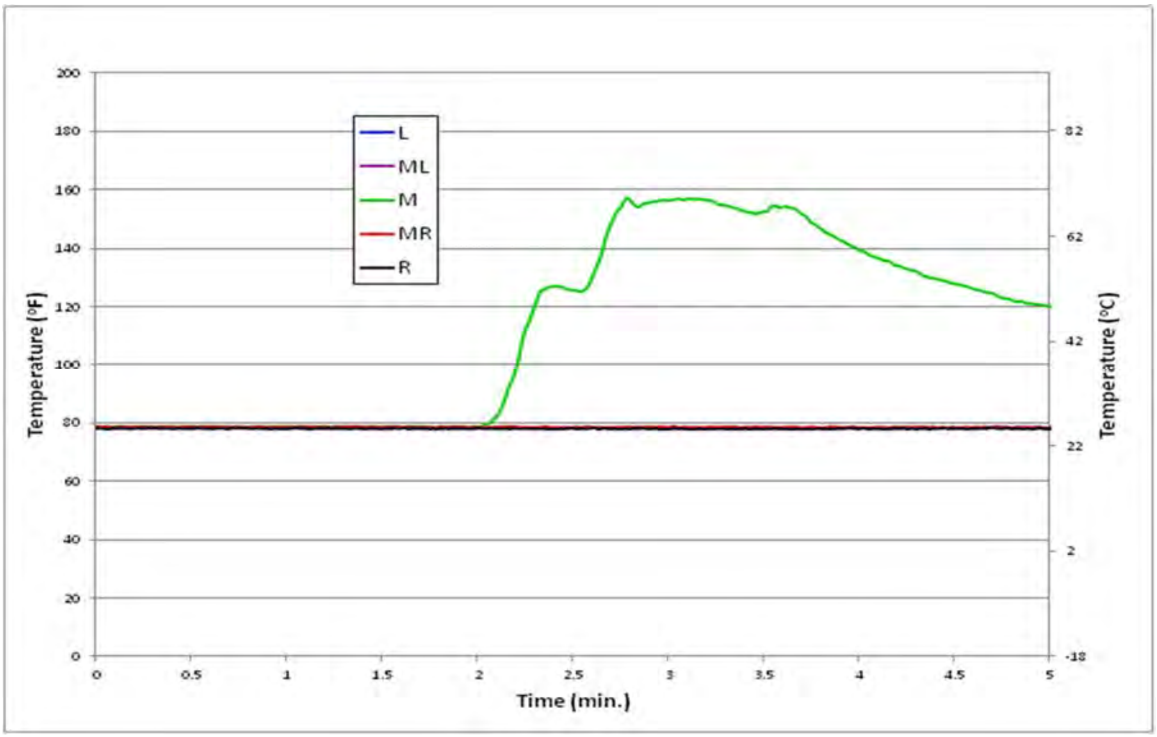


Figure H. 21: Eave Experiment 2 Middle Bottom Wall Cavity Temperatures

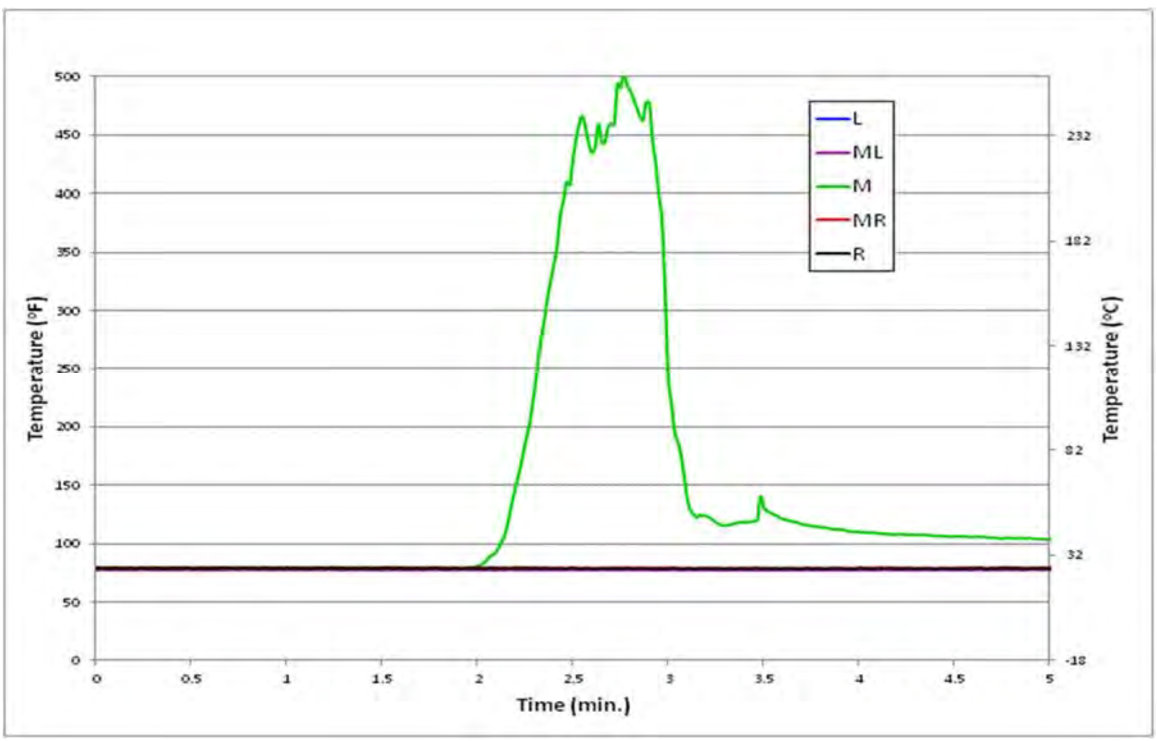


Figure H. 22: Eave Experiment 2 Middle Top Wall Cavity Temperatures

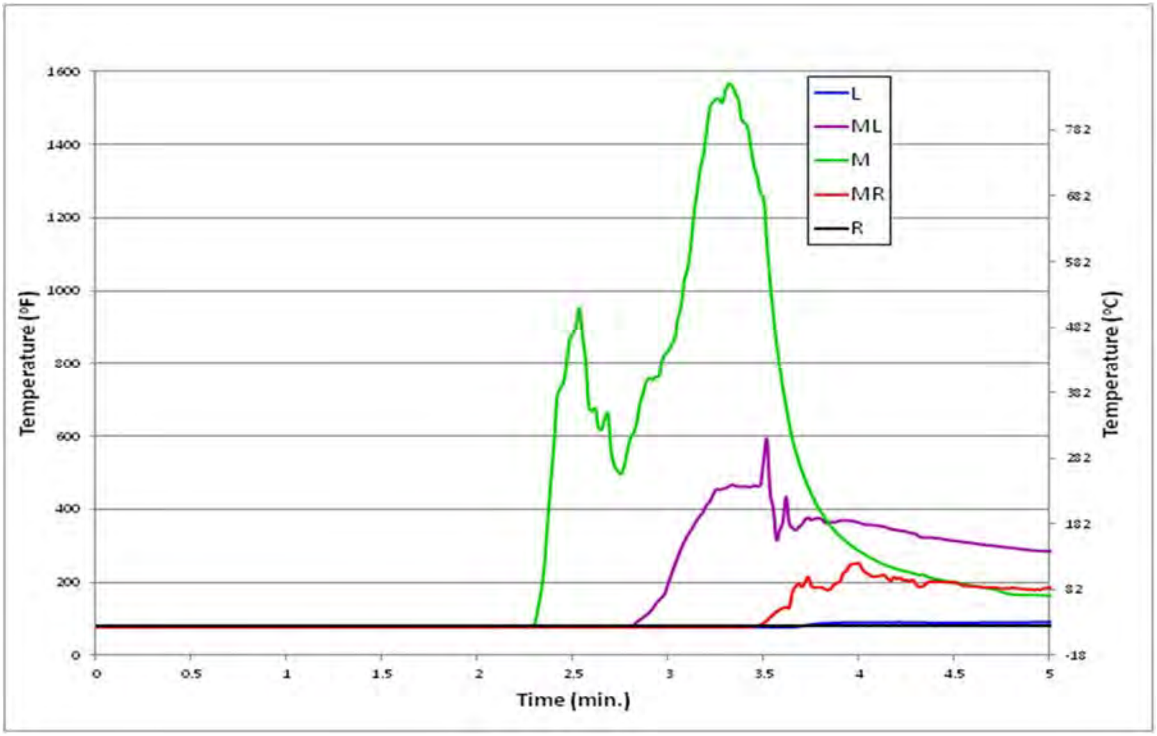


Figure H. 23: Eave Experiment 2 Top Wall Cavity Temperatures

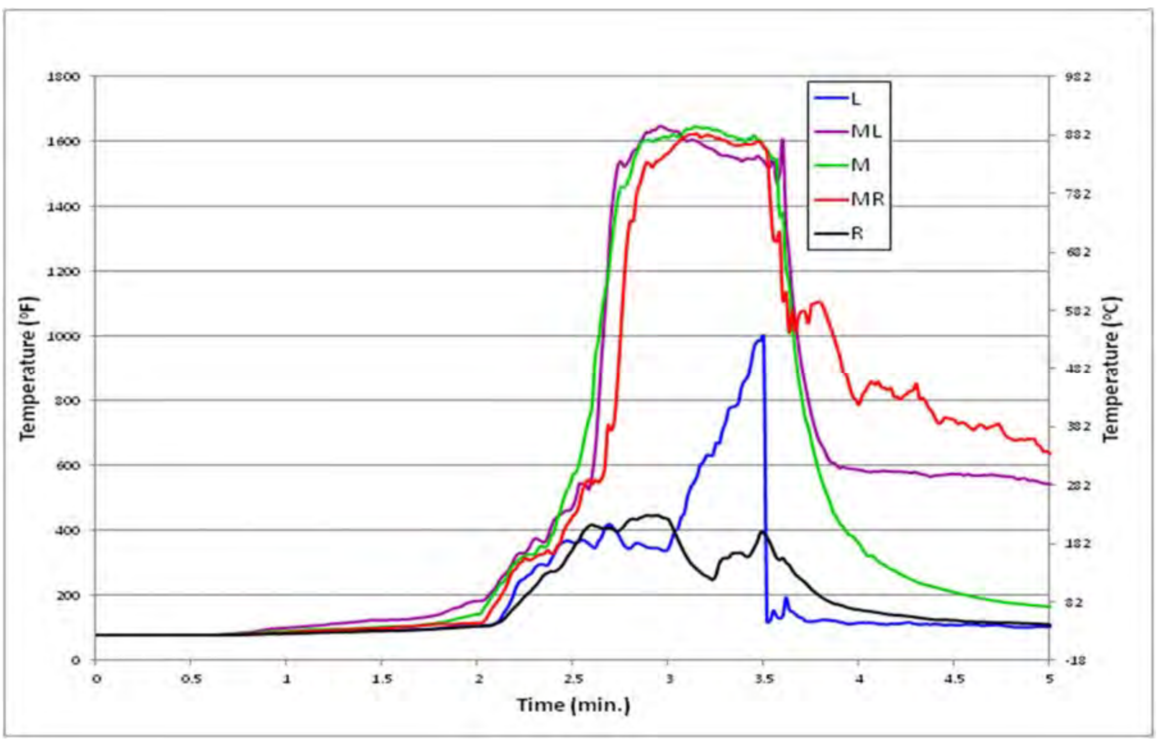


Figure H. 24: Eave Experiment 2 Eave Attic Temperatures

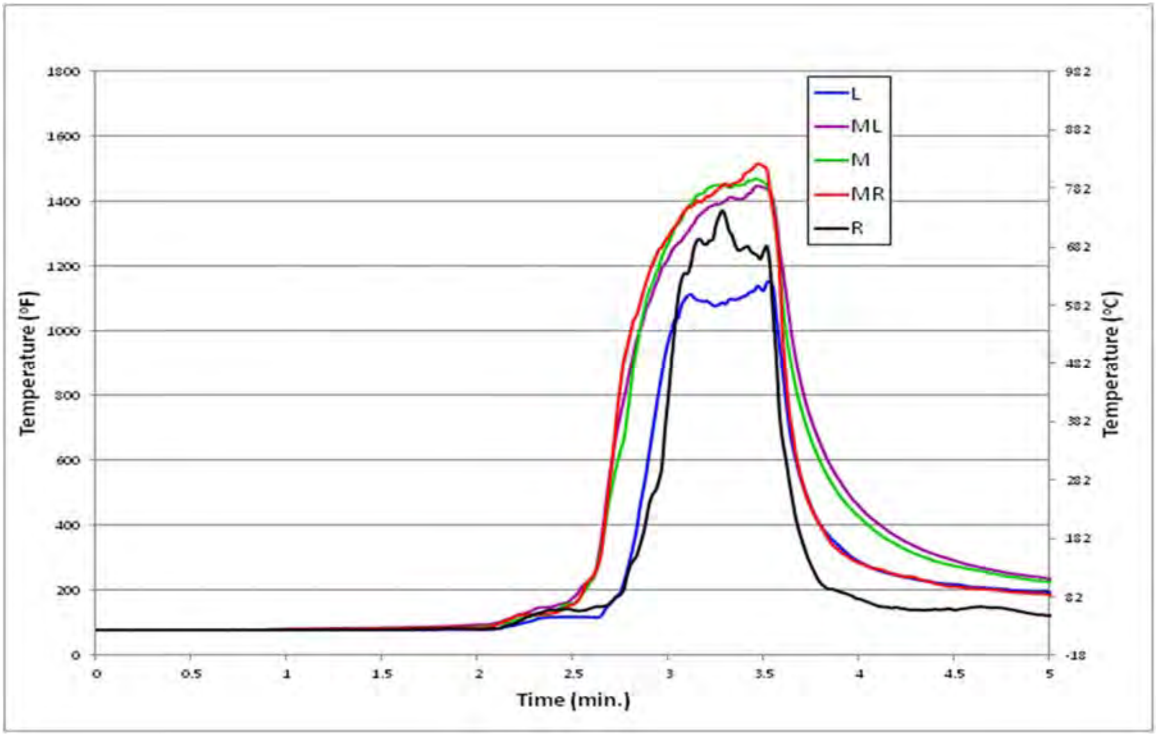


Figure H. 25: Eave Experiment 2 Back Attic Temperatures

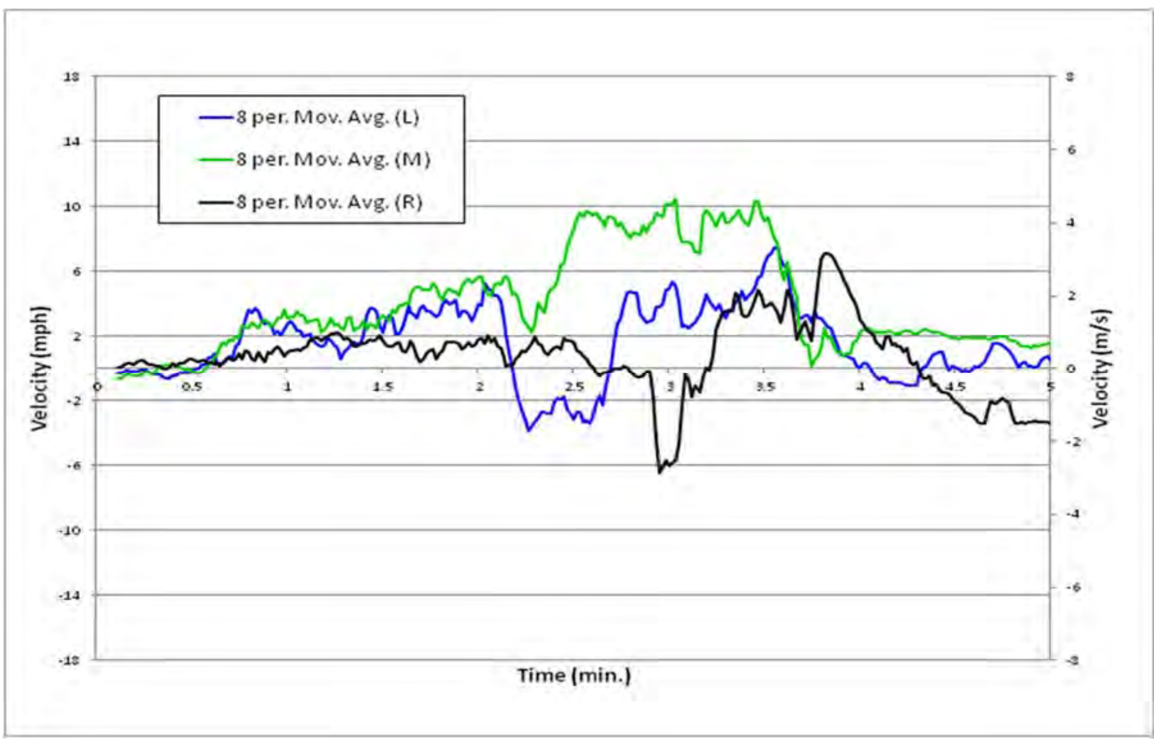


Figure H. 26: Eave Eave Experiment 2 Eave Flow Velocity

Experiment 3

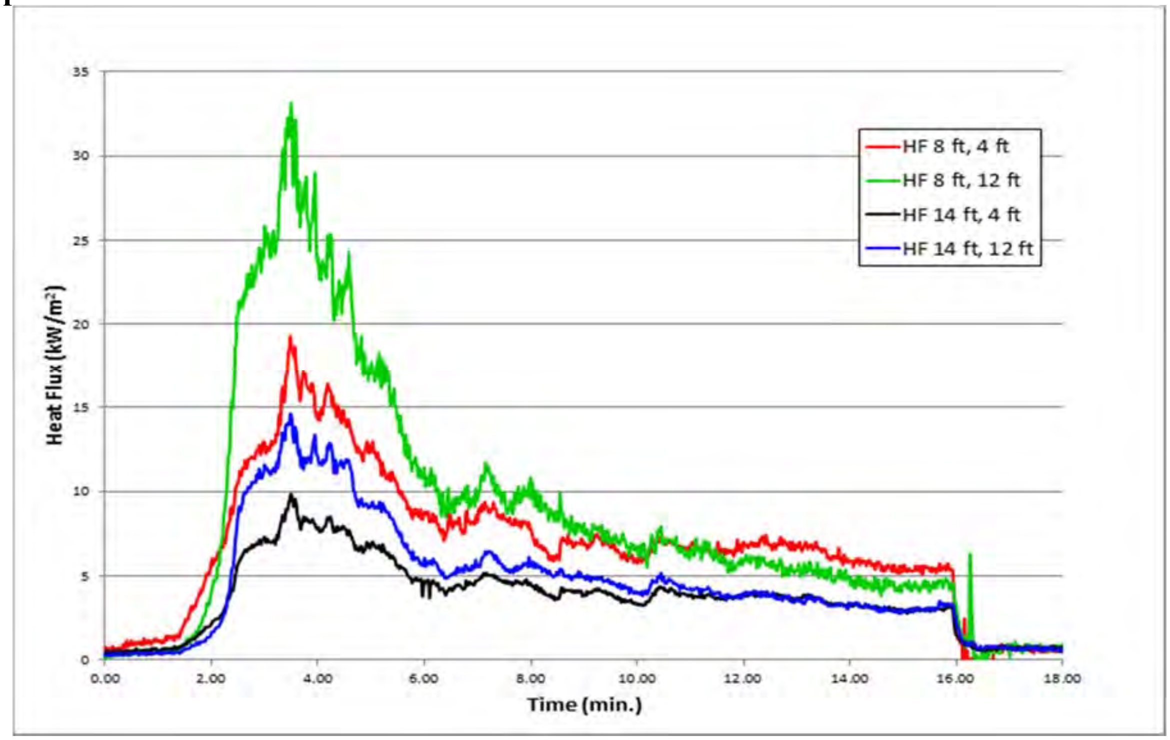


Figure H. 27: Eave Experiment 3 Heat Flux

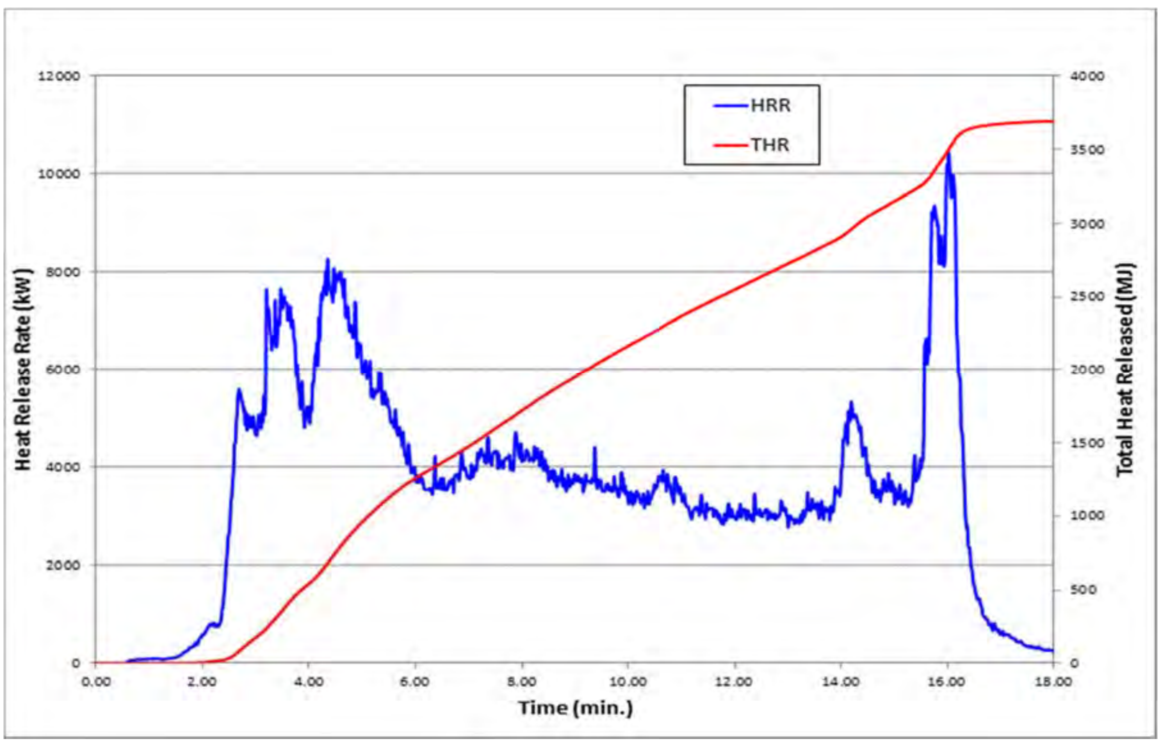


Figure H. 28: Eave Experiment 3 Heat Release Rate and Total Heat Released

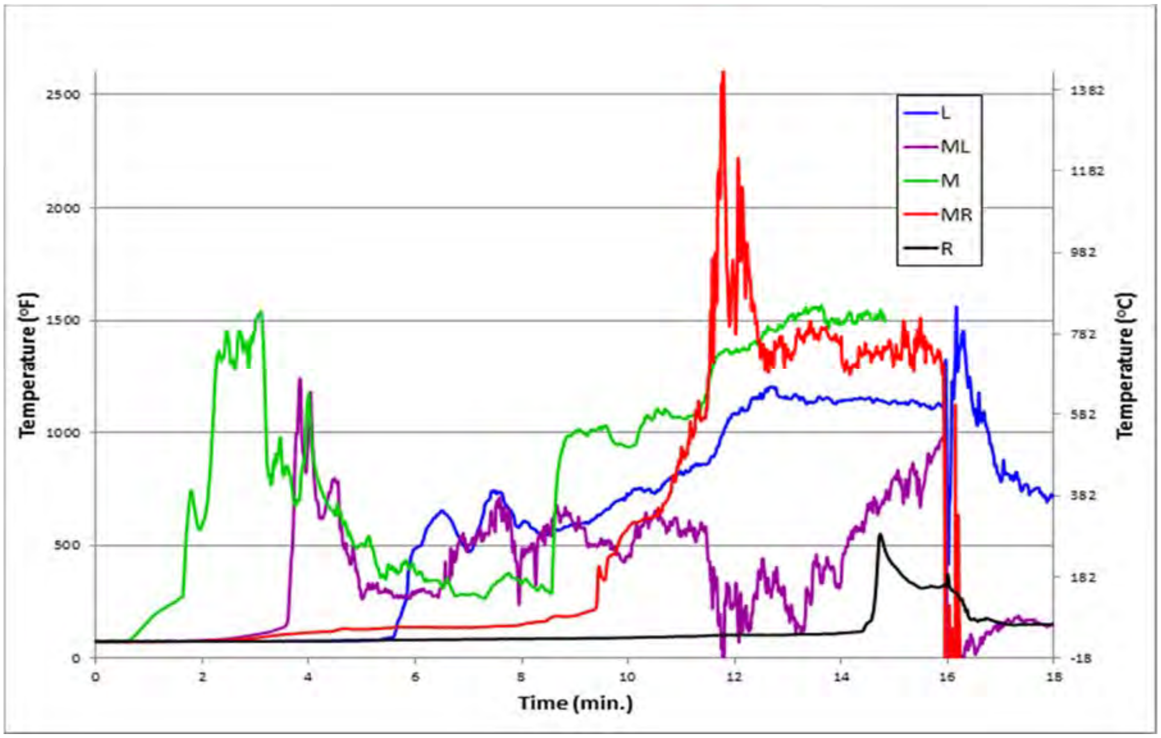


Figure H. 29: Eave Experiment 3 Bottom under Siding Temperatures

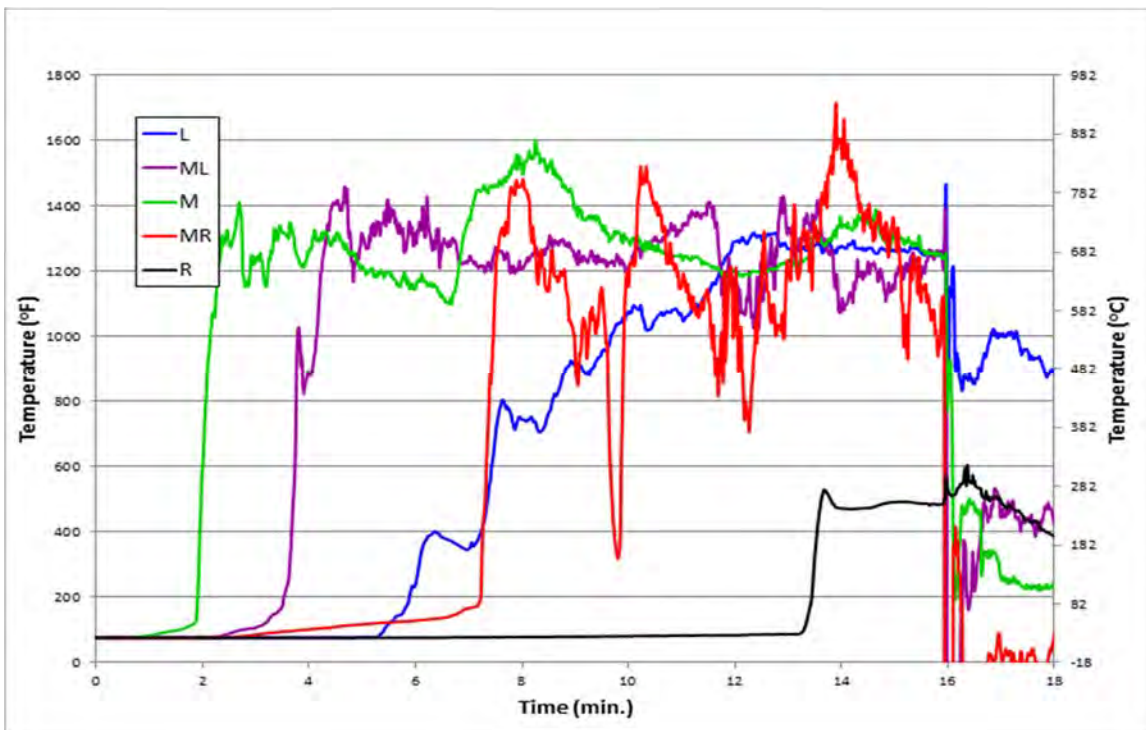


Figure H. 30: Eave Experiment 3 Middle Bottom under Siding Temperatures

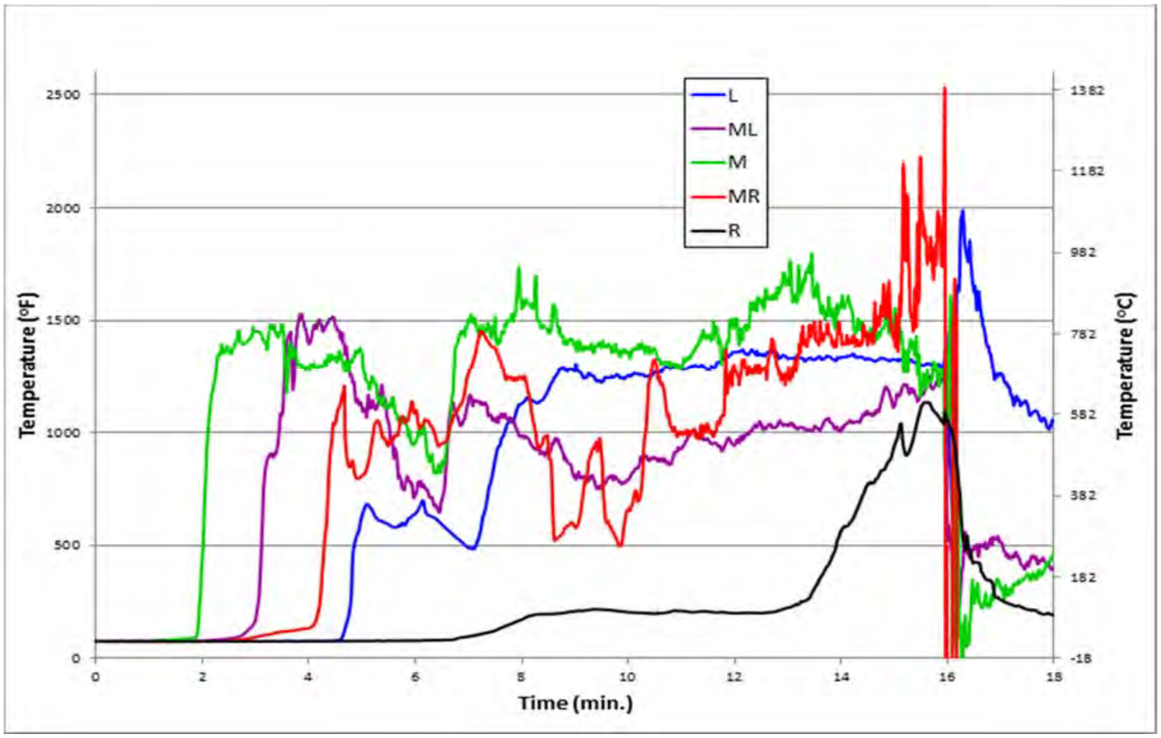


Figure H. 31: Eave Experiment 3 Middle Top under Siding Temperatures

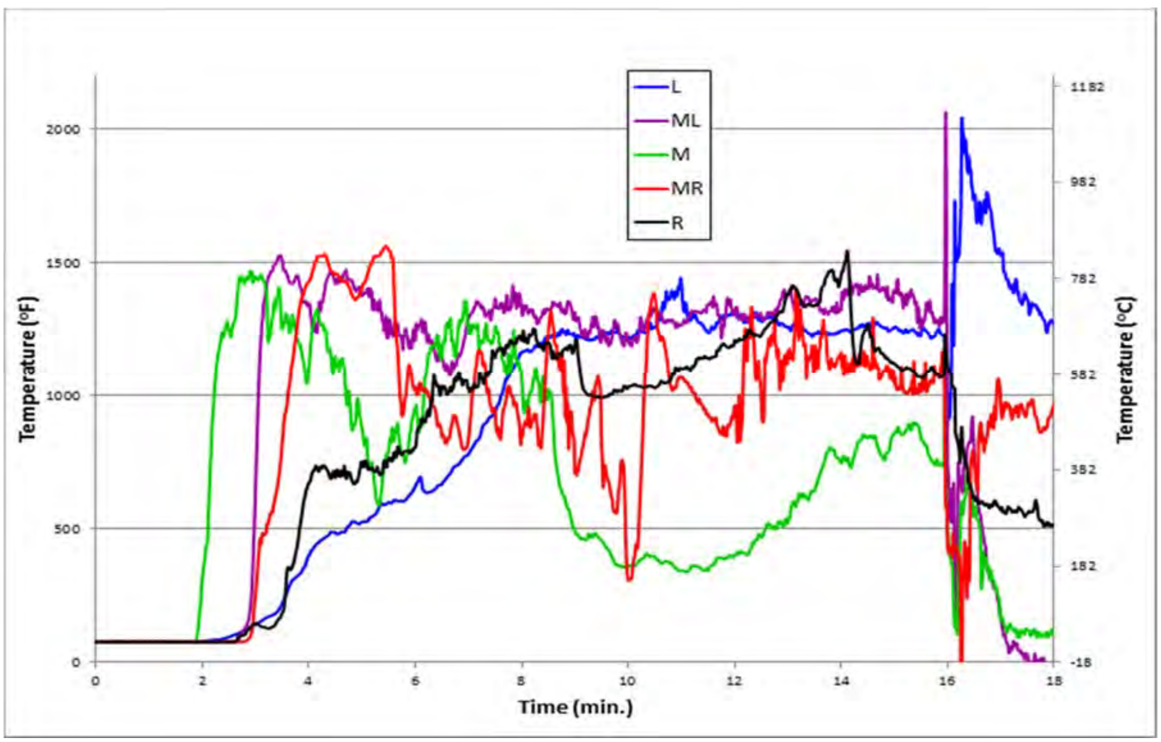


Figure H. 32: Eave Experiment 3 Top under Siding Temperatures

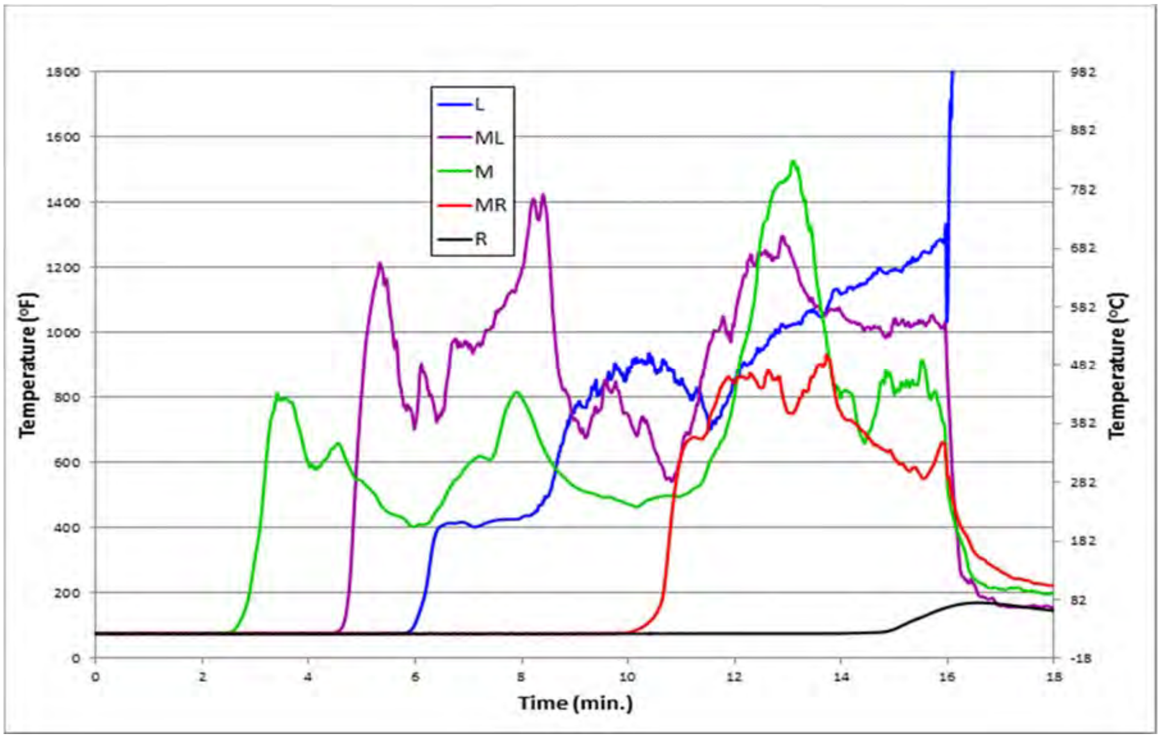


Figure H. 33: Eave Experiment 3 Bottom Wall Cavity Temperatures

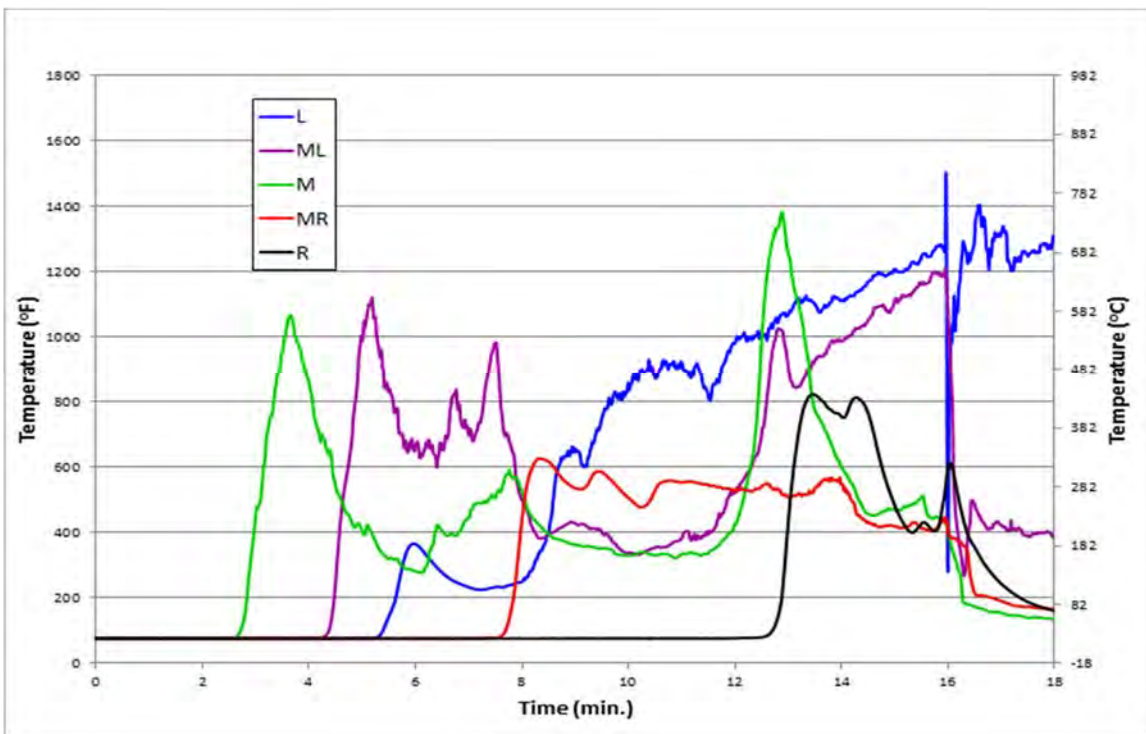


Figure H. 34: Eave Experiment 3 Middle Bottom Wall Cavity Temperatures

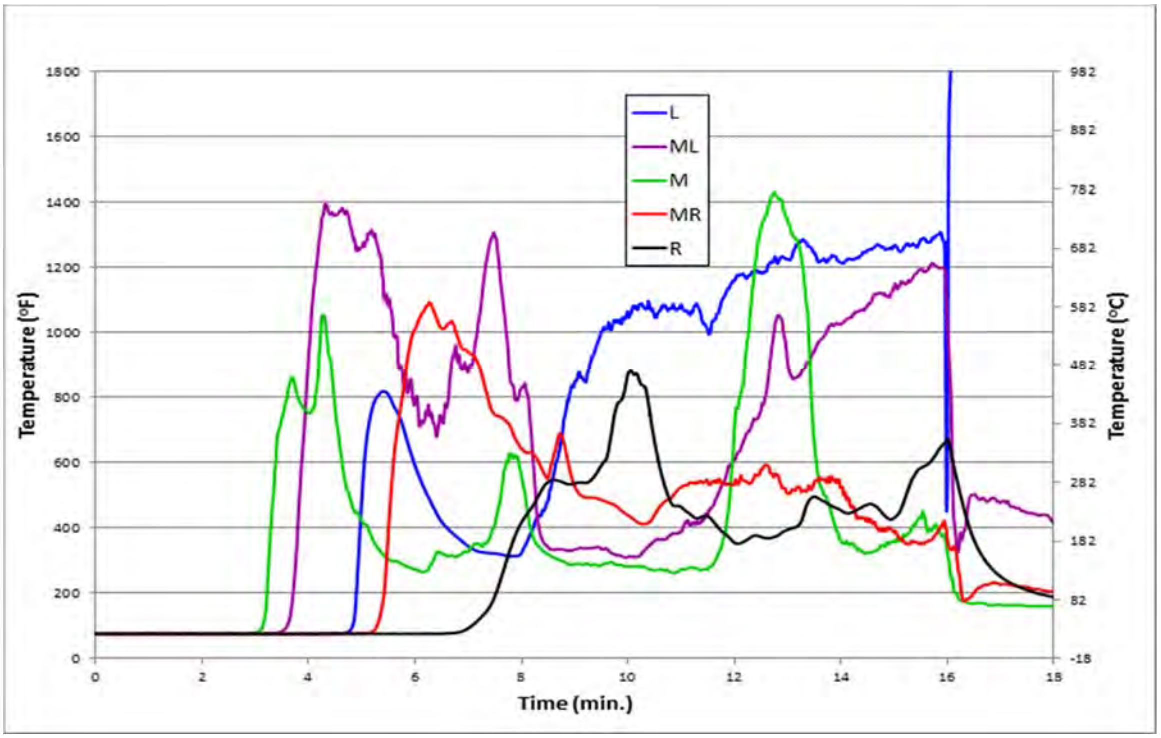


Figure H. 35: Eave Experiment 3 Middle Top Wall Cavity Temperatures

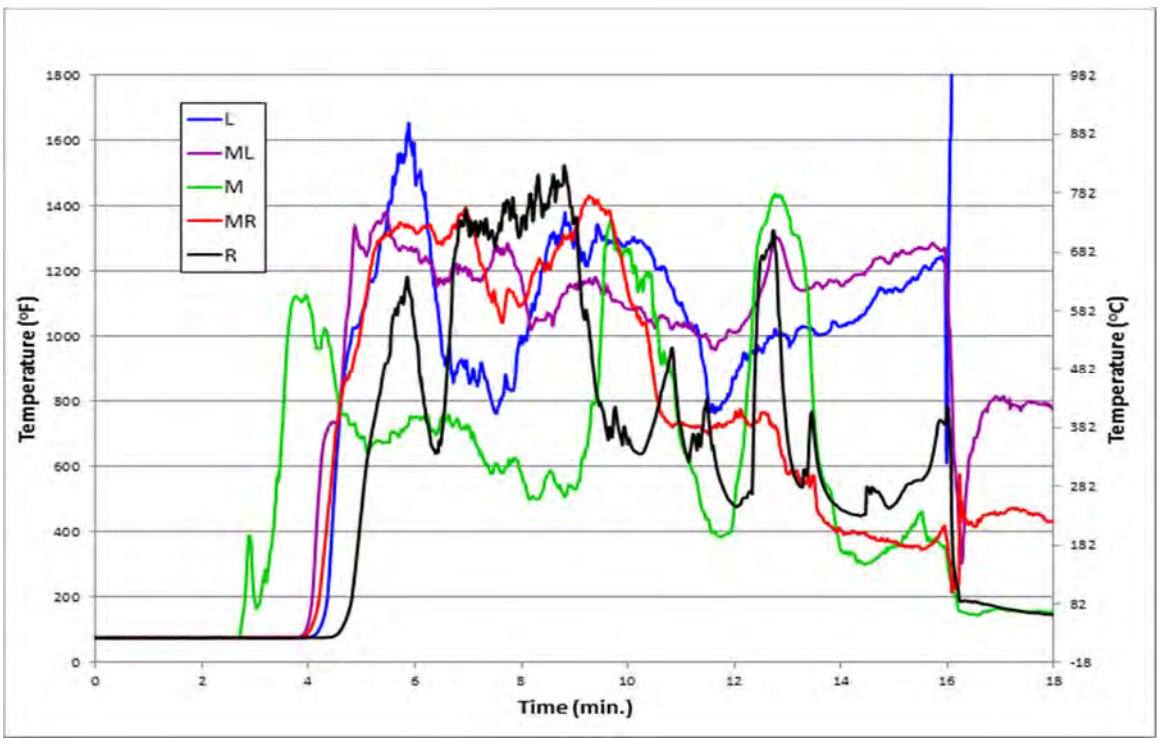


Figure H. 36: Eave Experiment 3 Top Wall Cavity Temperatures

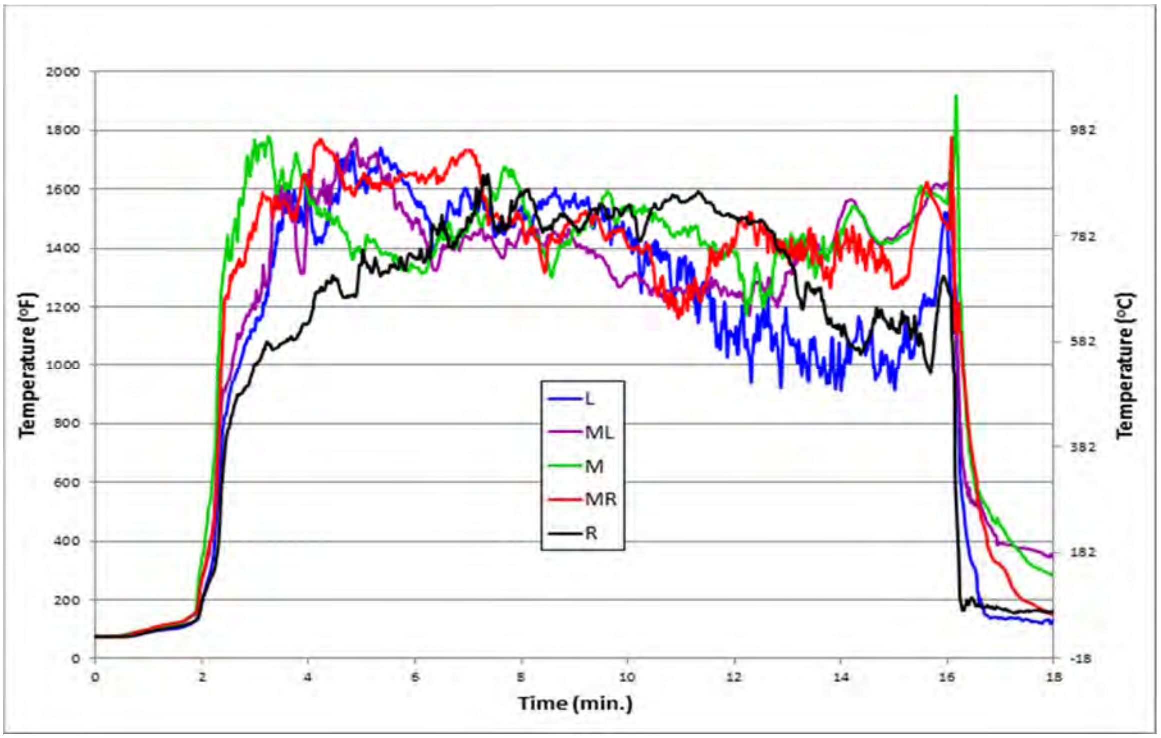


Figure H. 37: Eave Experiment 3 Eave Attic Temperatures

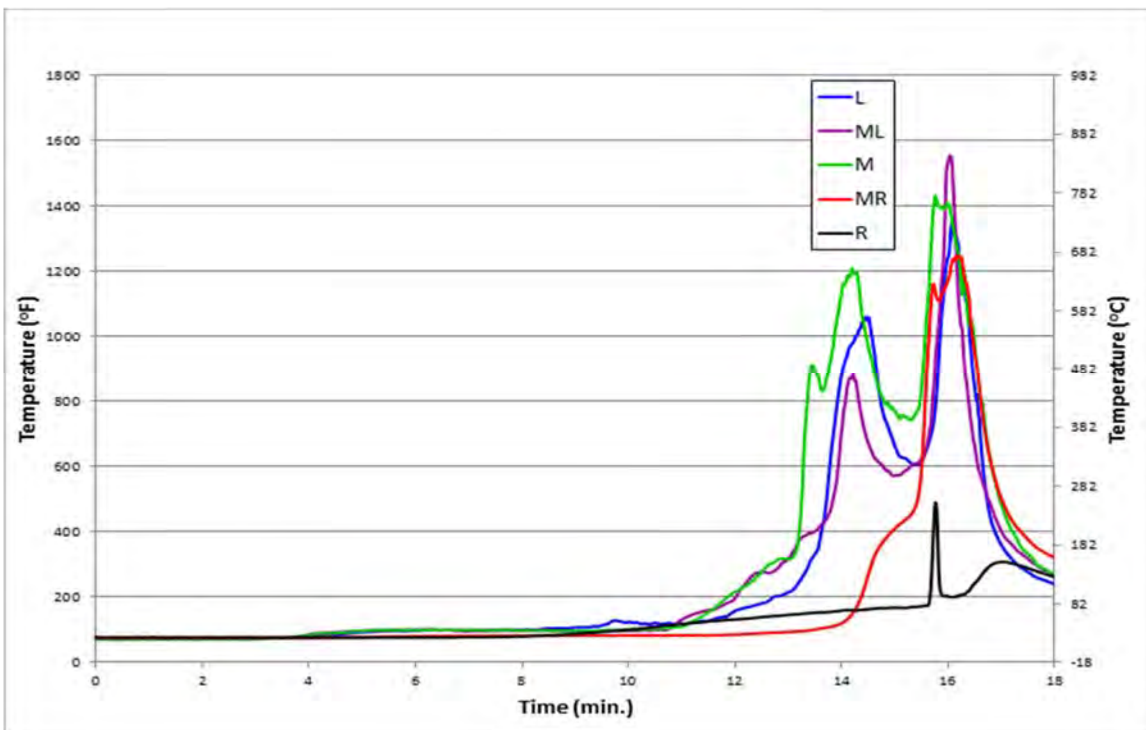


Figure H. 38: Eave Experiment 3 Back Attic Temperatures

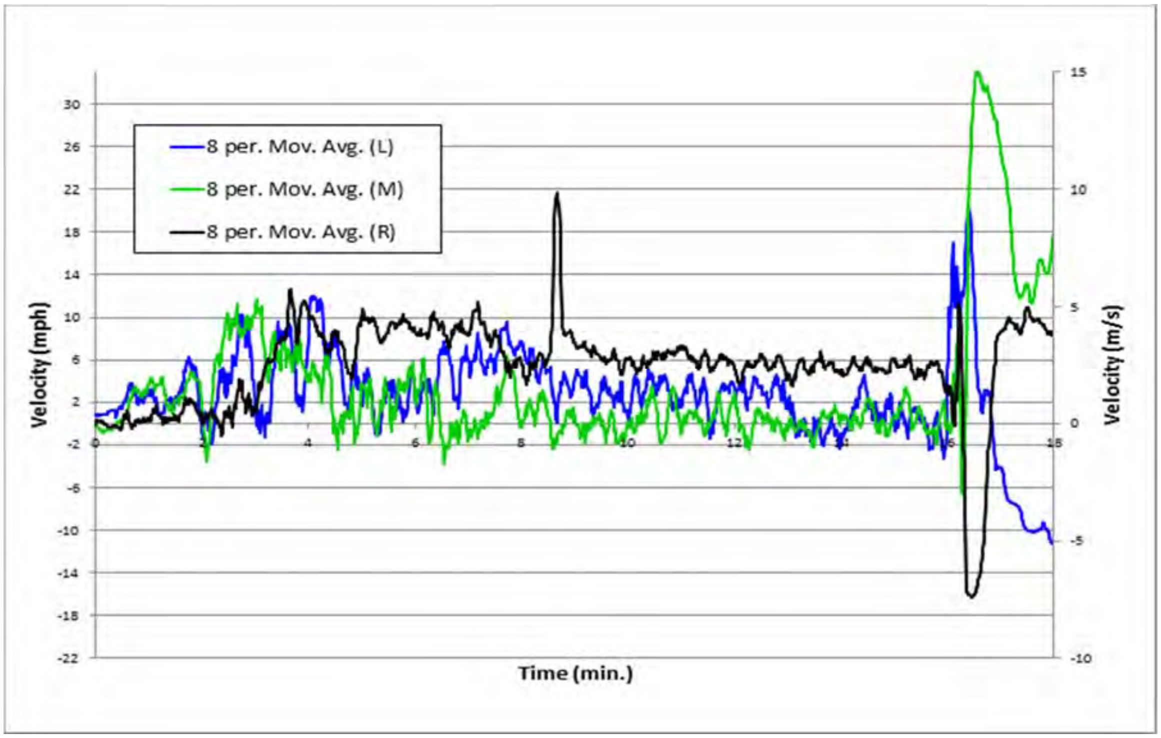
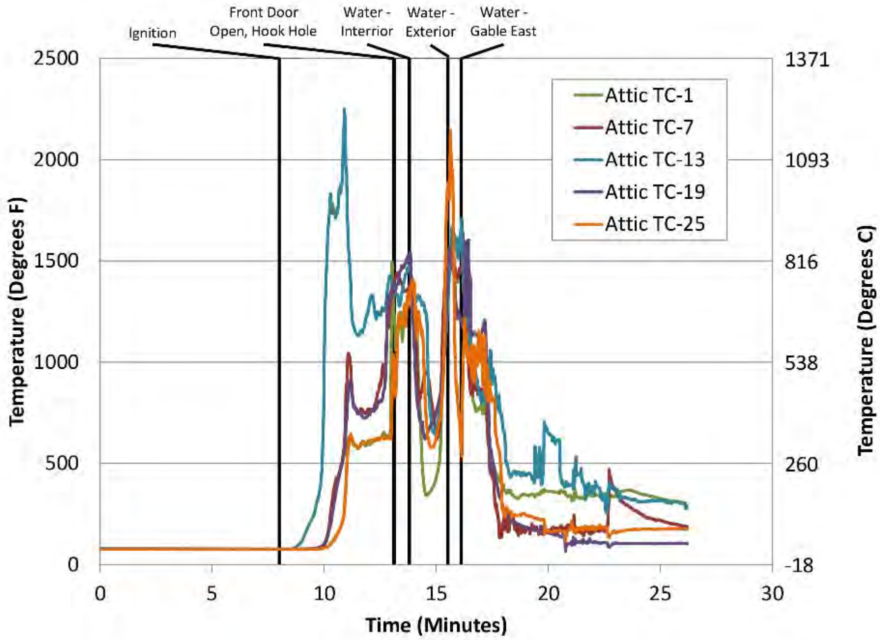


Figure H. 39: Eave Experiment 3 Eave Flow Velocity

Appendix I: Full Scale Attic Experiment Data

Experiment 1



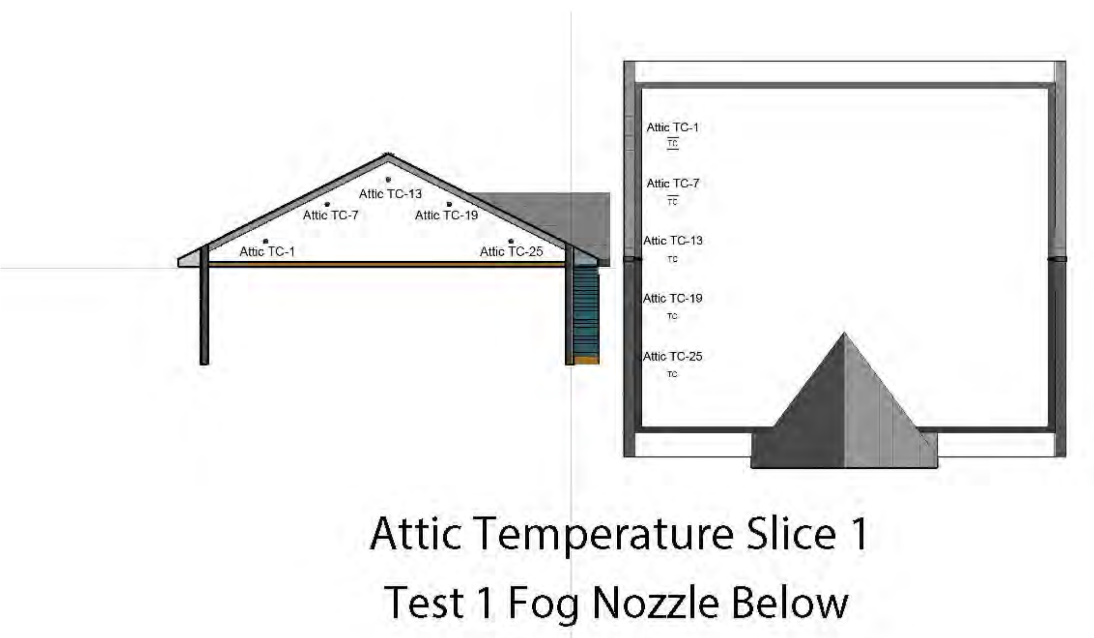
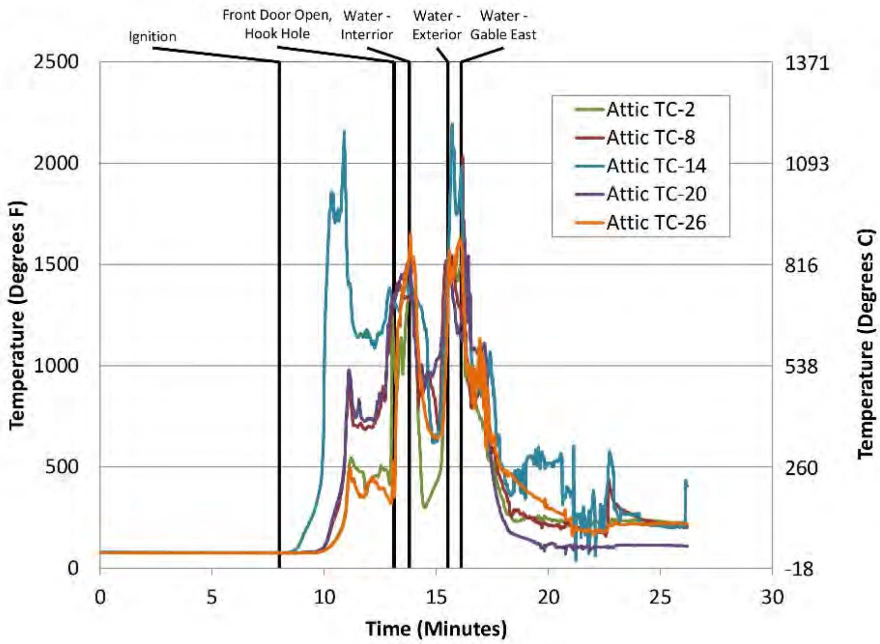
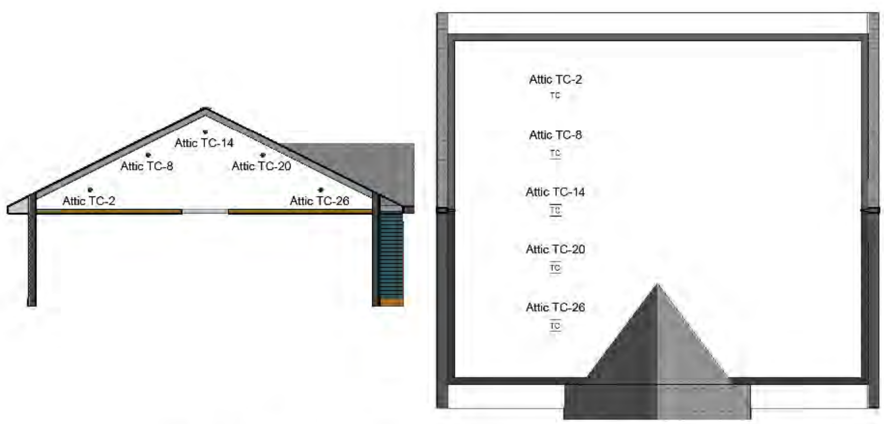


Figure I. 1: Attic Experiment 1 Attic Temperature Slice 1

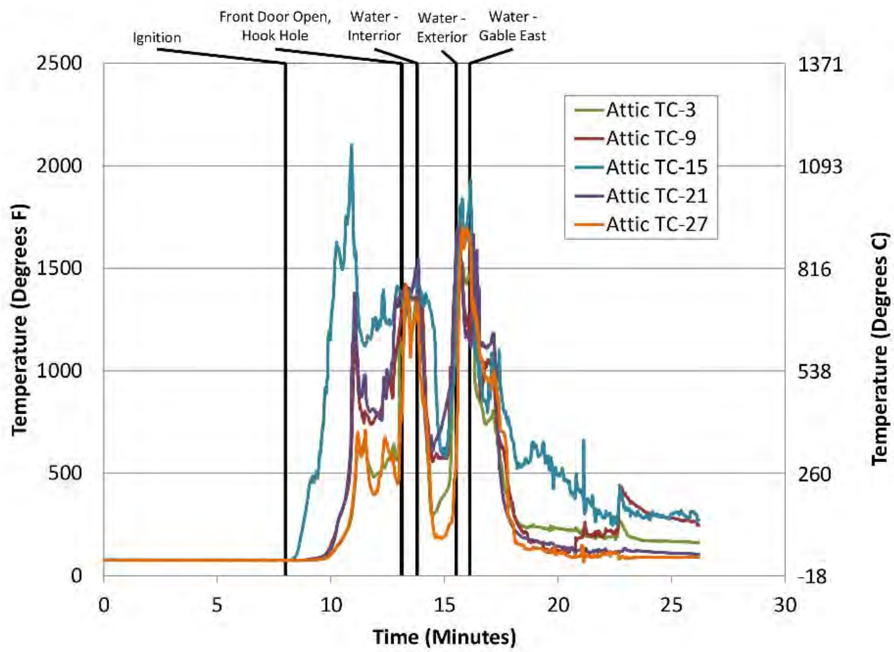




Attic Temperature Slice 2

Test 1 Fog Nozzle Below

Figure I. 2: Attic Experiment 1 Attic Temperature Slice 2



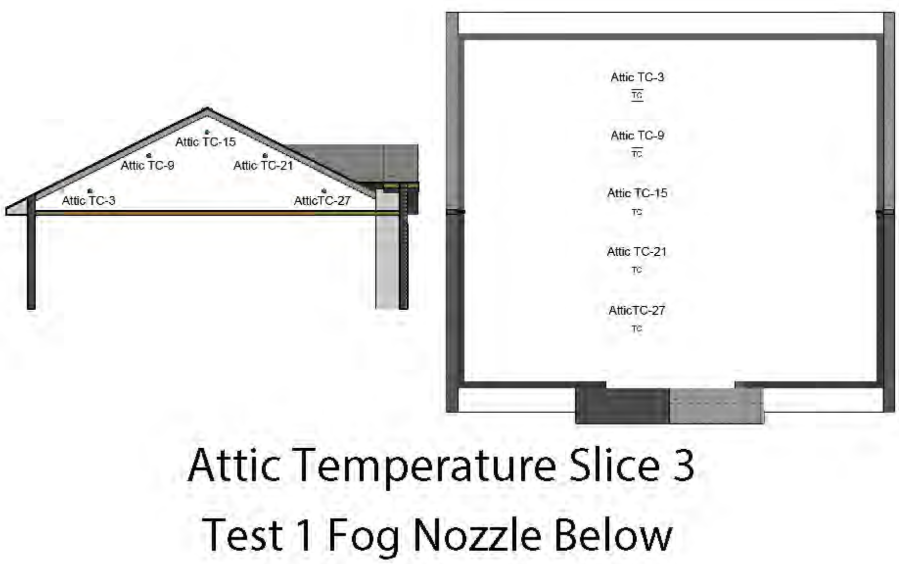
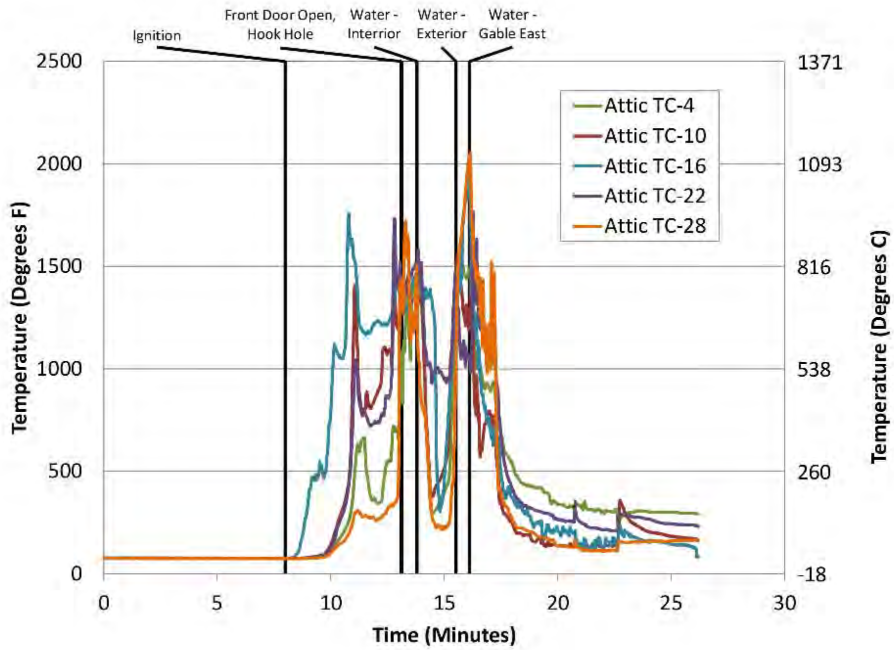


Figure I. 3: Attic Experiment 1 Attic Temperature Slice 3



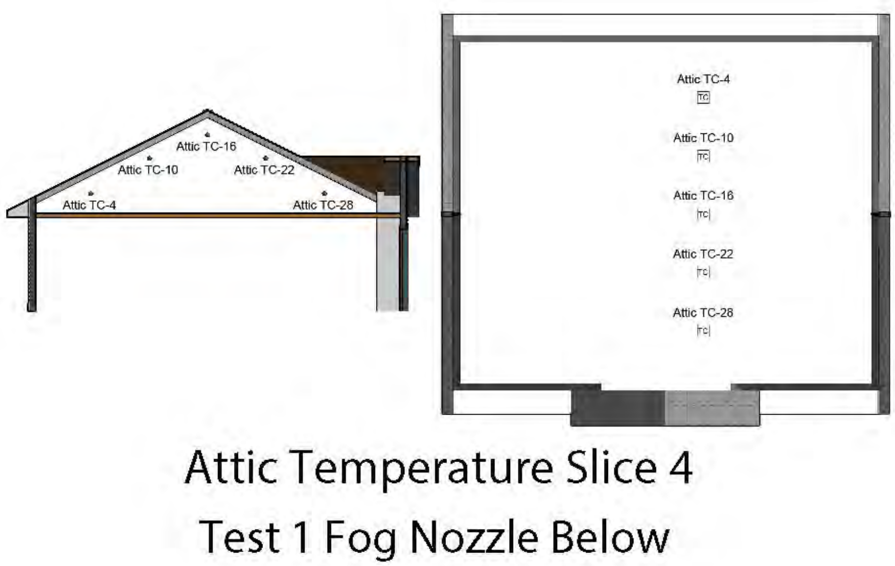
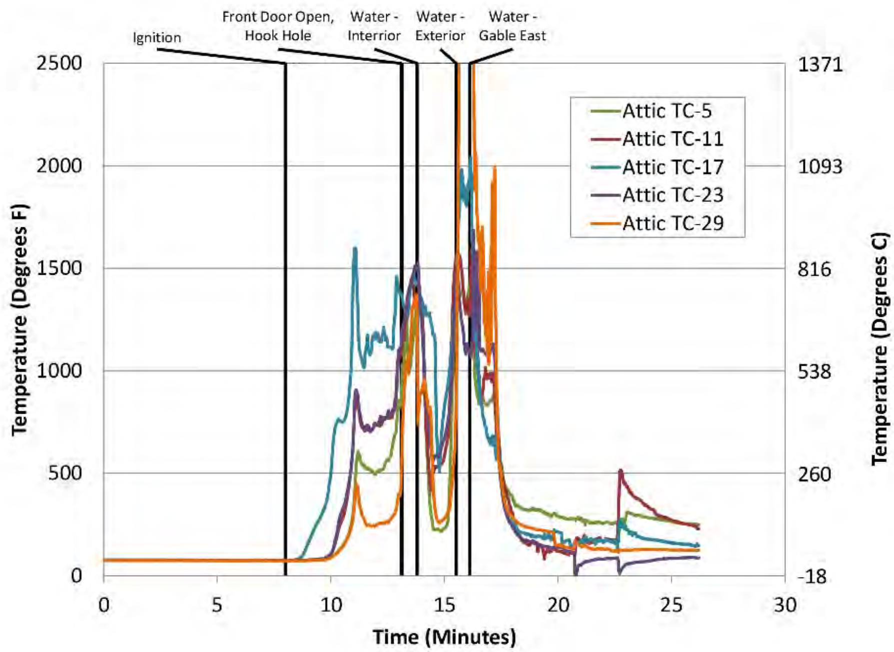


Figure I. 4: Attic Experiment 1 Attic Temperature Slice 4



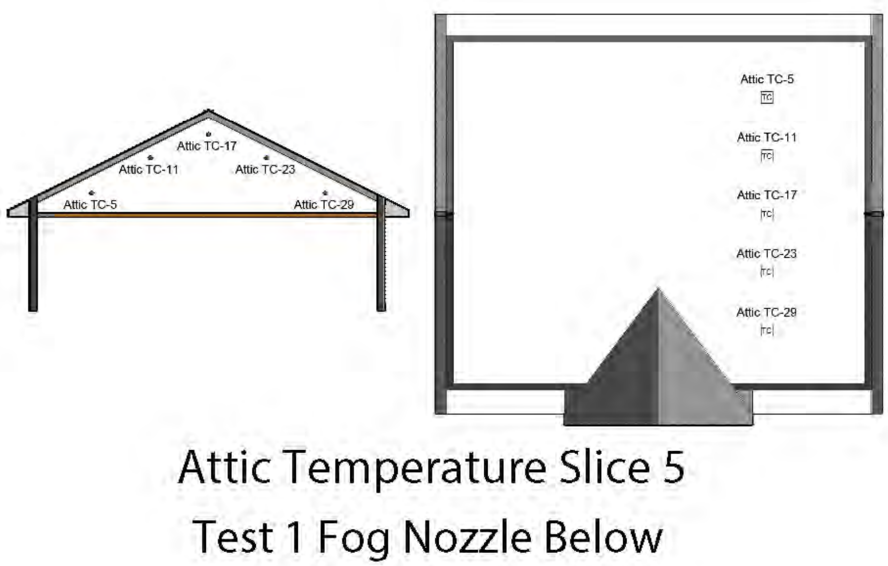
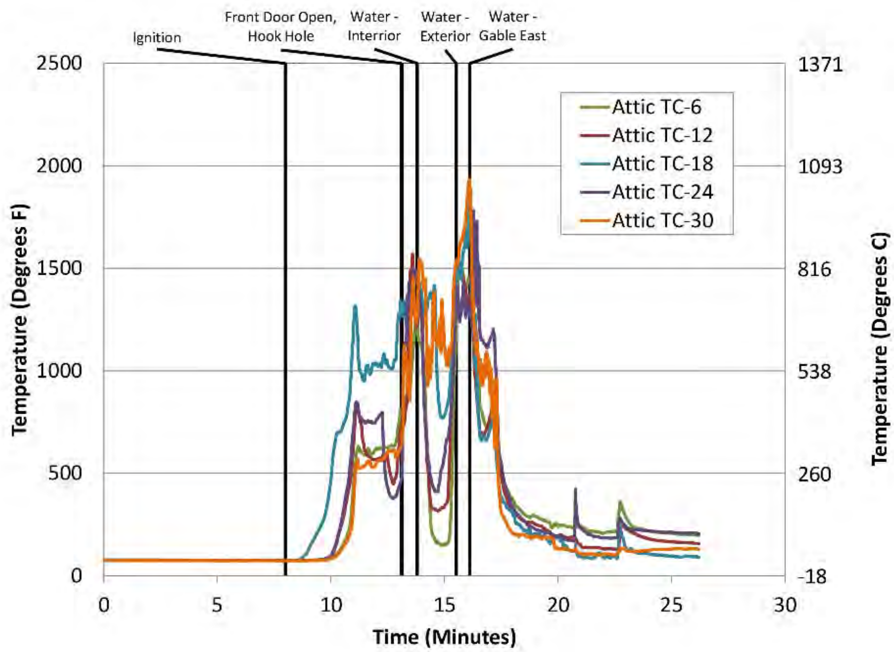


Figure I. 5: Attic Experiment 1 Attic Temperature Slice 5



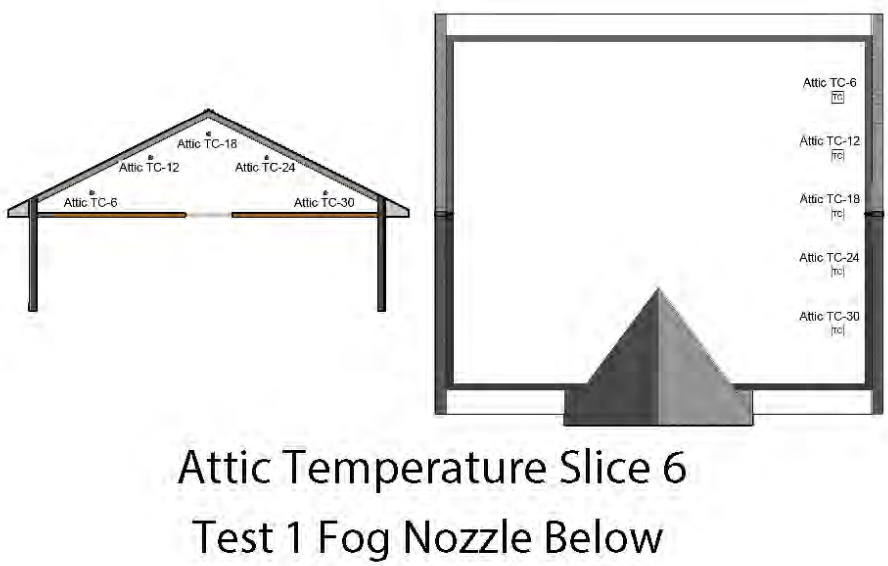
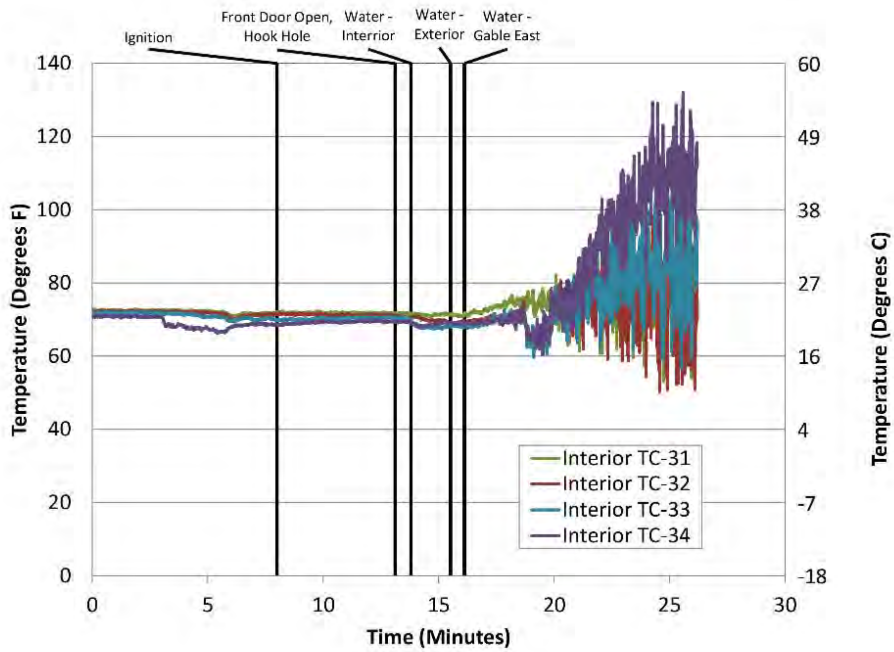


Figure I. 6: Attic Experiment 1 Attic Temperature Slice 6



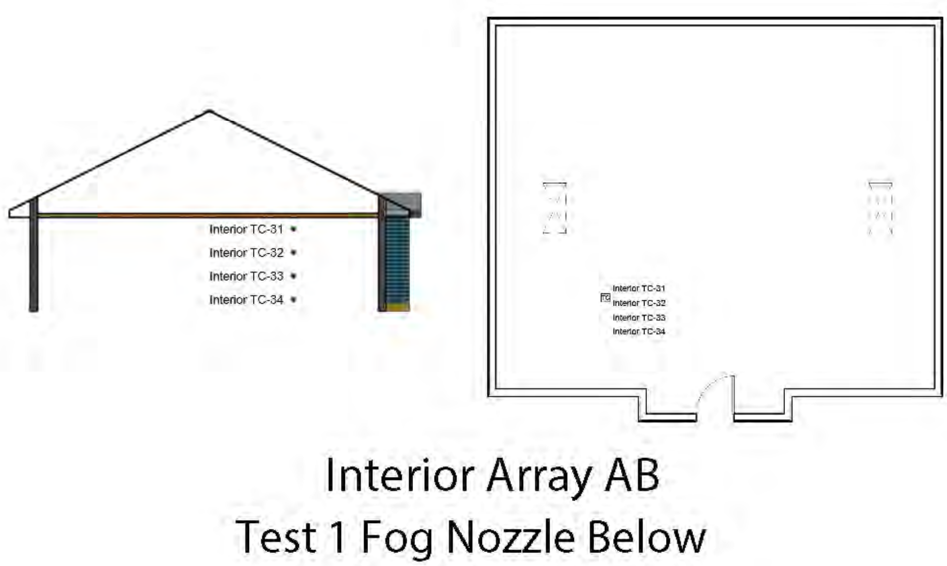
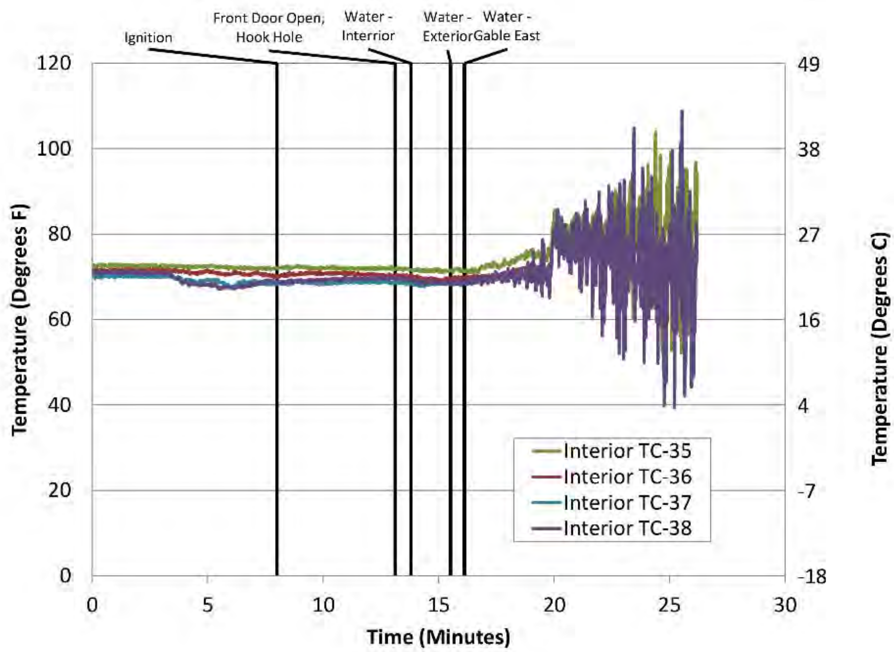


Figure I. 7: Attic Experiment 1 Attic Interior Array AB



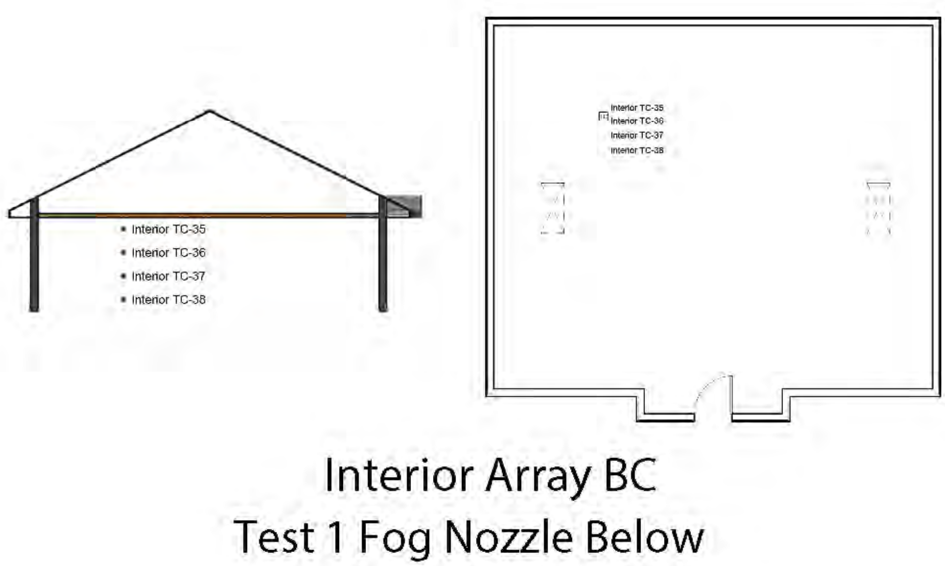
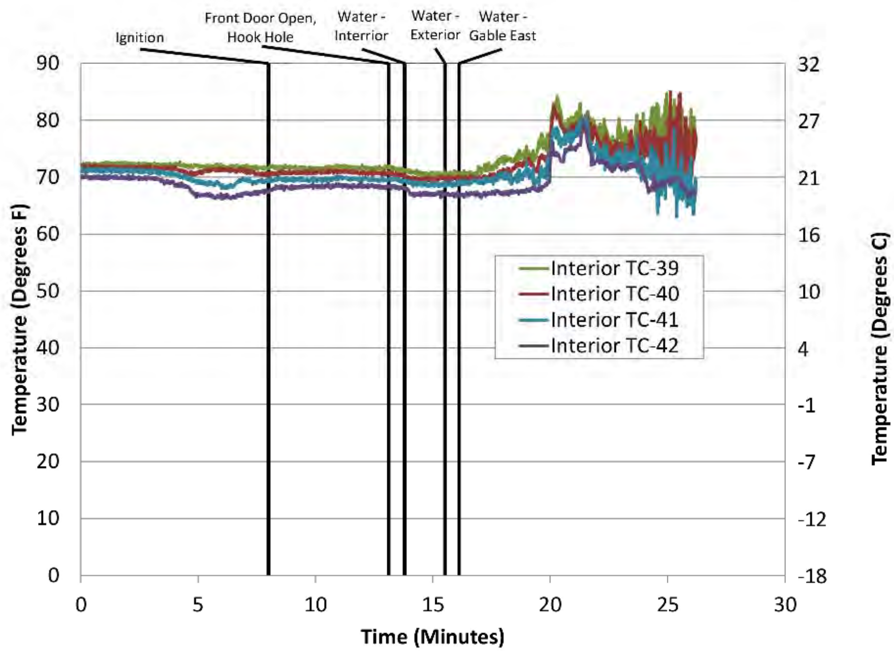


Figure I. 8: Attic Experiment 1 Attic Interior Array AB



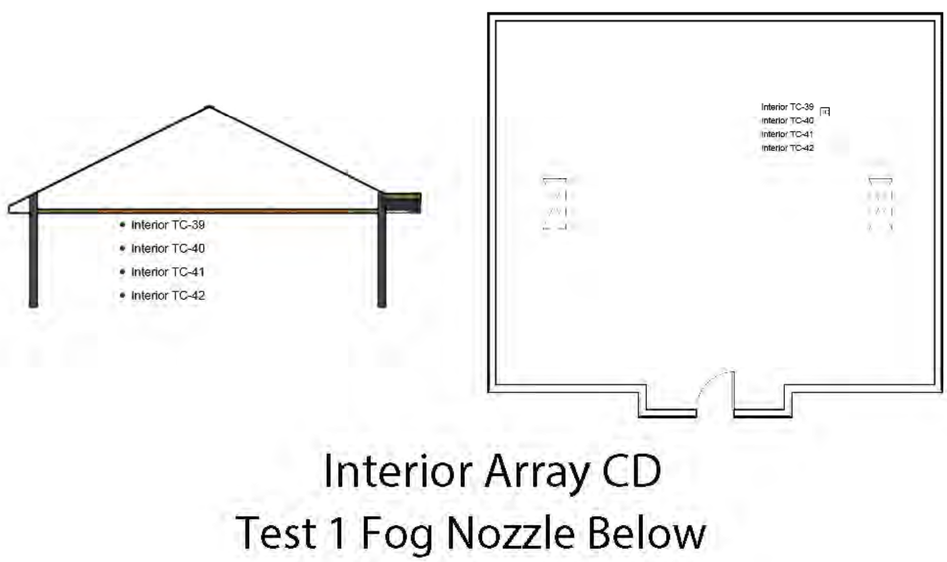
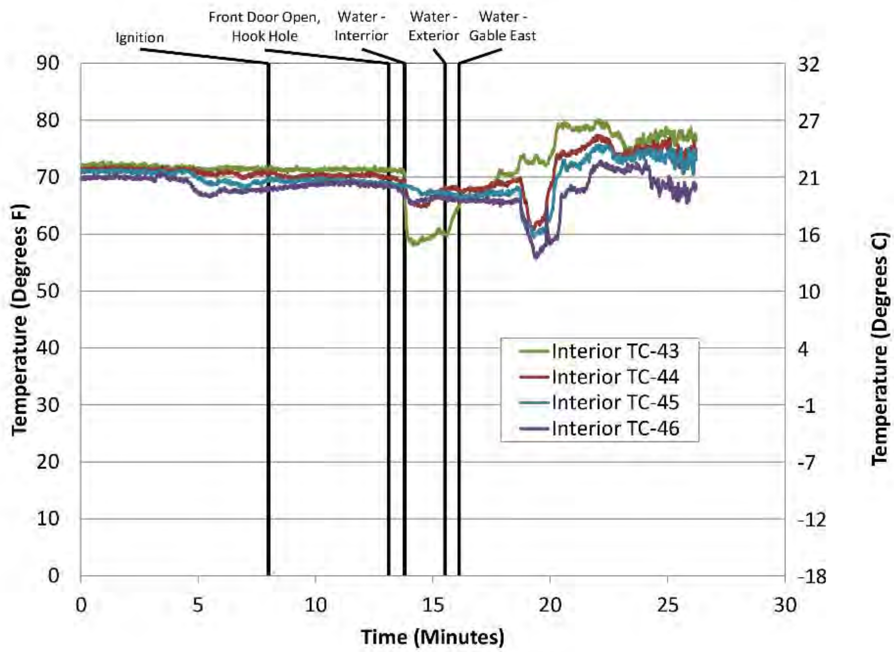


Figure I. 9: Attic Experiment 1 Attic Interior Array CD



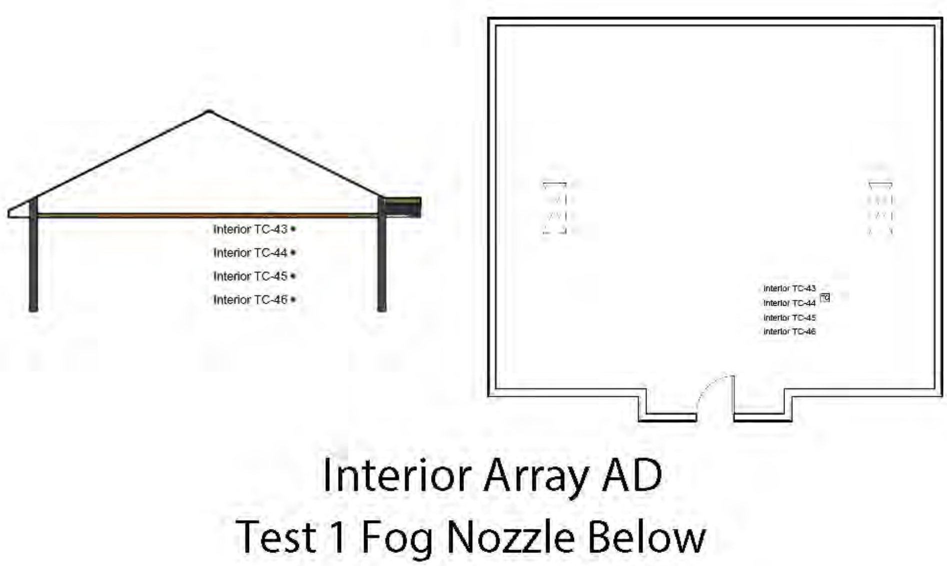
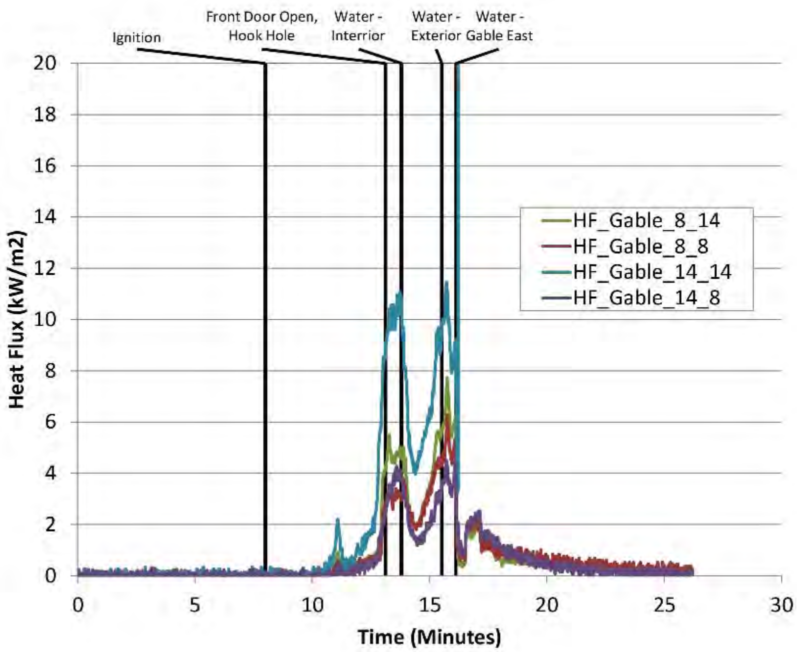
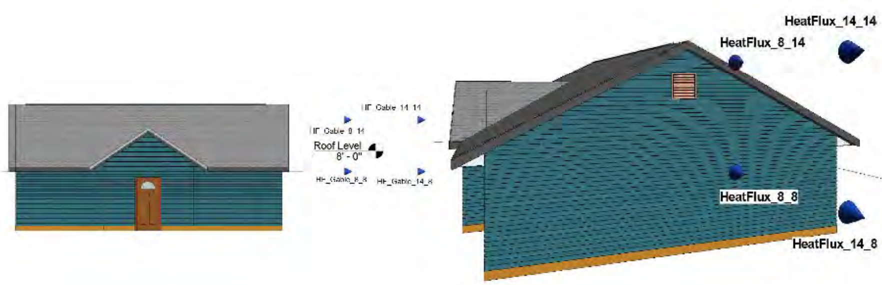


Figure I. 10: Attic Experiment 1 Attic Interior Array AD

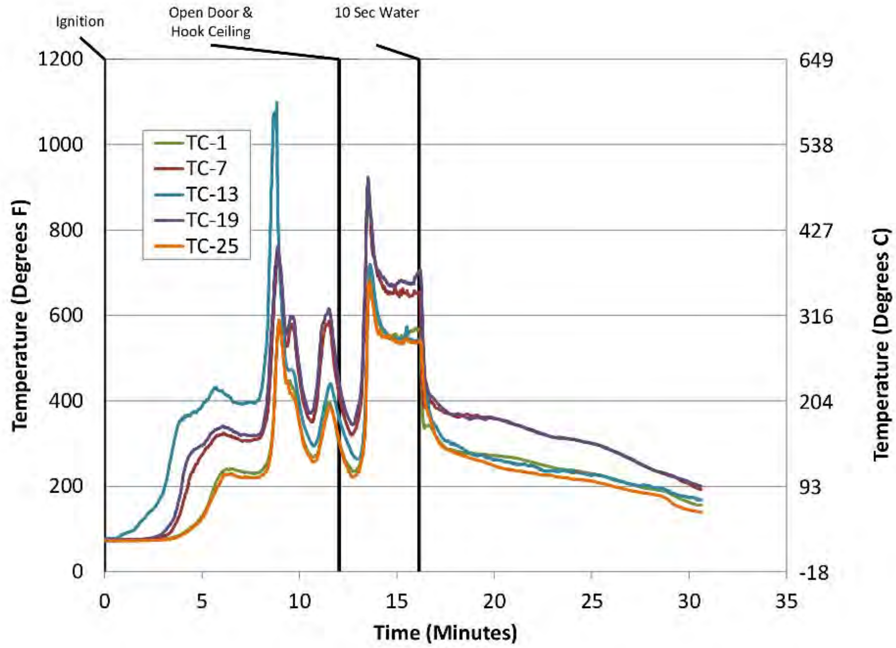




Heat Flux Gable End
Test 1 Fog Nozzle Below

Figure I. 11: Attic Experiment 1 Gable Heat Flux

Experiment 2A



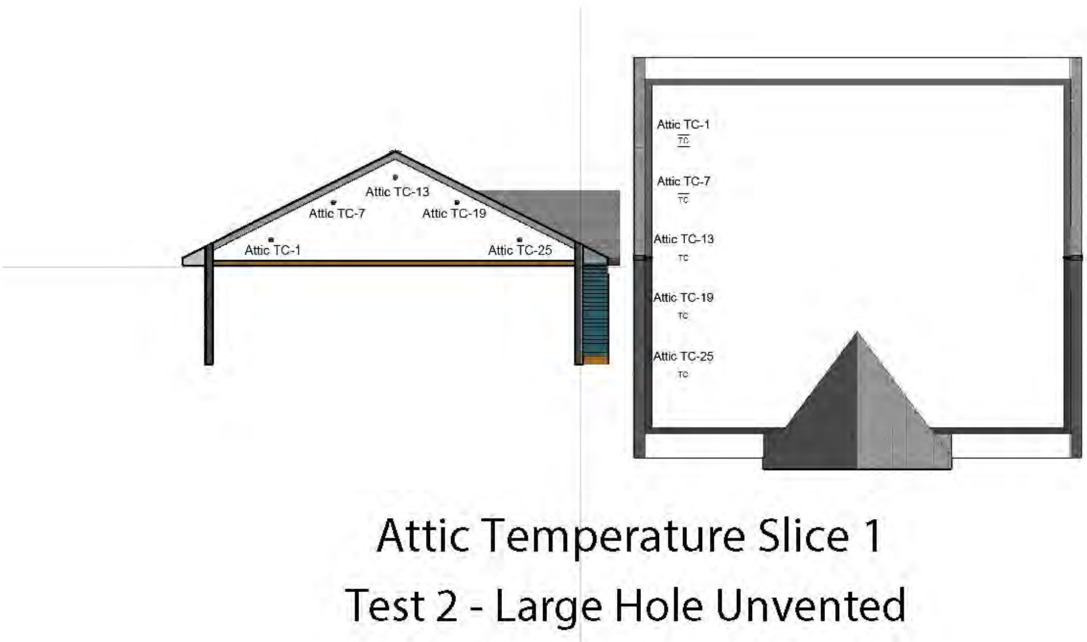


Figure I. 12: Attic Attic Experiment 2A Attic Temperature Slice 1

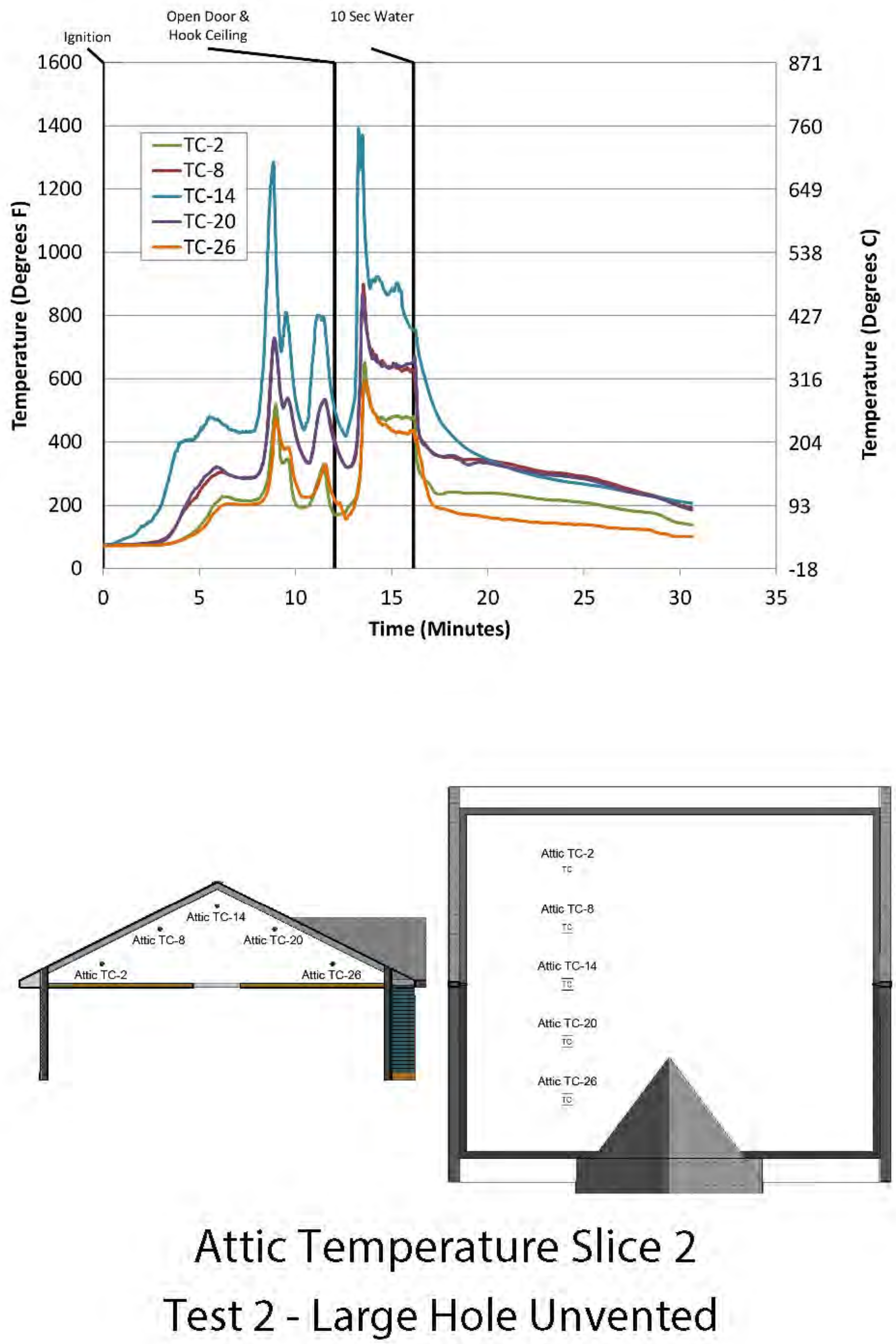
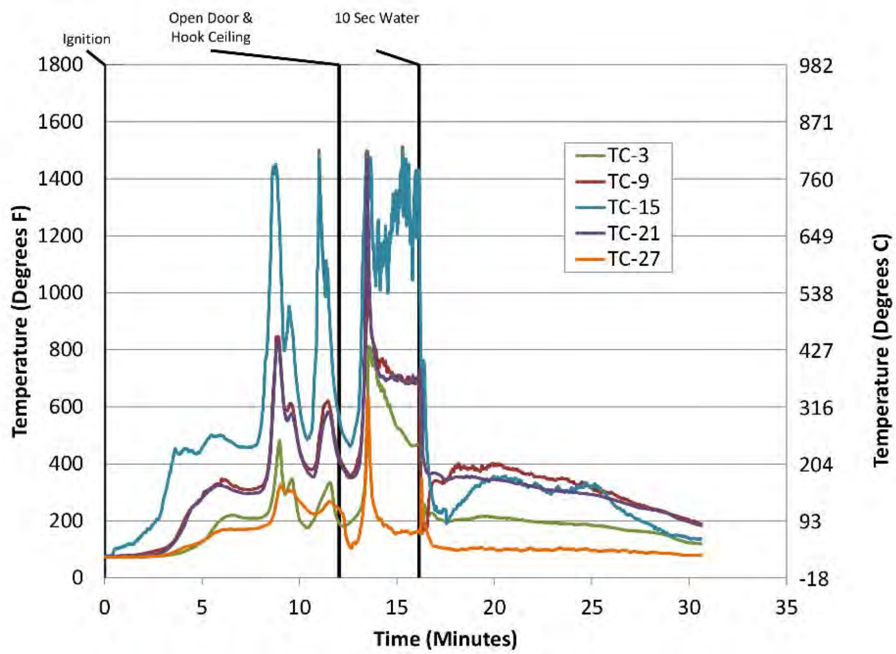


Figure I. 13: Attic Experiment 2A Attic Temperature Slice 2



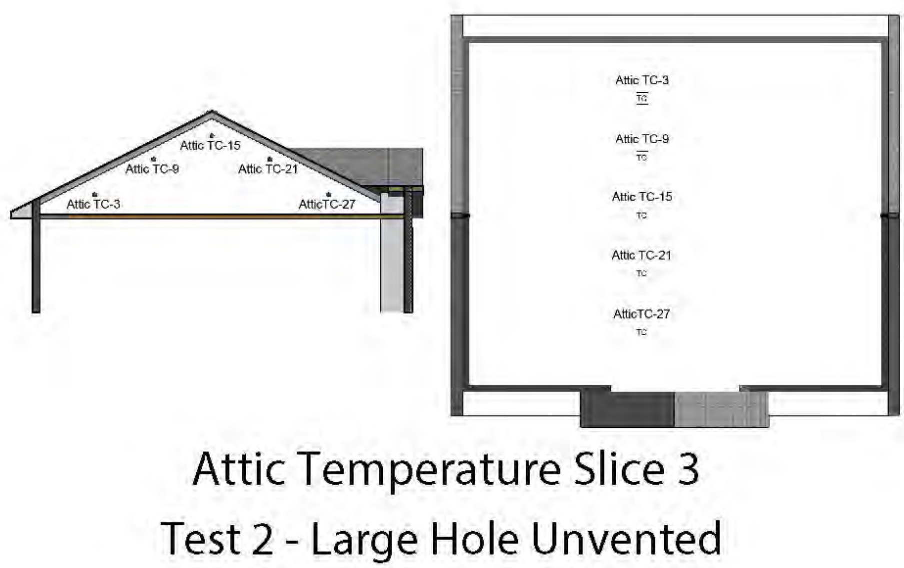


Figure I. 14: Attic Experiment 2A Attic Temperature Slice 3

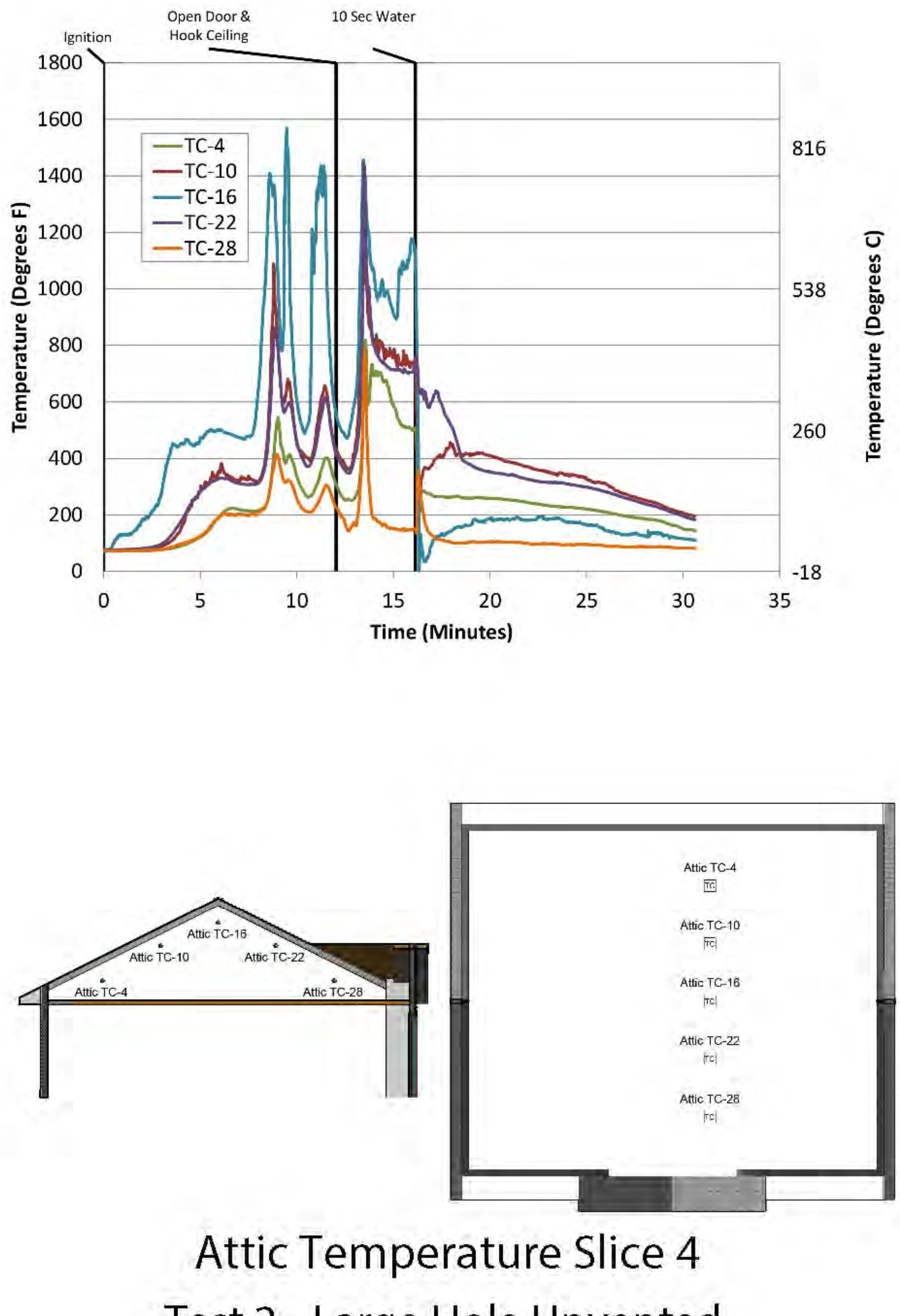
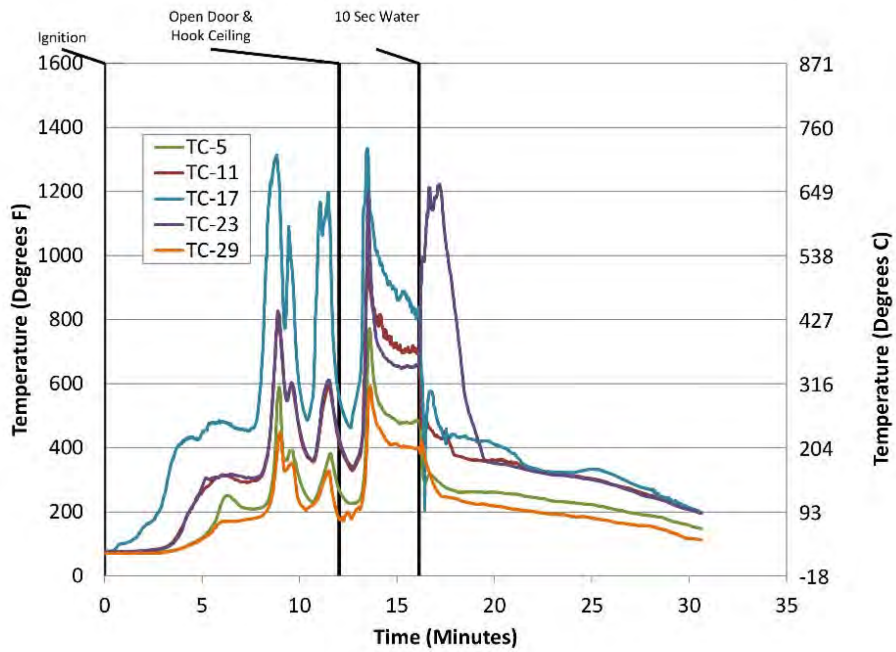


Figure I. 15: Attic Experiment 2A Attic Temperature Slice 4



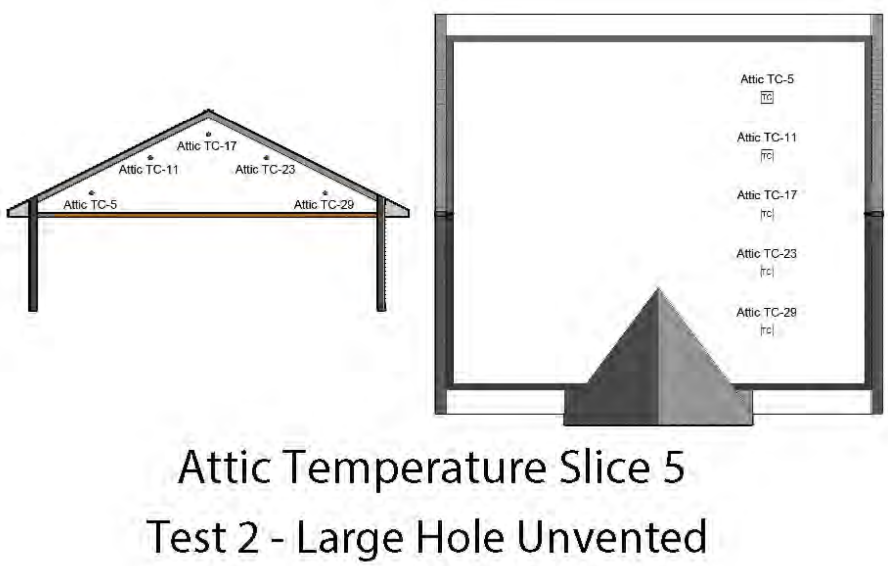
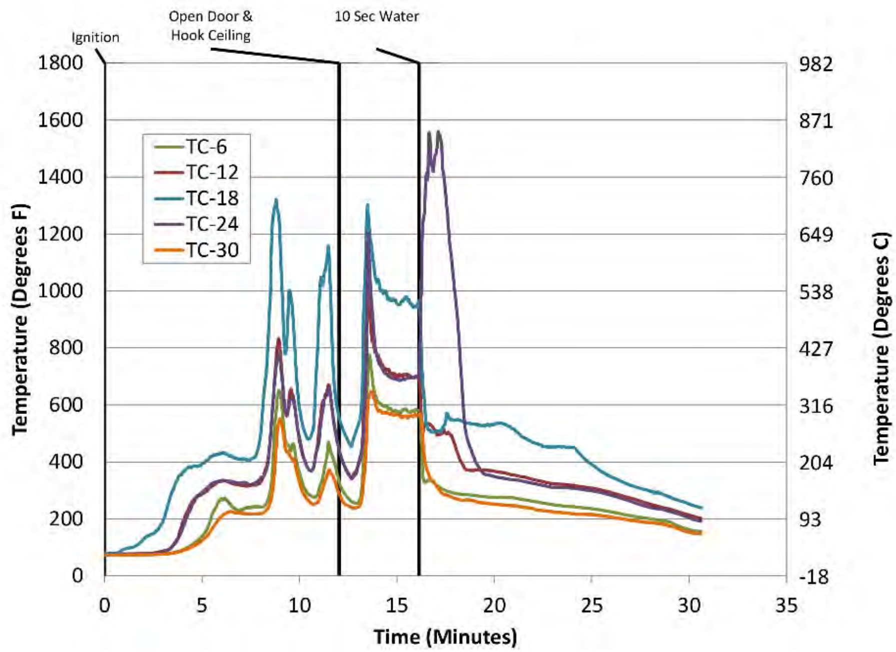


Figure I. 16: Attic Experiment 2A Attic Temperature Slice 5



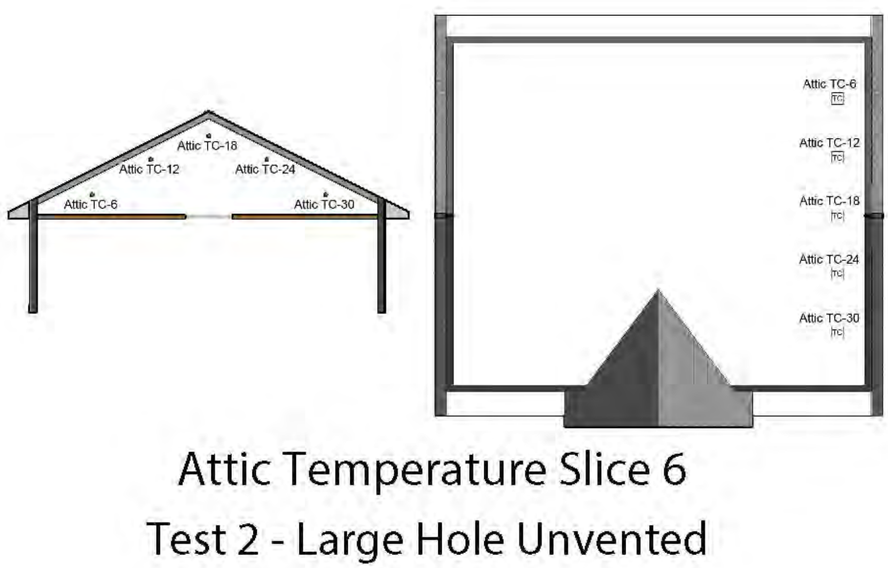
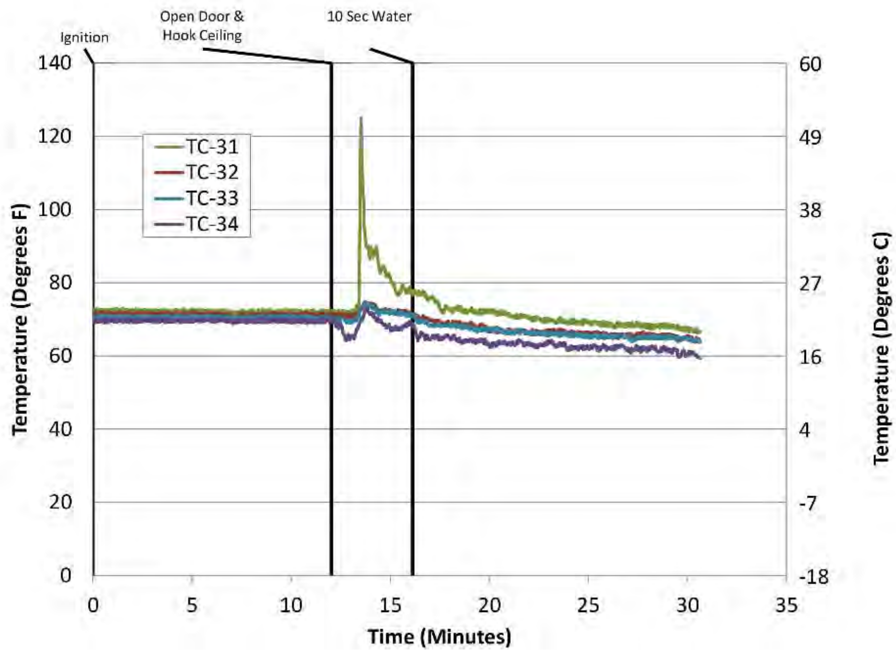


Figure I. 17: Attic Experiment 2A Attic Temperature Slice 6



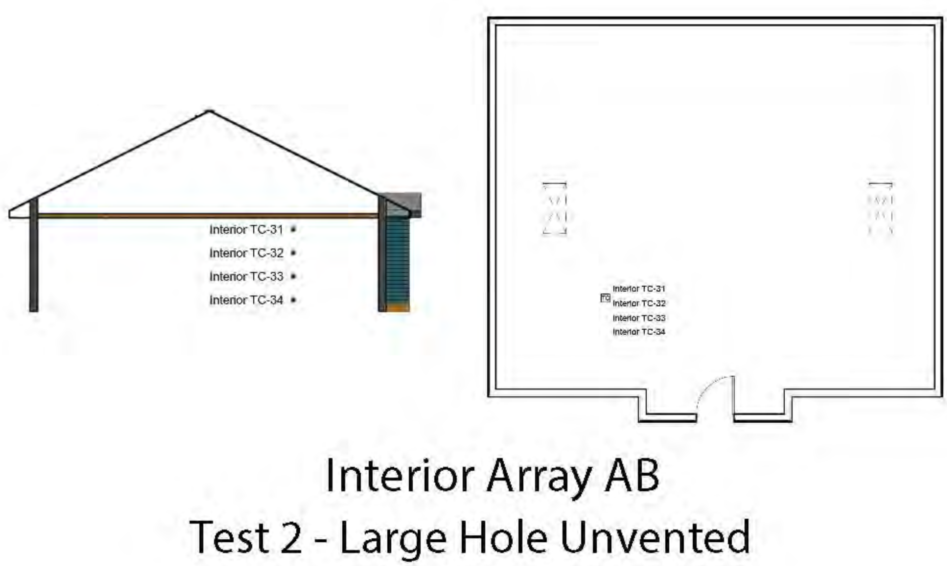
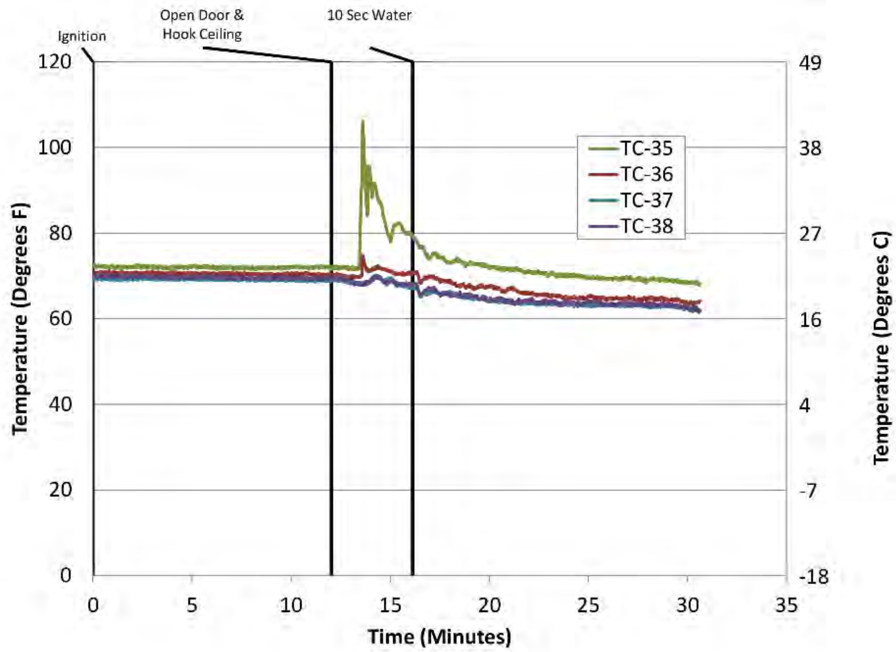


Figure I. 18: Attic Experiment 2A Interior TC Array AB



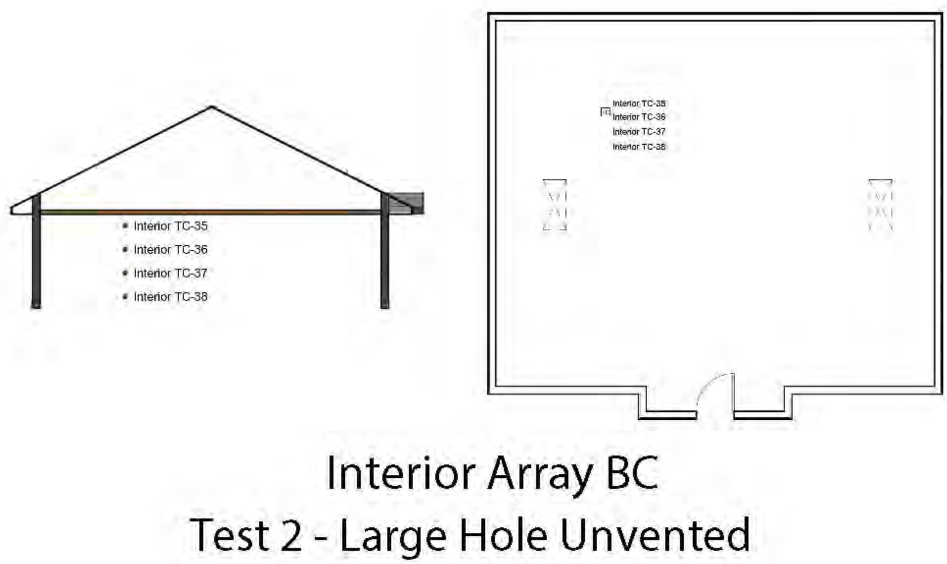
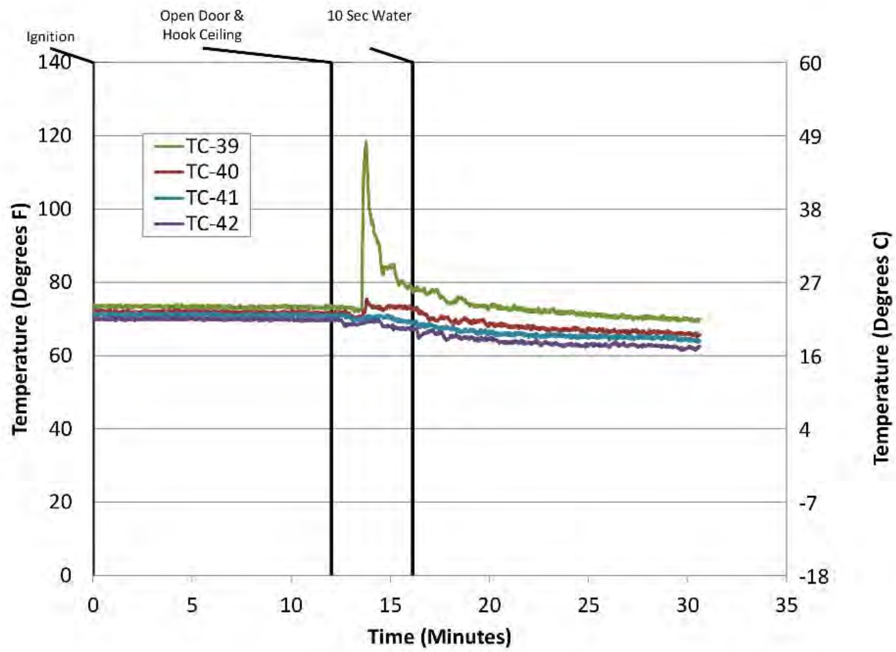


Figure I. 19 Attic Experiment 2A Interior TC Array BC



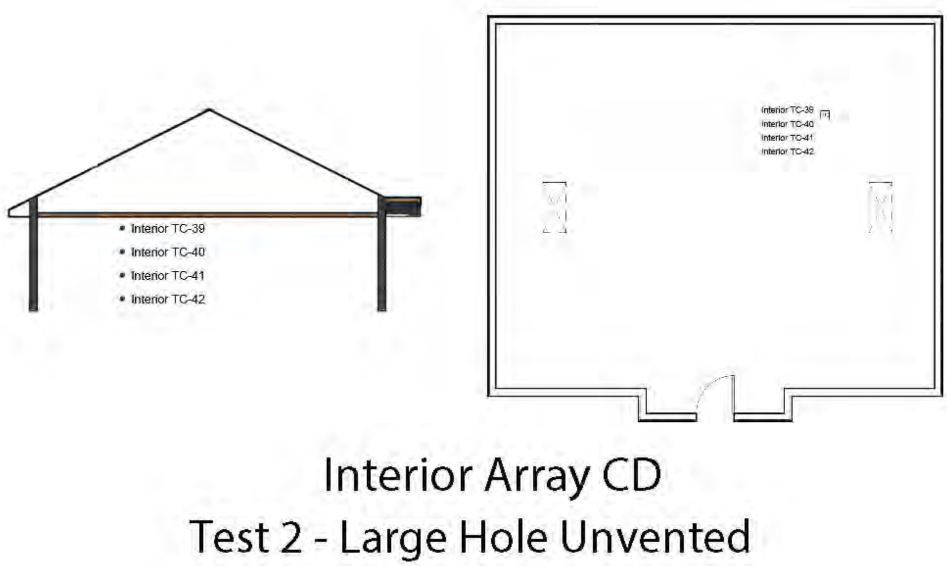


Figure I. 20: Attic Experiment 2A Interior TC Array CD

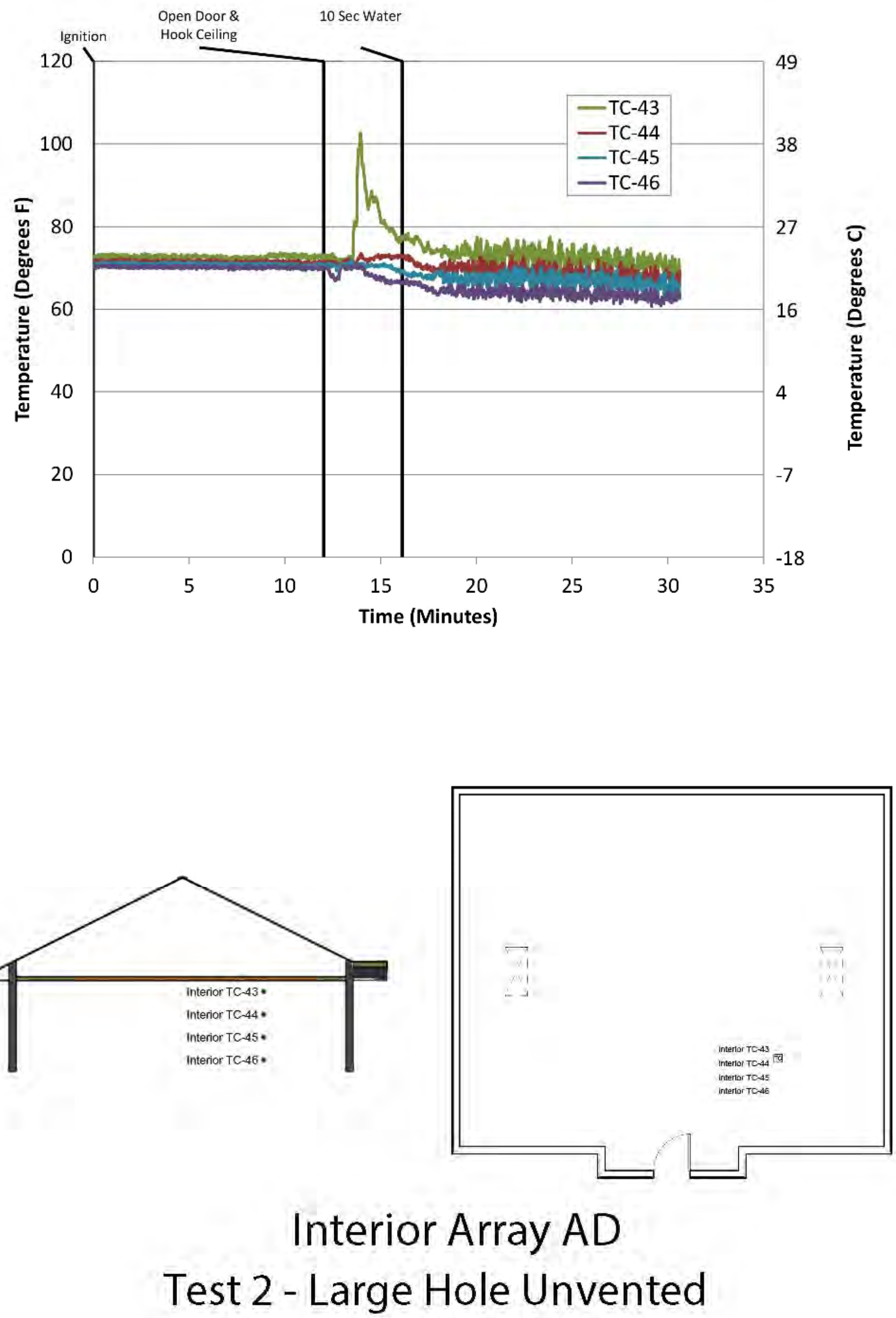


Figure I. 21: Attic Experiment 2A Interior TC Array AD

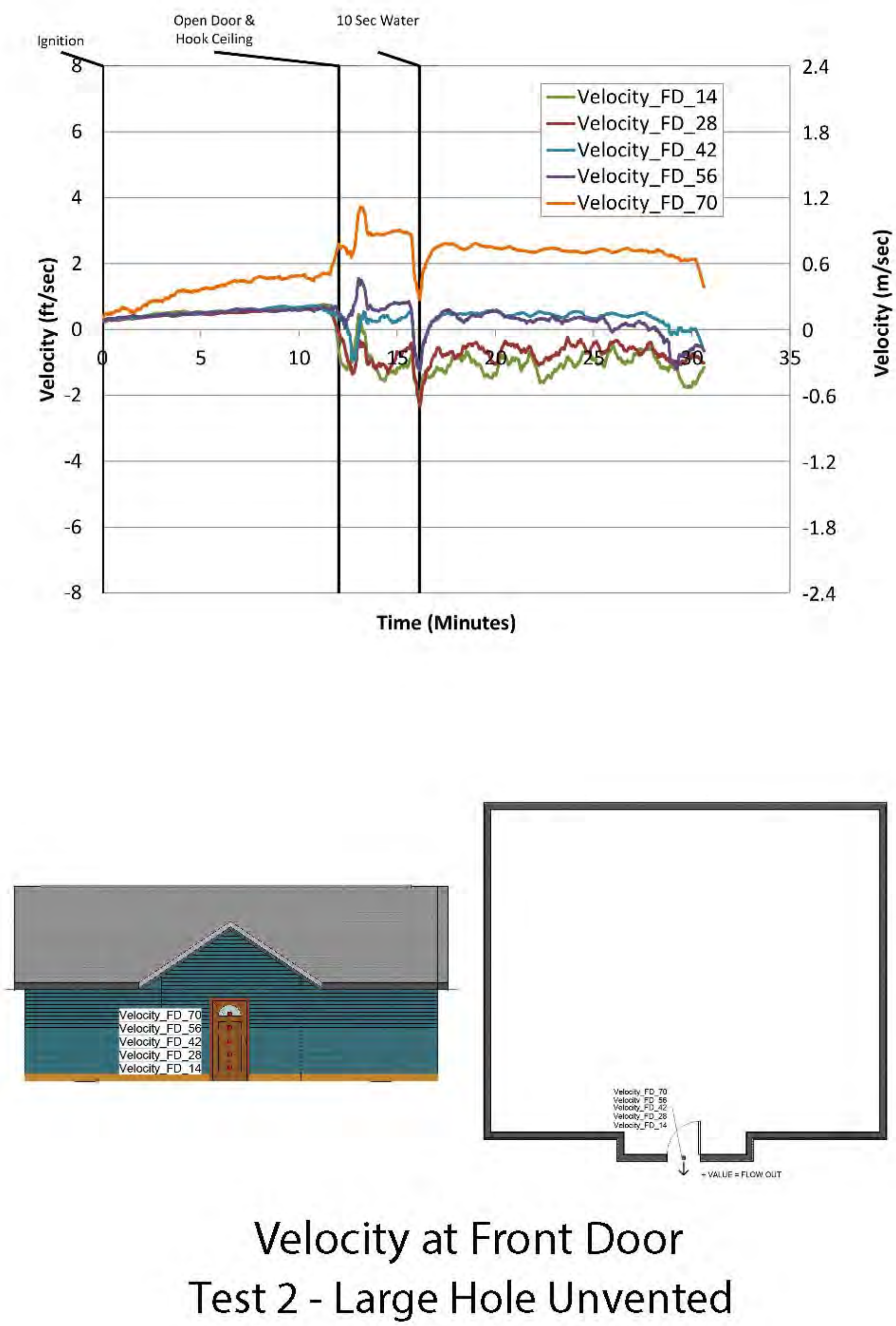


Figure I. 22: Attic Experiment 2A Front Door Velocity

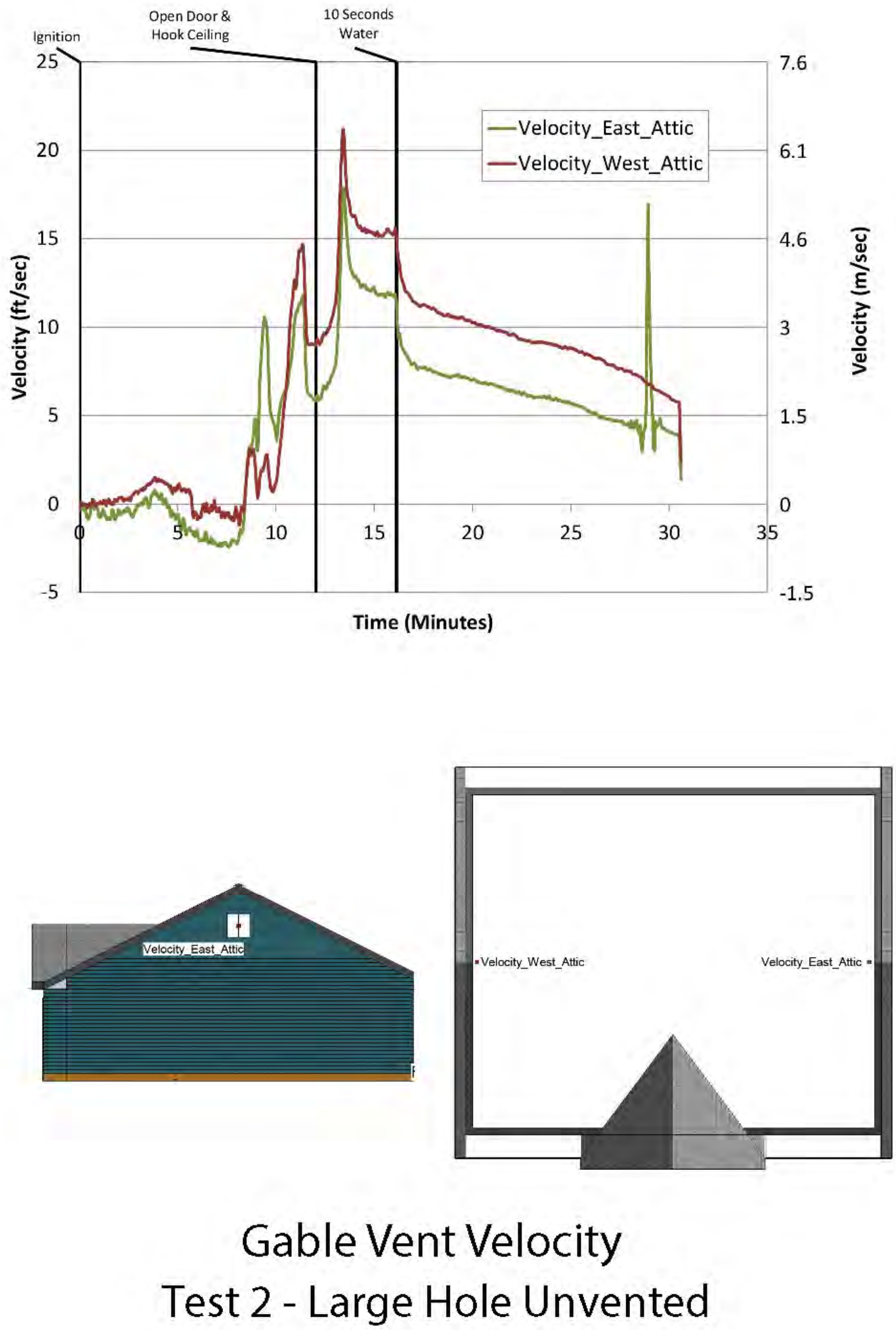
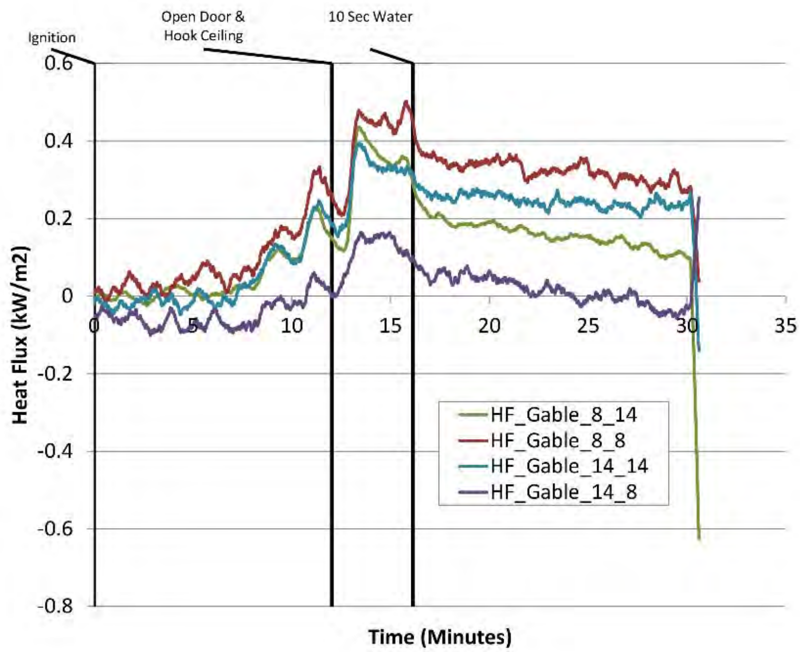
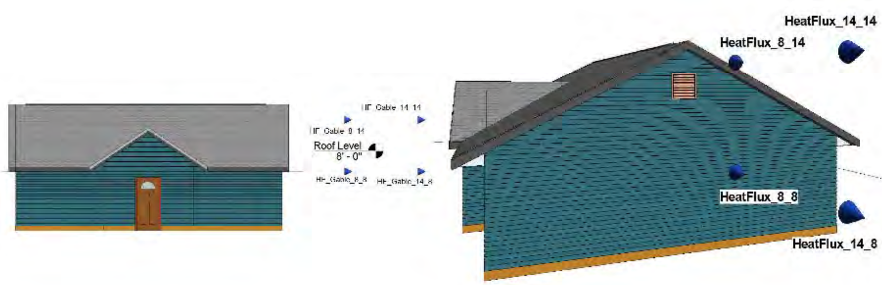


Figure I. 23: Attic Experiment 2A Gable Vent Velocity





Heat Flux Gable End
Test 2 - Large Hole Unvented

Figure I. 24: Attic Experiment 2A Gable Heat Flux

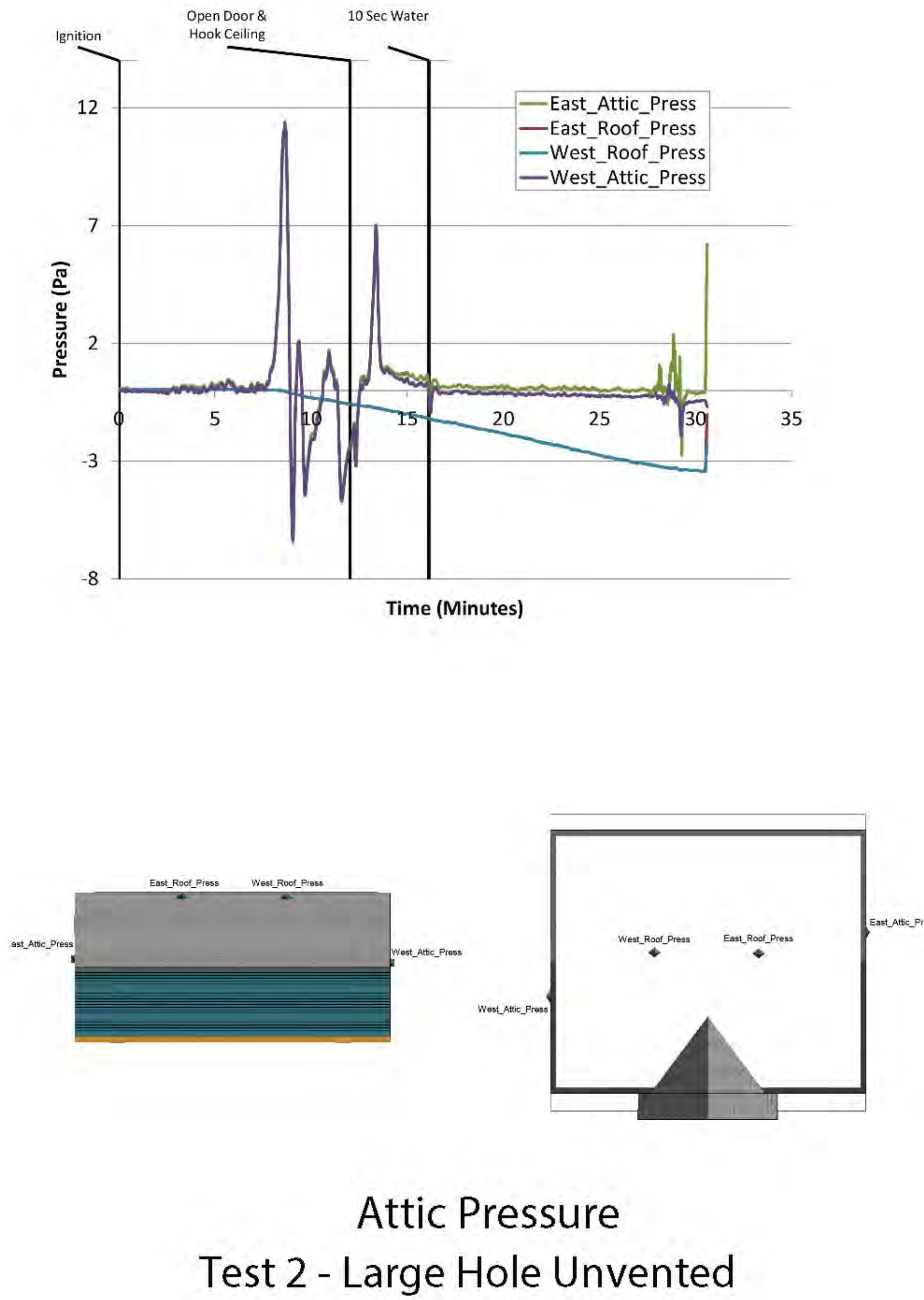


Figure I. 25 Attic Experiment 2A Attic Pressure

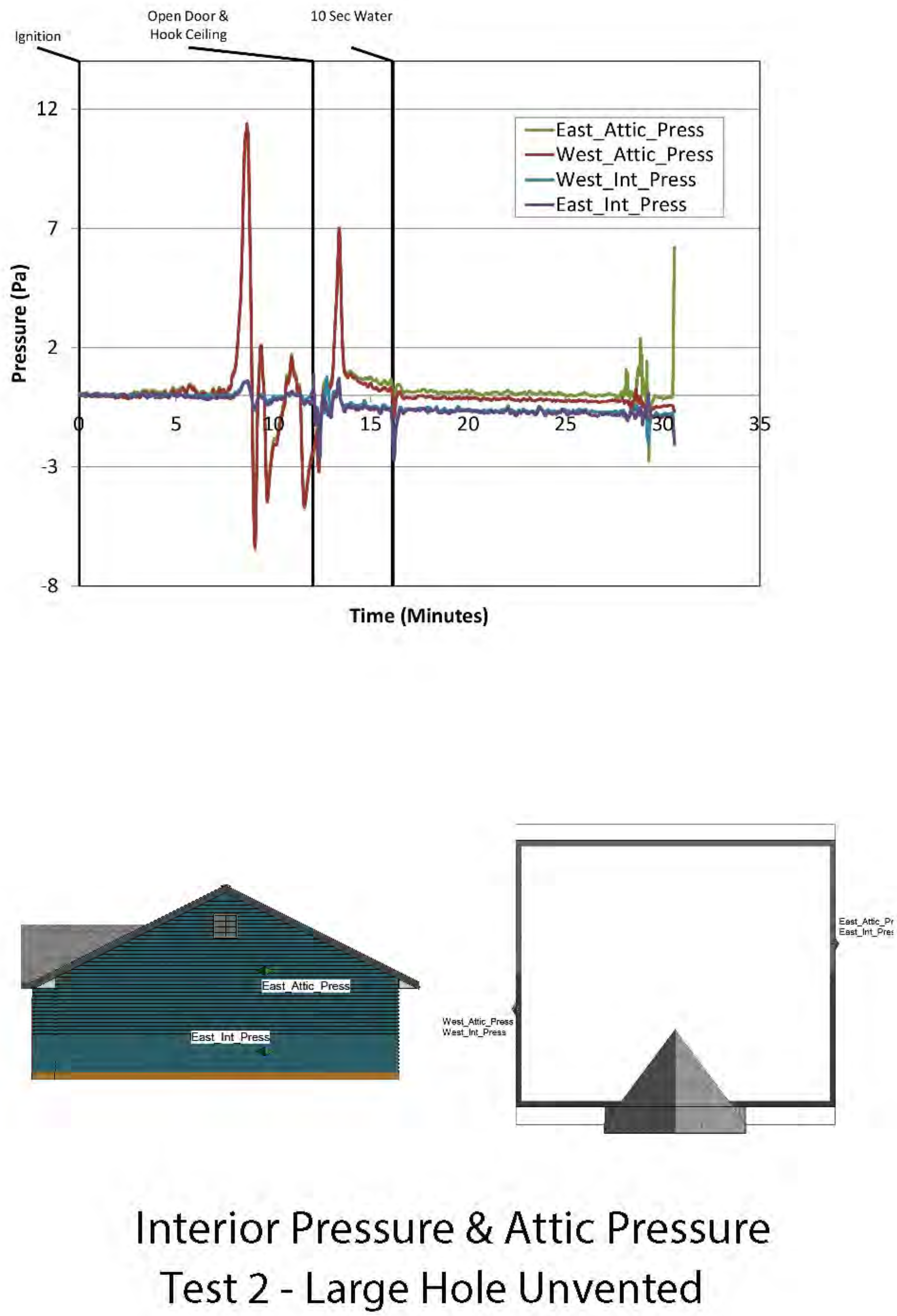
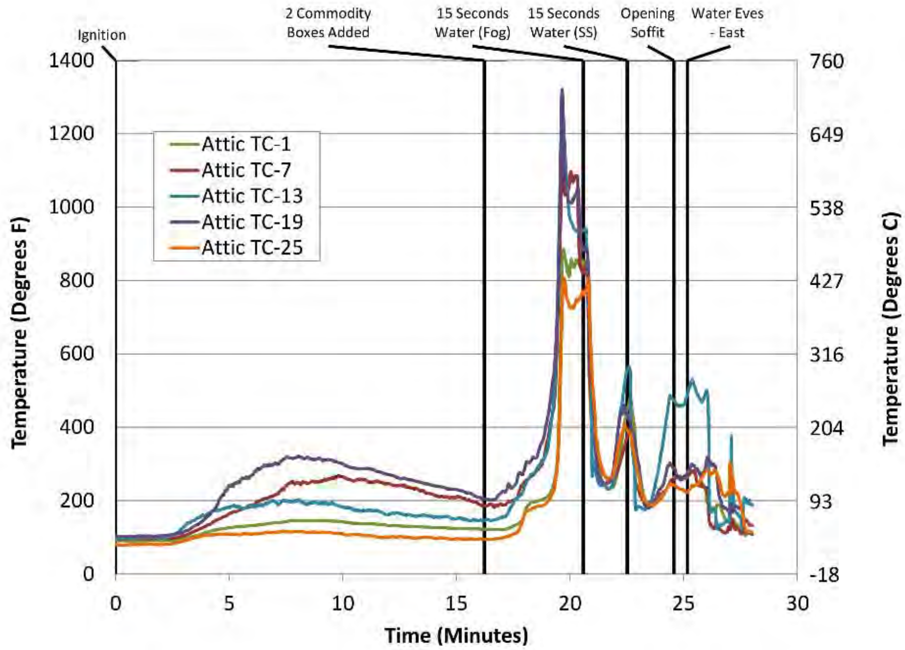


Figure I. 26: Attic Experiment 2A Interior VS. Attic Pressure

Experiment 2B



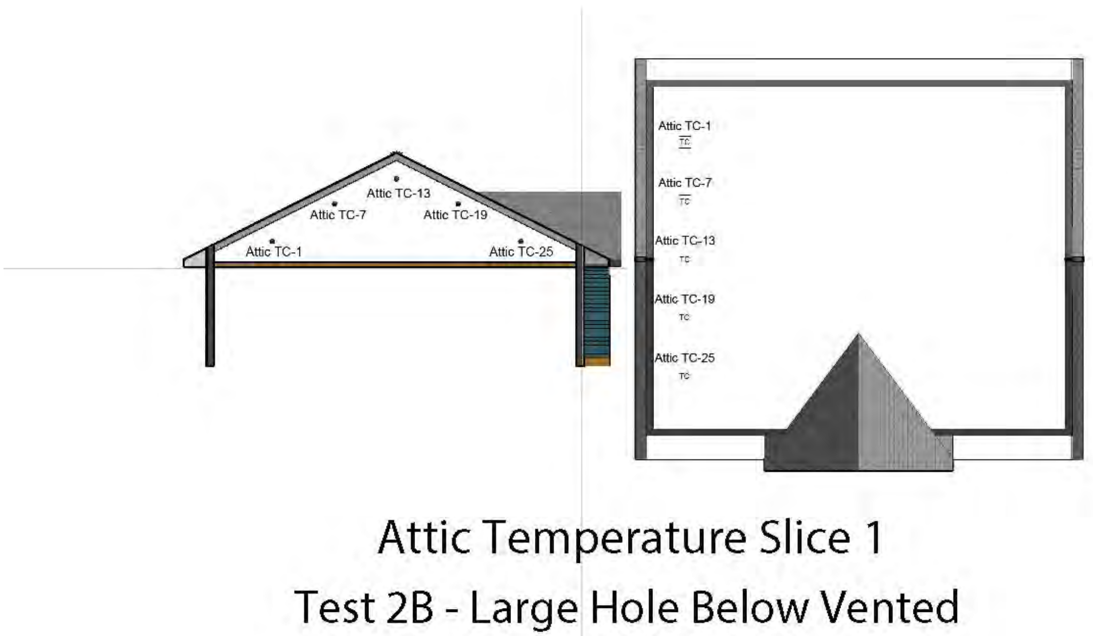
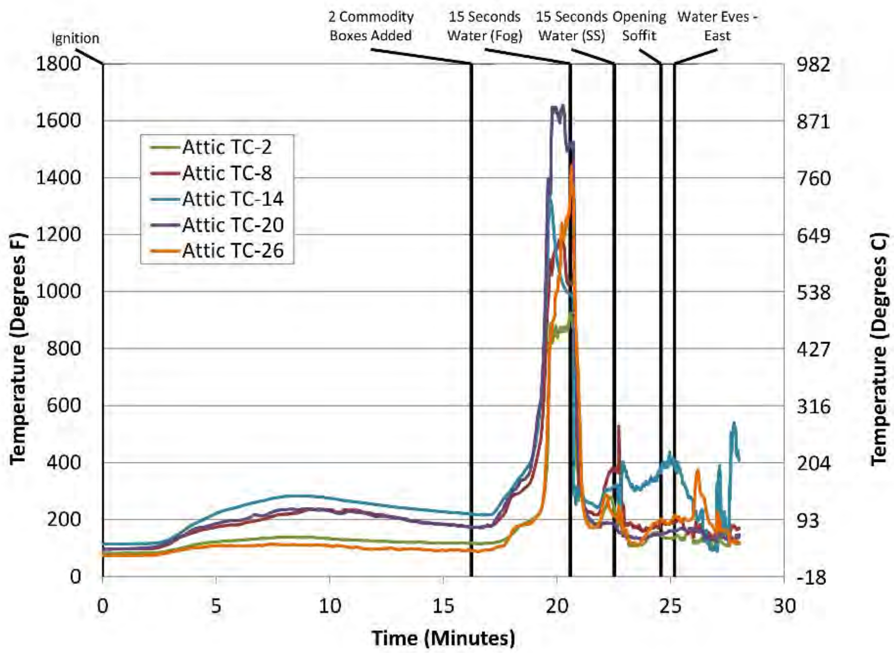


Figure I. 27: Attic Experiment 2B Attic Temperature Slice 1



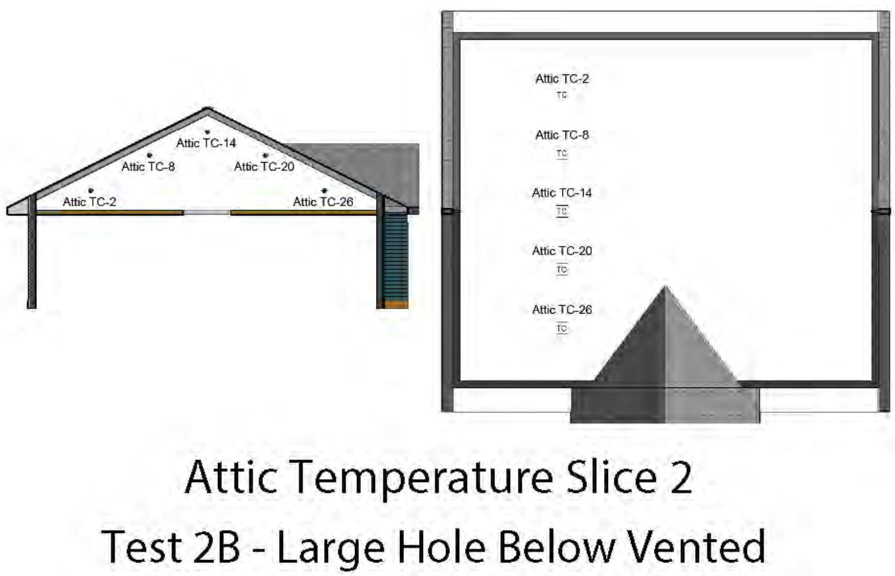


Figure I. 28: Attic Experiment 2B Attic Temperature Slice 2

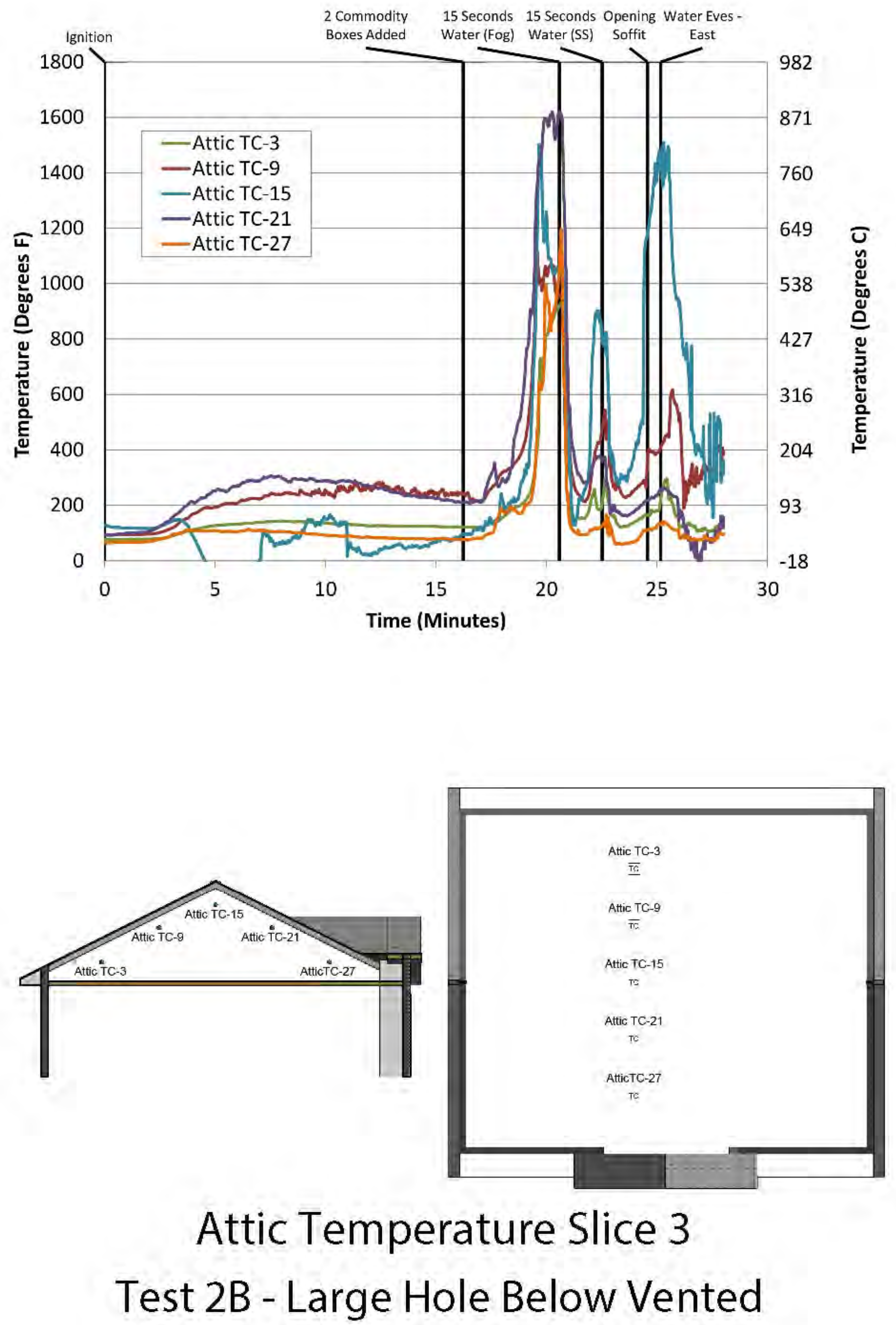
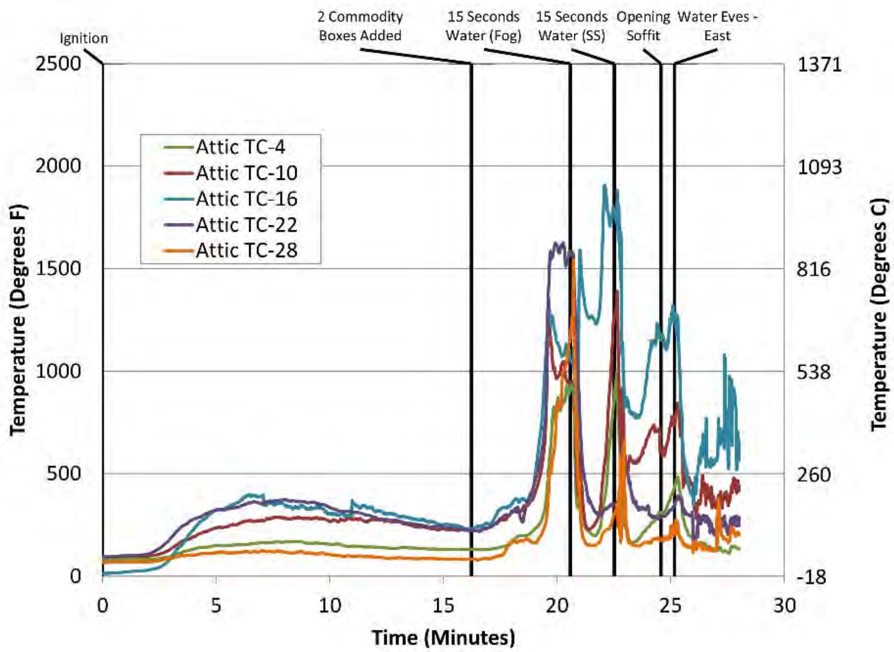


Figure I. 29: Attic Experiment 2B Attic Temperature Slice 3



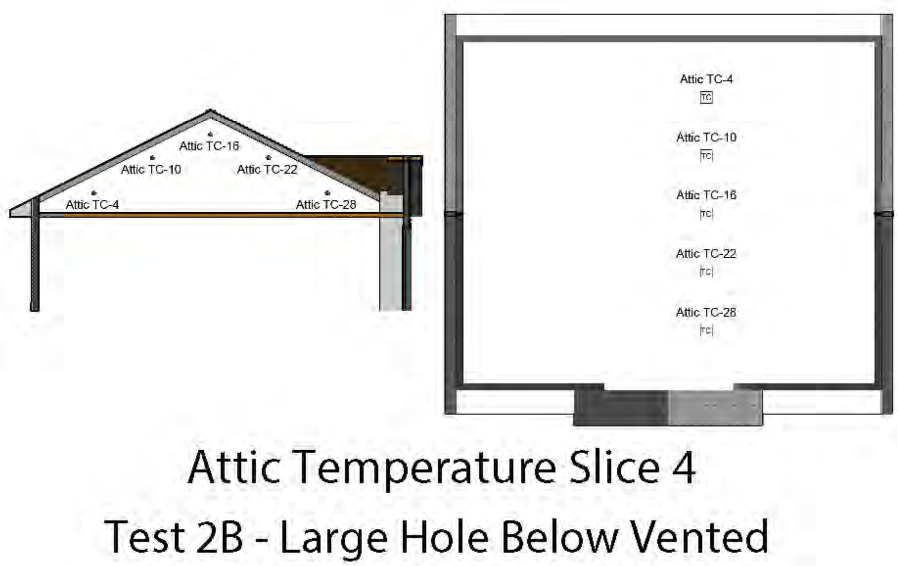
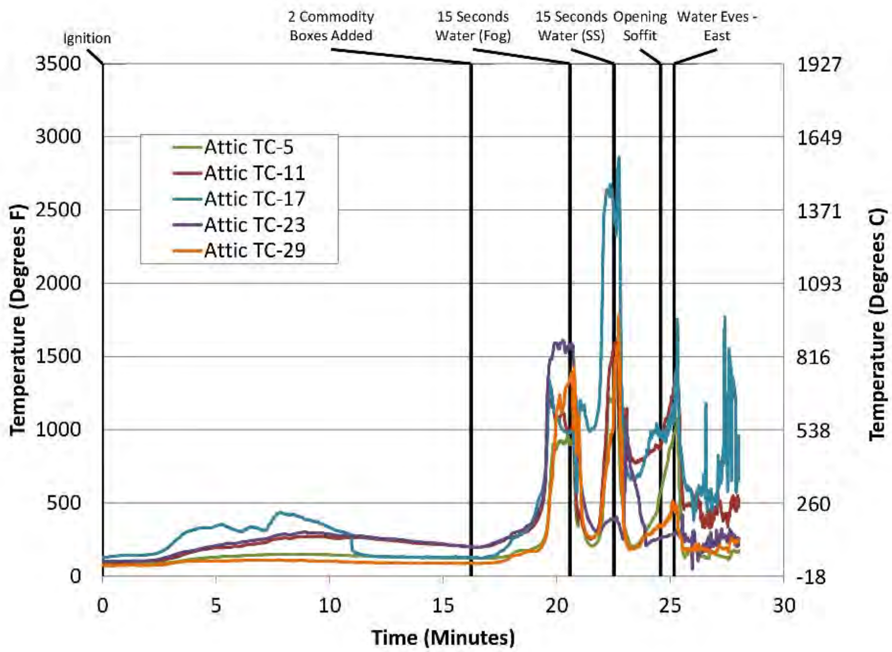


Figure I. 30: Attic Experiment 2B Attic Temperature Slice 4



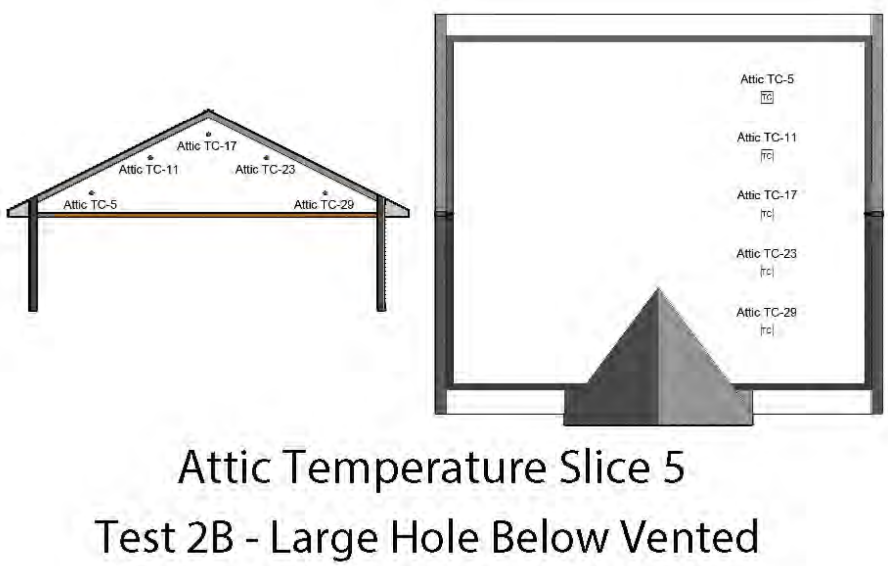
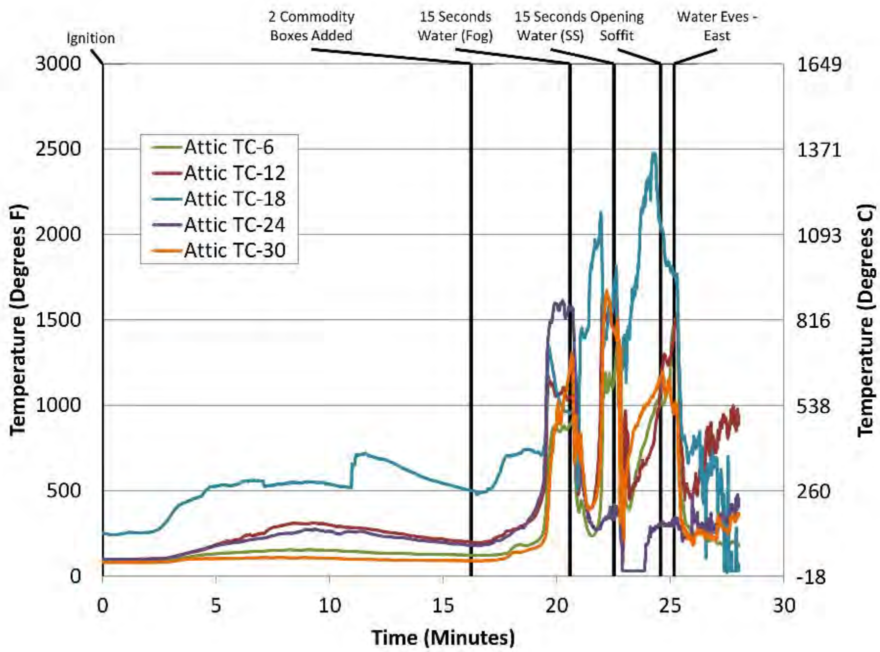


Figure I. 31: Attic Experiment 2B Attic Temperature Slice 5



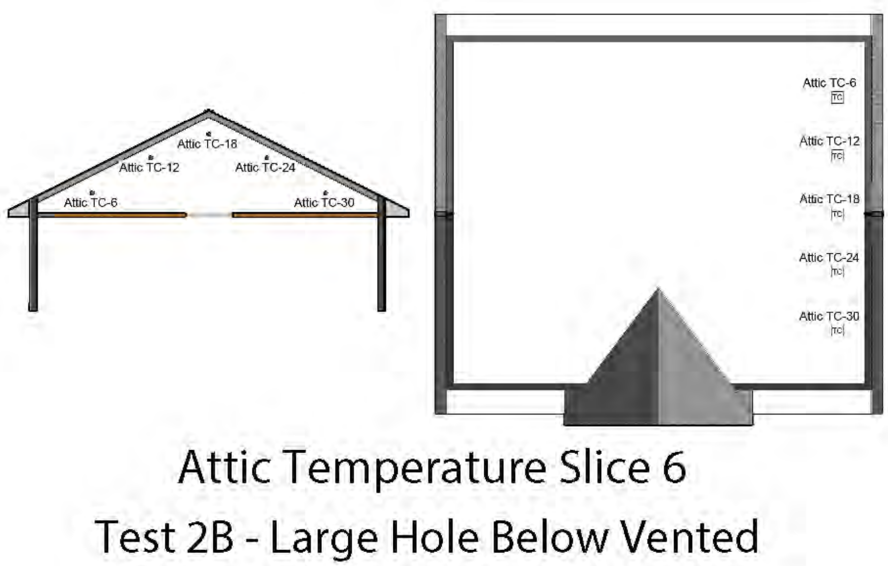
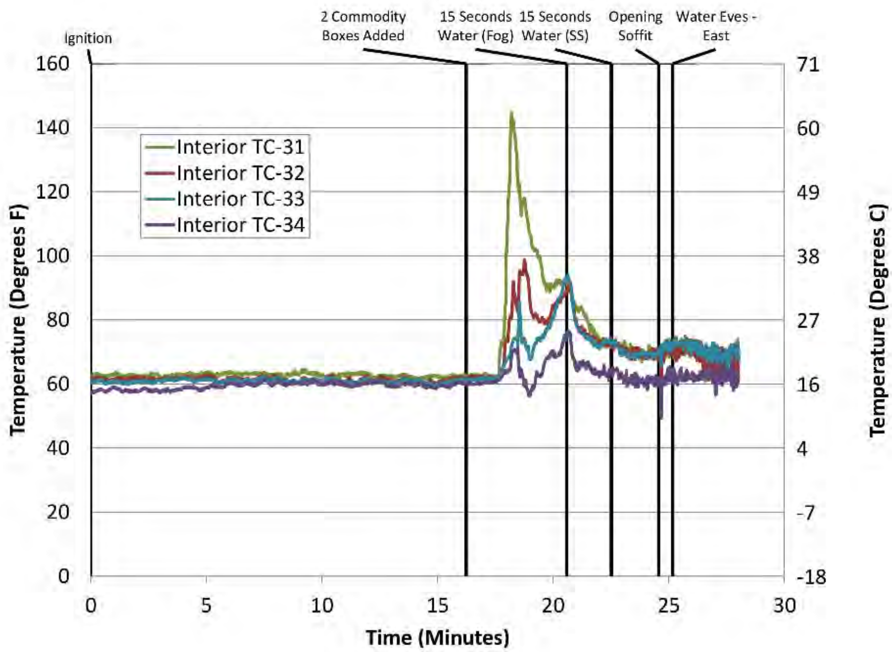


Figure I. 32: Attic Experiment 2B Attic Temperature Slice 6



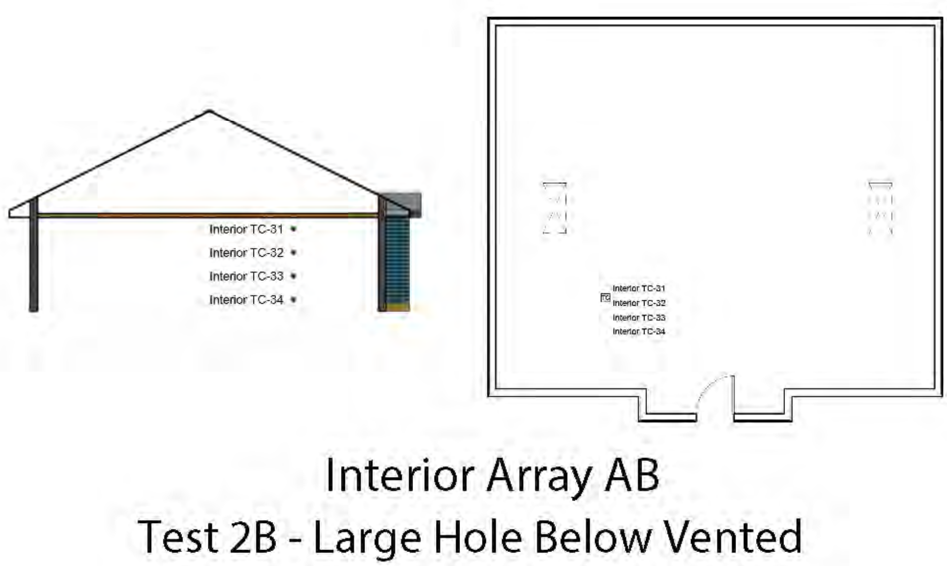
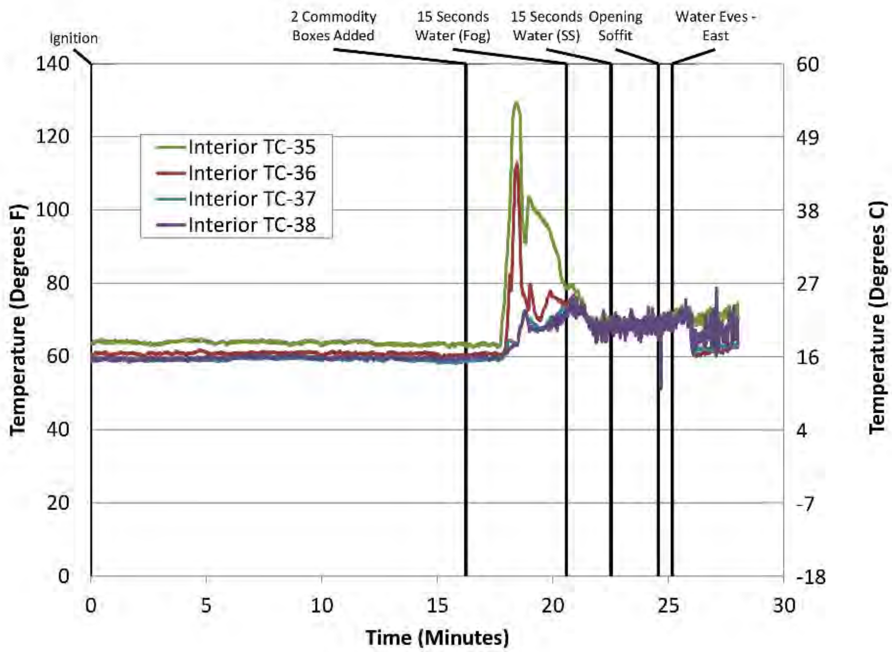


Figure I. 33: Attic Experiment 2B Interior TC Array AB



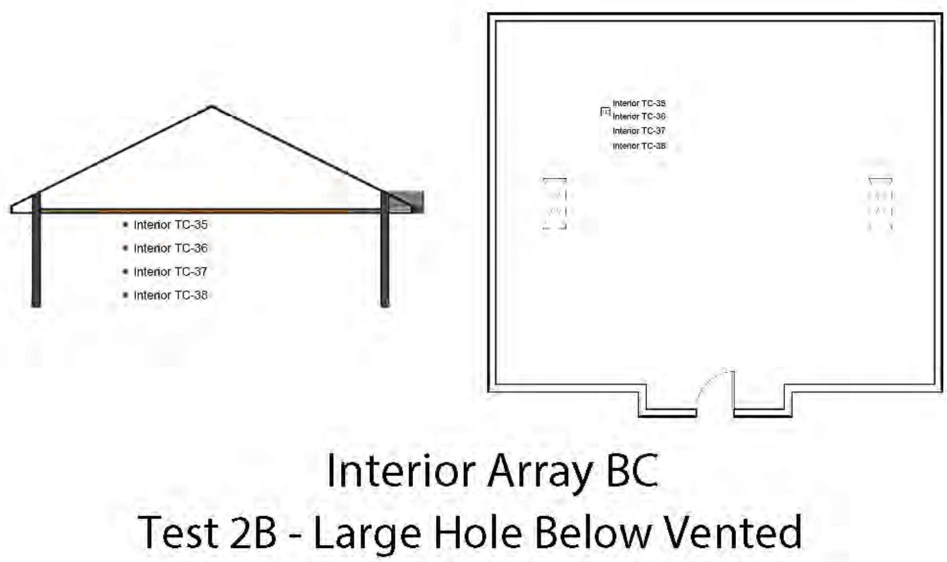
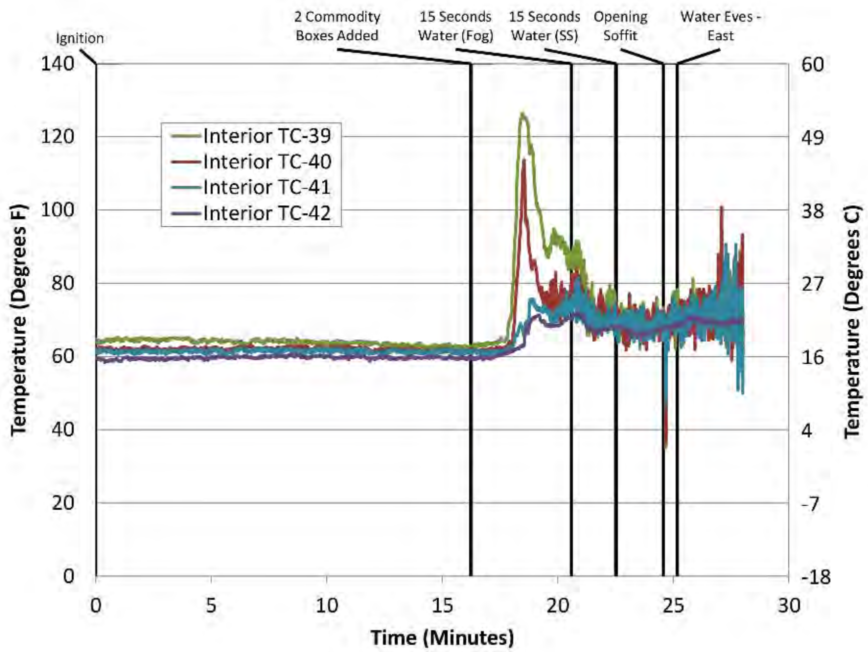


Figure I. 34: Attic Experiment 2B Interior TC Array BC



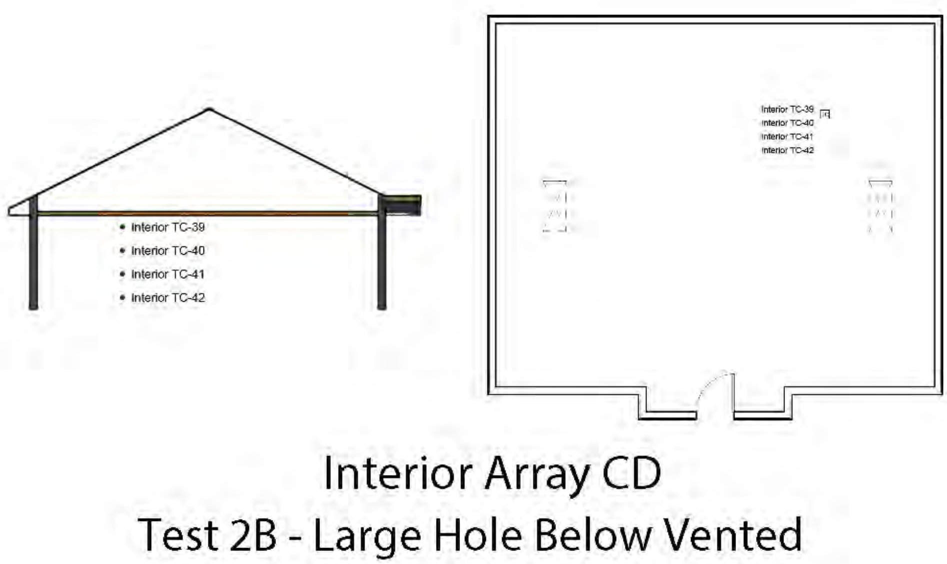
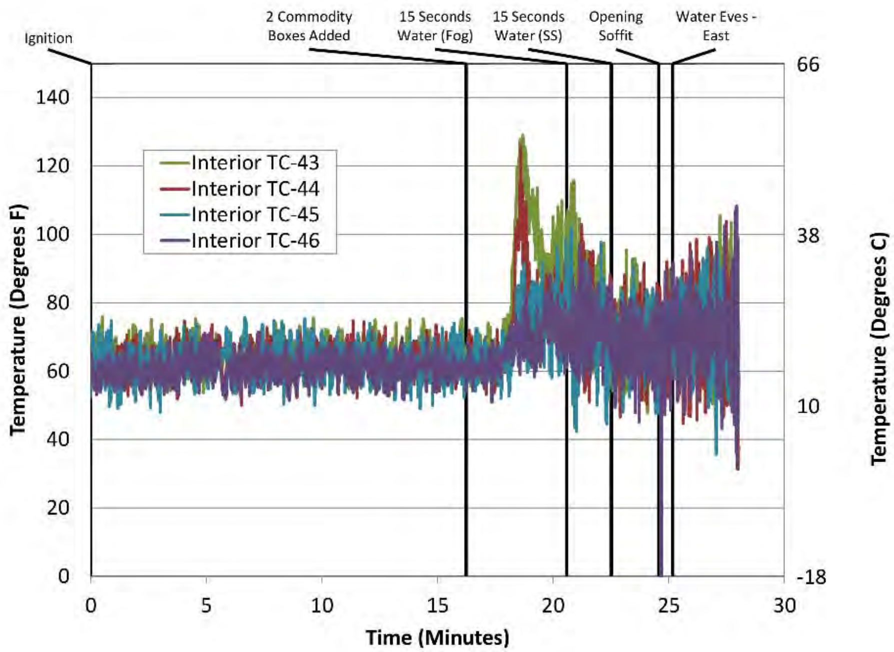


Figure I. 35: Attic Experiment 2B Interior TC Array CD



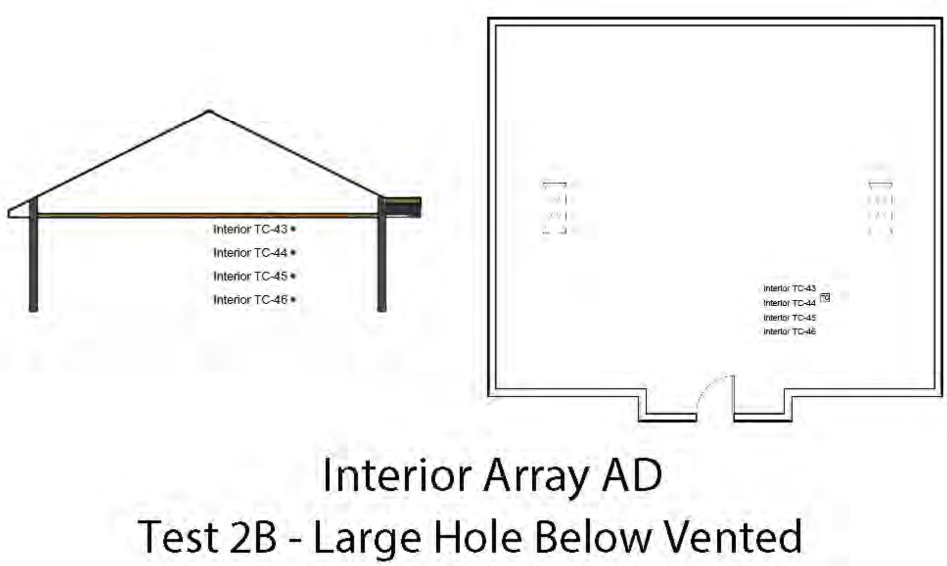
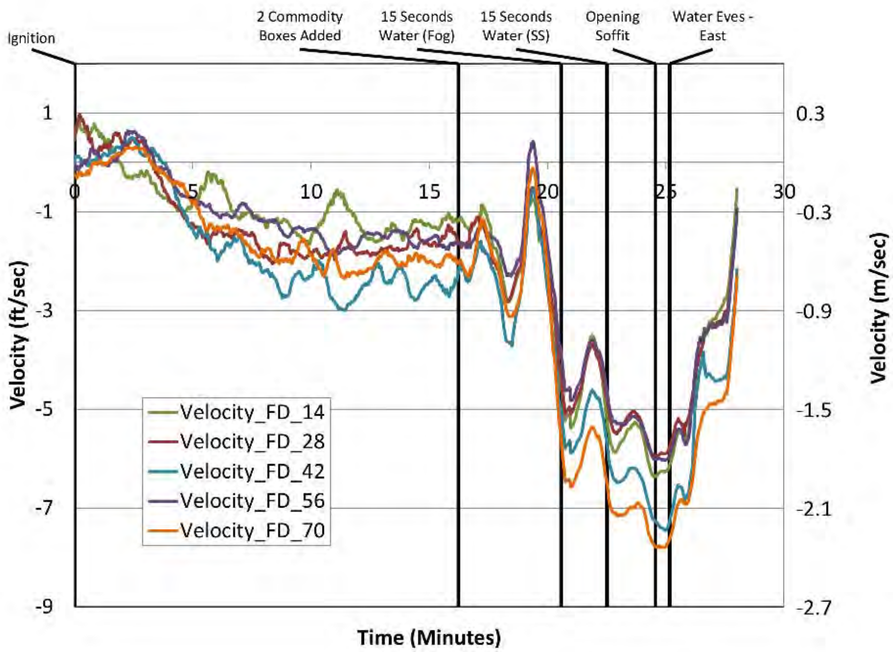


Figure I. 36: Attic Experiment 2B Interior TC Array AD



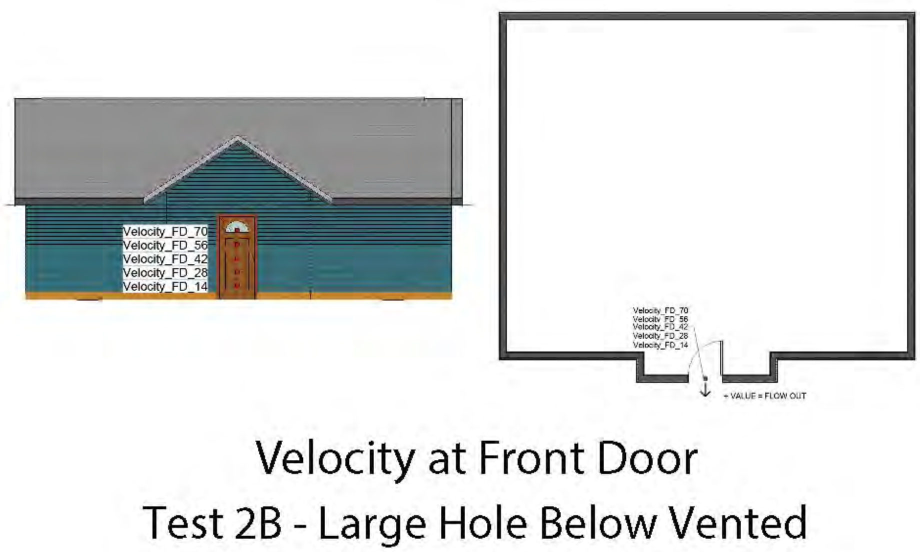
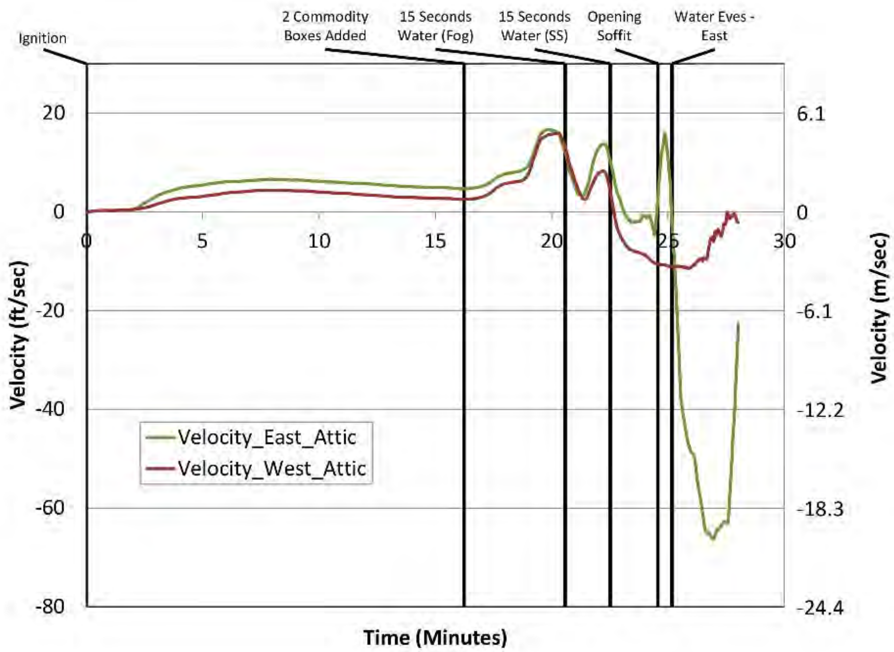


Figure I. 37: Attic Experiment 2B Door Velocity



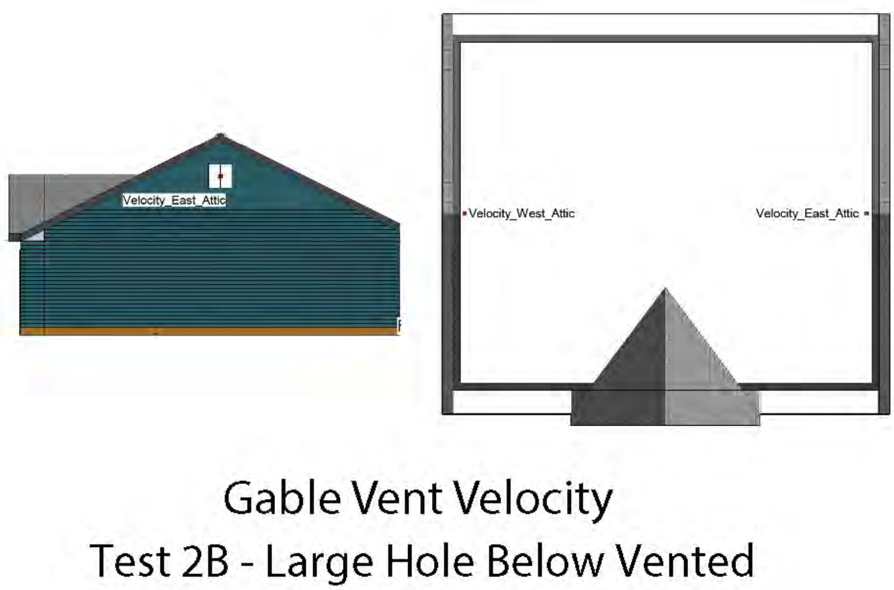
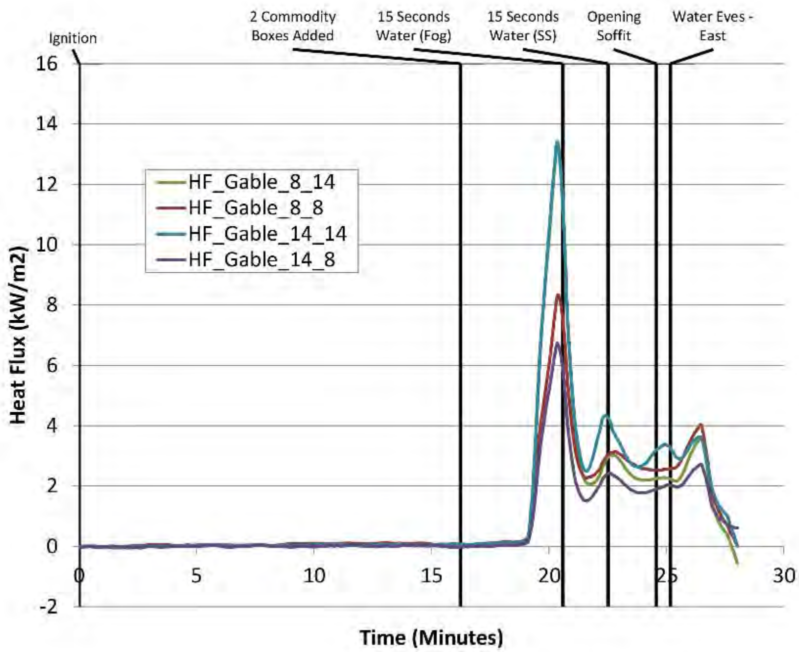
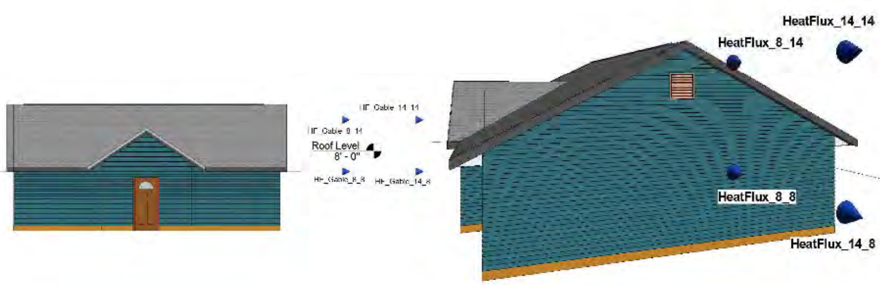


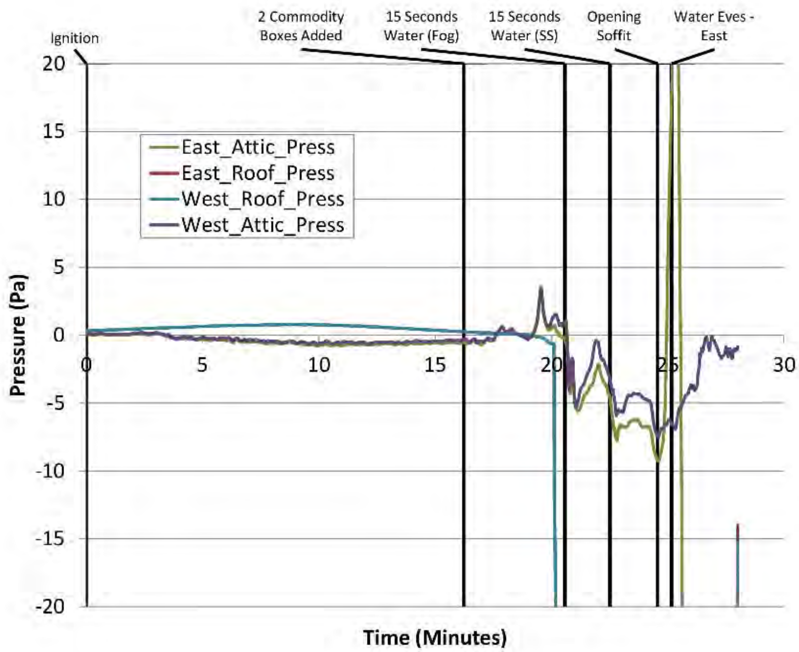
Figure I. 38: Attic Experiment 2B Gable Velocity

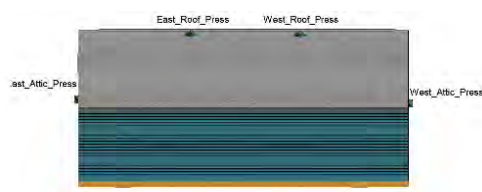


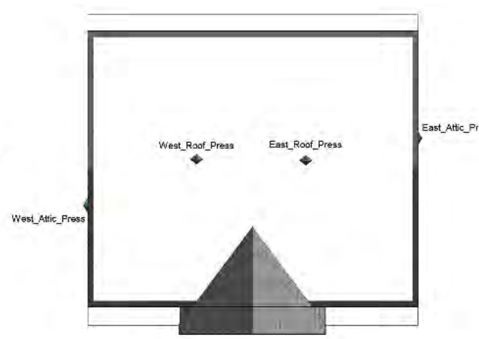


Heat Flux Gable End
Test 2B - Large Hole Below Vented

Figure I. 39: Attic Experiment 2B Gable Heat Flux







Attic Pressure
Test 2B - Large Hole Below Vented

Figure I. 40: Attic Experiment 2B Attic Pressure

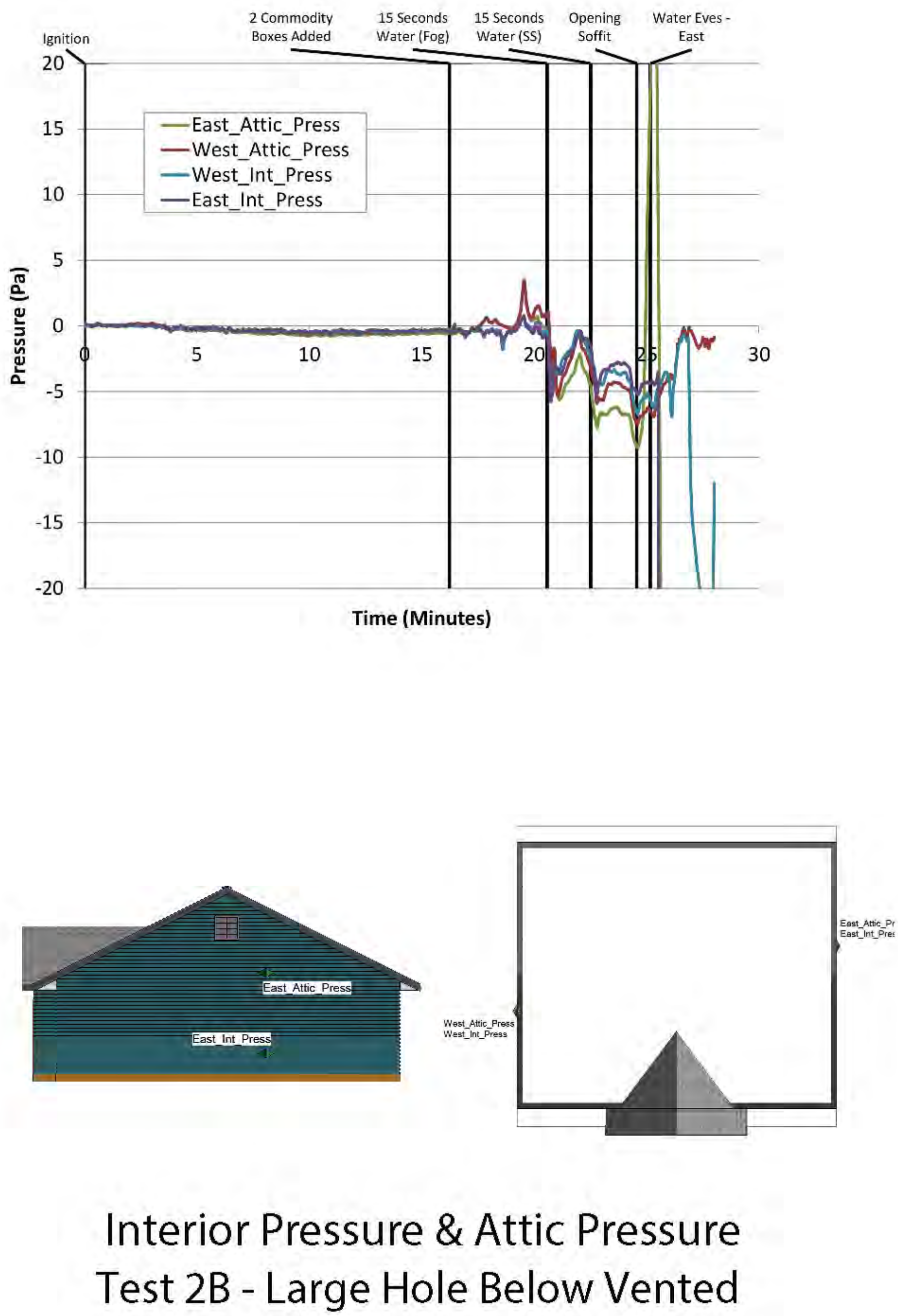


Figure I. 41: Attic Experiment 2B Interior Vs. Attic Pressure

Experiment 3A

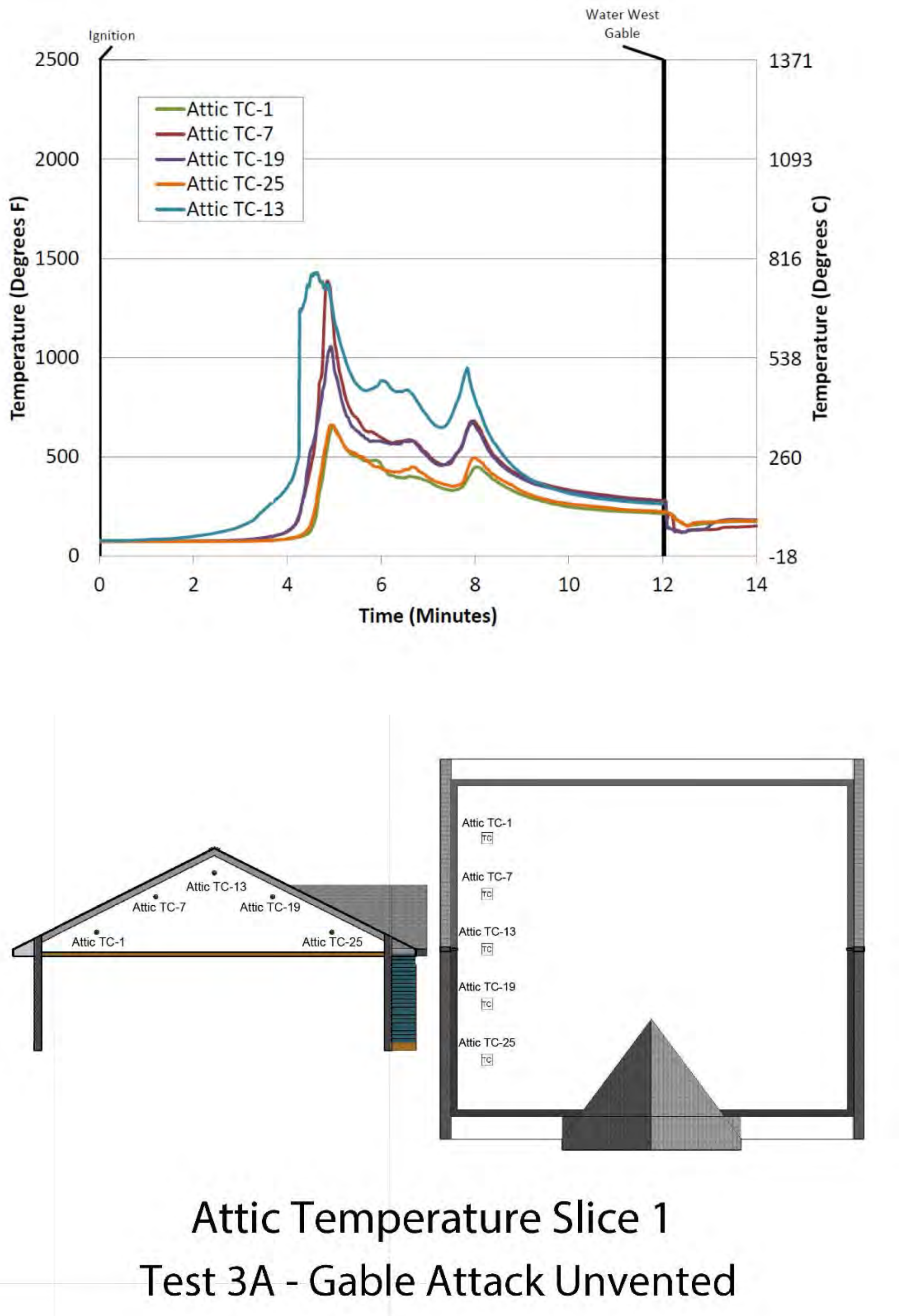
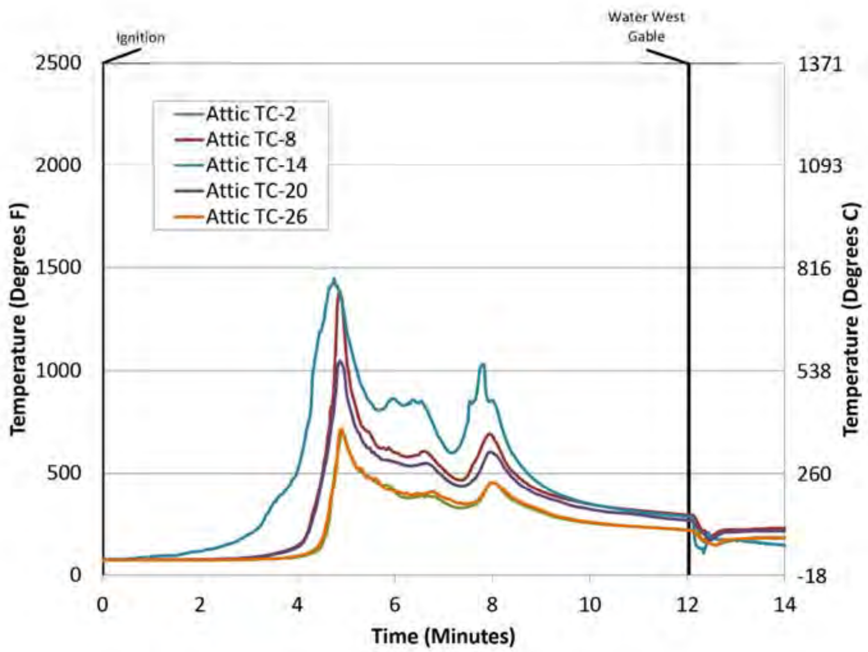


Figure I. 42: Attic Experiment 3A Attic Temperature Slice 1



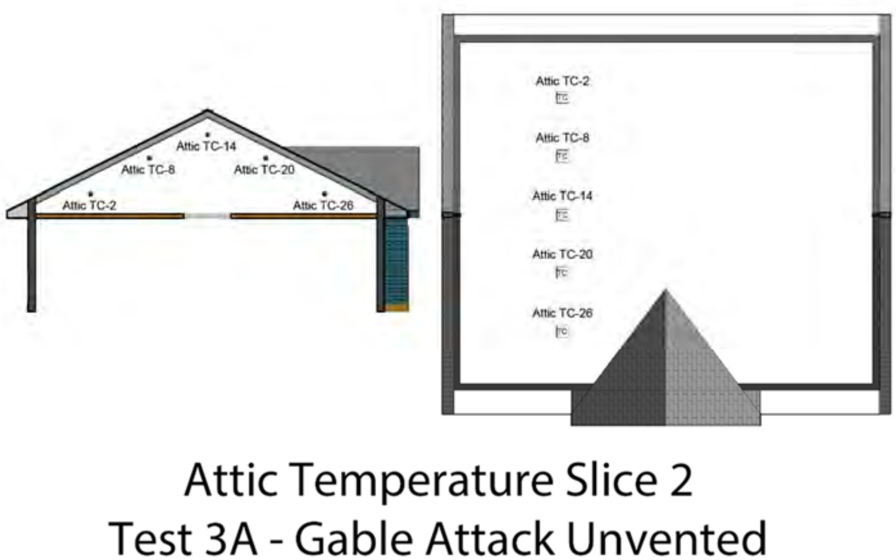
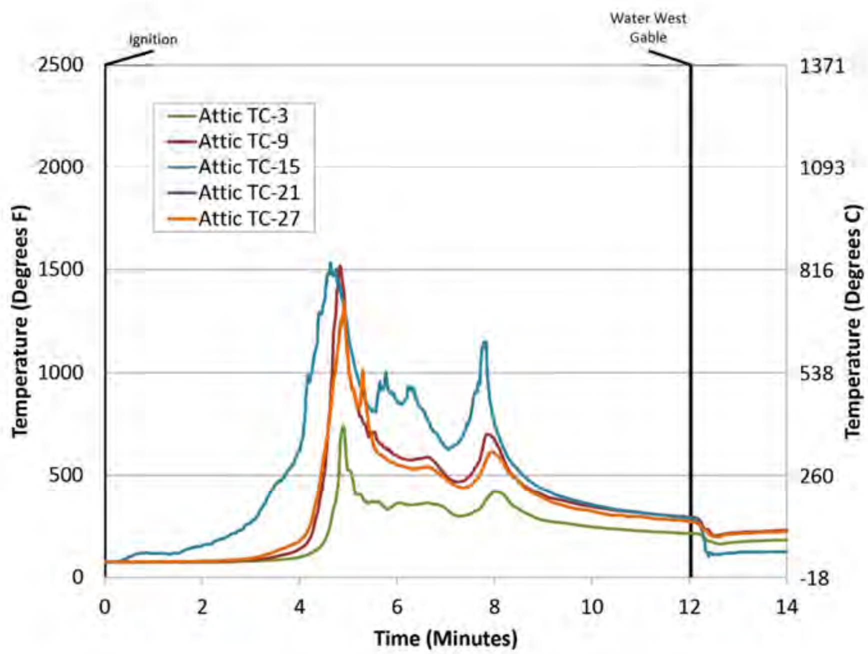
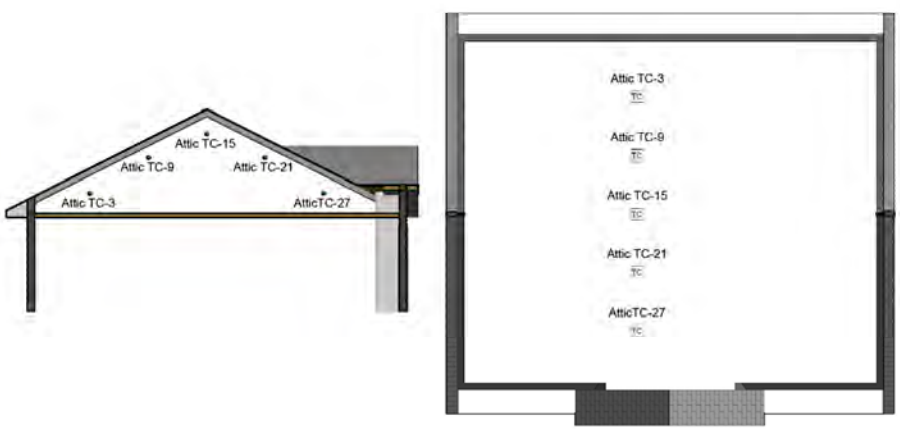


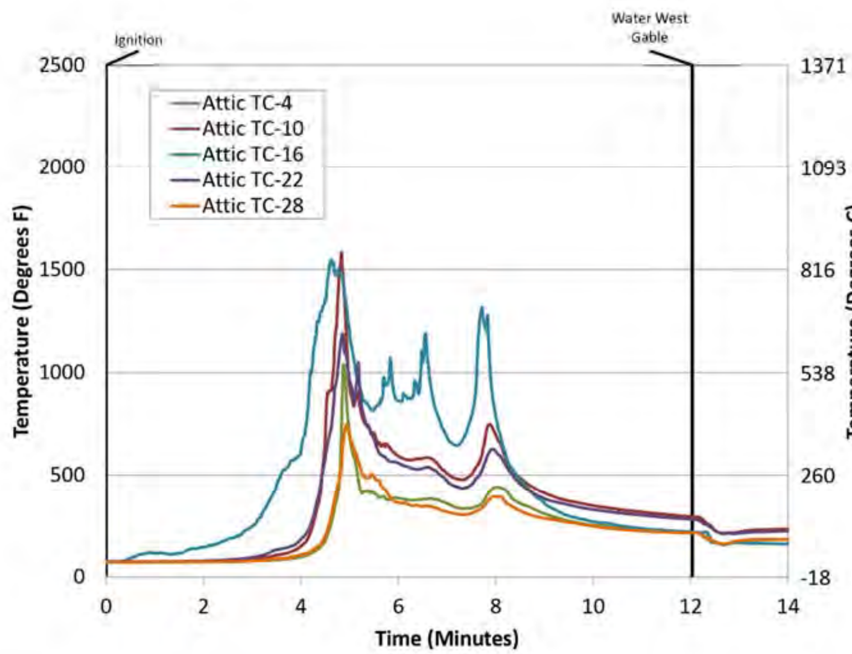
Figure I. 43: Attic Experiment 3A Attic Temperature Slice 2





Attic Temperature Slice 3
Test 3A - Gable Attack Unvented

Figure I. 44: Attic Experiment 3A Attic Temperature Slice 3



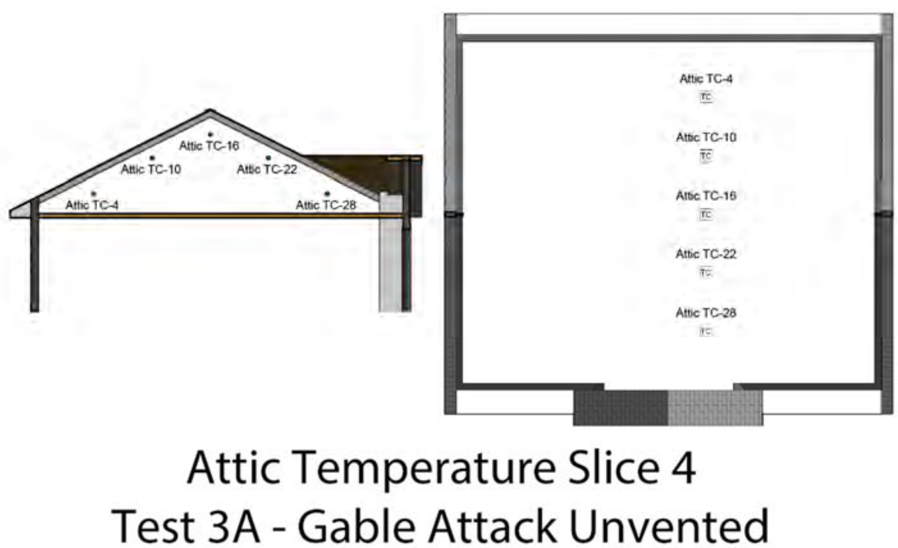
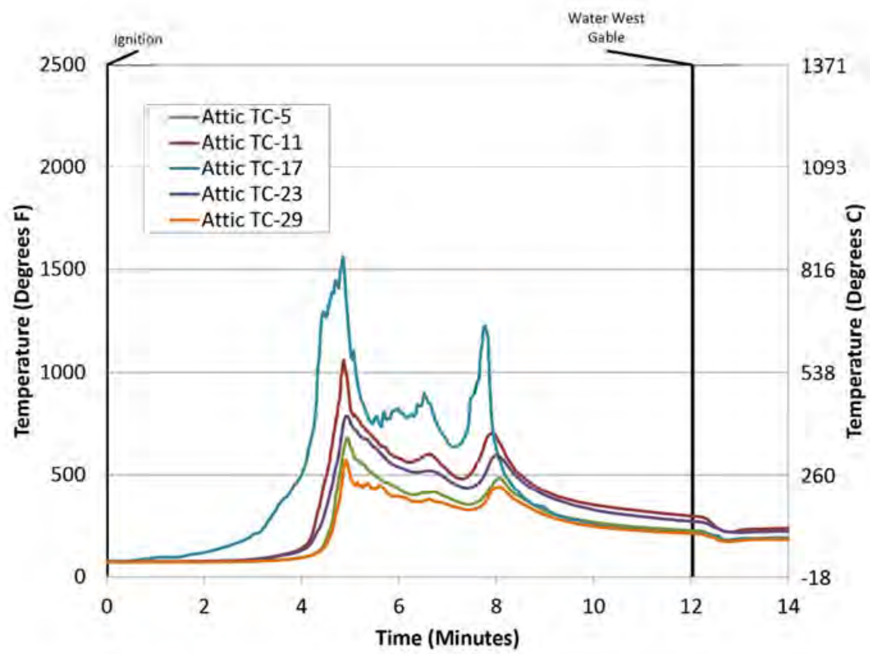
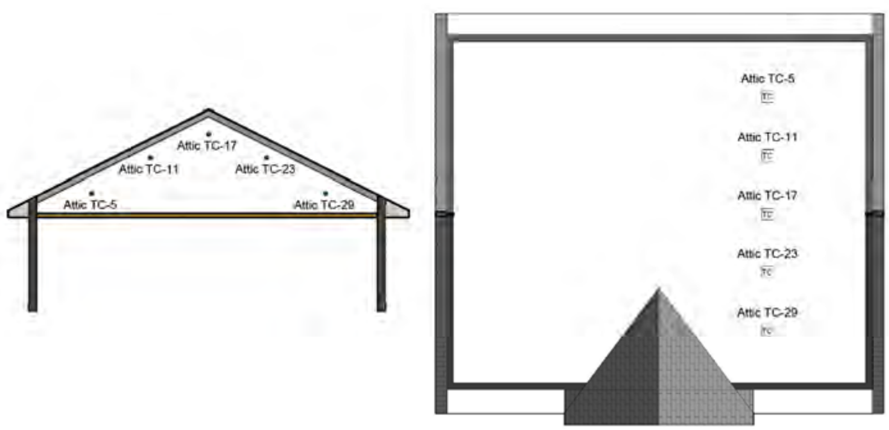


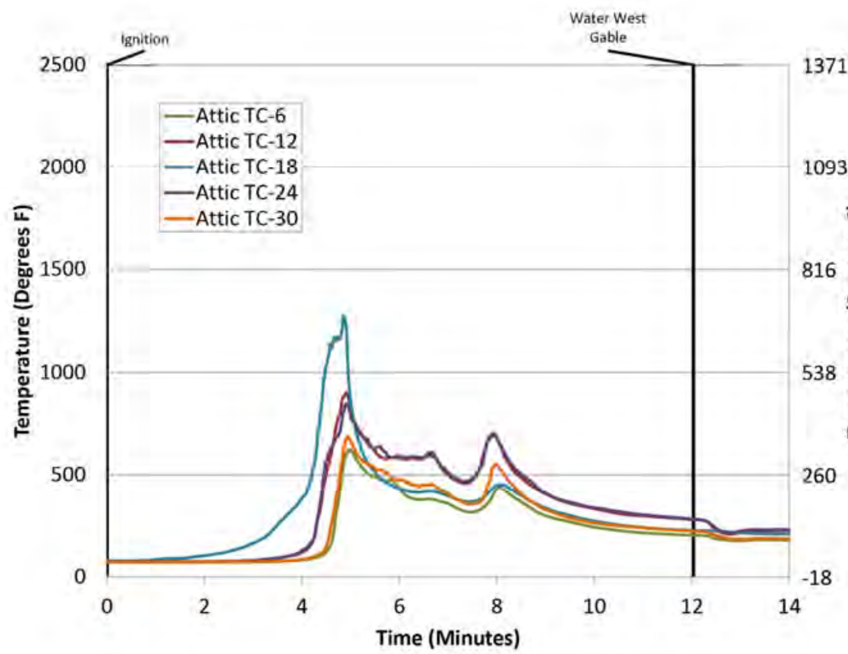
Figure I. 45: Attic Experiment 3A Attic Temperature Slice 4





Attic Temperature Slice 5
Test 3A - Gable Attack Unvented

Figure I. 46: Attic Experiment 3A Attic Temperature Slice 5



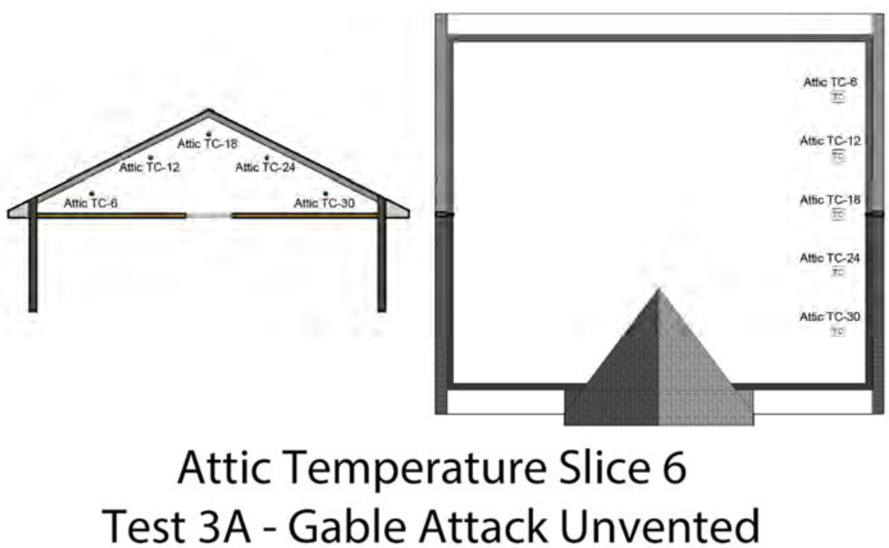
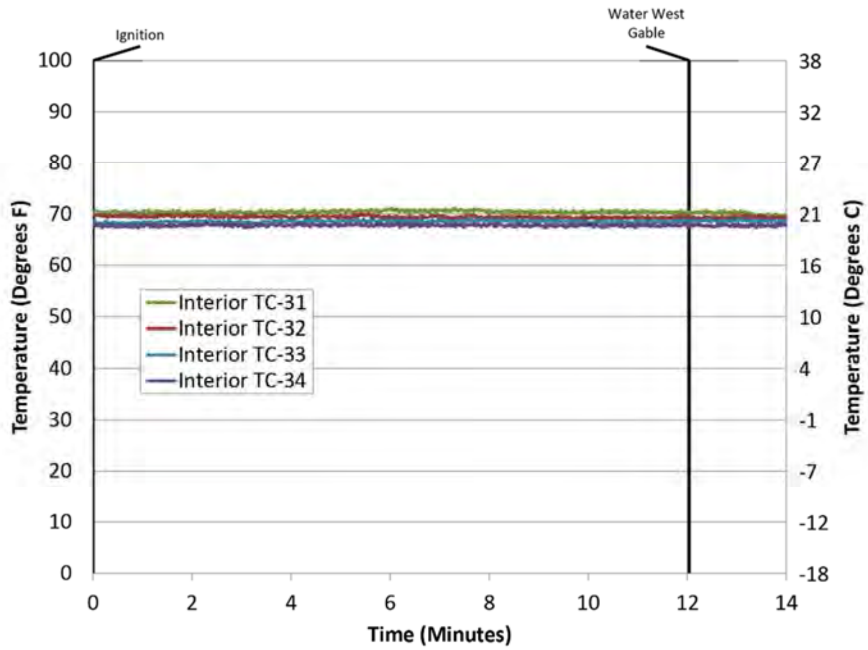


Figure I. 47: Attic Experiment 3A Attic Temperature Slice 6



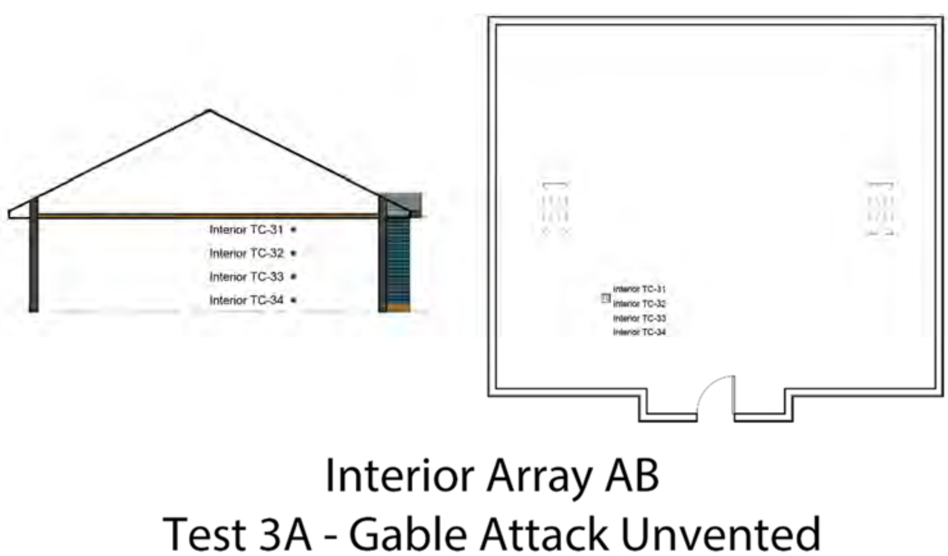
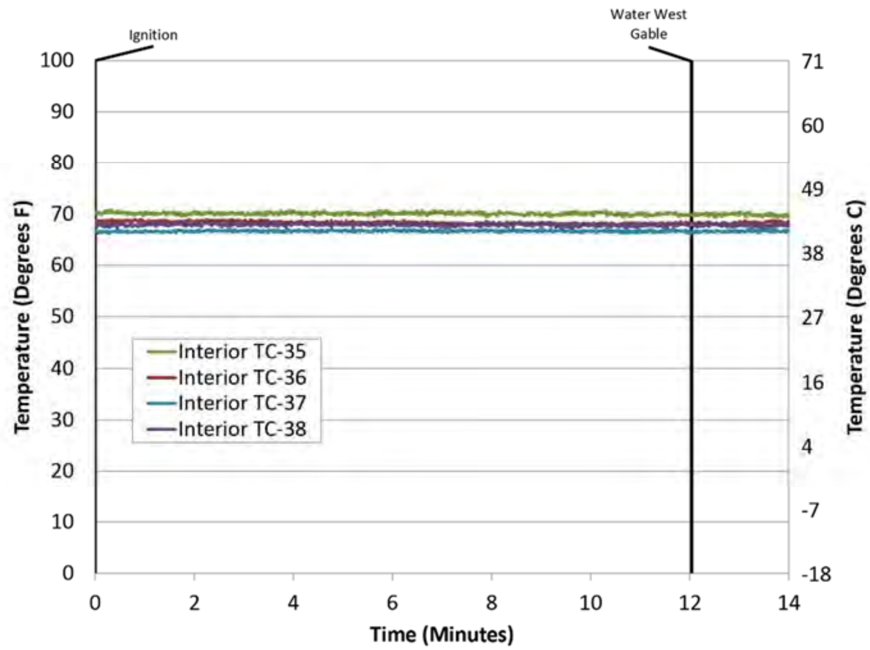


Figure I. 48: Attic Experiment 3A Interior TC Array AB



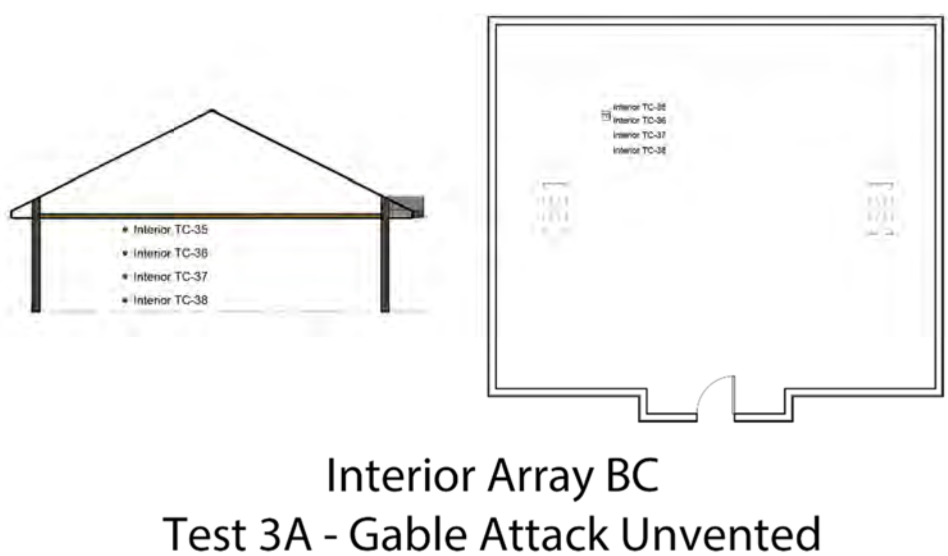
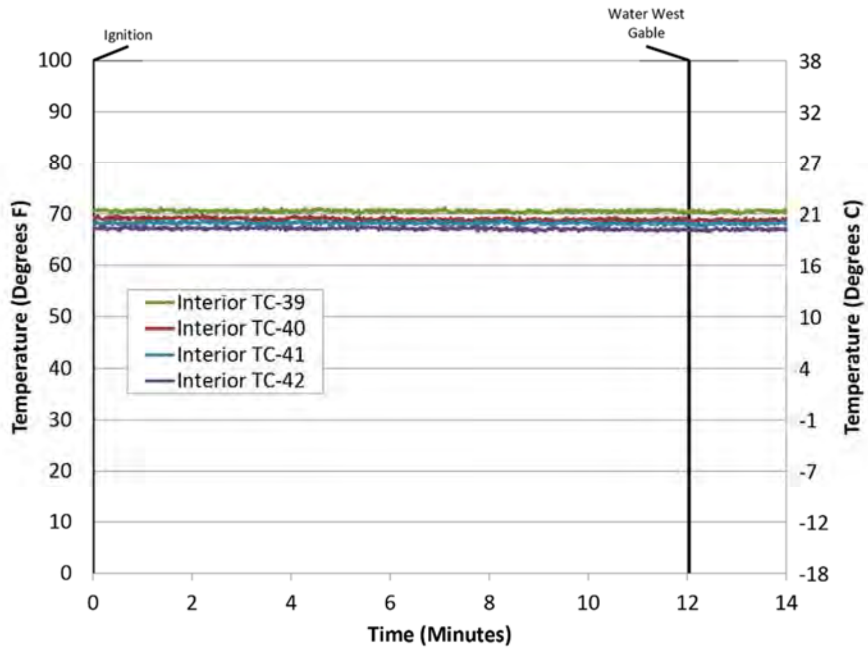


Figure I. 49: Attic Experiment 3A Interior TC Array BC



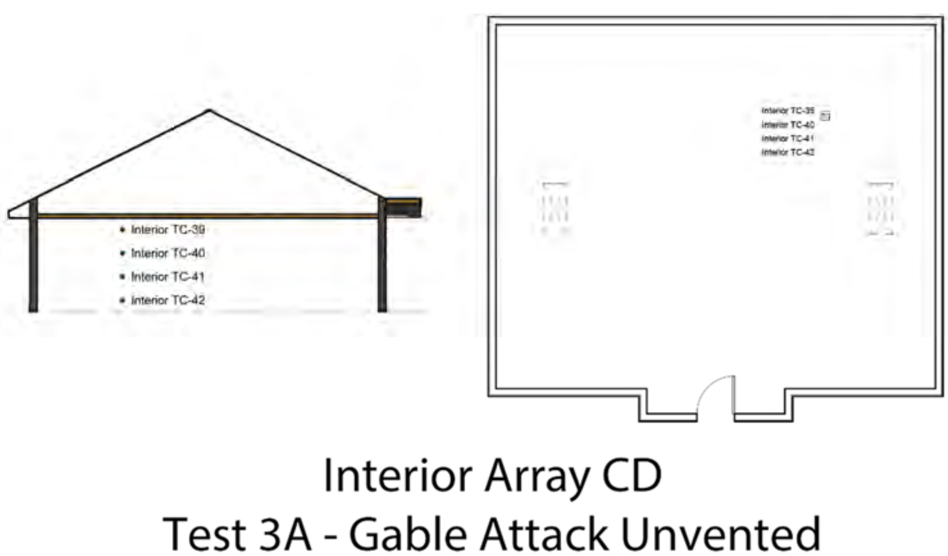
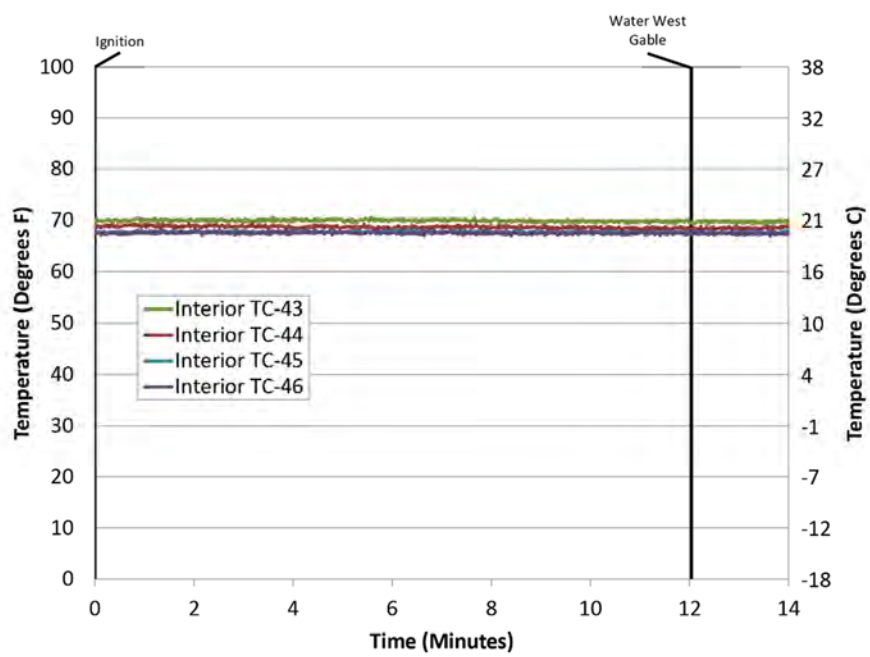
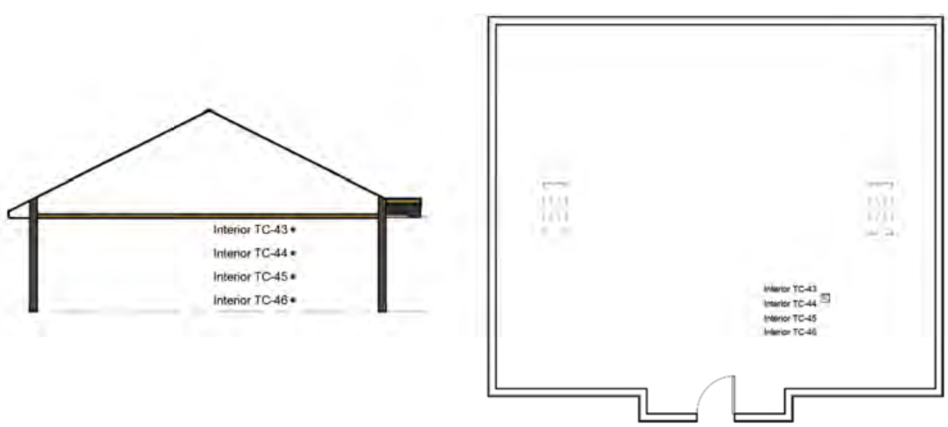


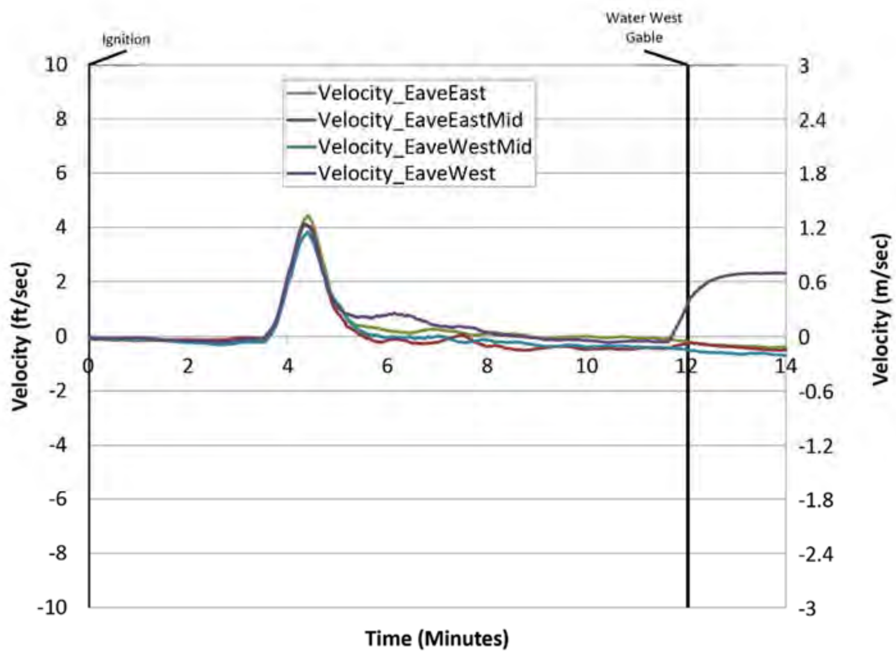
Figure I. 50: Attic Experiment 3A Interior TC Array CD





Interior Array AD
Test 3A - Gable Attack Unvented

Figure I. 51: Attic Experiment 3A Interior TC Array AD



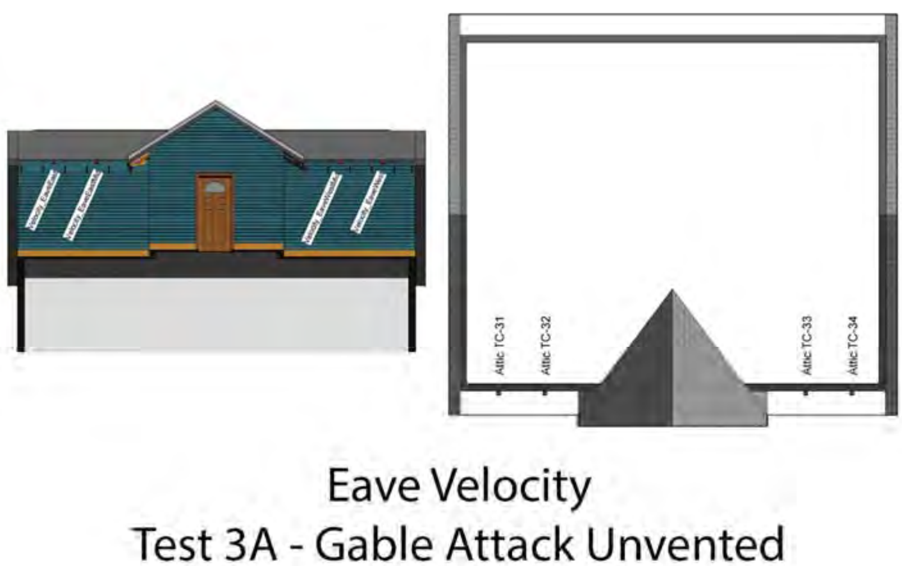
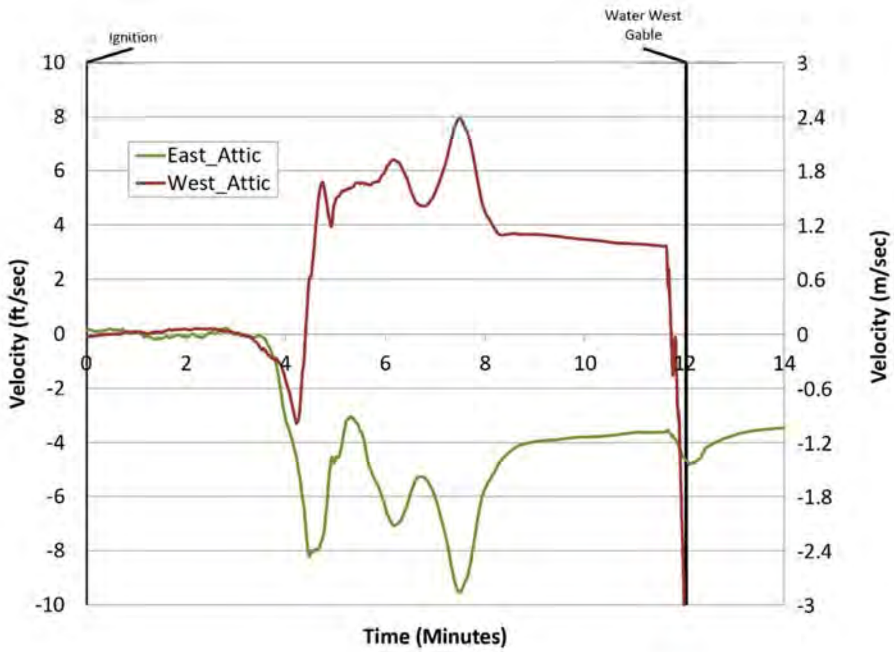
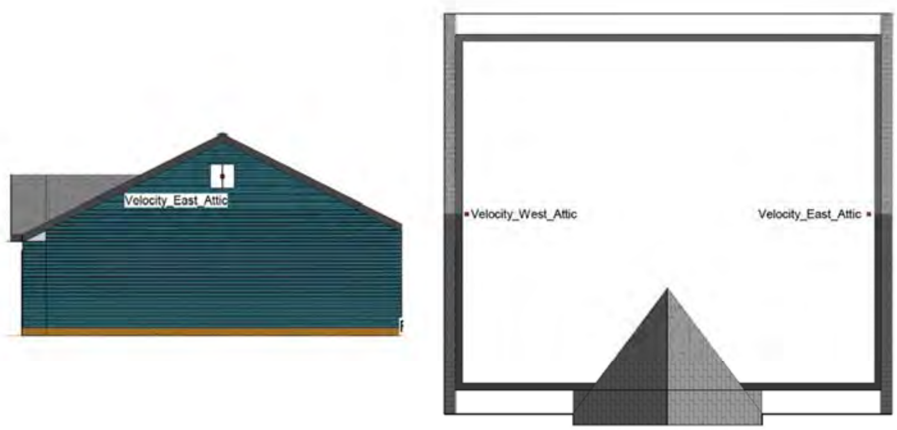


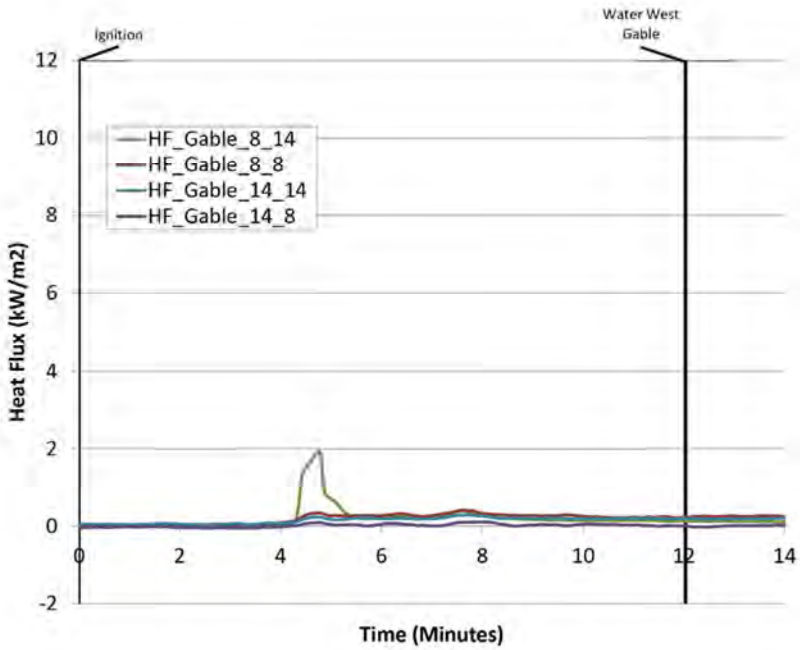
Figure I. 52: Attic Experiment 3A Eave Velocity

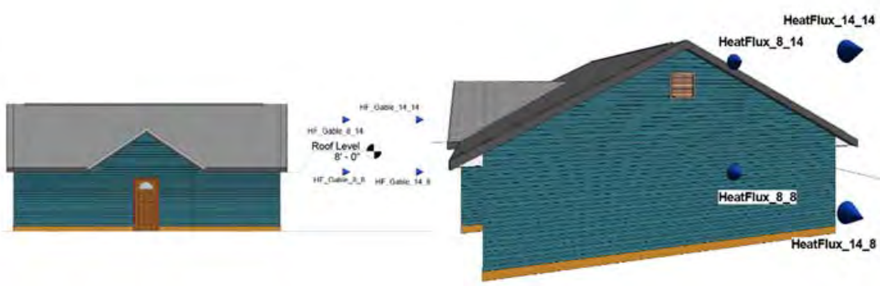




Gable Vent Velocity
Test 3A - Gable Attack Unvented

Figure I. 53: Attic Experiment 3A Gable Vent Velocity





Heat Flux Gable End
Test 3A - Gable Attack Unvented

Figure I. 54: Attic Experiment 3A Heat Flux Gable End

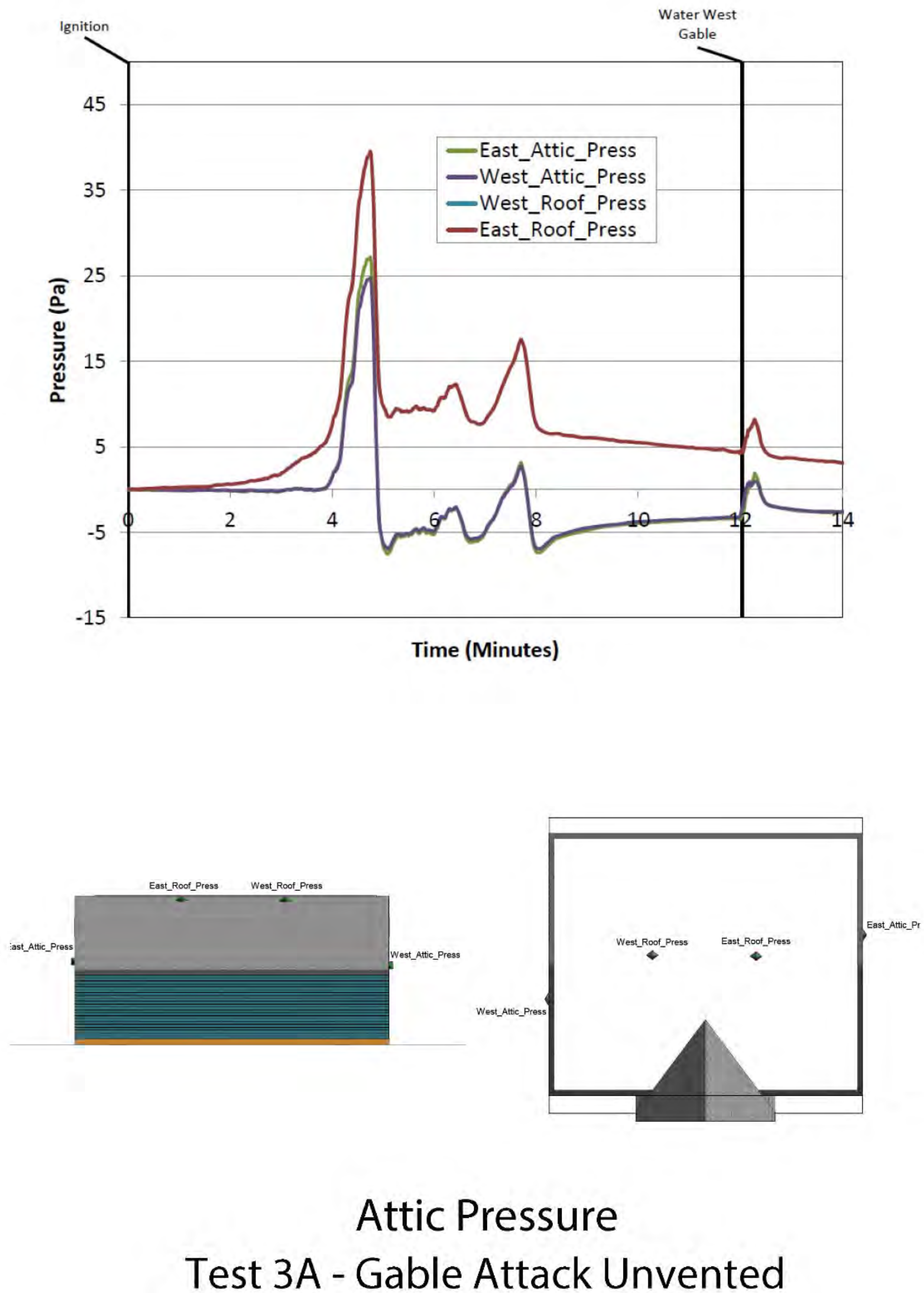


Figure I. 55: Attic Experiment 3A Attic Pressure

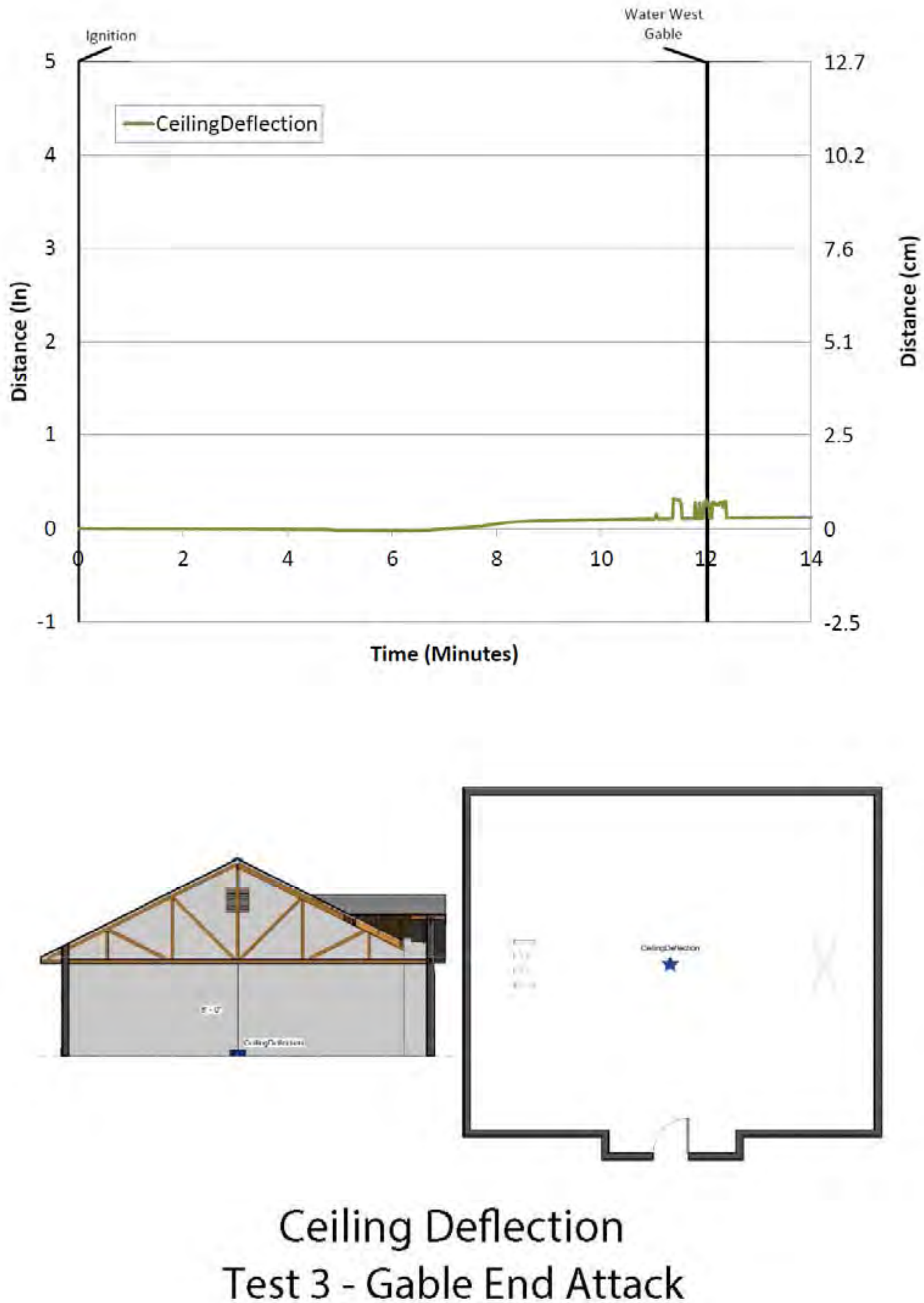
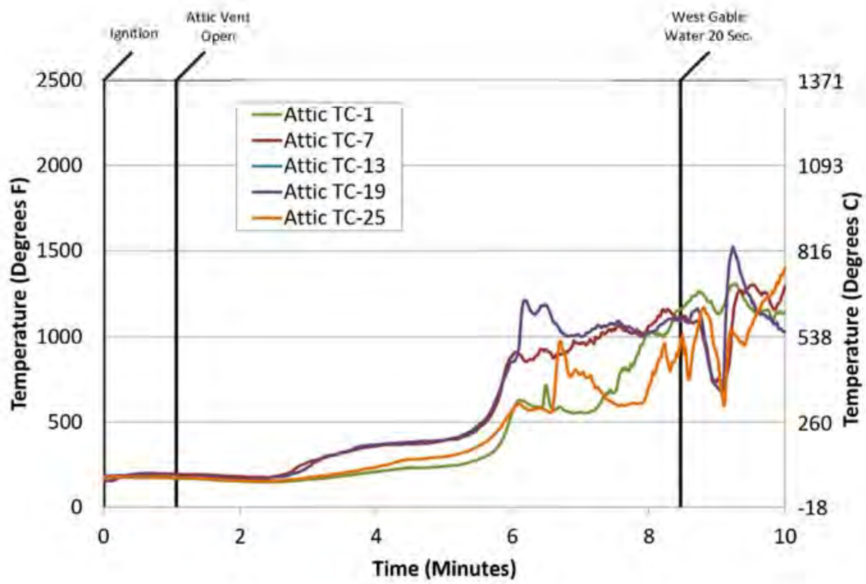


Figure I. 56: Attic Experiment 3A Ceiling Deflection

Experiment 3B



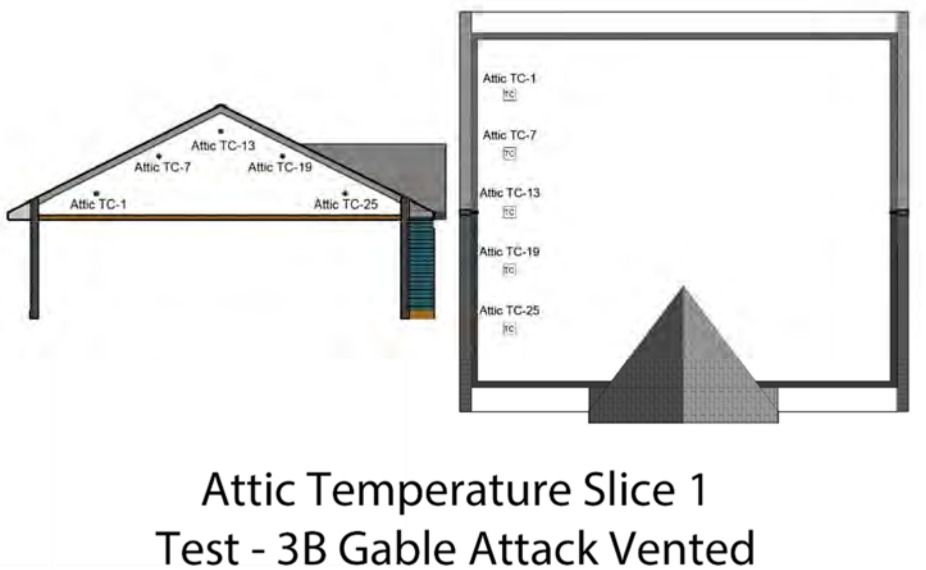
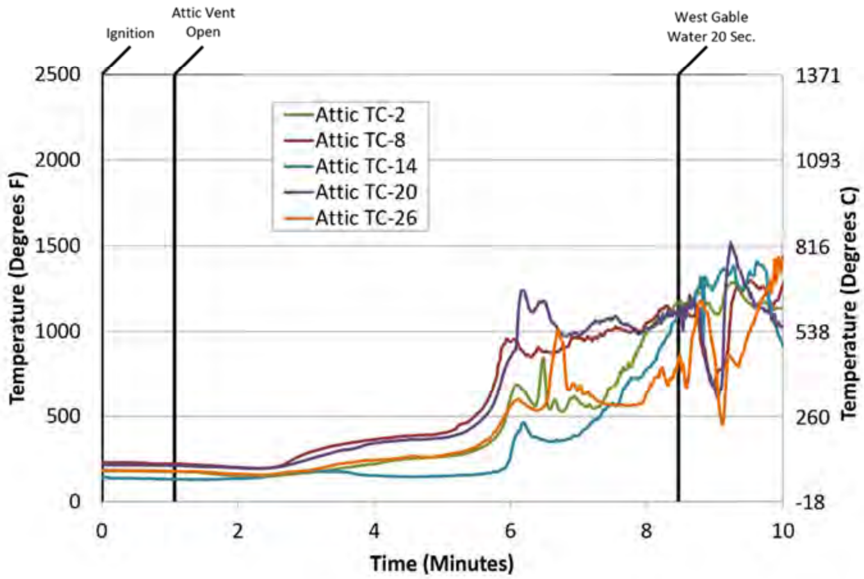
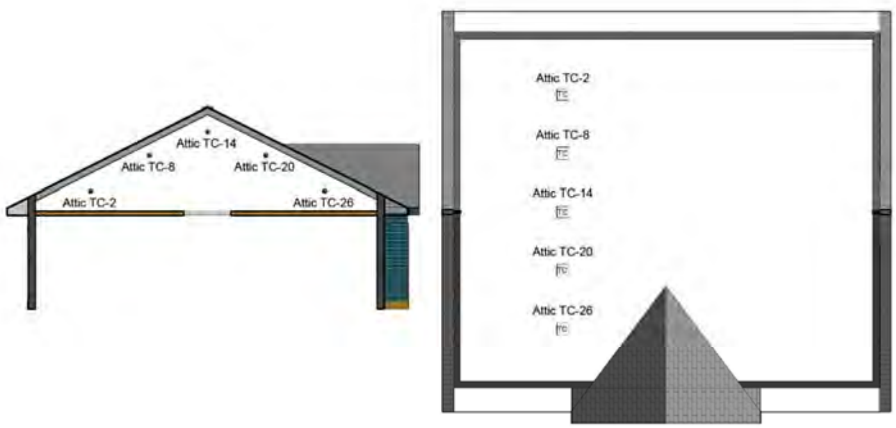


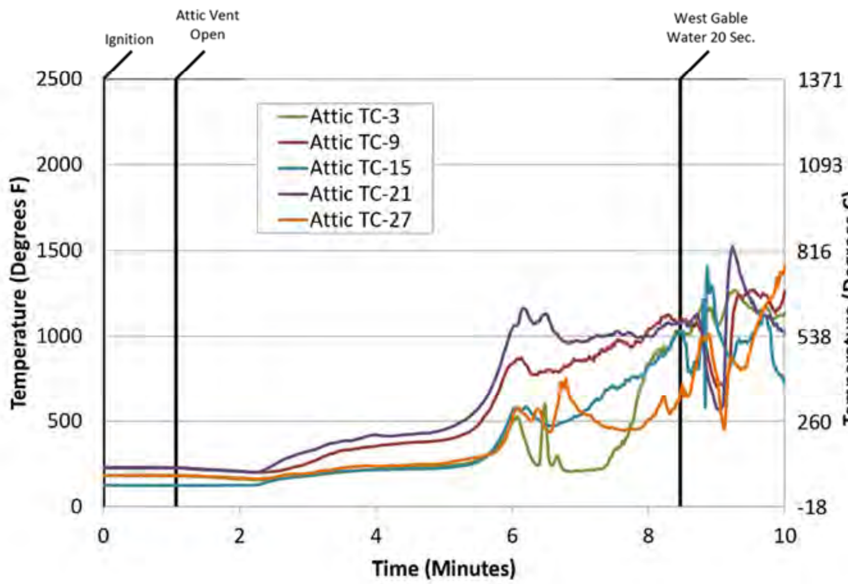
Figure I. 57: Attic Experiment 3B Attic Temperature Slice 1

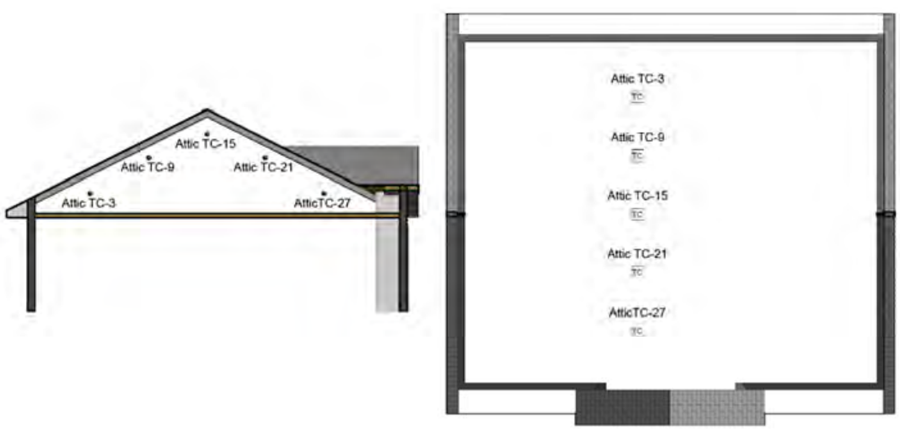




Attic Temperature Slice 2
Test - 3B Gable Attack Vented

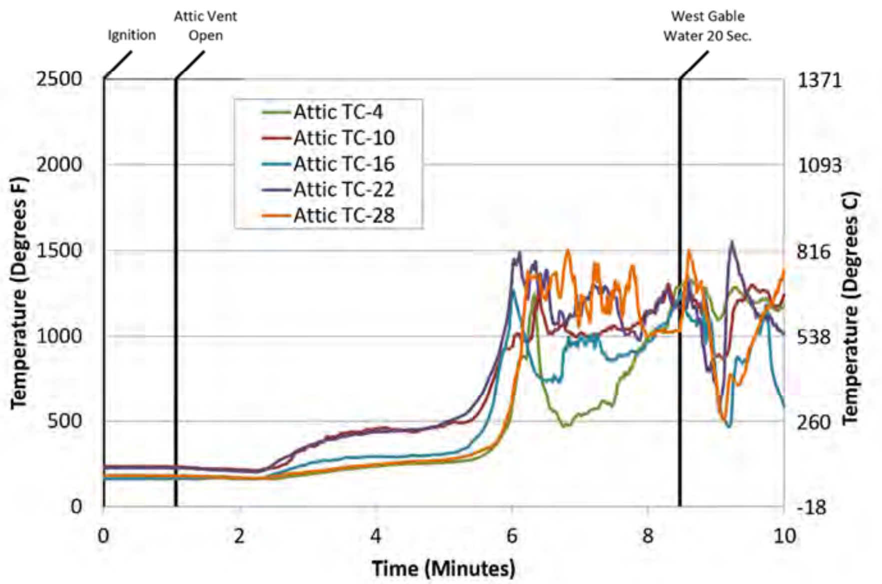
Figure I. 58: Attic Experiment 3B Attic Temperature Slice 2





Attic Temperature Slice 3
Test - 3B Gable Attack Vented

Figure I. 59: Attic Experiment 3B Attic Temperature Slice 3



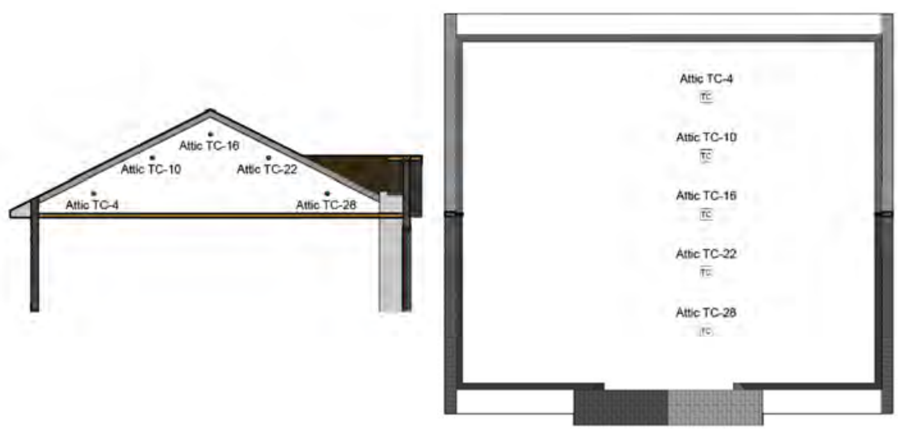
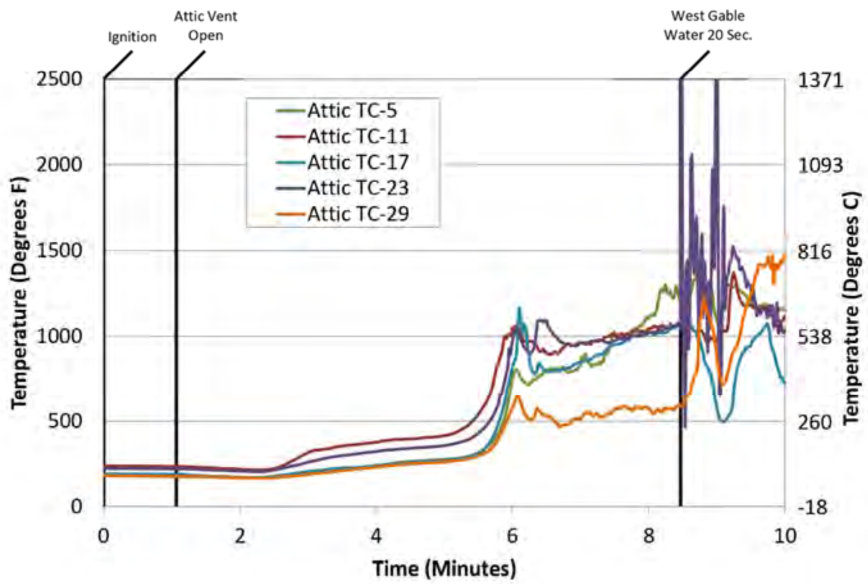


Figure I. 60: Attic Experiment 3B Attic Temperature Slice 4



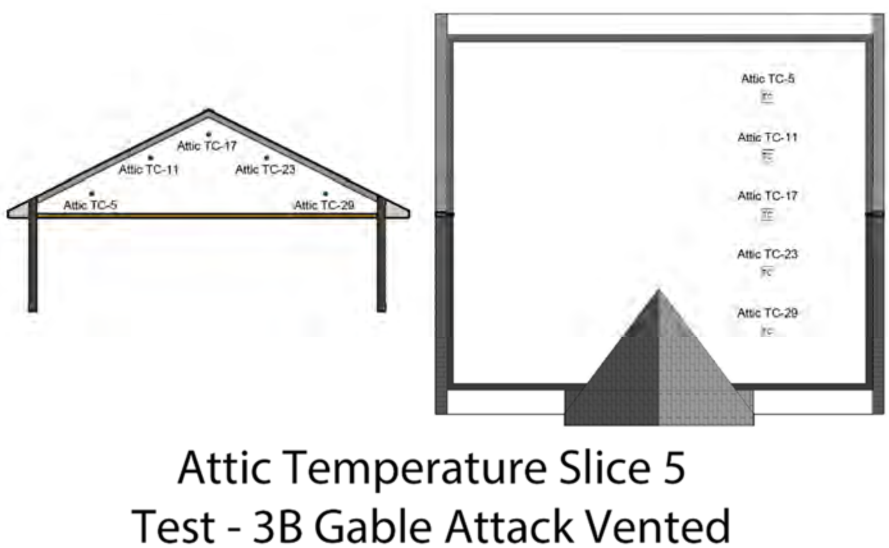
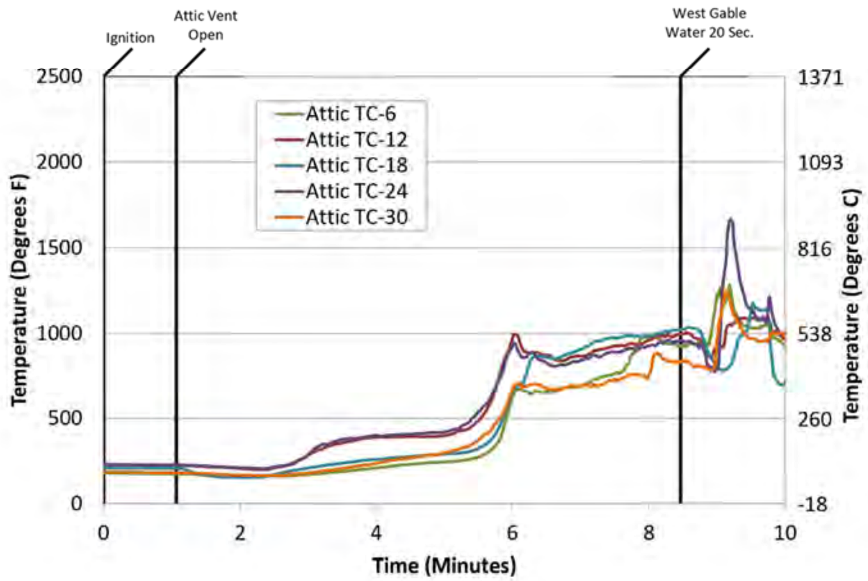


Figure I. 61: Attic Experiment 3B Attic Temperature Slice 5



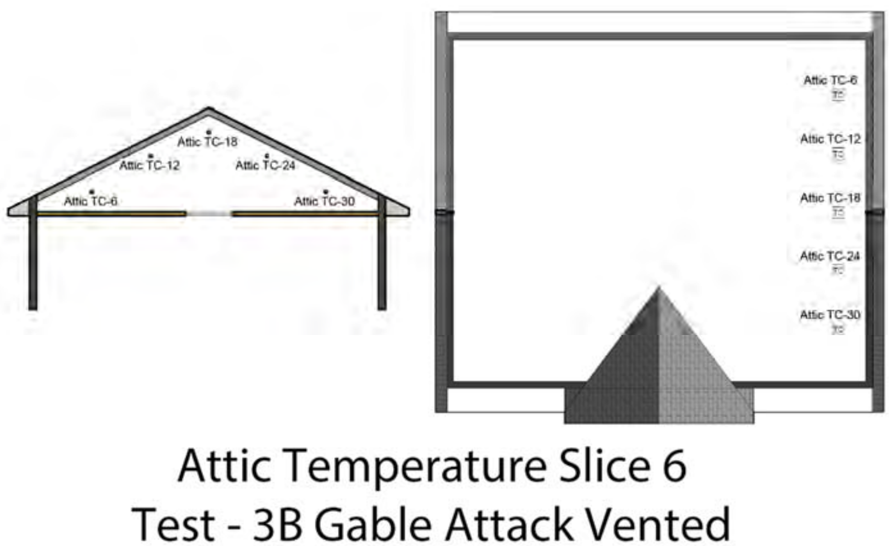


Figure I. 62: Attic Experiment 3B Attic Temperature Slice 6

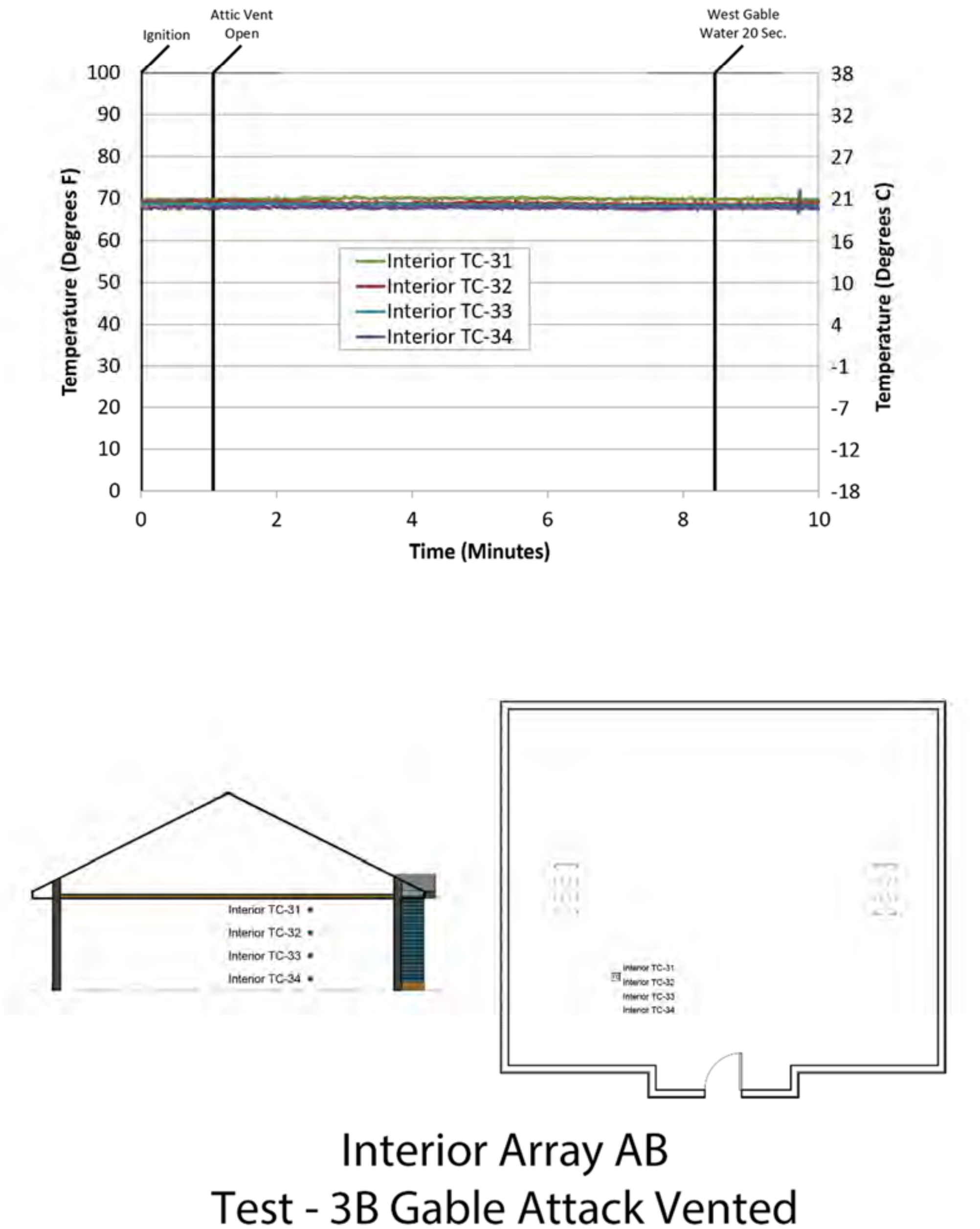
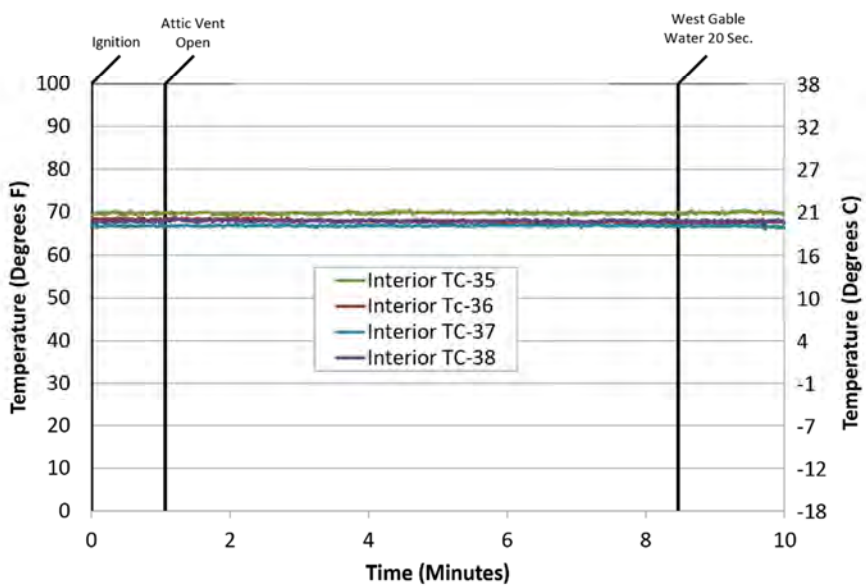


Figure I. 63: Attic Experiment 3B Interior TC Array AB



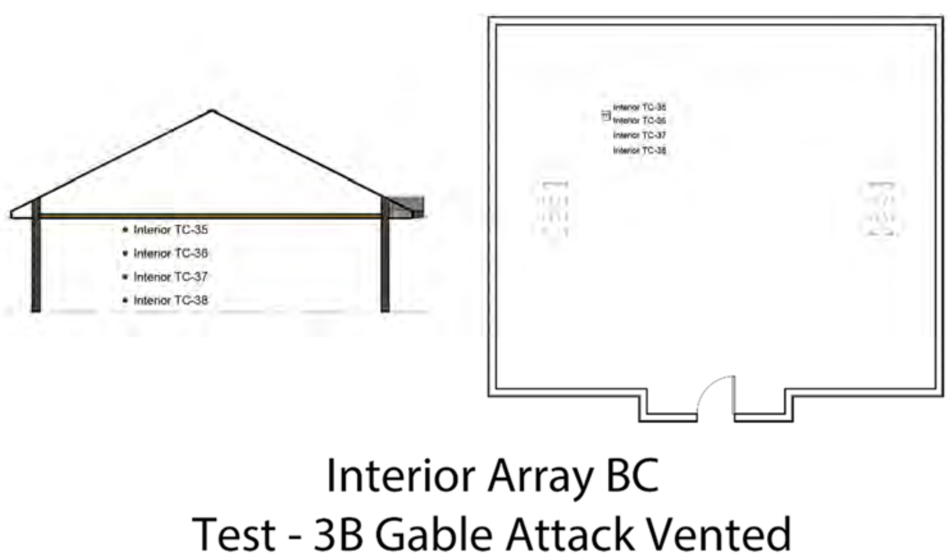
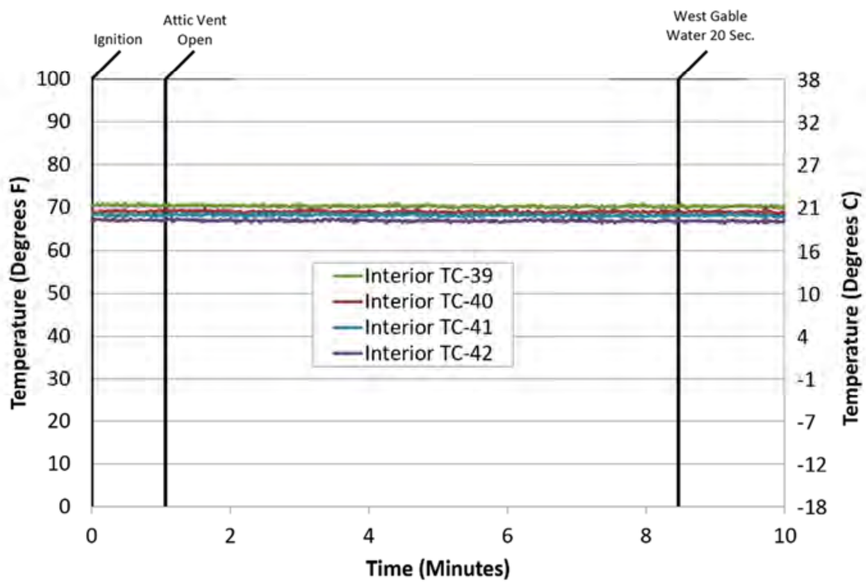


Figure I. 64: Attic Experiment 3B Interior TC Array BC



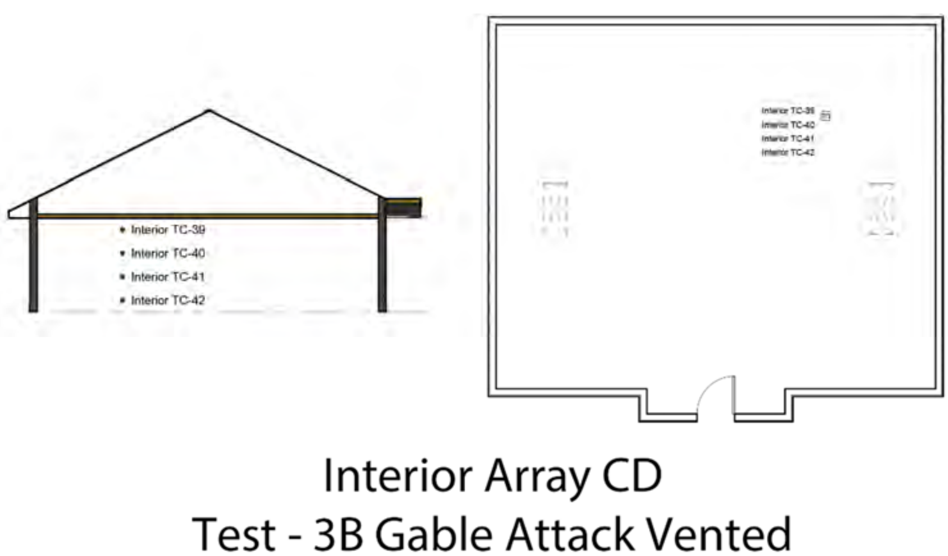


Figure I. 65: Attic Experiment 3B Interior TC Array CD

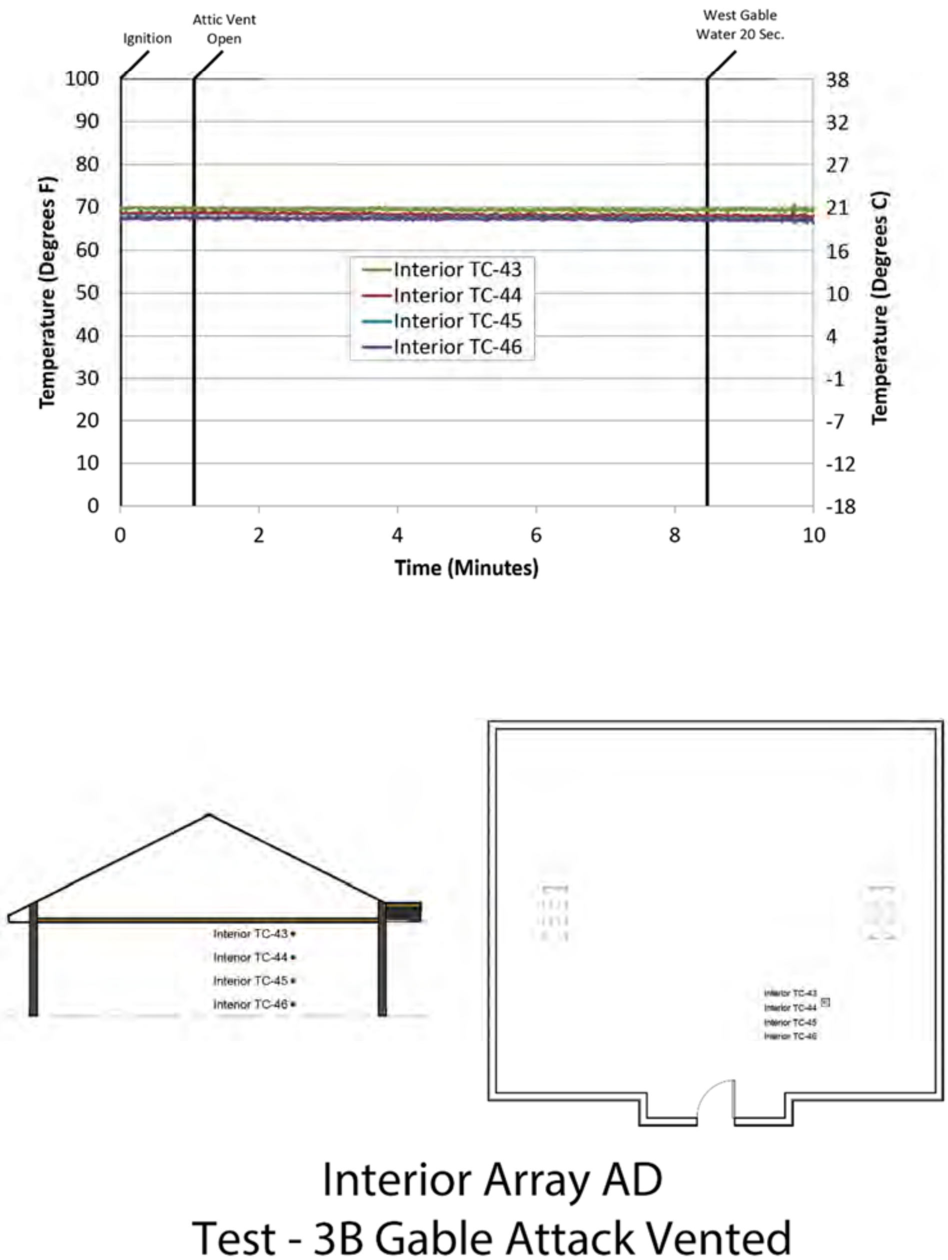


Figure I. 66: Attic Experiment 3B Interior TC Array AD

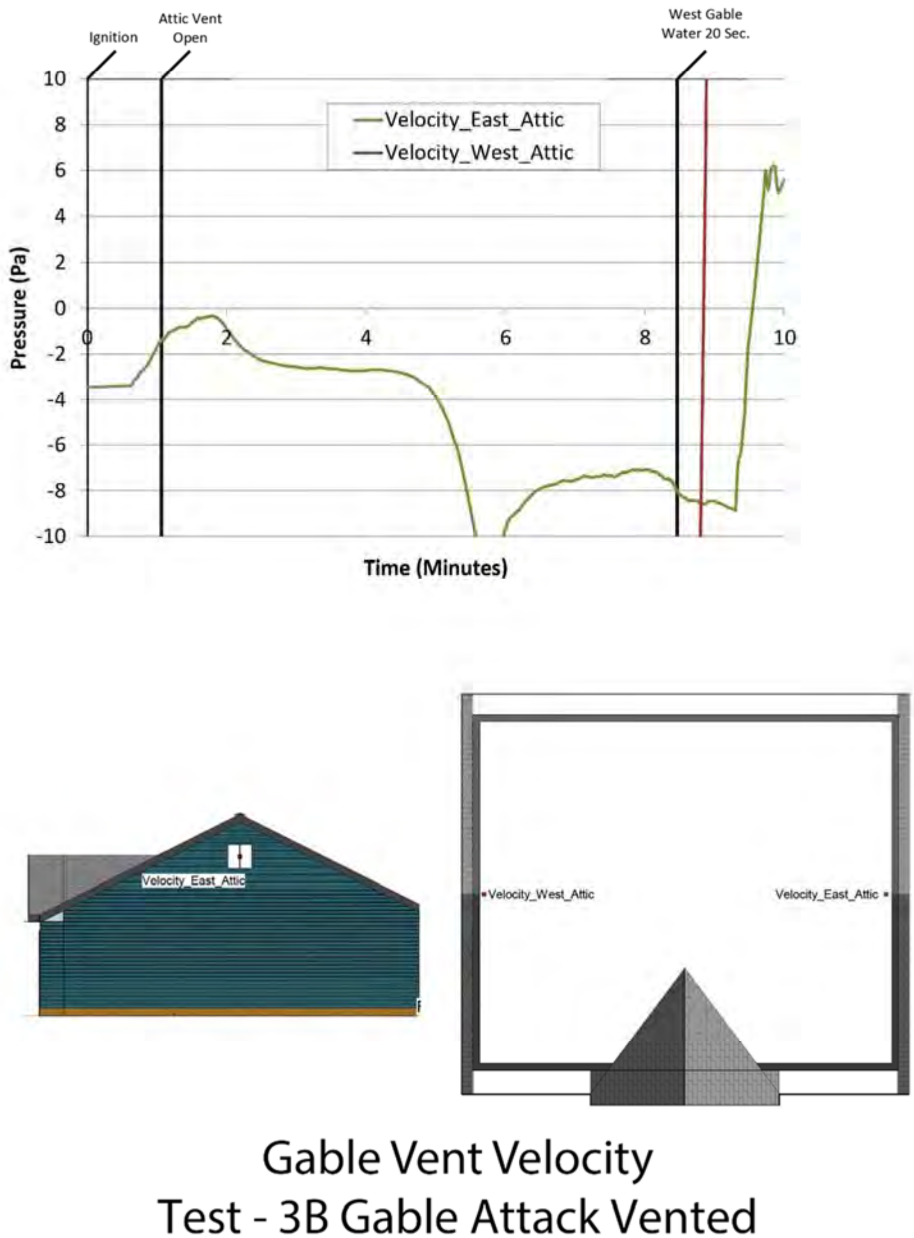


Figure I. 67: Attic Experiment 3B Gable Velocity

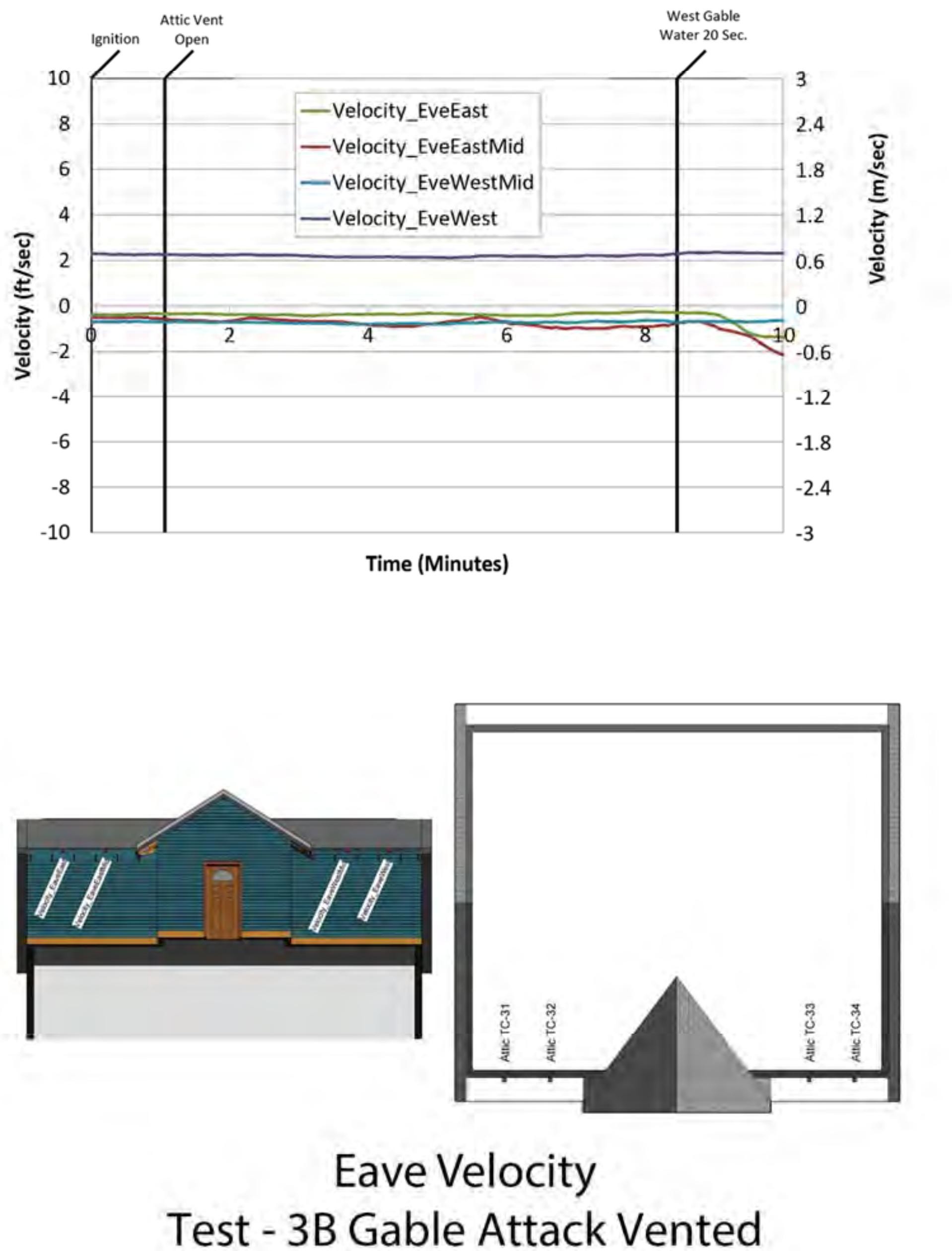


Figure I. 68: Attic Experiment 3B Eave VelotICy

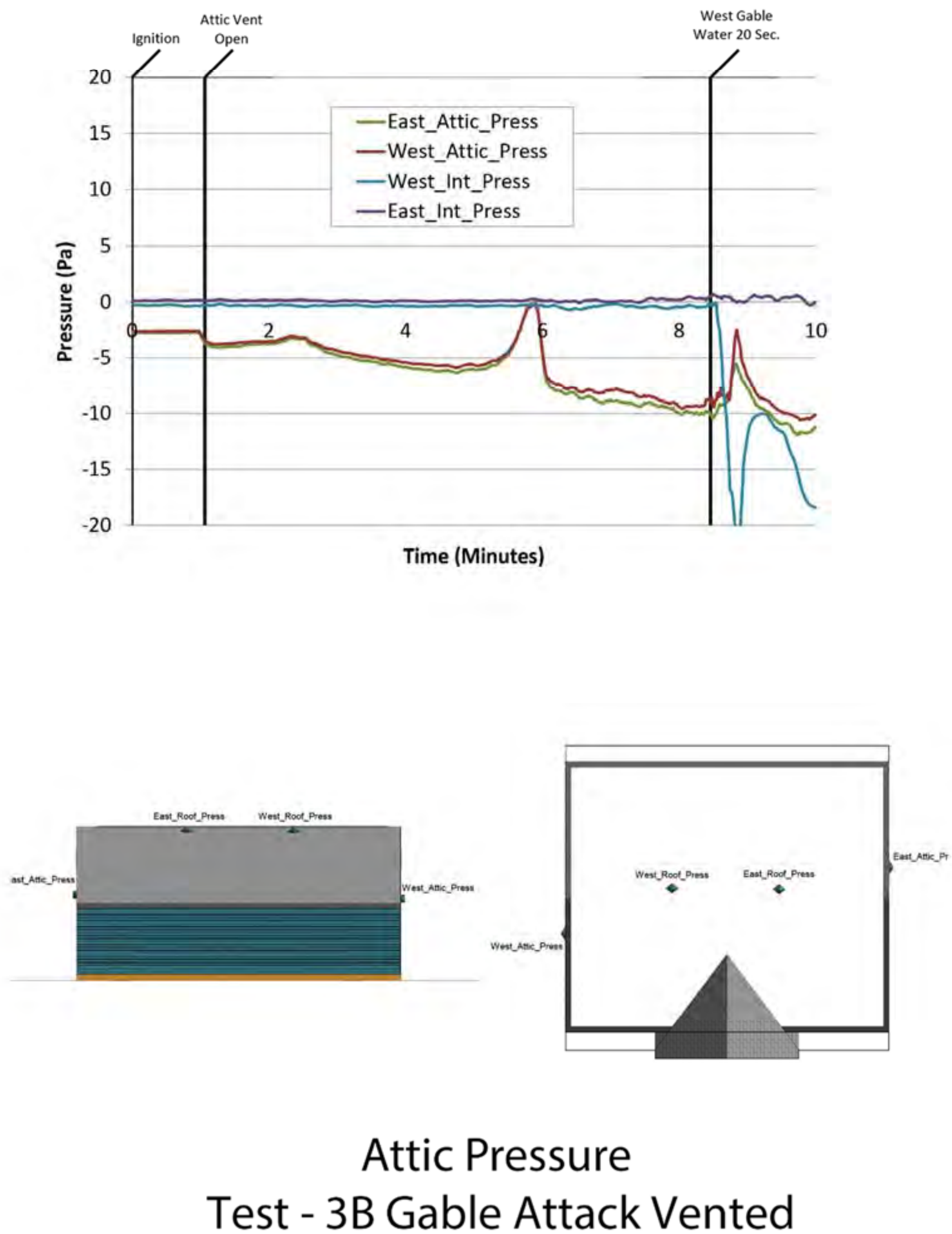
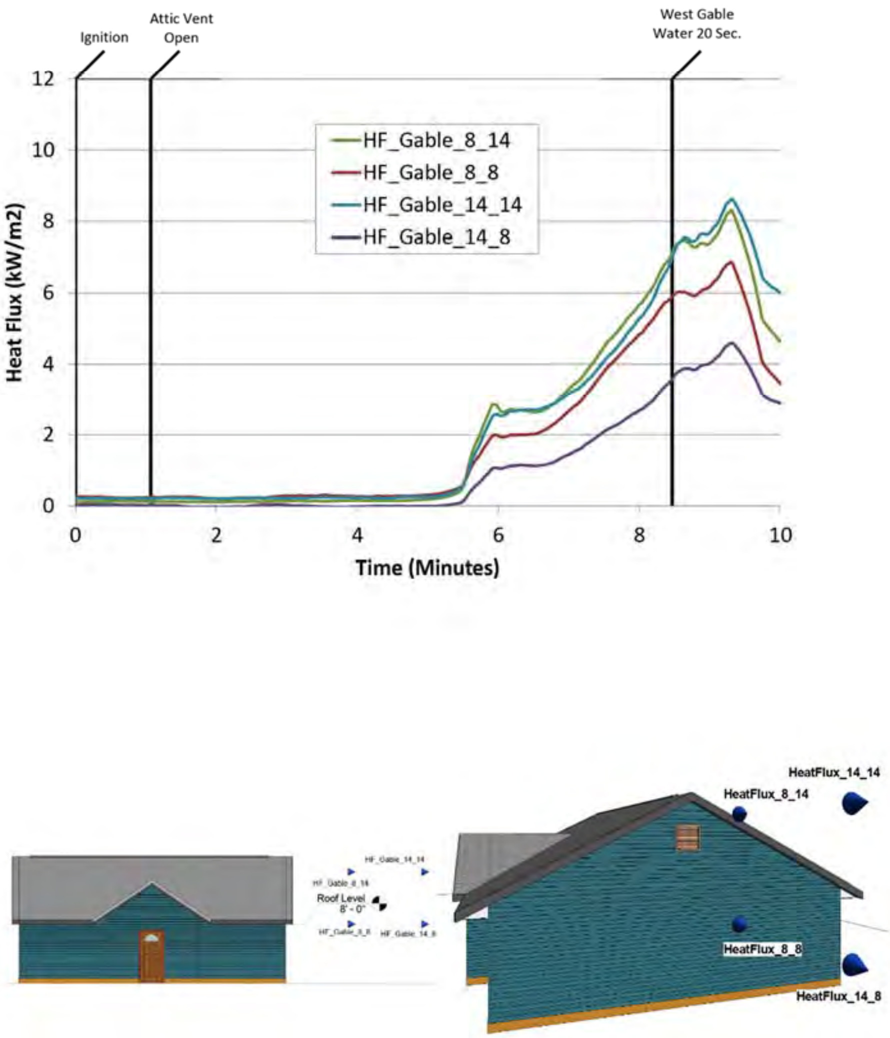


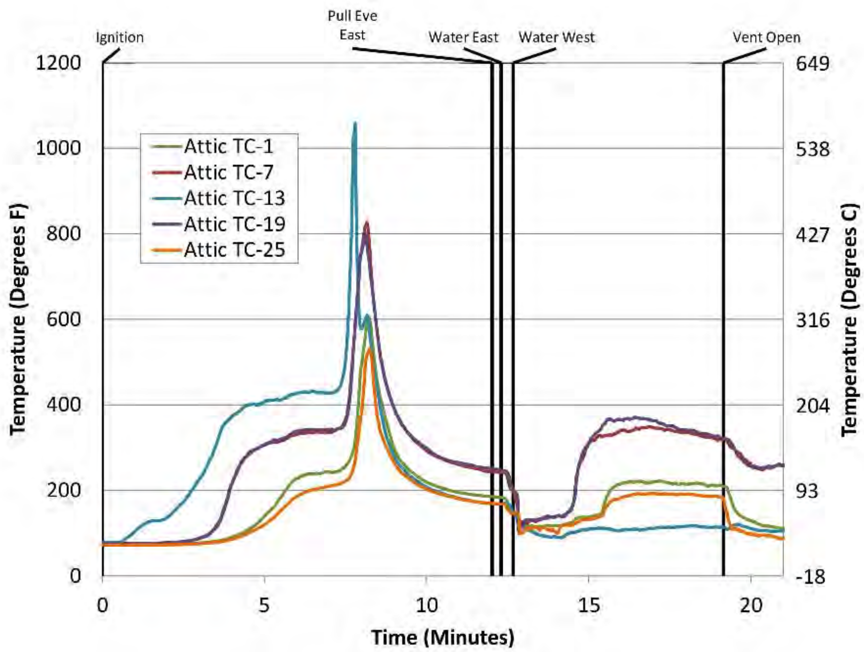
Figure I. 69: Attic Experiment 3B Attic Pressure



Heat Flux Gable End
Test - 3B Gable Attack Vented

Figure I. 70: Attic Experiment 3B Gable End Heat Flux

Experiment 4A



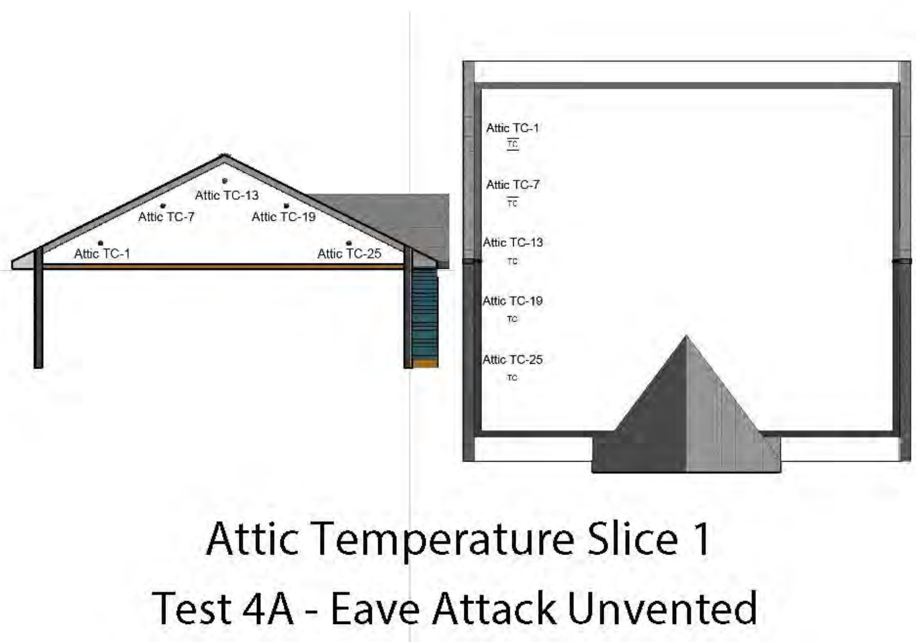


Figure I. 71: Attic Experiment 4A Attic Temperature Slice 1

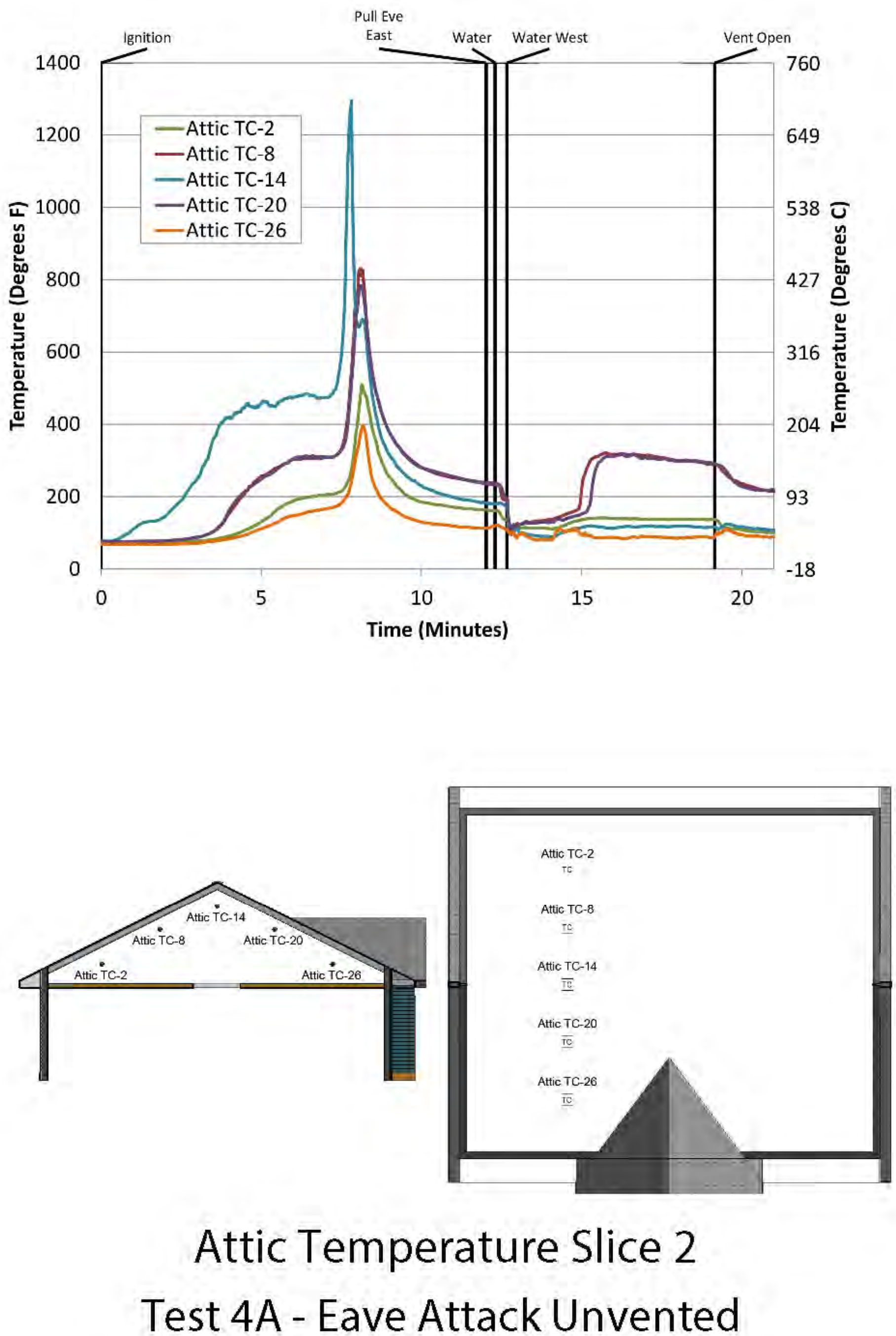


Figure I. 72: Attic Experiment 4A Attic Temperature Slice 2

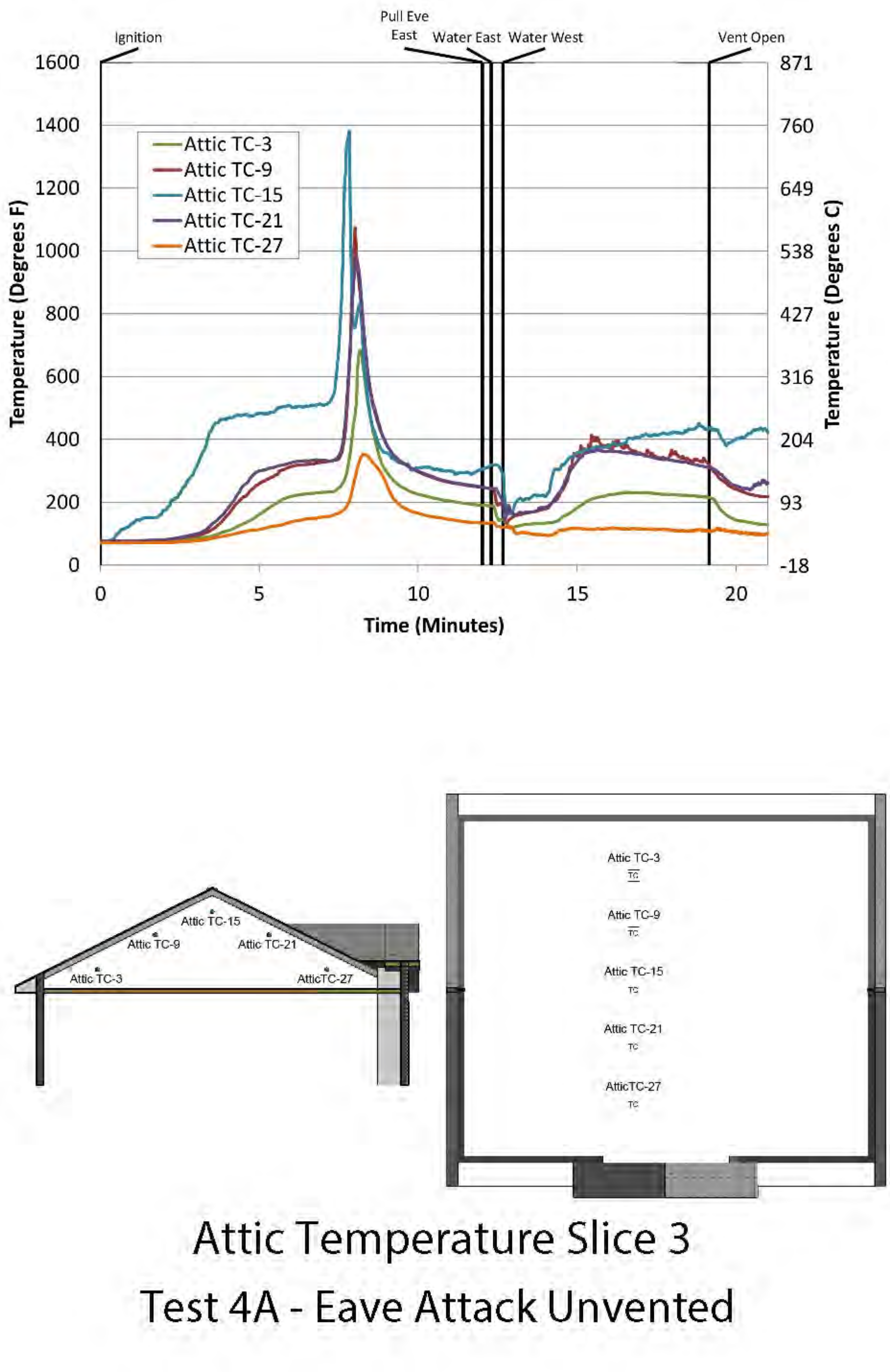


Figure I. 73: Attic Experiment 4A Attic Temperature Slice 3

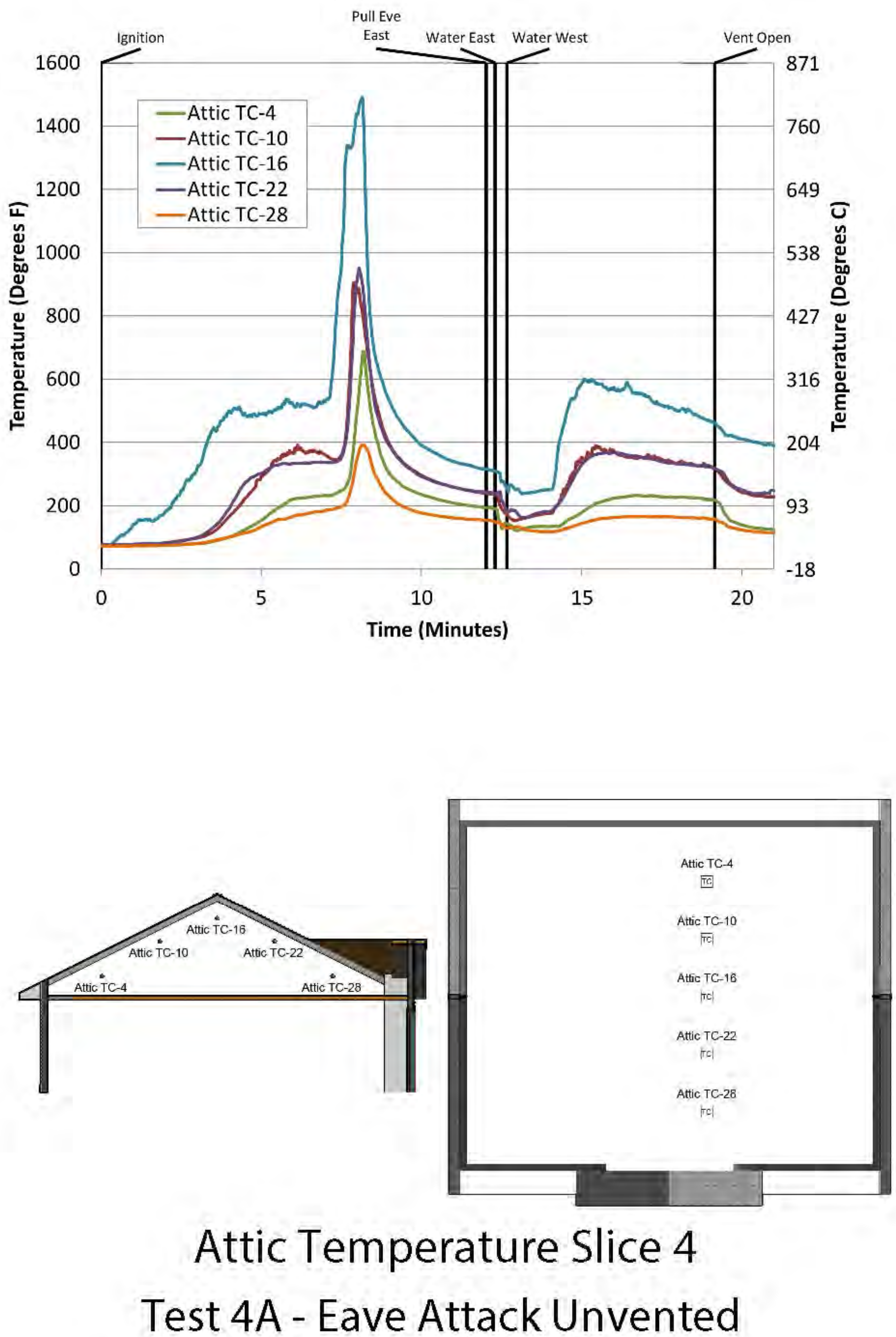


Figure I. 74: Attic Experiment 4A Attic Temperature Slice 4

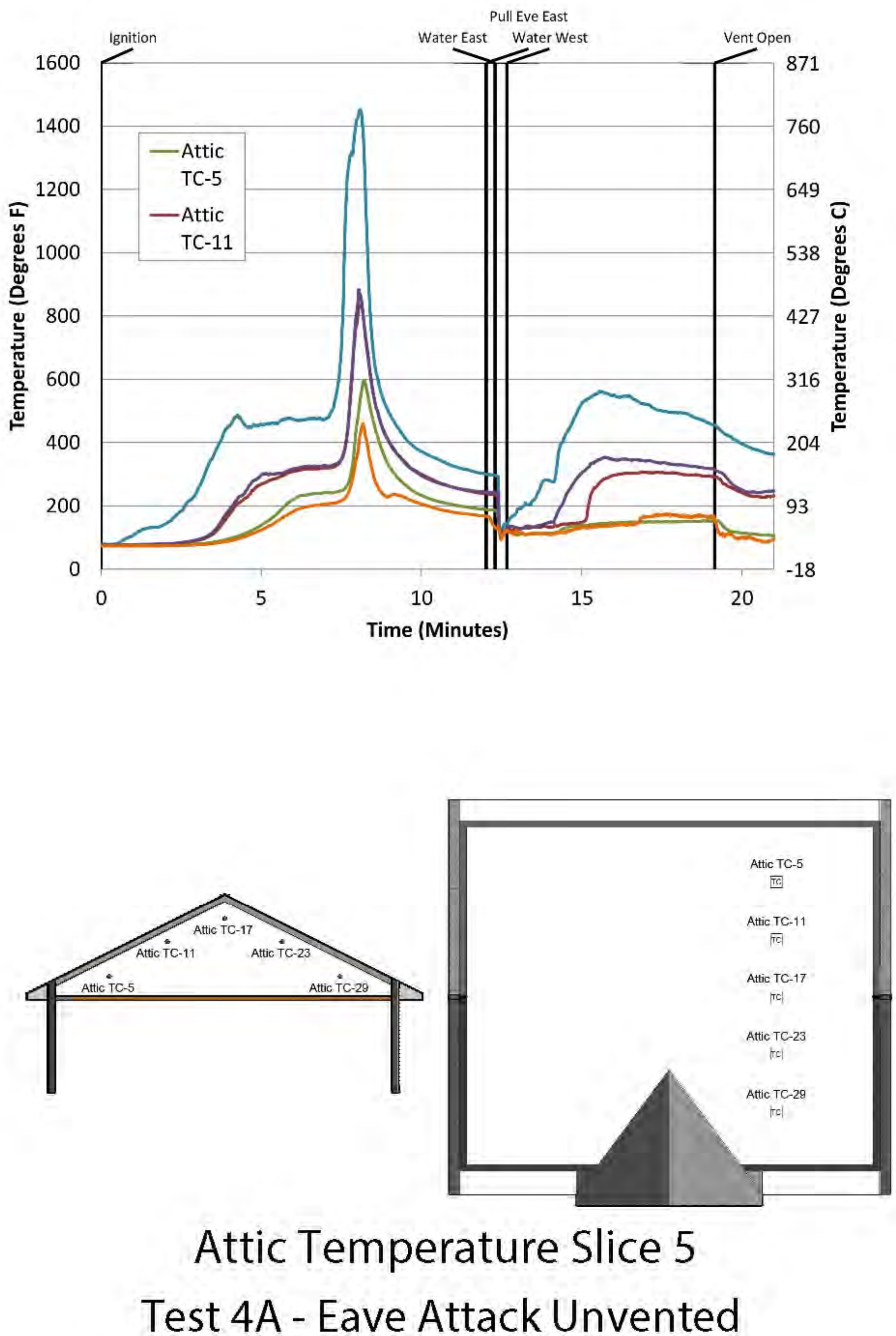


Figure I. 75: Attic Experiment 4A Attic Temperature Slice 5

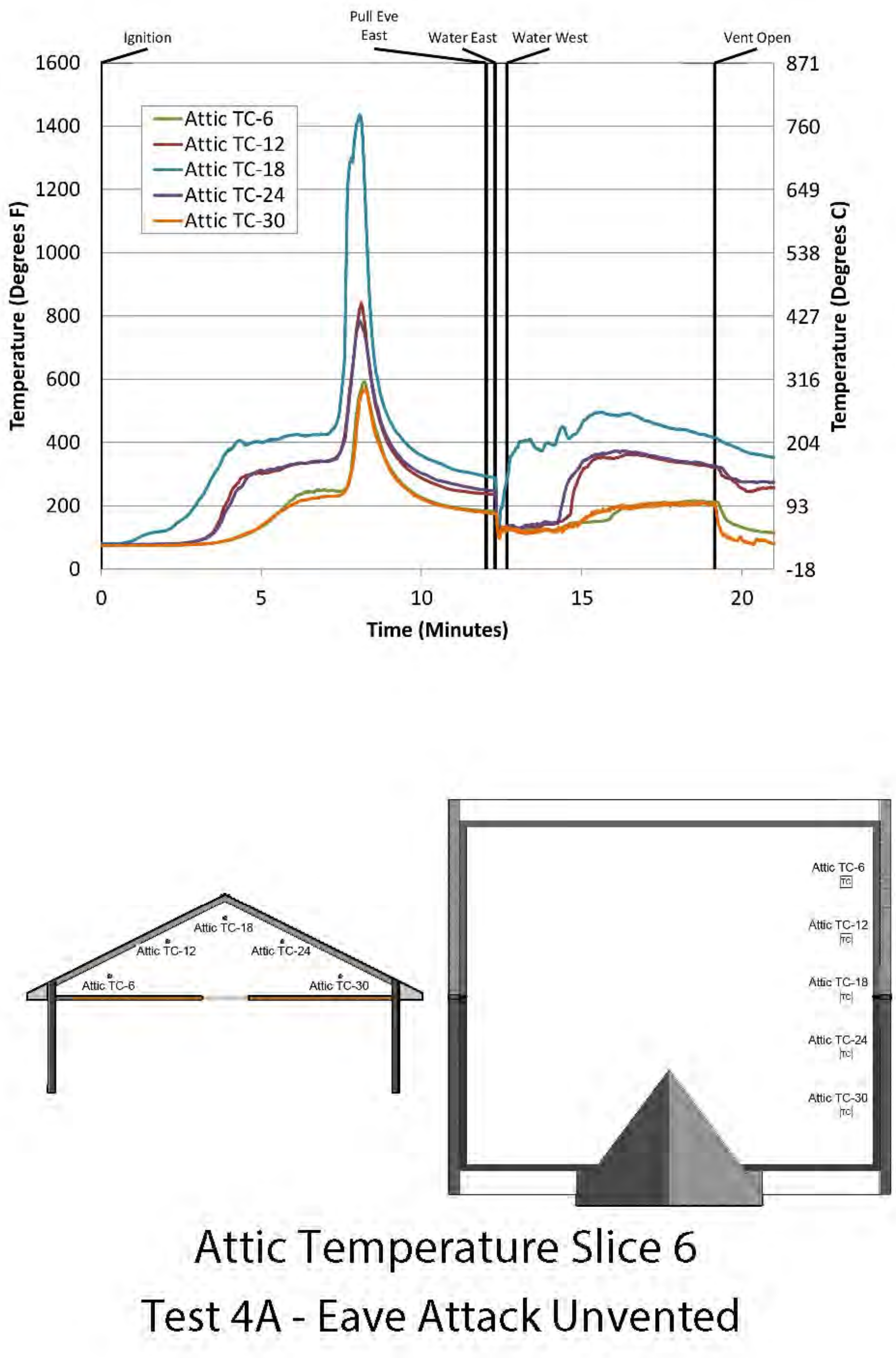
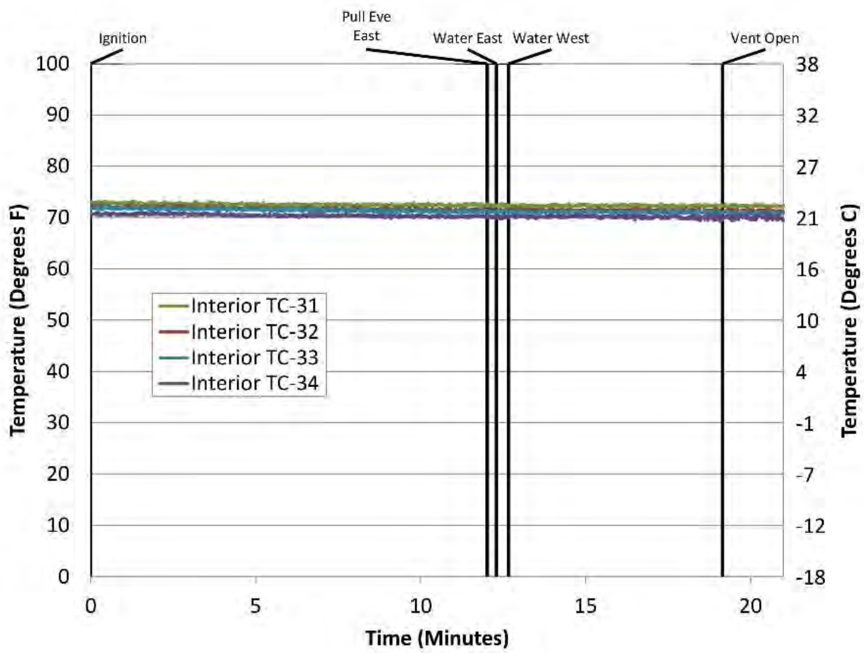


Figure I. 76: Attic Experiment 4A Attic Temperature Slice 6



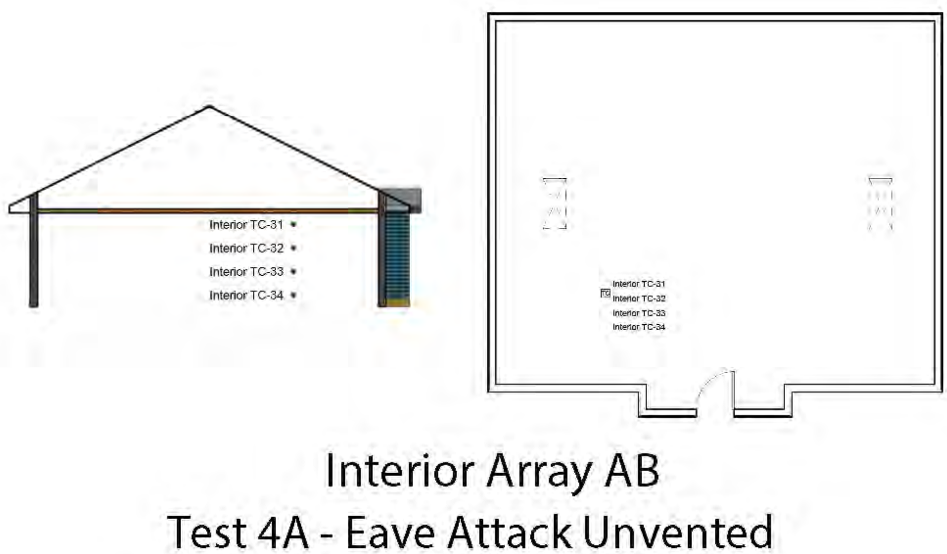
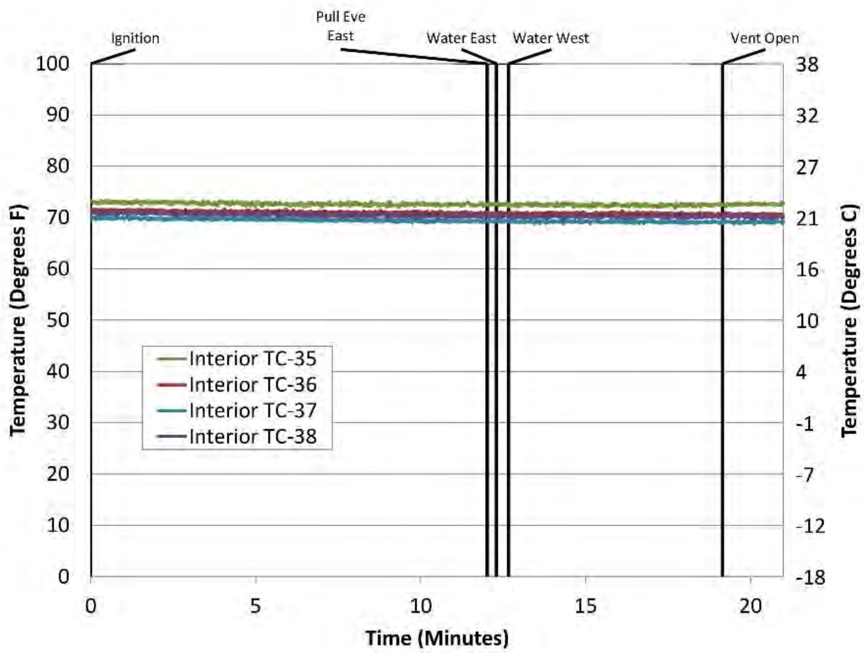


Figure I. 77: Attic Experiment 4A Interior TC Array AB



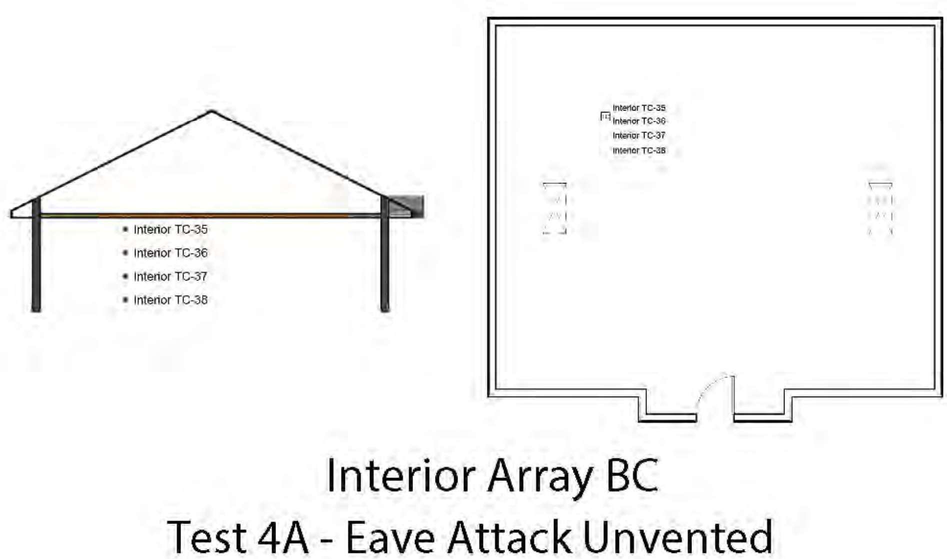
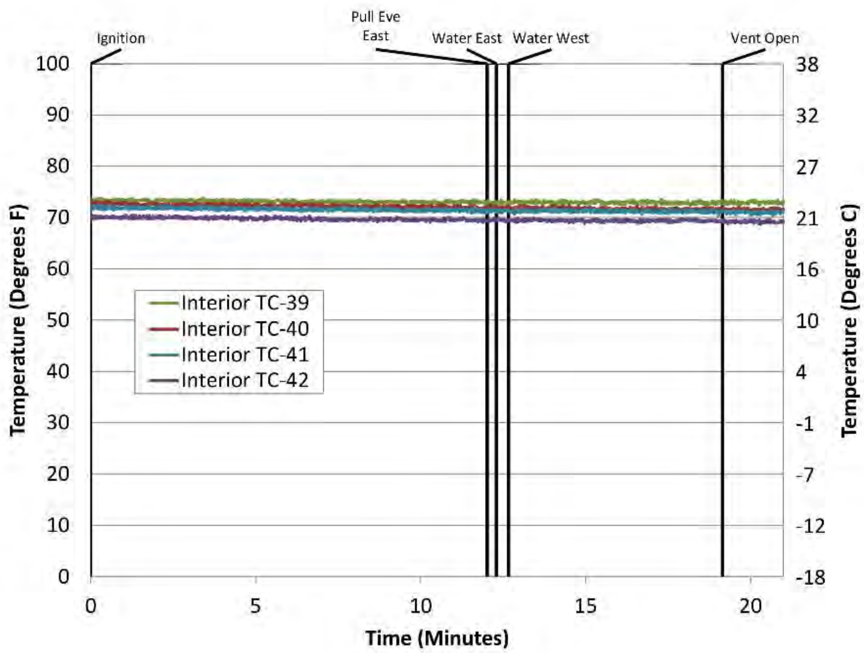


Figure I. 78: Attic Experiment 4A Interior TC Array BC



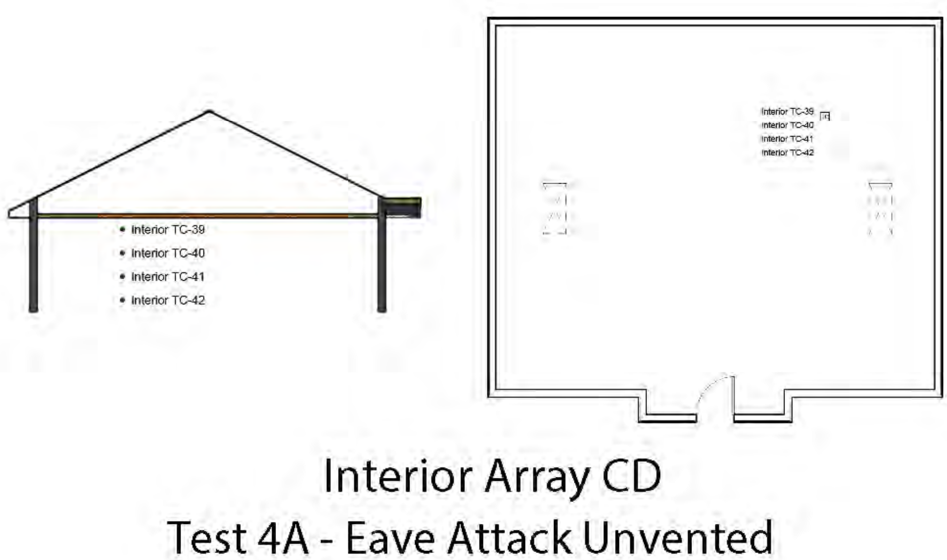
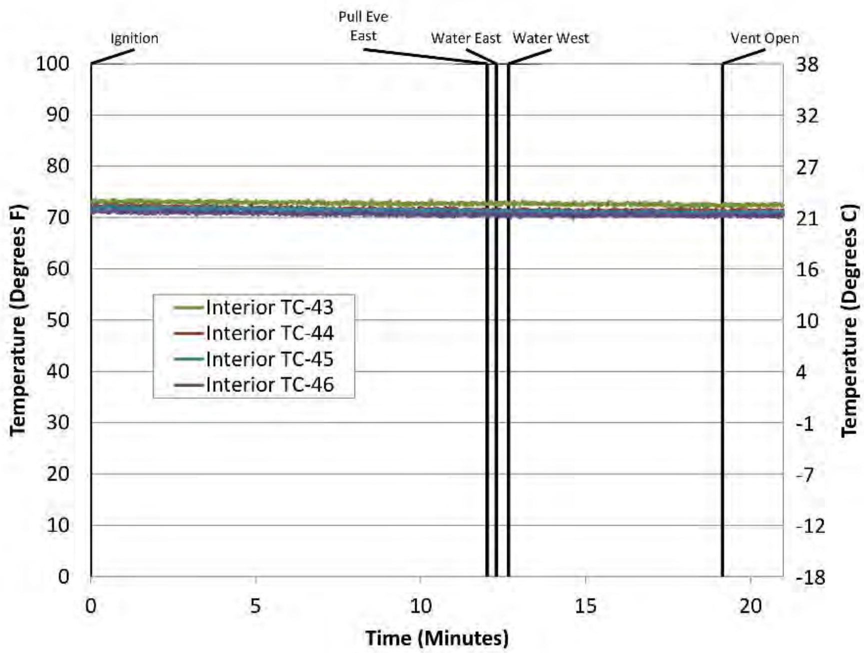


Figure I. 79: Attic Experiment 4A Interior TC Array CD



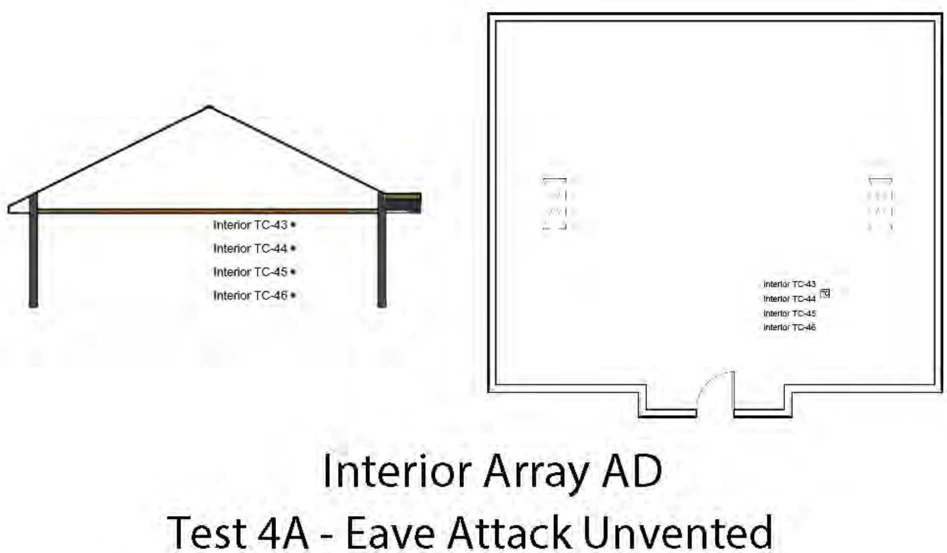
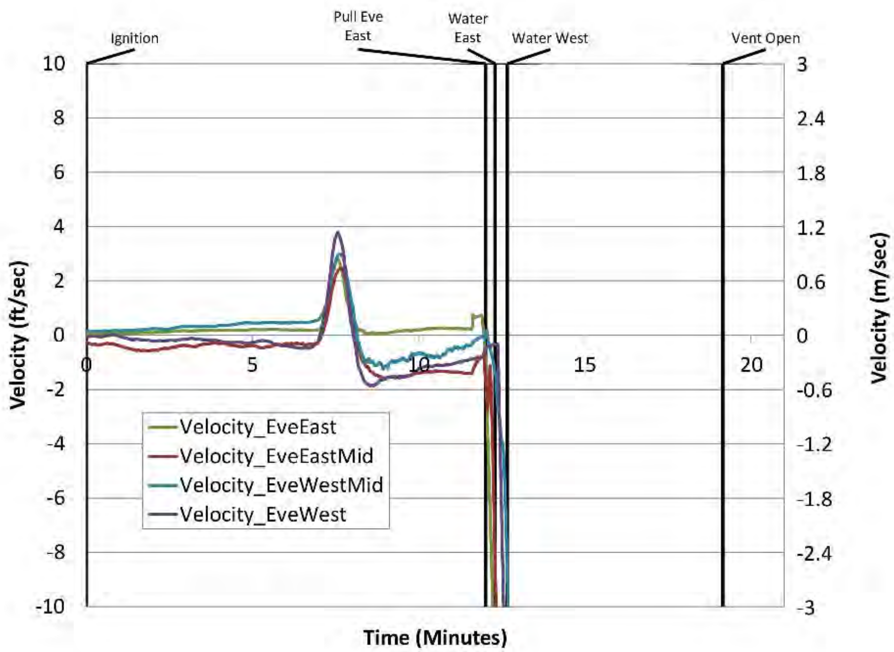


Figure I. 80: Attic Experiment 4A Interior TC Array AD



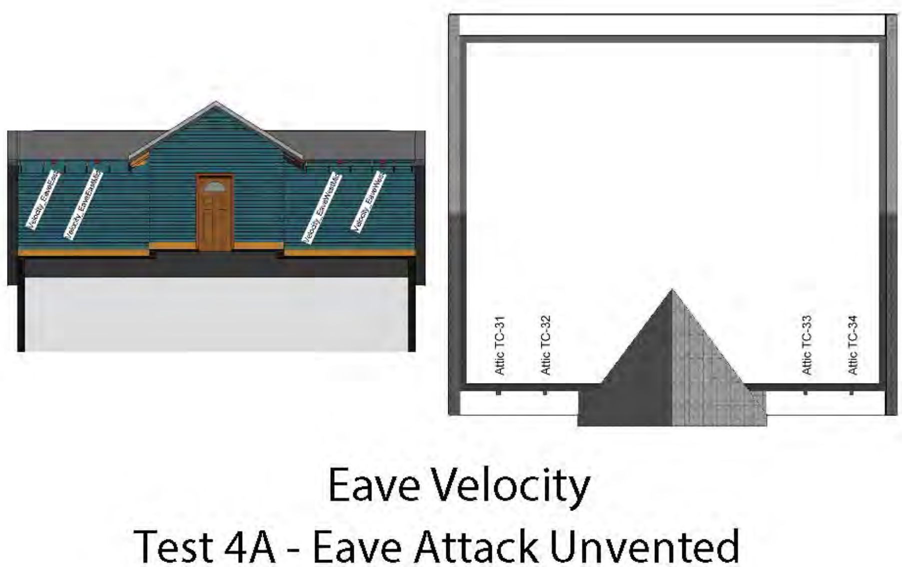
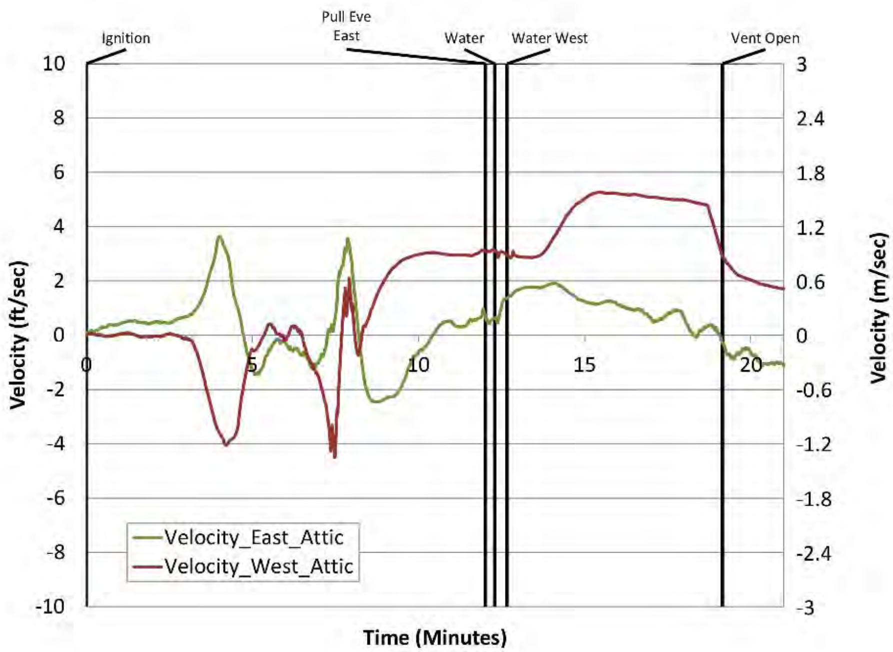
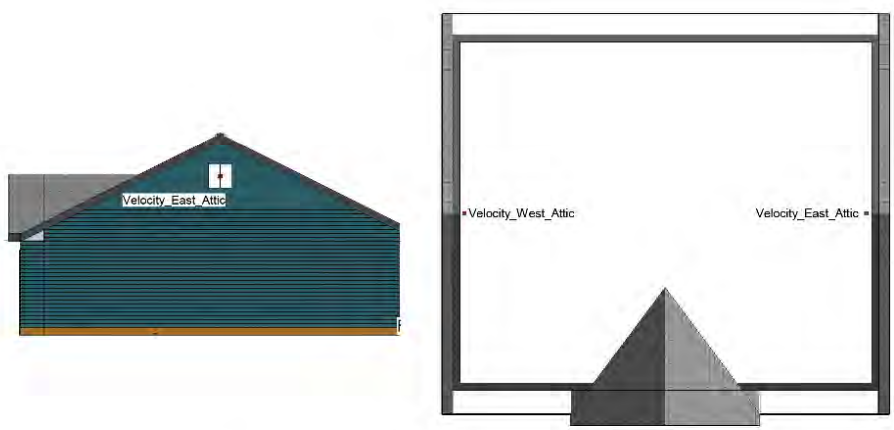


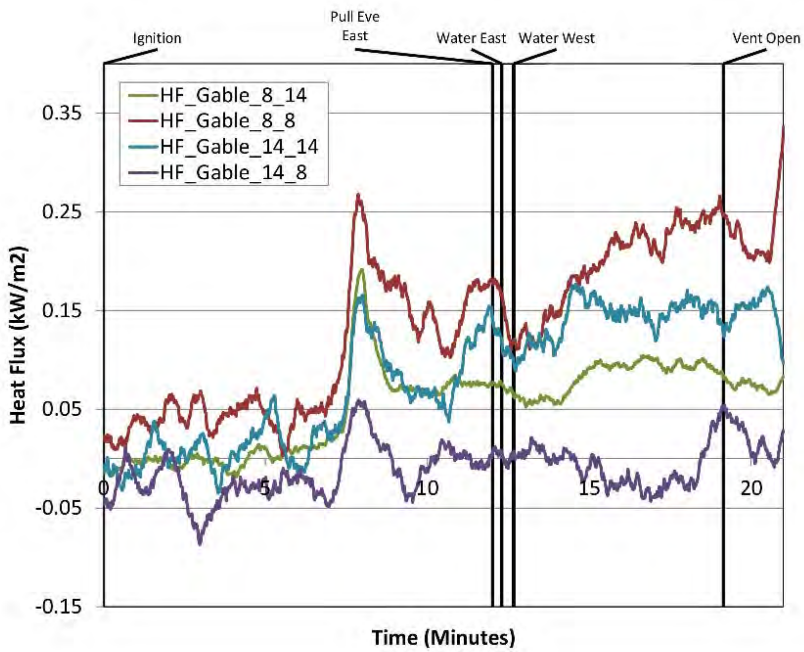
Figure I. 81: Attic Experiment 4A Eave Velocity

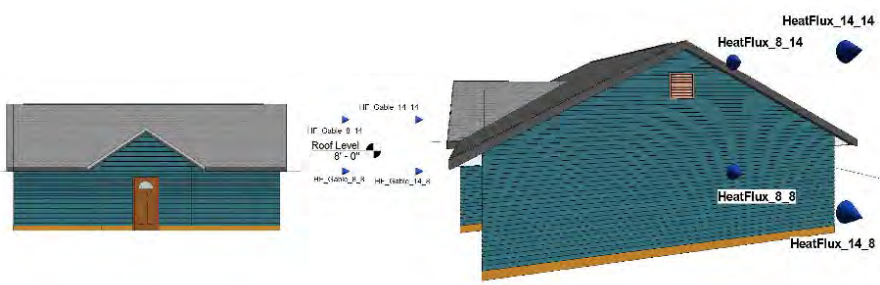




Gable Vent Velocity
Test 4A - Eave Attack Unvented

Figure I. 82: Attic Experiment 4A Gable Vent Velocity





Heat Flux Gable End
Test 4A - Eave Attack Unvented

Figure I. 83: Attic Experiment 4A Gable End Heat Flux

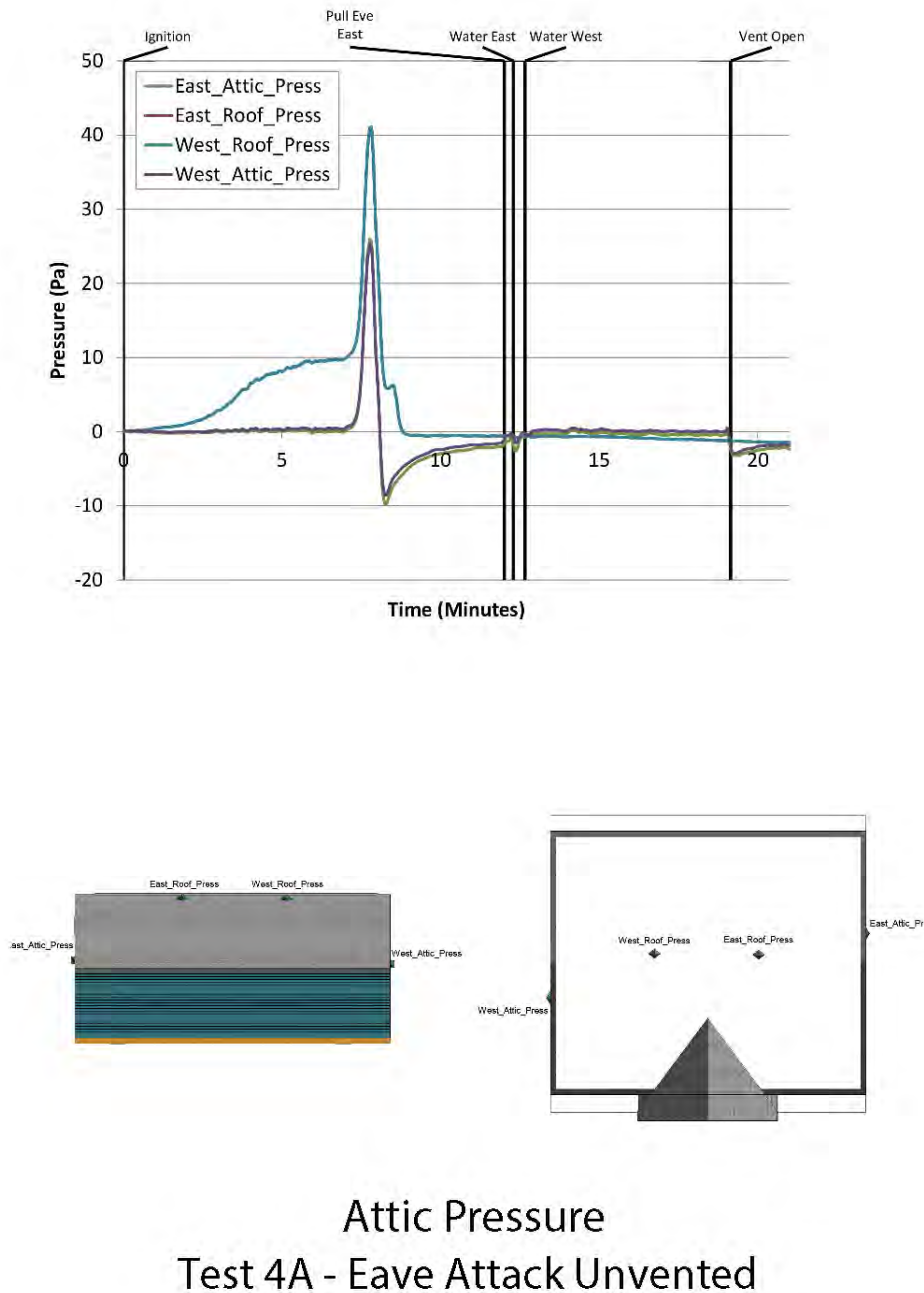


Figure I. 84: Attic Experiment 4A Attic Pressure

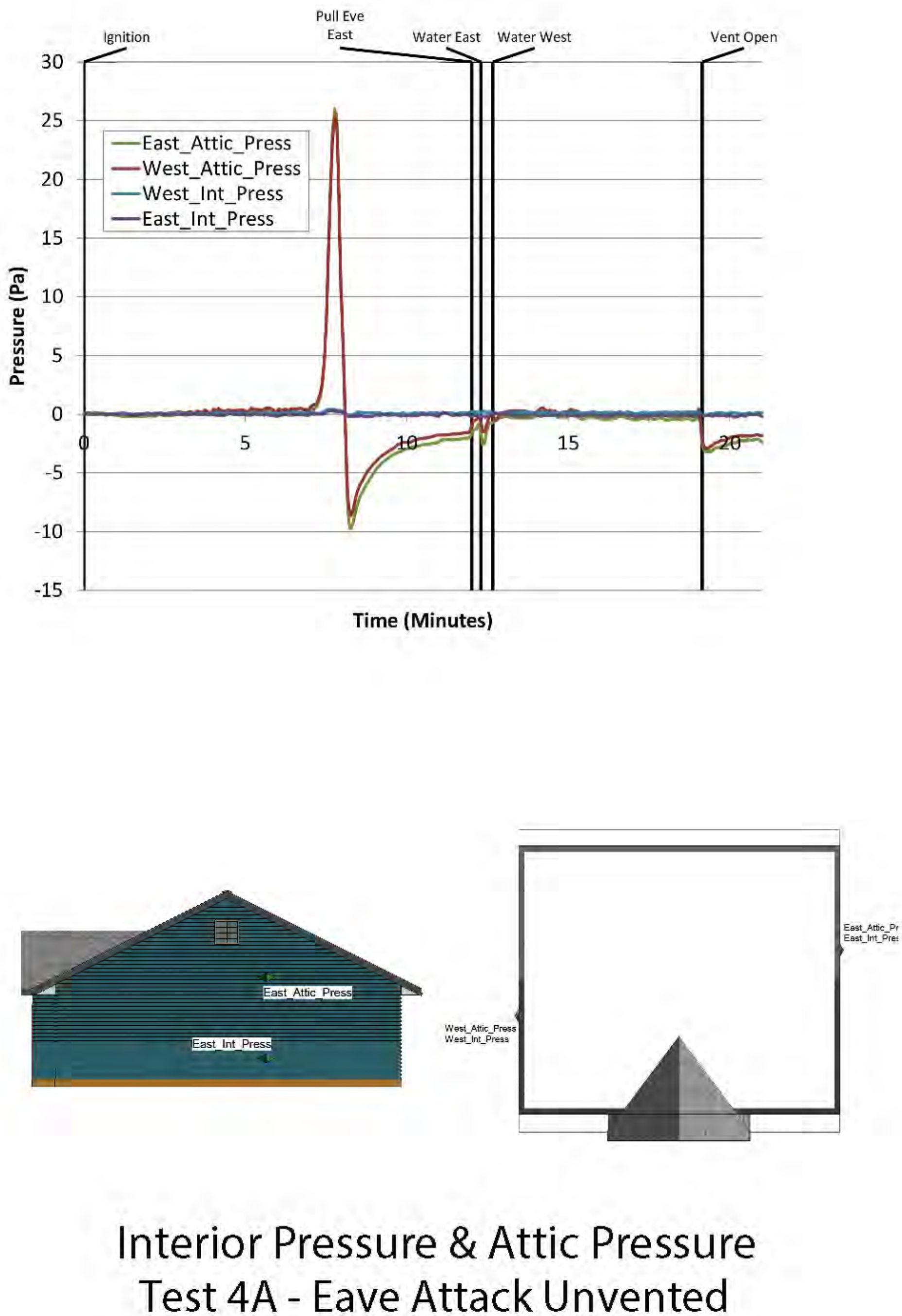
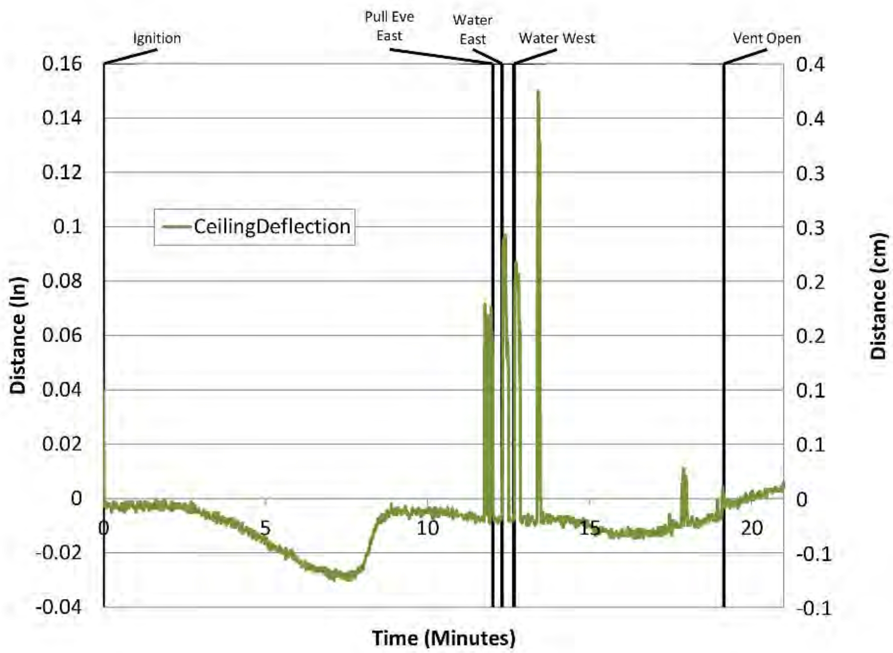
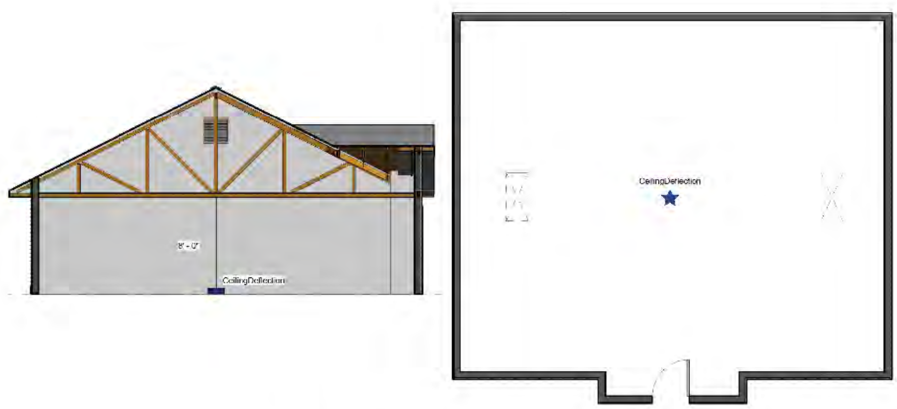


Figure I. 85: Attic Experiment 4A Attic Vs. Interior Pressure

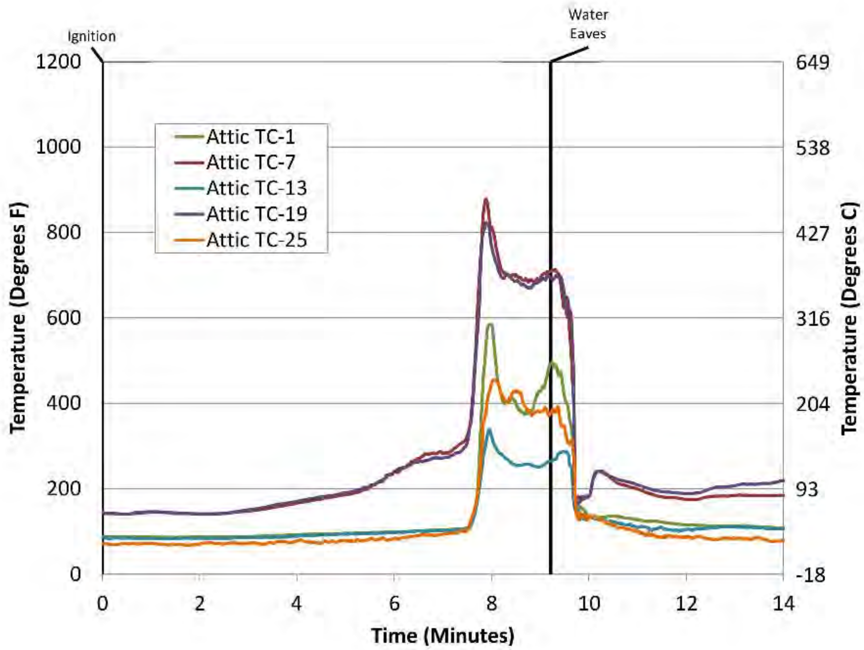




Ceiling Deflection
Test 4A - Eave Attack Unvented

Figure I. 86: Attic Experiment 4A Ceiling Deflection

Experiment 4B



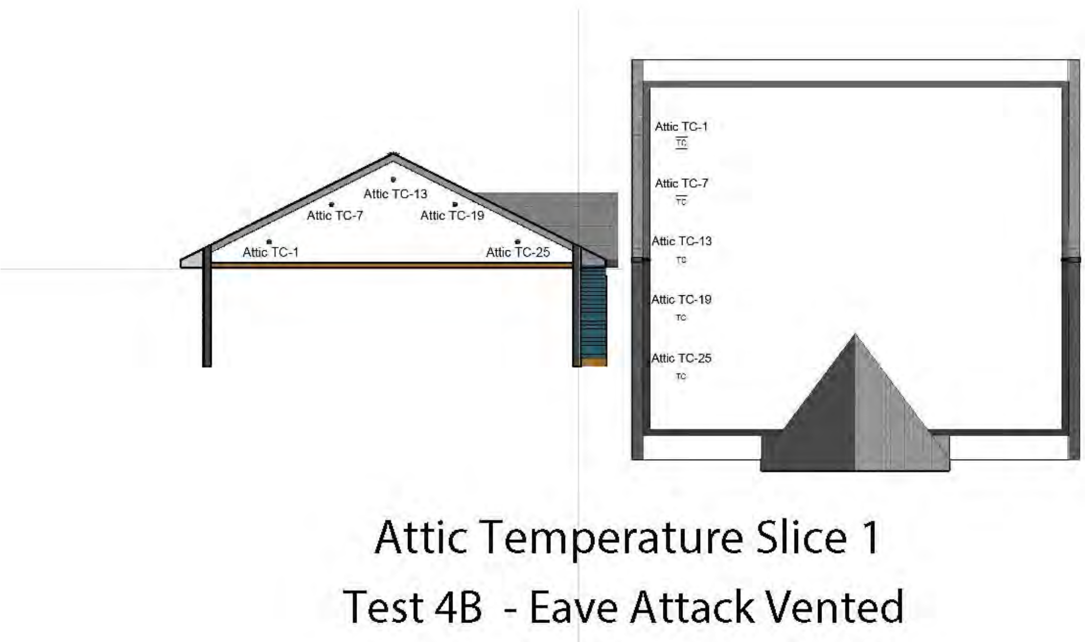


Figure I. 87: Attic Experiment 4B Attic Temperature Slice 1

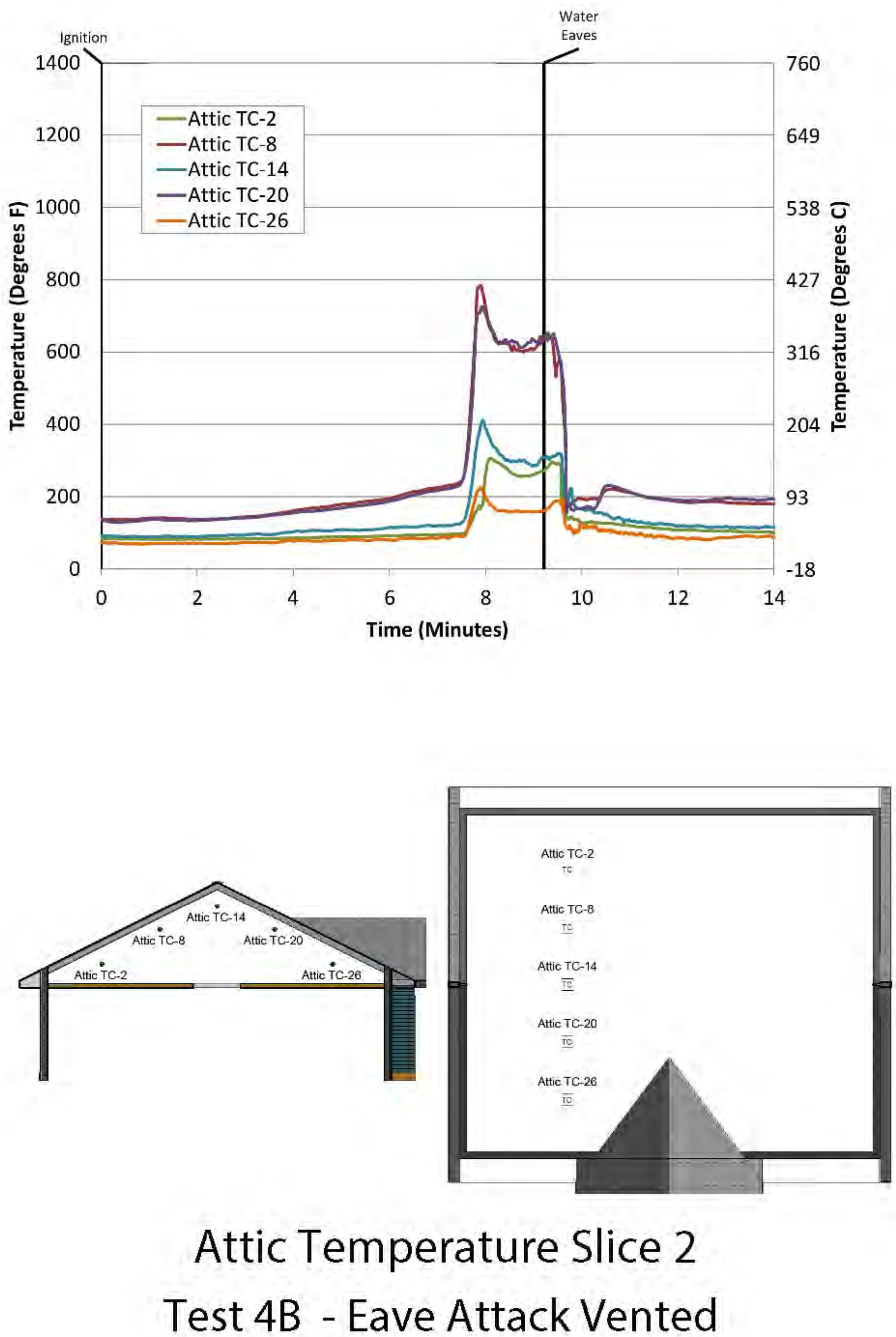
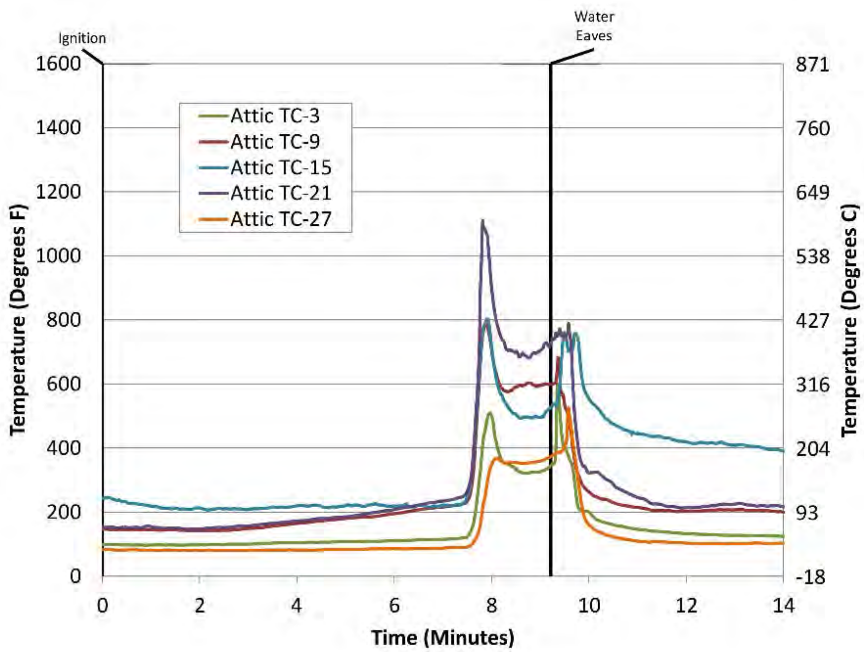


Figure I. 88: Attic Experiment 4B Attic Temperature Slice 2



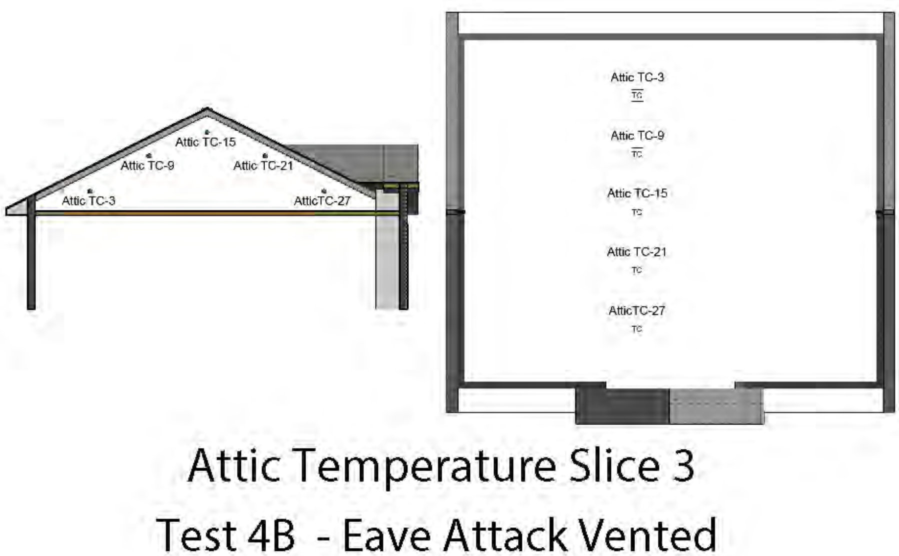


Figure I. 89: Attic Experiment 4B Attic Temperature Slice 3

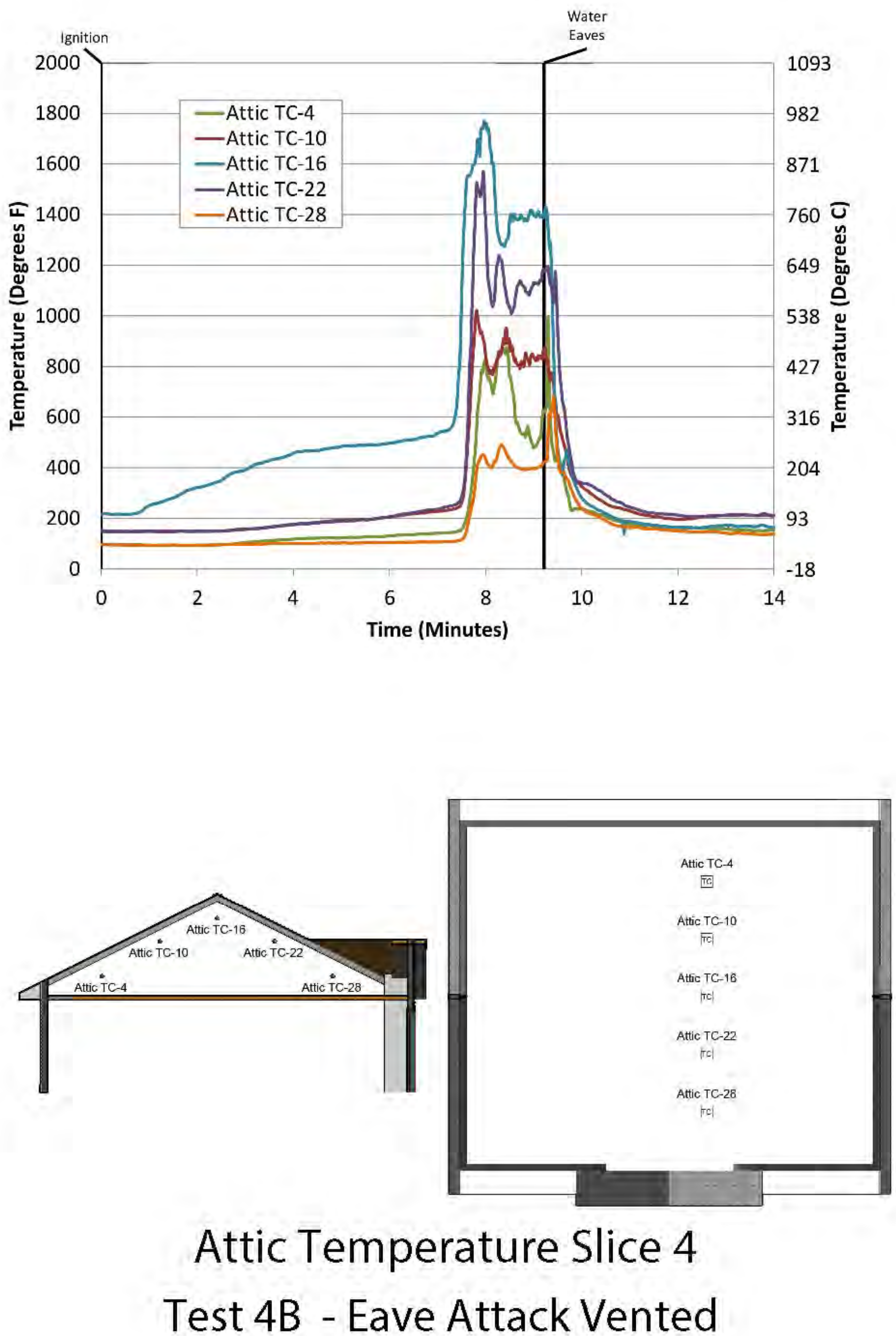
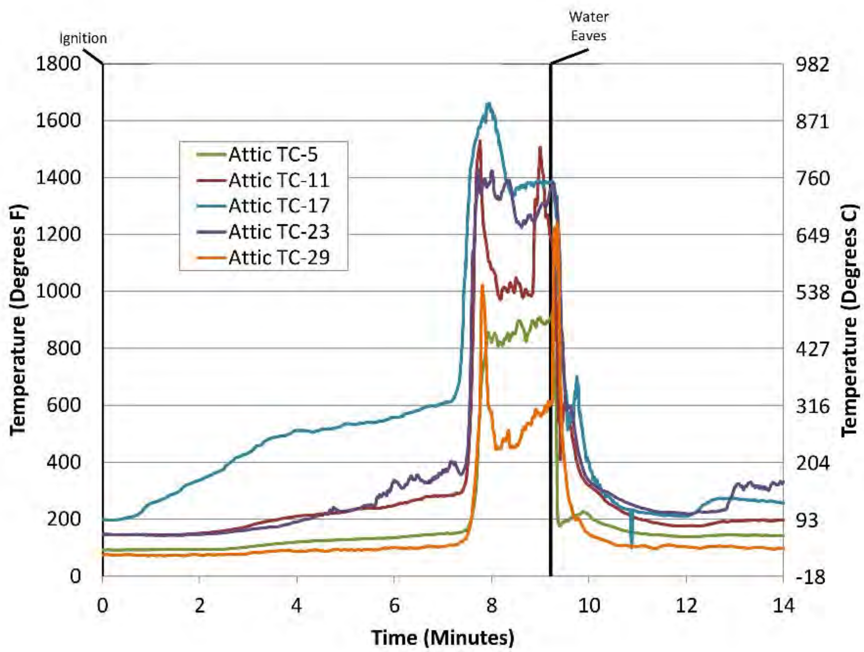


Figure I. 90: Attic Experiment 4B Attic Temperature Slice 4



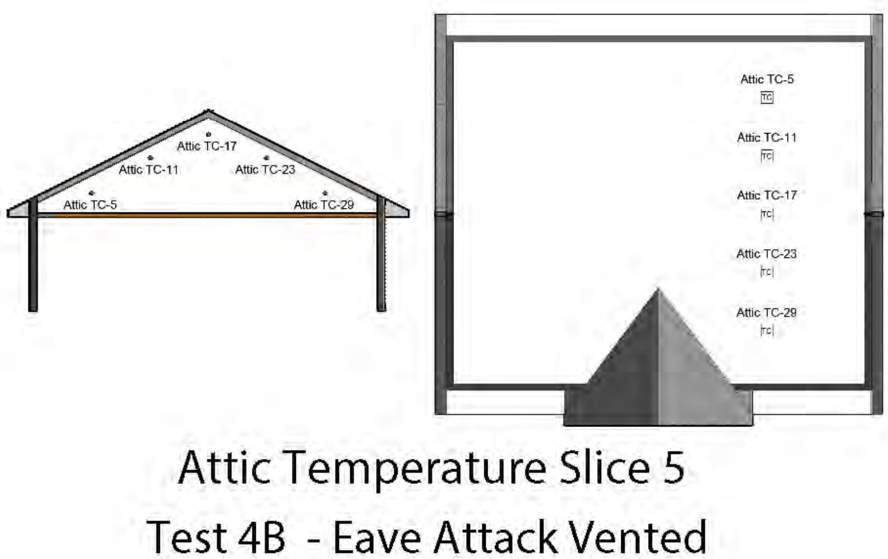
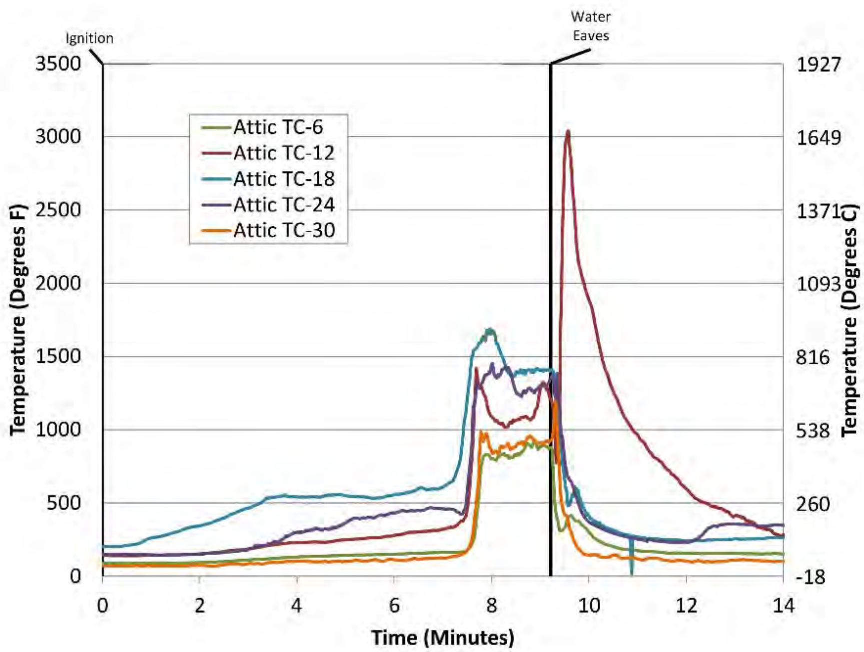


Figure I. 91: Attic Experiment 4B Attic Temperature Slice 5



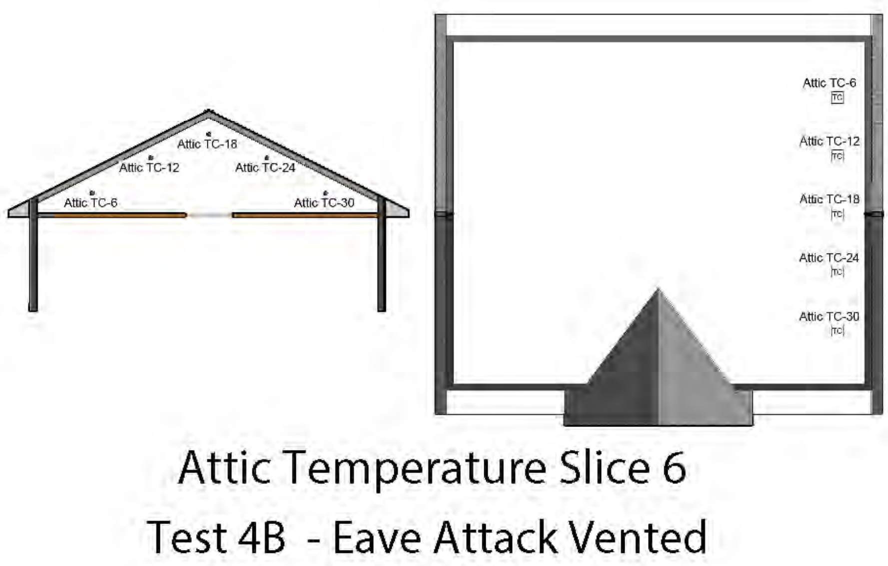
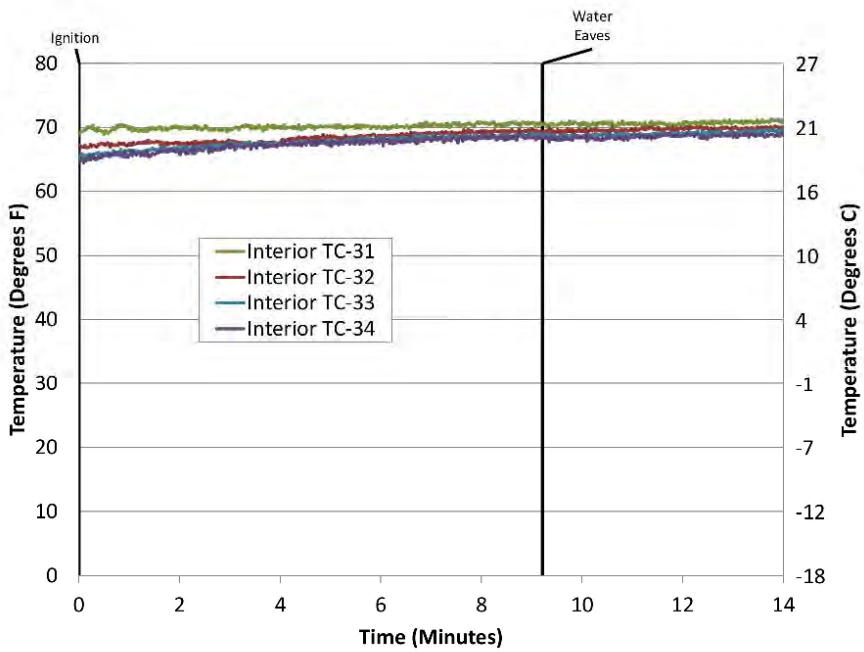


Figure I. 92: Attic Experiment 4B Attic Temperature Slice 6



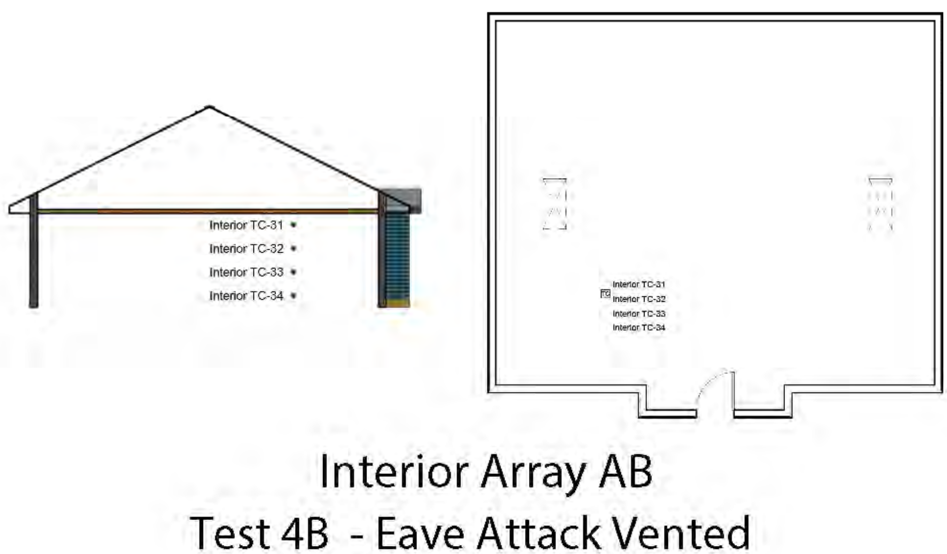
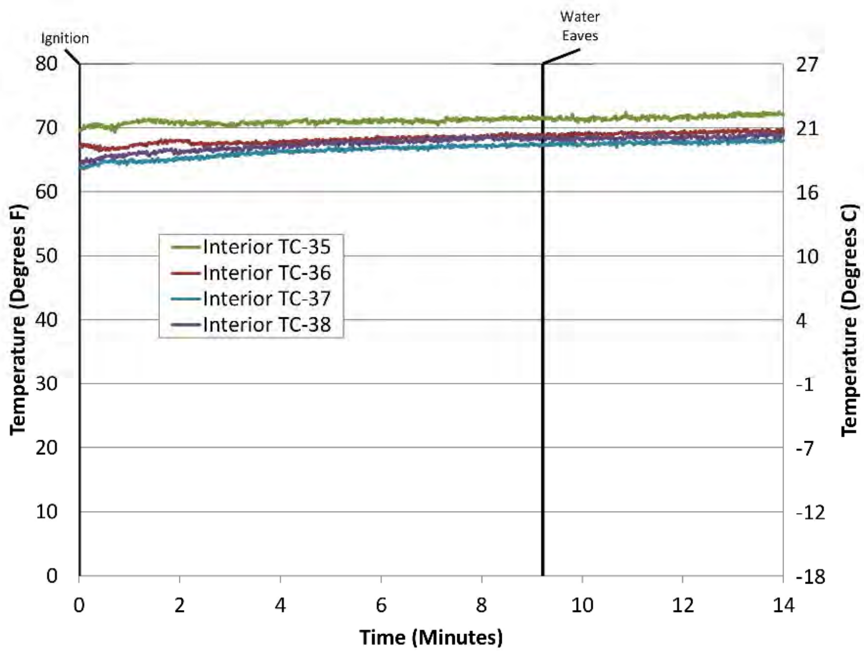


Figure I. 93: Attic Experiment 4B Interior Array AB



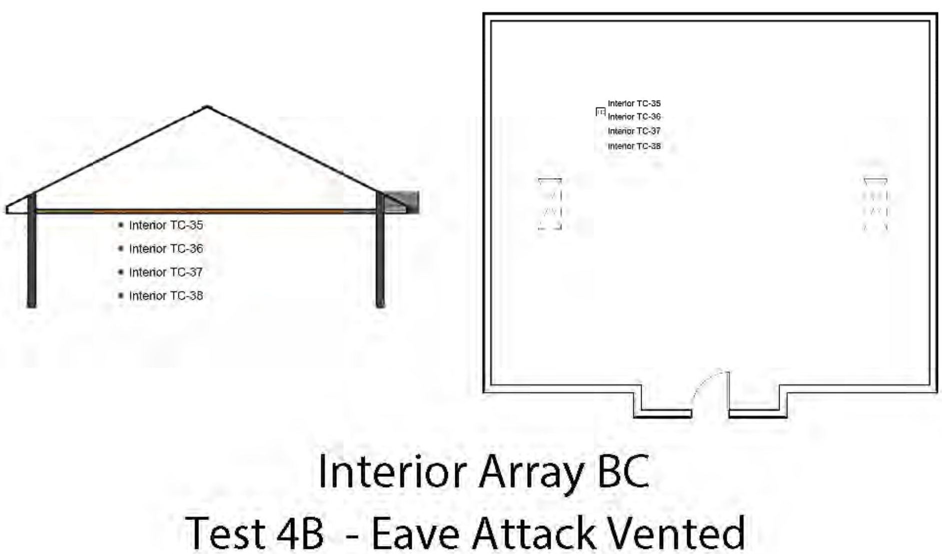
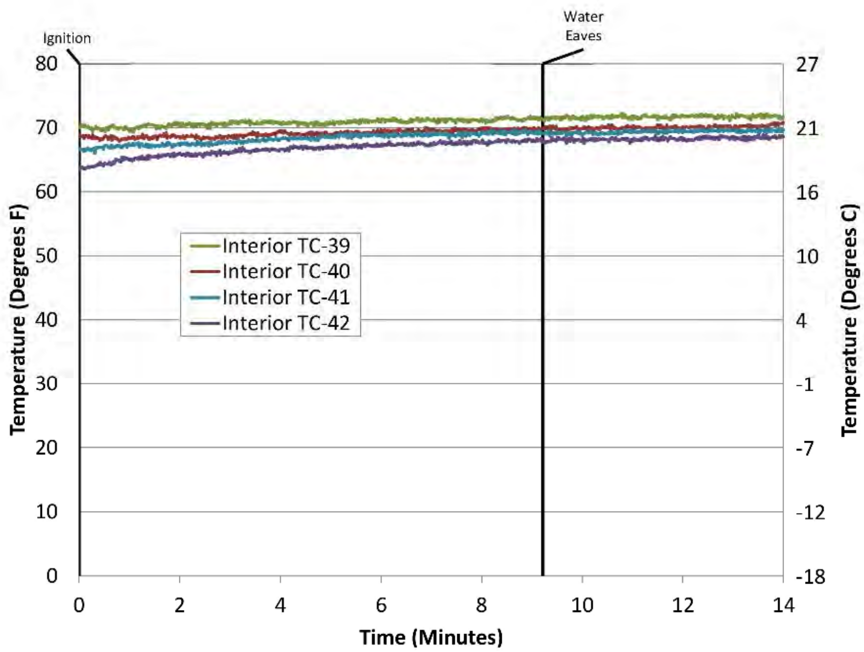


Figure I. 94: Attic Experiment 4B Interior Array BC



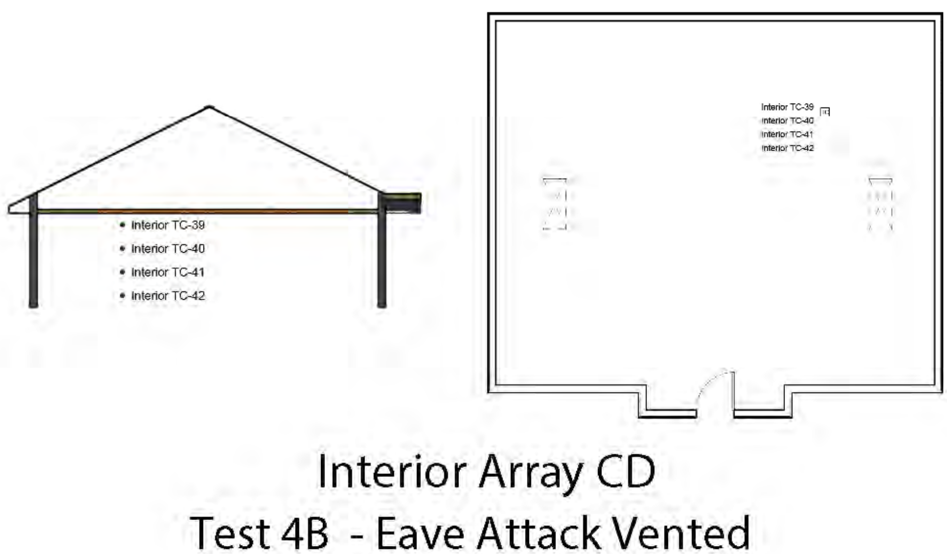
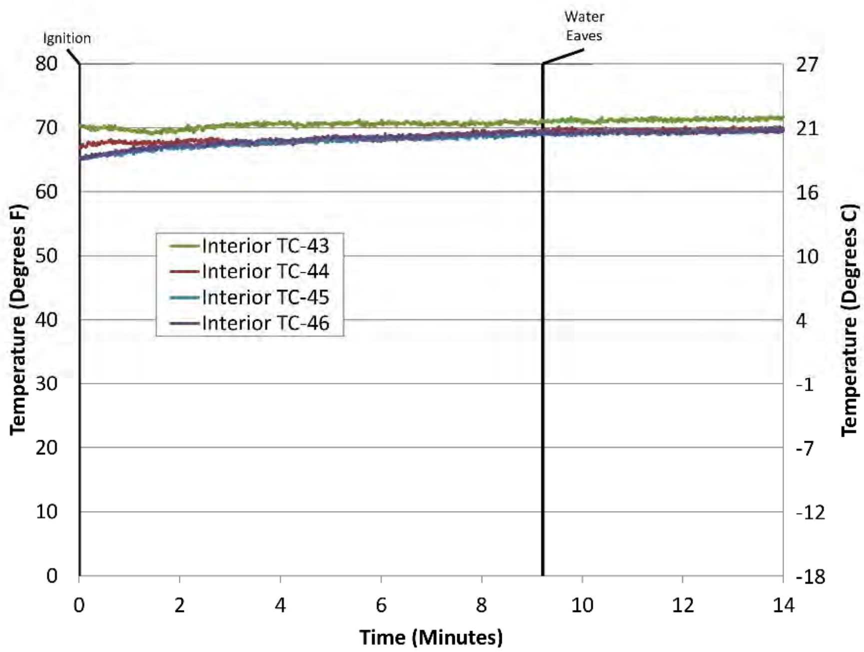


Figure I. 95: Attic Experiment 4B Interior Array CD



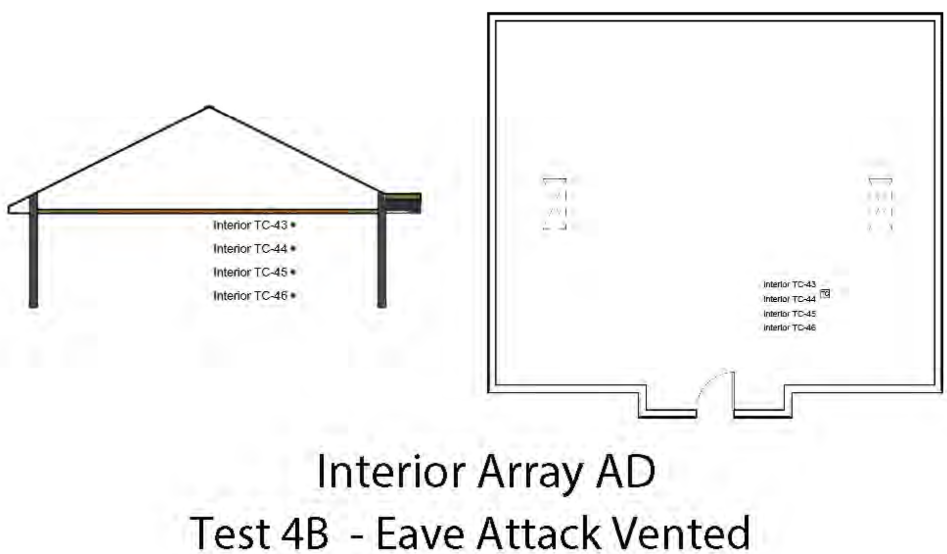


Figure I. 96: Attic Experiment 4B Interior Array AD

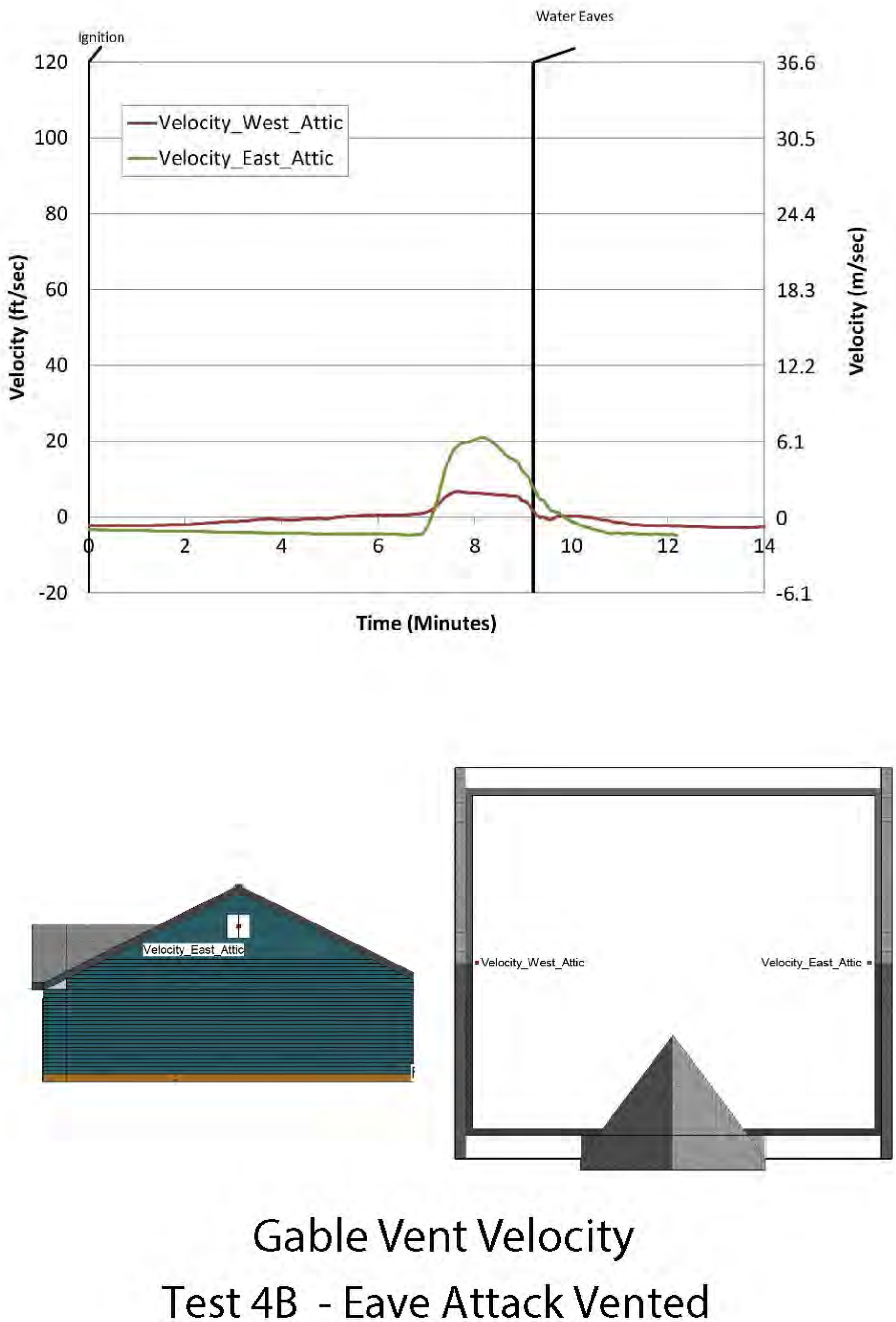
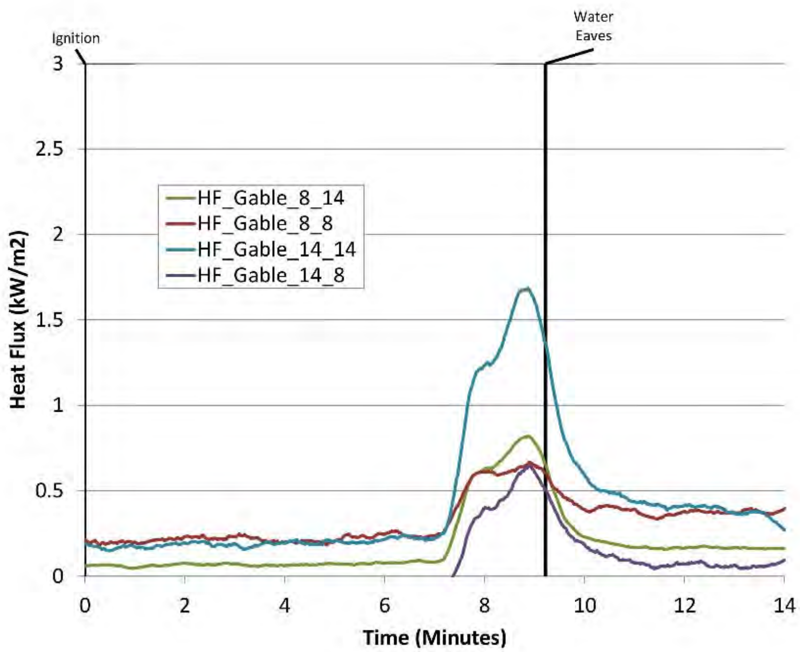
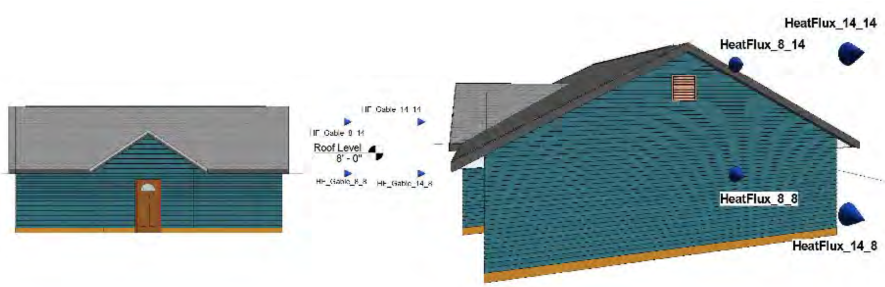


Figure I. 97: Attic Experiment 4B Gable Vent Velocity

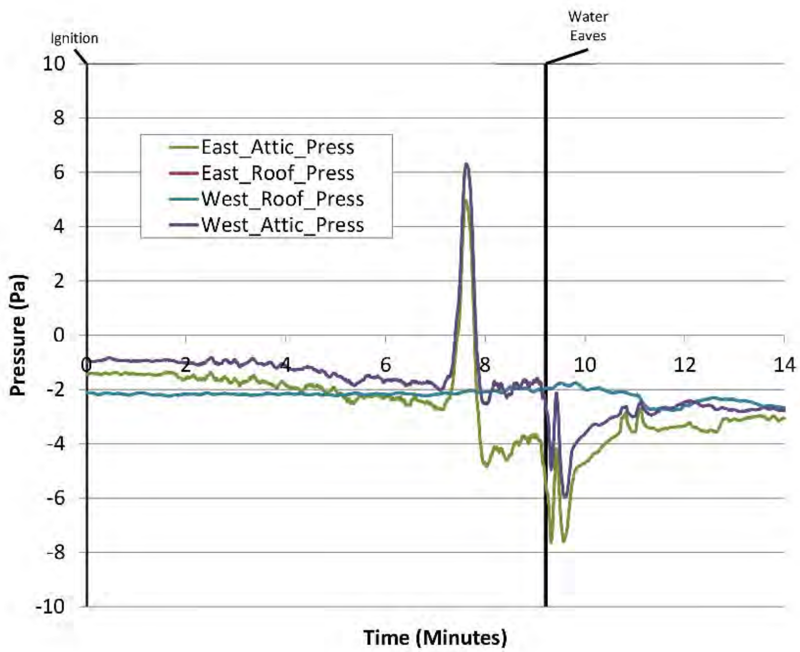


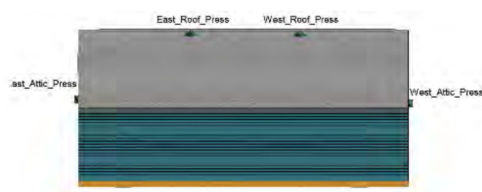


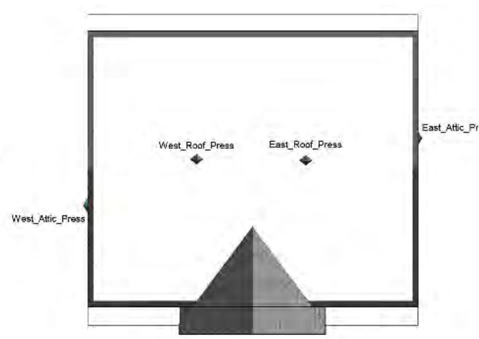
Heat Flux Gable End

Test 4B - Eave Attack Vented

Figure I. 98: Attic Experiment 4B Gable Heat Flux







Attic Pressure
Test 4B - Eave Attack Vented

Figure I. 99: Attic Experiment 4B Attic Pressure

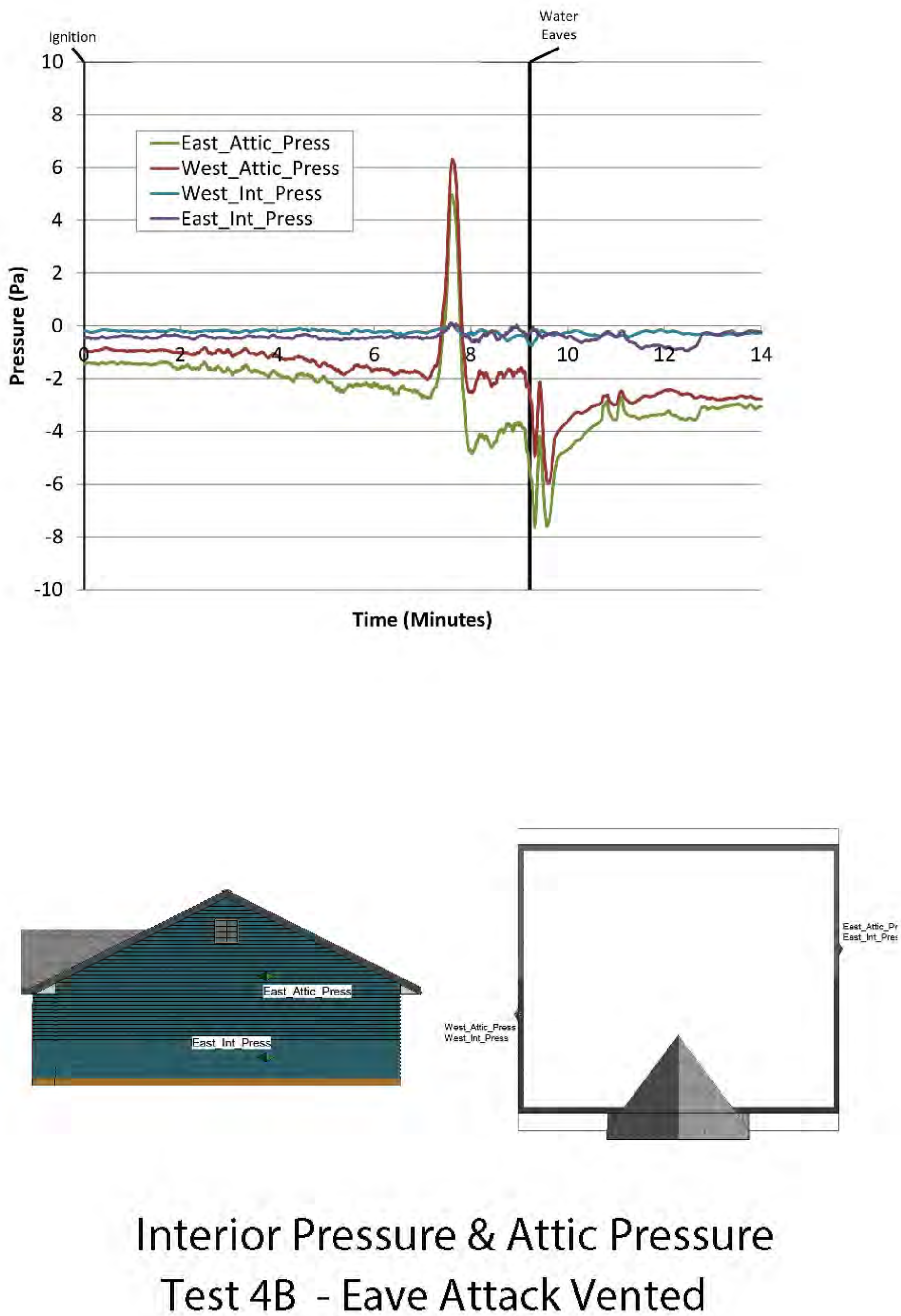
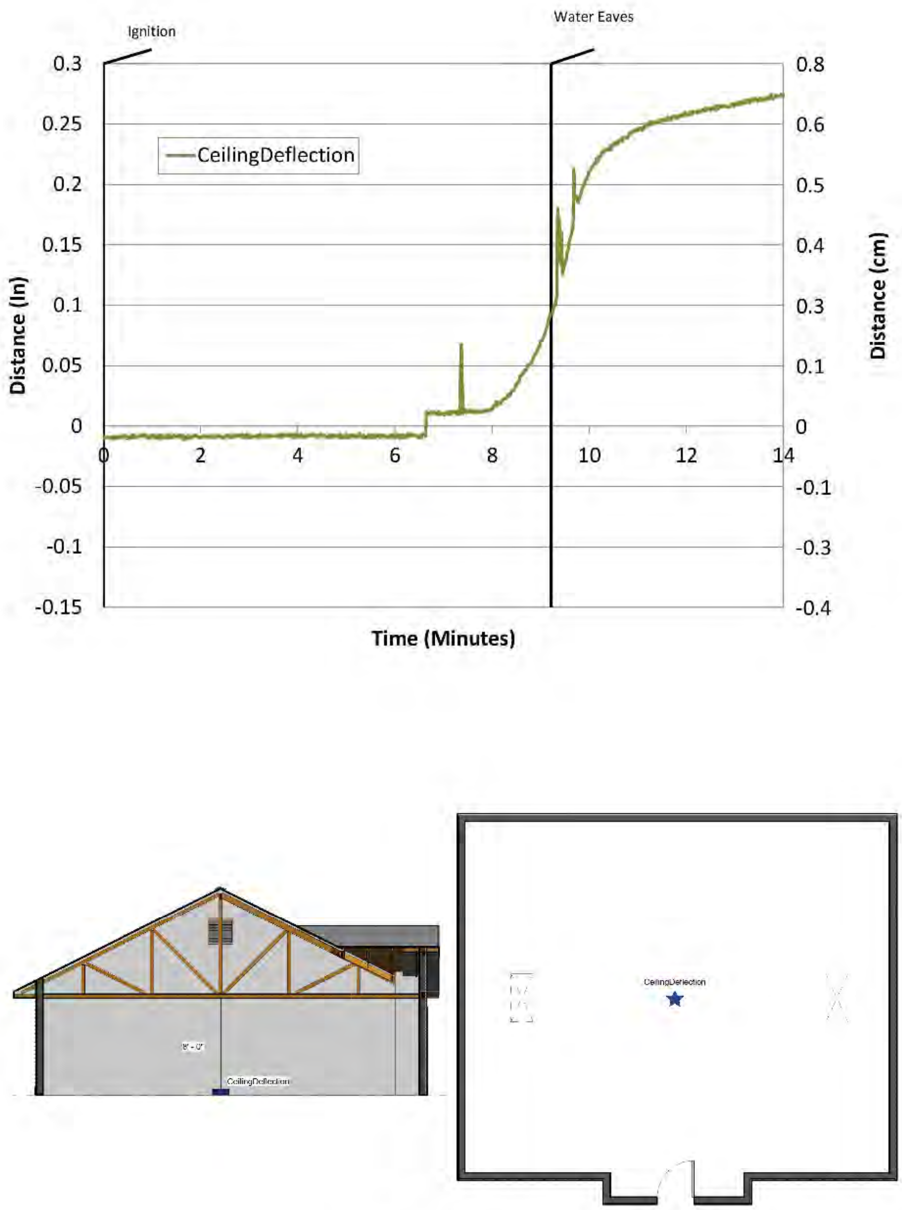


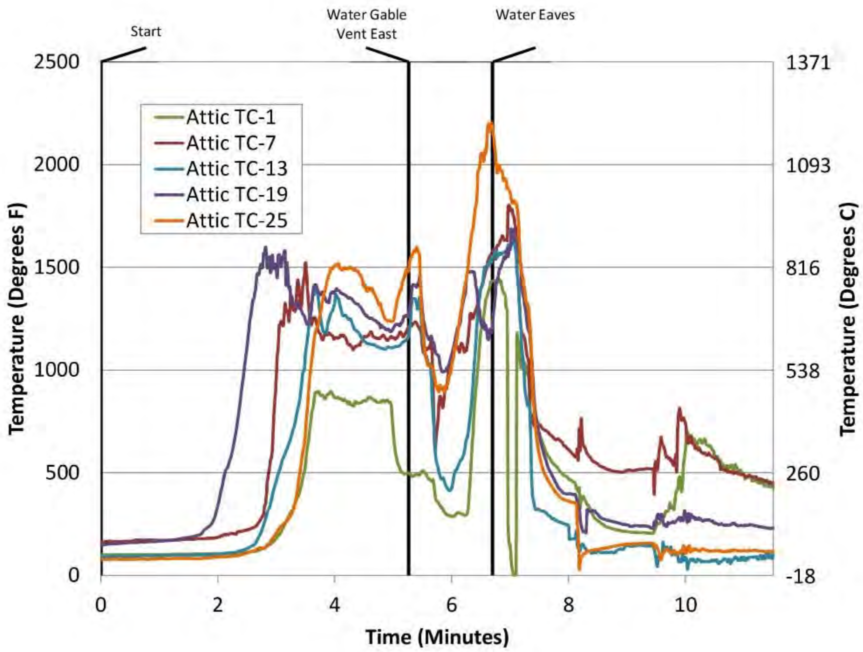
Figure I. 100: Attic Experiment 4B Attic Vs. Interior Pressure



Ceiling Deflection
Test 4B - Eave Attack Vented

Figure I. 101: Attic Experiment 4B Ceiling Deflection

Experiment 4C



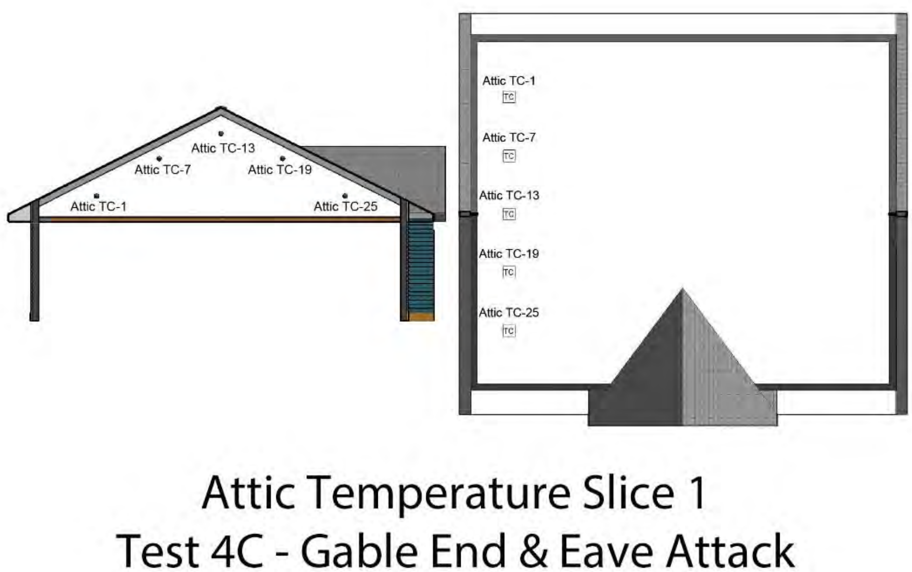


Figure I. 102: Attic Experiment 4C Attic Temperature Slice 1

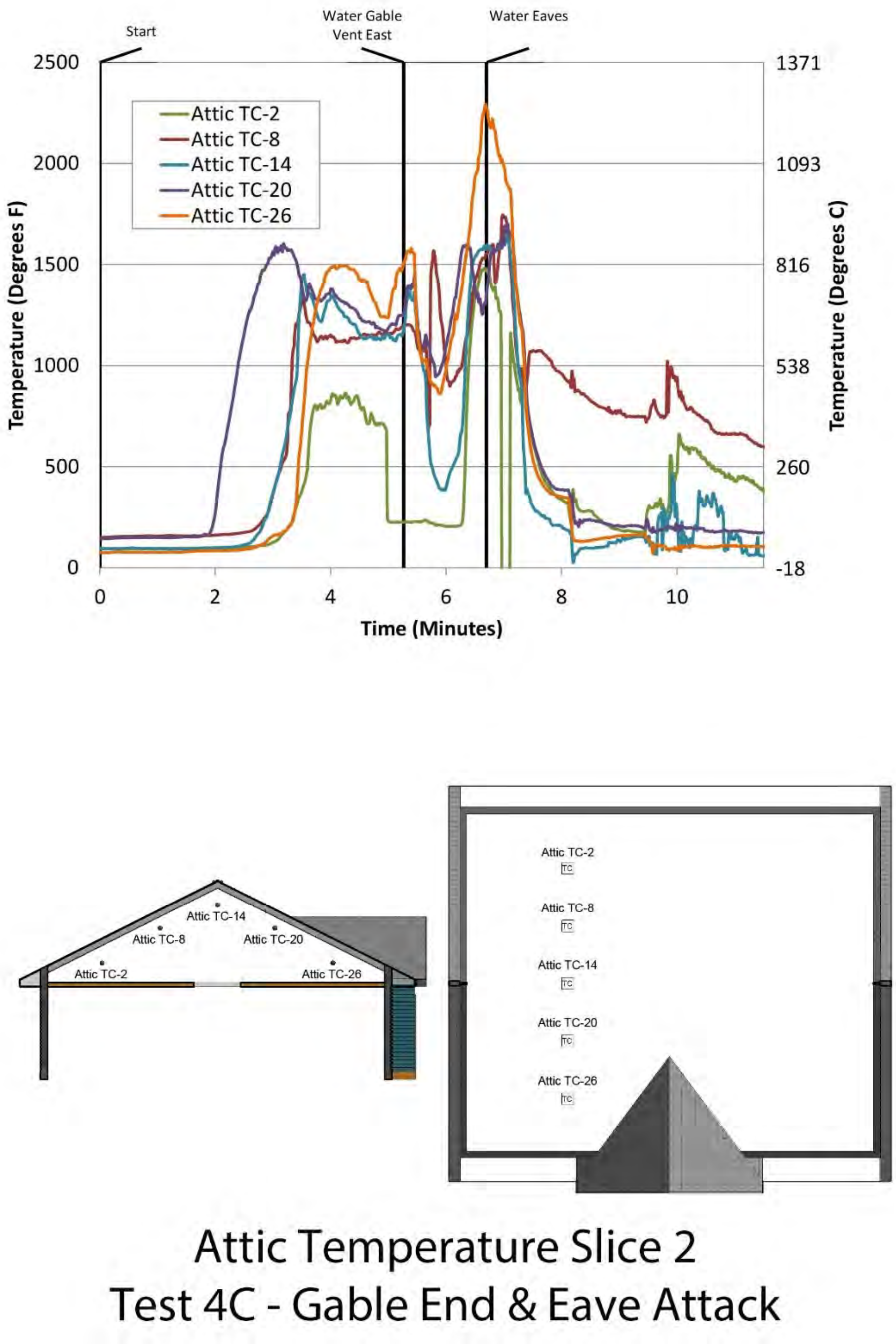
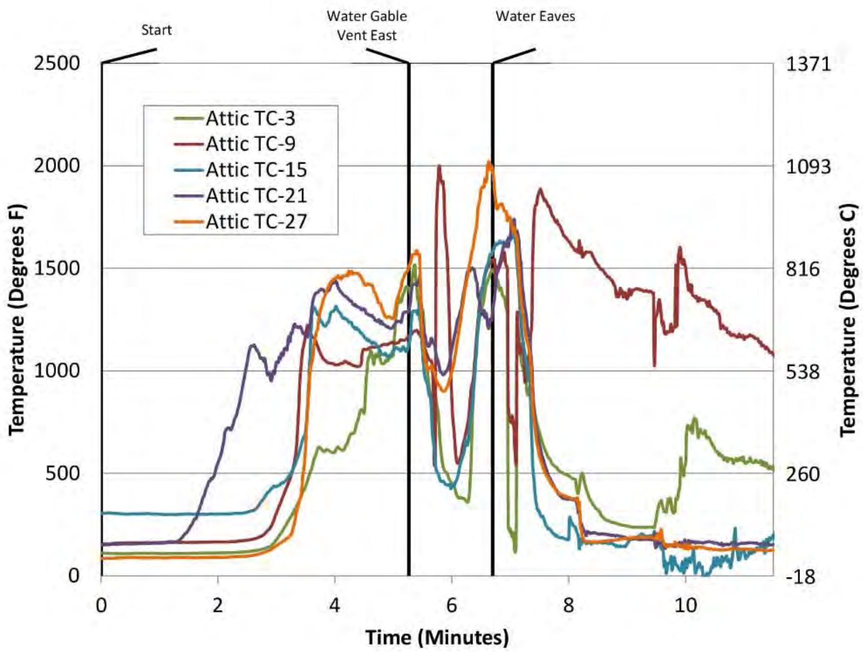


Figure I. 103: Attic Experiment 4C Attic Temperature Slice 2



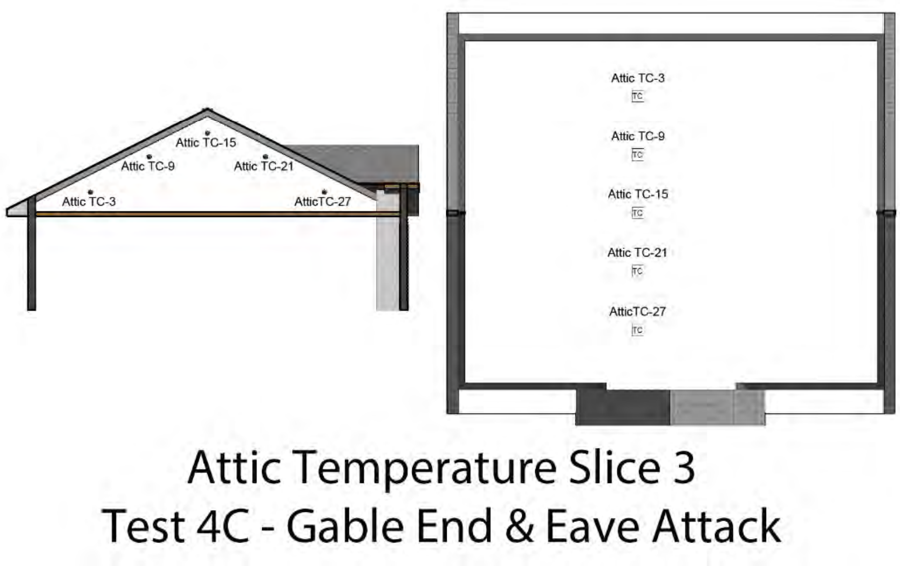
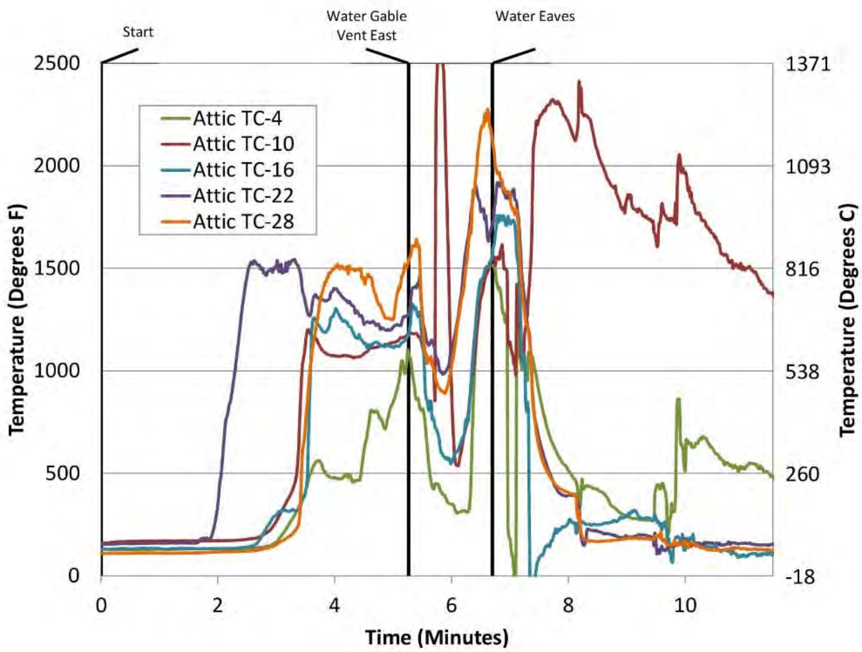


Figure I. 104: Attic Experiment 4C Attic Temperature Slice 3



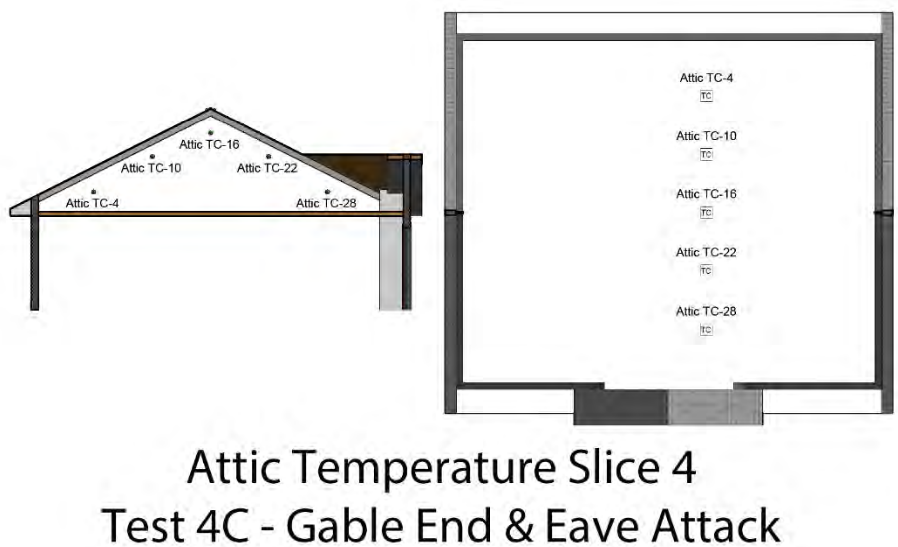
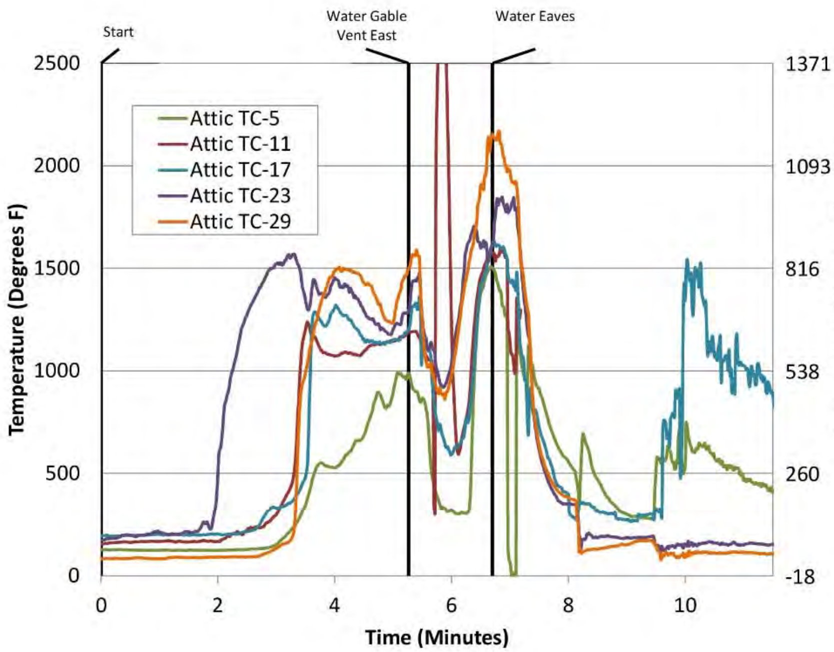


Figure I. 105: Attic Experiment 4C Attic Temperature Slice 4



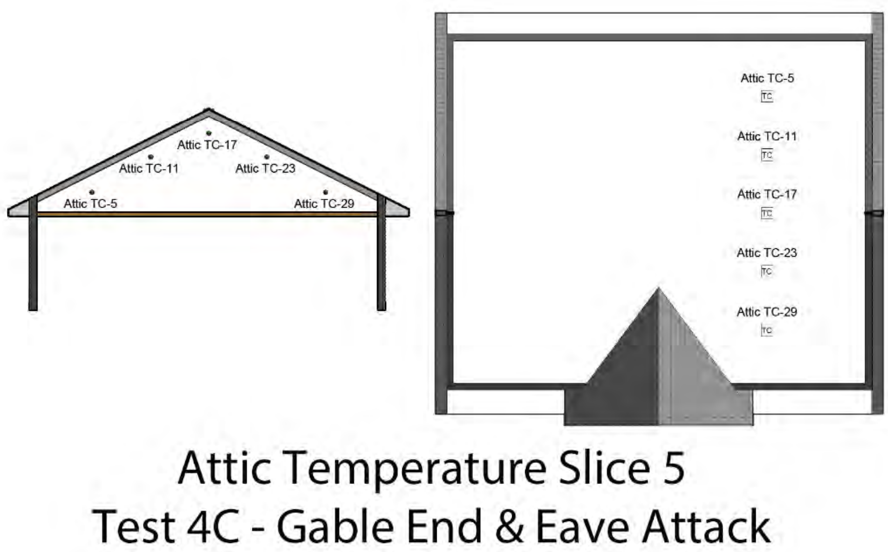
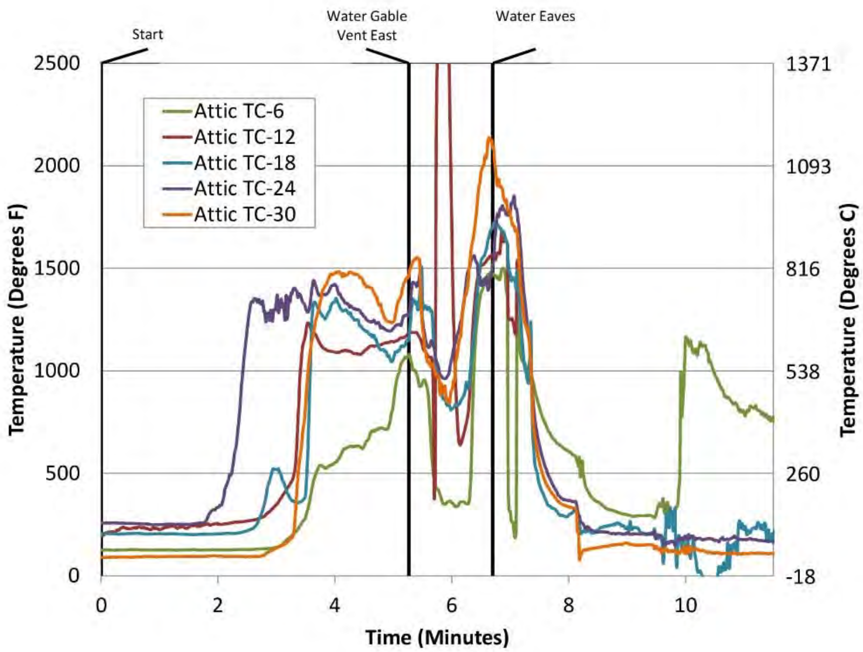


Figure I. 106: Attic Experiment 4C Attic Temperature Slice 5



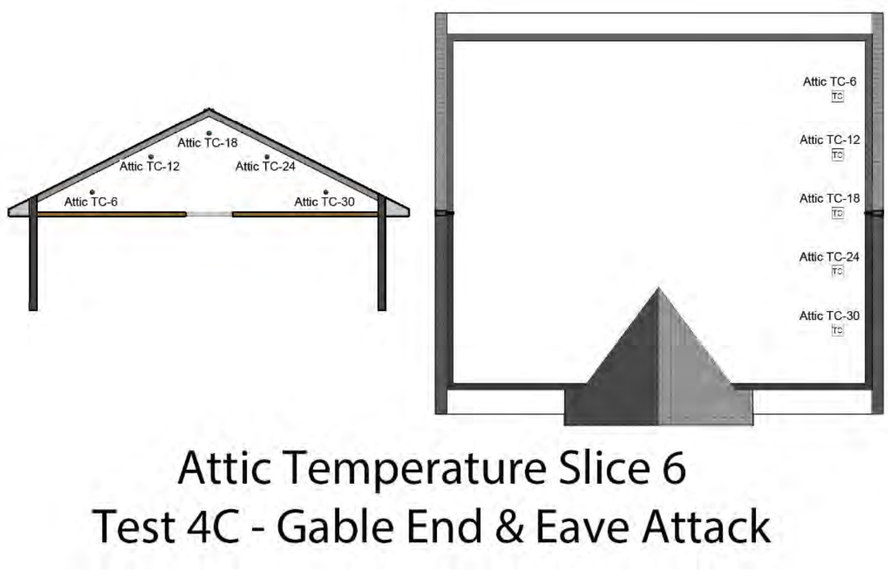
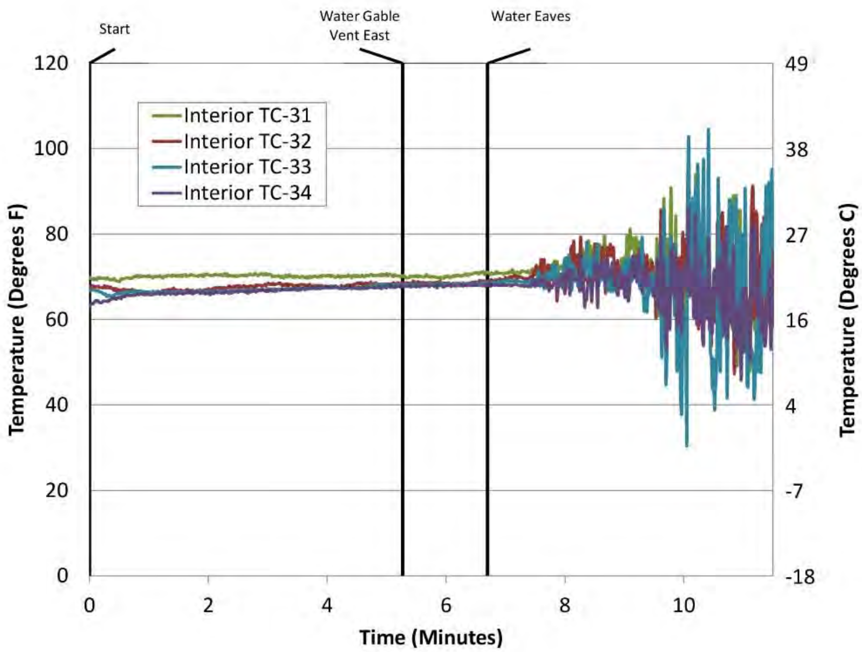


Figure I. 107: Attic Experiment 4C Attic Temperature Slice 6



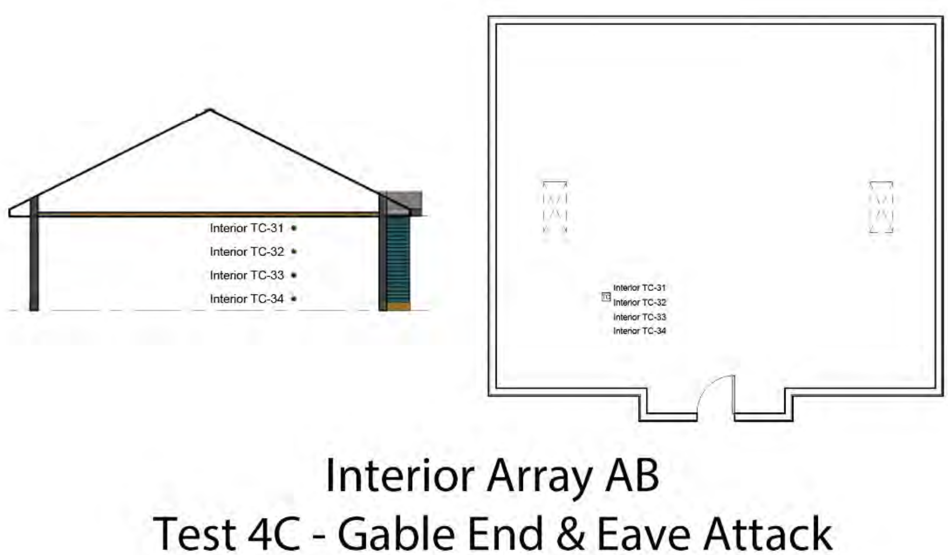
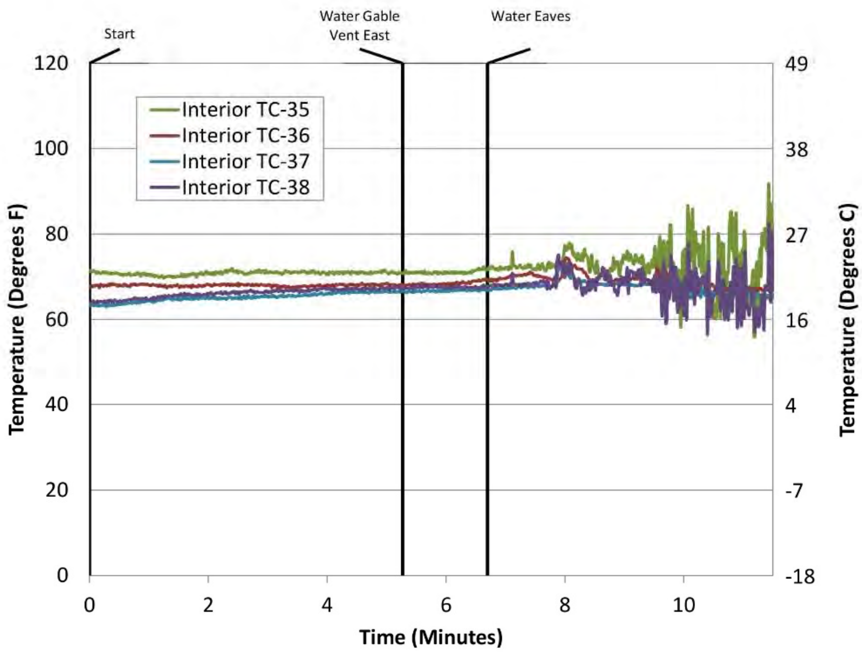


Figure I. 108: Attic Experiment 4C Interior Array AB



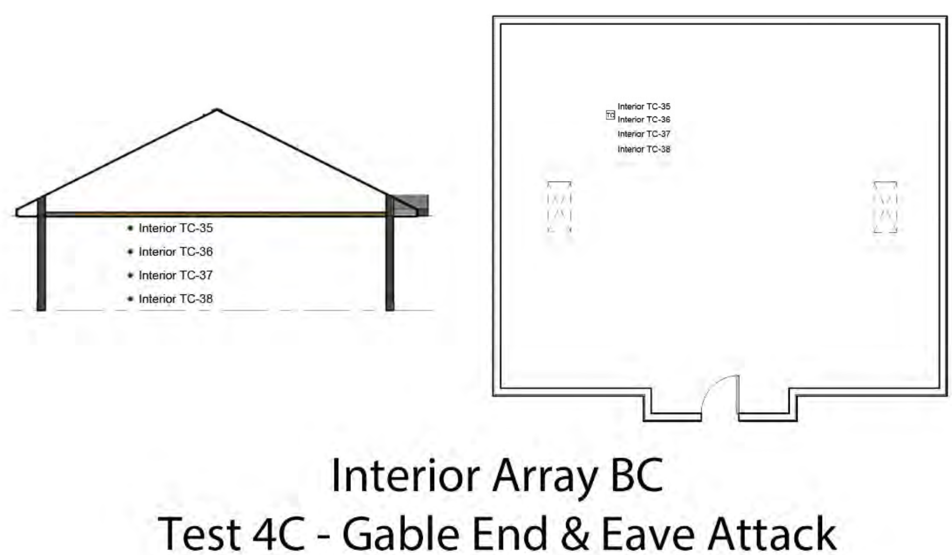
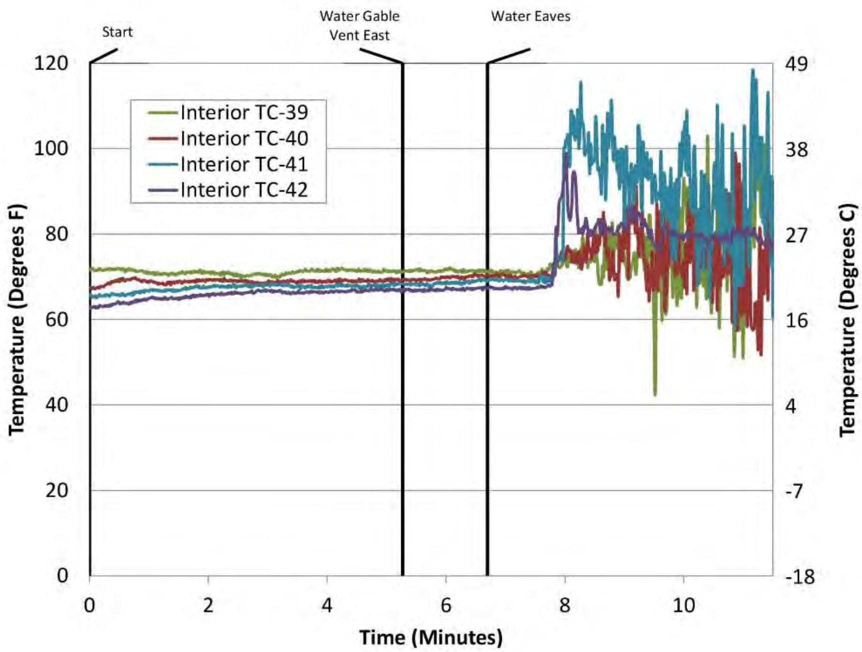
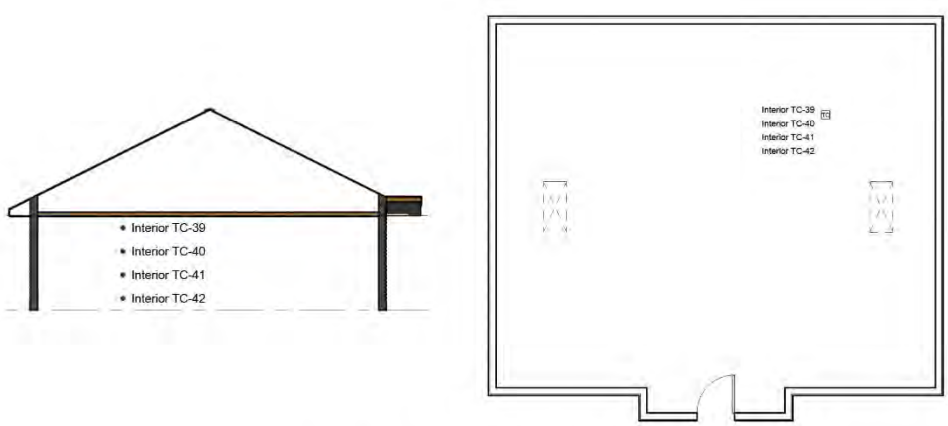


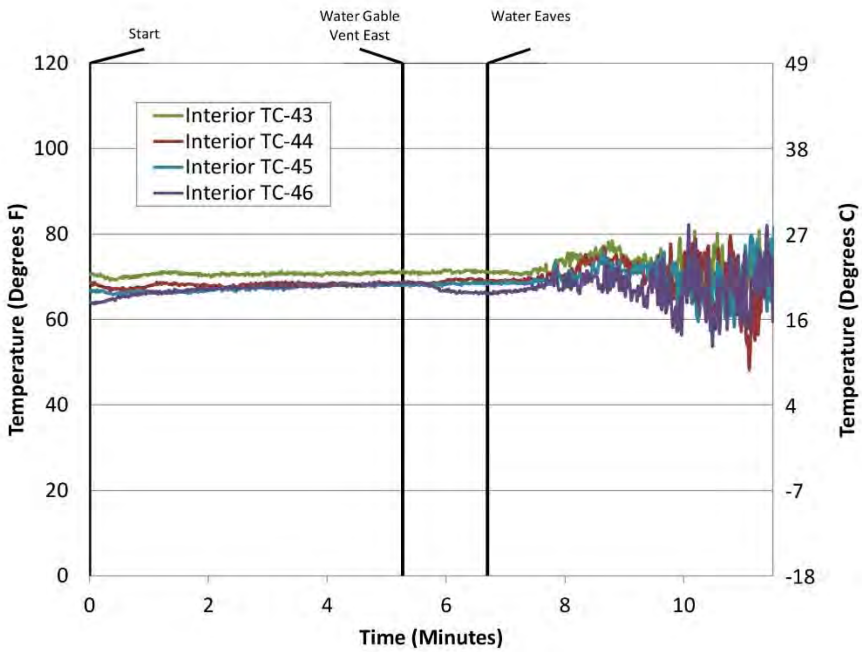
Figure I. 109: Attic Experiment 4C Interior Array BC





Interior Array CD
Test 4C - Gable End & Eave Attack

Figure I. 110: Attic Experiment 4C Interior Array CD



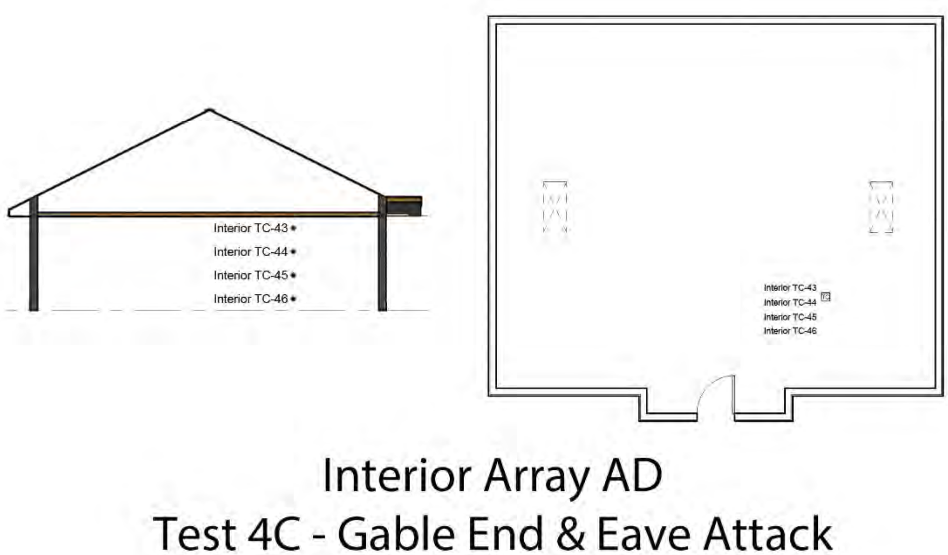
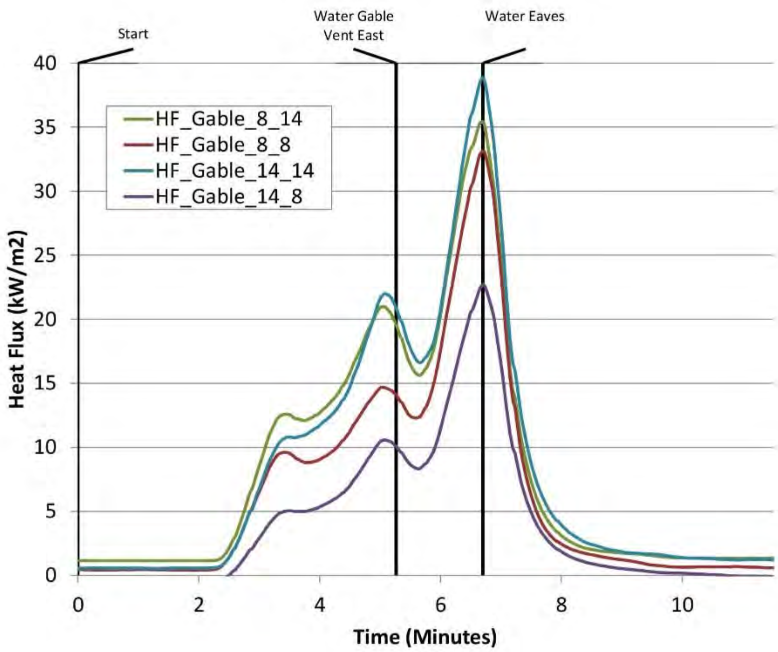
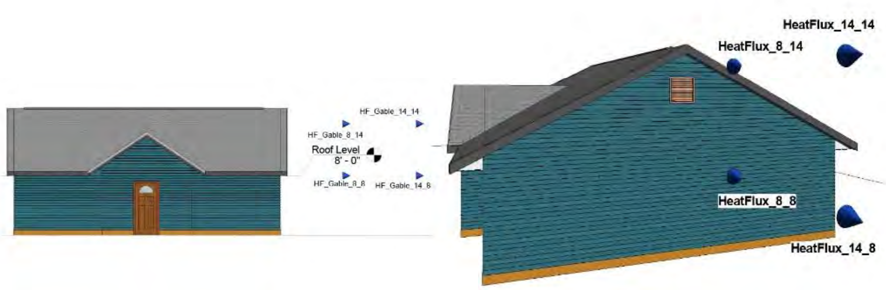


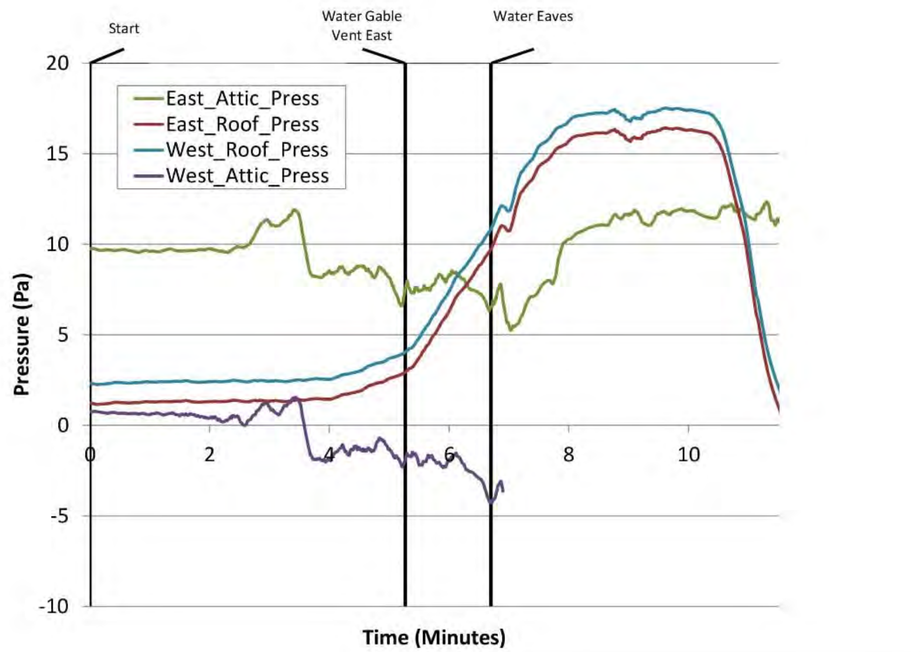
Figure I. 111: Attic Experiment 4C Interior Array AD

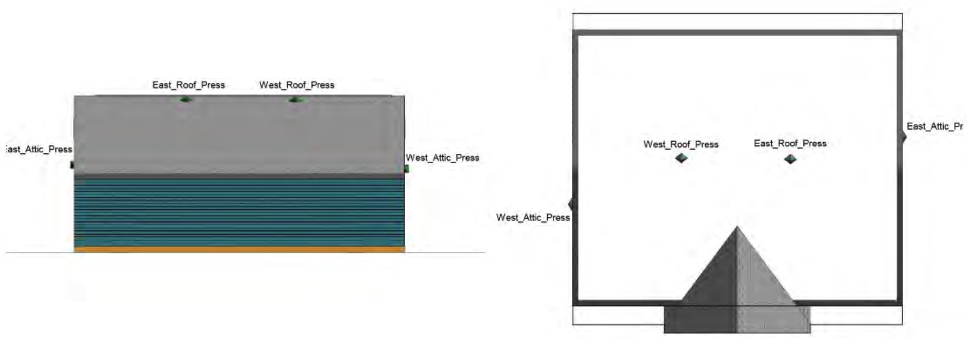




Heat Flux Gable End
Test 4C - Gable End & Eave Attack

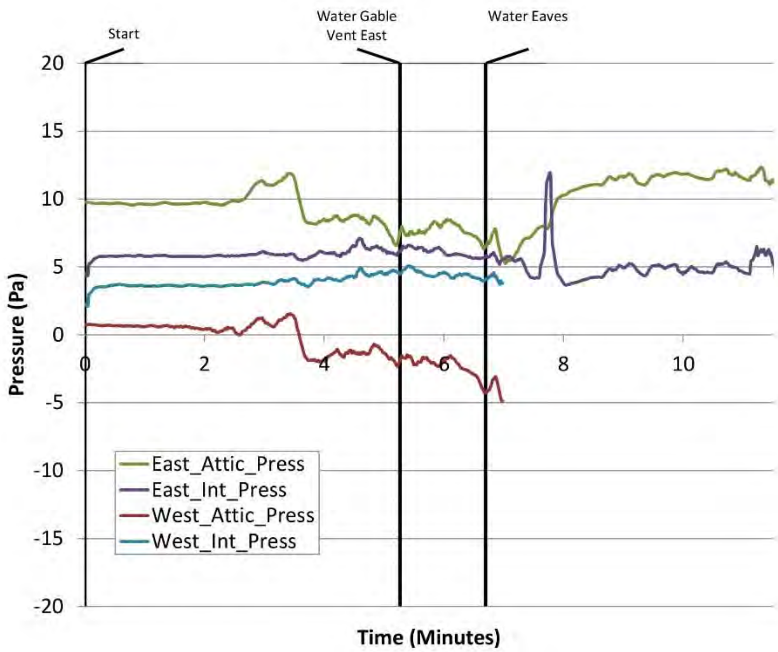
Figure I. 112: Attic Experiment 4C Gable End Heat Flux

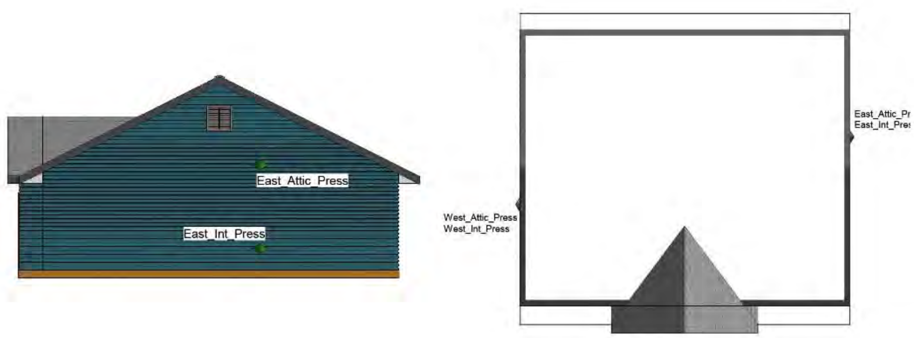




Attic Pressure
Test 4C - Gable End & Eave Attack

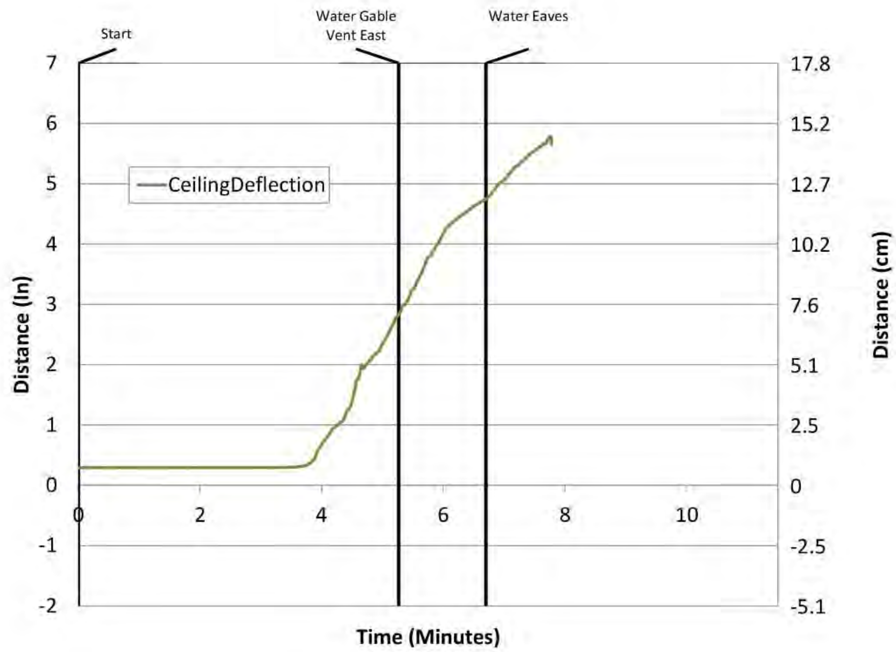
Figure I. 113: Attic Experiment 4C Attic Pressure





Interior Pressure & Attic Pressure
Test 4C - Gable End & Eave Attack

Figure I. 114: Attic Experiment 4C Attic Vs. Interior Pressure



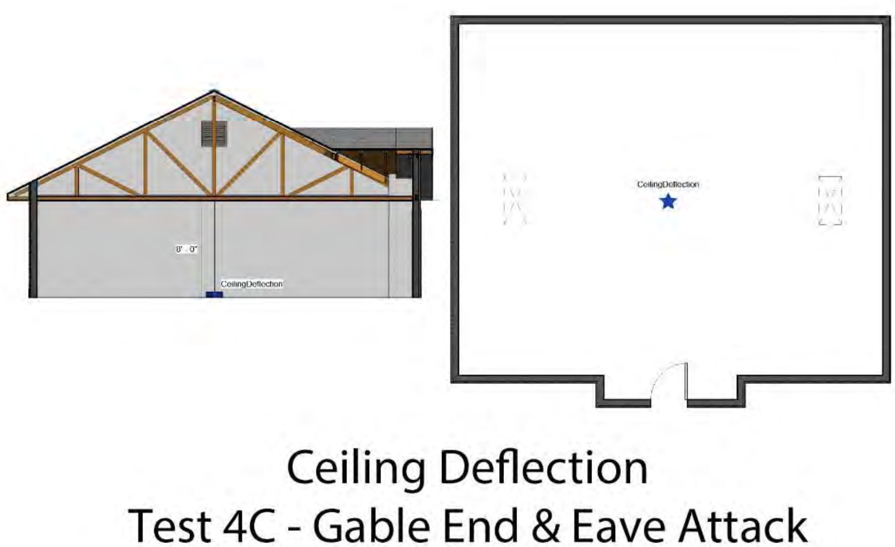


Figure I. 115: Attic Experiment 4C Ceiling Deflection

Appendix J: Knee Wall Experiment Data

Experiment 1 (3150 N 9th Street)

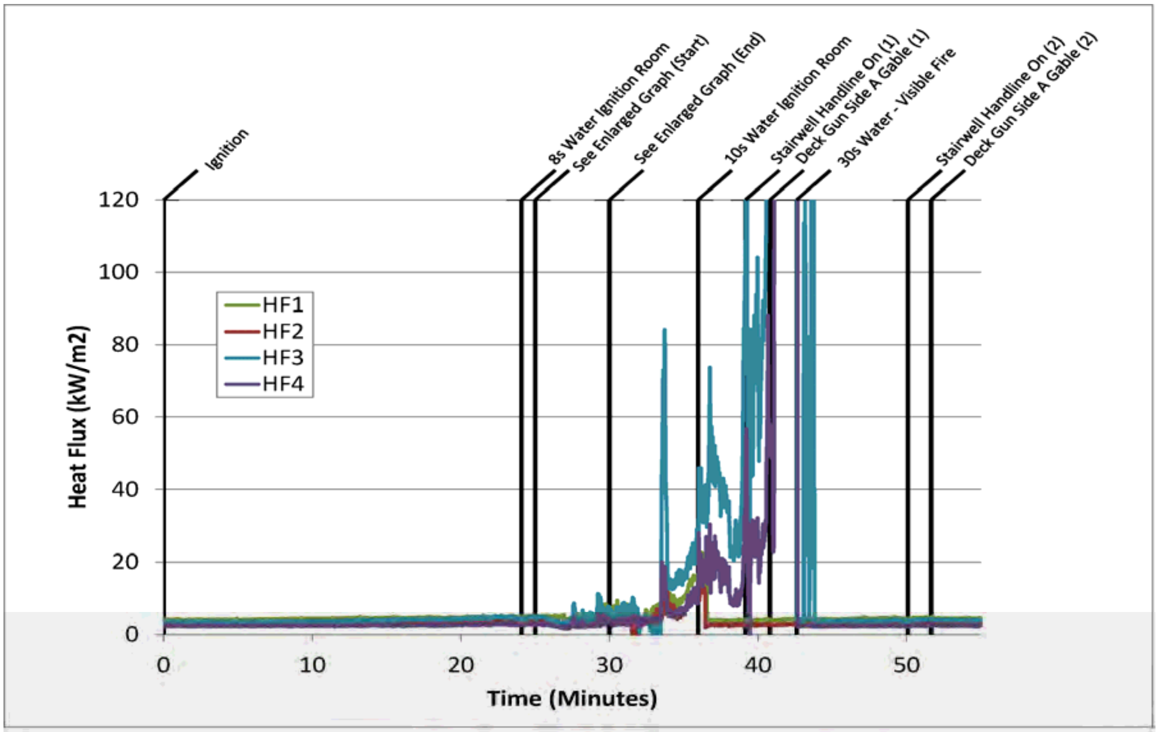


Figure J. 1: Knee Wall Experiment 1 Heat Flux Measurements

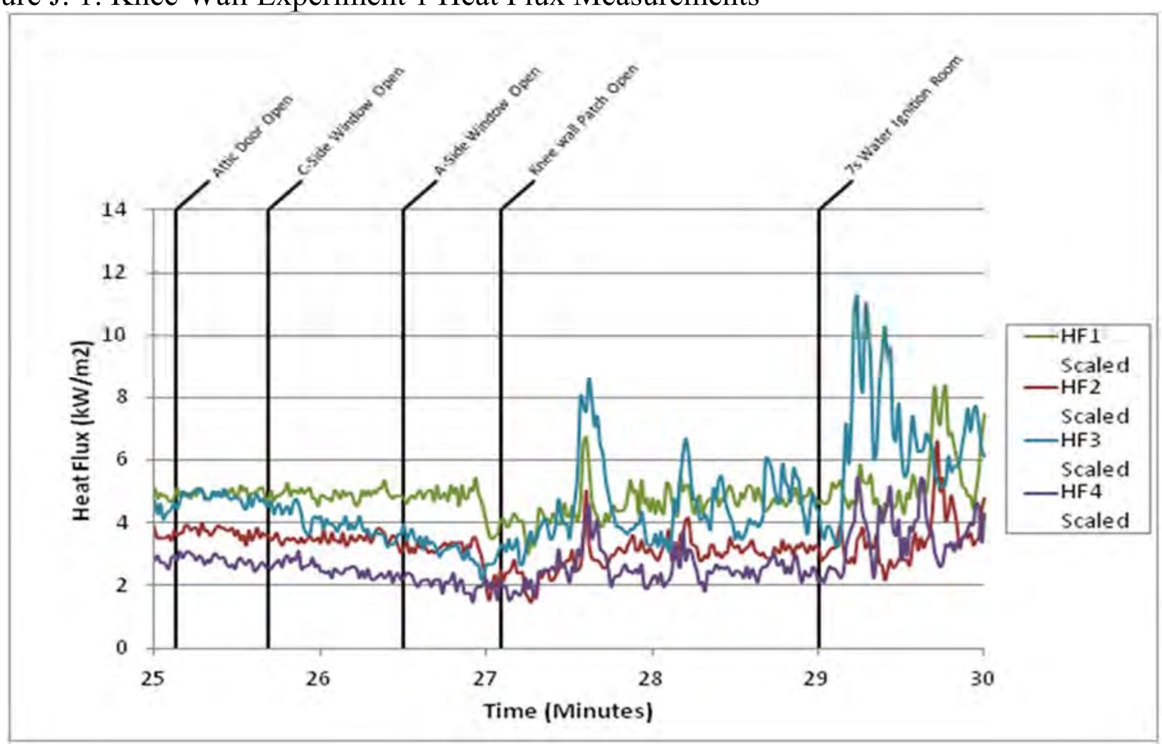


Figure J. 2: Knee Wall Experiment 1 Heat Flux Measurements (from 25 to 30 min)

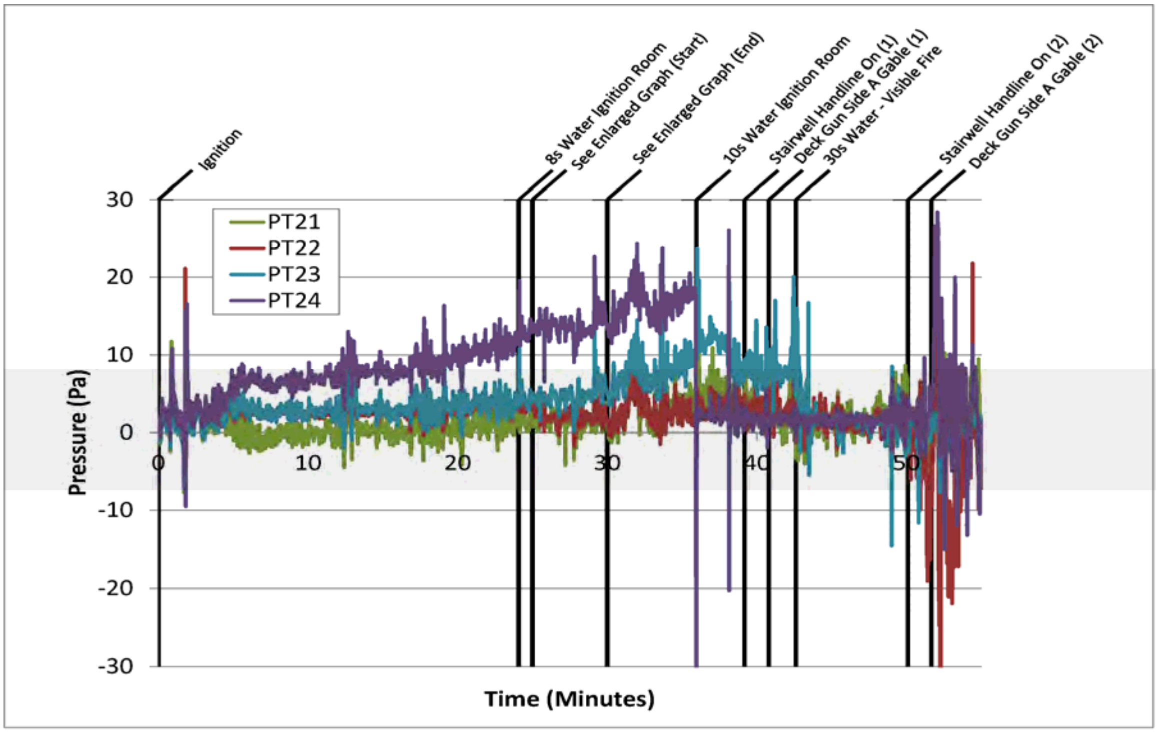


Figure J. 3: Knee Wall Experiment 1 Pressure Measurements Side C

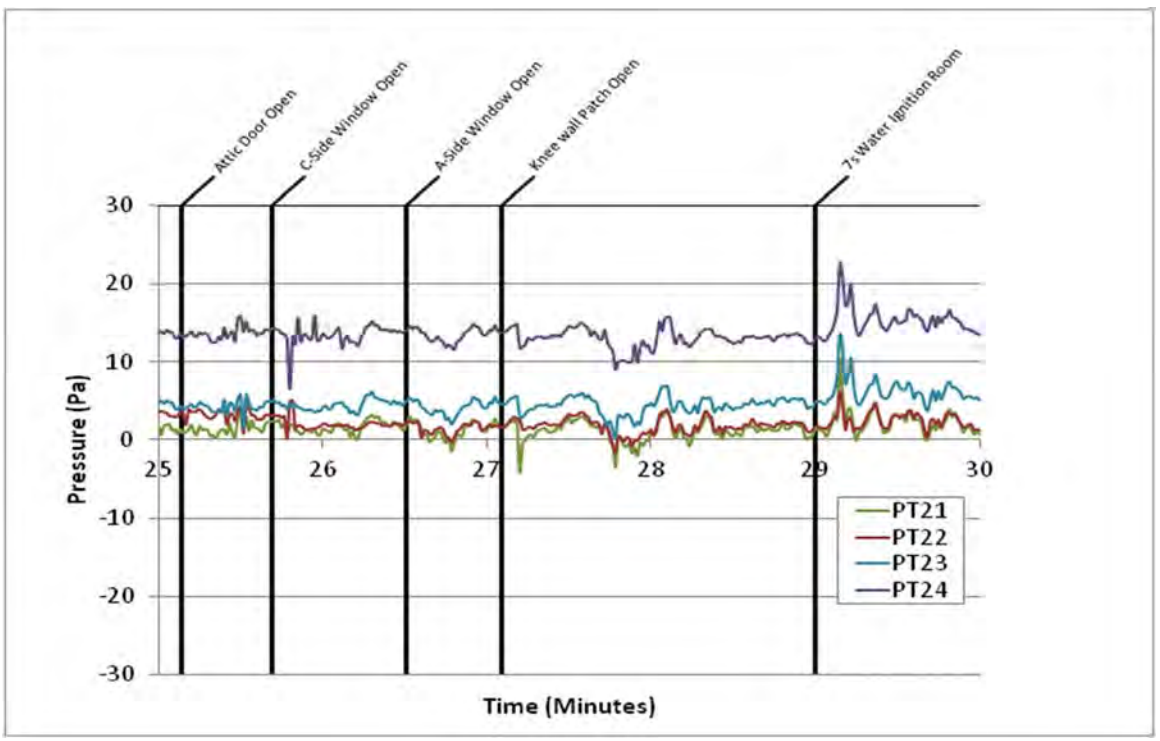


Figure J. 4: Pressure Measurements Side C (from 25 to 30 min)

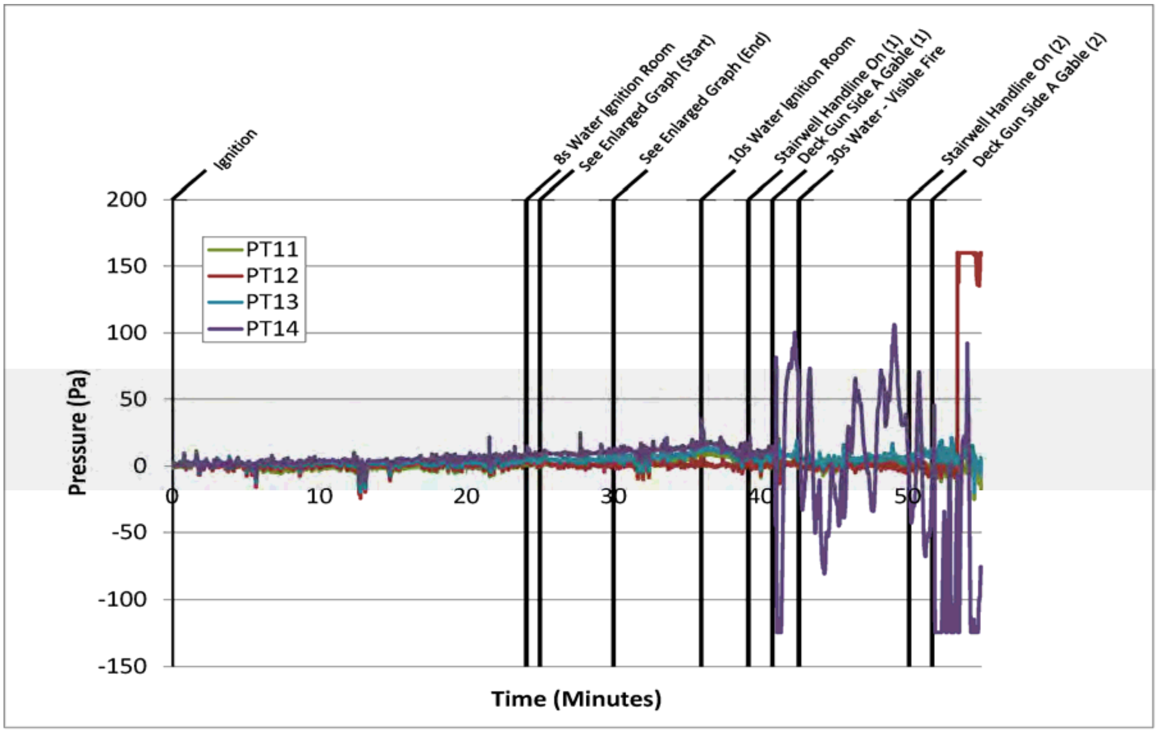


Figure J. 5: Pressure Measurements Side A

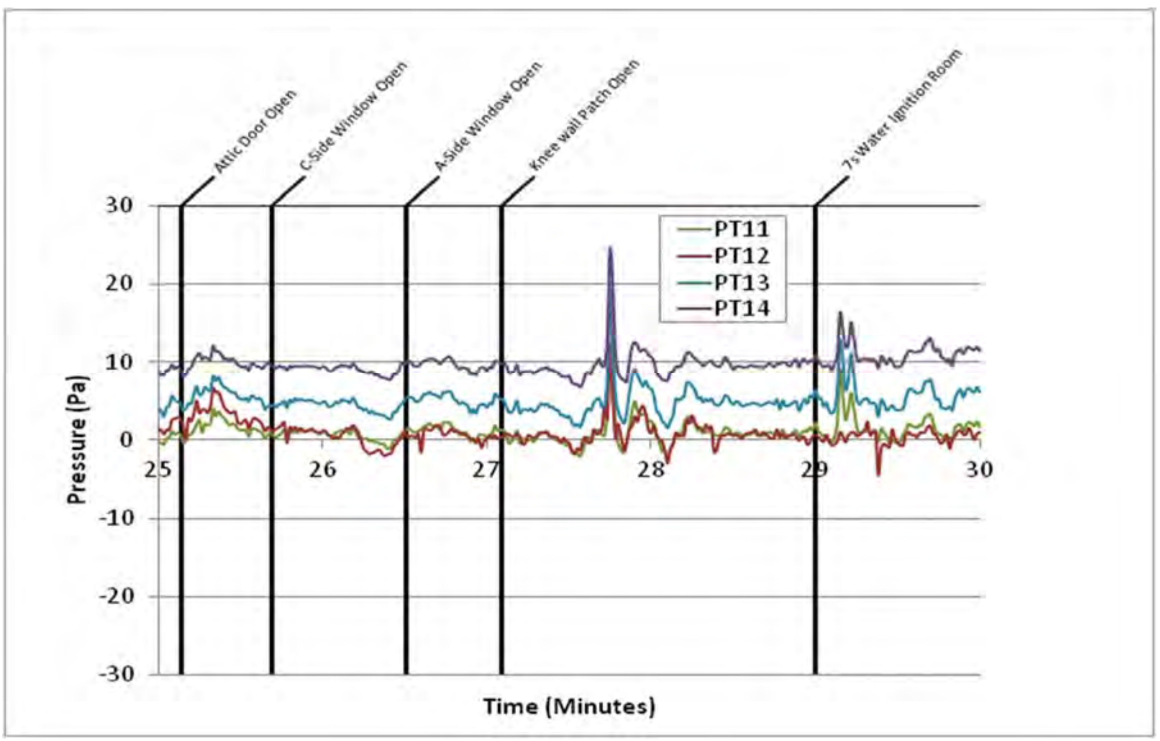


Figure J. 6: Pressure Measurements Side A (from 25 to 30 min)

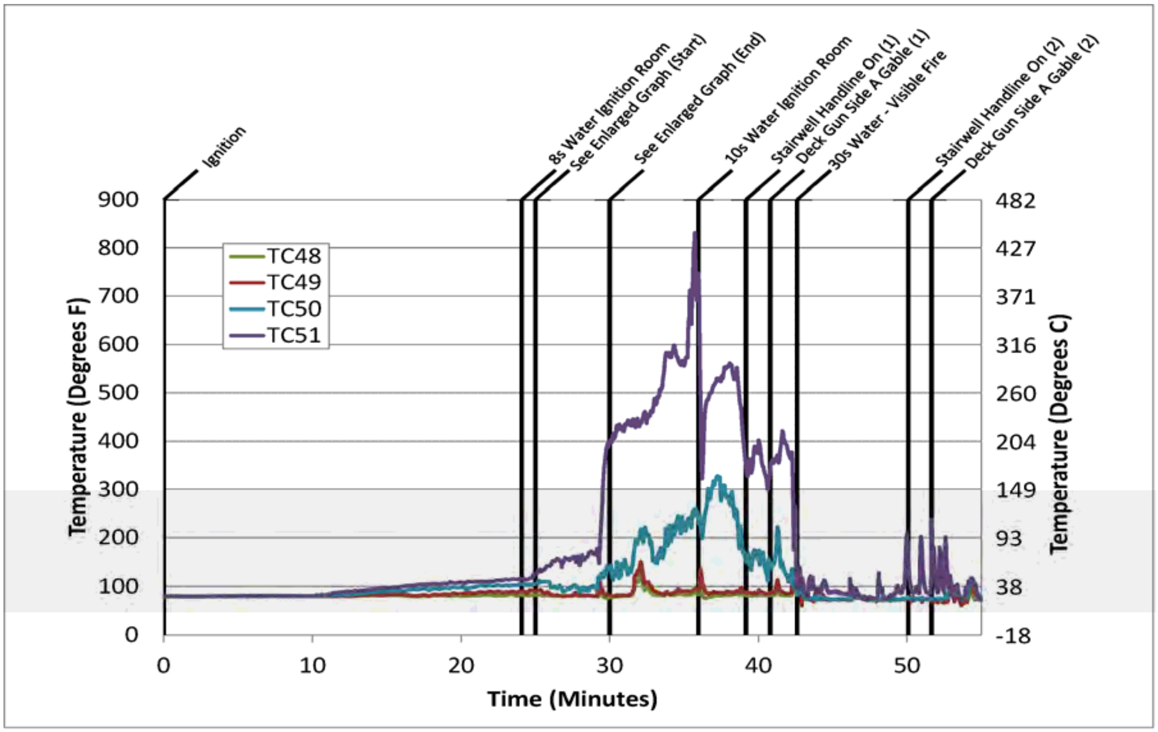


Figure J. 7: Second Floor Hallway Temperatures

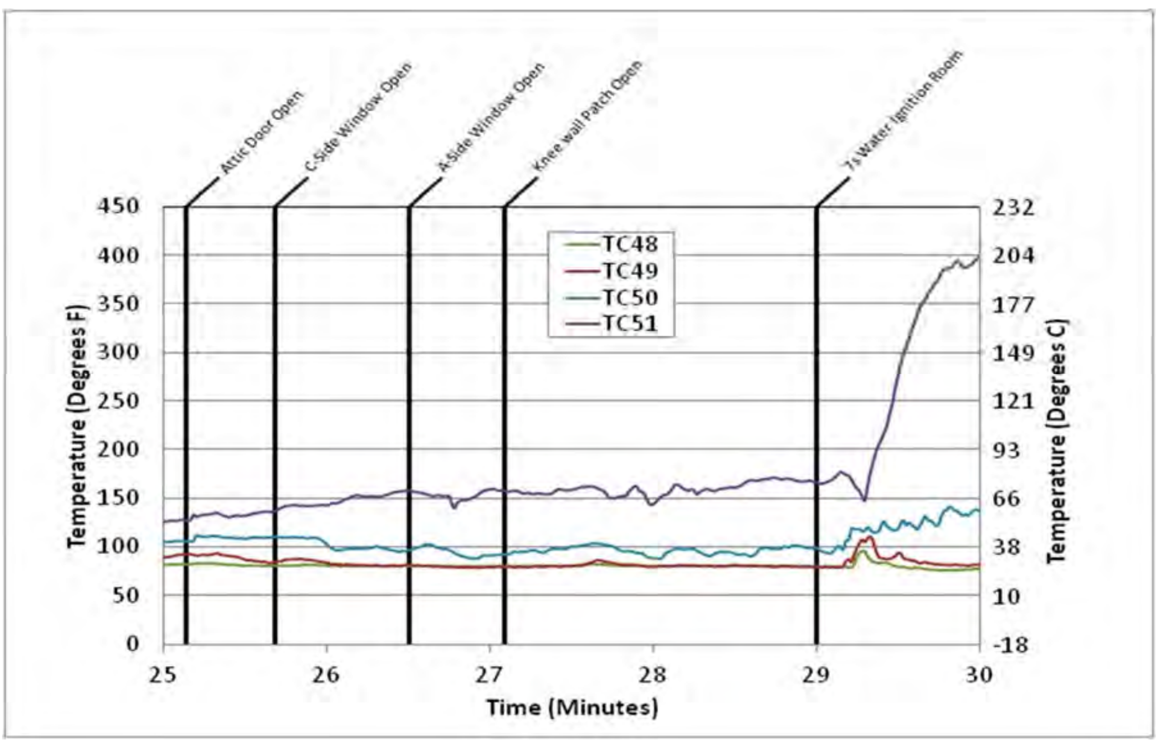


Figure J. 8: Second Floor Hallway Temperatures (from 25 to 30 min)

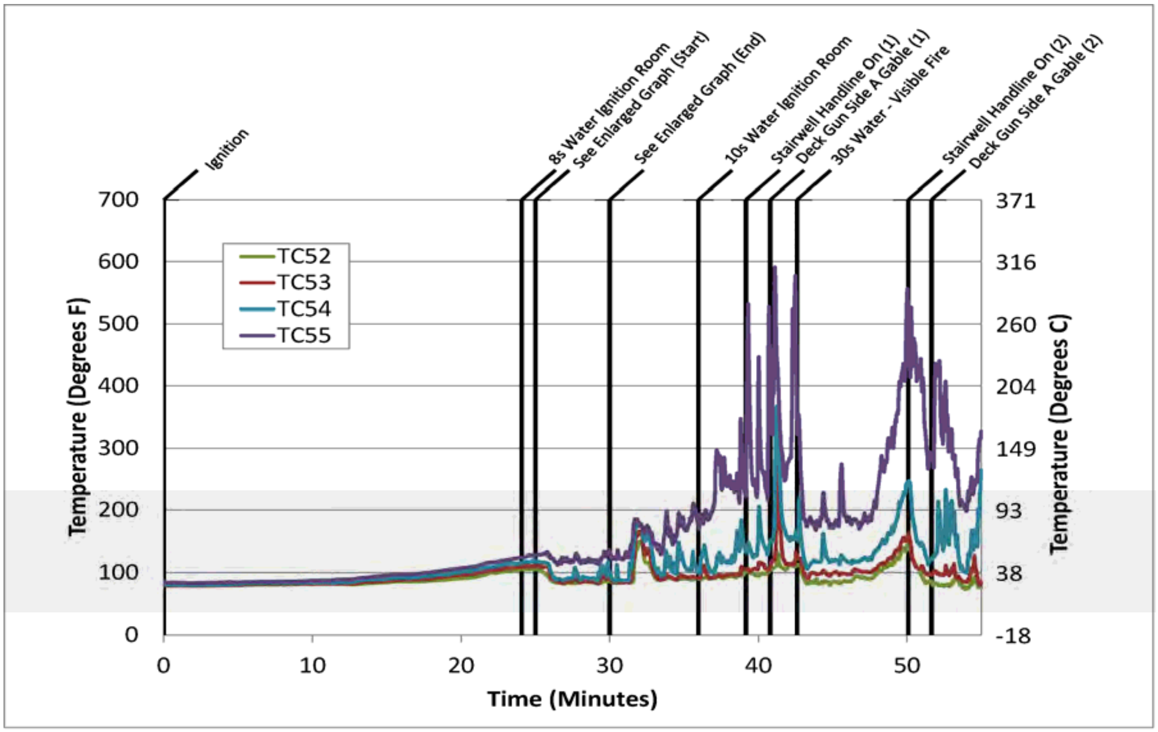


Figure J. 9: Stairwell Temperatures

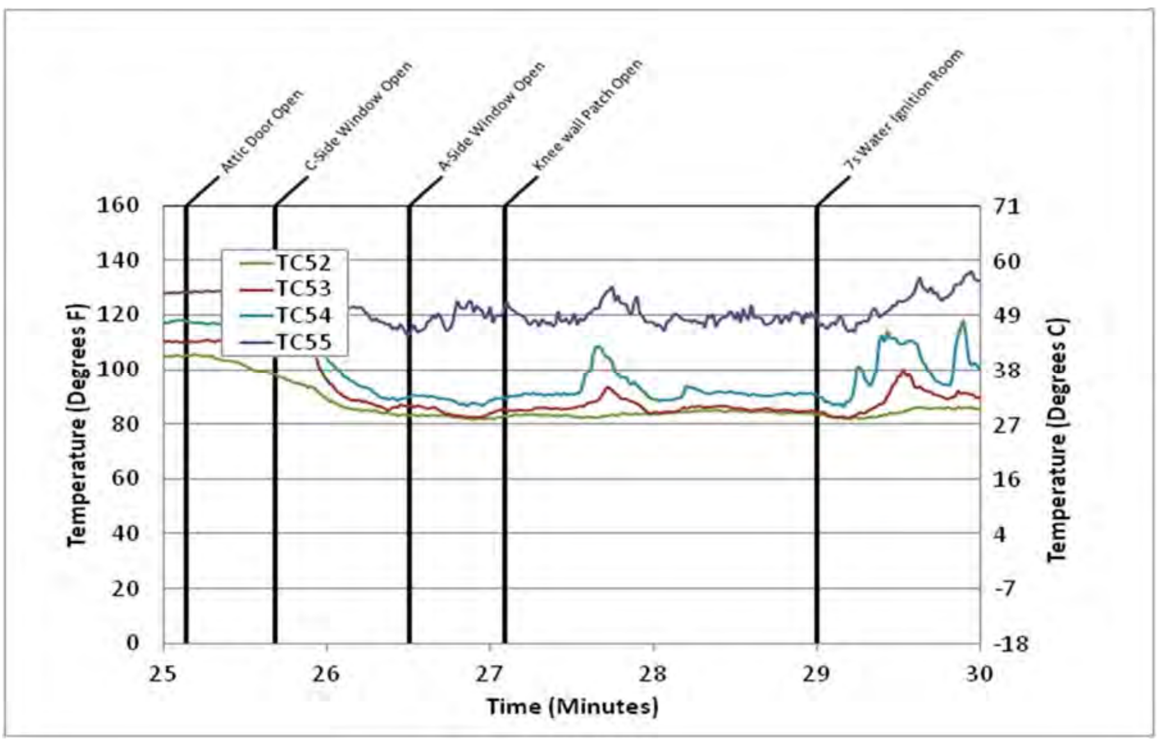


Figure J. 10: Stairwell Temperatures (from 25 to 30 min)

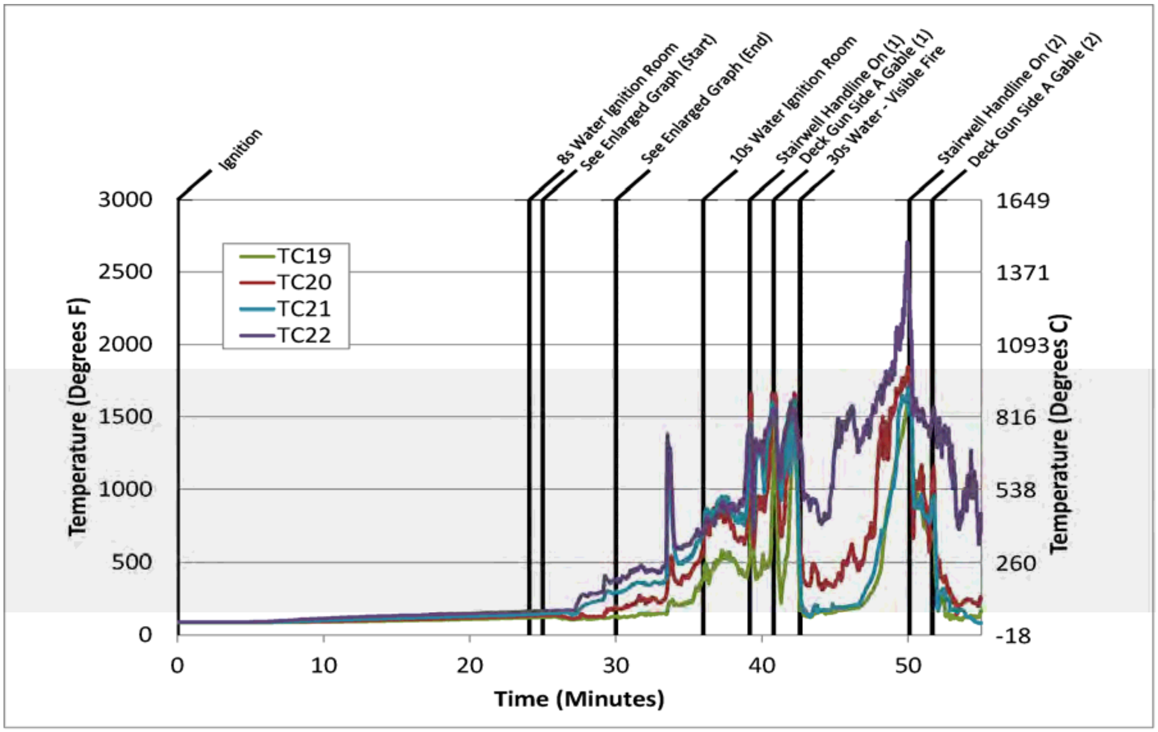


Figure J. 11: Entrance/Den Temperatures

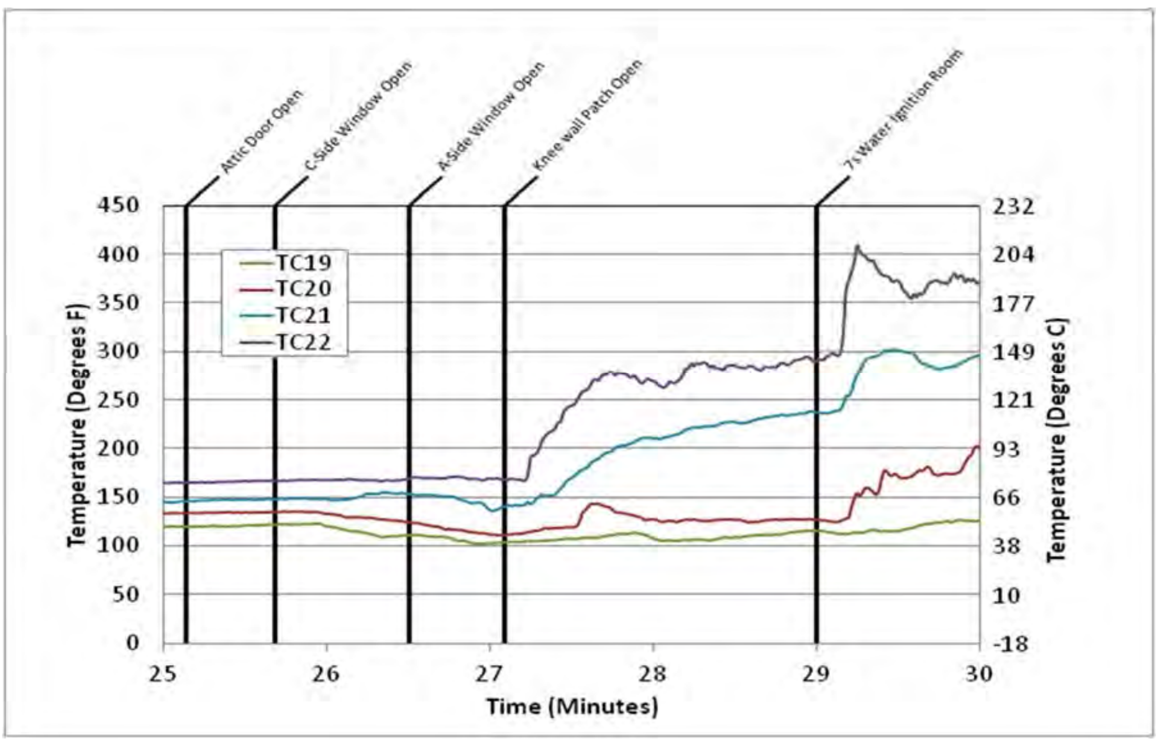


Figure J. 12: Entrance/Den Temperatures (from 25 to 30 min)

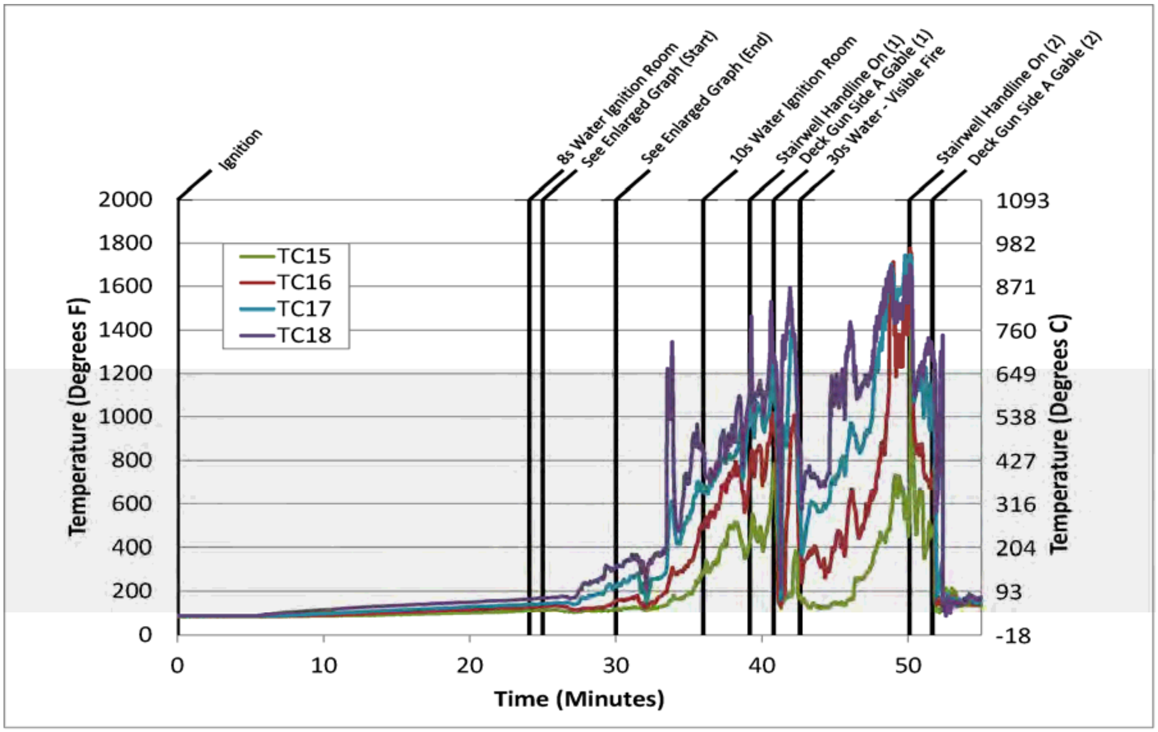


Figure J. 13: Center Room Temperatures

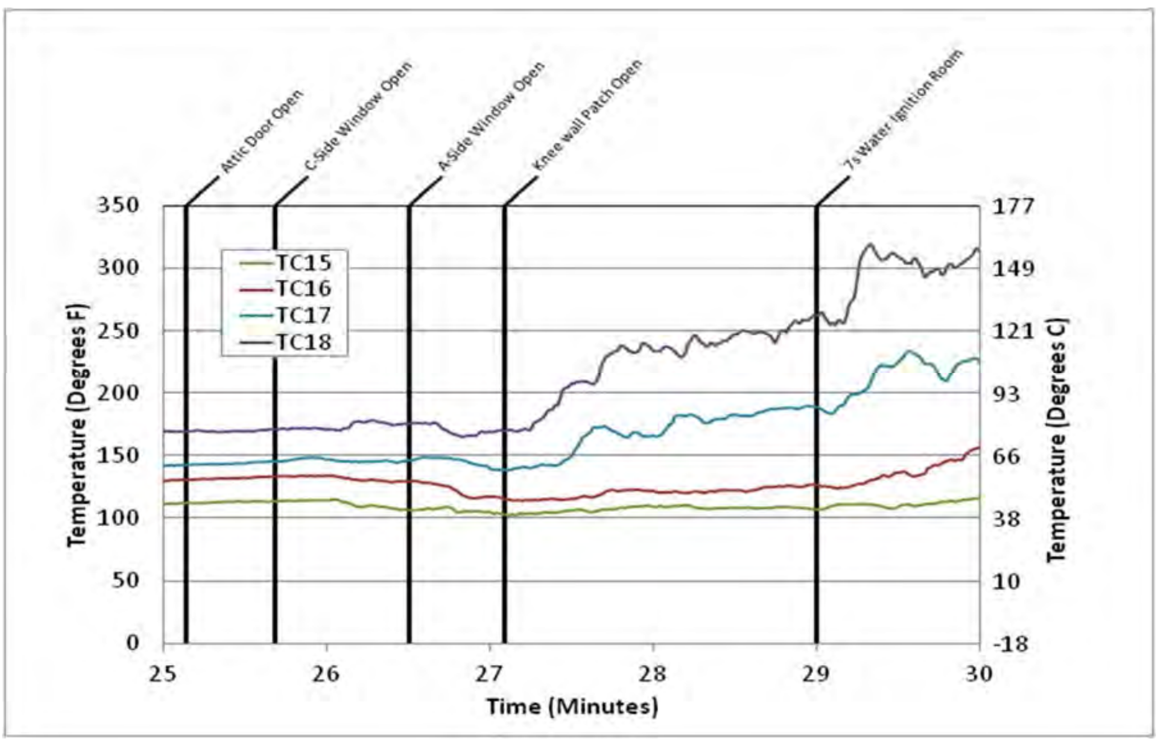


Figure J. 14: Center Room Temperatures (from 25 to 30 min)

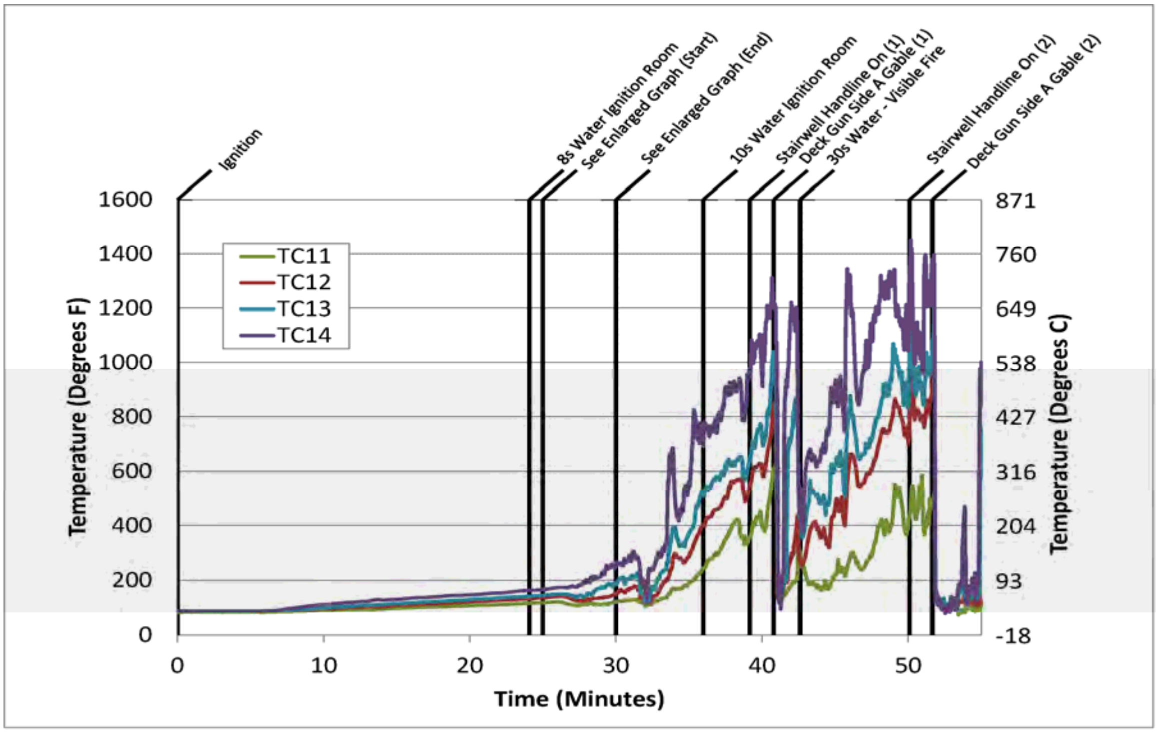


Figure J. 15: Attic Bedroom Temperatures

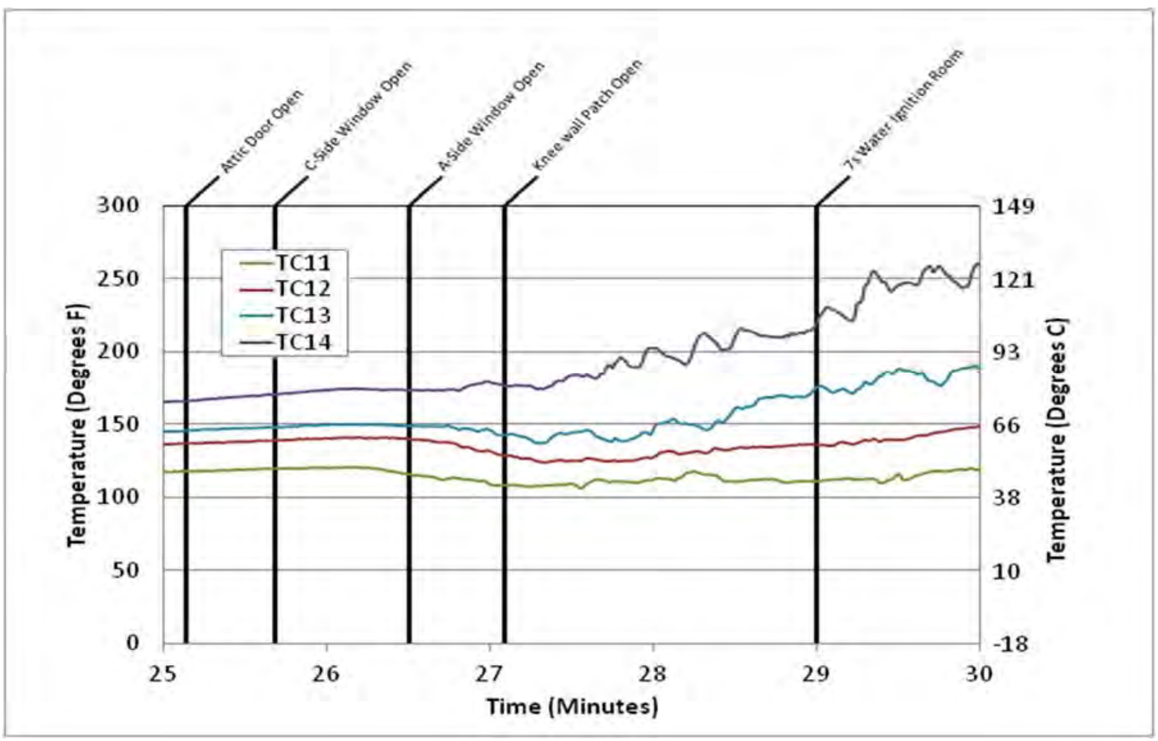


Figure J. 16: Attic Bedroom Temperatures (from 25 to 30 min)

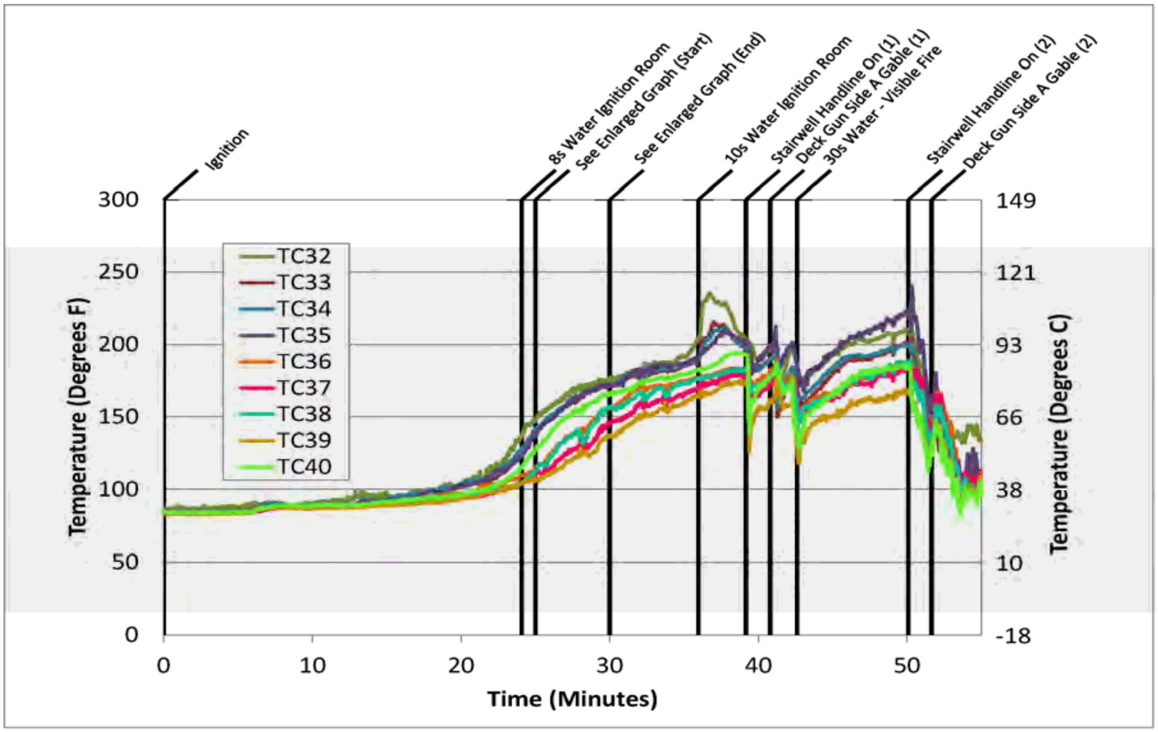


Figure J. 17: Knee Wall D Temperatures

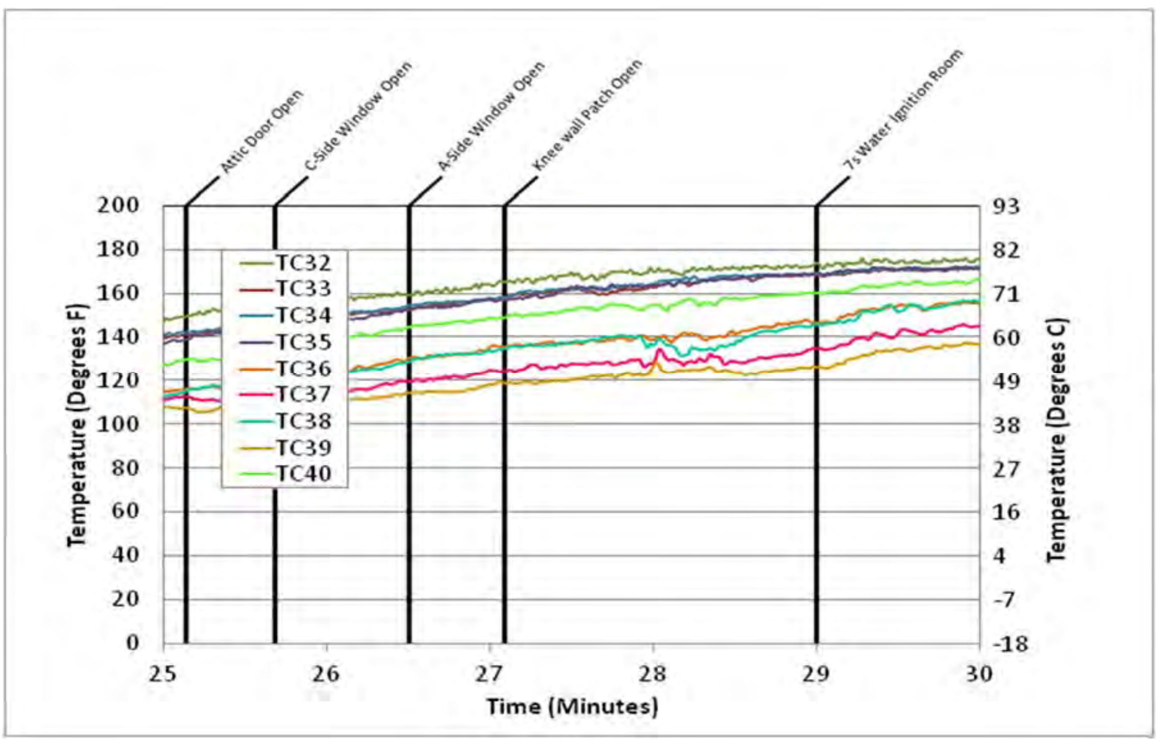


Figure J. 18: Knee Wall D Temperatures (from 25 to 30 min)

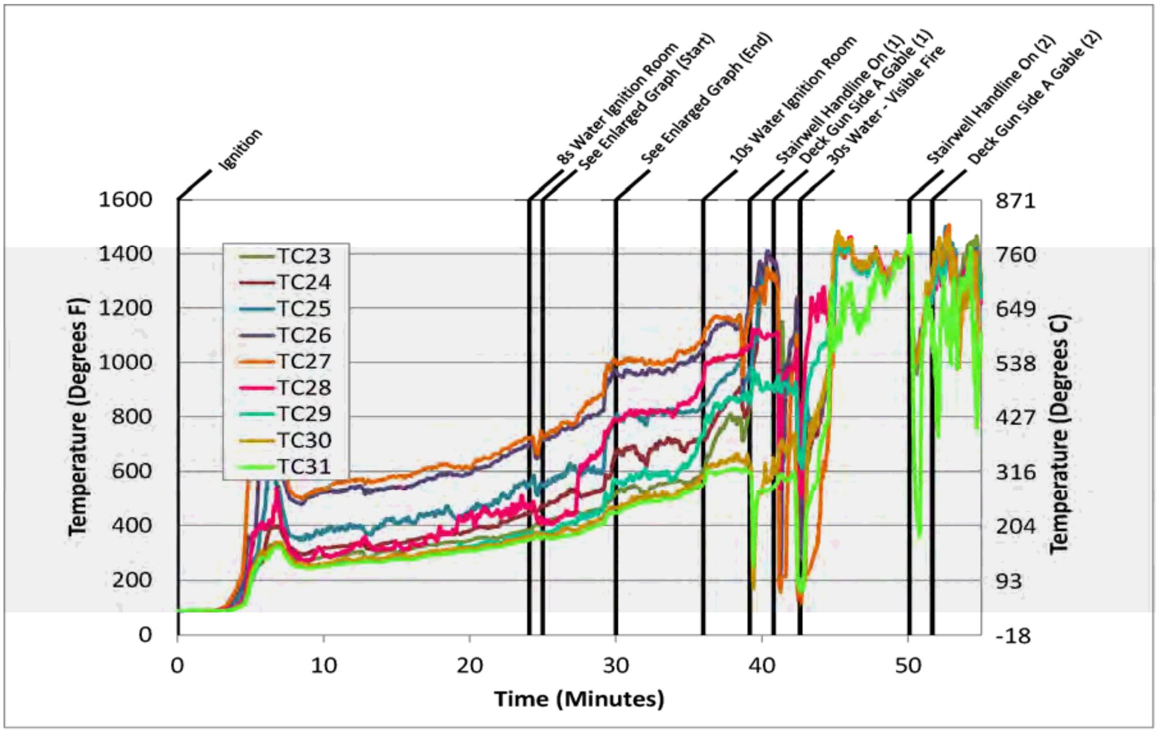


Figure J. 19: Temperatures in the Peak of the Attic

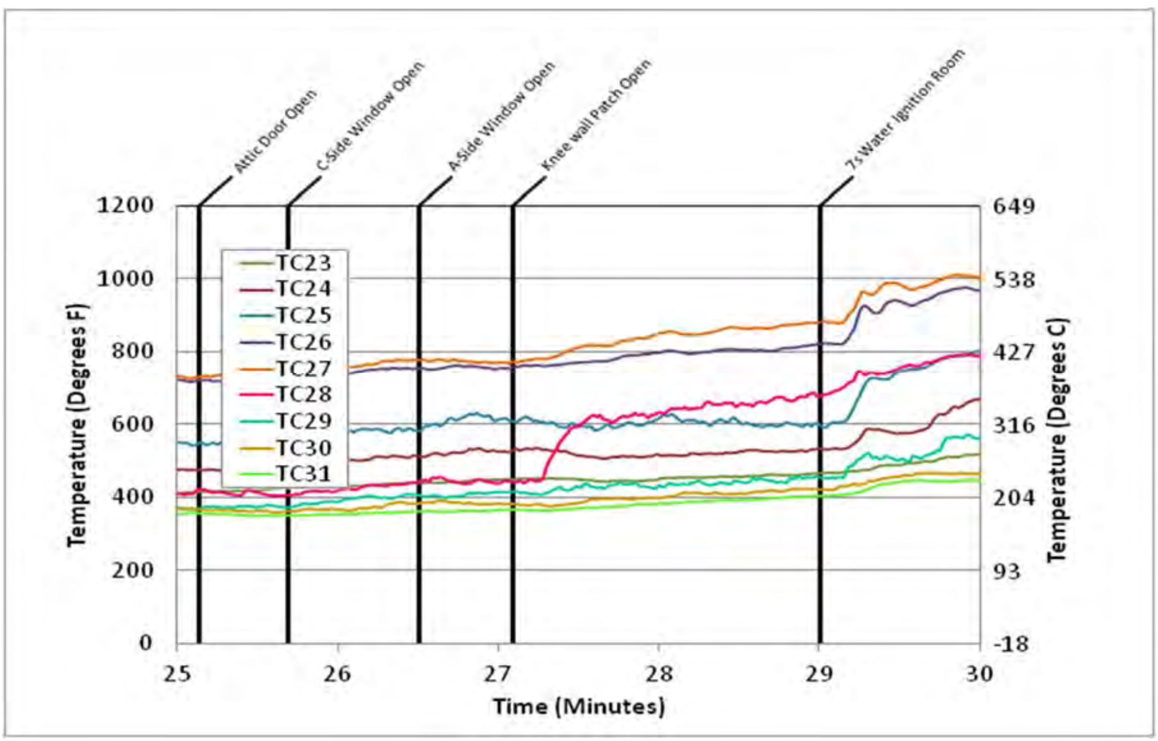


Figure J. 20: Temperatures in the Peak of the Attic (from 25 to 30 min)

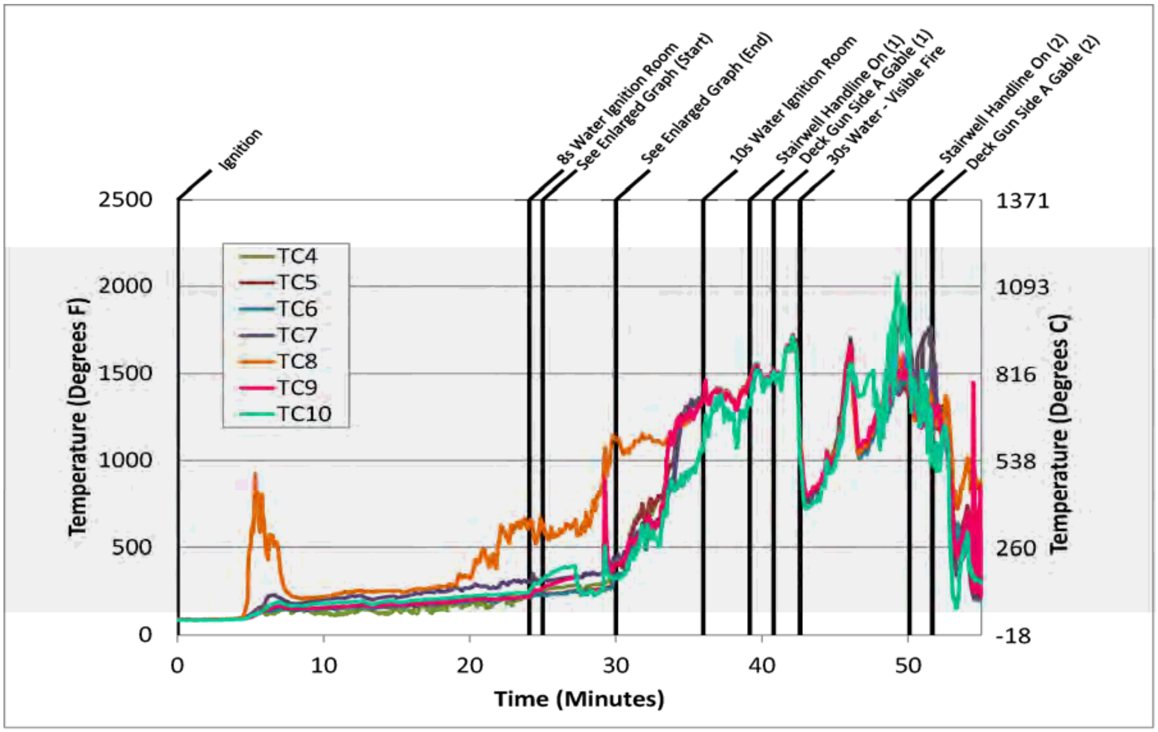


Figure J. 21: Knee Wall B Temperatures

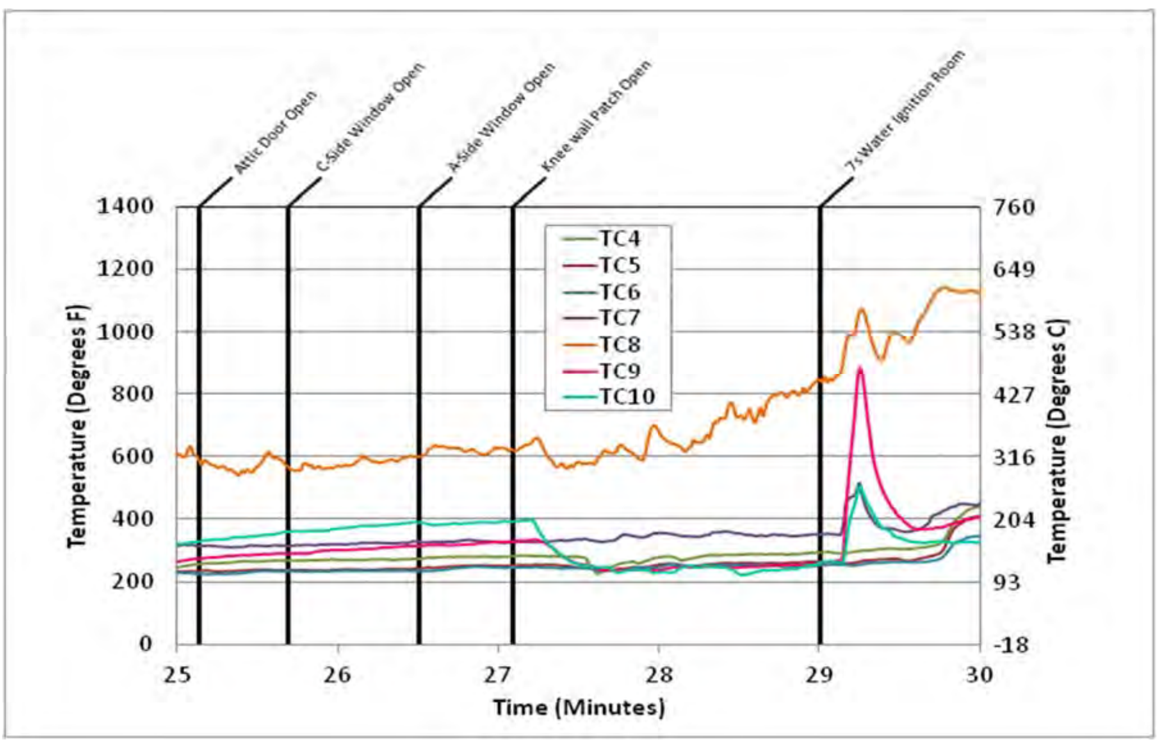


Figure J. 22: Knee Wall B Temperatures (from 25 to 30 min)

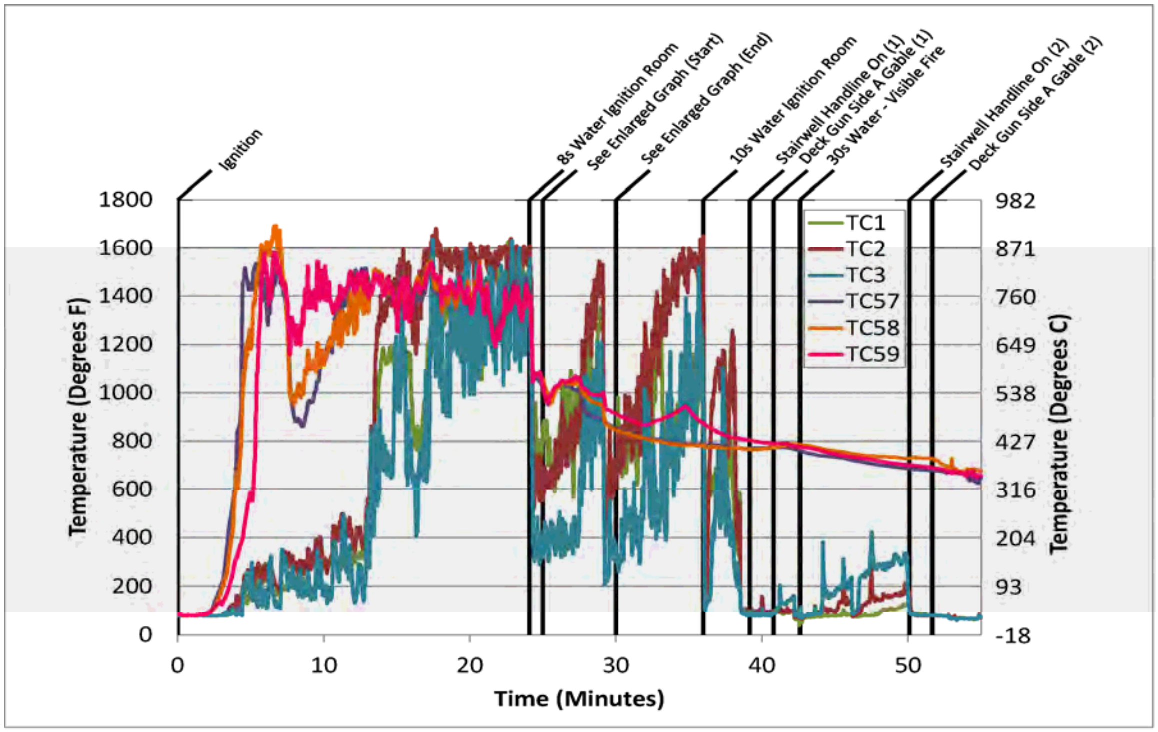


Figure J. 23: Exterior and Interior Temperatures in the Eave

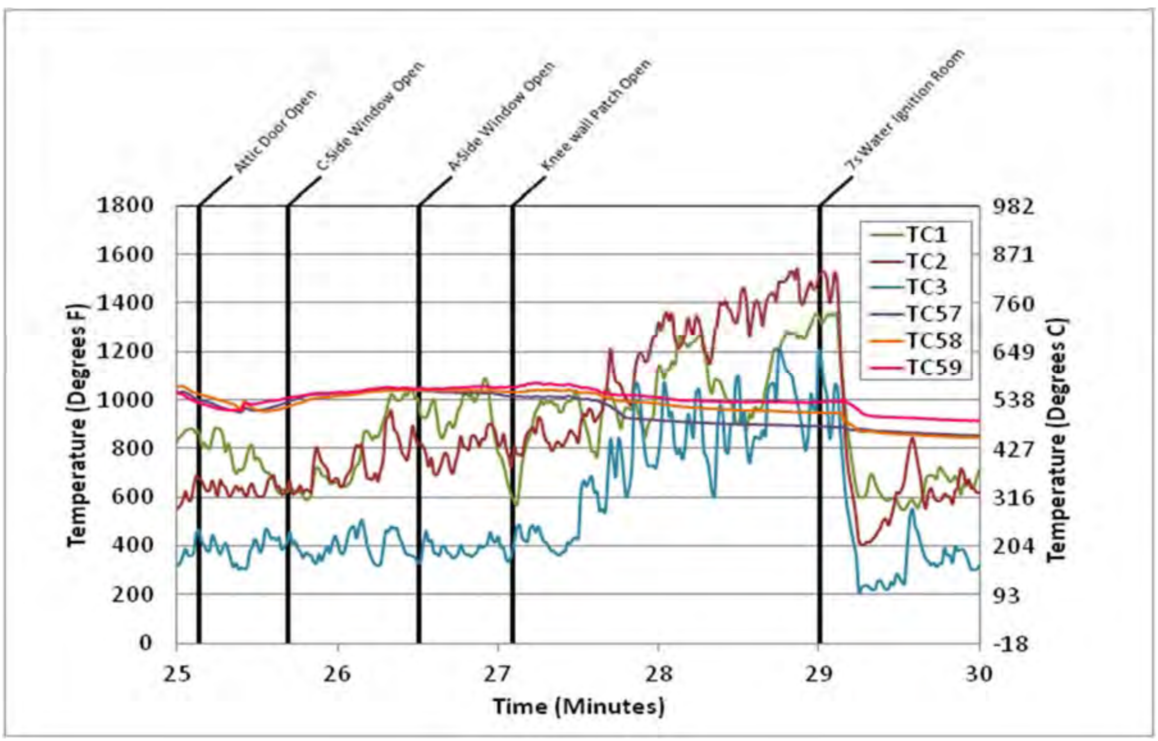


Figure J. 24: Exterior and Interior Temperatures in the Eave (from 25 to 30 min)

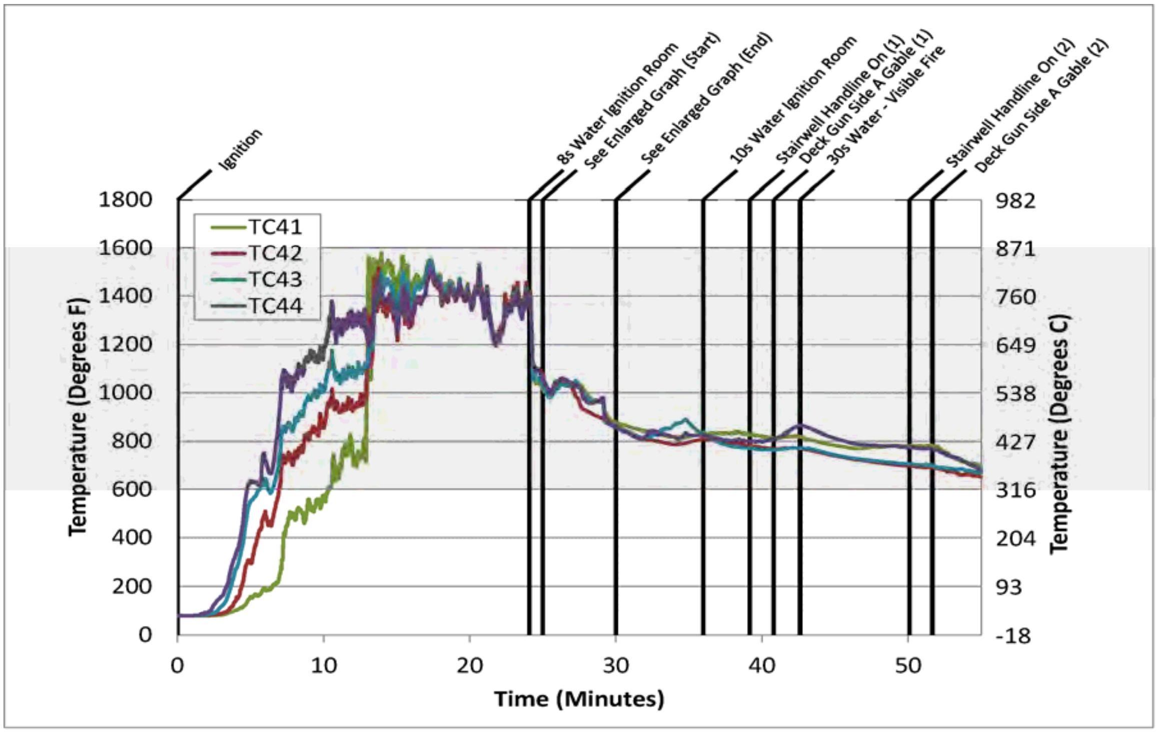


Figure J. 25: Second Floor Bedroom Temperatures

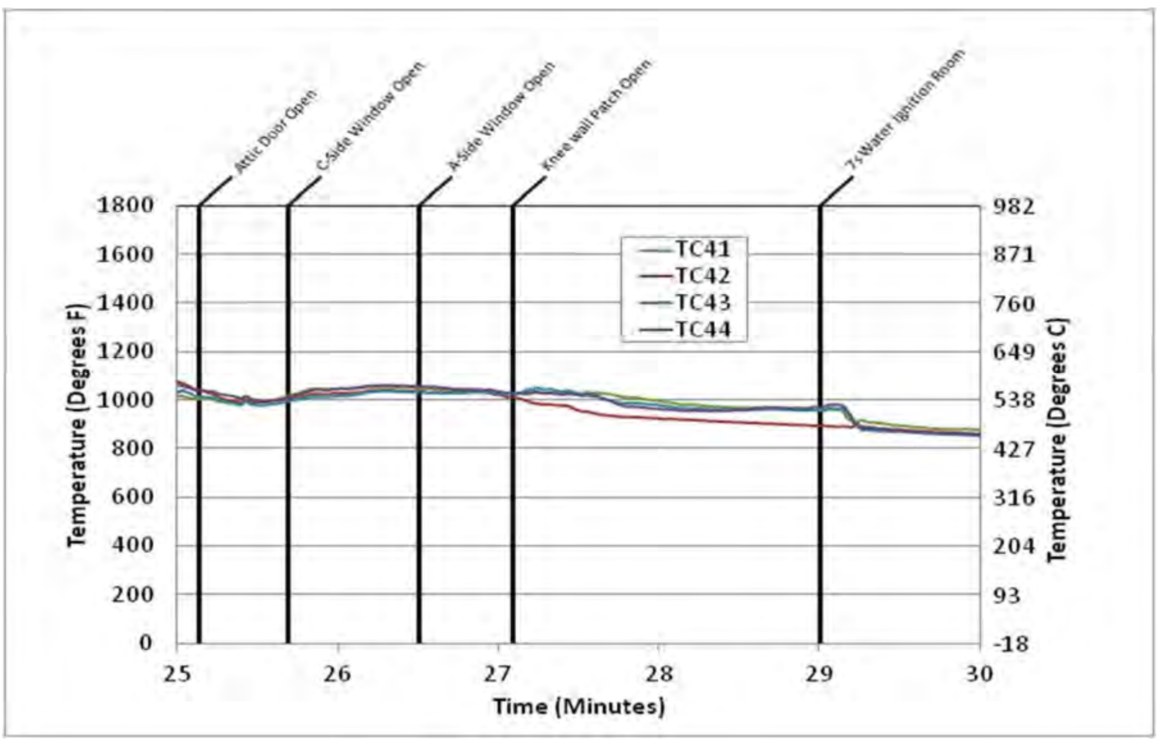


Figure J. 26: Second Floor Bedroom Temperatures (from 25 to 30 min)

Experiment 2 (426 W Burleigh Street)

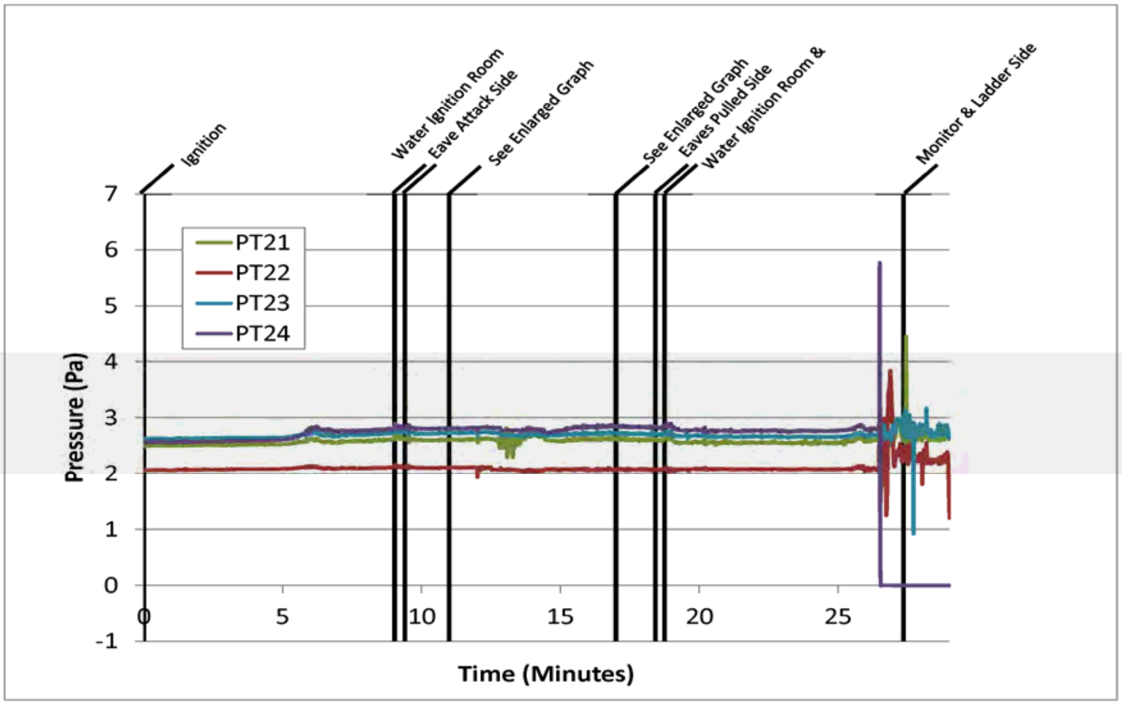


Figure J. 27: Pressure Measurements Side C

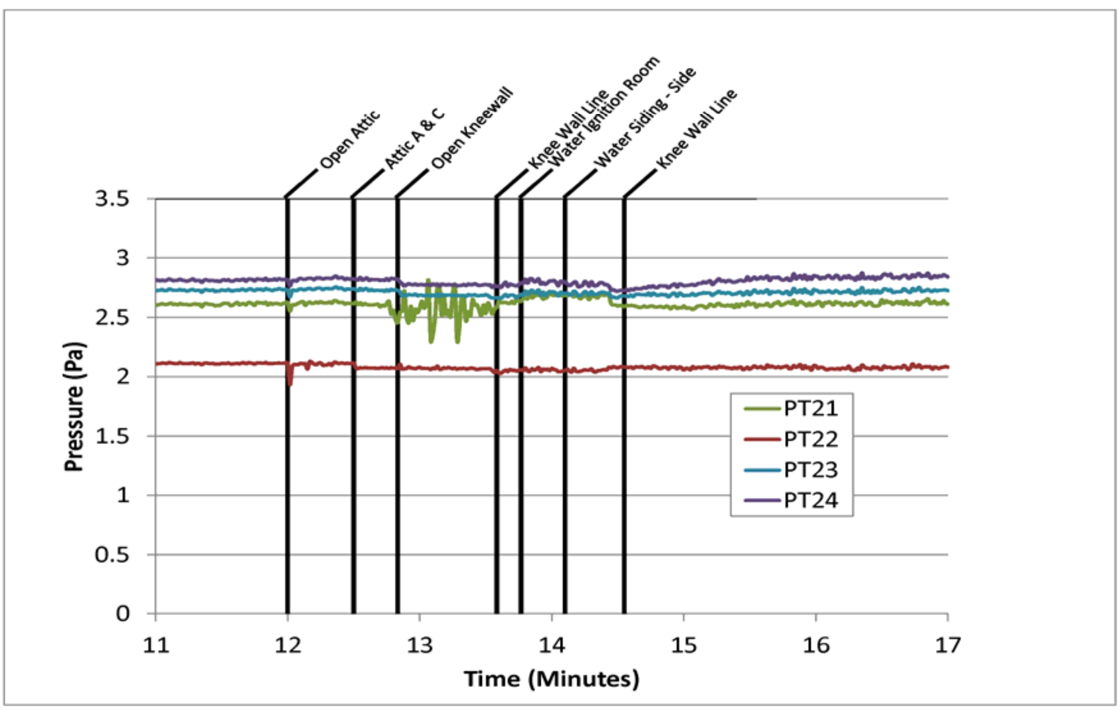


Figure J. 28: Pressure Measurements Side C (from 11 to 17 min)

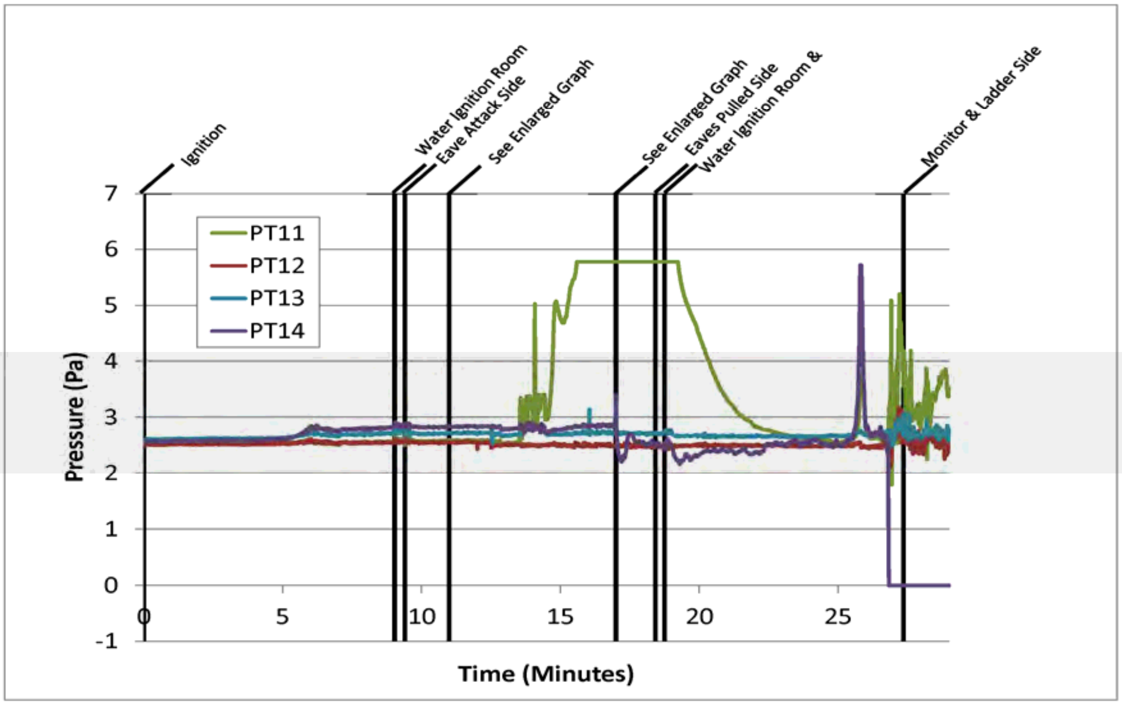


Figure J. 29: Pressure Measurements Side A

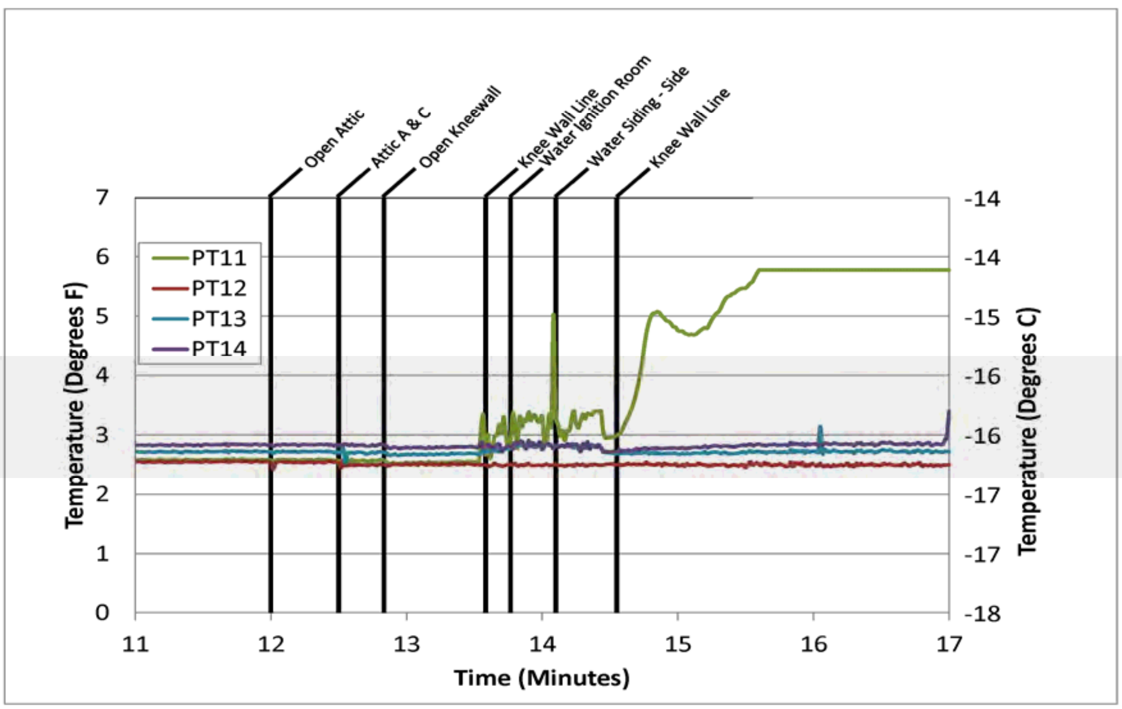


Figure J. 30: Pressure Measurements Side A (from 11 to 17 min)

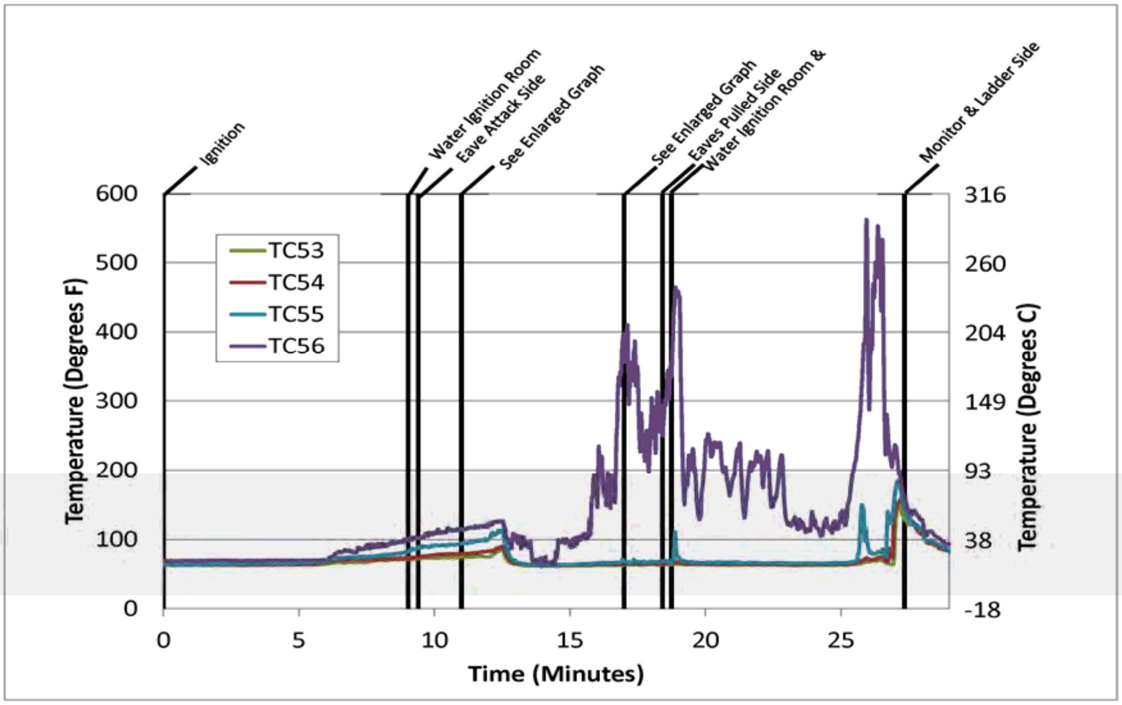


Figure J. 31: Stairwell Temperatures

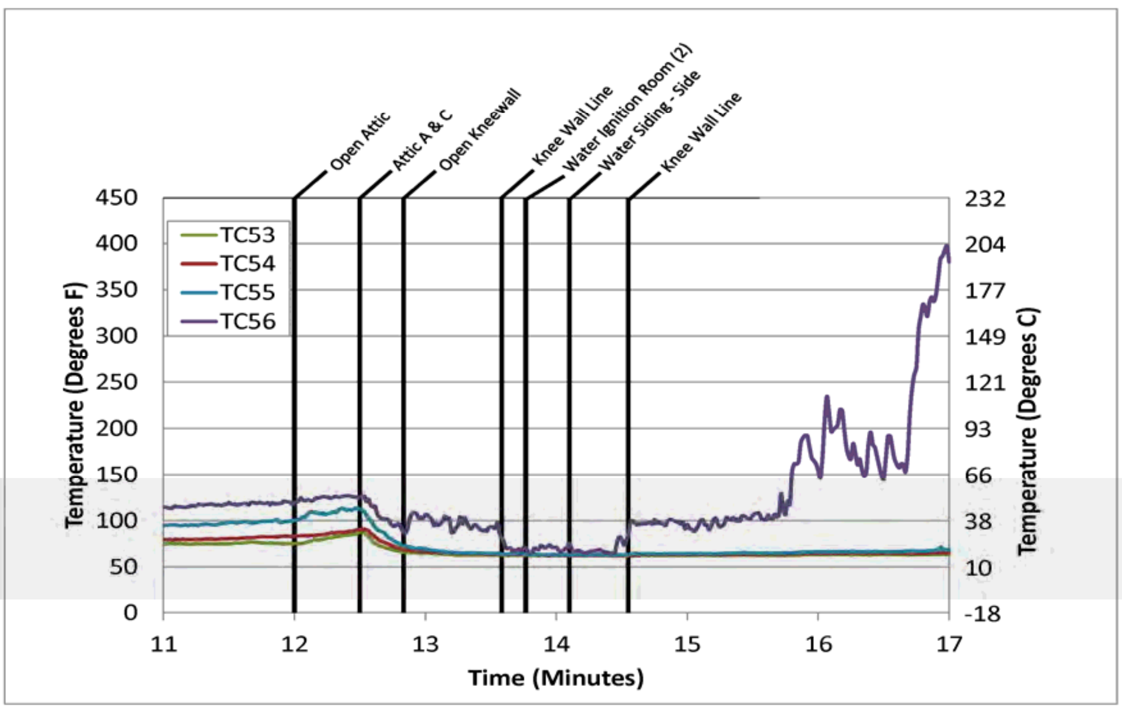


Figure J. 32: Stairwell Temperatures (from 11 to 17 min)

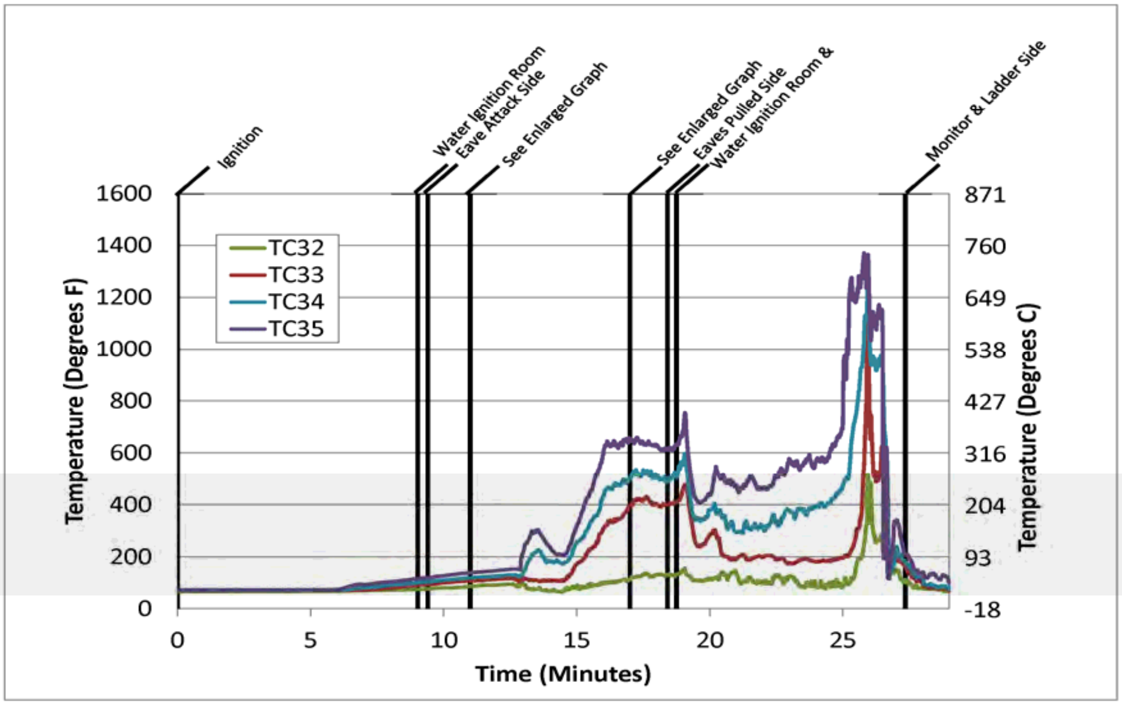


Figure J. 33: Entrance/Den Temperatures

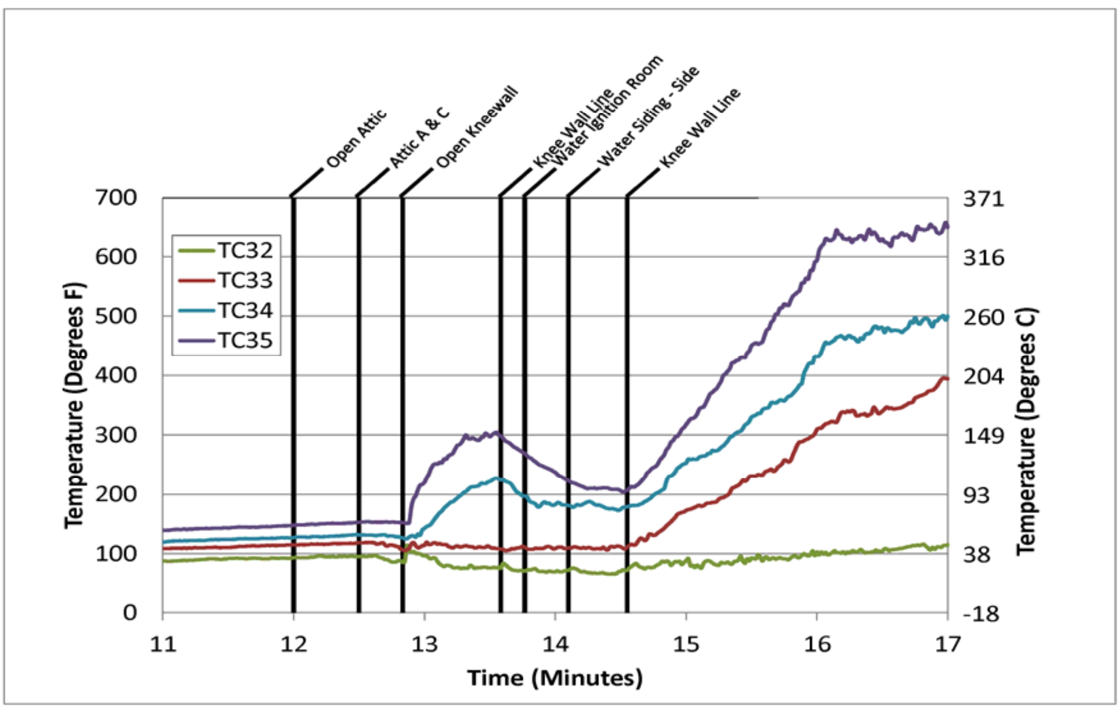


Figure J. 34: Entrance/Den Temperatures (from 11 to 17 min)

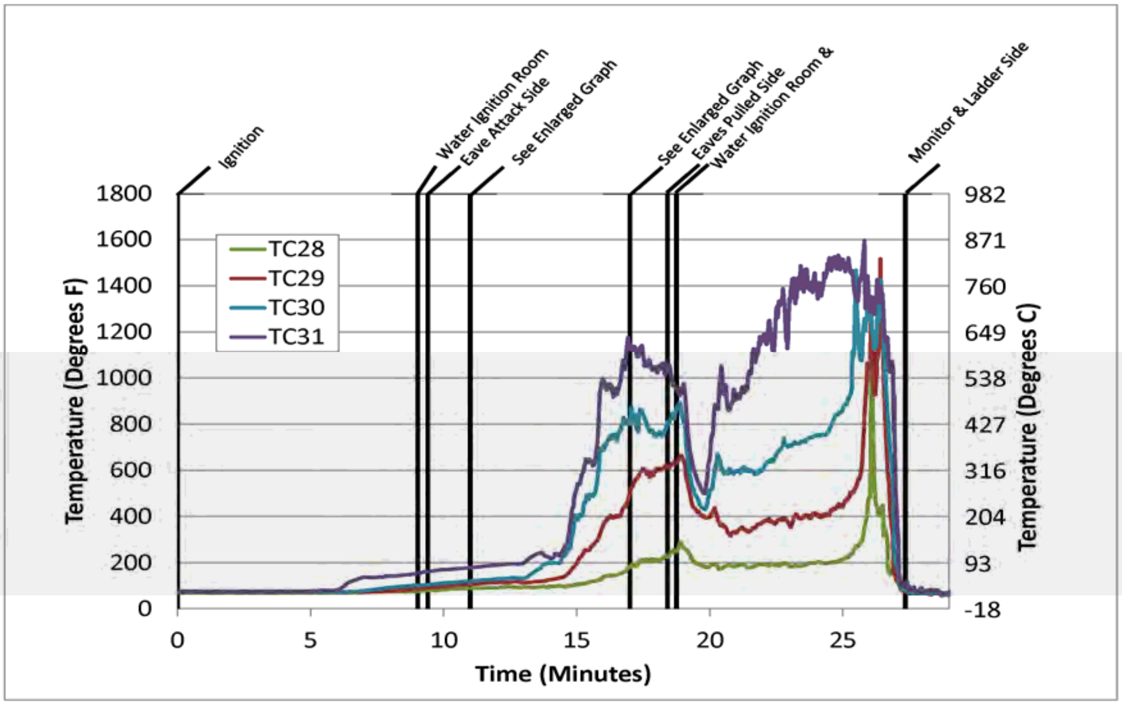


Figure J. 35: Center Room Temperatures

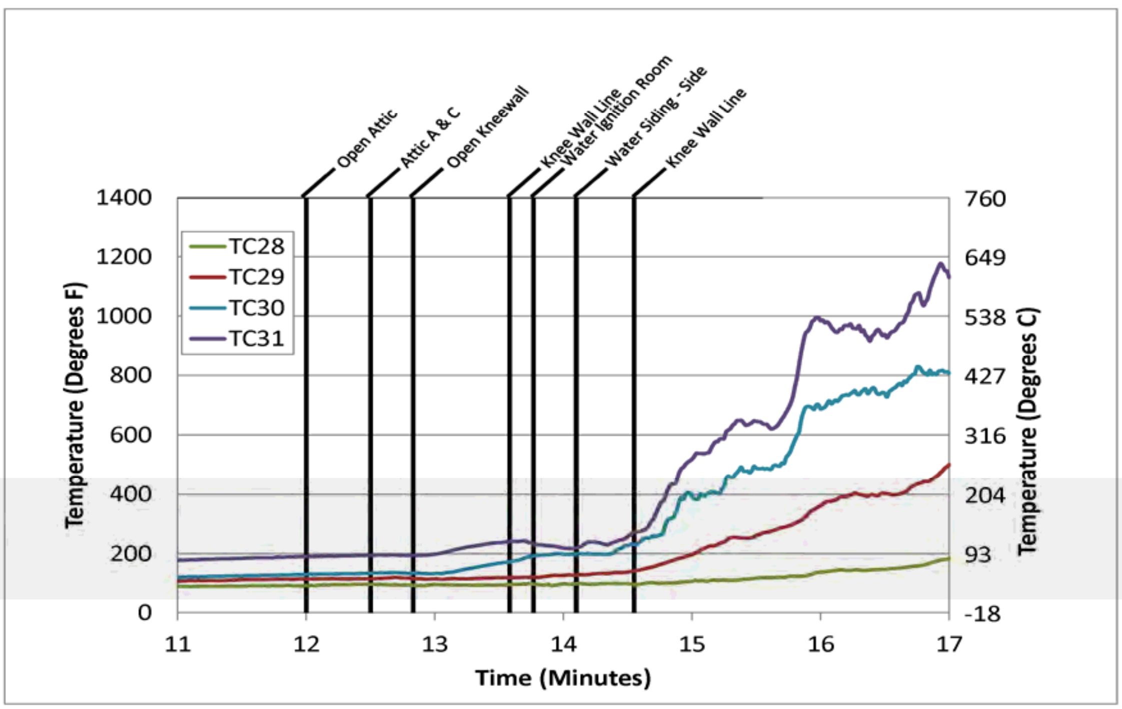


Figure J. 36: Center Room Temperatures (from 11 to 17 min)

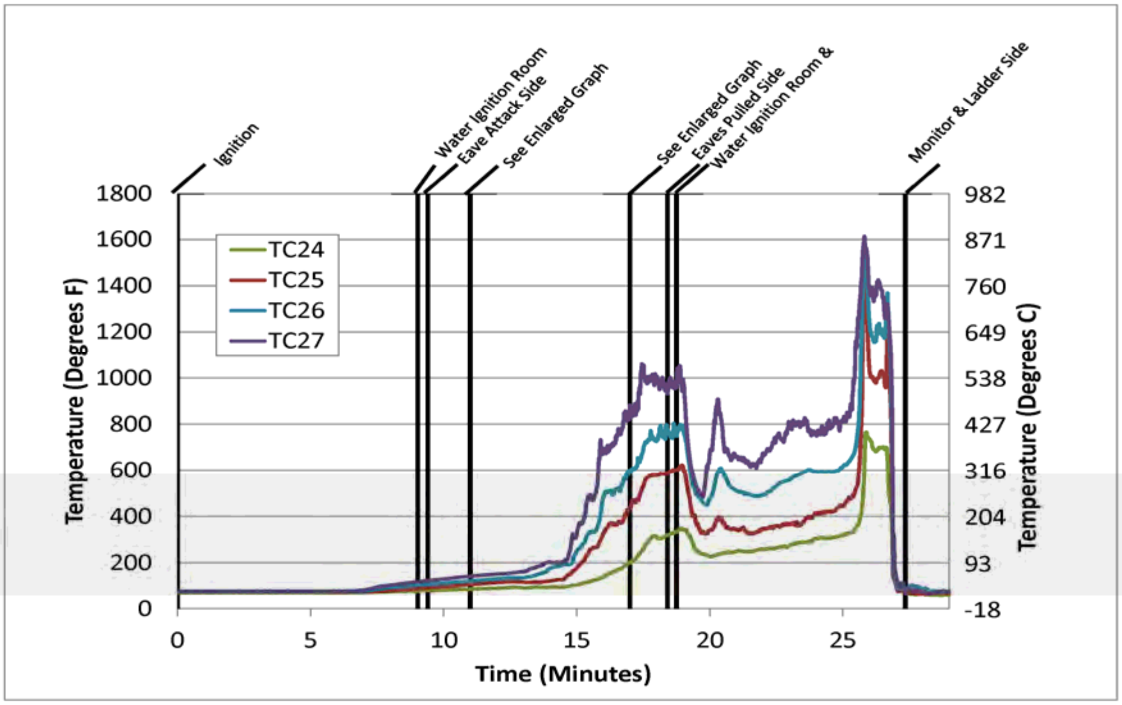


Figure J. 37: Attic Bedroom Temperatures

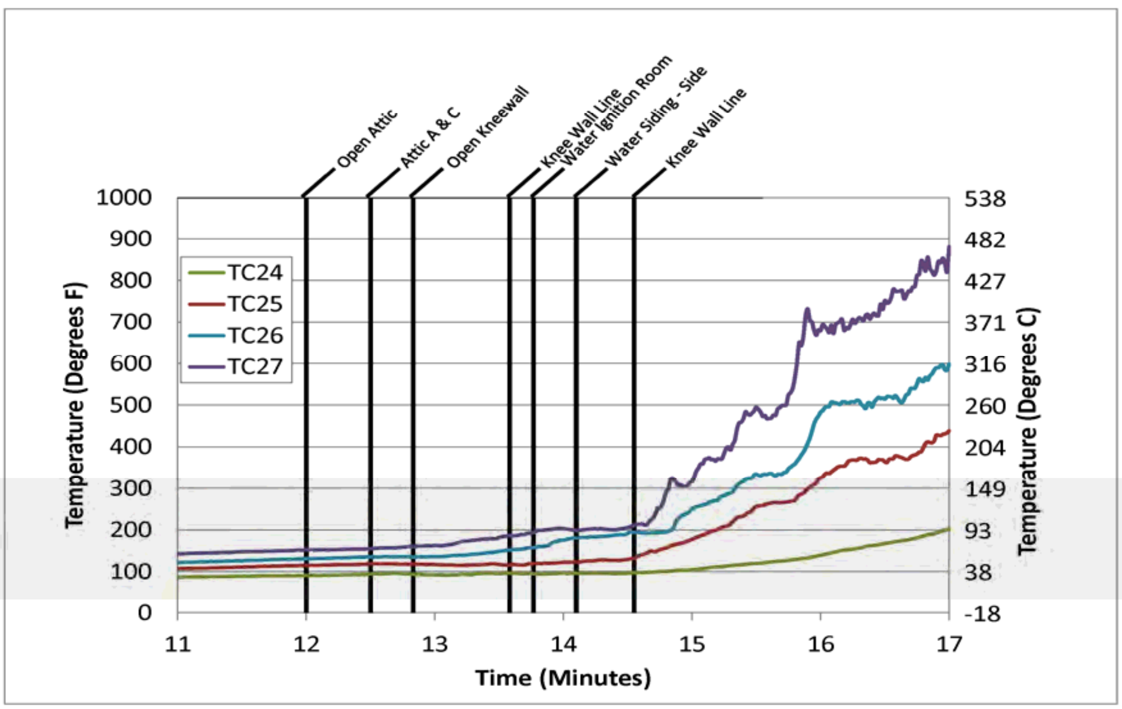


Figure J. 38: Attic Bedroom Temperatures (from 11 to 17 min)

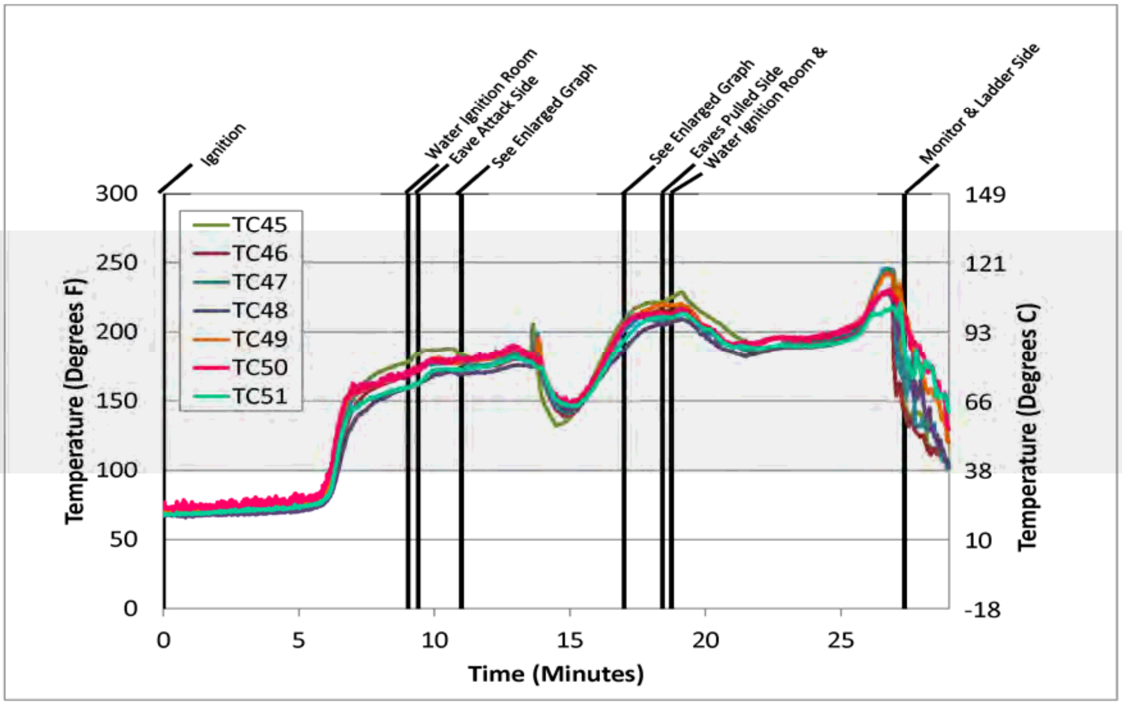


Figure J. 39: Knee Wall D Temperatures

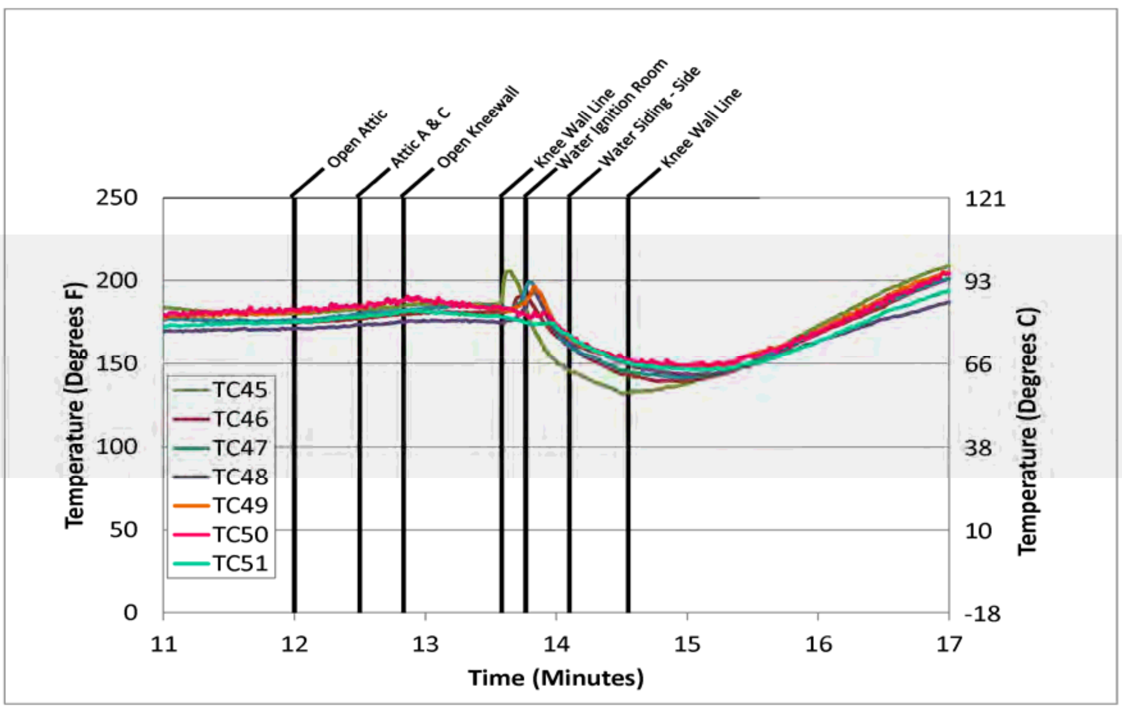


Figure J. 40: Knee Wall D Temperatures (from 11 to 17 min)

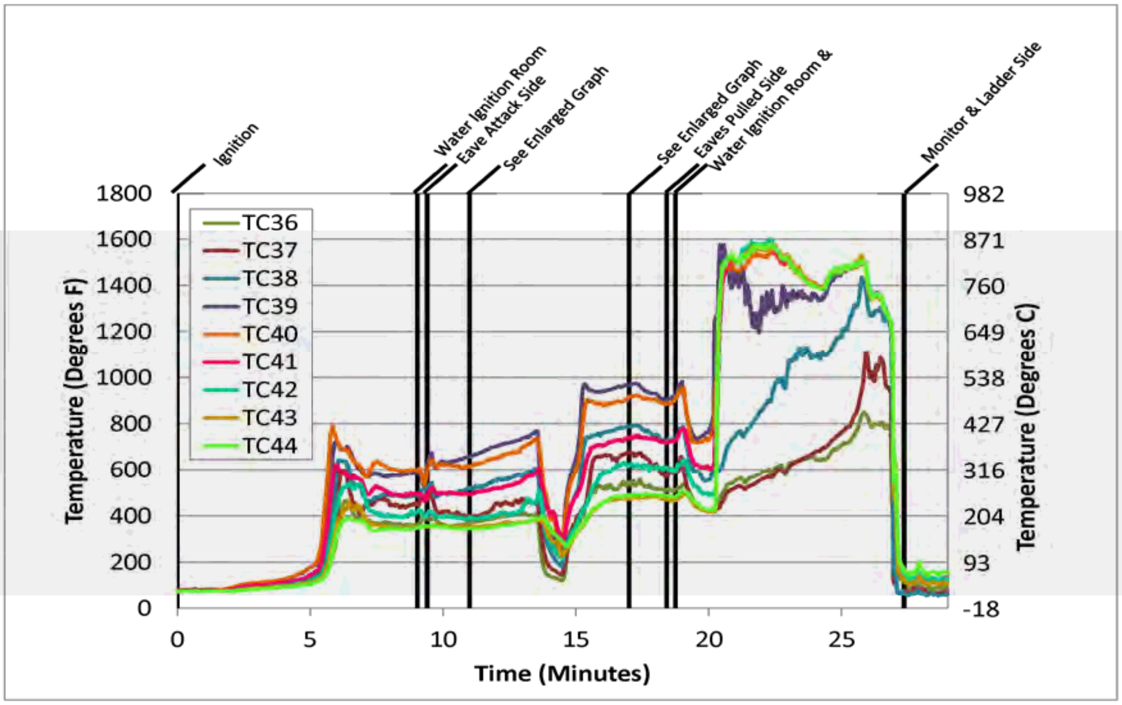


Figure J. 41: Temperatures in the Peak of the Attic

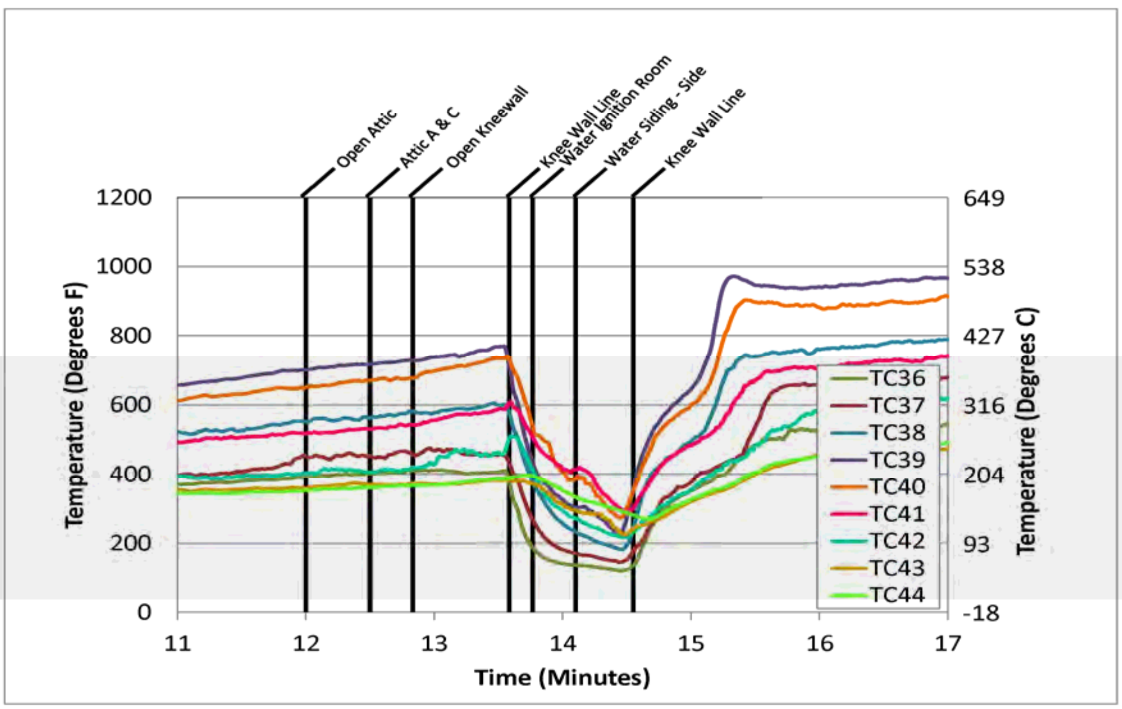


Figure J. 42: Temperatures in the Peak of the Attic (from 11 to 17 min)

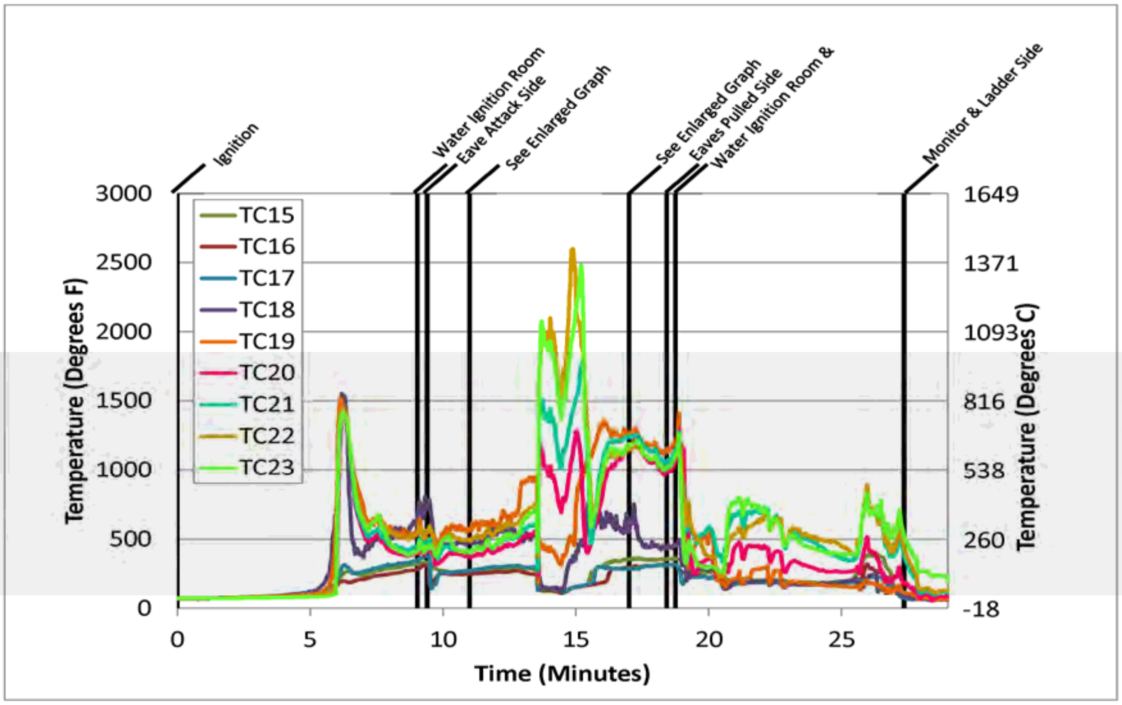


Figure J. 43: Knee Wall B Temperatures

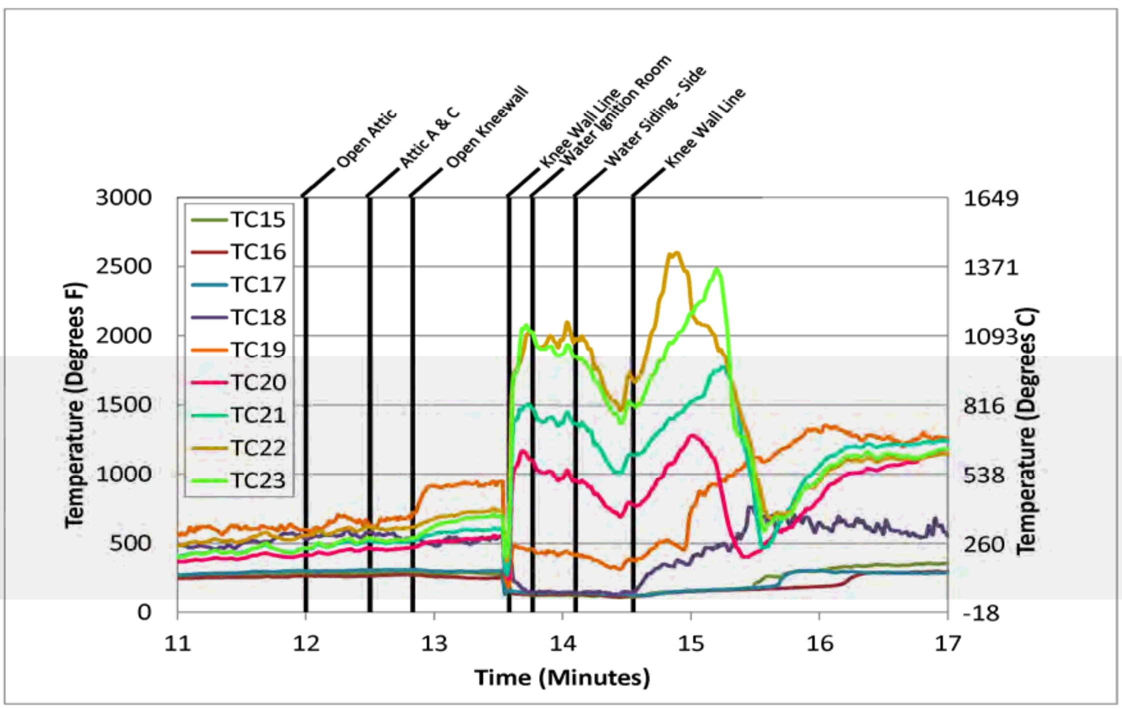


Figure J. 44: Knee Wall B Temperatures (from 11 to 17 min)

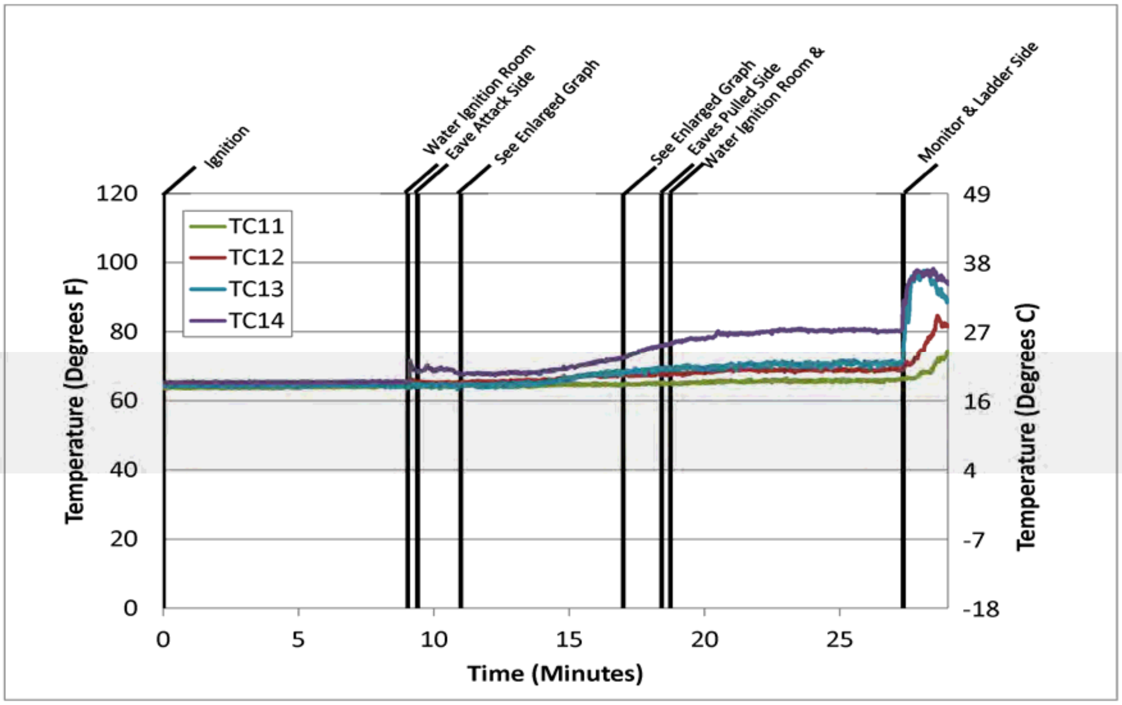


Figure J. 45: Second Floor Hallway Temperatures

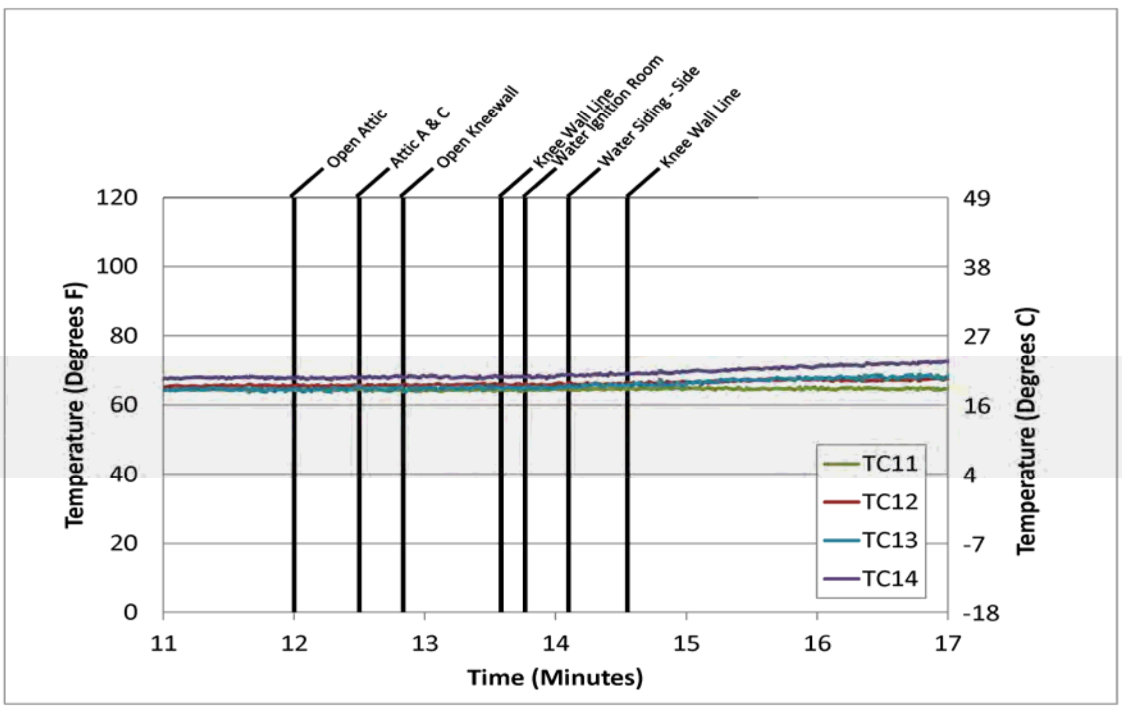


Figure J. 46: Second Floor Hallway Temperatures (from 11 to 17 min)

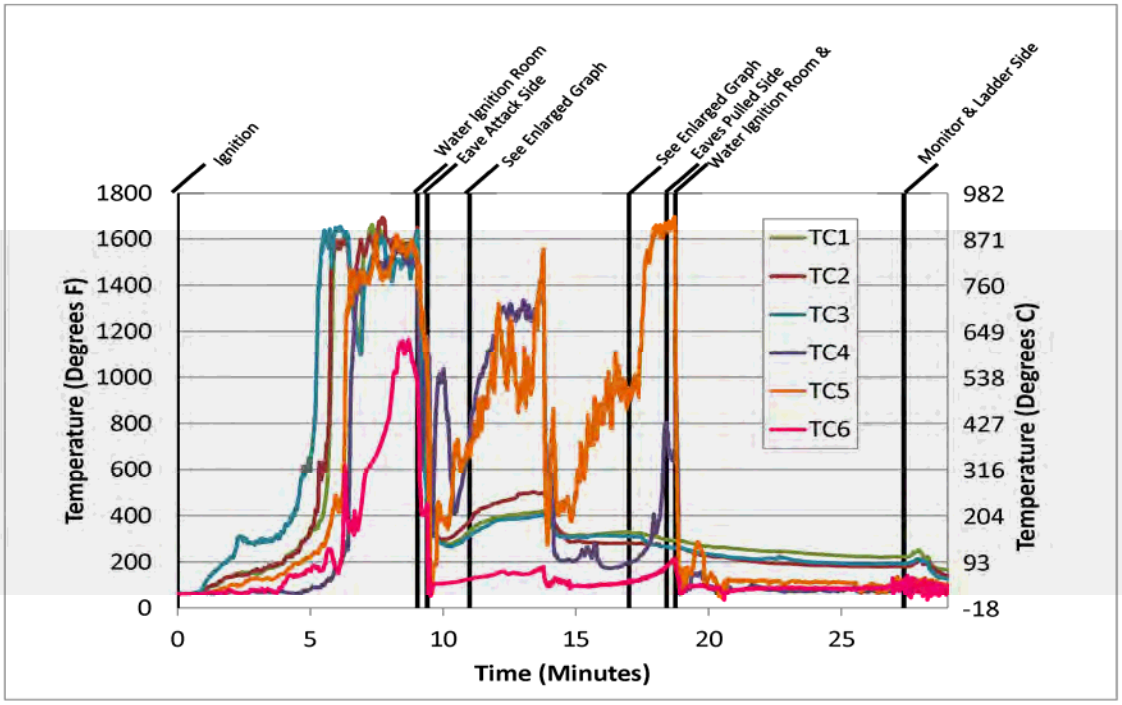


Figure J. 47: Exterior and Interior Temperatures in the Eave

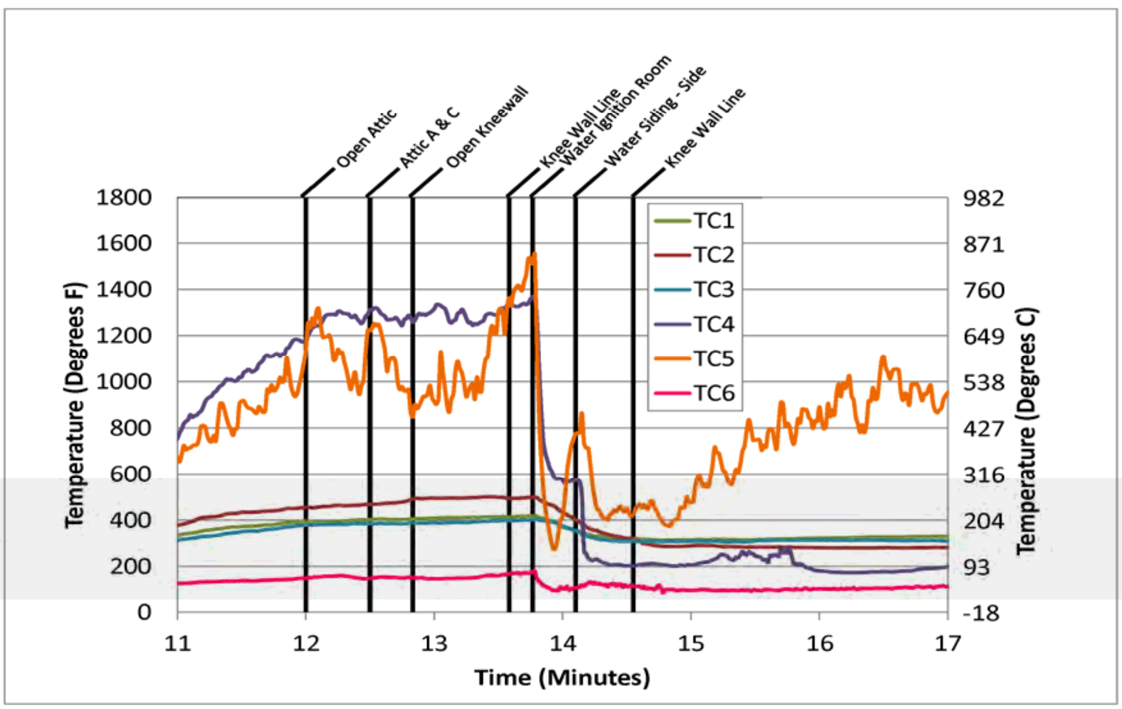


Figure J. 48: Exterior and Interior Temperatures in the Eave (from 11 to 17 min)

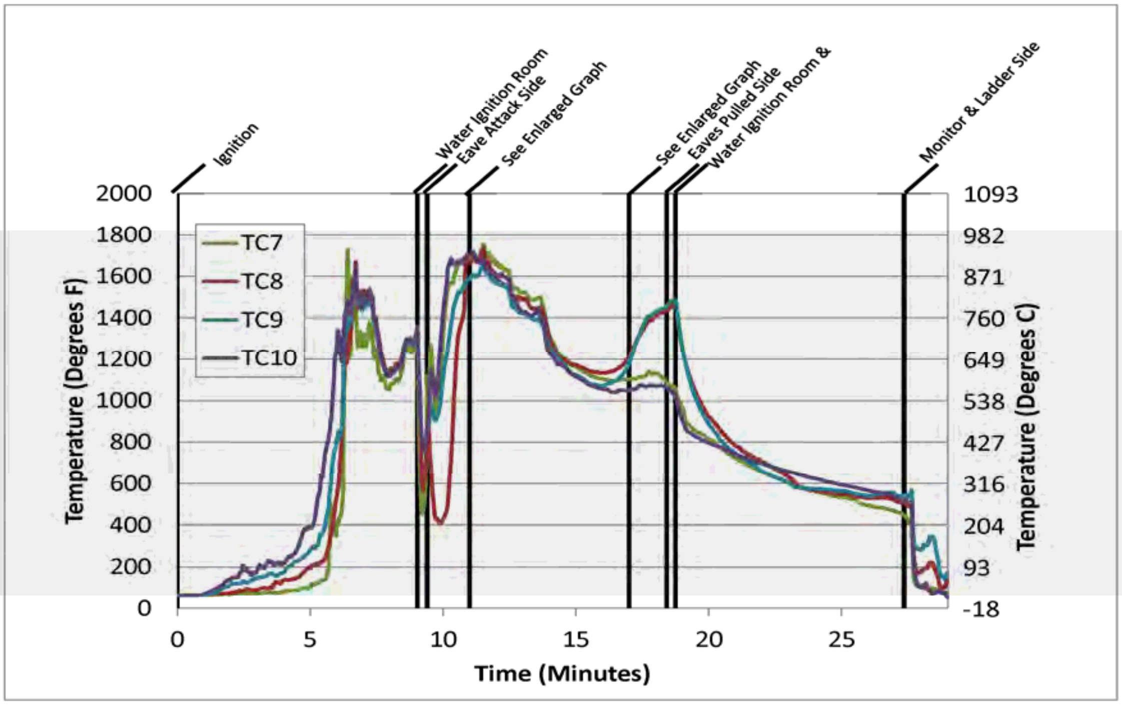


Figure J. 49: Second Floor Bedroom Temperatures

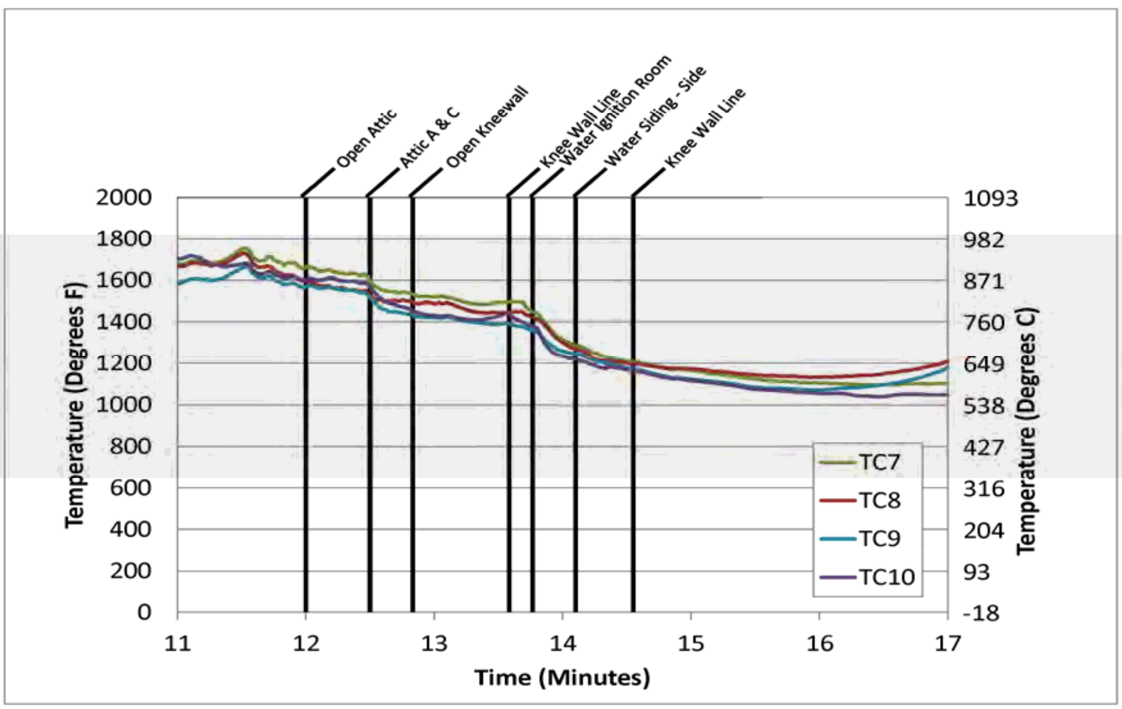


Figure J. 50: Second Floor Bedroom Temperatures (from 11 to 17 min)

Experiment 3 (3378 N 25th Street)

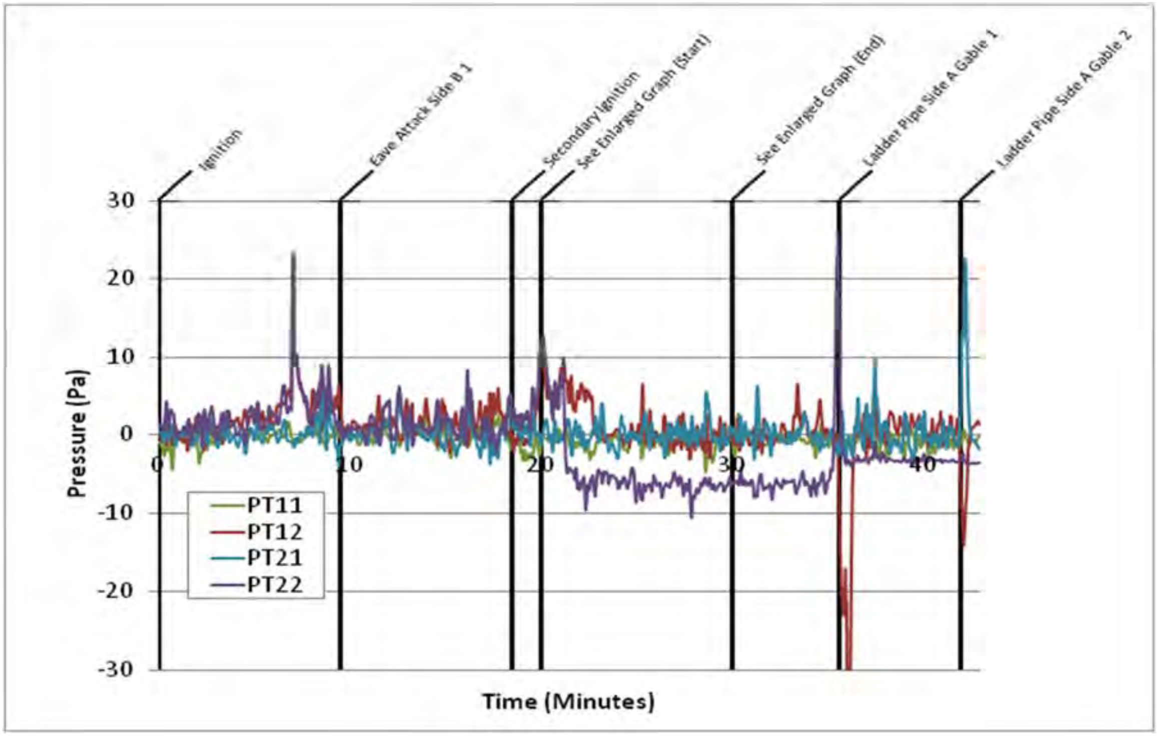


Figure J. 51: Pressure Measurements

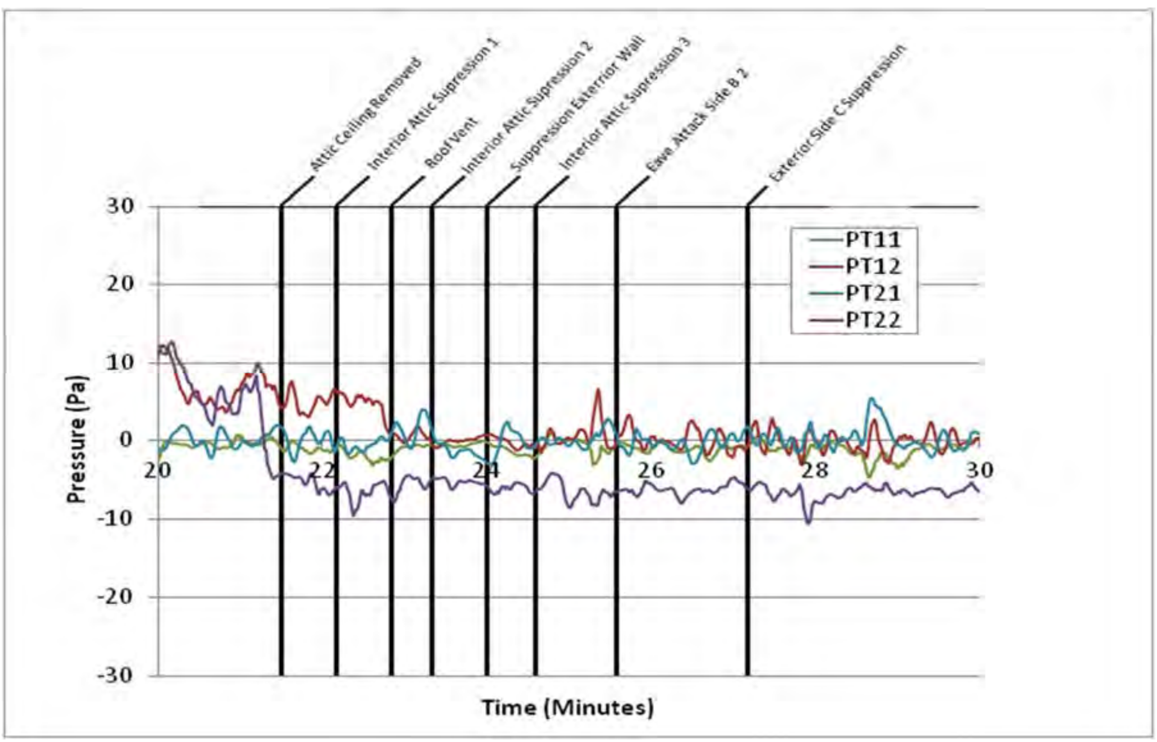


Figure J. 52: Pressure Measurements (from 20 to 30 min)

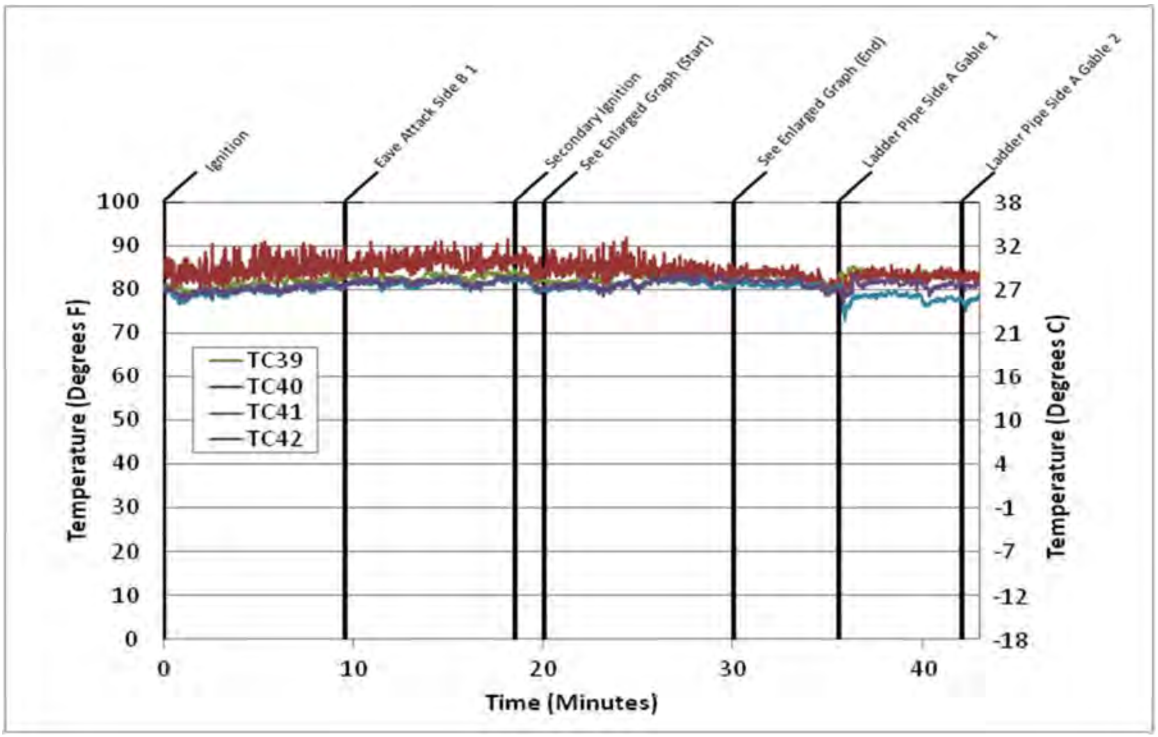


Figure J. 53: Stairwell Temperatures

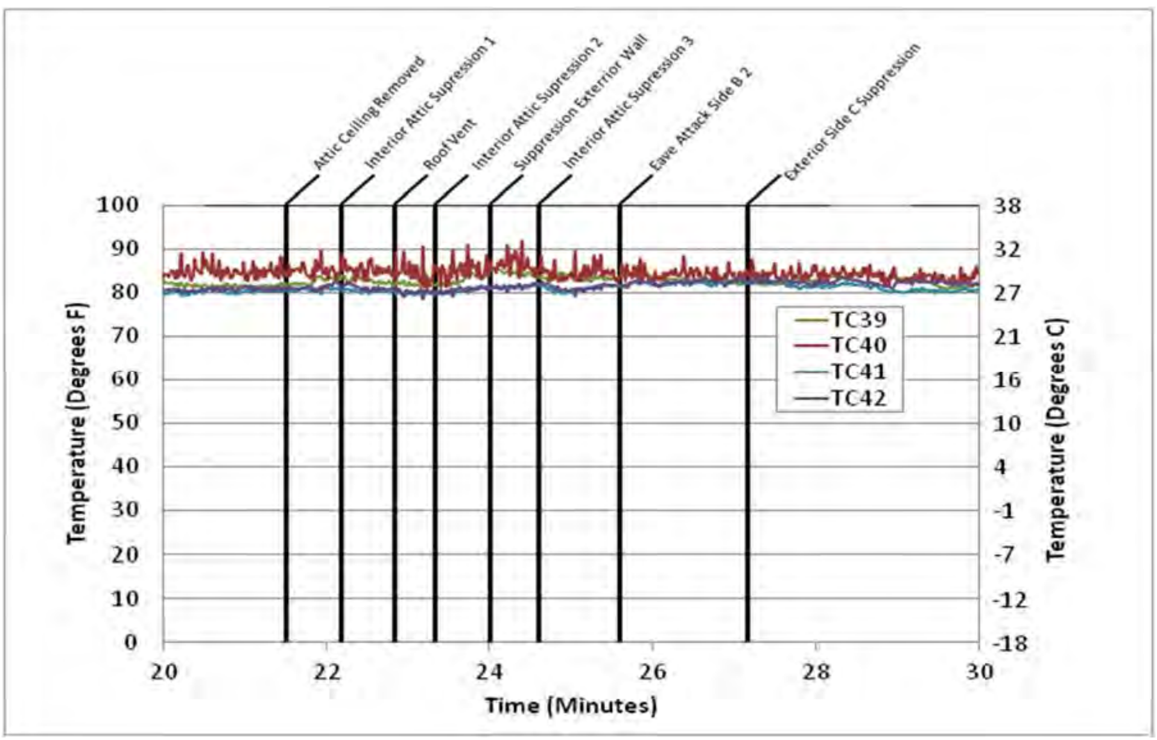


Figure J. 54: Stairwell Temperatures (from 20 to 30 min)

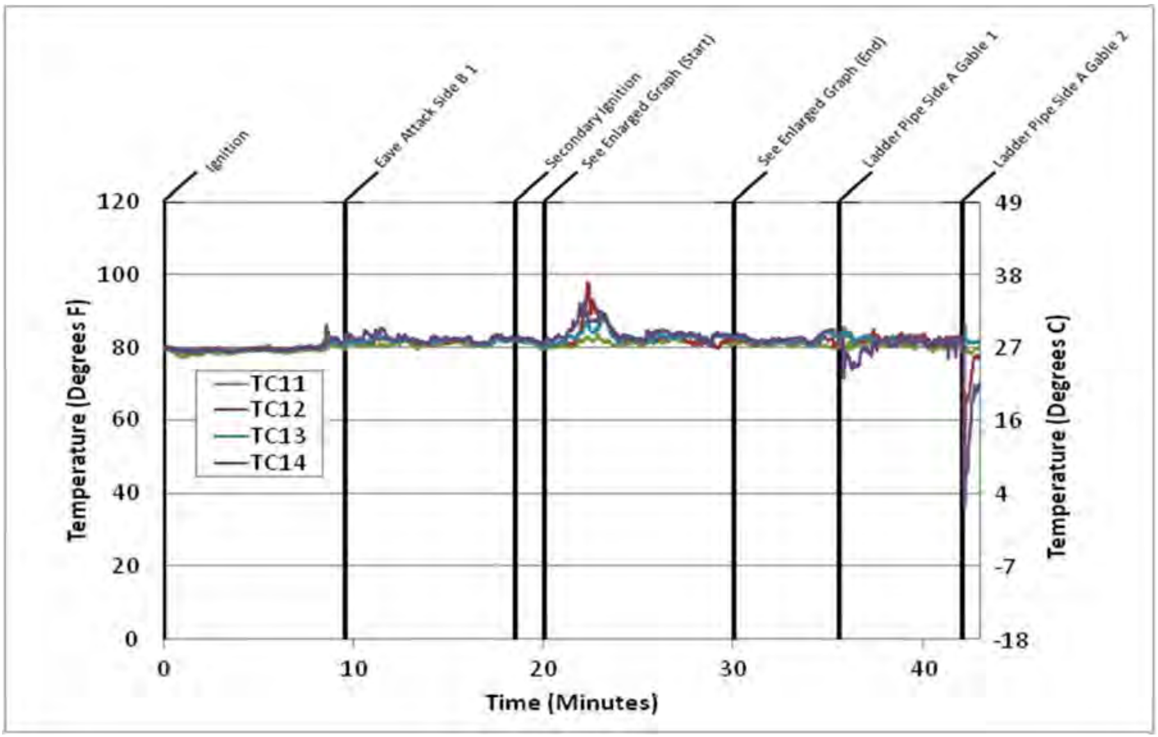


Figure J. 55: Entrance Area Temperatures

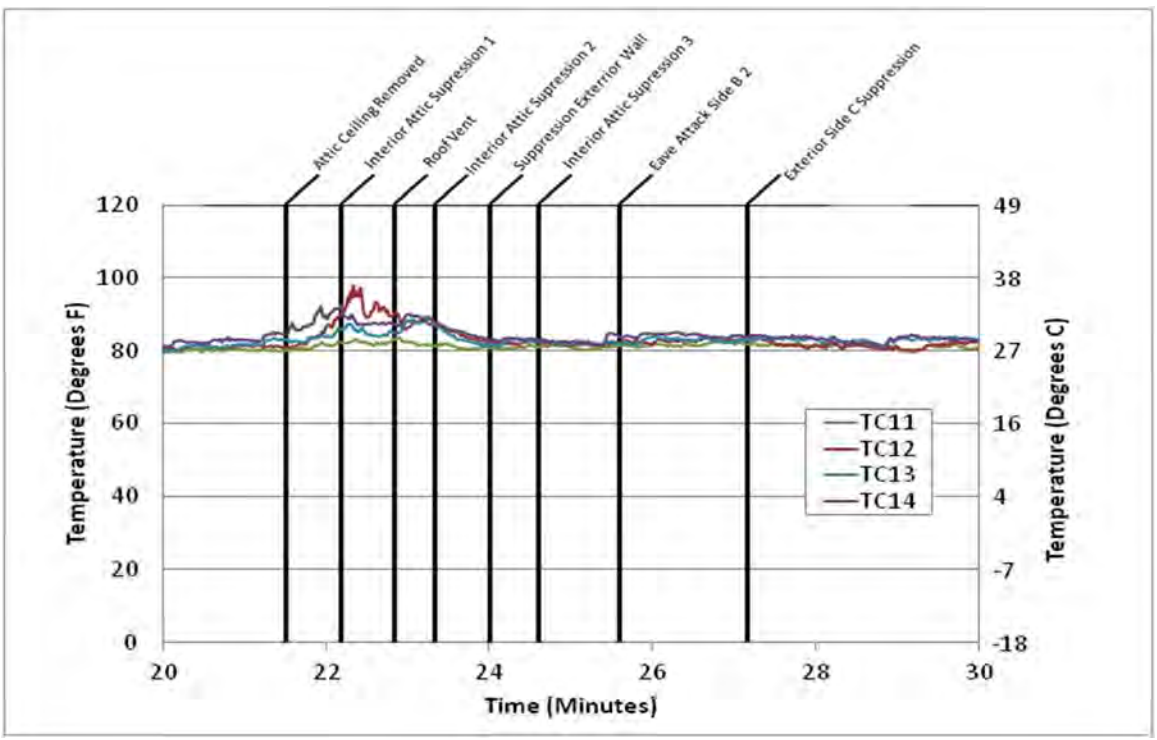


Figure J. 56: Entrance Area Temperatures (from 20 to 30 min)

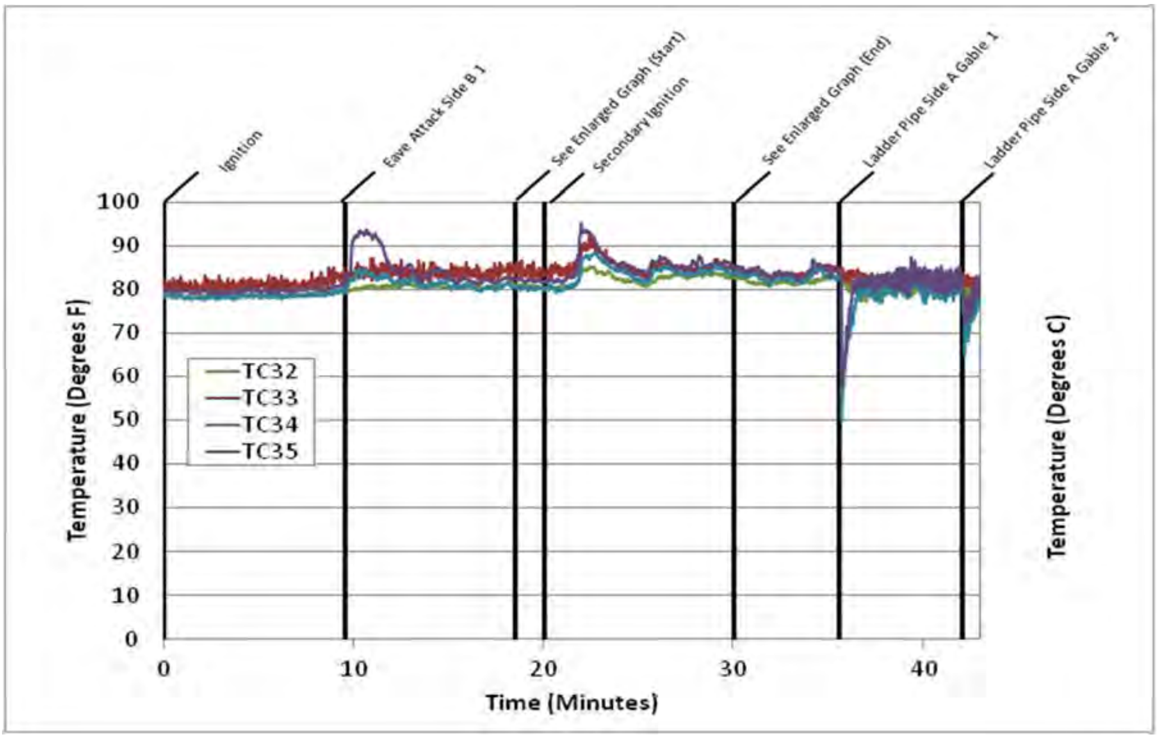


Figure J. 57: Den Temperatures

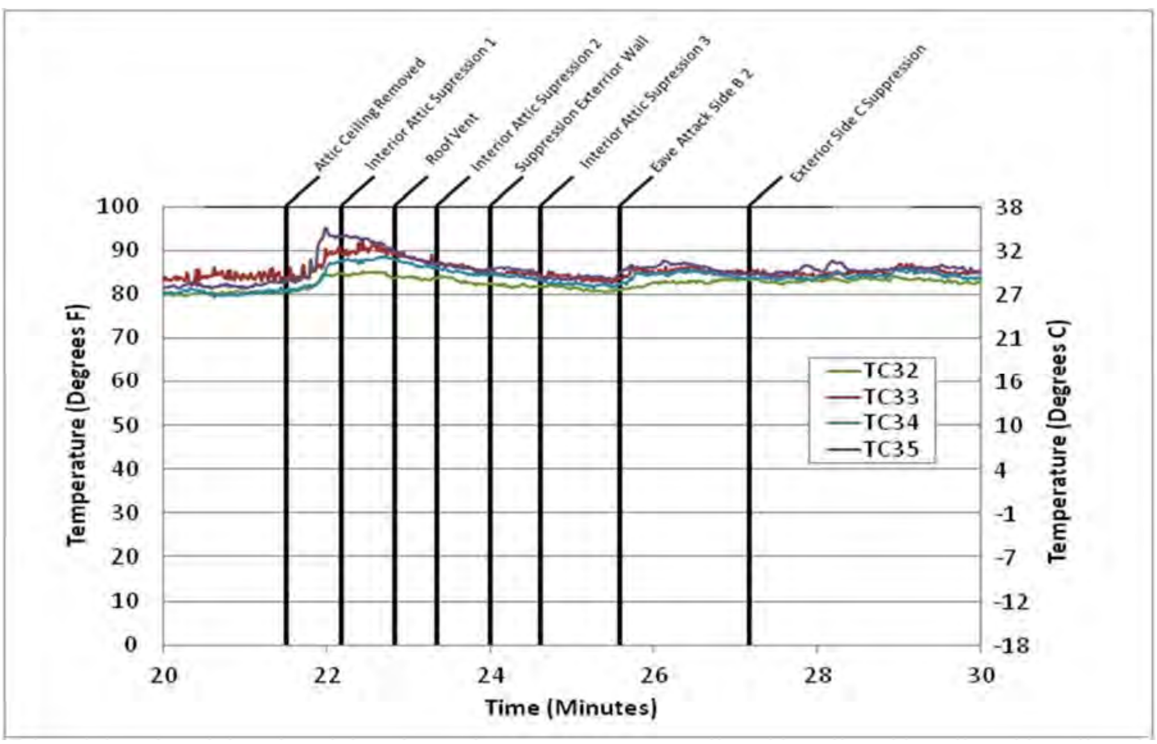


Figure J. 58: Den Temperatures (from 20 to 30 min)

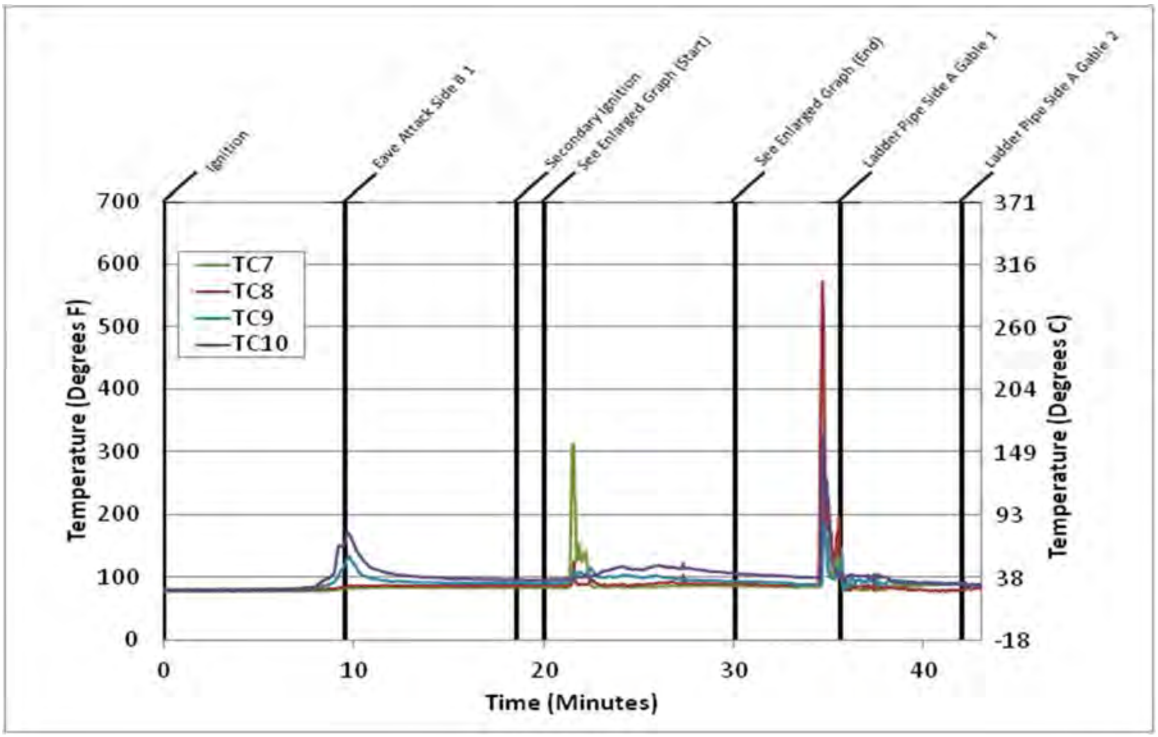


Figure J. 59: Bedroom 3 Temperatures

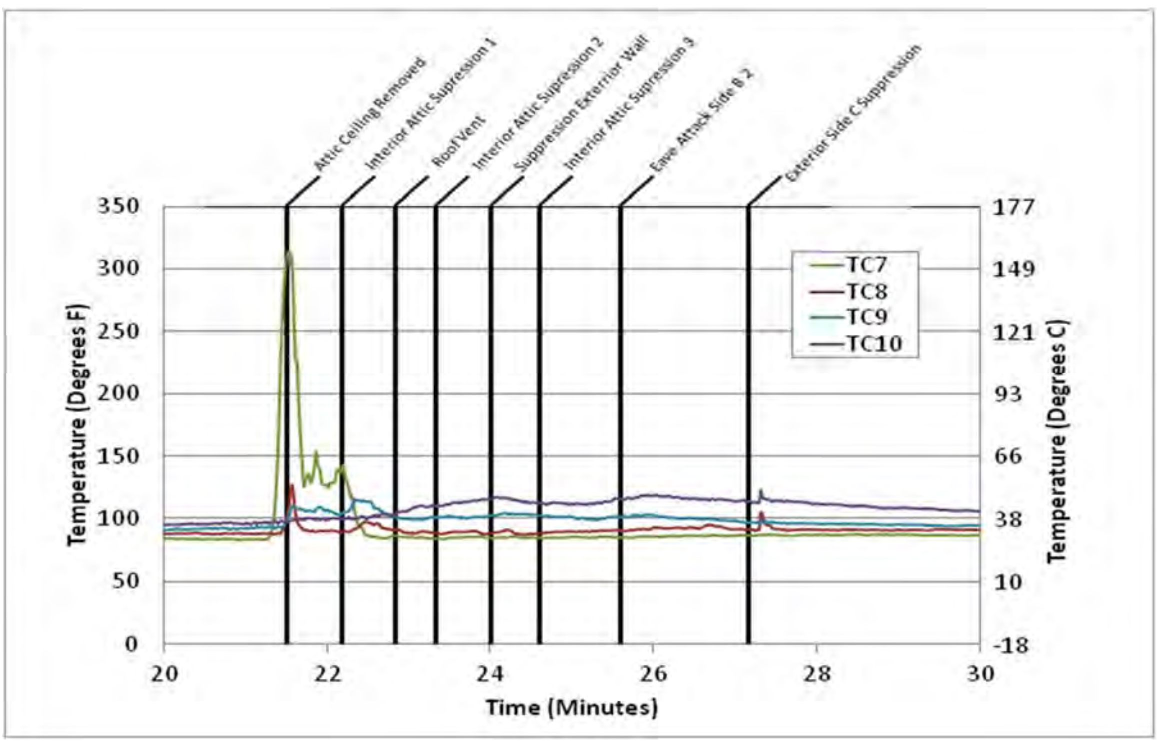


Figure J. 60: Bedroom 3 Temperatures (from 20 to 30 min)

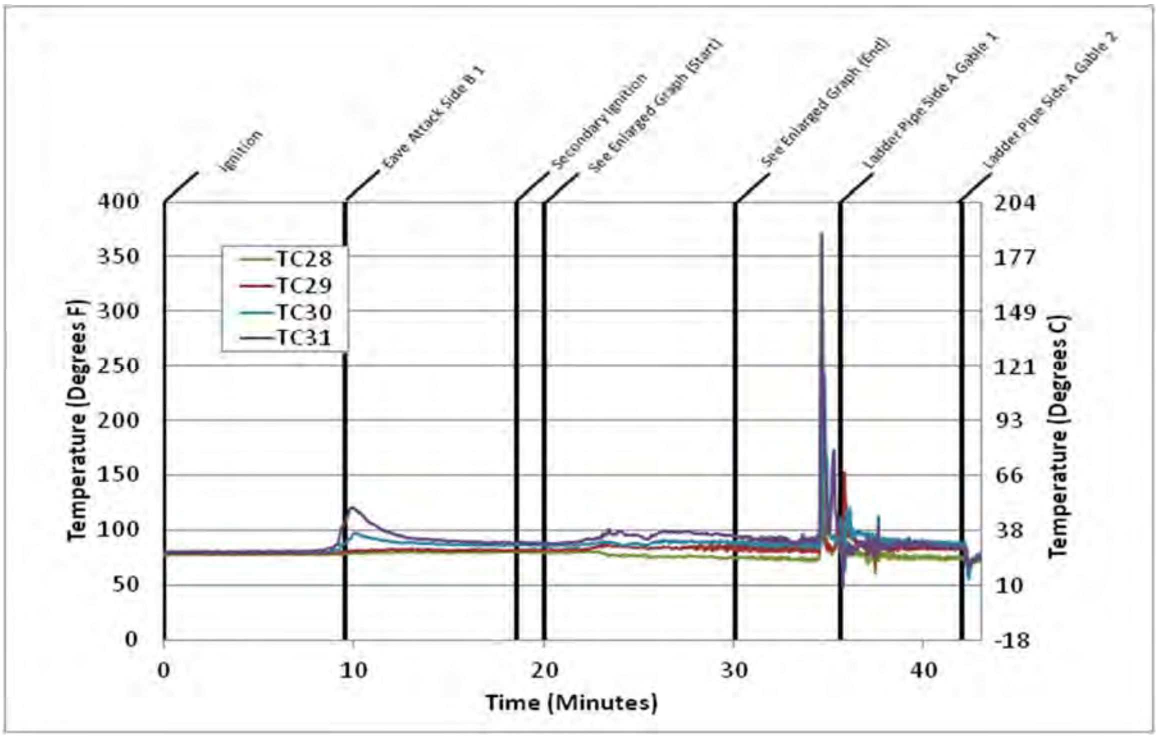


Figure J. 61: Bedroom 2 Temperatures

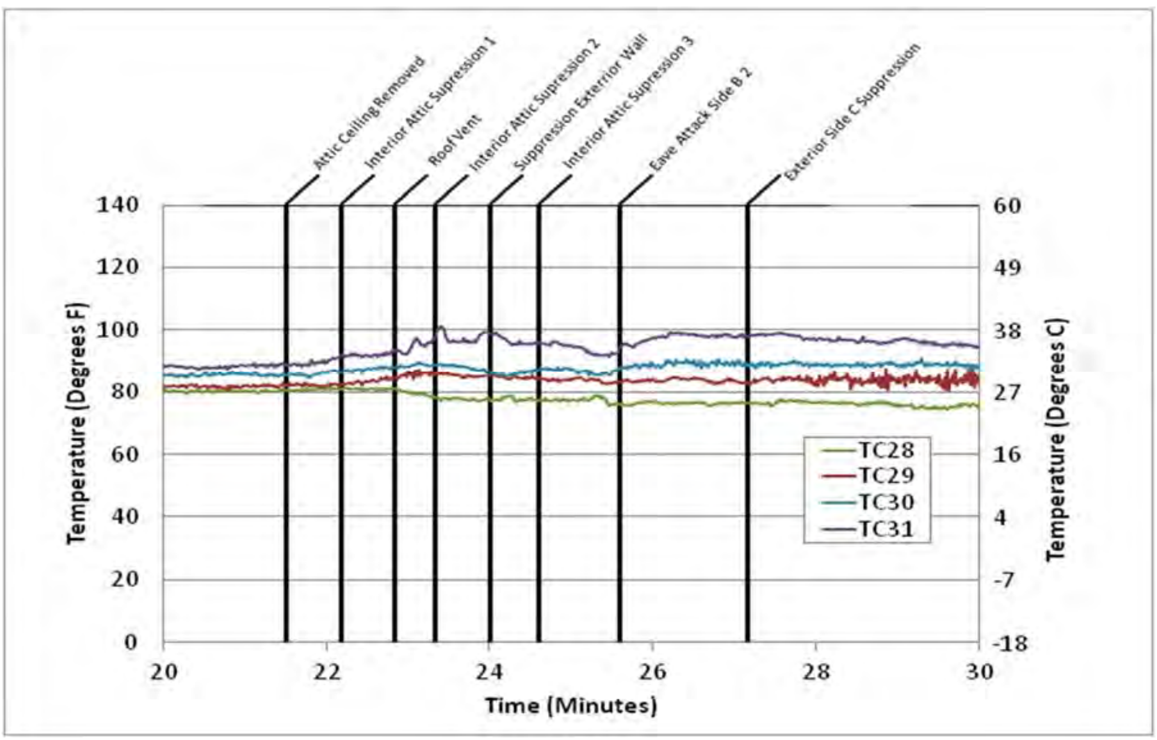


Figure J. 62: Bedroom 2 Temperatures (from 20 to 30 min)

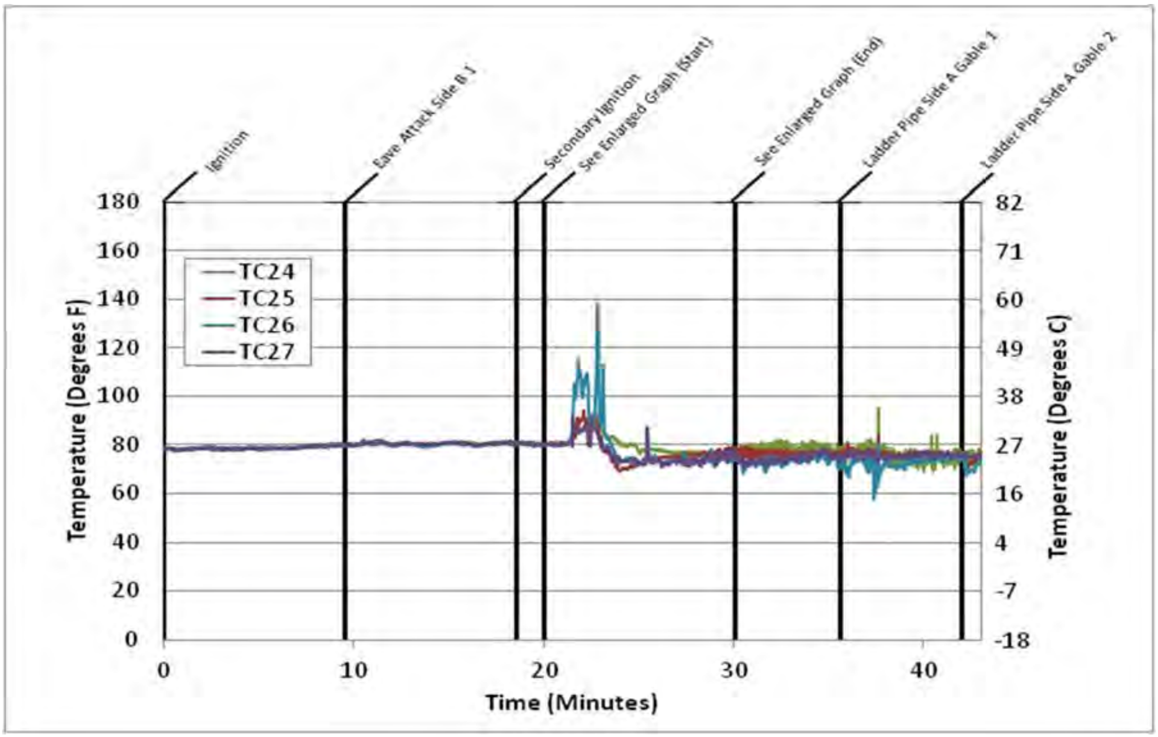


Figure J. 63: Bedroom 1 Temperatures

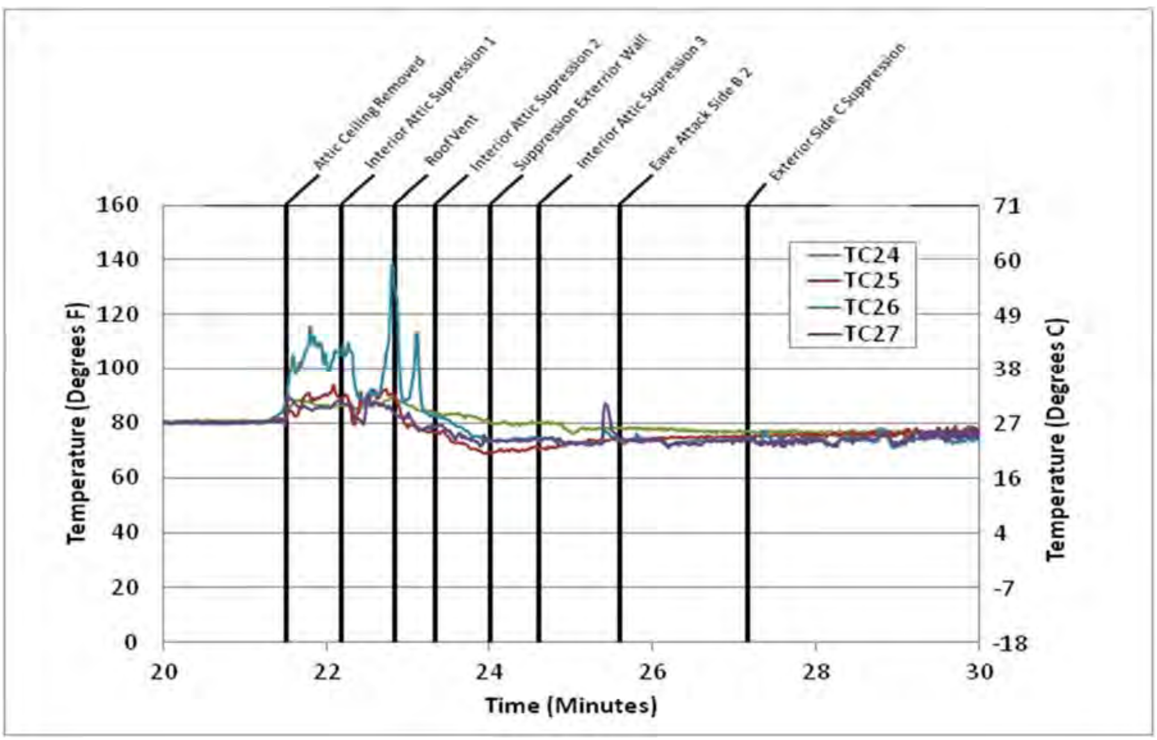


Figure J. 64: Bedroom 1 Temperatures (from 20 to 30 min)

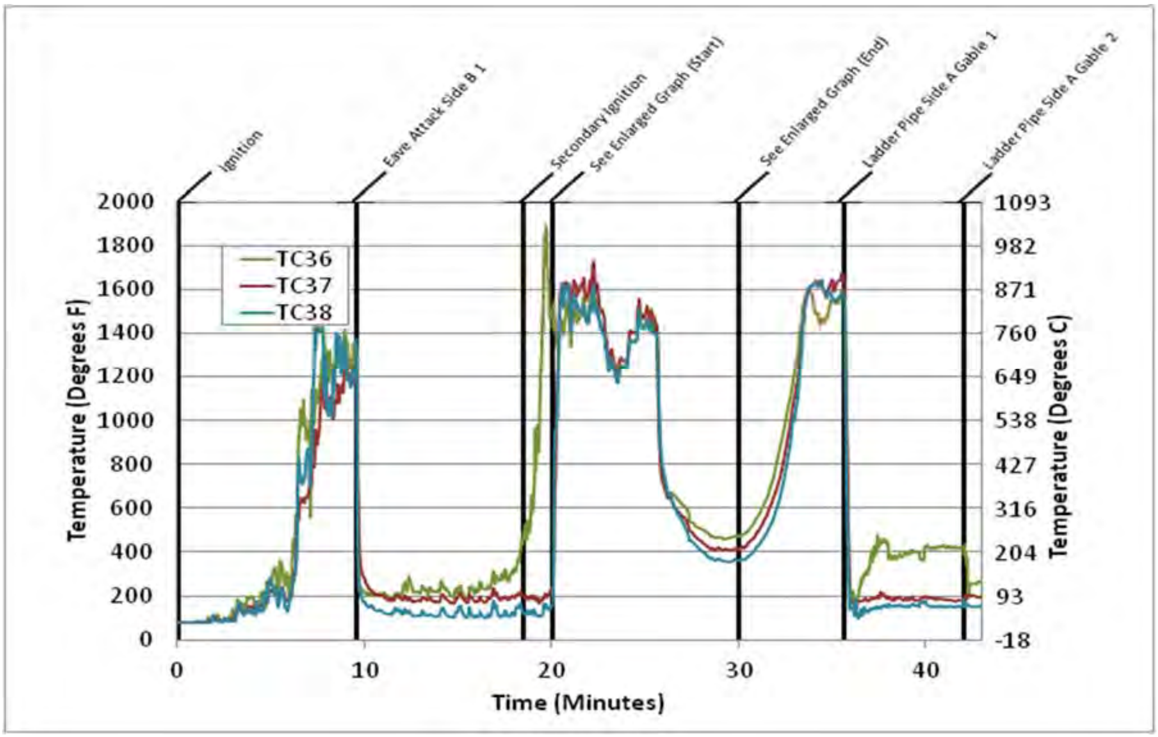


Figure J. 65: Joist Bay Temperatures

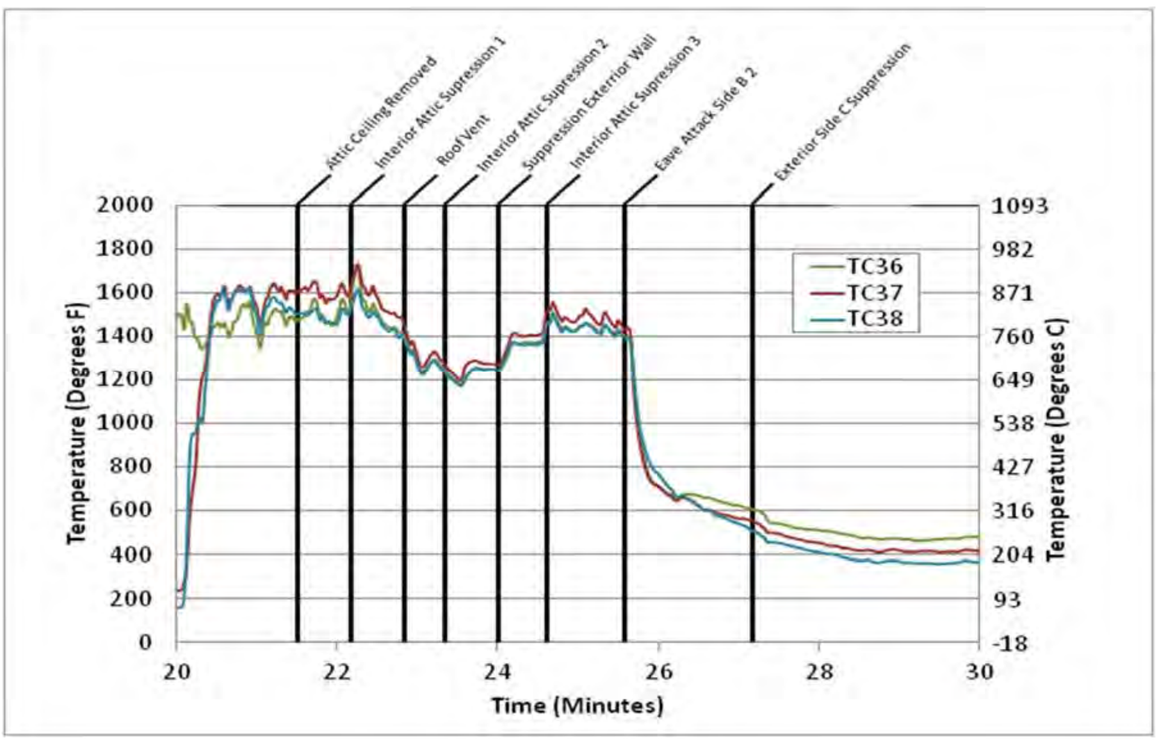


Figure J. 66: Joist Bay Temperatures (from 20 to 30 min)

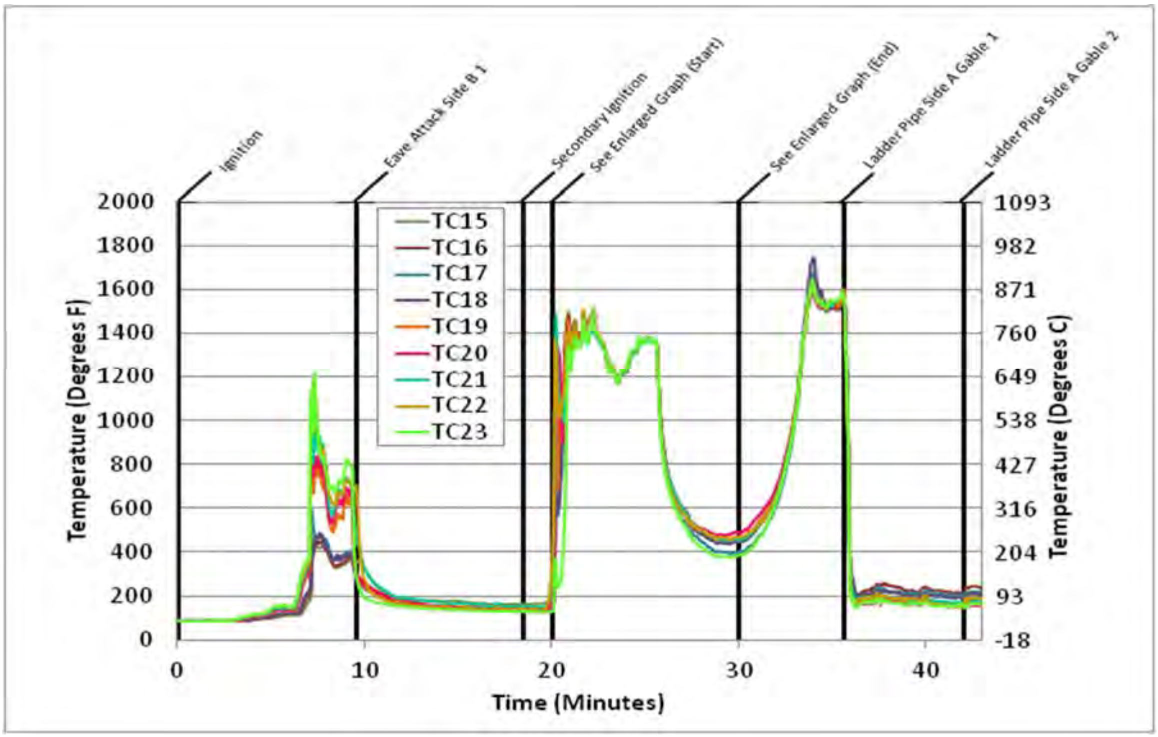


Figure J. 67: Attic Space Temperatures 1 Ft. above second story ceiling

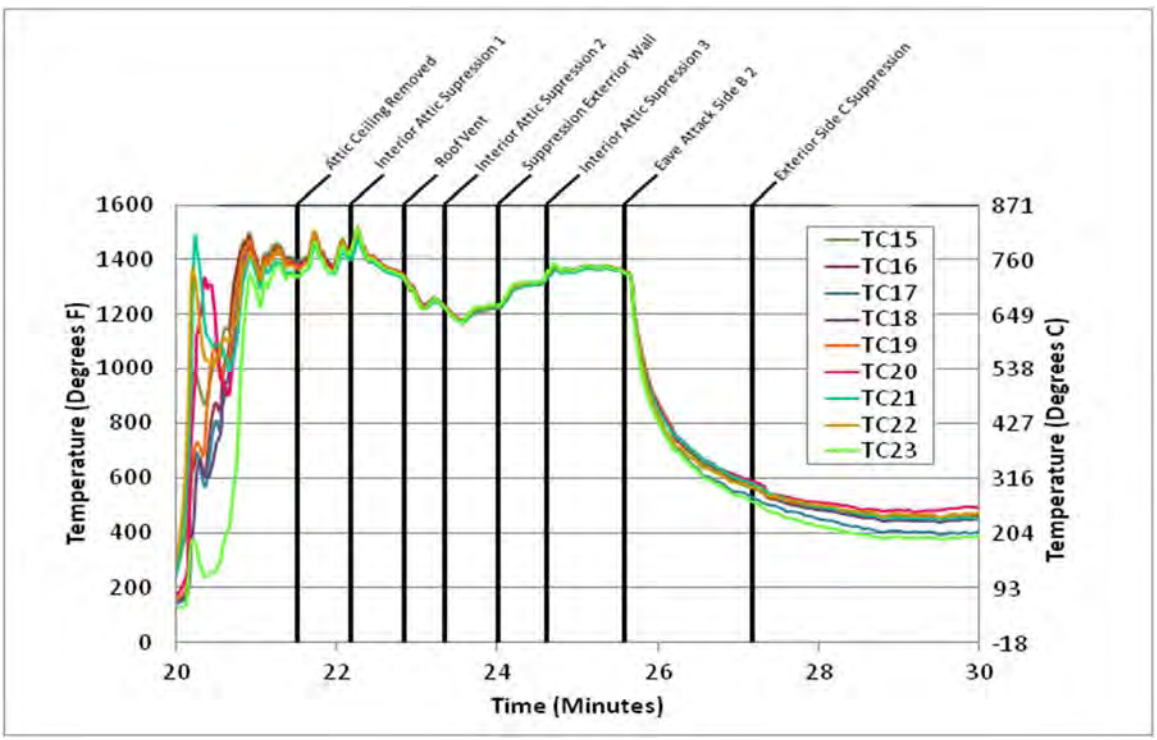


Figure J. 68: Attic Space Temperatures 1 Ft. above second story ceiling (from 20 to 30 min)

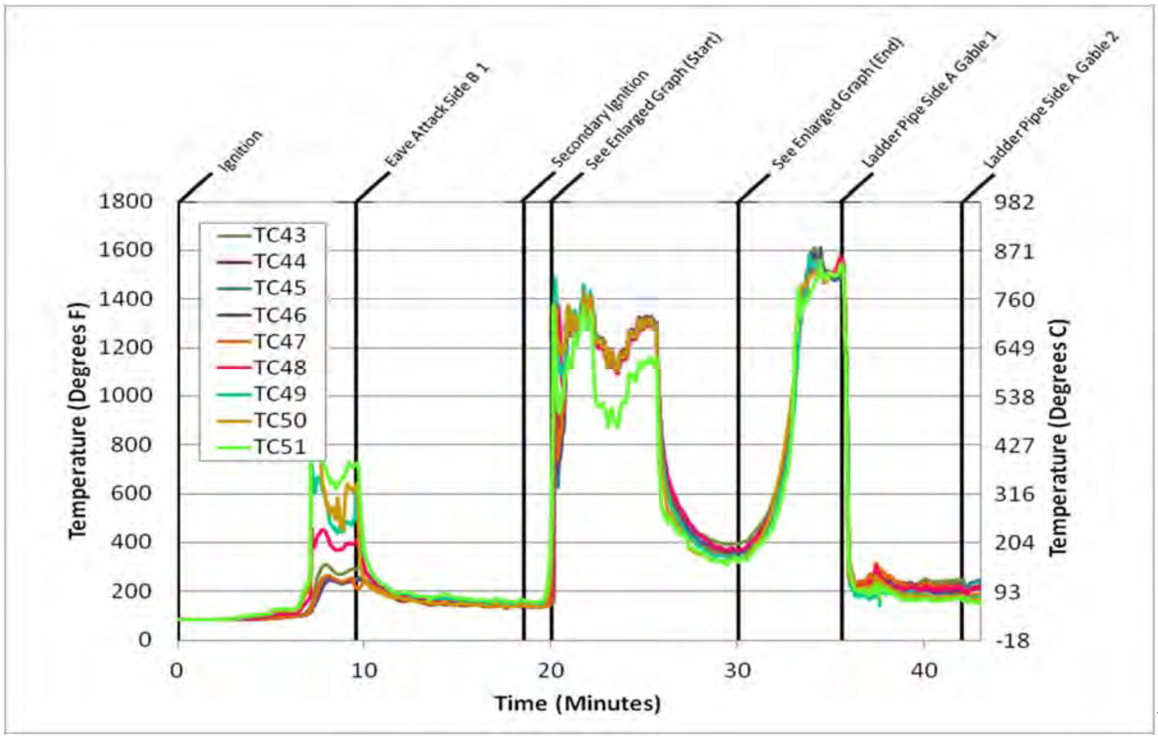


Figure J. 69: Attic Space Temperatures 1 Ft. below roof

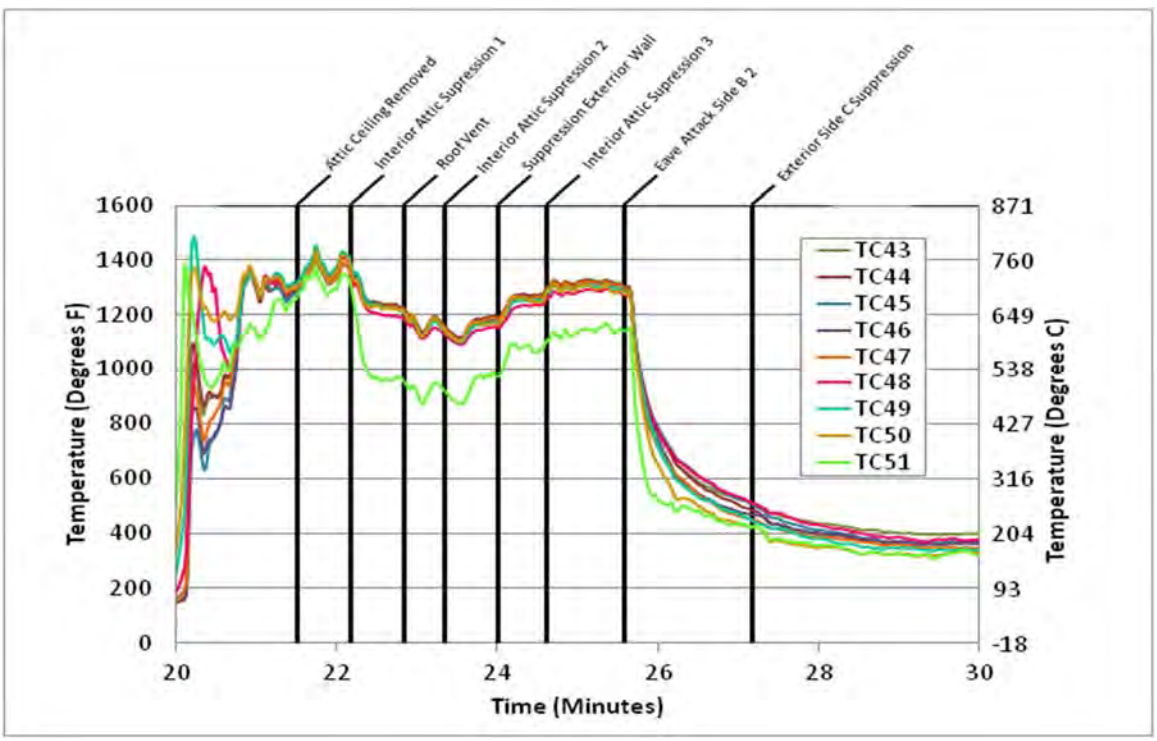


Figure J. 70: Attic Space Temperatures 1 Ft. below roof (from 20 to 30 min)

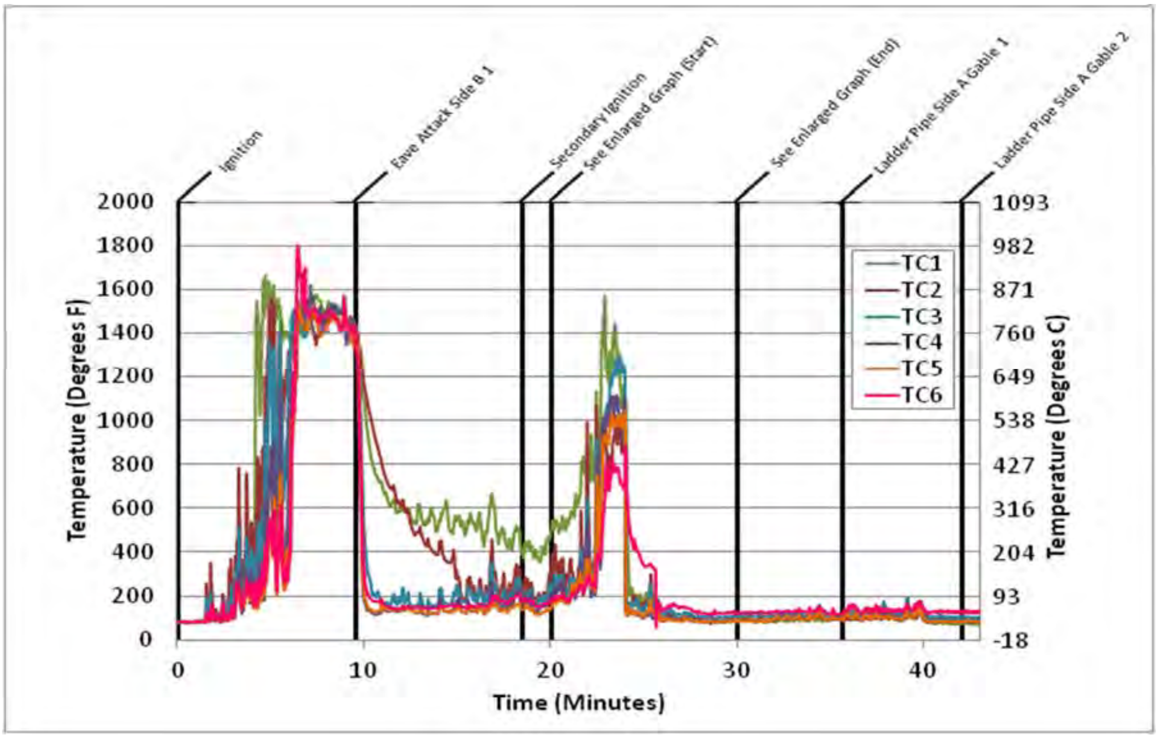


Figure J. 71: Exterior Siding Temperatures

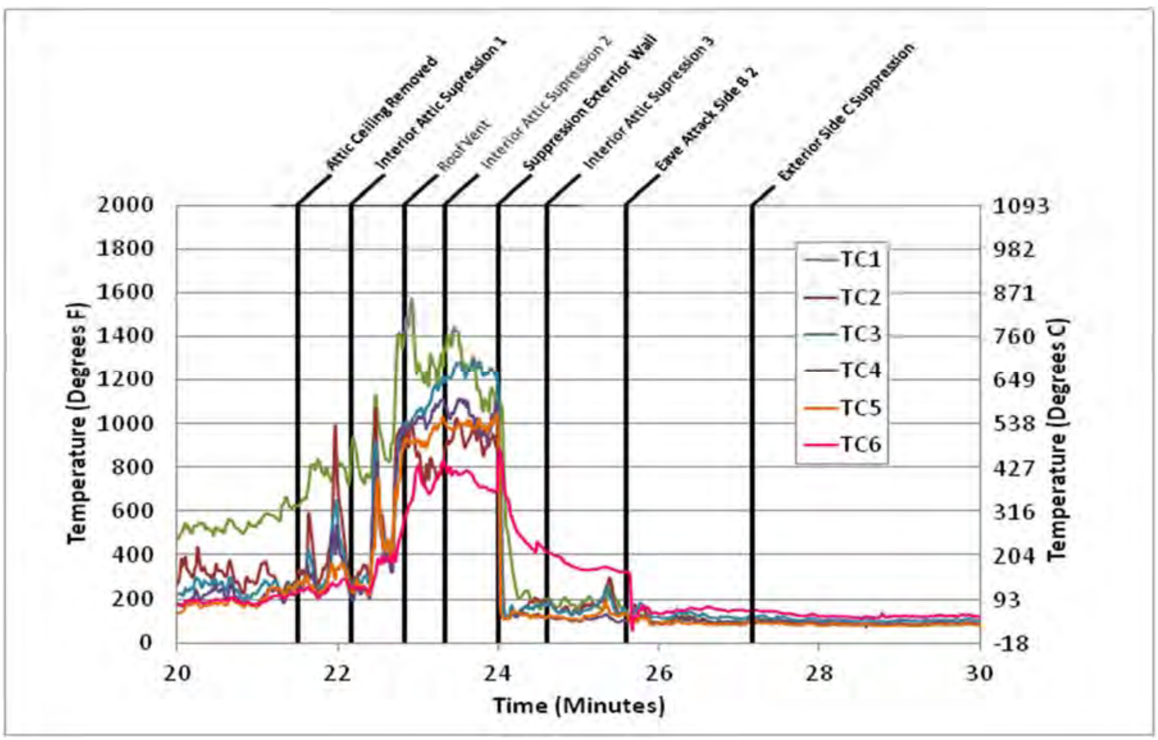


Figure J. 72: Exterior Siding Temperatures (from 20 to 30 min)

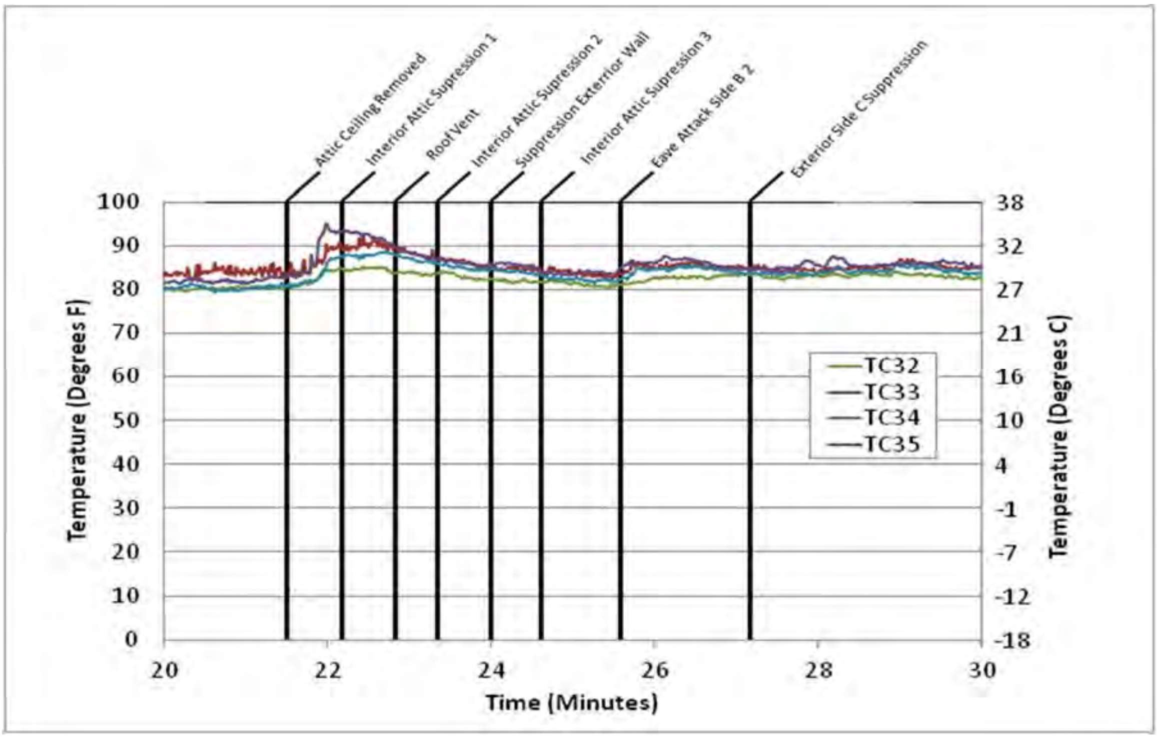


Figure J. 73: Den Temperatures (from 20 to 30 min)