RESEARCH AND DEVELOPMENT REPORT

Evaluation of Flame Propagation of Retrofit Energy Efficient Wall Assemblies

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Notice

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Introduction

The US Department of Energy (DOE) funds research grants every year to study advancements in energy efficiency and renewable energy. Their Building Technologies Office specifically "develops, demonstrates, and accelerates the adoption of cost-effective technologies, techniques, tools and services that enable high-performing, energy-efficient and demand-flexible residential and commercial buildings in both the new & existing buildings markets, in support of an equitable transition to a decarbonized energy system by 2050, starting with a decarbonized power sector by 2035 [1]." These efforts have led to significant improvements in residential building technologies. The fire performance of these some of these technologies has been identified as an area where further research is needed [2] [3]. With the increased interest in retrofitting existing residential buildings comes the potential for increased risk of exterior fire spread into the structure and structure-to-structure fire spread, both in wildland urban interface (WUI) and urban settings.

Typically, local authorities having jurisdiction (AHJ) adopt model building codes, such as the International Building Code (IBC), Residential Building Code (IRC), and National Fire Protection Association (NFPA) 5000 "Building Construction and Safety Code" to regulate building construction. The IBC and NFPA 5000 require exterior wall assemblies be tested to NFPA 285, "*Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components* [4]." However, the application of this test method is mainly limited to exterior combustible wall assemblies applied to Types I through IV buildings greater than 40 ft. in height, leaving a gap for buildings less than 40 ft. in height, typical wood frame buildings (Type V), and residential buildings.

With the increase in construction in the wildland urban interface (WUI) and changes in building materials, wildfires have become increasingly destructive and costly [5]. The need for fire testing requirements for residential exterior wall assemblies in combination with quickly advancing building technologies and growing threat of wildfires led to the development of several test methods and protocols addressing fire performance of building materials. One example is the creation of ASTM E2707, "*Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure*. [6]" The standard was first published in 2009 and includes a test method to evaluate a wall assembly's resistance to fire penetrating the wall cavity from the exterior.

In 2012, UL Firefighter Safety Research Institute (FSRI) released a study entitled, "Study of Residential Attic Fire Mitigation Tactics and Exterior Fire Spread Hazards on Firefighter Safety." The intent of this study was to provide the fire service with the science necessary to examine their standard operating procedures utilized during attic fires. The study showed that fire could quickly propagate (spread) up the exterior of the walls and into the attic space through the eaves [7]. In consideration of these findings, code development discussions ultimately led to ASTM Committee E05.14 – External Fire Exposures committee work towards a new test method to address vertical fire propagation on exterior, residential walls. The new test method would be based on a modified version of ASTM E2707.

Leveraging safety science experience and industry relationships, UL Solutions and the International Association of Fire Fighters (IAFF) initiated a joint project in 2022 under an agreement with the US Department of Energy to evaluate the flame propagation of retrofit energy efficient wall assemblies. A draft of the protocol from the ASTM work was used to test and comparatively study various retrofit energy efficient designs to gain a better understanding of their fire behavior. The goals of this study were as follows:

- Develop an understanding of fire propagation across new, cost effective, and energy efficient exterior retrofit wall assemblies.
- Refine the flame propagation draft test method for exterior wall assemblies based on ASTM E2707.
- Identify conditions that create fire propagation hazards in exterior wall assemblies and educate the fire service on the findings.

1. Background

1.1. The Codes – IBC, IRC and NFPA 5000

Requirements for exterior fire propagation of building construction can be found in the IBC and NFPA 5000. There are five types of construction within the IBC and NFPA 5000: Type I, Type II, Type III, Type IV, and Type V. These were formerly referred to as Fire Resistive, Non-Combustible, Ordinary, Heavy Timber, and Wood-frame. The building types generally start with the most fire resistive construction and progress to the least fire resistive. Types I through IV specifically require wall assemblies to be tested to the fire tests in NFPA 285 given the conditions outlined in Figure 1. Type V construction is not specifically addressed in either code for this purpose. The majority of one- and two-family dwellings are under 40 ft in elevation, and these constructions are addressed in the International Residential Code, which also does not require NFPA 285.

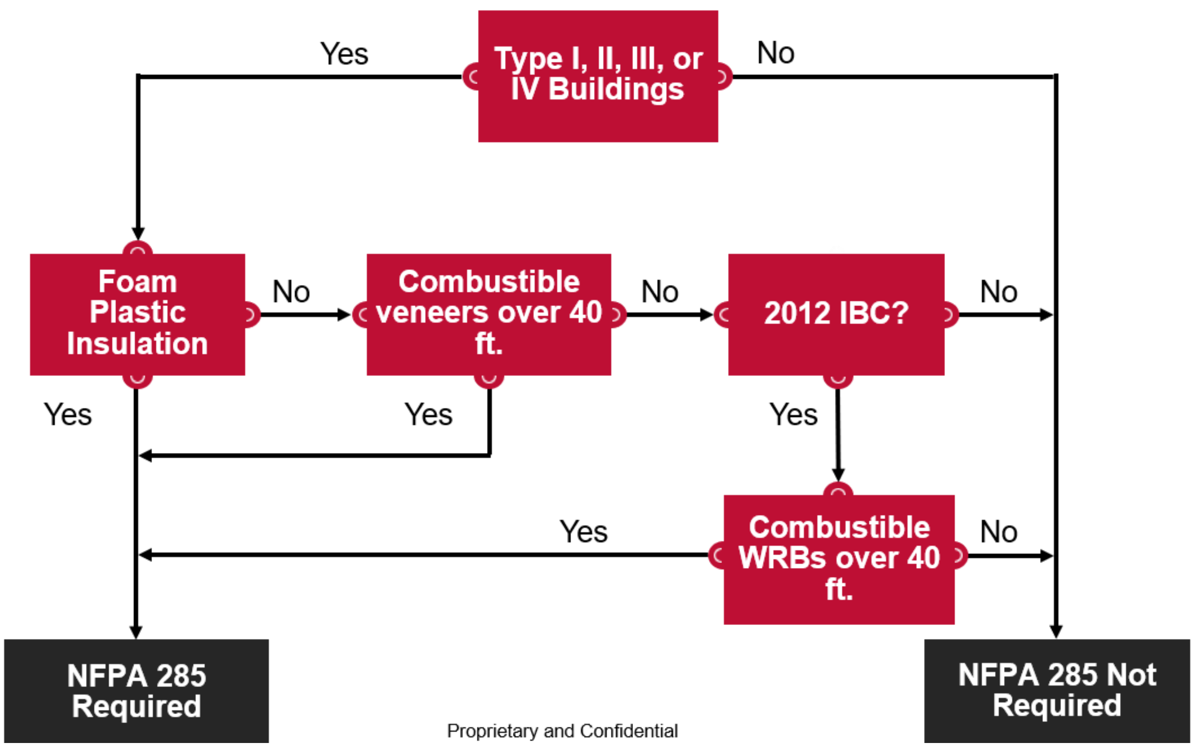

Figure 1 - Wall Assembly Conditions Requiring Testing to NFPA 285

1.2. More on NFPA 285

NFPA 285 is a test method used to evaluate fire spread across vertical exterior wall assemblies containing combustible materials intended to be used in building construction. According to NFPA, "in the late 1970s, the use of foam plastic insulation and other combustible materials in exterior, non-load-bearing walls on noncombustible construction (typically Types I, II, III, and IV) was proposed. [8]" Concerns were voiced about the fire spread potential for the materials. A study of several wall assemblies was funded by the Society of Plastics Industries. They successfully demonstrated the fire resistance of several of the industry's plastic wall assemblies [8]. A two story building was constructed with the wall assemblies on two sides and an open window and wood crib in the lower compartment. The wood crib was ignited and fire spread out the window. This was the basis of the NFPA 285 test method.

The test apparatus is a two level structure. Two gas burners are used, one inside the first story room and the other near the top of the window opening. The wall test specimens are secured in a movable, steel test frame for testing. The specimens are at least 17 ft 6 in. high and 13 ft 4 in. wide and contain a 30 in. tall and 78 in. wide window opening at the first floor level. The samples are secured to the front of the two story test apparatus. Temperature is measured on the exterior wall surface, combustible insulation, cavity air space, wall and stud cavity insulation, and interior surface of the test specimen as applicable. Temperature is also measured inside the first and second story test rooms.

The test procedure is to ignite the test room burner. Five minutes later, the window burner is ignited. Thirty minutes later the burner are turned off. During the entire test duration, the assembly shall not spread flames "vertically or horizontally beyond the area of flame plume impingement by the window burner flames" or vertically or horizontally "through the combustible components or the combustible insulation installed within the test specimen" as verified by limits on the tempertures measured on and in the test specimen [8]. Additonally, temperatures cannot exceed 500°F (278°C) above the ambient air temperature an inch into the second story opening, "flames shall not occur in the second story test room", and "flames shall not occur beyond the intersection of the test specimen and side walls of the test apparatus. [8]"

Photographs of the test are provided below in Figure 2.

The NFPA 285 test method was designed to replicate the post flashover fires of interior origin. The size, configuration, and severity of the test conditions is not representative of a typical ignition of the exterior of residential one- and two- family homes.

Figure 2 - Photographs of NFPA 285 Tests

1.3. ASTM E2707

ASTM E2707, *Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure*, was first published in 2009. The "test method was developed in response to recommendations developed by the California Office of the State Fire Marshal (SFM) and the International Wildland-Urban Interface Code (IWUIC) regarding the enhancement of exterior fire protection of structures in a wildland fire (exterior wildfire exposure). [6]" The intent of the test was to create a method to evaluate a wall assembly's resistance to fire penetration from an ignition source representative of the items expected to initiate fire spread to and between residential structures - "plants, trash, a deck or shed, etc. [6]" It was anticipated that a fire at the base of an exterior wall would burn "into the wall cavity (directly or indirectly through the wall assembly, or through seams) and then into the building. For non-combustible cladding, the major concern is conductive heat transfer through the wall cavity that can ignite studs or other wall cavity materials. Also, for materials having seams, there is a possibility of penetration via these openings. [6]"

The test method defines the test specimen to be 4 ft (1.2 m) by 8 ft (2.4 m) in size. The fire source is a slotted gas burner set to 150 kW placed at the bottom of the test specimen such that the flame can impinge on the exterior of the test specimen. The specimen is exposed to the fire for 10 minutes. The test specimen is observed for the absence of flame penetration through the wall assembly & absence of glowing combustion on the interior surface at the end of the 70-minute test (1 hour observation period).

This test method was based on testing conducted by the Forest Products Fire Research Laboratory. The heat release rate (HRR) or fire size of 150 kW was intended to represent ornamental plants and the 10-minute exposure was intended to simulate the time necessary for a wildfire to pass the structure [6]. The ASTM standard committee believed an additional hour was needed to detect smoldering combustion, which can reignite the assembly after a fire appears to be extinguished [6].

A photograph of the test method is shown in Figure 3.

The test method is designed to evaluate fire penetration into an exterior wall. It does not, however, evaluate fire propagation (spread) vertically up the wall or horizontally across the wall.

Figure 3 - Photograph of ASTM E2707 Test

1.4. UL FSRI "Study of Residential Attic Fire Mitigation Tactics and Exterior Fire Spread Hazards on Fire Fighter Safety"

In consideration of the concerns of vertical fire spread, UL FSRI conducted a study on the fire spread of exterior walls into residential attic spaces as it relates to fire fighter safety.

Attic fires are challenging for the fire service to fight. Attic spaces can hide the presence and extent of building fires [9]. In 2019, 29.9% of reported fires occurred on residential property [10]. The U.S. Fire Administration (USFA) states that "Residential is the leading property type for fire deaths (72.2%), fire injuries (76.4%) and fire dollar loss (46.4%). [10]" In a study of attic fire statistics, USFA identified that between 2006 and 2008, "An estimated 10,000 residential building attic fires are reported to U.S. fire departments each year and cause an estimated 30 deaths, 125 injuries, and $477 million in property loss. [11]" In the same study, it was revealed that 99.2% of residential attic fires were non-confined and spread beyond the local area of ignition. Similarly, in NFPA's research report entitled Residential Structure Fires Originating on Outer Walls, Spreading on Exterior Walls or Trim, and Beginning on an Outer Wall with Plastic, there was a documented annual average of 7,645 residential fires that spread on exterior wall surfaces causing 50 casualties, 345 injuries and $539M in property damage [12].

In 2010, UL FSRI received a two-year grant from the Department of Homeland Security's Assistance to Firefighters grant program "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. [7]" In the study researchers looked at exterior fire spread up different exterior wall assemblies, fire spread from exterior fires into attic spaces, fire development in attic spaces, and fire spread through knee wall spaces to the attic.

The fire challenges posed by residential attic and building construction identified in the report are:

- Attic fires are slow to be detected because attics are usually unoccupied. Attic fires are often detected when smoke or fire is seen from the exterior of the building.
- The attic ventilation system is intended to pull fresh air into the attic to reduce moisture but in a fire, it can draw smoke, hot gases, and fire into the attic space.
- An attic fire can degrade the ceiling enough to cause collapse, potentially on occupants or firefighters.
- An attic fire can degrade the roof structure enough to cause collapse, potentially on firefighters working on or under the roof.
- Design features such as knee walls and collar ties leave openings for fire to spread into attic spaces.
- The average home size has increased by 1,000 ft^2 between 1970 and 2010, meaning that there is more oxygen available to fuel the fires.
- Older homes tend to have one, continuously open attic spaces. There are no walls to block fire spread.
- Newer homes attics are built with trusses constructed with smaller lumber. This creates a complicated web of lumber to navigate through to locate a fire.
- Energy efficiency efforts has led to increasing use of new technologies, for example foam insulation, that has the potential to be more flammable than traditional materials.
- Between 2006 and 2012, the minimum R value required by the International Energy Conservation Code for wood frame walls has increased. The increased minimum R value is often met by using a layer of foam insulation board.

The research testing was conducted in four parts – Wall Experiments, Eave Experiments, Full Scale Attic Experiments, and Knee Wall & Attic Field Experiments. The Wall Experiments were a series of 32 fire experiments with 13 different 8 ft by 8 ft (2.4 m by 2.4 m) exterior wall assemblies constructed of common building materials. The Eave Experiments consisted of three fire tests of structures built to simulate an exterior wall and attic space with eaves. The Full Scale Attic Experiments were four fire tests initiated in the attic space of a mock house. The Knee Wall & Attic Field Experiments were three fires tests conducted in acquired, vacant homes with knee wall spaces in Milwaukee, WI in partnership with the Milwaukee Fire Department.

Photographs of the structures burned are provided in Figure 4 – Figure 7.

The tactical considerations for firefighters as excerpted from the report are as follows:

- Increased use of plastics in exterior walls will change what [fire] you arrive to
    - Exterior walls ignite more readily
    - Exterior wall fires spread more rapidly
    - Exterior fires can easily become structure fires prior to [firefighter] arrival
    - Exposure to adjacent structures occurs prior to [firefighter] arrival
- If the fire starts on the outside, start fighting it from the outside.
- Learn to anticipate where and how an exterior fire will migrate to the interior
- Attic fires are commonly ventilation-limited [fuel rich and oxygen deprived] fires
- Closely time or limit vertical ventilation [an opening in the roof to vent smoke and hot gases] until water is in the attic.
- Plastic ridge vents can affect [firefighter] size-up [of the structure and fire upon arrival] and fire dynamics
- Wetting sheathing with an eave [hose line] attack slows attic fire growth
- Attic construction affects hose stream penetration
- Consider flowing up instead of down with a master stream

- Knee wall fire dynamics
    - During a structure fire, it is possible for fire to enter void spaces and surround [firefighter] crews conducting interior operations
    - Even though there is a delay between making the breach [penetrating a structural separation] and the change in [fire] 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.
- 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.

Figure 4 - Photograph of FSRI Wall Experiment [7]

Figure 5 - Photograph of FSRI Eave Experiment [7]

Figure 6 - Photograph of a FSRI Full Scale Attic Experiment Structure [7]

Figure 7 - Photograph of a FSRI Knee Wall & Attic Field Experiment House [7]

1.5. Wall Experiments

To understand exterior fire growth, FSRI researchers studied different siding, sheathing, and insulation materials, ignition source sizes, ignition sources (gas burners vs. propane gas grill), and effect of power receptacles on fire penetration through the assembly. The wall assemblies were 8 ft by 8ft (2.4 m by 2.4 m) sections. The materials investigated were combinations of:

- Siding: 4 inch vinyl, 8 inch wood lap, polypropylene shingle, 8 inch fiber cement, 4 inch aluminum lap, none, 2 coat stucco, and Exterior Insulation Finishing System (EIFS)
- Sheathing: Plywood, ½ inch (13 mm) and 1 inch (25 mm) polystyrene, ½ inch (13 mm) and 1 inch (25 mm) polyisocyanurate
- Insulation: Fiberglass, open cell spray foam, closed cell spray foam, none

The wall section frames were constructed with 2 x 6 or 2 x 4 lumber. The interior side was covered with ½ inch (13 mm) gypsum board. The HRRs studied were 25 kW, 50 kW, 100 kW, 150 kW, 200 kW, and 300 kW. For context, Figure 8 shows images of fires between 30 kW and 300 kW in size.

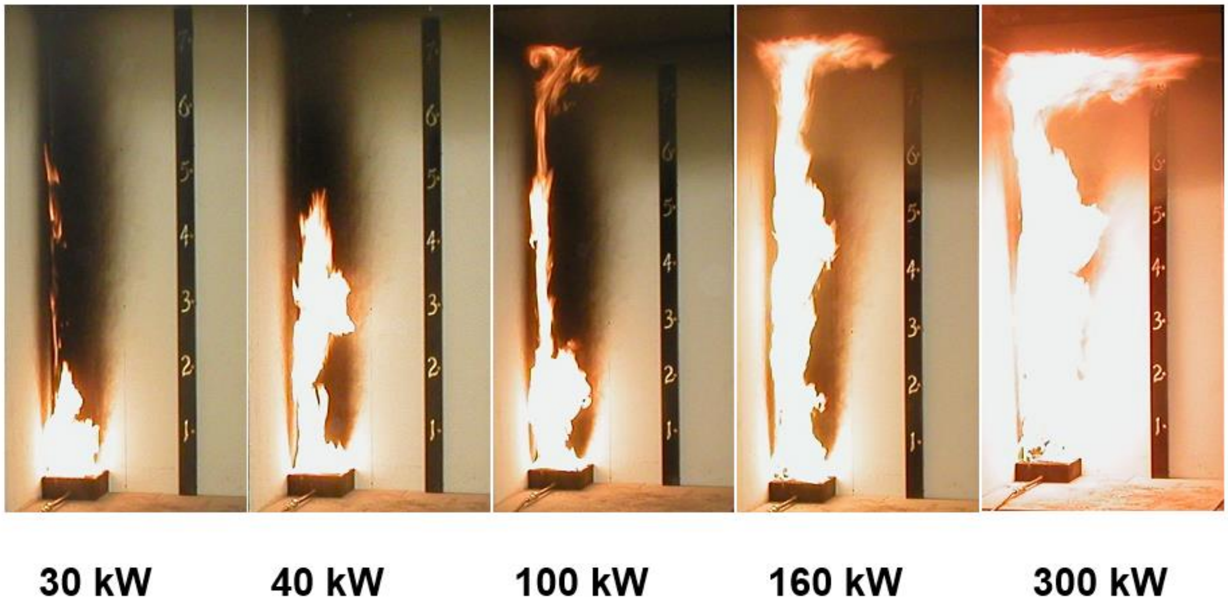

Figure 8 - Images of fires ranging in size between 30 kW and 300 kW

Wall Assemblies Investigated

Experiment results from fire tests conducted on vinyl, polypropylene shingles, fiber cement, aluminum, wood lap, stucco, and EIFS siding over a weather resistant barrier (WRB), 1 inch (25 mm) expanded polystyrene (EPS) insulation board, and 2 x 6 studs with kraft faced insulation with integral vapor barrier, with a 100 kW ignition source were compared. A table of the results is provided in Table 1. Figure 1 shows flame spread on each of the materials, excluding the EIFS. Researchers noted the following:

- The aluminum siding delayed ignition until it melted at about 5 minutes
- The fiber cement delayed ignition until it eventually broke apart at 16 minutes.
- The wood lap ignited early but delayed penetration to the sheathing.
- Once the polystyrene sheathing was ignited the fire rapidly spread.
- The thinner vinyl siding peaked in HRR early and declined while the thicker polypropylene shingles maintained a steady high HRR due to the quantity of fuel.
- The wood lap siding and polypropylene shingle siding contained the most fuel (as measured by total energy released during the testing), but most of the fuel from the polypropylene shingle siding wall was consumed in the first 20 minutes and most of the fuel from the wood lap siding wall was consumed after 20 minutes.
- Fire resistive materials delayed penetration into the wall keeping the HRR low.
- Synthetic materials melted or burned early resulting in higher HRRs.

Test results from fire tests conducted with ½ inch (13 mm) plywood, 1 inch (25 mm) polystyrene, and 1 inch (25 mm) polyisocyanurate sheathing covered with vinyl siding and a weather resistant barrier and placed over 2 x 6 or 2 x 4 studs with kraft faced insulation with integral vapor barrier (KFI w/ IVB) and ½ inch (13 mm) gypsum board with a 100 kW ignition source were compared.

Table 2 provides a summary of the results. Researchers found that the sheathing material had little impact on ignition time (varied within 17 seconds). Plywood provided the most fire resistance. Polystyrene resulted in the largest HRR, but then quickly reduced in fire size. The polyisocyanurate fire reached its peak fire size at a similar time but stayed high for a longer time, resulting in longer sustained burning at 7 ft (2.1 m).

Researchers next compared the fire results from walls constructed with different insulations. Fiberglass, Open Cell Spray Foam 1, Open Cell Spray Foam 2, and Closed Cell Spray Foam were investigated with a 100 kW fire source. In each experiment, vinyl siding, a WRB, EPS sheathing with the thickness adjusted to meet the IBC requirements, and ½ inch (13 mm) gypsum board was used to complete the wall assembly. The insulation had a minimal effect on the ignition time. The ignition times varied by 32 seconds. The time for the fire to reach 7 ft (2.1 m) was similar for all the insulations because the flame spread was initially driven by the synthetic siding and sheathing. However, the use of spray foam insulations resulted in an over 50% increase in fire size from fiberglass. The duration of burning at 7 ft was also longer for the spray foams versus fiberglass.

Table 1 - Siding Materials over Expanded Polystyrene and Fiberglass Batt Insulation Listed by Fire Severity [7]

Siding Materials Arranged By:			
Time to Ignition (shortest to longest)	Time Fire Spread to Top of Wall (shortest to longest)	Fire Size (largest to smallest)	Duration of Flaming at 7 ft. (2.1 m) Above the Burner (longest to shortest)
Wood Lap	Vinyl	Wood Lap*	Aluminum
Vinyl	Polypropylene Shingle	Polypropylene Shingle	Polypropylene Shingle
Polypropylene Shingle	Aluminum	Vinyl	Vinyl
Aluminum	Wood Lap	Aluminum	Wood Lap**
Fiber Cement	Fiber Cement	EIFS (No Sustained Ignition)	Fiber Cement**
EIFS (No Sustained Ignition)	EIFS (No Sustained Ignition)	Fiber Cement	Stucco** (No Sustained Ignition)
Stucco (No Sustained Ignition)	Stucco (No Sustained Ignition)	Stucco (No Sustained Ignition)	EIFS** (No Sustained Ignition)

*Occurs 30 minutes and 41 seconds after ignition.
**No or no sustained burning at 7 ft (2.1 m)
Note: Once the burner was turned off in the fiber cement experiment, no wall ignition was observed.

Table 2 - Sheathing Material Under Vinyl Siding and Over Fiberglass Batt Insulation Listed by Fire Severity [7]

Sheathing Materials Arranged By:		
Time Fire Spread to Top of Wall (shortest to longest)	Fire Size (largest to smallest)	Duration of Flaming at 7 ft. (2.1 m) Above the Burner (longest to shortest)
1 inch (25 mm) Polyisocyanurate/ 1 inch (25 mm) Polystyrene*	1 inch (25 mm) Polystyrene	1 inch (25 mm) Polyisocyanurate
½ inch (13 mm) Plywood	1 inch (25 mm) Polyisocyanurate	1 inch (25 mm) Polystyrene
	½ inch (13 mm) Plywood	½ inch (13 mm) Plywood

*The fire reached the top of the wall at the same time.
Note: The ignition times varied by 17 seconds indicating that the sheathing material had a minimal impact on the ignition time of the wall.

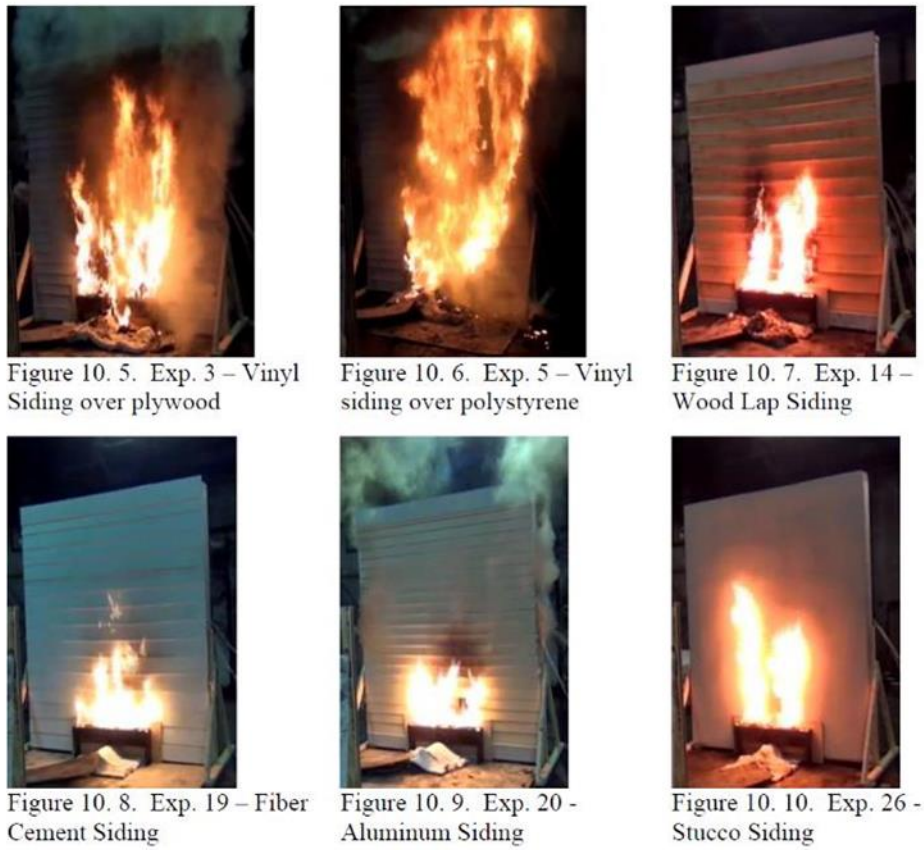

Figure 9 - Photographs of Flame Spread on Different Siding Materials [7]

Ignition Fire Sizes

Three different wall assemblies were exposed to different sized ignition sources – vinyl siding, plywood sheathing, and fiberglass insulation; vinyl siding, 1 inch (25 mm) polystyrene sheathing, and fiberglass insulation; and vinyl siding, ½ inch (13 mm) polystyrene, and closed cell spray foam. 25 kW, 50 kW, 100 kW, and 150 kW gas burner fires were studied in the vinyl/plywood/fiberglass tests. Researchers demonstrated that the wall assembly ignited quicker as the fire size was increased. The same was true for the time for flame spread to 7 ft (2.1 m) except for 25 kW. For most of the testing, researchers were able to use a line burner (Figure 10) that exposes 39 inches (1 m) of the wall surface to fire. However, to reach 25 kW, researchers had to use a smaller burner that exposed only 1 ft (0.3 m) of the wall to fire. As a result, the fire failed to spread at 25 kW. The peak fire size (excluding the burner contribution) increased with the burner size. The duration of burning at 7ft was not impacted by the burner fire size.

Ignition fires of 50, 100, and 150 kW were investigated with the vinyl/polystyrene/ fiberglass wall assemblies. The ignition time decreased 20 seconds from 50 kW to 100 kW and did not change between 100 kW and 150 kW. The flame spread to 7 ft was quicker as the burner size increased and the fire size (excluding the burner contribution) increased with burner size. Lastly, the burning time at 7 ft decreased as the burner size increased indicating the assembly burned more quickly.

The last combination of materials investigated was Vinyl, ½ inch (13 mm) polystyrene, and closed cell spray foam with a fire source size of 25 kW and 100 kW. With the increase in ignition fire size, the ignition time decreased, the fire more quickly reached 7 ft (2.1 m), the fire size (excluding the contribution of the ignition source) was larger, and the time the fire burned at 7 ft was shorter.

Figure 10 - Photograph of the 39 inch (1 m) Gas Line Burner [7]

Real Ignition Source

Two experiments were conducted with a propane grill. The grill was positioned in contact with the wall for ignition to occur. Two wall assemblies with different sheathing were investigated. The two sheathings were 1 inch (25 mm) EPS and ½ inch (13 mm) plywood. Each experiment had vinyl siding, WRB, KFI w/ IVB and ½ inch (13 mm) gypsum board. The ignition time in both tests was much longer than the equivalent tests with the 50 kW burner. The fire on the assembly with plywood self-extinguished when the grill was removed. The fire on the assembly with EPS did extend above 7 ft (2.1 m) and continue to burn at 7 ft (2.1 m) for 4 minutes.

Use of Receptacles

Two experiments were conducted with outlets on the interior wall. Each wall assembly tested had vinyl siding, WRB, 1 inch (25 mm) EPS, and ½ inch (13 mm) gypsum board. The insulation varied. One experiment included spray polyurethane foam and the other KFI w/ IVB. In each case, the fire penetrated the outlet. In no other experiment, did the fire penetrate the interior gypsum board.

Summary of Wall Experiments

- Ten experiments had fire spread extend to the top of the assembly in under 2 minutes. Each had vinyl siding. All but one had polystyrene or polyisocyanurate sheathing.
- Eight experiments resulted in a fire size greater than 1000 kW. Seven had vinyl siding and polystyrene sheathing. Those also contained different types of foam insulation, which could also burn unlike fiberglass for example. All eight had synthetic materials.
- In five experiments, the total heat energy released was greater than 700 MJ. Two had spray polyurethane foam insulation, one has polypropylene shingle siding, one has wood lap, and the last required a 300 kW ignition source and manually opening the wall. Wood

lap has the potential to release a similar amount of heat energy as synthetic materials. But it burns much more slowly giving the fire service more time to respond.

1.6. Eave Experiments

Based on the results from the wall experiments, three exterior walls with an eave and a partial attic space were burned to study flame spread and penetration into the attic. In Experiment 1, the exterior wall was constructed with vinyl siding, plywood sheathing, and fiberglass insulation. The attic space had fiberglass insulation lying on the attic space floor. The exterior wall in Experiment 2 had vinyl siding, polystyrene sheathing, and fiberglass insulation. The attic space had fiberglass insulation lying on the attic space floor. In Experiment 3, the exterior wall had vinyl siding, polystyrene sheathing, and spray foam insulation. The underside of the roof was also coated with spray foam insulation to create a continuous insulation system. Each structure had a WRB and an interior finished with ½ inch (13 mm) gypsum board. Each was wood framed with 2 by 4 or 2 by 6 lumber. Each test was ignited with a 100 kW line burner as was done in the prior wall experiments.

The fires in Experiments 2 and 3 initially grew similarly in size reaching 5 MW in 2-3 minutes while the fire in the first experiment took 27 minutes to reach the same size. Similarly in the same experiment, the fire took 25 minutes to penetrate the attic space. The slower burning plywood sheathing and non-combustible insulation in Experiment 1 substantially slowed the fire spread up the exterior wall. However, the time to penetrate the attic space in Experiments 2 and 3 was substantially different – 2 minutes in Experiment 2 and 10 minutes in Experiment 3. The time to the peak fire size was also similarly timed for each experiment. The largest fire size occurred in Experiment 2 even though the insulation in Experiment 3 was combustible and it was not in Experiment 3. This indicated that the two experiments with vinyl siding and polystyrene demonstrated similar fire spread up the exterior wall but deviated once the fire reached the eave. The continuous insulation in Experiment 3 delayed the fire's penetration into the attic. In Experiments 1 and 2, the vinyl covered eave and plastic baffles melted away opening the attic space to the fire. In Experiments 1 and 2, the fire spread vertically. In Experiment 3, the fire spread vertically and extended horizontally to both sides of the structure. The highest heat flux (measured 8 ft [2.4 m] from the wall) recorded was in Experiment 3. The combination of horizontal flame spread and high heat flux showed that the spray foam under the sheathing was contributing to and changing the fire behavior. More material on the exterior wall in Experiment 3 was burning than 2 even though the highest fire size was recorded in Experiment 2.

1.7. Full Scale Attic Fire Experiments & Knee Wall & Attic Field Experiments

The focus of the full scale attic experiments was to investigate firefighting tactics once the fire has spread inside the attic. In the Knee Wall & Attic Field Experiments, researchers studied the unique challenges of fire spread through knee wall spaces to the attic and the appropriate firefighting tactics to suppress the fires. In these experiments, the fire was ignited inside of the structure. A summary of the findings can be found under the introduction to the study starting on page 15. The details for all the experiments can be found in Reference [7].

1.8. Impact of UL FSRI Study

In pursuing an understanding of attic fires, researchers demonstrated the ease of which a fire can spread up the exterior of a house and into the structure through the eaves. They also showed that the materials and construction of wall assemblies can greatly impact fire spread and growth.

At the ICC Committee Action Hearings held in Columbus Ohio in March (2018), proposals were heard that would address fire performance of exterior wall vertical fire spread in buildings other than Types I, II, III, or IV. There was much discussion over the concern for walls having combustible exterior wall envelope components, where ignition occurs either directly (by radiation, convection, flame contact) or indirectly (combustion of materials near the base of the wall), followed by flame propagation up the exterior wall surface and then into the building attics through eaves.

The Code proposal proponents were urged to have ASTM develop a test method for a future submittal to the Code. In response to this activity, later in 2018, the Committee E05.14 – External Fire Exposures took on the task of developing a new test method. This new ASTM Standard is similar to ASTM E2707 (a flame penetration test method discussed earlier) but modified to address flame propagation (spread) on the exterior wall and to align with the procedure used in the FSRI study.

1.9. New ASTM Fire Propagation Test Method

ASTM E2707 was developed assuming that a residential structure fire initiated from the exterior would spread into the structure by penetrating through the exterior wall materials. The ASTM Committee E05.14 decided the new, draft test method, based on ASTM E2707, will instead test for fire propagation up the exterior as was seen in the UL FSRI study. Amongst the ASTM committee, several ASTM E2707 test method aspects needed to change or be considered to evaluate propagation appropriately. Below is a list of concerns or questions initially raised by the committee.

- The wall size should be larger so that it is easier to differentiate the performance between samples - possibly 8 ft wide by 16 ft (2.4 m by 4.8 m) wall samples?
- The ignition fire size of 150 kW was agreed to be too high, too aggressive. More data was needed to determine the appropriate fire size.
- The ignition fire exposure should be longer, maybe to 20 minutes?
- Should there be classes of performance?
- Should the focus on wildland fires be removed to widen the applicability?
- Is it necessary to keep the soffit?
- Should lateral flame spread be addressed?
- Removal of the observation period after the burner is turned off
- What happens if the fire burns through the test sample?
- What ignition fire sizes should be investigated? 100, 75, 50 kW?
- What is a viable passing baseline?
- Should there be a thermocouple to measure temperature near the 16 ft level?
- Should there be a pass / fail criteria?

Given the list of questions and concerns, UL Solutions conducted sponsored research to further develop the method.

1.10. UL Solutions Early Research

Eight co-sponsored experiments were conducted to refine the draft, modified ASTM E2707 test method. These experiments studied four different ignition burner fire sizes with a combination of different common exterior wall materials. Some experiments were conducted with insulation and interior gypsum board and others without. The sidings investigated were vinyl and 8 inch (20 cm) wood lap siding. Three WRB conditions were investigated - polyethylene fiber barrier, construction paper, and none. Oriented strand board (OSB) or plywood was used as sheathing. In the tests with insulation, fiberglass was used. Lastly in one test, 1 inch (25 mm) extruded polystyrene (XPS) was applied under the vinyl siding to simulate continuous insulation. In each experiment the wall assembly was wood framed and 8 ft (2.4 m) wide and 16 ft (4.9 m) in height. 2 by 4 lumber was used. The studs were 16 inch (41 cm) on center. The siding was attached with fasteners at a nominal 8 inch (20 cm) on-center and included staggered joints at vertical centerline of assembly. The same line burner (Figure 10) used in the UL FSRI study was used in this series of experiments. The burner was left on for 20 minutes in each test. The experimental test matrix can be found in Table 3. A photograph of an experiment is presented in Figure 11.

Temperature and heat release rate (HRR) were recorded in these experiments. Thermocouples were positioned at the following locations:

- Interior surface of plywood sheathing at mid-height and mid-width of assembly
- Interior surface of plywood sheathing at mid-width and 1 ft (0.3 m) below the top of assembly
- Top of assembly on surface of siding at mid-width
- Top of assembly 1 inch (25 mm) away from surface of siding at mid-width

Post-test photographs, heat release rate plots, and temperature plots for each test can be found in Appendix A: Early UL Solutions Testing. The results of the tests are provided in Table 3.

During this testing, the intent was to examine materials on a common sheathing over a larger 8 ft (2.4 m) wide and 16 ft (4.9 m) in height test sample with a 20 minute, 100 kW fire exposure. The ASTM committee generally agreed that the 150 kW fire exposure from ASTM E2707 were too aggressive, burning the wall sections too quickly to differentiate the performance of the wall materials, so researchers started with 100 kW. This ignition level was also consistent with the majority of testing in the FSRI study. Vinyl siding, spun-bonded polyolefin WRB, and OSB sheathing were selected because they are the most common siding, WRB, and sheathing. Over the first four tests, the 100 kW exposure was dropped to 40 kW and again to 25 kW. In each, the flame spread too quickly to the top of the test sample, leading researchers to adjust their approach and assess the differences between their test parameters and the FSRI study. In the FSRI study, plywood was used as sheathing. In the last four tests, the sheathing was changed to plywood. Researchers also chose to include wood lap siding for comparison because it traditionally performs well in fire testing.

The key findings from this test series were:

- A 20 minute long, 75 kW fire exposure provided clear differentiation in flame propagation time to the top of the wall assembly for wood lap and vinyl siding over spun-bonded polyolefin WRB, and OSB sheathing.

- Switching from OSB to plywood sheathing slowed the flame penetration through the assembly.

A base wall of sheathing and studs alone was inadequate to prevent burn through and flame spread up the interior of the test sample. Only the tests with interior drywall did not burn through. Photographs of test sample burn through are provided in Figure 12.

Table 3 - UL Solutions Early Experimental Test Matrix

Test No.	Siding	Continuous Insulation	WRB	Sheathing	Studs	Stud Cavity Insulation	Interior Finish	Burner Placement	Burner Output	Flame Propagation @ 16' Time, mm:ss	Sheathing Breach Time, mm:ss
1	Vinyl	None	Spun-bonded Polyolefin	3/8" oriented strand board	2X4 lumber - 16" on center spacing	None	None	As per E2707	100 kW	6:30	10:00
2	Vinyl	None	Construction Paper	3/8" oriented strand board	2X4 lumber - 16" on center spacing	R11 glass fiber	1/2" non-rated gypsum	As per E2707	40 kW	6:30	--
3	Vinyl	None	Spun-bonded Polyolefin	3/8" oriented strand board	2X4 lumber - 16" on center spacing	R11 glass fiber	1/2" non-rated gypsum	As per E2707	25 kW	App. 10	--
4	Vinyl	1" XPS	None	3/8" oriented strand board	2X4 lumber - 16" on center spacing	R11 glass fiber	1/2" non-rated gypsum	As per E2707	25 kW	15:00	--
5	Vinyl	None	Spun-bonded Polyolefin	3/8" plywood	2X4 lumber - 16" on center spacing	None	None	As per E2707	100 kW	26:30	19:30
6	8" Wood Lap	None	Spun-bonded Polyolefin	3/8" plywood	2X4 lumber - 16" on center spacing	None	None	As per E2707	100 kW	06:40 (interior)	04:20
7	Vinyl	None	Spun-bonded Polyolefin	3/8" plywood	2X4 lumber - 16" on center spacing	None	None	As per E2707	75 kW	28:00 (interior)	18:18
8	8" Wood Lap	None	Spun-bonded Polyolefin	3/8" plywood	2X4 lumber - 16" on center spacing	None	None	As per E2707	75 kW	11:30	7:30

Figure 11 - Photograph of a Modified ASTM E2707 Fire Experiment

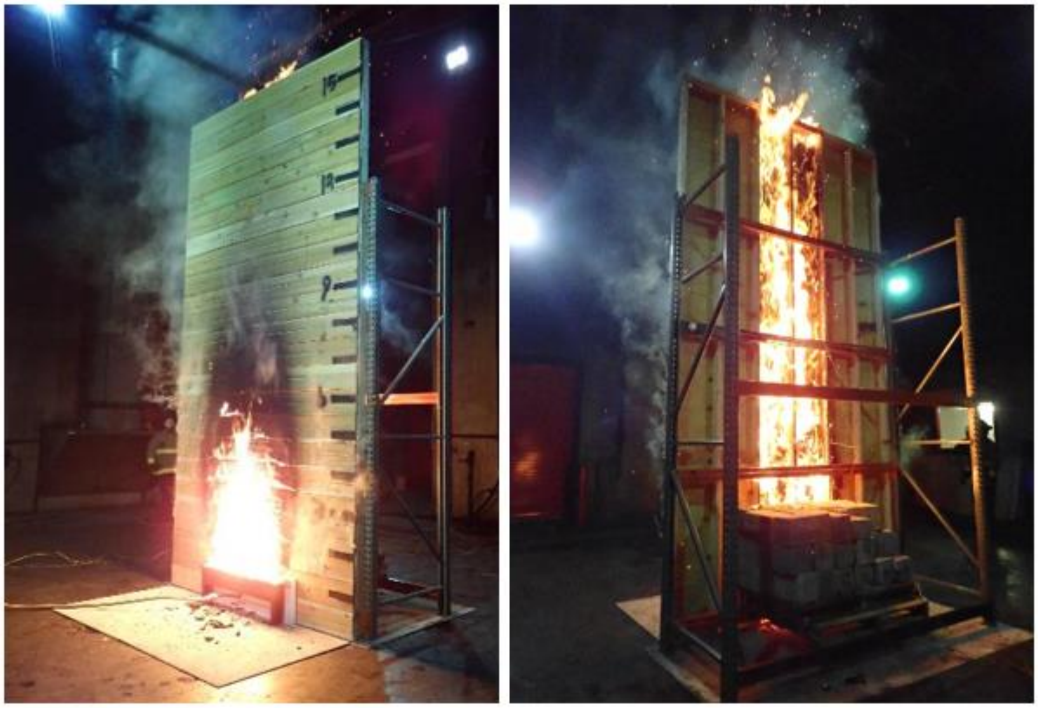

Figure 12 - Photographs of Fire Burning through Test Sample

2. Literature Review

In 2019, the DOE funded a 3-year project with Pacific Northwest National Laboratory (PNNL) to conduct a techno-economic study on residential exterior wall upgrades for energy retrofits. An in-depth literature review was completed to identify current practices and new technologies for retrofits and approaches to evaluate the techno-economic value, thermal performance, and hygrothermal performance of wall assemblies [13] Based on the literature review, 15 wall assemblies were selected, modeled for thermal and hygrothermal performance, tested for energy efficiency and ease of construction, and analyzed for the economic impact and likelihood of adoption [3]. Researchers recognized the need to evaluate the fire performance of the wall assemblies but did not include it in the study.

2.1. PNNL "Wall Upgrades for Residential Deep Retrofits: A Literature Review"

In 1991, the DOE started their Building Energy Codes Program. The program allows the DOE "to participate in industry processes to develop model building energy codes, issue determinations as to whether updated codes result in energy savings and provide technical assistance to states to implement and comply with the codes [14]." The program has successfully driven the construction industry to build new homes with higher energy efficiency. Despite this, an estimated 34.5 million homes are wood framed without insulation and "71% of existing homes have air leakage rates of 10 or more air changes per hour at 50 pascals of pressure [13]." As a result, there is a growing demand for retrofit energy saving solutions with "approximately one in five homeowners invested in energy efficiency retrofits" in 2017 [13]. In "Wall Upgrades for Residential Deep Retrofits: A Literature Review," PNNL identified existing building materials, current retrofit practices, and innovative solutions in order to conduct a study of the performance and adoptability of retrofit solutions.

Existing Residential Building Materials

According to researchers, "The materials that compose the building envelope, the integrity of their assembly, and their resulting collective properties of thermal resistance, airtightness, and moisture control determine the thermal and hygrothermal performance of the wall system…. In addition to the construction of the wall assembly itself, many interior and exterior environmental factors impact the movement of heat, air, and moisture within a wall assembly. These include ambient temperature and humidity levels, indoor temperature and humidity, solar radiation, exterior condensation, wind-driven rain, construction moisture, ground- and surface water, and air pressure differentials. [13]" These complexities drive the vast variety of wall assemblies in use.

To study exterior wall thermal performance, researchers first identified the most common framing, insulation, and exterior materials used in existing residential buildings. They are listed below.

Framing

- Framing Lumber/Dimensional Lumber
- Engineered Wood
- Panelized Wall Systems (Frameless)
- Steel Framing
- Concrete Block Framing

Insulation

- Cellulose
- Cementitious
- Cotton
- Fiberglass
- Mineral Wool
- Polyisocyanurate
- Polystyrene – Expanded (EPS)
- Polystyrene – Extruded (XPS)
- Polyurethane
- Sheep's Wool
- Radiant Barrier

Exterior

- Aluminum, vinyl, or steel siding
- Brick
- Wood
- Stucco
- Concrete or concrete block
- Shingles
- Stone

The prominence of each of the materials varies with the climate across the United States.

Three additional innovative products were also identified – aerogel thermal insulation, phase change materials, and vacuum insulation panels. For more detailed information on the materials and advantages and disadvantages of each, see Reference [13].

The second wall assembly property researched was hygrothermal. Historically, construction has been focused on solely thermal performance, which has led to building exterior failures from moisture damage [13]. The two properties are dependent on one another. As researchers stated, "they act in unison – moisture carries heat with it, and differences in temperature affect the way moisture moves. [13]" Historically used, natural materials, such as wood and stone, are permeable and porous, but the increased use of non-permeable materials and tighter, energy efficient construction can prevent moisture movement [13]. Increased moisture can degrade the building materials and result in mold, decreasing the indoor air quality. To combat moisture, drainage cavities and wall ventilation are recommended [13].

Current Retrofit Solutions

PNNL researchers identified the following retrofit solutions currently in use [13]:

- Drill and fill – refers to drilling into wall cavities and filling the spaces with dens-pack fiberglass or cellulose insulation. This method is sometimes used with rigid insulation on the exterior.
- Ventilated facades – refers to creating a gap between the cladding and WRB using furring strips, mesh, corrugated or dimpled house wrap. This method is used to manage moisture.
- Exterior insulated sheathing – refers to applying rigid insulation and a WRB to the existing sheathing and filling wall cavities with insulation. The rigid insulation can be "polyisocyanurate, extruded polystyrene (XPS), expanded polystyrene (EPS), rigid fiberglass board, and rigid mineral wool" and the cavity insulation is typically "batts, or blown-in insulation, and rigid foam boards."
- Thermal break shear wall assembly – refers to applying rigid insulation to the original wall studs and new sheathing in a staggered manner. In retrofits, the wall cavities are filled with batt or spray foam and new siding and WRB is applied.
- Furring strips over existing siding with spray foam – refers to applying furring strips with closed cell spray foam in between and new siding over existing sheathing.
- Stud framing over existing siding with spray foam – refers to applying 2x4 lumber framing with spray foam filling the cavities over existing siding. New sheathing and siding is applied over the new framing.
- Retrofit insulated panels – refers to applying prefabricated panels consisting of rigid foam on oriented strand board on the existing sheathing. New WRB and siding should be applied.
- Solid panel Perfect Wall system – refers to a continuous wall system comprised of a structural wood composite shell (in place of studs) with weather, vapor, air, and thermal barriers applied to the exterior.
- Insulated vinyl siding – refers to vinyl siding panels with foam insulation on the interior to replace existing siding.
- Exterior Insulation and Finish Systems (EIFS) – refers to combination continuous insulation and exterior siding to replace existing siding.
- Masonry retrofits – refers to applying rigid insulation using furring strips to secure the insulation and new siding to the wall.
- Prefabricated net zero energy panels – refers to panels consisting of oriented strand board, wood studs with mineral wool in the cavities, oriented strand board, WRB, rainscreen, and siding applied to the original wall.

2.2. PNNL "Wall Upgrades for Energy Retrofits: A Techno-Economic Study"

Following the initial literature review, the PNNL research team, with input from an advisory committee, identified and studied the following 15 wall assemblies [3].

A. Baseline – Painted cedar siding/asphalt impregnated building paper/spruce-pine-fir (SPF)/empty cavity wood framing/painted gypsum board
B. Drill and fill cellulose – Baseline wall with cellulose in the cavities
C. Injected cavity foam – Baseline wall with high density, closed cell spray foam in the cavities

D. Prefabricated external EPS – Baseline wall with compressible fiberglass, WRB, EPS panels with drainage channels, and vinyl siding
E. Drill and fill cellulose and external XPS – Baseline wall with cellulose in the wall cavities and a layer of XPS board with furring strips and XPS in the furring strip cavities.
F. Drill and fill cellulose and VIP/Vinyl Siding – Baseline wall with cellulose in the wall cavities and vacuum insulated panels with vinyl siding
G. Exterior mineral fiber board – Baseline wall with mineral fiber board, liquid membrane, furring strips, and cement fiber lap siding
H. Exterior gEPS structural panel system – Baseline wall with compressible fiberglass panels, OSB, a membrane, graphite impregnated EPS, furring strips, and metal siding
J. Drill and fill fiberglass – Baseline wall with dense-pack fiberglass in the cavities
K. Fiberglass batting and interior polyiso – Baseline wall with fiberglass batting in the cavities and polyiso foam on the interior of the wall behind the gypsum board
L. Drill and fill fiberglass and exterior polyiso – Baseline wall without asphalt paper and siding with dense-pack fiberglass in the cavities, without the bevel cedar siding, polyiso boards, furring strips, and wood composite lap siding
M. Prefabricated exterior EPS over EIFS panel system – Baseline wall without asphalt paper and siding and with liquid membrane and EPS panels
N. Prefabricated exterior vinyl siding covered polyurethane block system – Baseline wall with spunbonded WRB and prefinished polyurethane blocks
O. Drill and fill fiberglass and exterior fiberglass board – Baseline wall with spunbonded WRB, mineral fiberboard, wood furring strips, and fiber cement lap siding
P. Fiberglass batting over XPS over OSB (thermal break shear wall) – Gypsum board on the interior surface, fiberglass batting, XPS board, OSB sheathing, spunbonded WRB, and vinyl siding

The energy and moisture control performance in cold climates, ease of construction, ease of sourcing, and economic benefits of each wall assembly was assessed through testing, computer modeling, and economic data collection to determine the technology diffusional potential. The wall assemblies with the highest adoption potential are the Drill and Fill ellulose and Drill and Fill Fiberglass [3]. The Fiberglass Batting and Interior Polyiso, Prefabricated Exterior Vinyl Siding Covered Polyurethane Block System, and Injected Cavity Foam assemblies were also identified as high performers [3].

The PNNL report is an extensive and thorough review of many factors critical to adoptability of emerging retrofit technologies. However, the study did not address the fire performance of the wall assemblies.

3. UL Solutions and IAFF – DOE Funded Project

The UL Solutions and IAFF project funded by DOE was a natural evolution, stemming from the efforts of Pacific Northwest National Laboratories (PNNL) research on innovative retrofitted exterior wall systems. To initiate the project, the IAFF and UL Solutions team established a Project Advisory Panel and held several virtual meetings to present information on previous fire testing conducted by the UL Solutions Fire Research & Development team and the Fire Safety Research Institute of UL Research Institutes. The panel discussed the development and goals of the earlier PNNL project, and then they developed a test plan. A draft of the protocol from the ASTM exterior wall propagation protocol was used to test and comparatively study various retrofit energy efficient designs to gain a better understanding of their fire behavior.

4. Statement of Project Objectives

The technical plan below was developed with the IAFF to fulfill the needs of DOE grant DE-EE0009454.

Task 1:

- Identify and establish a Project Advisory Panel (PAP)
- Conduct a literature review
- Host a kick-off PAP meeting to review literature to date and begin to establish comparative fire test scenarios for building technologies
- Review feedback from PAP

Task 2:

- Develop comparative fire test plan for building technologies
- Share experiment plan with PAP
- Incorporate PAP feedback and finalize fire experiment plan

Task 3:

- Conduct initial comparative fire tests

Task 4:

- Determine initial findings
- Conduct additional fire tests on selected building technologies if necessary and funding allows

Task 5:

- Write and issue midterm report on the experimental findings to the PAP

Task 6:

- Host PAP meeting to review findings and develop initial training materials for the fire service
- Incorporate lessons learned into current IAFF training

Task 7:

- If funding allows, develop and execute follow up testing expanding on initial findings

Task 8:

- Update midterm report and issue draft report to PAP for review
- Obtain PAP feedback
- Finalize report

Task 9:

- Deliver training materials
- Disseminate findings through conference presentations and webinars
- Develop educational materials for the NFPA to support their fire service training programs

5. Project Advisory Panel

The technical plan for this study will be developed with input from Subject Matter Experts (SMEs) to maximize the usefulness and relevance of the findings. The SMEs are from the fire service or with experience within the fire service, industry representatives and experts in the renewable technology and building energy performance fields. The panel members are:

First Name	Last Name	Affiliation
Antonio	Aldykiewicz	Oak Ridge National Laboratory
Chrissi	Antonopolous	Pacific Northwest National Laboratory
John	Ceriello	Fire Department of the City of New York
Sean	DeCrane	UL Solutions
Andre	Desjarlais	Oak Ridge National Laboratory
Dan	Gorham	Insurance Institute for Business & Home Safety
Kristen	Hagerty	Interstate Renewable Energy Council
George	Healy	Fire Department of the City of New York
Steve	Kerber	UL Fire Safety Research Institute
Peter	LaBonte	Advanced Building Solutions
Cheryn	Metzger	Pacific Northwest National Laboratory
Kelly	Opert	UL Solutions
Tyler	Pilet	Pacific Northwest National Laboratory
Kevin	Reinertson	Riverside County Fire Department and CalChiefs FPO's
Madeline	Salzman	Department of Energy
Dwayne	Sloan	UL Solutions
Rick	Swan	International Association of Fire Fighters
Eric	Werling	Department of Energy

6. Fire Testing Laboratory

Testing was conducted at the UL Solutions large-scale fire test facility located in Northbrook, Illinois.

6.1. Large-Scale Fire Test Building

The large-scale fire test building used for this investigation includes four fire test areas that are used to develop data on the fire growth and fire suppression. A schematic of the test facility is shown in Figure 13.

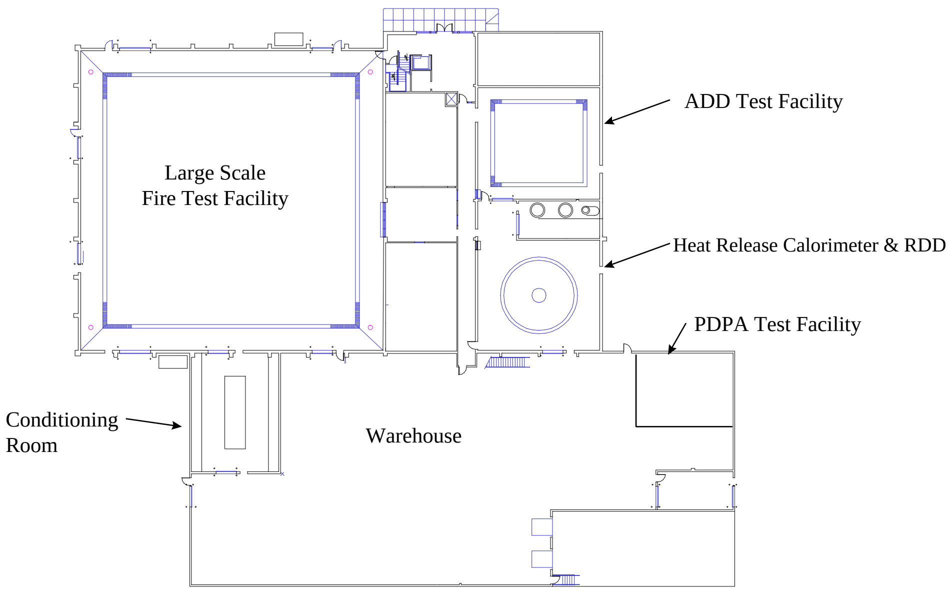

Figure 13 - Large Scale Test Facility

Heat Release Calorimeter

The heat release calorimeter is in a nominal 50 by 50-ft. fire test cell equipped with a 25-ft. diameter collection hood.

The test cell used in this investigation is equipped with an exhaust system capable of a maximum flow of 60,000 cubic feet per minute through a smoke abatement system. Four inlet ducts provide make up air in the test facility and are located at the walls 5-ft. above the test floor to minimize any induced drafts during the fire tests.

The center of the floor of the test facility is 30 by 30-ft, is smooth and flat, and is surrounded with a grated drain to insure adequate floor water drainage from the test area.

7. Instrumentation

During testing, fire heat release rate, temperature, heat flux, and video data was recorded.

7.1. Calorimeter

The calorimeter consists of a 25-ft. diameter collection hood connected to an exhaust system capable of 60,000 SCFM.

The heat release calorimeter is equipped with convective and total heat release instrumentation. The convective instrumentation calculates the heat release rate from the energy rise of the products of combustion entering the calorimeter. The total heat release instrumentation calculates fire size using oxygen consumption techniques.

The heat release calorimeter has been calibrated to a maximum total heat release rate of 10 MW. Any reported heat release rates greater than 10 MW are underestimated because not all products of combustion were collected.

7.2. Thermocouples

Temperature of wall assembly layers was measured with bare-bead, Chromel-Alumel (type K) thermocouples made from 30 gage special limits solid conductor wire. Thermocouples were located on the siding, between the layers, on the sheathing, and behind the sheathing at heights of 8 ft (2440 mm) and 15 ft (4570 mm) along the centerline of the wall sections. The detailed locations of the thermocouples are provided in Appendix B: Thermocouple Locations.

7.3. Heat Flux Gauges

Heat flux measurements were taken in various locations in front of the wall assembly to map the heat flux that may be experienced by nearby structures or property in the real world. The measurements were made using water-cooled Schmidt-Boelter heat flux gauges. The locations of the heat flux gauges are provided in Figure 14. The total number of heat flux gauges was 8. At the red locations, heat flux gauges were positioned at a height of 7 ft (2130 mm) off the floor. At the dark red location, heat flux gauges were positioned at a height of 5 ft, 7 ft, and 9 ft (1520 mm, 2130 mm, and 2740 mm) off the floor. The burner height is 12 inches, so the gauges were positioned 6 ft, 4 ft, or 8 ft (1830 mm, 1220 mm, or 2440 mm) above the top of the burner.

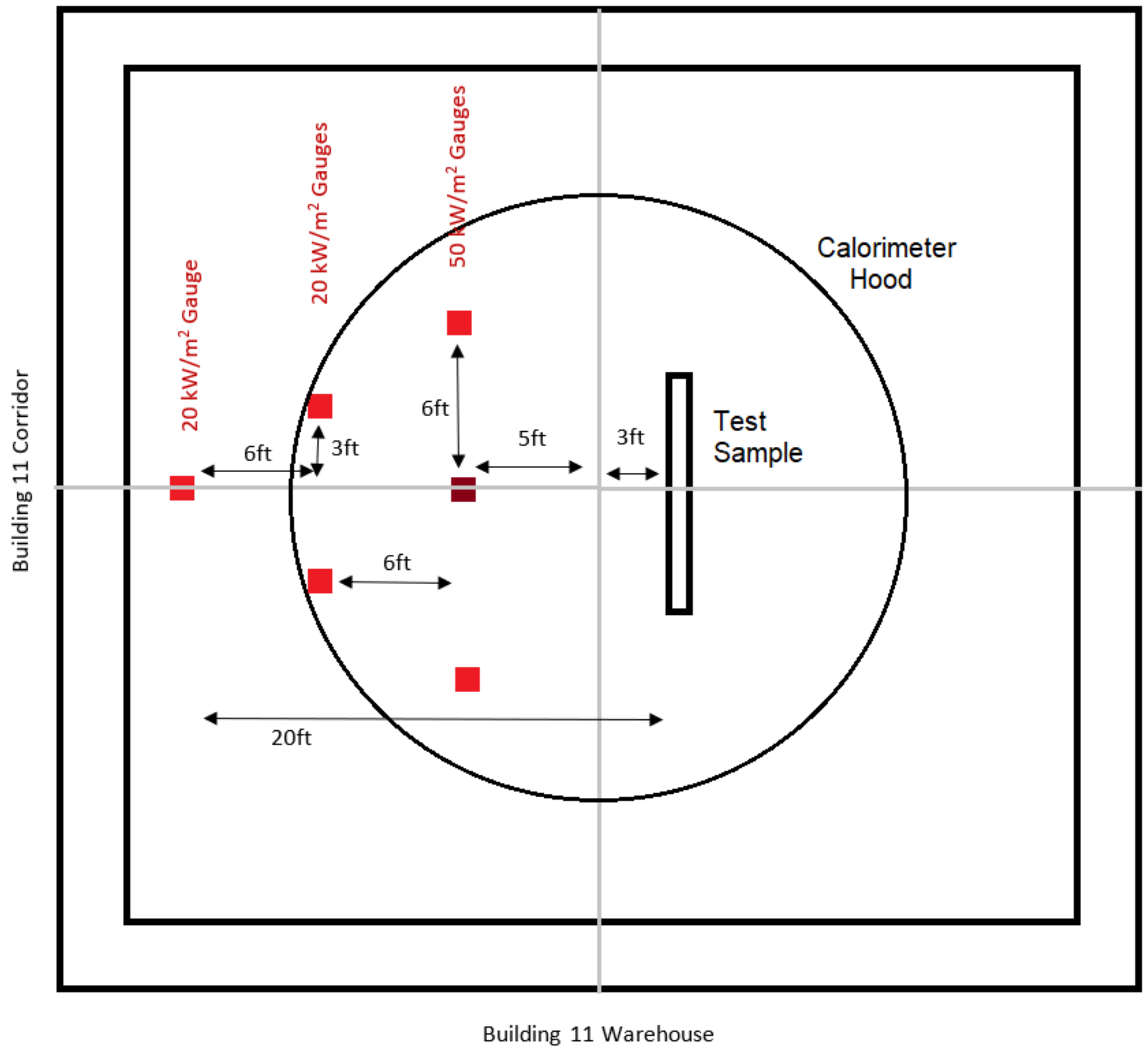

Figure 14 - Heat Flux Gauge Locations

7.4. Video

Four video cameras were used to record testing. Two high-definition cameras were positioned in front of and on either side of the test wall assembly. In addition, two high-definition laboratory cameras were used to record the tests with one located in front of the sample and the other positioned behind it.

7.5. Data Collection

All data was collected using an electronic data acquisition system at a one-second scan rate.

8. Test Parameters and Procedure

Eleven fire tests were conducted. Eleven vertical, wood framed wall assemblies were constructed with the materials as described in Table 4 with thermocouples on or between layers as indicated by the bold, dark lines.

The wall assemblies were 8 ft wide by 16 ft tall (2440 mm by 4880 mm). The assemblies had a base wall similar to the base wall used in the PNNL study. The base wall sheathing was Spruce-pine-fir (SPF) No.2 1 x 6 wall board, representative of older residential home construction likely to be considered for retrofitting. The boards were tightly aligned with one another to minimize gaps. The boards were secured to the wall frame with nails. 1 x 8 pine trim was installed at the top of the wall assembly over the test materials. 1 x 4 pine trim was installed at the bottom of the wall assembly over the test materials. 2 x 4 SPF lumber blocking was installed on thicker test assemblies at the top of the wall assembly to protect the test materials from burning debris and at the bottom of the wall assembly to protect the bottom during movement of the wall assembly and support the test materials. The blocking corresponded to the thickness of the test materials such that all trim is in contact with the siding. Steel flat stock was attached to the bottom of the wall assembly and supports for added ease of moving the wall assemblies. Drawings of the wall structure, sample face, and blocking detail are provided in
Figure 15 - Figure 17.

The wall frame was constructed of 2 x 4 SPF lumber with studs spaced at 16 in. (406 mm) on center with midspan 2 x 4 SPF lumber blocking at a height of 8 ft (2440 mm). 5/8 inch (16 mm) type X gypsum board was applied to the interior face of the base wall frame (2-coat fire taped). The gypsum board seams were taped. The gypsum board tape and screws were mudded.

The base wall had A frame supports attached to both sides of the wall assembly to brace the wall assembly and keep the wall assembly vertical. The A frame was constructed of 2 x 4 SPF lumber with an 8 ft (2440 mm) long 2 x 8 SPF lumber base. The midsection brace of the A frame was at a height of 3.5 ft (1070 mm). The top of the A frame shall be at 10 ft (3050 mm). The supports are depicted in
Figure 15.

The fire size of the ignition burner in each test is also provided in Table 4. Propane was used to fuel the fire. For a 75 kW fire size, propane was flowed at 110 SCFM (52 L/s) and one of the 11 test was conducted at 50 kW, 75 SCFM (35 L/s). A crumbled paper towel was place on top the burner and ignited prior to initiating propane flow. The line burner (same as used in the UL FSRI and UL Solutions early studies) was positioned against the wall assembly with a piece of gypsum wall board separating the wall sample and the hot metal of the burner such that the sample was only exposed to the radiant heat from the fire. A photo of the burner is provided in
Figure 18.

In each test, the ignition fire was ignited. At 20 minutes, the burner was turned off. The wall assembly was allowed to burn for another 10 minutes at which time any remaining fire was extinguished with a fire hose. Several tests were terminated early. Tests were terminated early if the fire spread to the outer limits of the test sample face.

Table 4 - Wall Assembly Fire Test Parameters

Test #	Cladding	Additional Layer	Additional Layer	WRB	Sheathing	Insulation	Interior	Fire Size
1	8 inch Wood Composite Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
2	8 inch Wood Composite Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	50 kW
3	5 inch Vinyl Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
4	8 ¼ inch Fiber Cement Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
5	8 inch Wood Composite Lap Siding	Two layers 2.5-in. EPS panels with cable chases and drainage channels	House wrap, 1 inch mineral wool	None	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
6	5 inch Vinyl Lap Siding	Two layers 2.5-in. EPS panels with cable chases and drainage channels	House wrap, 1 inch mineral wool	None	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
7	8 ¼ inch Fiber Cement Lap Siding	Two layers 2.5-in. EPS panels with cable chases and drainage channels	House wrap, 1 inch mineral wool	None	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
8	5 inch Vinyl Lap Siding	1x4 furring strips with XPS infill	2 in. XPS	House wrap	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
9	5 inch Vinyl Lap Siding	1x4 furring strips	1-in. foil-faced polyiso foam board	Drainage wrap weather resistant barrier	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
10	8 inch Wood Composite Lap Siding	1x4 furring strips	1-in. foil-faced polyiso foam board	Drainage wrap weather resistant barrier	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW
11	5 inch Vinyl Lap Siding	1x4 furring strips	Drainage wrap weather resistant barrier over 2 in. high compressive (80) mineral wool over	Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW

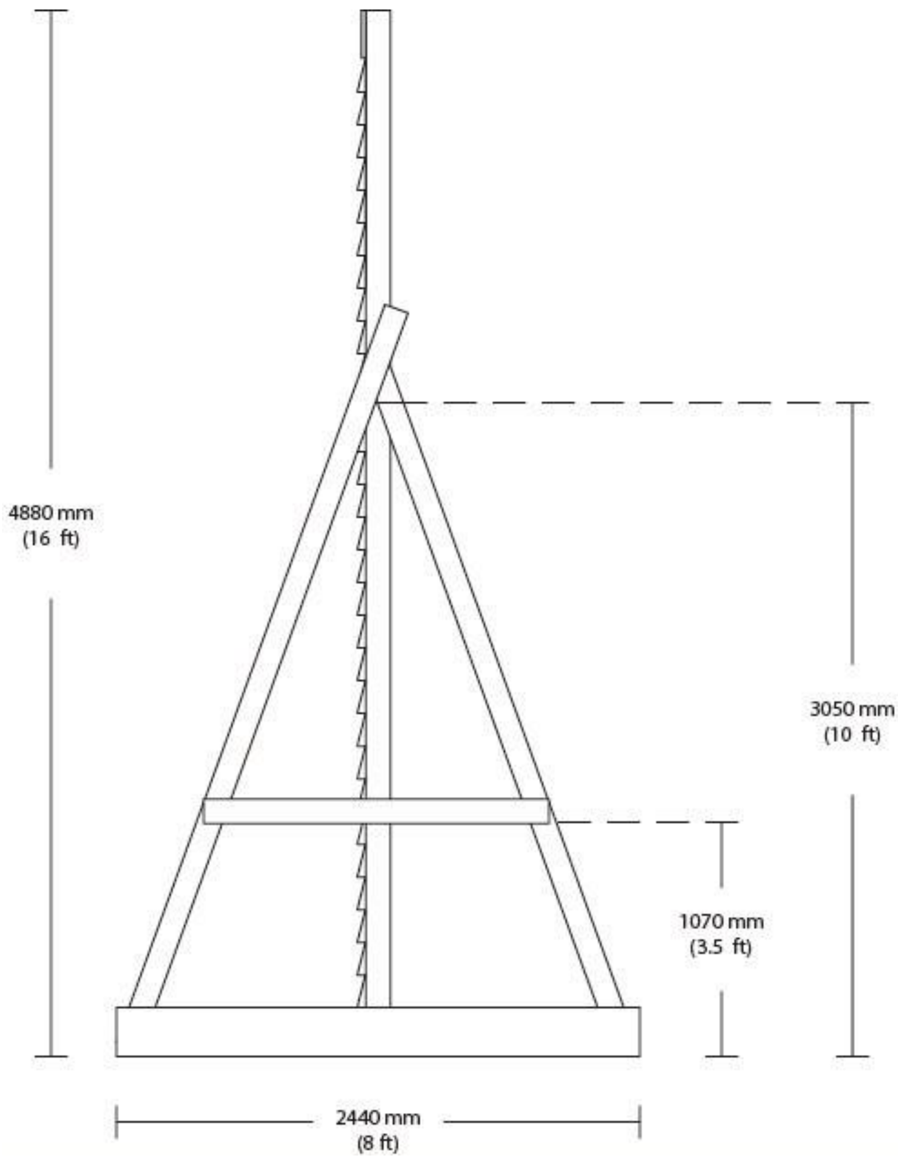

Figure 15 - Test Sample Drawing

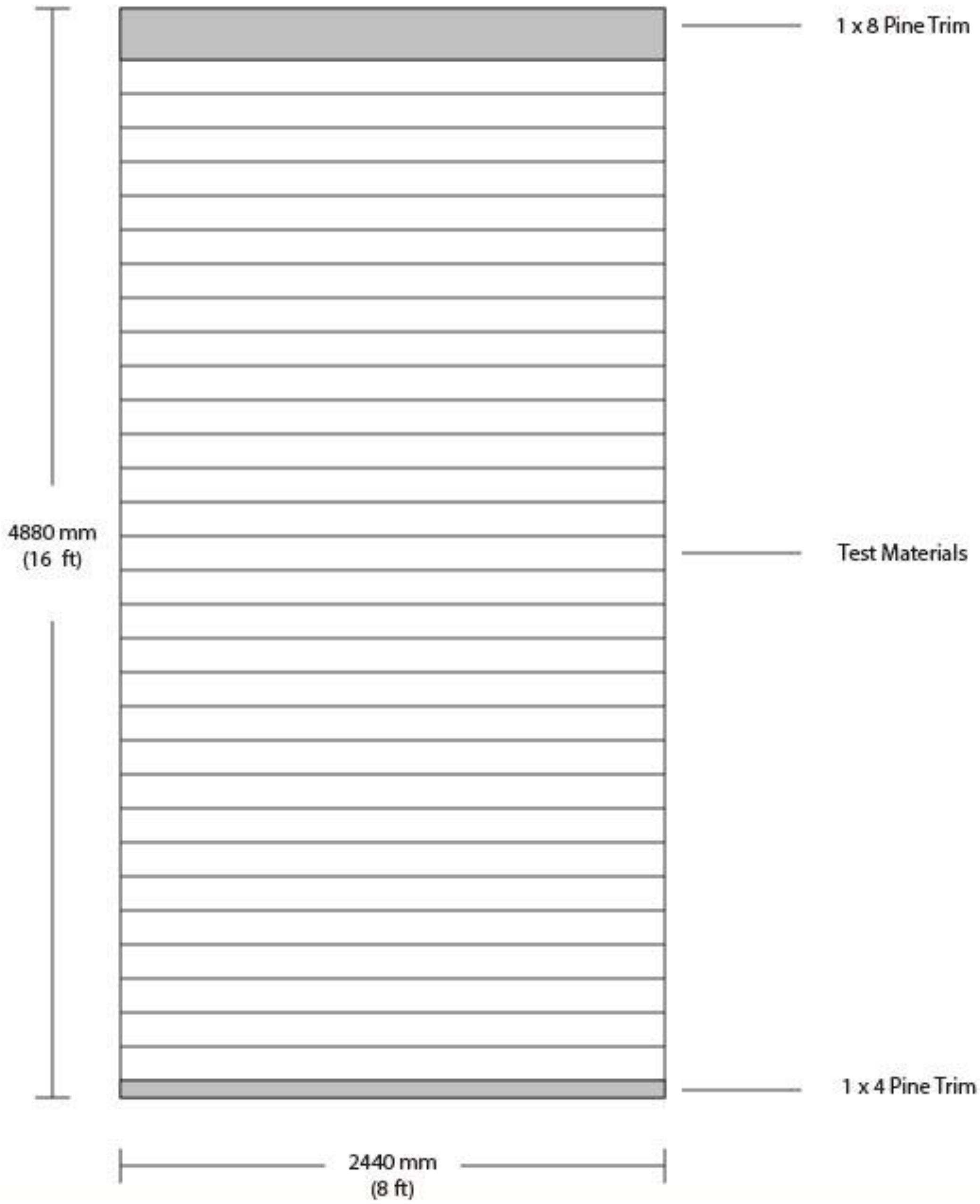

Figure 16 - Test Sample Face Drawing

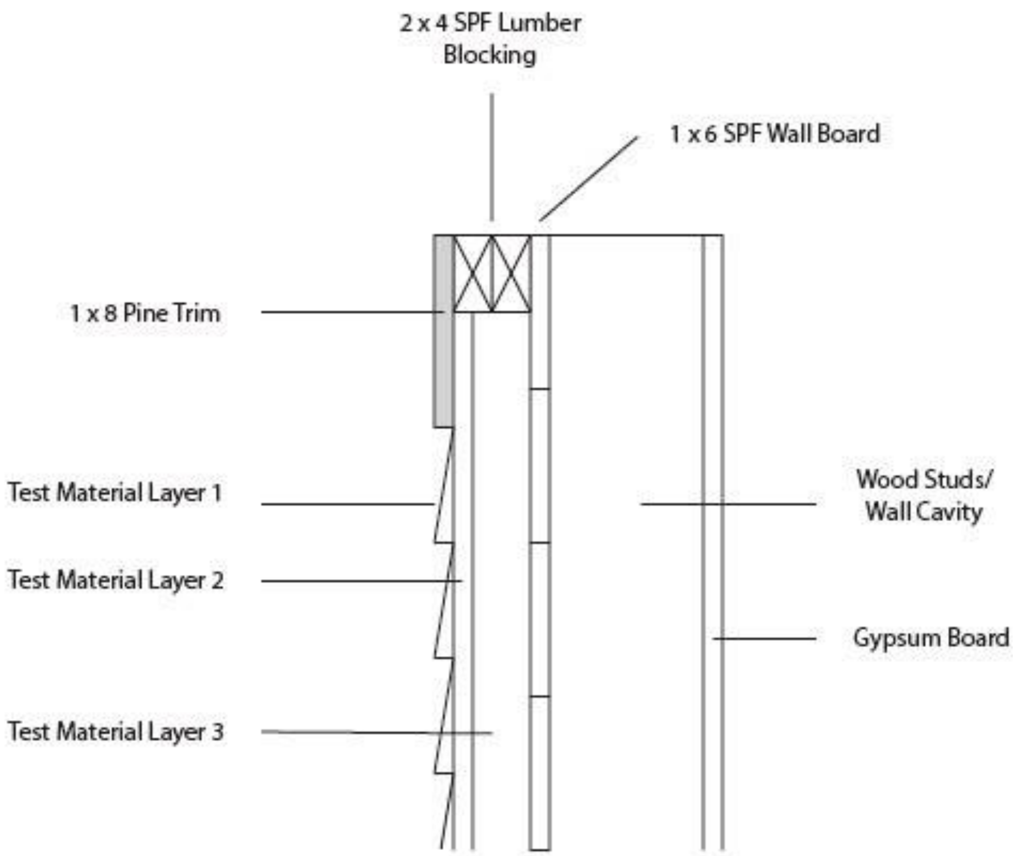

Figure 17 - Test Sample Blocking Detail Drawing

Figure 18 - Photographs of the Test Burner and 75kW Ignition Fire

9. Results

Eleven fire propagation tests were conducted with the parameters provided in Table 5 and Table 6. The times for flame spread to reach the top and a side and test termination of each wall assembly are also provided in the tables. The colored, highlighted cells in the tables indicated layers that burned away exposing the layer underneath during testing.
Figure 19 through
Figure 30 show post-test photographs for each test. The HRR, temperatures, and heat fluxes recorded during testing are plotted in Appendix C: Heat Release Rate Plots through Appendix F: Heat Flux Plots.

Note: The ignition fire tended to lean right due to smoke exhaust system drafts. Slower growing fires were more affected because there was not enough heat driven buoyancy to overcome the drafts.

Table 5 - Test Parameters and Results (1 of 2)

Test #	Cladding	Additional Layer	Additional Layer	WRB	Sheathing	Insulation	Interior	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
1	8 inch Wood Composite Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	17:30	19:08	No
2	8 inch Wood Composite Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	50 kW	Did Not Reach	Did Not Reach	No
3	5 inch Vinyl Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	3:08	4:03	Yes 4:36
4	8 ¼ inch Fiber Cement Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	Did Not Reach	Did Not Reach	No
5	8 inch Wood Composite Lap Siding	Two layers 2.5-in. EPS panels with cable chases and drainage channels	House wrap, 1 inch mineral wool	None	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	7:25 (interior foam) 7:42 (exterior siding)	7:51 (interior foam)	Yes 7:55
6	5 inch Vinyl Lap Siding	Two layers 2.5-in. EPS panels with cable chases and drainage channels	House wrap, 1 inch mineral wool	None	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	4:22	4:22	Yes 4:42

Note: Red cells indicate layers that burned away exposing the layer underneath.

Table 6 - Test Parameters and Results (2 of 2)

Test #	Cladding	Additional Layer	Additional Layer	WRB	Sheathing	Insulation	Interior	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
7*	8 ¼ inch Fiber* Cement Lap Siding	Two layers 2.5-in.* EPS panels with cable chases and drainage channels	House wrap*, 1 inch mineral wool	None*	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	Did Not Reach*	Did Not Reach*	No*
8	5 inch Vinyl Lap Siding	1x4 furring strips with XPS infill	2 in. XPS	House wrap	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	4:20	4:16	Yes 5:56
9	5 inch Vinyl Lap Siding	1x4 furring strips	1-in. foil-faced polyiso foam board	Drainage wrap weather resistant barrier	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	2:58	Did Not Reach	Yes 9:51
10	8 inch Wood Composite Lap Siding	1x4 furring strips	1-in. foil-faced polyiso foam board	Drainage wrap weather resistant barrier	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	9:34 (fuel rich gases above) 10:01 (exterior siding)	Did Not Reach	Yes 18:40
11	5 inch Vinyl Lap Siding	1x4 furring strips	Drainage wrap weather resistant barrier over 2 in. high compressive (80) mineral wool over	Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	Did Not Reach	Did Not Reach	No

*At 10:55, it was identified that the burner had not been pushed into place against the wall and was ~2 in. further than the wall than it should have been. At this time, the burner was pushed into the correct position. After 30 min. with the burner on, three panels of siding were removed. The foam had melted away from the ignition source. The burner was lit again. The fire went into the cavity and through a horizontal chase and up the side.

Note: Red cells indicate layers that burned away exposing the layer underneath.

Figure 19 - Post-test Photographs of Test 1 Wood Composite Siding/Asphalt Paper Wall Assembly with 75 kW Ignition

Figure 20 - Post-test Photographs of Test 2 Wood Composite Siding/Asphalt Paper Wall Assembly with 50 kW Ignition

Figure 21 - Post-test Photographs of Test 3 Vinyl Siding/Asphalt Paper Wall Assembly with 75 kW Ignition

Figure 22 - Post-test Photographs of Test 4 Fiber Cement Siding/Asphalt Paper Wall Assembly with 75 kW Ignition

Figure 23 - Post-test Photographs of Test 5 Wood Composite Siding/EPS/Mineral Wool Wall Assembly with 75 kW Ignition

Figure 24 - Post-test Photographs of Test 6 Vinyl Siding/EPS/Mineral Wool Wall Assembly with 75 kW Ignition

Figure 25 - Post-test Photographs of Test 7 Fiber Cement Siding/EPS/Mineral Wool Wall Assembly with 75 kW Ignition Prior to Panel Removal

Figure 26 - Post-test Photographs of Test 7b Fiber Cement Siding/EPS/Mineral Wool Wall Assembly with 75 kW Ignition After Panel Removal

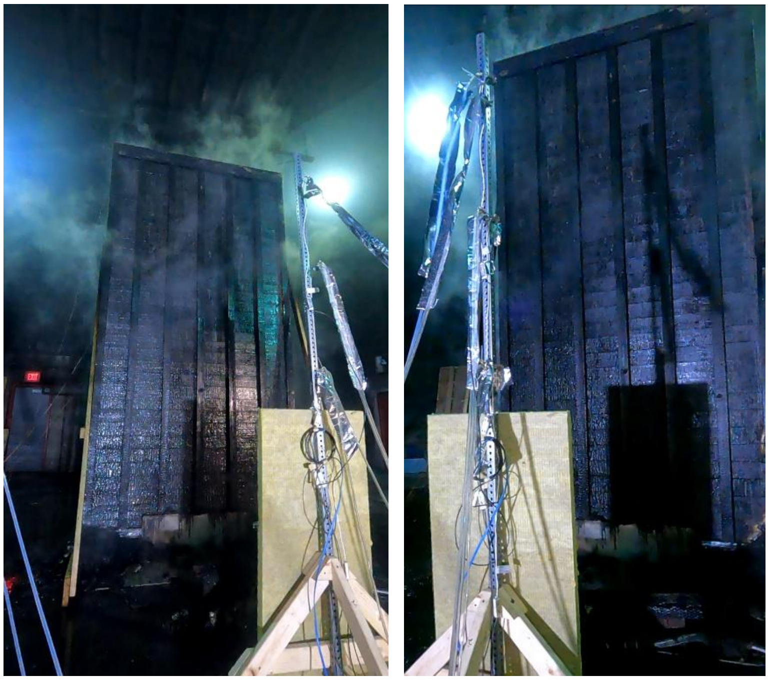

Figure 27 - Post-test Photographs of Test 8 Vinyl Siding/Furring Strips with XPS/XPS Wall Assembly with 75 kW Ignition

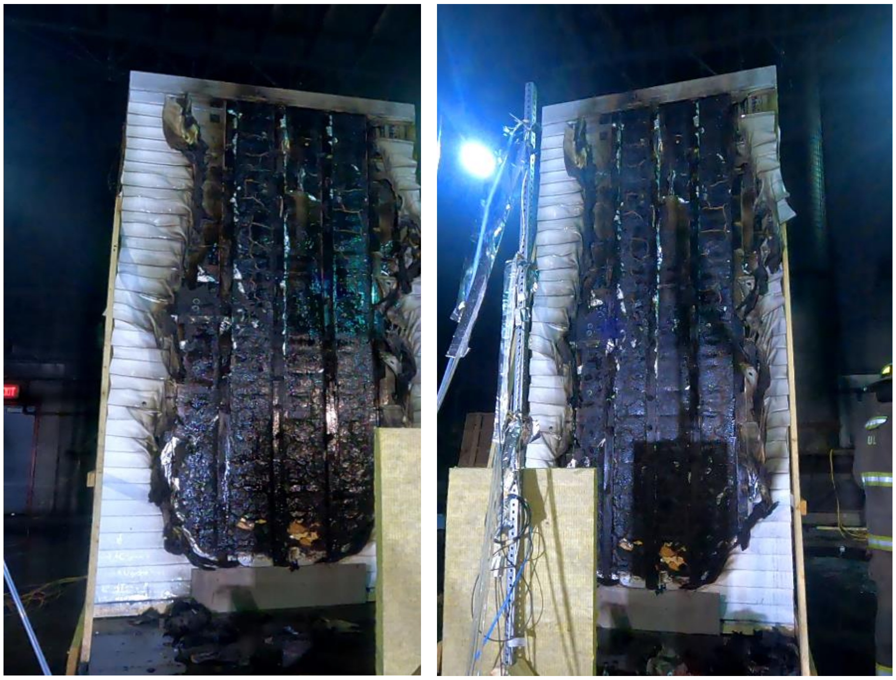

Figure 28 - Post-test Photographs of Test 9 Vinyl Siding/Furring Strips/Foil Polyiso Wall Assembly with 75 kW Ignition

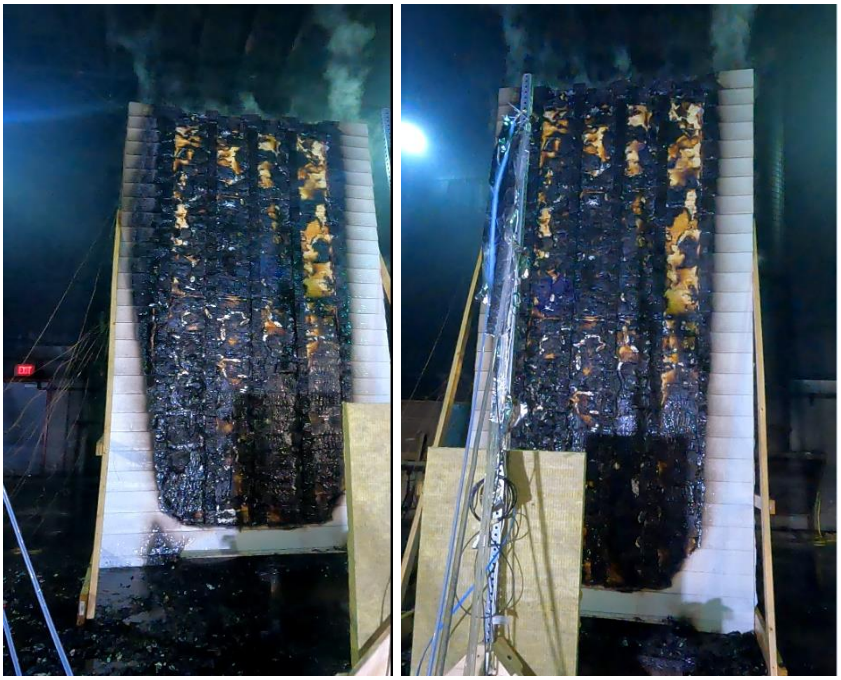

Figure 29 - Post-test Photographs of Test 10 Wood Composite Siding/Furring Strips/Foil Polyiso Wall Assembly with 75 kW Ignition

Figure 30 - Post-test Photographs of Test 11 Vinyl Siding/Furring Strips/Mineral Wool Wall Assembly with 75 kW Ignition

10. Discussion

Based on the flame spread of each test, several initial conclusions can be drawn. The ignition fire size, siding material, intermediate layers, and openings in energy efficient high performing siding can impact flame propagation.

10.1. Ignition Fire Size

As was demonstrated in the UL FSRI study and reflected in the early UL Solutions experiments, the size of the ignition fire impacts the performance of the test sample. In Test 1 and Test 2, wood composite siding over the PNNL baseline wall with asphalt paper was tested as a reasonable baseline performing construction. In Test 1 with a 75 kW burner, the flame spread to the top of the sample in 17-1/2 minutes of the 20 minute test duration. In Test 2 with a 50 kW burner, the flame spread reached only half way up the test sample over the same 20 minute exposure period. Table 1 shows the test results for each. A photograph of each is provided in
Figure 31.

The objective of these two tests was to corroborate the appropriateness of the 75 kW exposure established in the early UL Solutions study using a baseline construction. At 75 kW, the flame spread reached the edges of the test sample around the 20 minute mark. With a 50 kW exposure, the baseline sample was not significantly challenged; therefore, 75 kW was used in all remaining tests in this study. Choosing an appropriate exposure fire size should allow for differentiation in performance between samples. The differentiation in the performance can be seen in the flame spread times to the tops and sides of the samples in Table 5 and Table 6.

Table 7 - Test Result Summary for Similar Wall Assemblies with Different Fire Exposure Sizes

Test #	Brief Description	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
2	Wood composite siding/asphalt paper	50 kW	Did Not Reach	Did Not Reach	No
1	Wood composite siding/asphalt paper	75 kW	17:30	19:08	No

Figure 31 - 20 Minute Ignition Fire Exposure 50 kW (Left) versus 75 kW (Right)

10.2. Wall Size

In terms of wall size for a fire test method, the wall should be tall and wide enough to allow the differentiation of fire performance results of the assemblies. In Table 4 and Table 5, we see that the time to the top and sides of the wall assemblies ranged from “did not reach” to “3 to 4 minutes” with several test times falling in between. This indicated a reasonable differentiation of performance results.

Additionally, the laboratory in which the testing was conducted has a smoke abatement system with a draw of 60,000 SCFM. The smoke abatement system must exhaust successful and unsuccessful fire tests. In this test series, the fire size ranged from 50 kW to 6,000 kW (6 MW). As a result, there were drafts that caused the ignition fire to favor the right side. The drafts were more impactful for the smaller, slower growing fires as the heat driven buoyancy from the fire was not sufficient to overcome the drafts. This was observed in Test 1 and 2, which had the slowest fire spread (
Figure 31). In these tests, the fire did not reach the side of the assembly prior to reaching the top of the assembly (Table 1). The width of the assembly was sufficient to differentiate good performing assemblies from poor performing assemblies. This was the case even in light of inadvertent draft induced leaning of the flames for Tests 1 and 2.

10.3. Siding Material

In discussions with the advisory panel for this project, it was identified that the type of siding was not the most critical component to the energy saving performance of homes. However, siding can significantly impact the fire propagation performance of the exterior wall. Two sets of similar wall assemblies were tested, varying the siding between vinyl, wood composite, and fiber cement. The test result summary for each set is provided in Table 8. The difference in performance can also be seen in the post testing photographs in
Figure 32 and
Figure 33. In each set of photographs only the siding was different. Fiber cement did not result in flame spread to the top or sides of the sample over the test period. Both the wood composite and vinyl siding had flame propagation to the top and sides of the wall assemblies. The vinyl siding assemblies had propagation to the top and sides more quickly than the wood composite siding assemblies.

Table 8 - Test Result Summary for Similar Wall Assemblies with Different Siding

Test #	Brief Description	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
4	Fiber cement siding/asphalt paper	75 kW	Did Not Reach	Did Not Reach	No
1	Wood composite siding/asphalt paper	75 kW	17:30	19:08	No
3	Vinyl siding/asphalt paper	75 kW	3:08	4:03	Yes 4:36
7*	Fiber cement siding/EPS/mineral wool	75 kW	Did Not Reach*	Did Not Reach*	No*
5	Wood composite siding/EPS/mineral wool	75 kW	7:25 (interior foam) 7:42 (exterior siding)	7:51 (interior foam)	Yes 7:55
6	Vinyl siding/EPS/mineral wool	75 kW	4:22	4:22	Yes 4:42

*At 10:55, it was identified that the burner had not been pushed into place against the wall and was ~2 in. further than the wall than it should have been. At this time, the burner was pushed into the correct position. The burner remained on for 30 minutes.

Figure 32 - Side by Side Post-test Photographs from Test 1 and Tests 3-4 of Similar Wall Assemblies with Different Siding - Fiber Cement, Wood Composite, and Vinyl (Left to Right)

Figure 33 - Side by Side Post-test Photographs from Tests 5-7 of Similar Wall Assemblies with Different Siding - Fiber Cement, Wood Composite, and Vinyl (Left to Right)

10.4. Intermediate Layers

Siding was not the sole determining factor in whether the test wall assembly would or would not have flame propagation to the top or sides of the assembly during the test. The intermediate layers between the siding and the sheathing also played a role in the overall fire performance in either promoting or slowing flame spread.

In Test 1 wood composite siding was tested over asphalt paper and in Test 10 it was tested over furring strips and polyiso boards. In Test 10 the flame propagated to the top of the wall assembly 7.5 minutes faster than in Test 1 and the vertical flame spread was significantly more extensive. The test result summary is provided in Table 9 and post-test photograph comparison in
Figure 34.

Similarly, in Test 3 vinyl siding was tested over asphalt paper and in Test 11 it was tested over furring strips and mineral wool. In Test 3 the vinyl siding and asphalt paper had burned completely off the wall assembly in 4.5 minutes. In Test 11 the flame spread was limited to the area around the burner and never reached the top or sides of the assembly. The test result summary is provided in Table 10 and post-test photograph comparison in
Figure 35.

Table 9 - Test Result Summary for Different Wall Assemblies with Wood Composite Siding

Test #	Brief Description	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
1	Wood composite siding/asphalt paper	75 kW	17:30	19:08	No
10	Wood composite siding/furring strips/foil polyiso	75 kW	9:34 (fuel rich gases above) 10:01 (exterior siding)	Did Not Reach	Yes 18:40

Figure 34 - Side by Side Post-test Photographs of Two Wood Composite Siding Tests (Test 1 & 10) with Differing Interior Layers

Table 10 - Test Result Summary for Different Wall Assemblies with Vinyl Siding

Test #	Brief Description	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
3	Vinyl siding/asphalt paper	75 kW	3:08	4:03	Yes 4:36
11	Vinyl siding/furring strips/mineral wool	75 kW	Did Not Reach	Did Not Reach	No

Figure 35 - Side by Side Post-test Photographs of Two Vinyl Siding Tests (Test 3 & 11) with Differing Interior Layers

10.5. Openings in Fire Resistant Siding

Fiber cement lap siding performed well in the two tests conducted in this series. In each test, there was no sustained flame attachment to the siding. However, in Test 7, after the test method was completed, panels were intentionally removed to expose the interior EPS foam underneath. When the burner was reignited, the fire quickly spread into the wall and followed open, drainage/cable channels in the foam. The fire spread to the side and then the top of the wall assembly without any flame spread over the exterior fiber cement siding. Photographs on the flame spread are shown in Figure 36. Photographs before and after the panels were removed are provided in Figure 37.

The purpose of this test series was to evaluate exterior flame propagation. While this is an extreme example, penetrations in siding can alter the fire performance of wall assemblies. Penetrations can be caused by window or door installations, installation of electrical outlets, and wear and tear from age, for example. The impact of penetrations on wall assembly fire performance is an area of potential future study.

Figure 36 - Photograph of Test 7 with Fiber Cement Siding Panels Removed Showing Interior Fire Spread

Figure 37 - Test 7 Photographs of After the First Test Exposure (Left) and After the Second Test Exposure with Fiber Cement Siding Panels Removed (Right)

10.6. Heat Release Rates

The HRR data for each test with a 75 kW ignition source is shown in
Figure 38. While several tests were terminated early (Tests 3, 5, 6, 8, 9, and 10), the data does provide some insight into the difference in fire growth and size between more and less combustible assemblies. The highest recorded HRR was 6,000 kW and the lowest was 200 kW (including the 75 kW contribution from the burner).

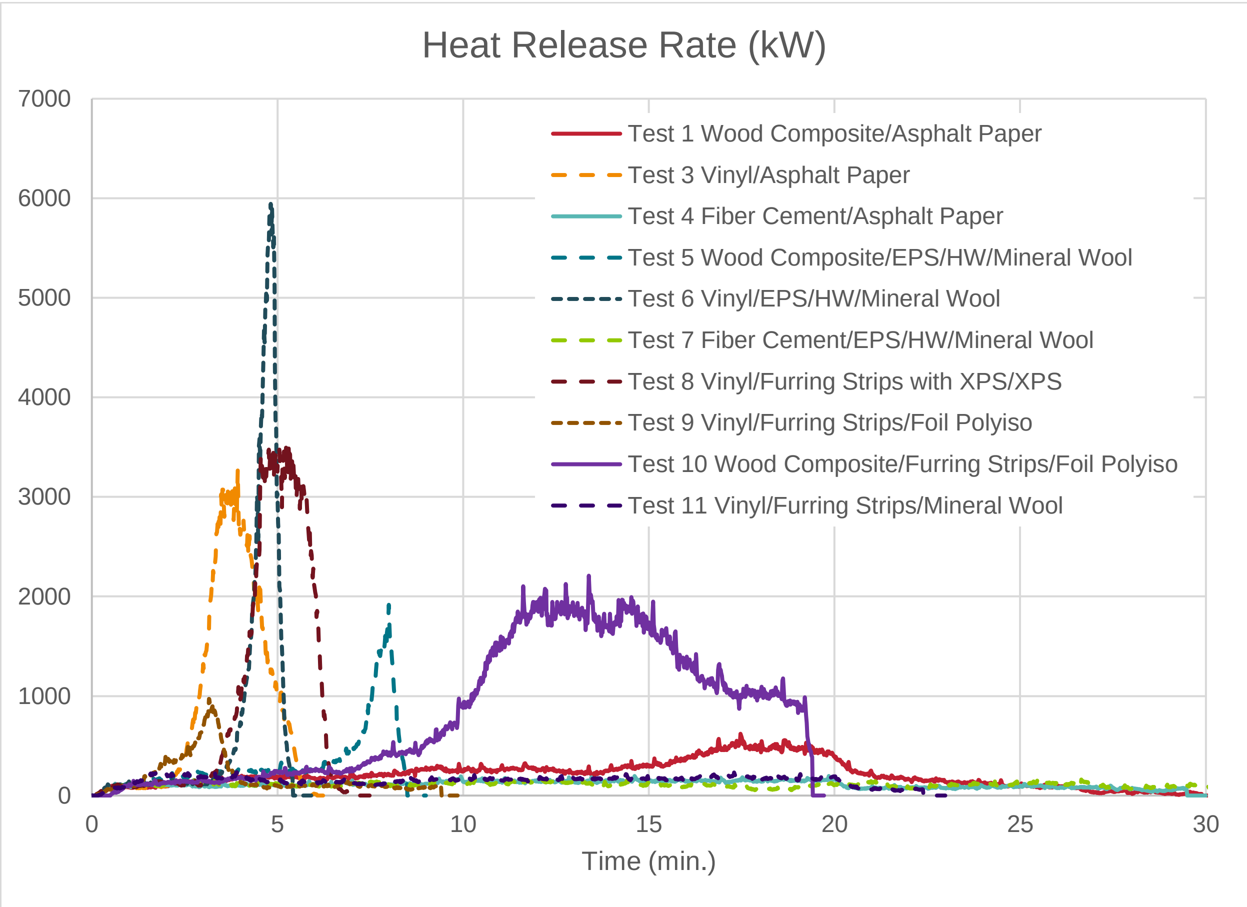

Figure 38 - Heat Release Rates over Time for Tests with 75 kW Ignition Source

10.7. Heat Fluxes

The highest heat fluxes measured in the test series were recorded in Test 6 - the wall assembly with vinyl siding, wood furring strips and EPS insulation, over house wrap, and a layer of mineral wool. The peak heat flux, 24 kW/m^2, was recorded in the center of the wall assembly, 8 ft (2.4 m) away from the assembly, and 8 ft (2.4 m) above the top of the burner. At 8 ft (2.4 m) from the center of the wall assembly, heat fluxes in excess of 20 kW/m^2 were recorded at all three elevations. 20 kW/m^2 is commonly accepted as the heat flux threshold for the onset of flashover within a room [15]. It is possible to ignite another structure at this distance from the wall assembly.

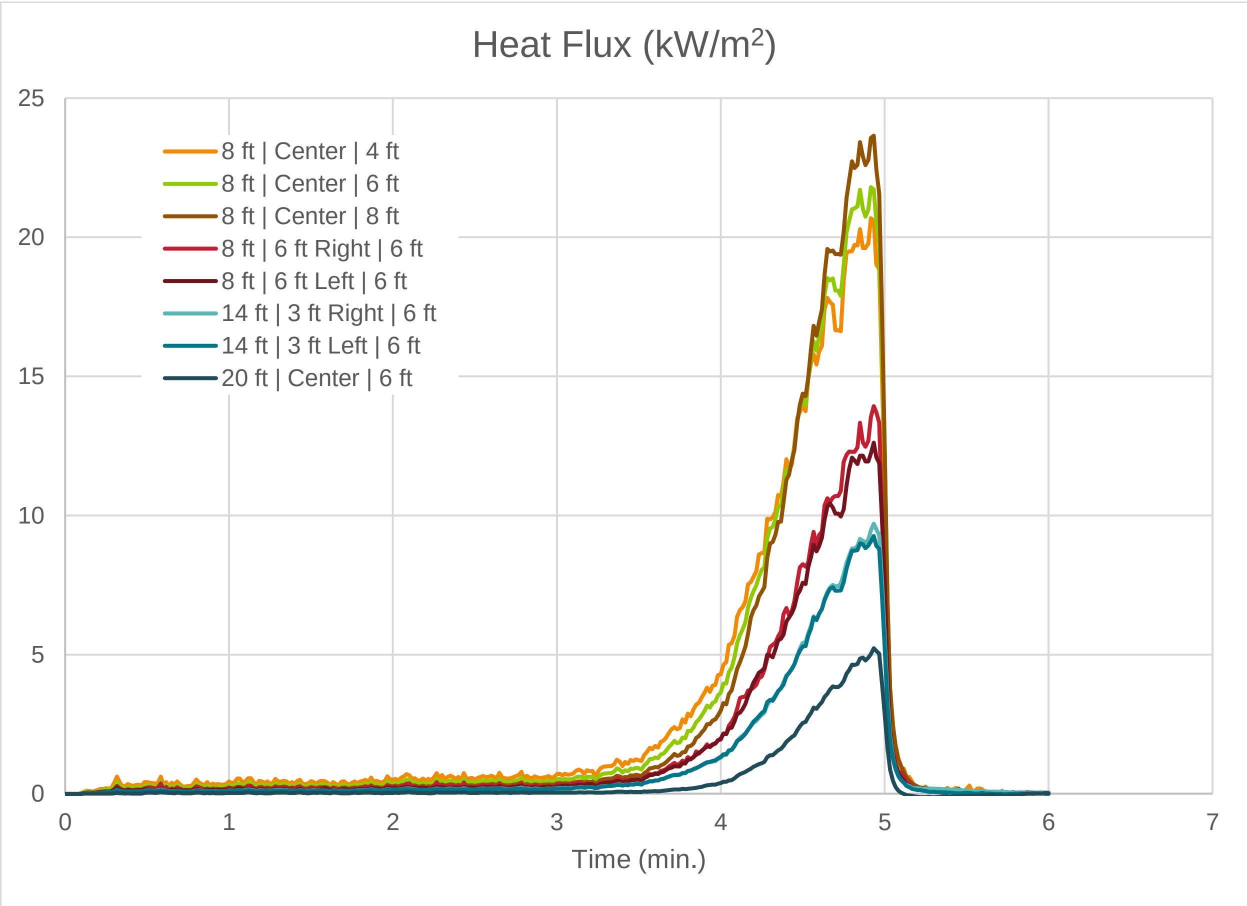

Figure 39 - Test 6 Vinyl Siding/EPS/Mineral Wool Heat Flux Plot

11. Observations

The research conducted provided a test method to assess the fire propagation performance of residential wall assemblies. During the testing several observations were made as follows:

1. The choice of siding can impact the fire performance of wall assemblies with results ranging from no sustained fire to rapid flame spread.
2. Vinyl siding has a tendency to melt and fall away from the wall assembly. This exposes the materials behind the siding to direct flame exposure.
3. Noncombustible siding, such as fiber cement siding, can provide a strong, fire-resistant outer shell for the wall assembly. However, inevitability there will be penetrations in the siding for cables, outlets, etc. or siding board misalignments that will provide an opening for an exterior fire to move past the siding and into the wall interior. The fiber cement siding has the ability to maintain its integrity while a fire consumes the interior of the wall assembly, potentially hiding the extent and severity of the fire.
4. Applying combustible insulation outside of the house studs was suggested as a means to increase energy efficiency. A key difference between installing insulation outside of the studs versus inside of the studs is that the studs, midspan breaks, oriented strand board (OSB), and gypsum board create fire-resistant compartmentalization of the potentially more flammable insulation. However, when applying continuous insulation there is no compartmentation of the insulation. Fire can burn through the insulation and directly up into the eaves and into the interior of the structure.
5. In some cases, furring strips were used to secure the additional energy efficient layers to the building studs. The space between the furring strips was examined both empty and filled with combustible insulation, in both cases providing a potential unobstructed path of fire to the eaves.
6. Other innovative features were added to increase ventilation and to minimize humidity/mold in the assemblies, such as house wrap with drainage features and insulation with holes running the length and height of the panel. These features have a potential to provide oxygen for fire spread and pathways for fire to spread.
7. Based on the data collected, the Test 6 wall assembly is capable of igniting structures 8 ft. away from the wall assembly. This was the case with the simulated space between the structures being clear of combustibles, such as plants, outdoor storage, cars, and decks. Additional combustibles will increase the likelihood of building-to-building fire spread.

12. Summary

The DOE has identified fire performance as a significant consideration for market acceptance of emerging energy efficient, retrofit solutions for residential buildings [2]. This study focused on evaluating the exterior fire performance of select solutions and in the process develop a residential fire propagation test method.

NFPA 285 is currently used to evaluate the fire performance of exterior wall assemblies for multi-story commercial buildings where the fire originates from the interior. However, this test method is not representative of a typical exterior house fire exposures. In WUI fires, houses are likely to catch fire from fire brands igniting shrubs, debris, or outdoor storage along the base of the wall. ASTM E 2707 was created to simulate this scenario and evaluate fire penetration into residential wall assemblies. However, it did not address fire propagation up the exterior. In 2010, UL FSRI identified exterior wall flame propagation as a vector by which fire can enter attic spaces and ultimately spread into the house. Their study prompted the ASTM Committee E05.14 to pursue developing a test method to address fire propagation. UL Solutions ran initial research funded by industry to begin to frame a possible propagation test method based on ASTM E 2707. Based on the prior UL FSRI study and PNNL's extensive study of retrofit solutions and adoptability, 10 wall assemblies were selected and tested using the method framed by UL Solutions.

The HRRs, temperatures within the wall layers, and heat flux exposures from the wall assemblies were studied. The difference in HRRs ranged from 200 kW to 6,000 kW, with the 6,000 kW test being terminated early. Noncombustible materials contributed to the performance of the 200 kW tests, while combustible materials and ventilation features contributed to the 6 MW fire. In the latter, heat fluxes in excess of 20 kW/m^2 were observed 8 ft (2.4 m) away from the wall assembly, indicating the potential for fire spread to adjacent structures.

Overall, 11 tests were conducted (one test was repeated with a different fire size). Testing was conducted with a 20-minute, 75 kW fire exposure at the base of an 8 ft by 16 ft (2.4 m by 4.9 m) size wall assembly. The results are provided in Table 11 and Table 12. There were a variety of fire spread times to the top and sides of the wall sample, indicating differentiation in performance. Flame spread to the top and sides of the wall assembly could potentially be used as performance criteria in the future. A common base wall, as described in section Test Parameters and Procedure pg. 42, was used in each test. The base wall was designed to intentionally prevent the burn through of the sheathing that was seen in the early UL Solutions research where the fire spread internally up the wall cavity. This allows for the test method to assess the exterior flame propagation behavior and not penetration as was intended.

Additional study is needed to better understand how individual energy efficient features of emerging residential wall assembly technologies impact fire behavior. However, this data is critical to advancement of a standardized ASTM test method to evaluate the flame propagation performance of residential wall assemblies.

Table 11 - Test Parameters and Results (1 of 2)

Test #	Cladding	Additional Layer	Additional Layer	WRB	Sheathing	Insulation	Interior	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
1	8 inch Wood Composite Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	17:30	19:08	No
2	8 inch Wood Composite Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	50 kW	Did Not Reach	Did Not Reach	No
3	5 inch Vinyl Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	3:08	4:03	Yes 4:36
4	8 ¼ inch Fiber Cement Lap Siding			Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	Did Not Reach	Did Not Reach	No
5	8 inch Wood Composite Lap Siding	Two layers 2.5-in. EPS panels with cable chases and drainage channels	House wrap, 1 inch mineral wool	None	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	7:25 (interior foam) 7:42 (exterior siding)	7:51 (interior foam)	Yes 7:55
6	5 inch Vinyl Lap Siding	Two layers 2.5-in. EPS panels with cable chases and drainage channels	House wrap, 1 inch mineral wool	None	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	4:22	4:22	Yes 4:42

Note: Red cells indicate layers that burned away exposing the layer underneath.

Table 12 - Test Parameters and Results (2 of 2)

Test #	Cladding	Additional Layer	Additional Layer	WRB	Sheathing	Insulation	Interior	Fire Size	Flame Propagation @ 16' Time, mm:ss	Flame Propagation @ Side Time, mm:ss	Test Terminated Early?
7*	8 ¼ inch Fiber* Cement Lap Siding	Two layers 2.5-in.* EPS panels with cable chases and drainage channels	House wrap*, 1 inch mineral wool	None*	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	Did Not Reach*	Did Not Reach*	No*
8	5 inch Vinyl Lap Siding	1x4 furring strips with XPS infill	2 in. XPS	House wrap	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	4:20	4:16	Yes 5:56
9	5 inch Vinyl Lap Siding	1x4 furring strips	1-in. foil-faced polyiso foam board	Drainage wrap weather resistant barrier	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	2:58	Did Not Reach	Yes 9:51
10	8 inch Wood Composite Lap Siding	1x4 furring strips	1-in. foil-faced polyiso foam board	Drainage wrap weather resistant barrier	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	9:34 (fuel rich gases above) 10:01 (exterior siding)	Did Not Reach	Yes 18:40
11	5 inch Vinyl Lap Siding	1x4 furring strips	Drainage wrap weather resistant barrier over 2 in. high compressive (80) mineral wool over	Asphalt-impregnated building paper	1x6 Spruce/Pine boards	None	5/8 inch Gypsum wall board	75 kW	Did Not Reach	Did Not Reach	No

*At 10:55, it was identified that the burner had not been pushed into place against the wall and was ~2 in. further than the wall than it should have been. At this time, the burner was pushed into the correct position. After 30 min. with the burner on, three panels of siding were removed. The foam had melted away from the ignition source. The burner was lit again. The fire went into the cavity and through a horizontal chase and up the side.

Note: Red cells indicate layers that burned away exposing the layer underneath.

13. Recommendations

Based on the results of this study, several recommendations are made:

1. When energy efficient solutions are being developed, fire protection engineers and the fire service should be involved in the design process from the beginning to maximize the safety of the solutions and prepare the fire service for changing fire ground conditions. Codes, standards, and regulations often follow innovation; consequently, current fire safety codes, standards, and regulations can often have gaps relative to addressing the performance of these innovative technologies. In some cases, this delay in established requirements results in market barriers for the technologies. In other cases, not fully understood technologies that might comply to the existing codes, standards, and regulations are adopted with disastrous consequences. The Society of Fire Protection Engineers (SFPE) Foundation developed a grand challenge initiative to identify and address the most pressing fire challenges. The results can be found here - https://www.sfpe.org/foundation/gci/white-papers. Three of the four challenges identified directly or indirectly reference the fire hazards posed by energy efficient technologies.
2. The impact of a lack of compartmentation, increased ventilation within the assembly, direct flame exposure to the interior assembly layers, and potential for hidden interior wall fire spread is not well understood and can dramatically change the anticipated fire behavior. Additionally, higher heat fluxes can impact building separation distances and building-to-building fire spread. Each of these concerns can lead to disastrous and potentially deadly outcomes for homeowners. These areas require further study.
3. Fire fighters need to be aware of the impact of combustible exterior wall design, especially those residential locations with engineered energy performance enhancements. They should be aware of the potential impact of rapid fire spread and structure-to-structure propagation.
4. Given that these energy-efficient solutions are intended for residential structures, having publicly available fire performance information and fire-informed installation guidance will be critical. In many commercial applications, wall assemblies are governed by requirements that provide specific guidance and details for designers and installers to ensure that the wall assemblies are constructed as intended to achieve the necessary fire resistance. In most cases, the fire performance of the commercial wall designs are tested, as required, and documented through test reports, engineering analysis, or certified by third party organizations. The final construction is reviewed by an authority having jurisdiction to ensure compliance. When commercial wall assemblies are installed incorrectly or need modifications outside of the documented specifications, the financial means are available to conduct fire testing on a specific wall assembly and pay a consultant for an engineering judgment to ensure the fire performance of the wall assembly is unaffected. However, for homeowners and local permitting offices, knowledge and awareness of the fire performance and the potential for small changes to drastically change wall assembly fire performance is limited and the resources are not available to inform decision making. National energy-efficient technology and adoption guidance needs to be reviewed from a fire safety perspective, and revised so that consumers are making energy smart and fire safe choices.

14. Future Study

The following are suggestions for areas of future study:

1. Short term needs: Subject the wall materials used in this study to bench scale testing, at a minimum cone calorimeter testing (ASTM E1354), to develop heat and smoke release rates preserving critical material information for future use. This information can be used later to inform fire models, engineering judgements, and performance-based design which can be used to develop public guidance.
2. Mid-term needs: Develop an understanding of how impactful the innovative features, materials, ventilation changes are on fire performance by identifying or developing a small to mid-sized scale fire test method to screen combinations. This data can be simultaneously used to validate fire modeling to increase the applicability of fire models for wall assemblies, providing an alternative for studying fire performance of wall assemblies without destructive testing. A public database of the information and data and simplified public guidance for wall assembly construction and hazards should be developed.
3. Long term, strategic needs: Develop a 10-year plan to identify and address the fire service's energy efficient technology fire safety concerns, similar to the SFPE 10-year plan, and bring the DOE strategy, goal, and funding in alignment with the plan.

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[16] National Fire Protection Association, "Structural Fire Safety in One-and Two-Family Dwellings," in *Fire Protection Handbook*, Quincey, MA, National Fire Protection Association, 2008, pp. 19-58.

Appendix A: Early UL Solutions Testing Data

Photographs

Figure 40 - Post-test Photograph of Test 1 Vinyl Siding/House Wrap/OSB Wall Assembly with 100 kW Ignition

Figure 41 - Post-test Photograph of Test 2 Vinyl Siding/Construction Paper/OSB Wall Assembly with 40 kW Ignition

Figure 42 - Post-test Photograph of Test 3 Vinyl Siding/House Wrap/OSB Wall Assembly with 25 kW Ignition

Figure 43 - Post-test Photograph of Test 4 Vinyl Siding/1 in. XPS/OSB Wall Assembly with 100 kW Ignition

Figure 44 - Post-test Photograph of Test 5 Cedar Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition

Figure 45 - Post-test Photograph of Test 6 Vinyl Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition

Figure 46 - Post-test Photograph of Test 7 Cedar Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition

Figure 47 - Post-test Photograph of Test 8 Vinyl Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition

Heat Release Rate Plots

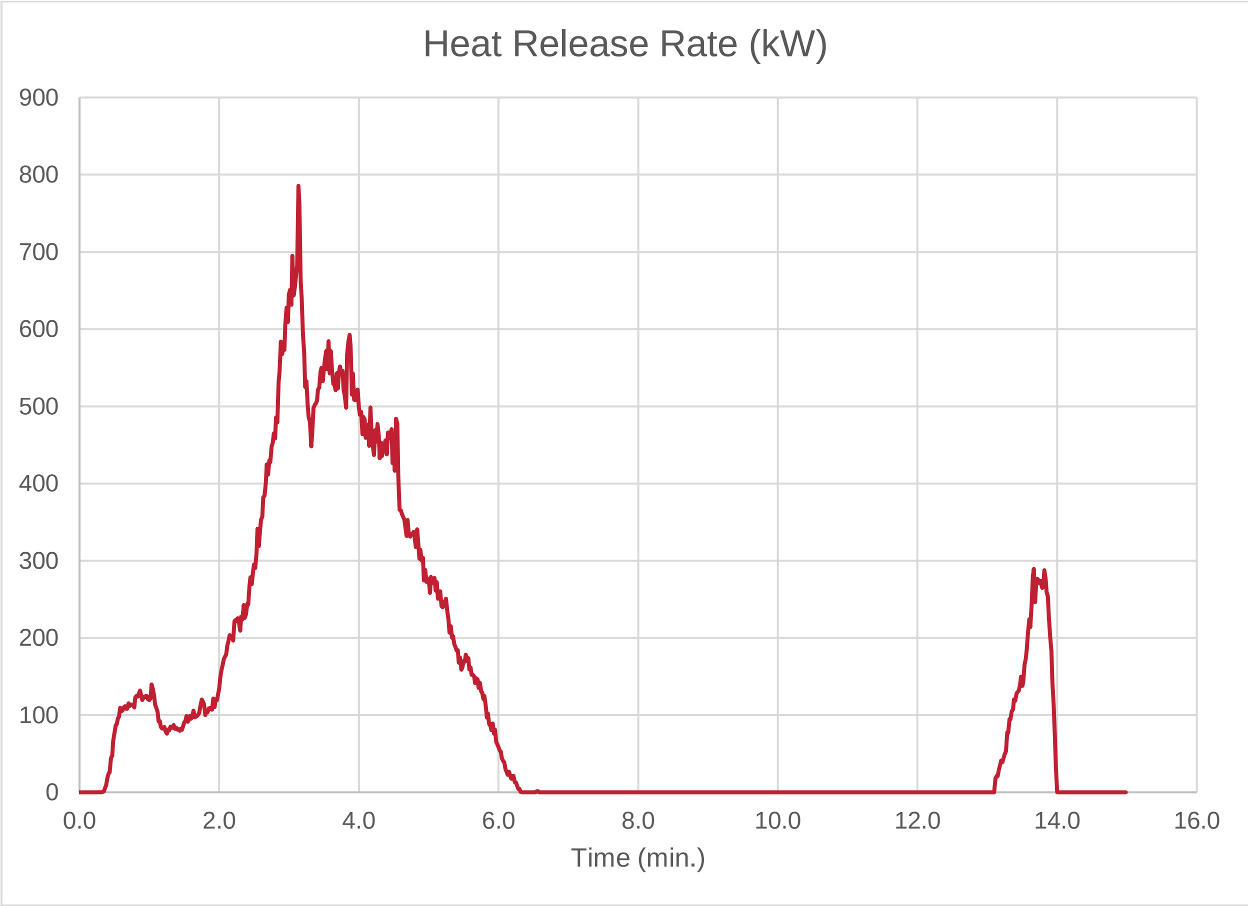


Figure 48 - Test 1 Vinyl Siding/House Wrap/OSB Wall Assembly with 100 kW Ignition Heat Release Rate Plot

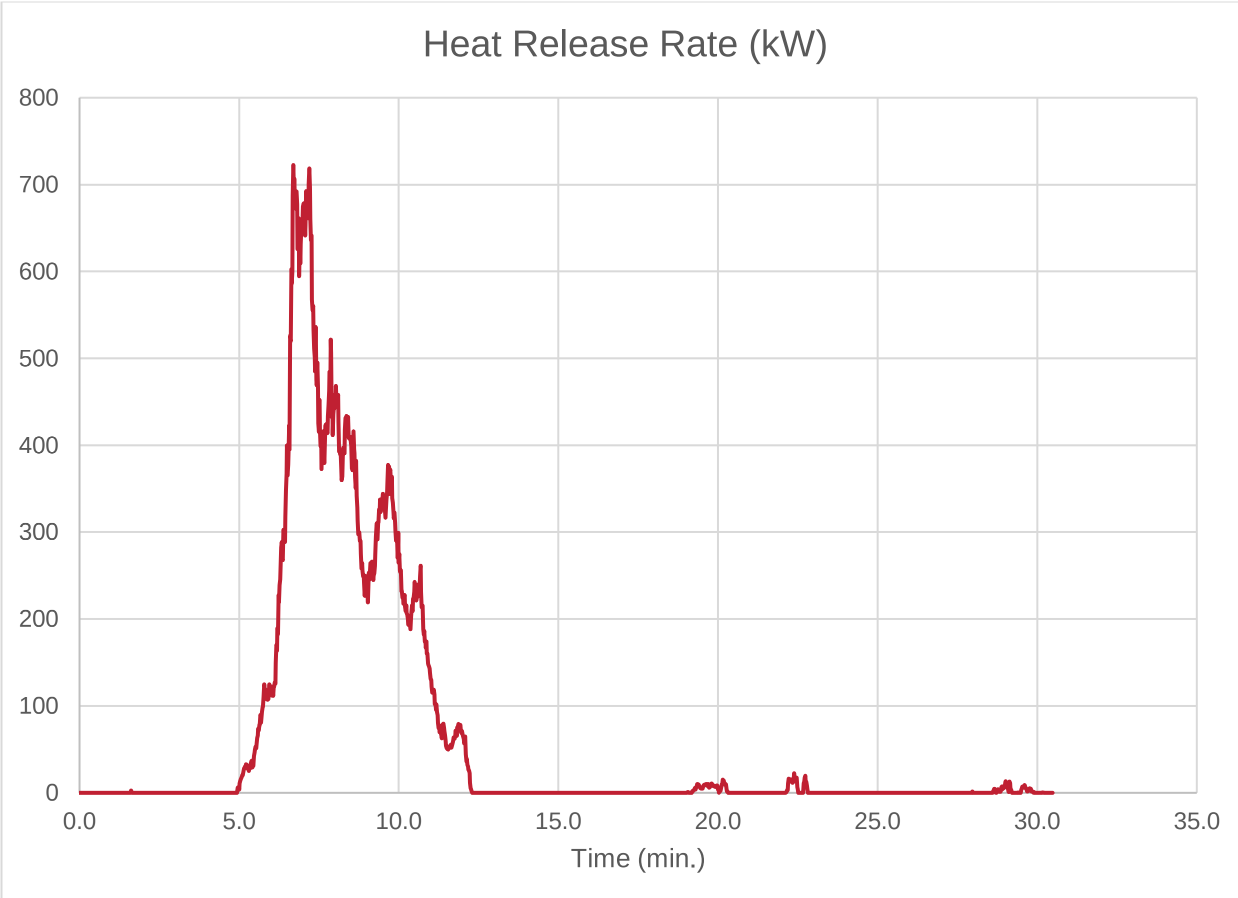


Figure 49 - Test 2 Vinyl Siding/Construction Paper/OSB Wall Assembly with 40 kW Ignition Heat Release Rate Plot

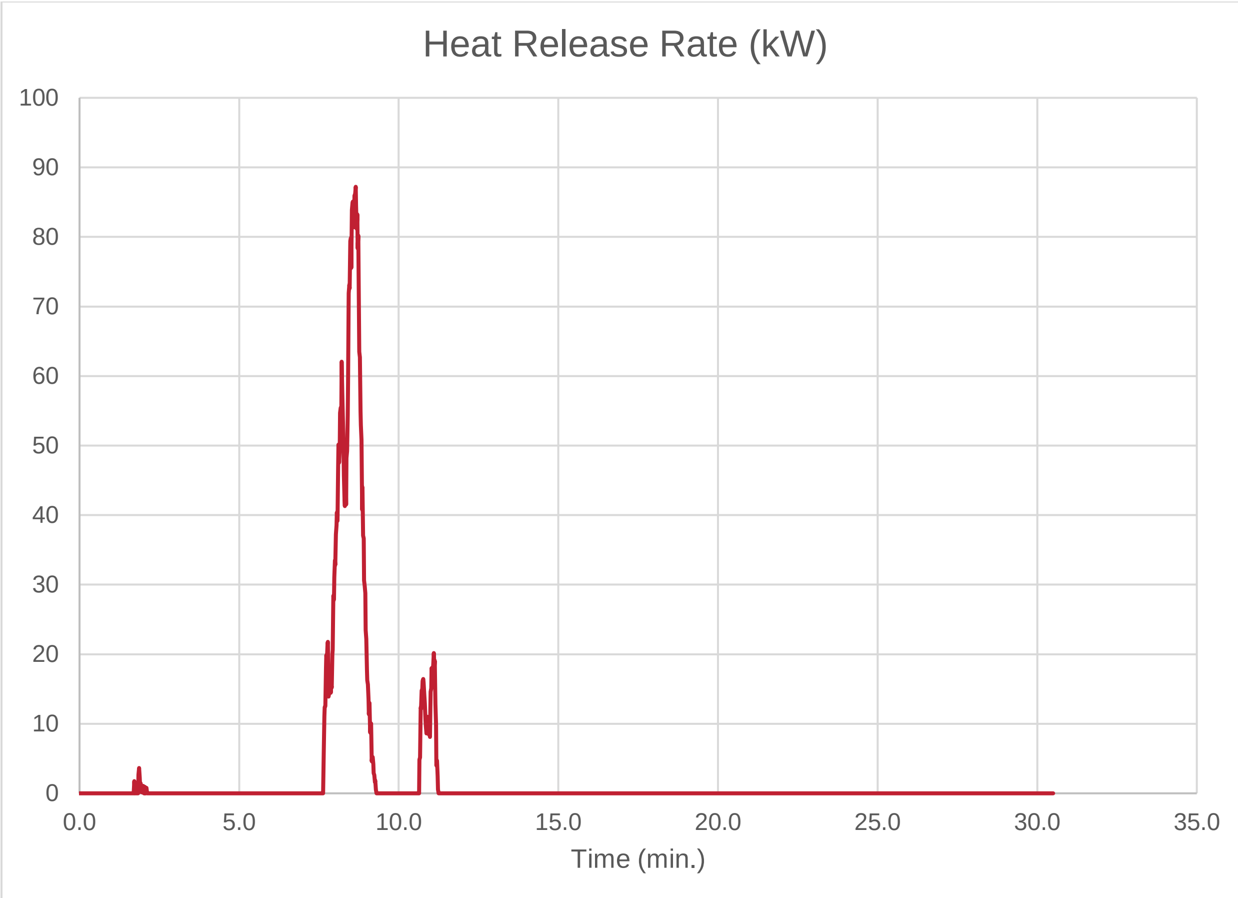


Figure 50 - Test 3 Vinyl Siding/House Wrap/OSB Wall Assembly with 25 kW Ignition Heat Release Rate Plot

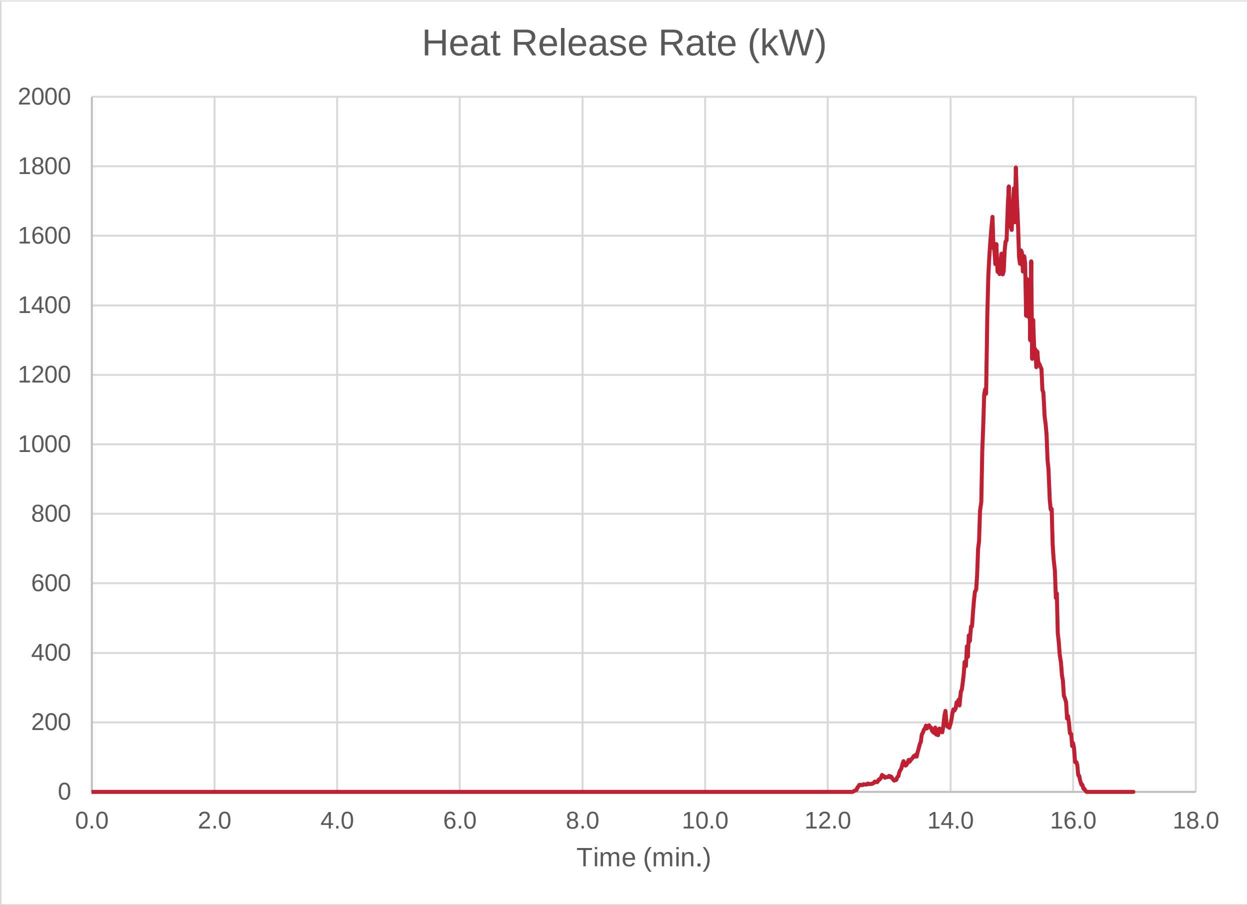


Figure 51 - Test 4 Vinyl Siding/1 in. XPS/OSB Wall Assembly with 100 kW Ignition Heat Release Rate Plot

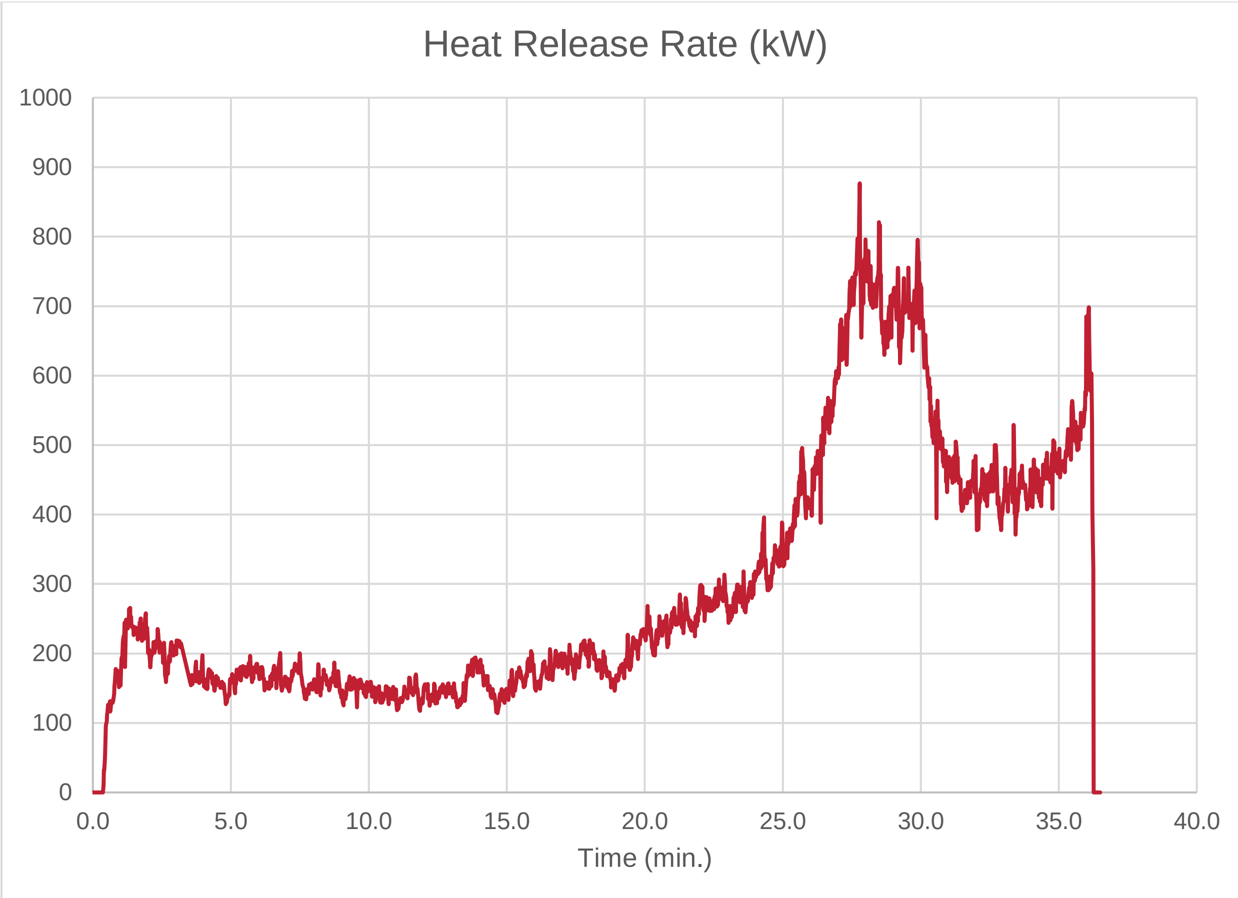


Figure 52 - Test 5 Cedar Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition Heat Release Rate Plot

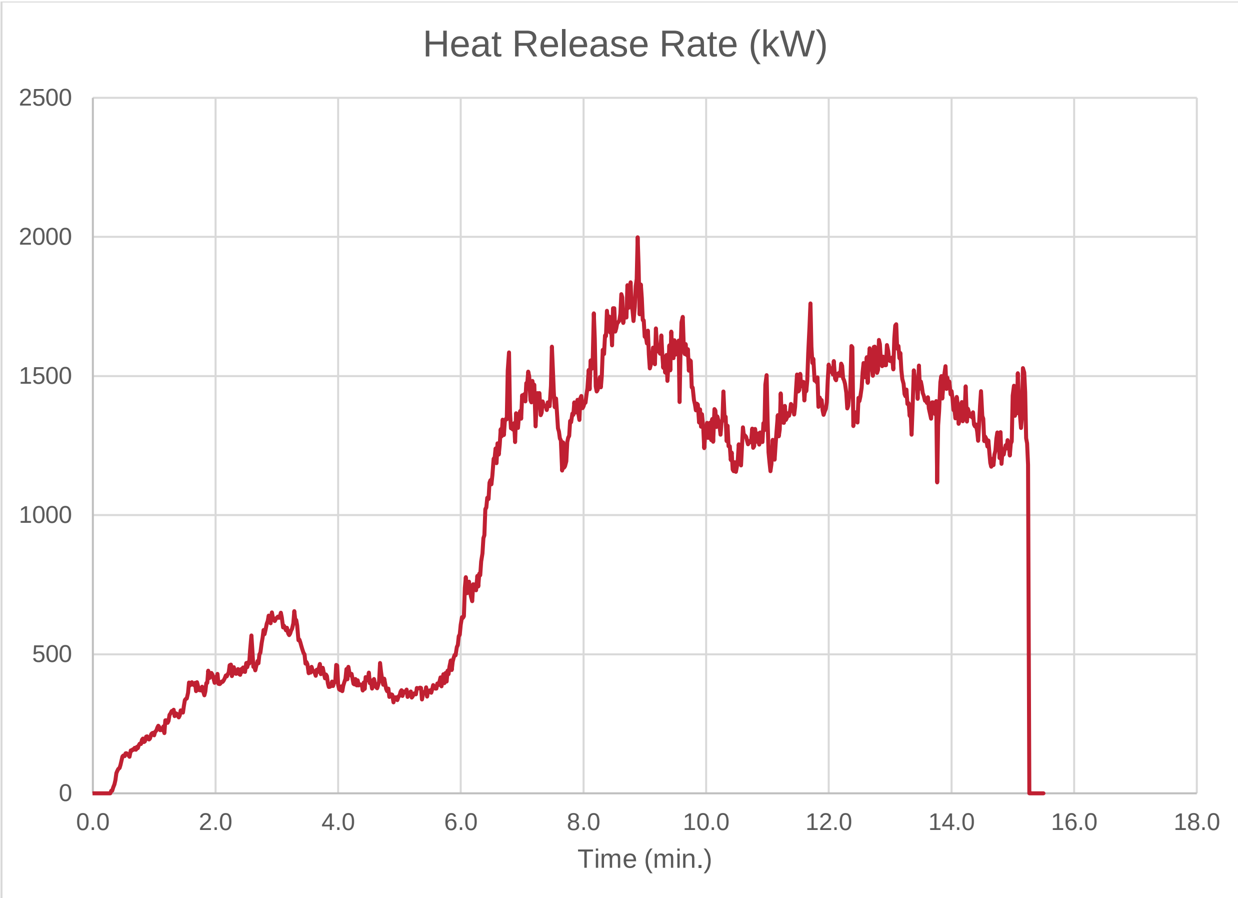


Figure 53 - Test 6 Vinyl Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition Heat Release Rate Plot

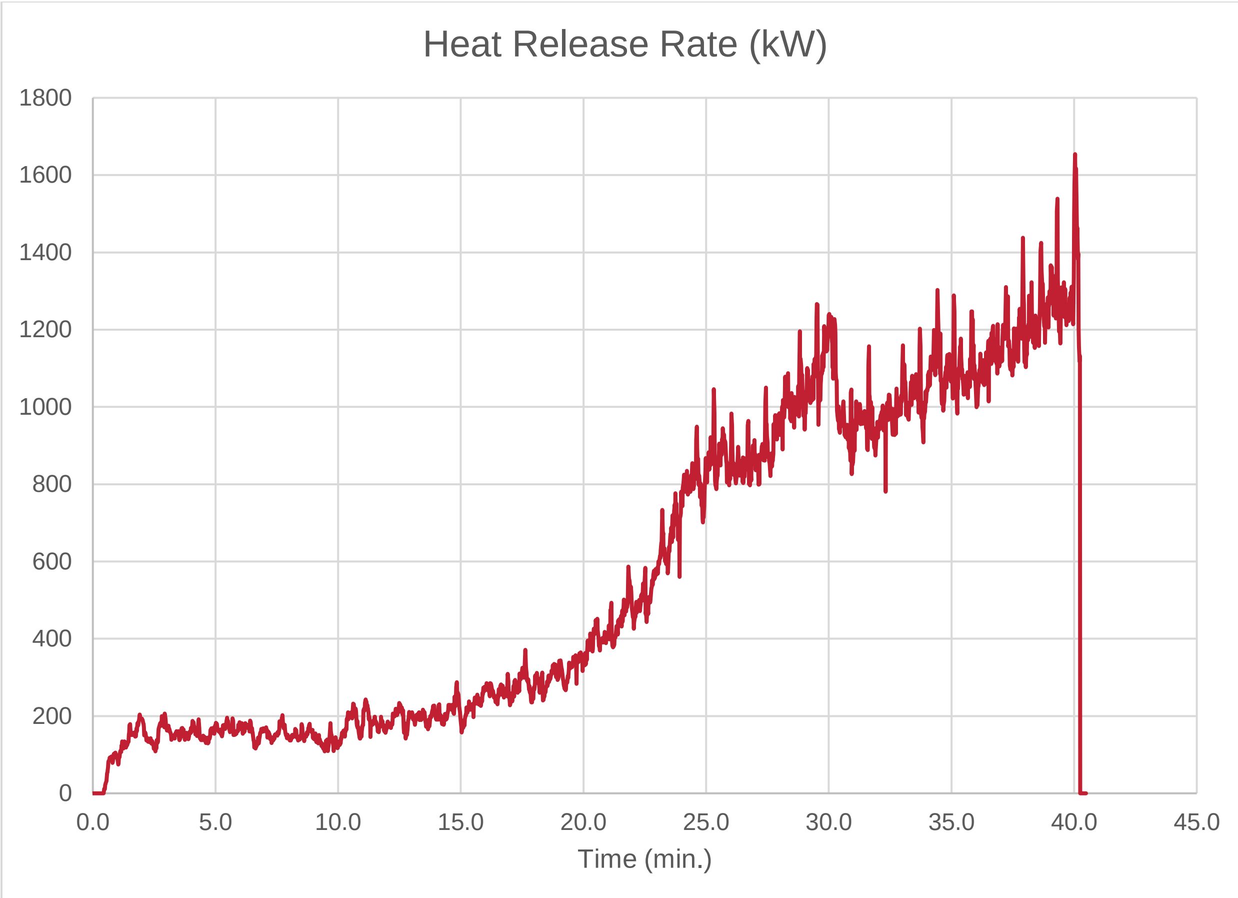


Figure 54 - Test 7 Cedar Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition Heat Release Rate Plot

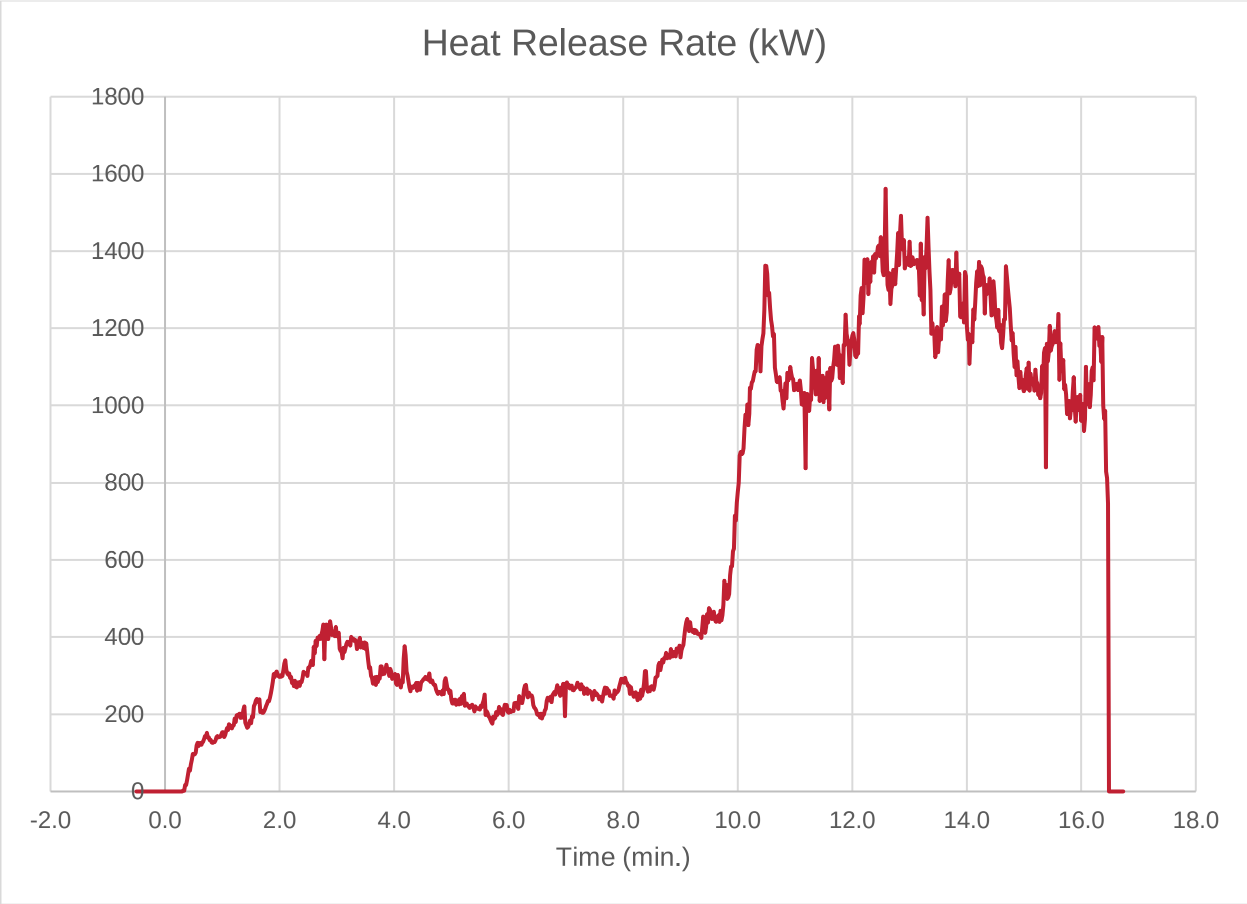


Figure 55 - Test 8 Vinyl Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition Heat Release Rate Plot

Temperature Plots (English Units)

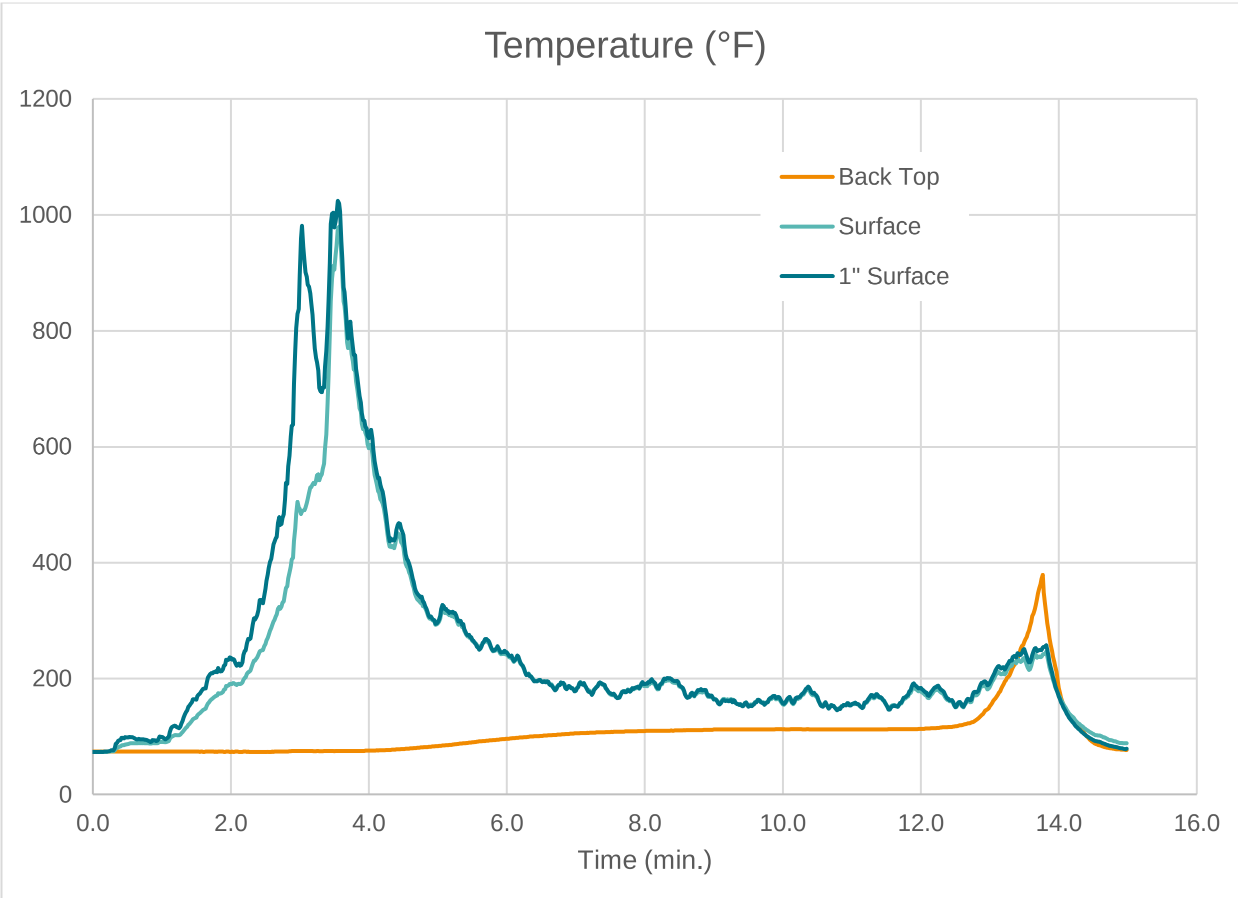


Figure 56 - Test 1 Vinyl Siding/House Wrap/OSB Wall Assembly with 100 kW Ignition Temperature Plot (English Units)

Note: Back Top channel was not functioning.

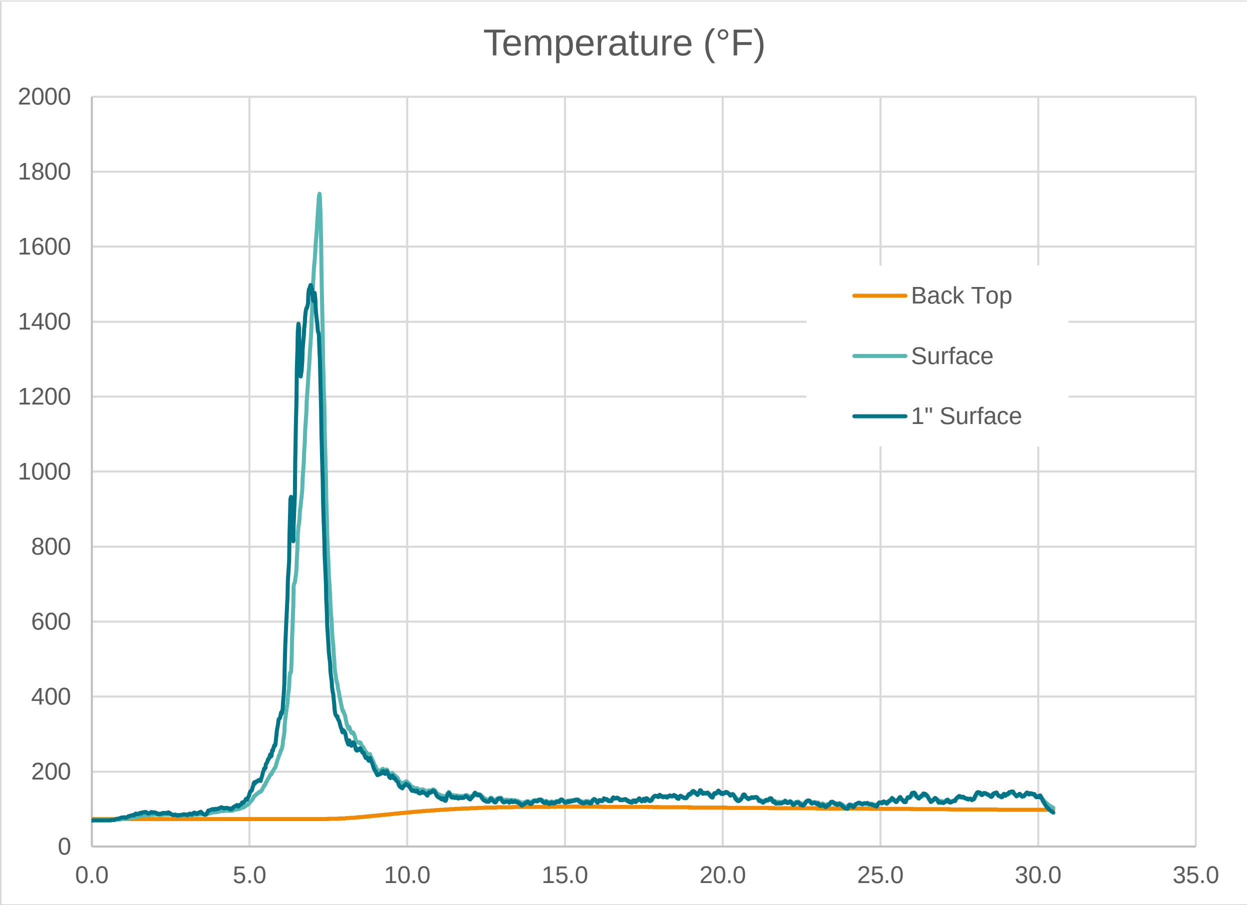


Figure 57 - Test 2 Vinyl Siding/Construction Paper/OSB Wall Assembly with 40 kW Ignition Temperature Plot (English Units)

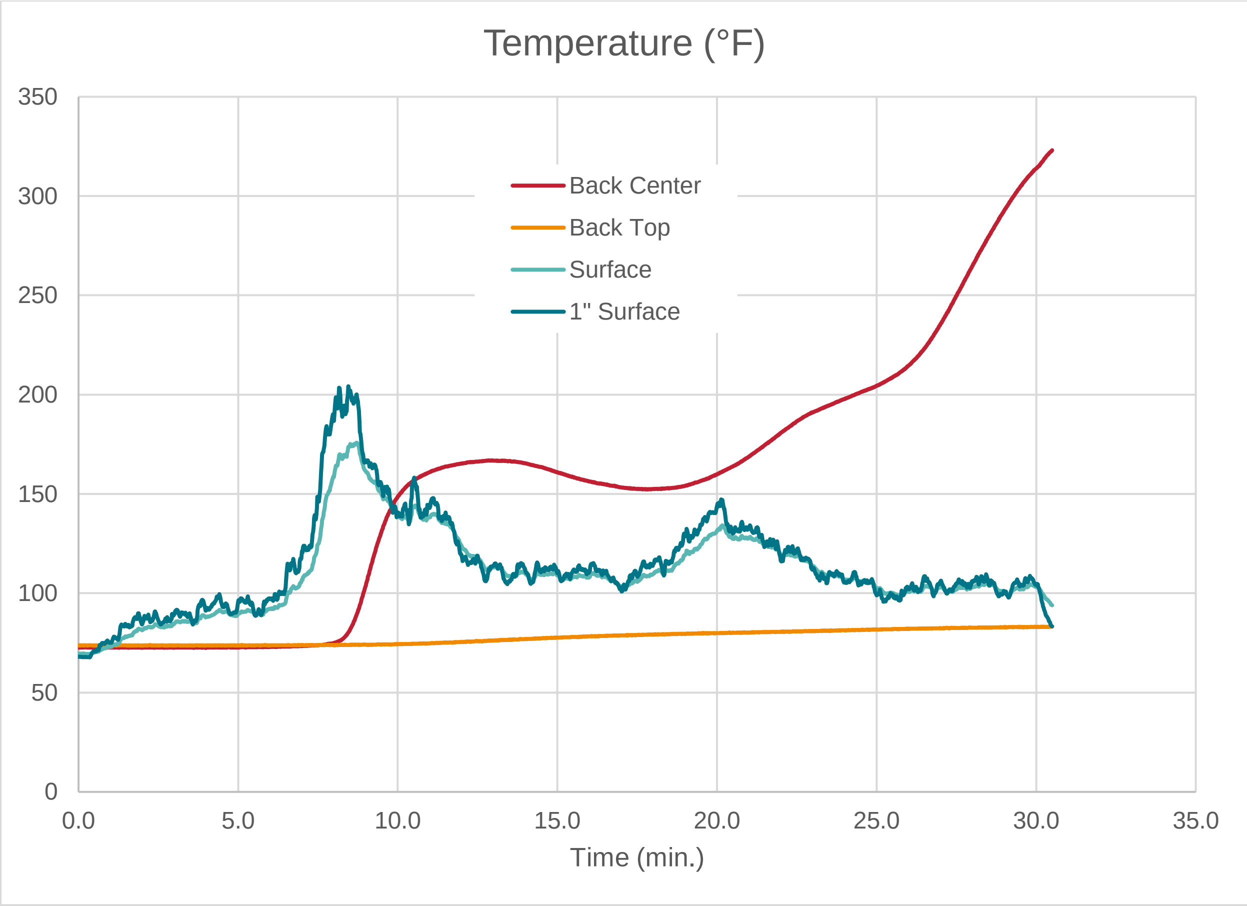


Figure 58 - Test 3 Vinyl Siding/House Wrap/OSB Wall Assembly with 25 kW Ignition Temperature Plot (English Units)

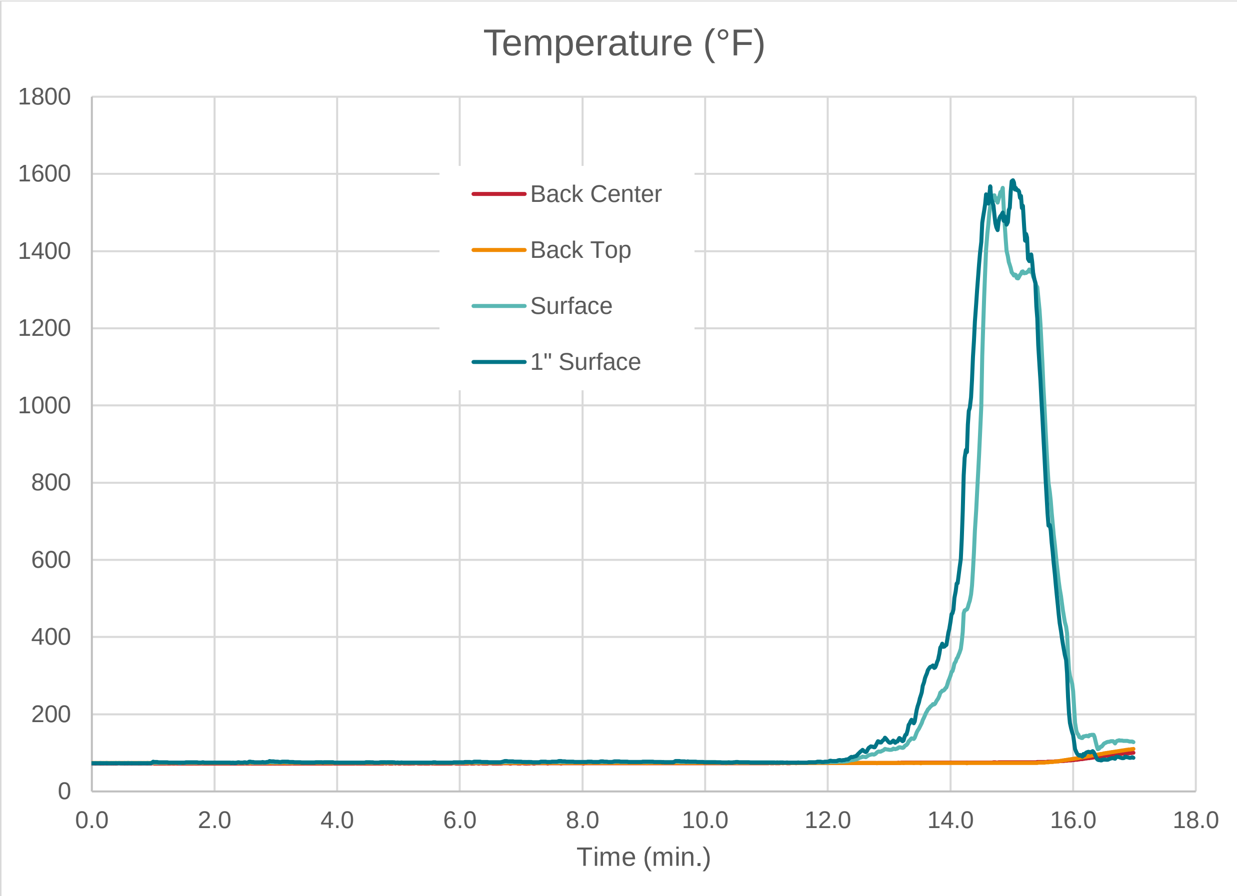


Figure 59 - Test 4 Vinyl Siding/1 in. XPS/OSB Wall Assembly with 100 kW Ignition Temperature Plot (English Units)

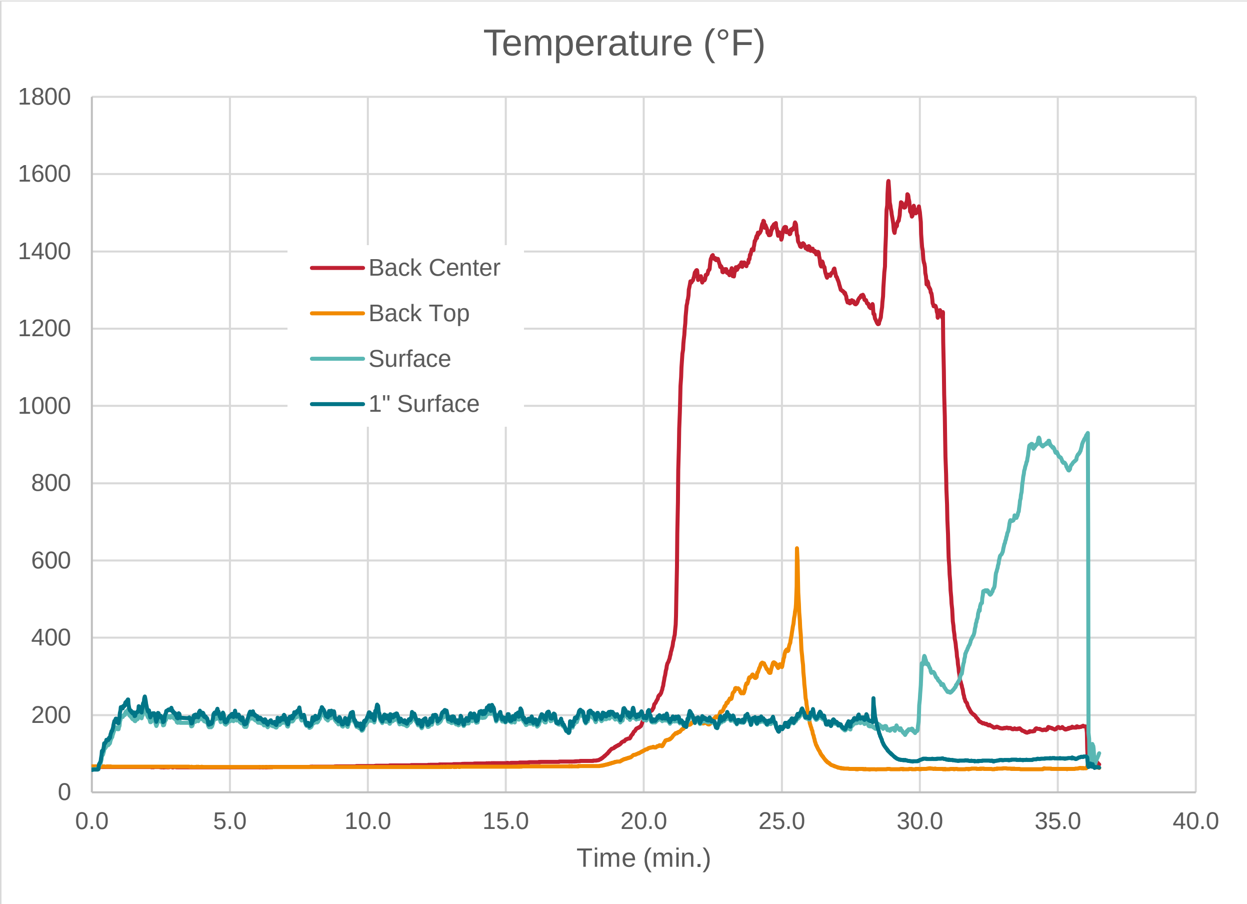


Figure 60 - Test 5 Cedar Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition Temperature Plot (English Units)

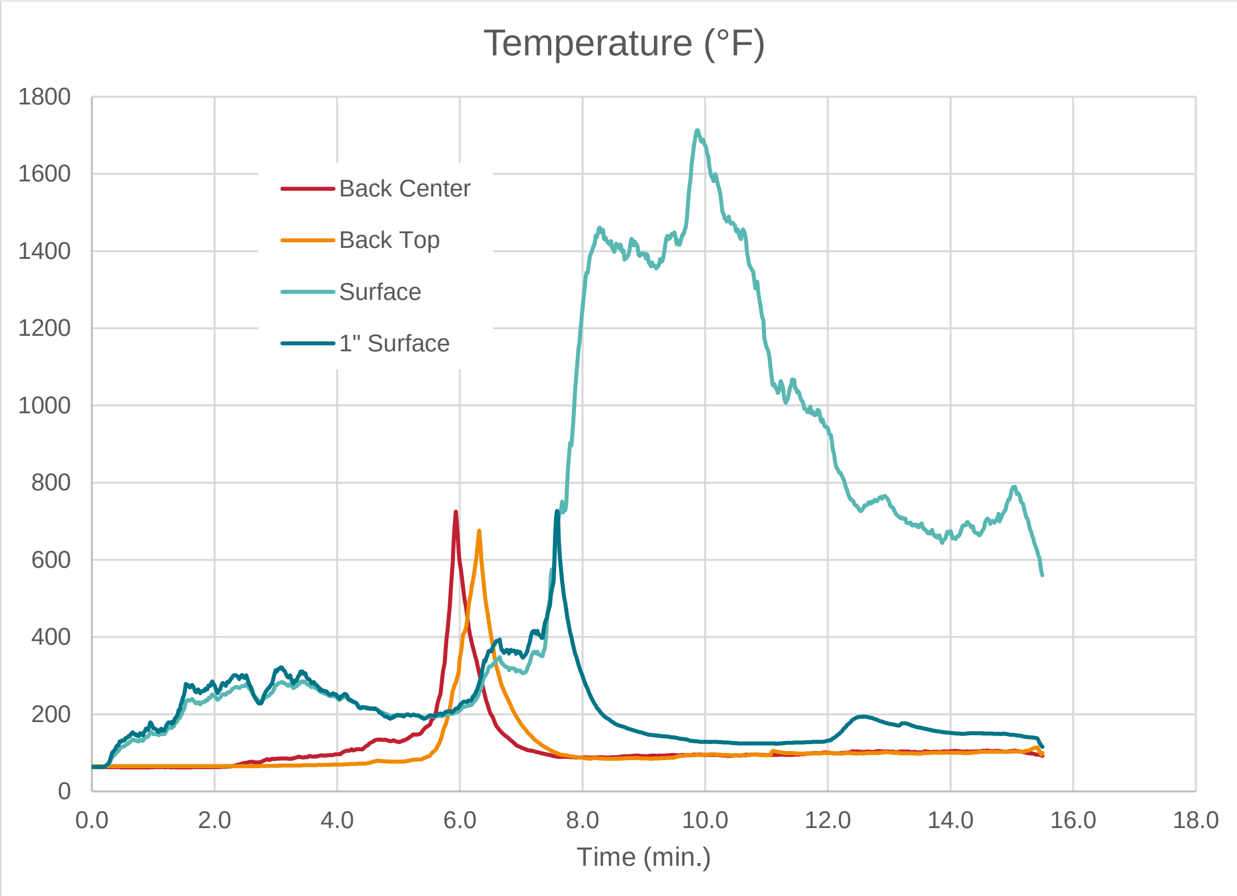


Figure 61 - Test 6 Vinyl Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition Temperature Plot (English Units)

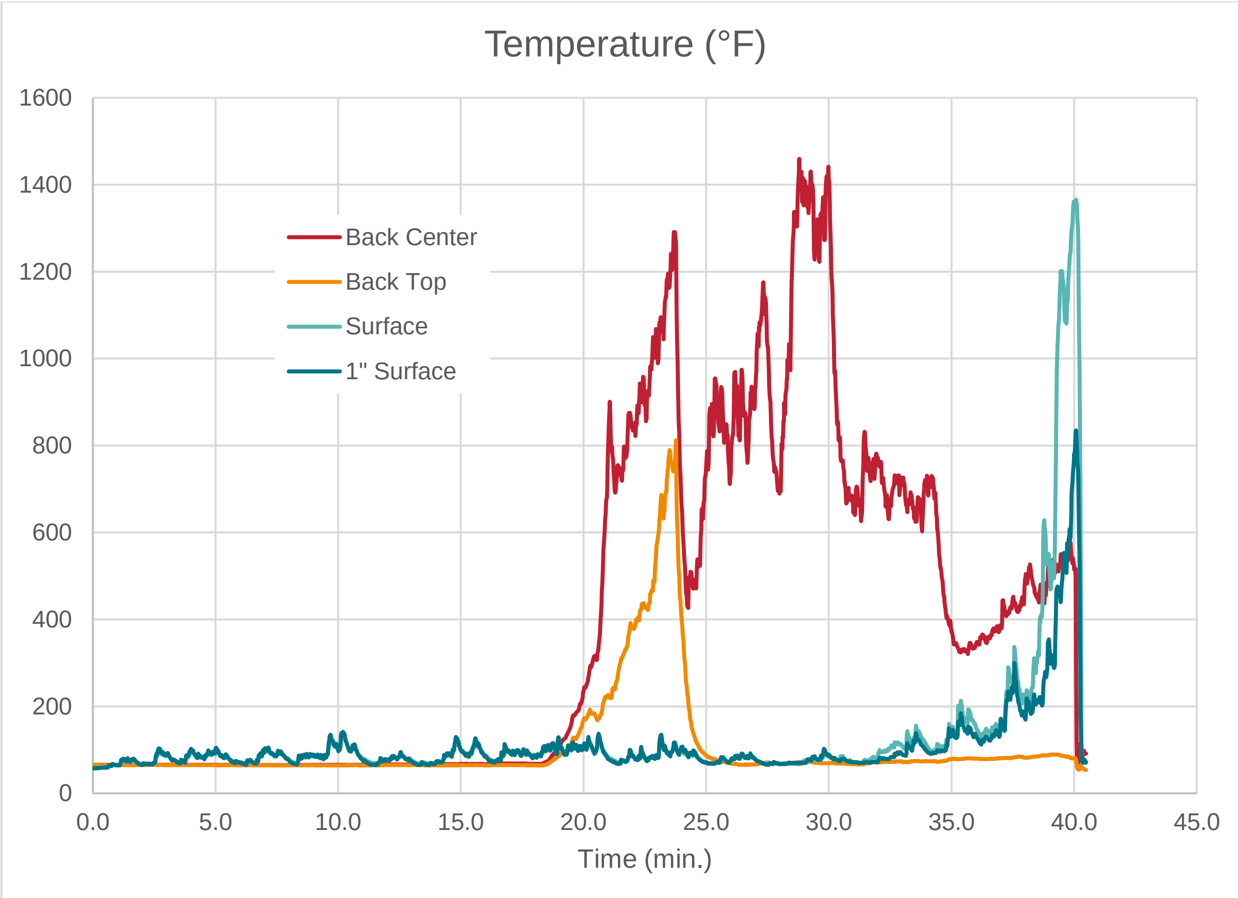


Figure 62 - Test 7 Cedar Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition Temperature Plot (English Units)

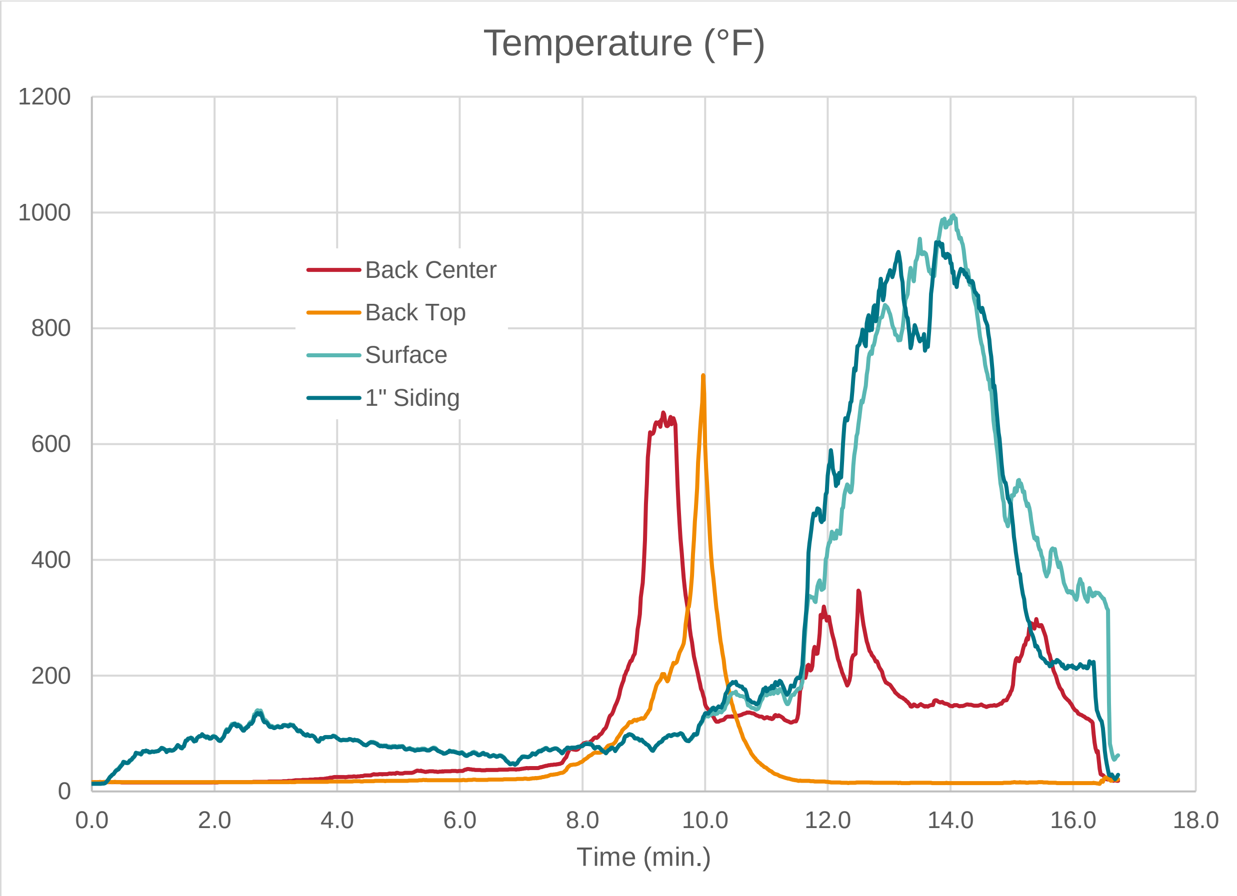


Figure 63 - Test 8 Vinyl Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition Temperature Plot (English Units)

Temperature Plots (Metric Units)

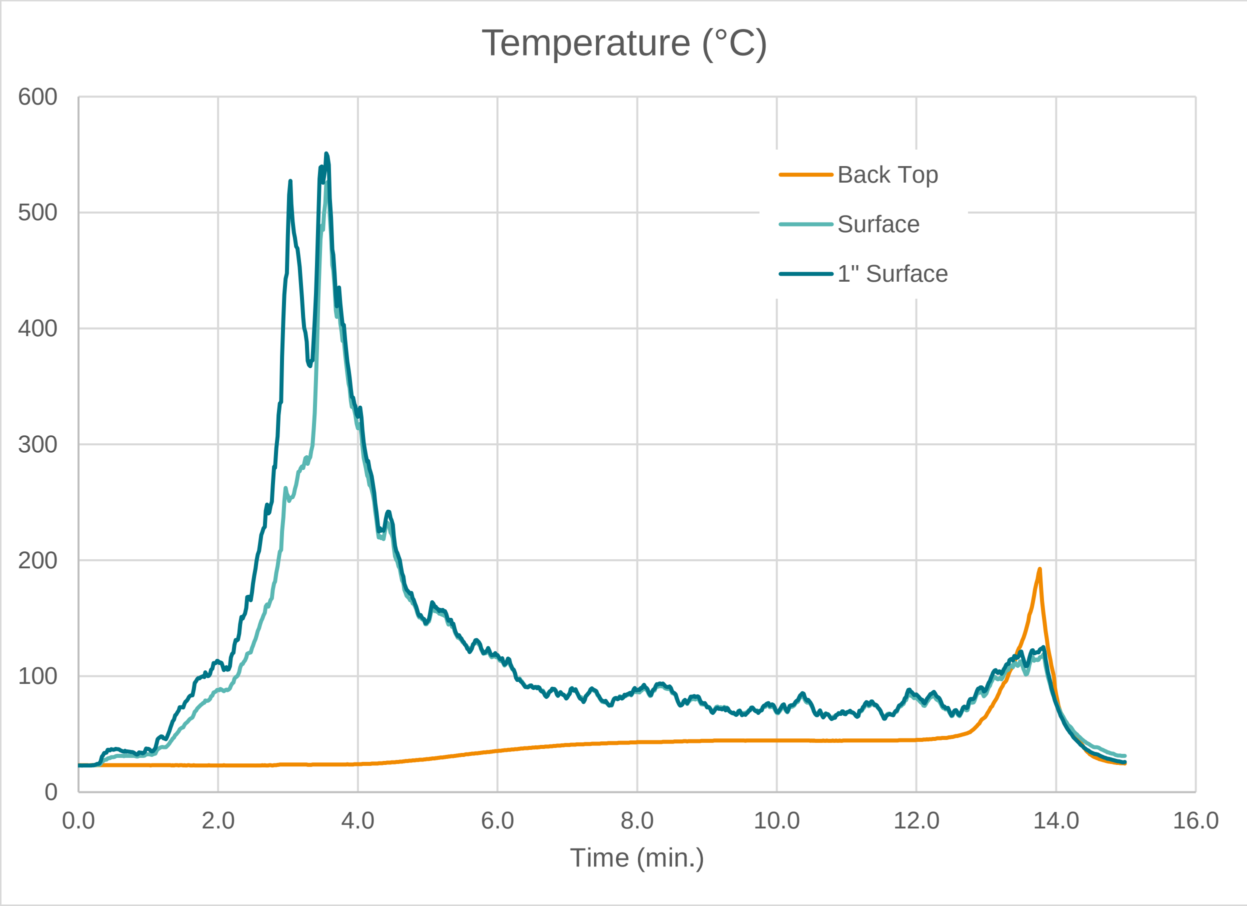


Figure 64 - Test 1 Vinyl Siding/House Wrap/OSB Wall Assembly with 100 kW Ignition Temperature Plot (Metric Units)

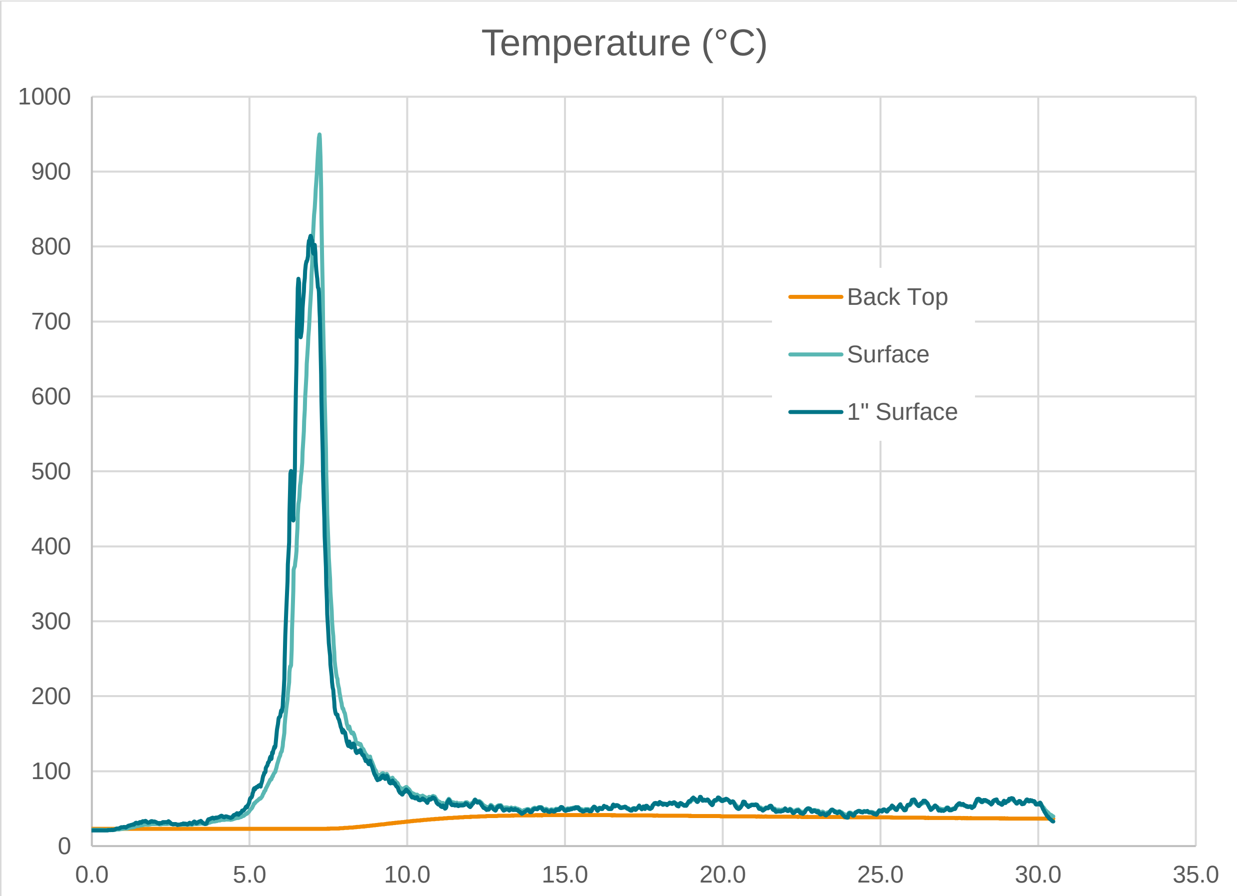


Figure 65 - Test 2 Vinyl Siding/Construction Paper/OSB Wall Assembly with 40 kW Ignition Temperature Plot (Metric Units)

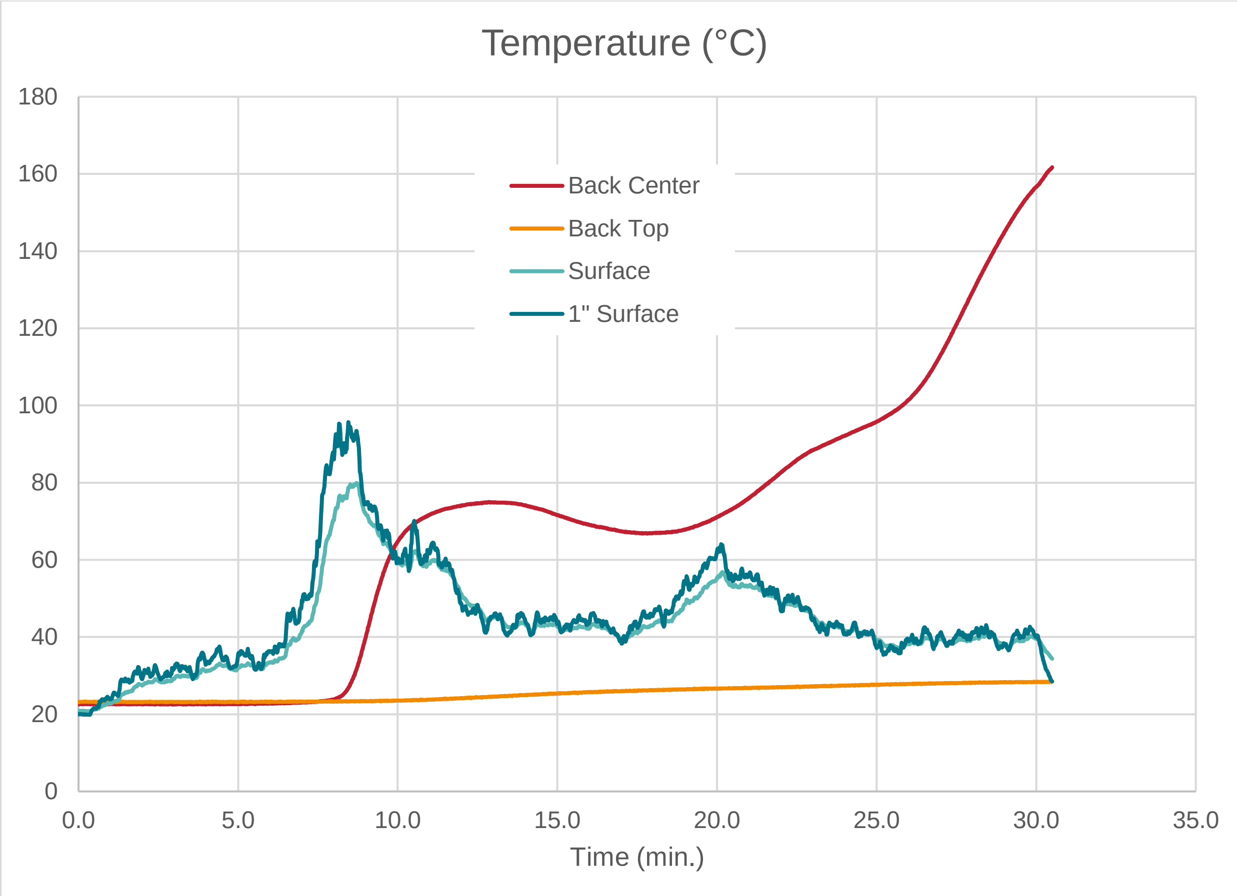


Figure 66 - Test 3 Vinyl Siding/House Wrap/OSB Wall Assembly with 25 kW Ignition Temperature Plot (Metric Units)

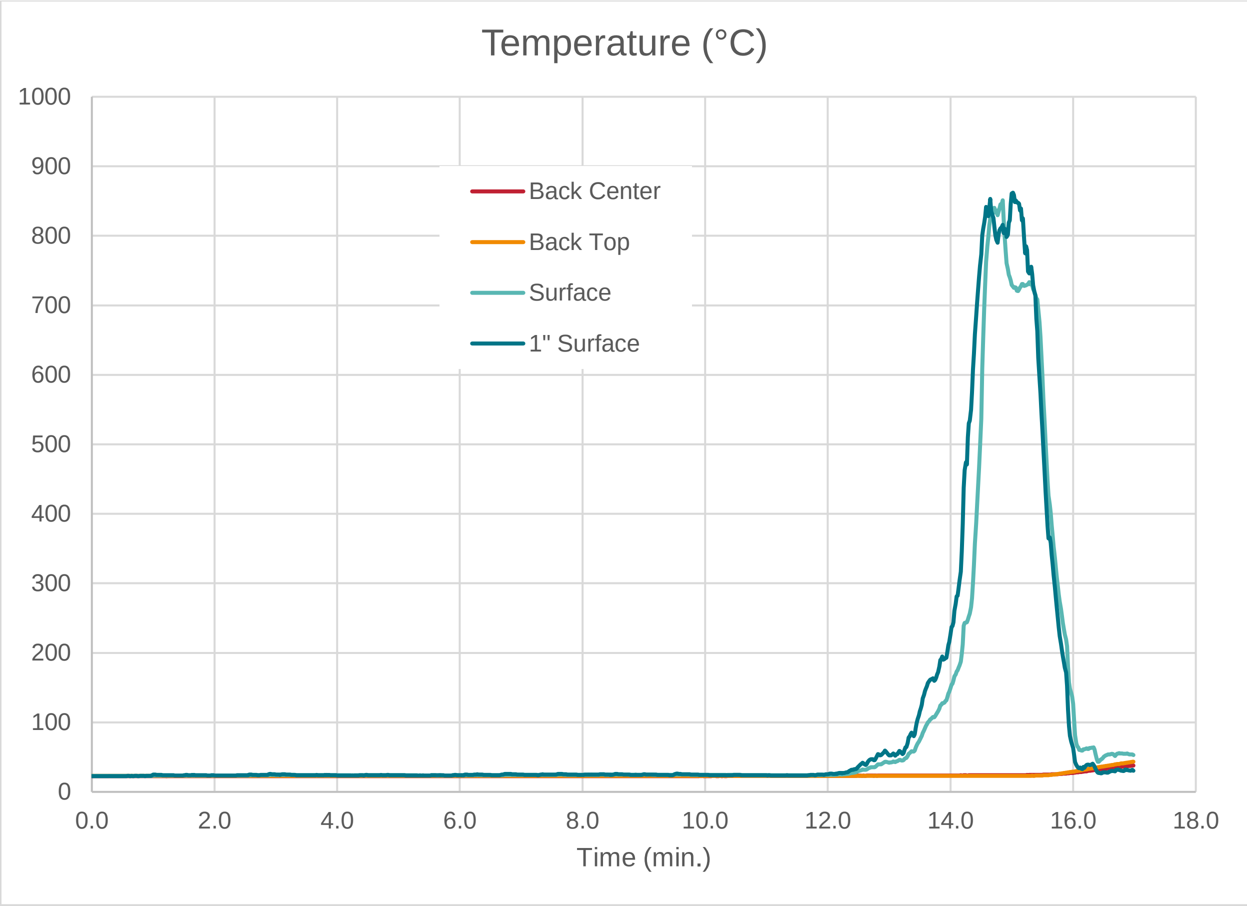


Figure 67 - Test 4 Vinyl Siding/1 in. XPS/OSB Wall Assembly with 100 kW Ignition Temperature Plot (Metric Units)

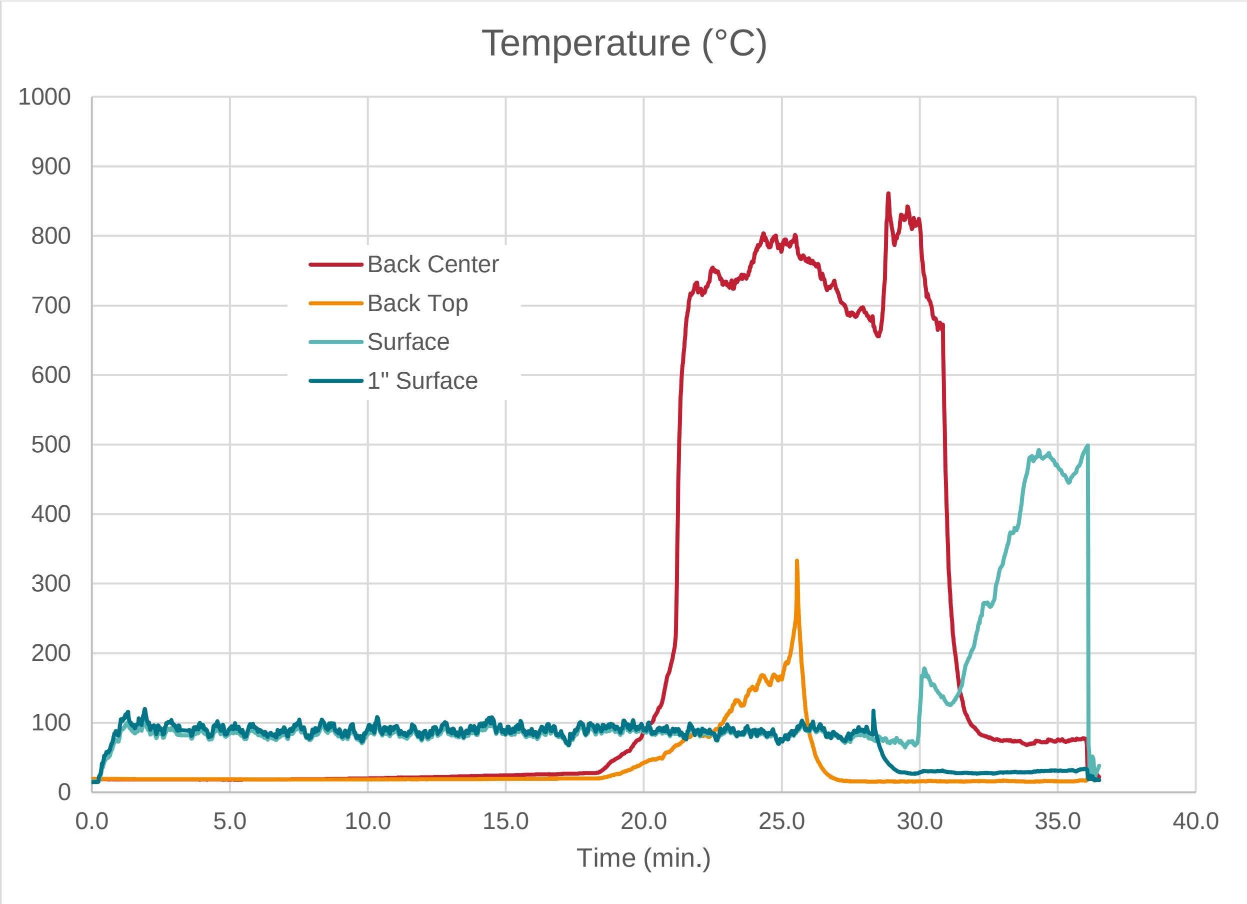


Figure 68 - Test 5 Cedar Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition Temperature Plot (Metric Units)

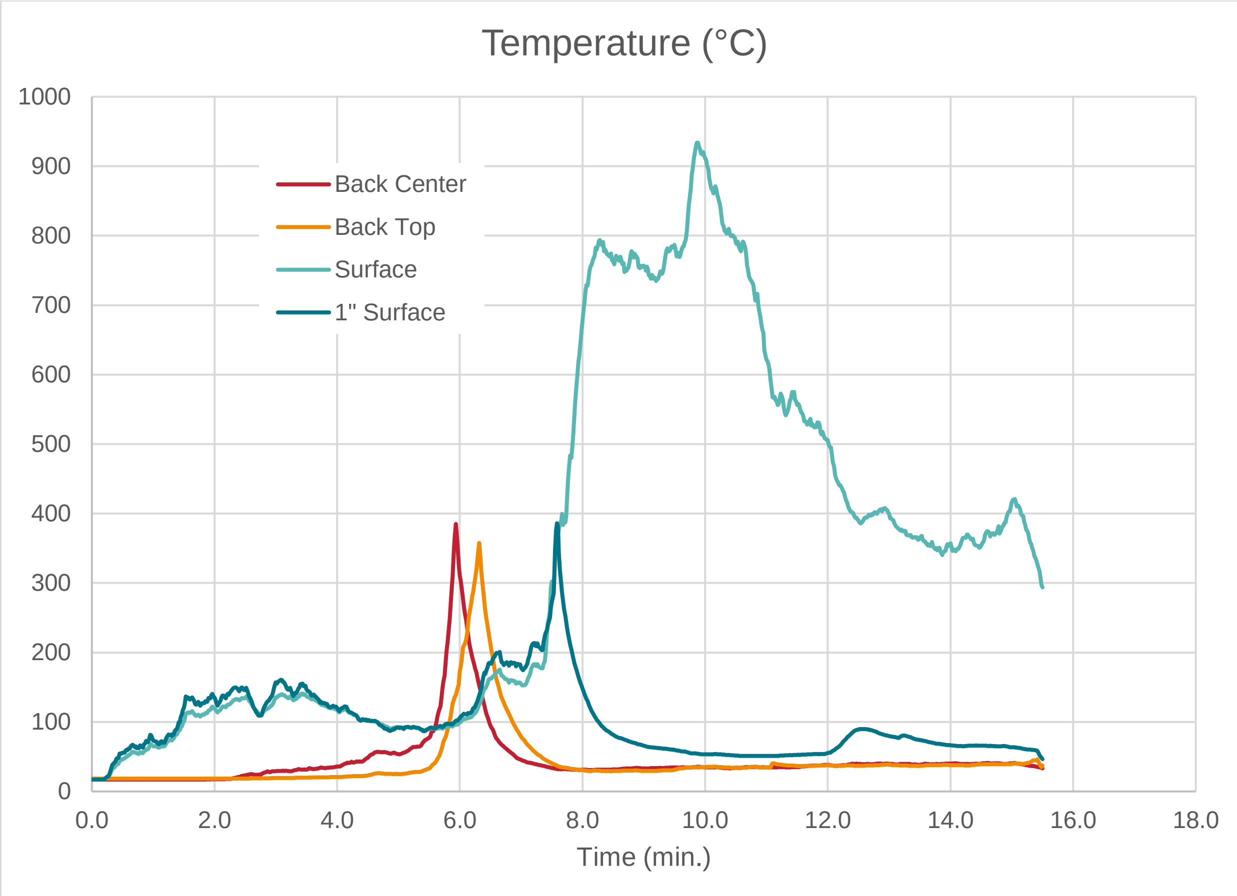


Figure 69 - Test 6 Vinyl Siding/House Wrap/Plywood Wall Assembly with 100 kW Ignition Temperature Plot (Metric Units)

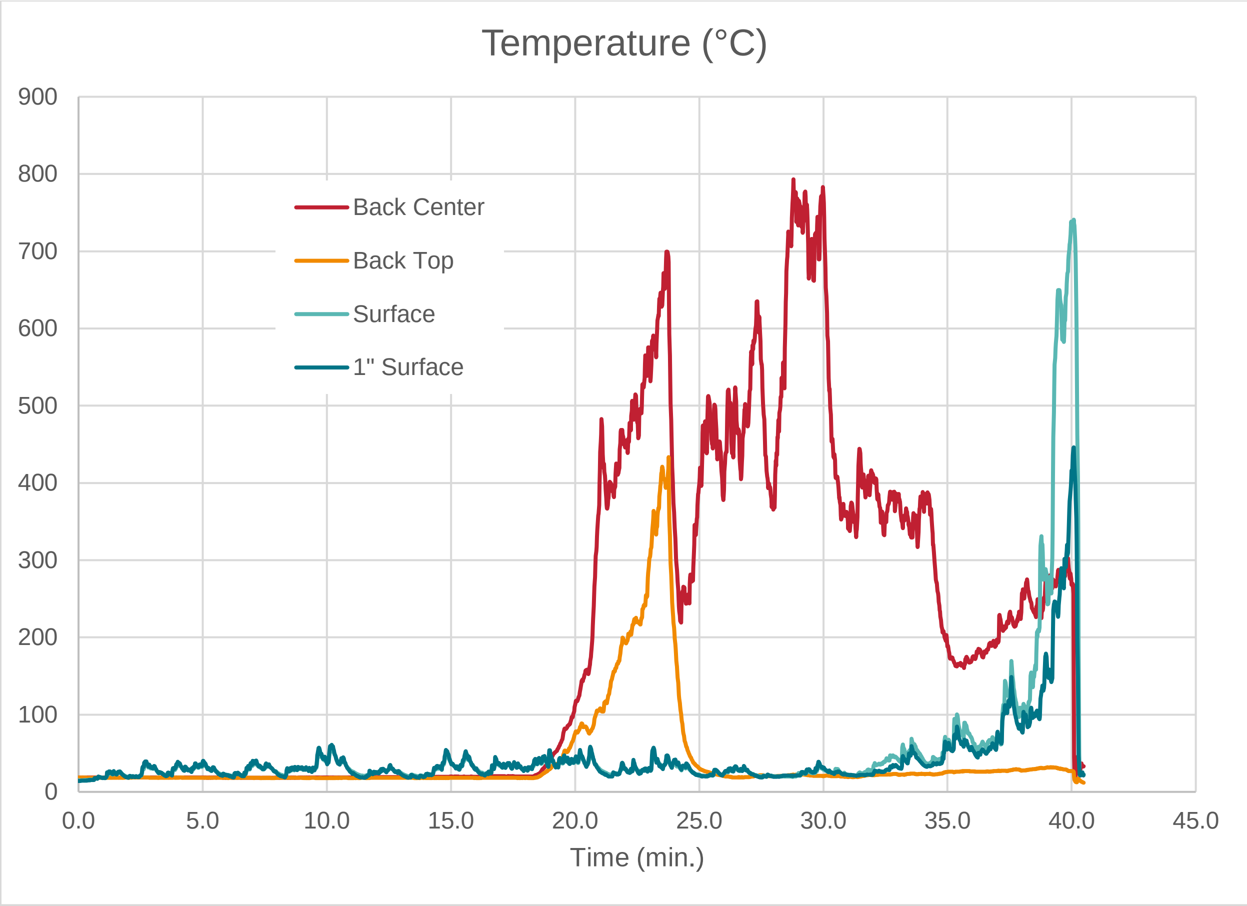


Figure 70 - Test 7 Cedar Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition Temperature Plot (Metric Units)

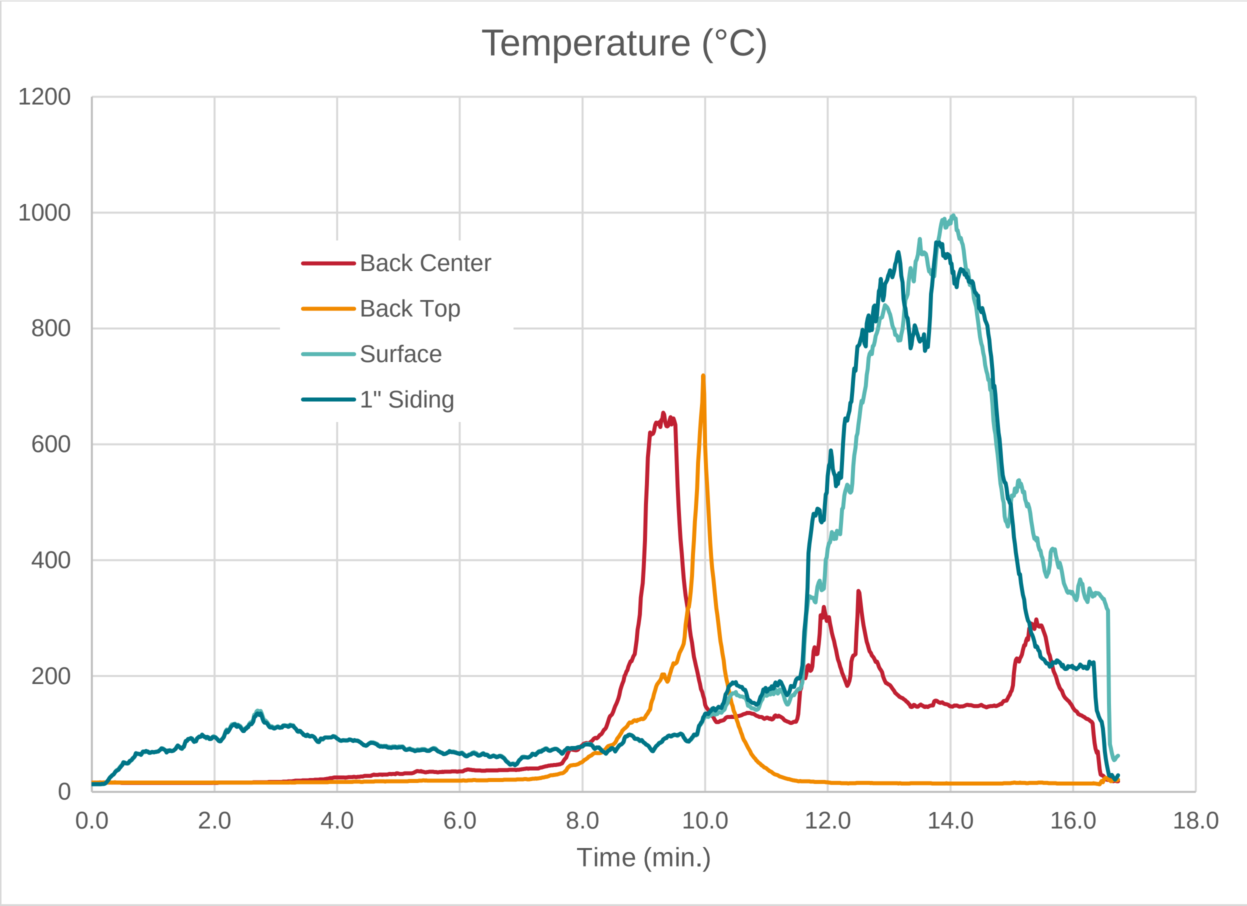
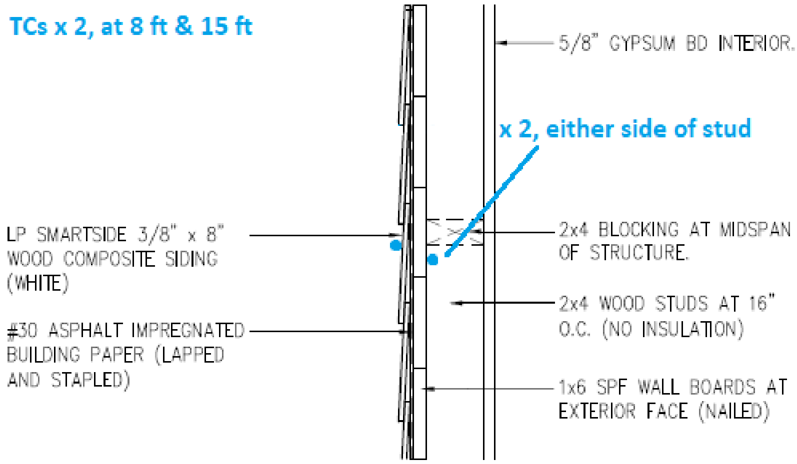


Figure 71 - Test 8 Vinyl Siding/House Wrap/Plywood Wall Assembly with 75 kW Ignition Temperature Plot (Metric Units)

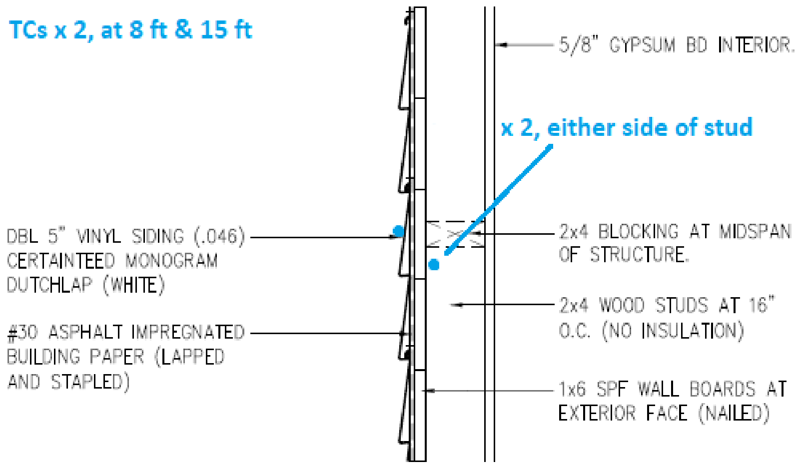
Appendix B: Thermocouple Locations

Test 1 & 2 –



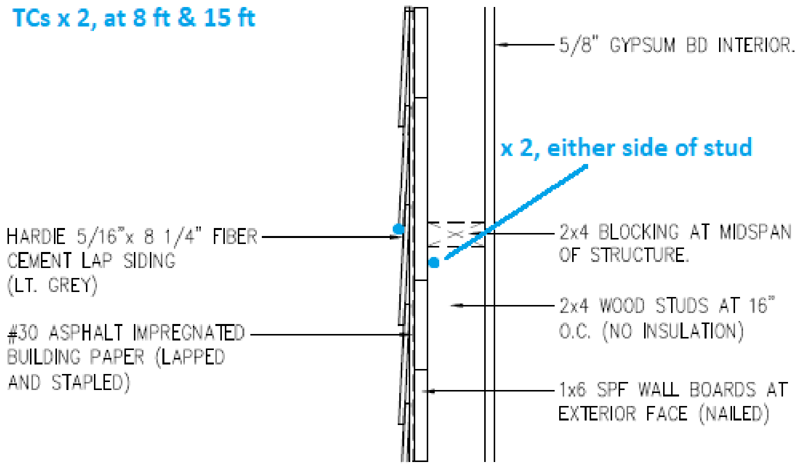
6 thermocouples total, thermocouples behind wall boards should be under blocking.

Test 3 –



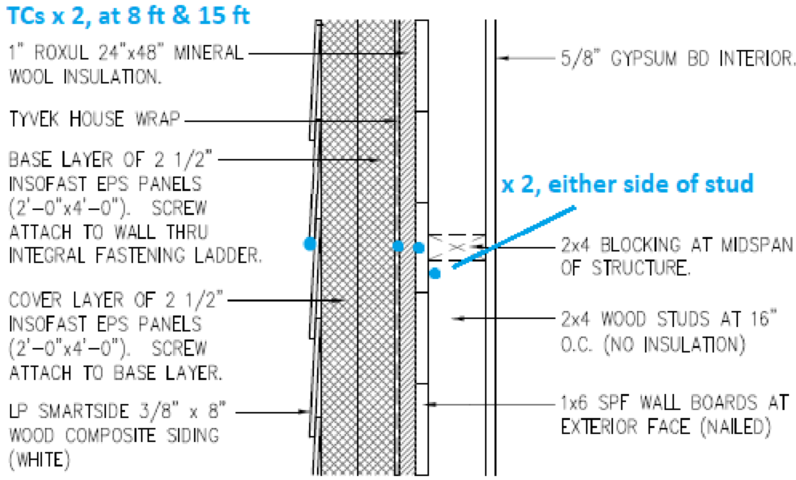
6 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud.

Test 4 –



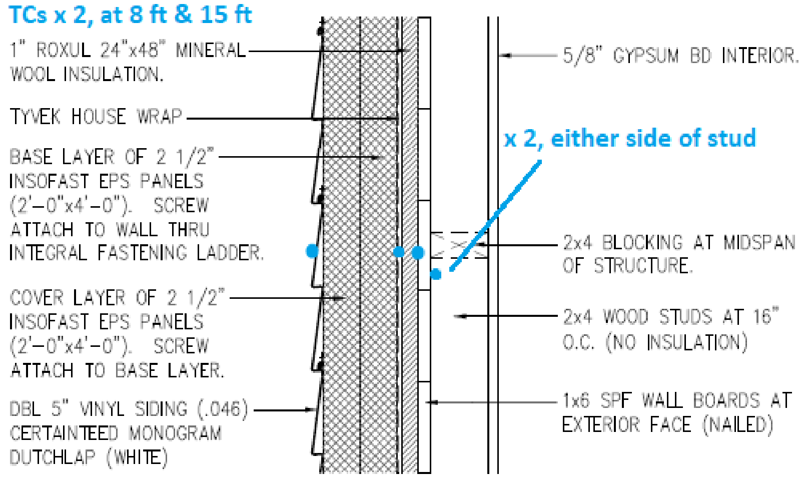
6 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud.

Test 5 –



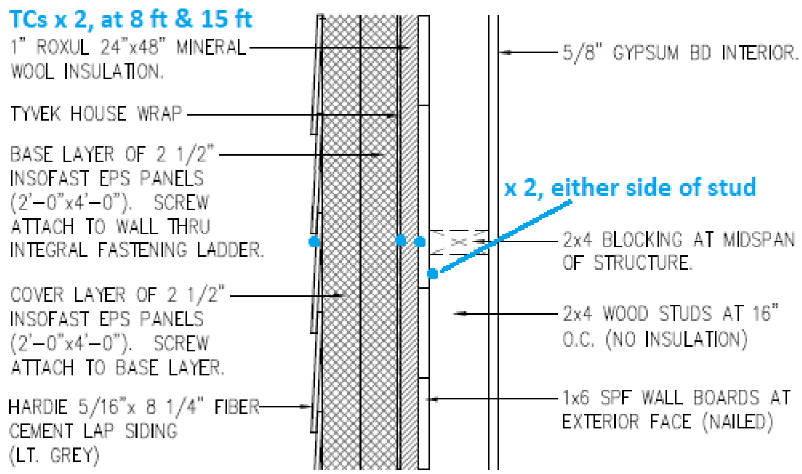
10 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud.

Test 6 –



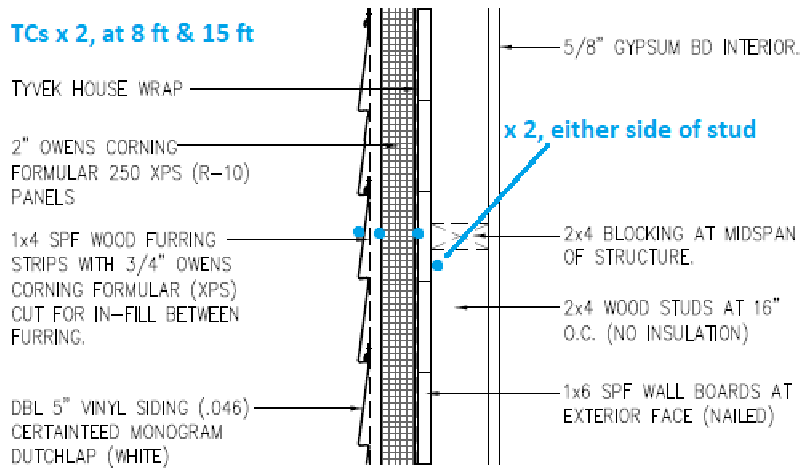
10 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud.

Test 7 –



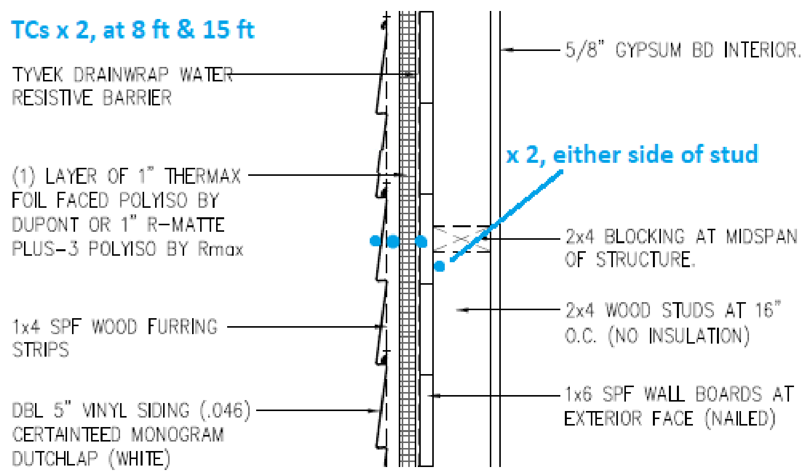
10 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud.

Test 8 –



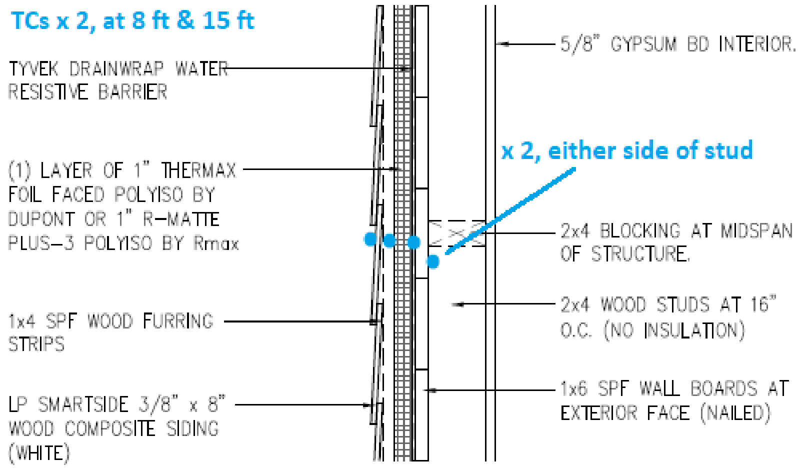
11 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud. The last thermocouple is centered between the furring strips at a height of 8 ft to the left of the furring strip on center.

Test 9 –



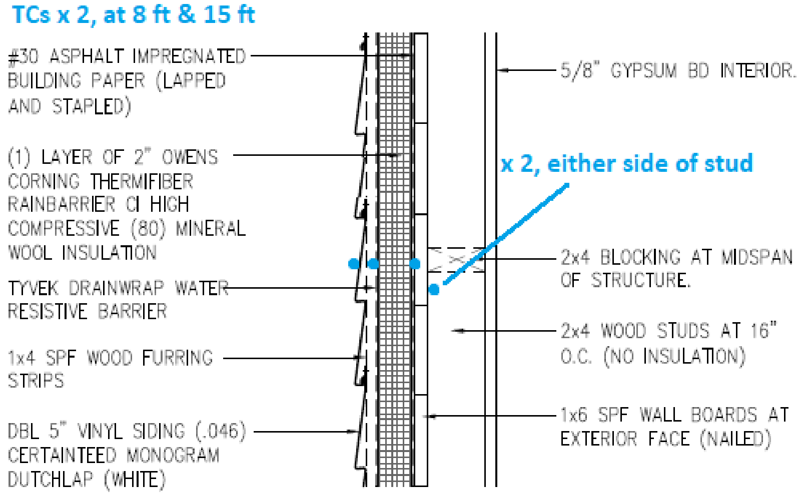
11 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud. The last thermocouple is centered between the furring strips at a height of 8 ft to the left of the furring strip on center.

Test 10 –



11 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud. The last thermocouple is centered between the furring strips at a height of 8 ft to the left of the furring strip on center.

Test 11 –



11 thermocouples total, thermocouples behind wall boards should be 1 in. under blocking on either side of the stud. The last thermocouple is centered between the furring strips at a height of 8 ft to the left of the furring strip on center.

Appendix C: Heat Release Rate Plots

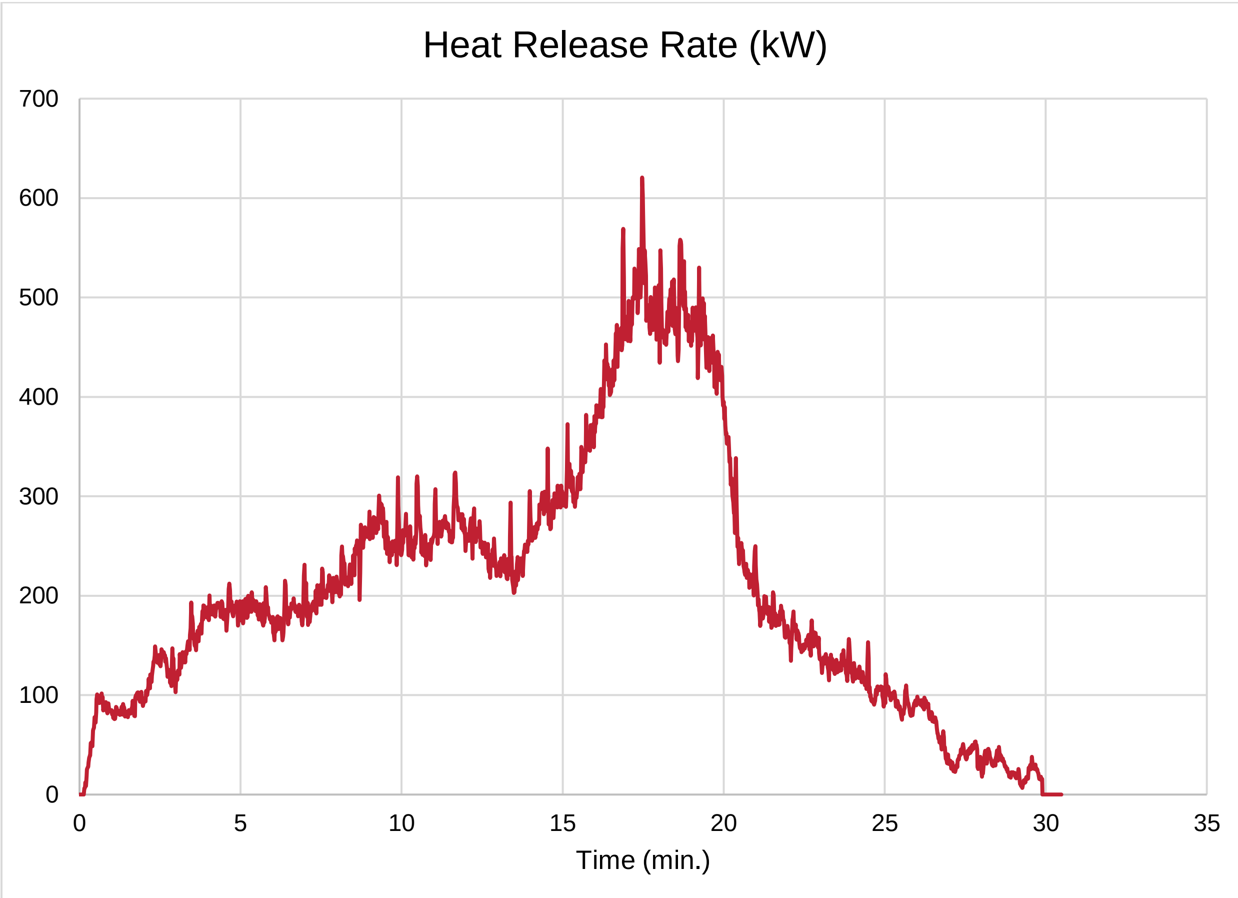


Figure 72 - Test 1 Wood Composite Siding/Asphalt Paper (75 kW) Heat Release Rate Plot

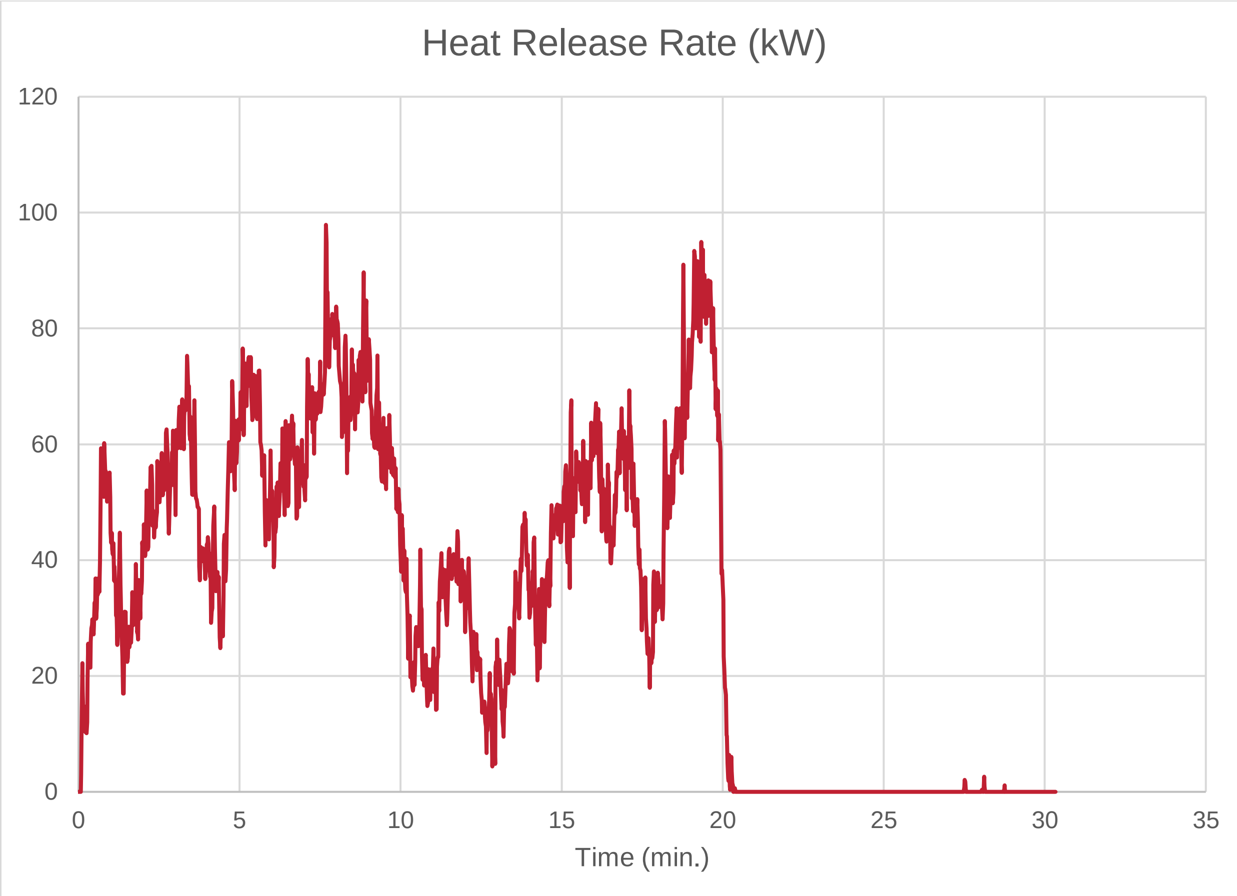


Figure 73 - Test 2 Wood Composite Siding/Asphalt Paper (50 kW) Heat Release Rate Plot

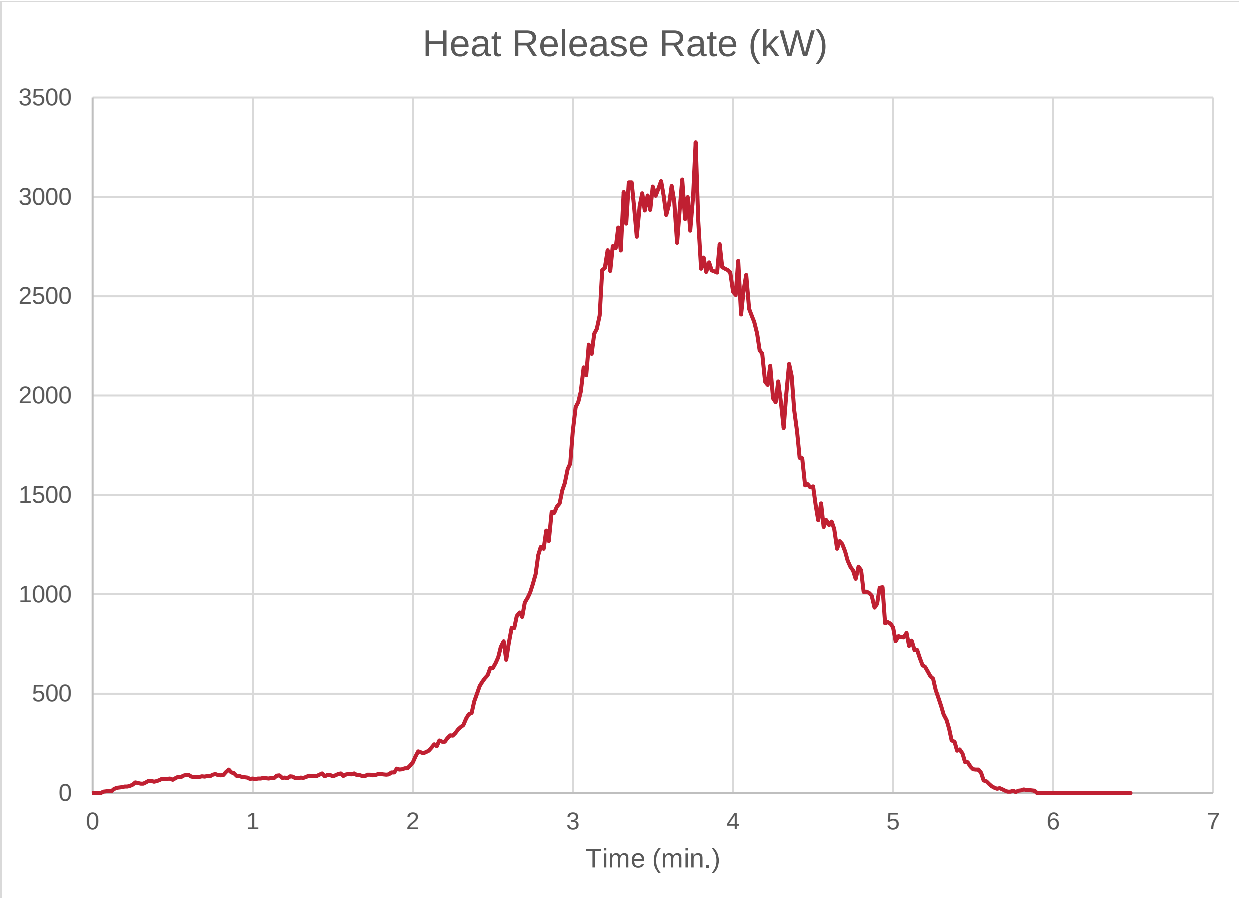


Figure 74 - Test 3 Vinyl Siding/Asphalt Paper Heat Release Rate Plot

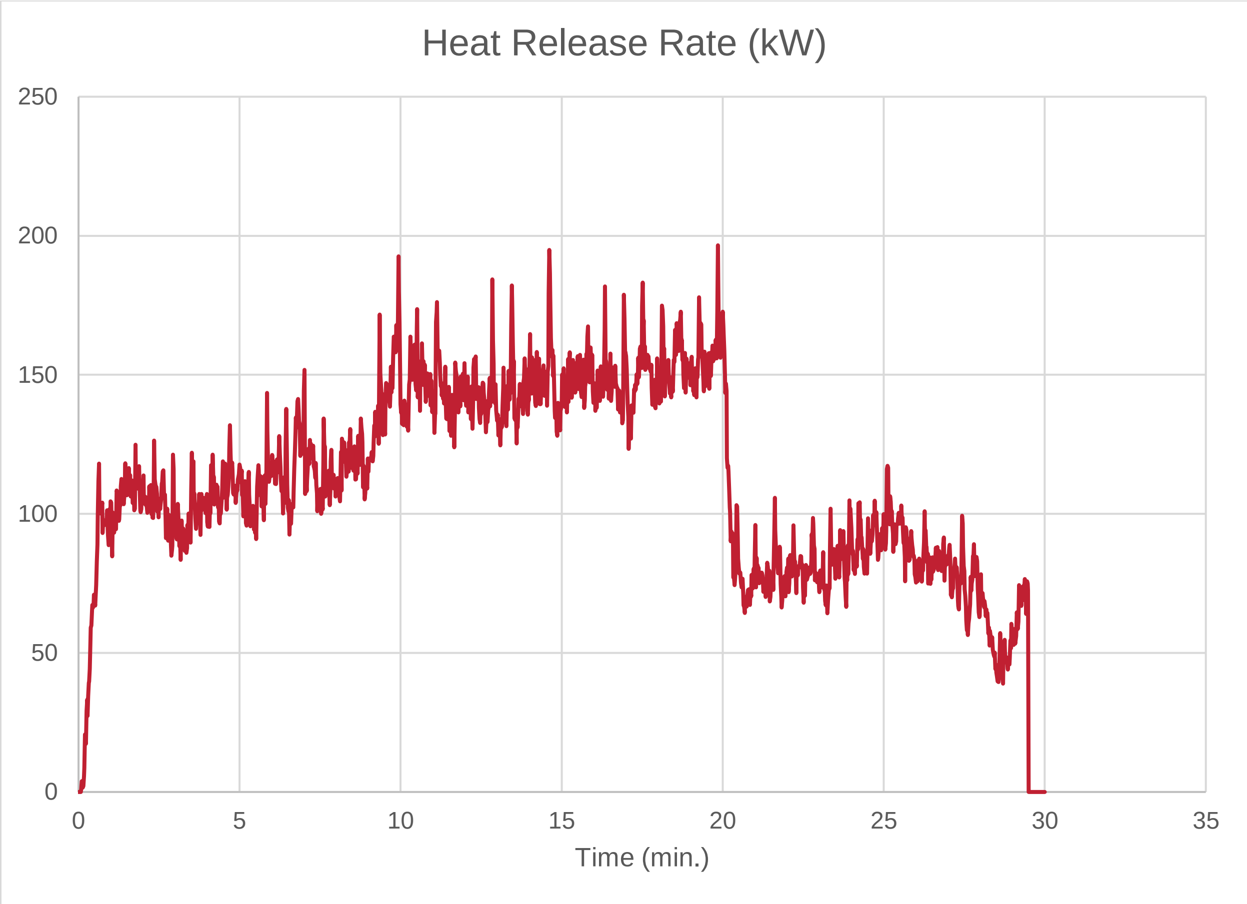


Figure 75 - Test 4 Fiber Cement Siding/Asphalt Paper Heat Release Rate Plot

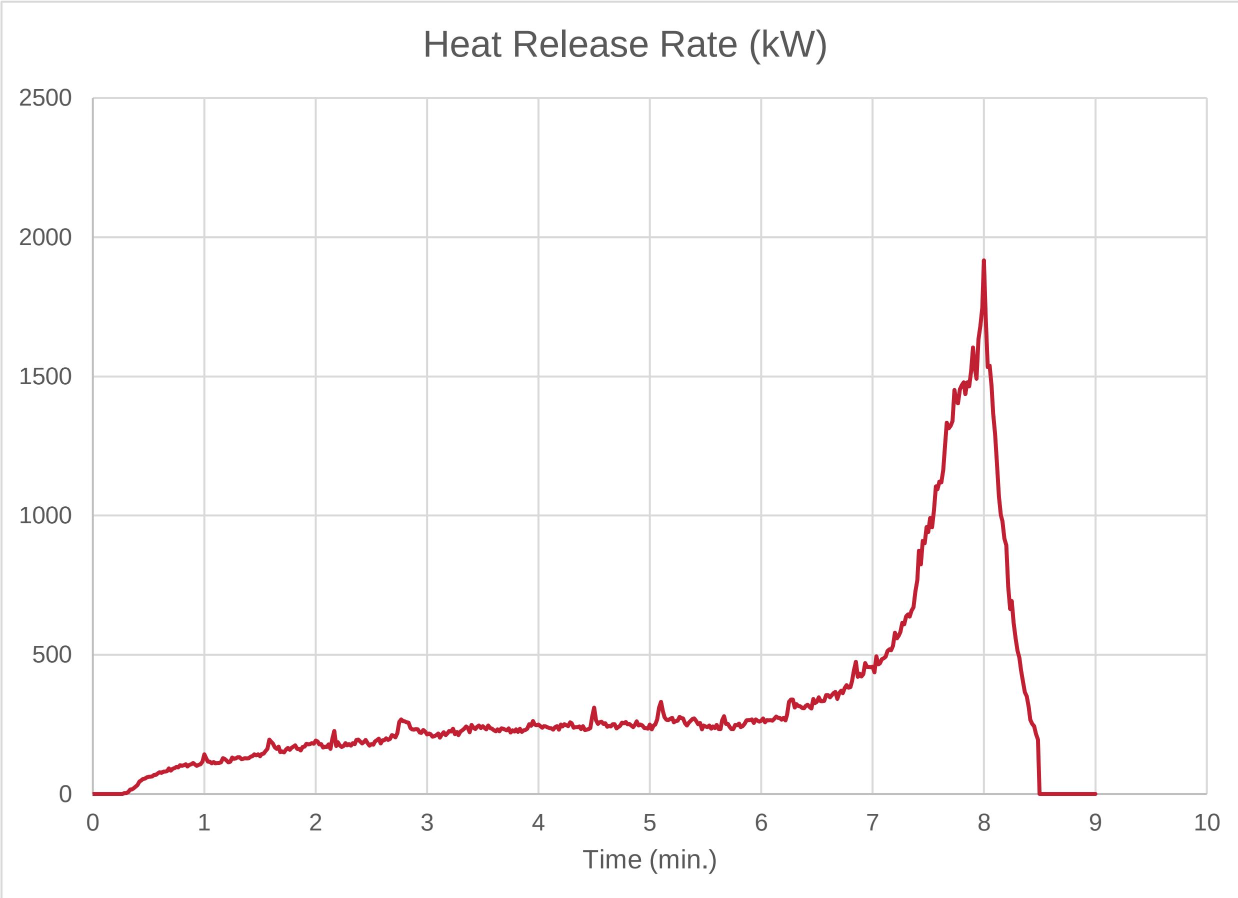


Figure 76 - Test 5 Wood Composite Siding/EPS/Mineral Wool Heat Release Rate Plot

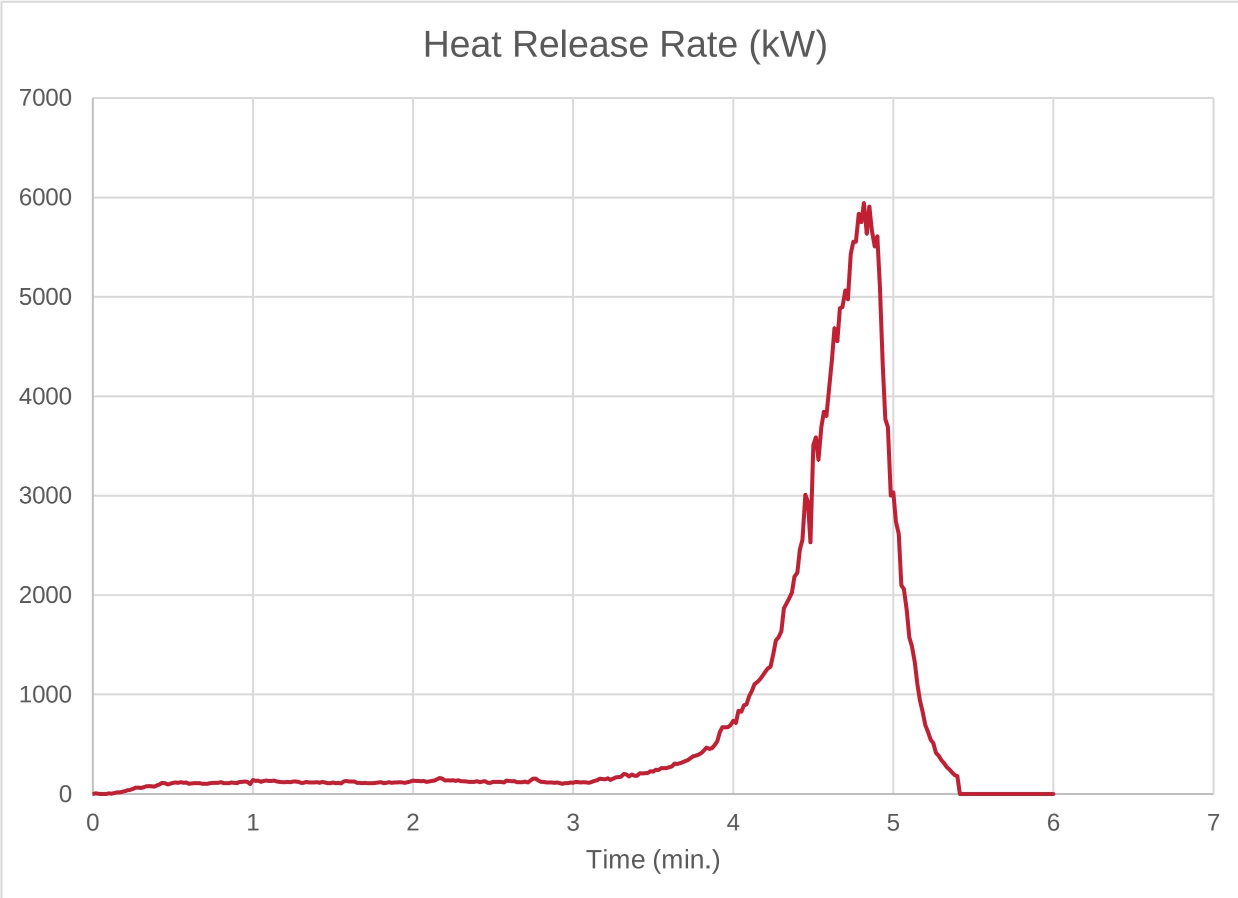


Figure 77 - Test 6 Vinyl Siding/EPS/Mineral Wool Heat Release Rate Plot

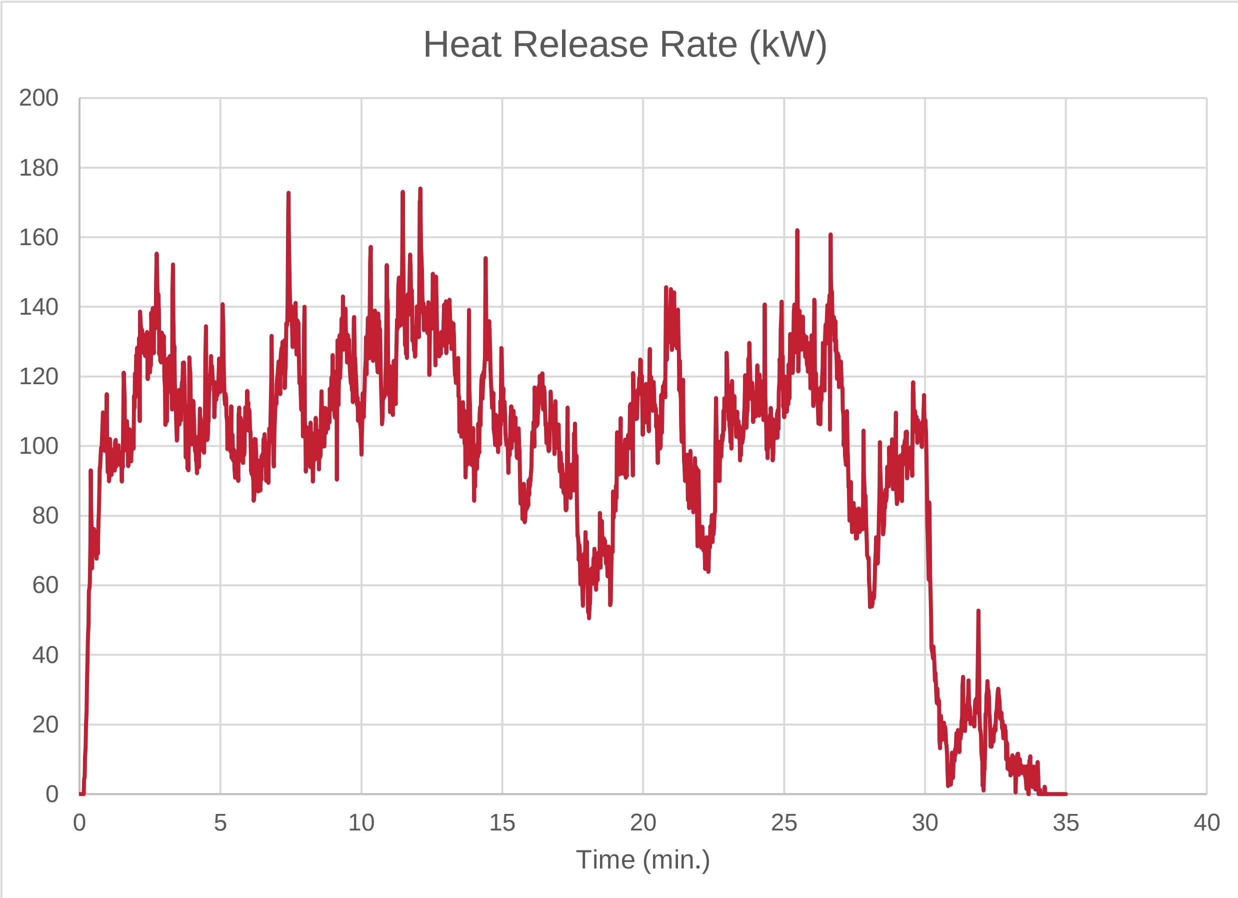


Figure 78 - Test 7 Fiber Cement Siding/EPS/Mineral Wool Heat Release Rate Plot

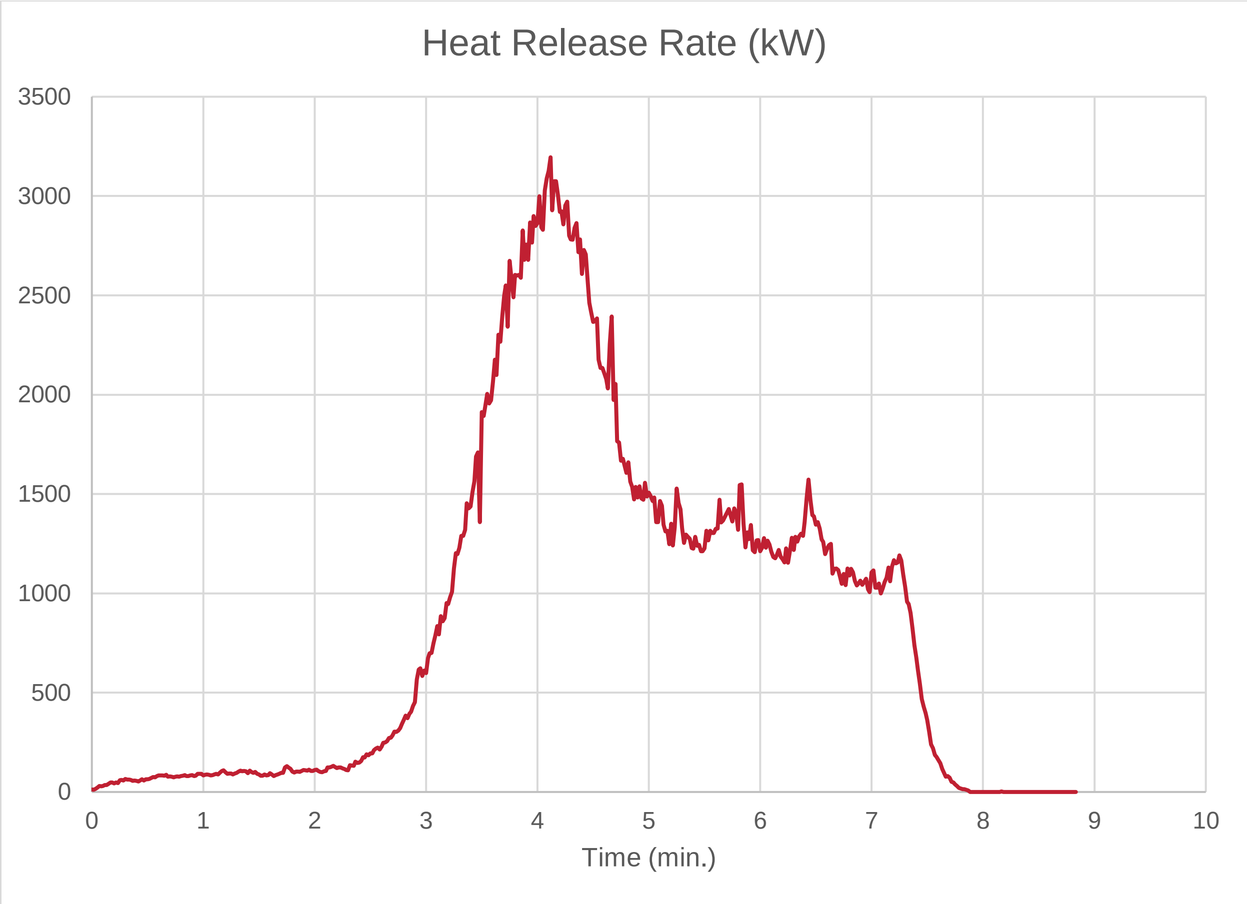


Figure 79 - Test 7 Fiber Cement Siding/EPS/Mineral Wool After Panels Removed Heat Release Rate Plot

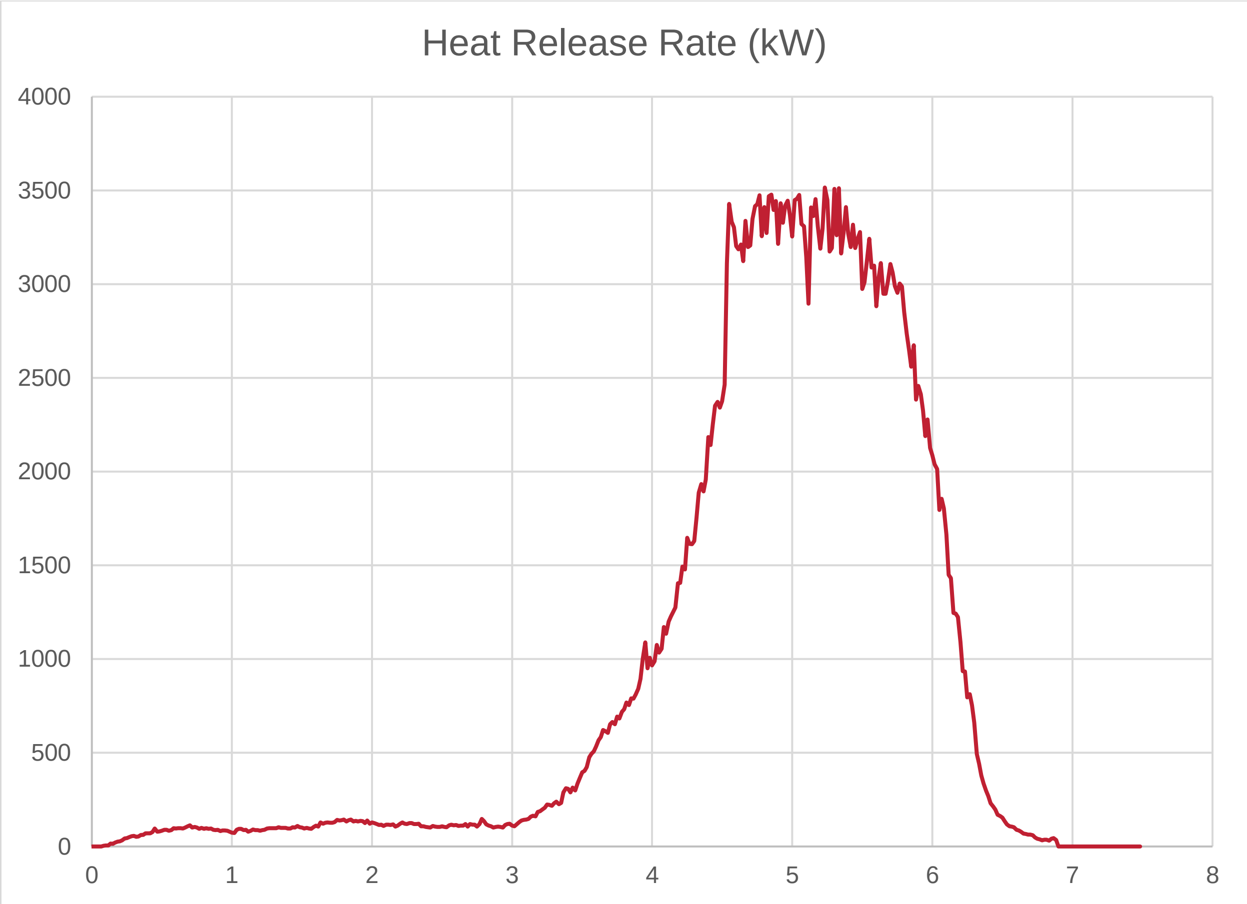


Figure 80 - Test 8 Vinyl Siding/Furring Strips with XPS/XPS Heat Release Rate Plot

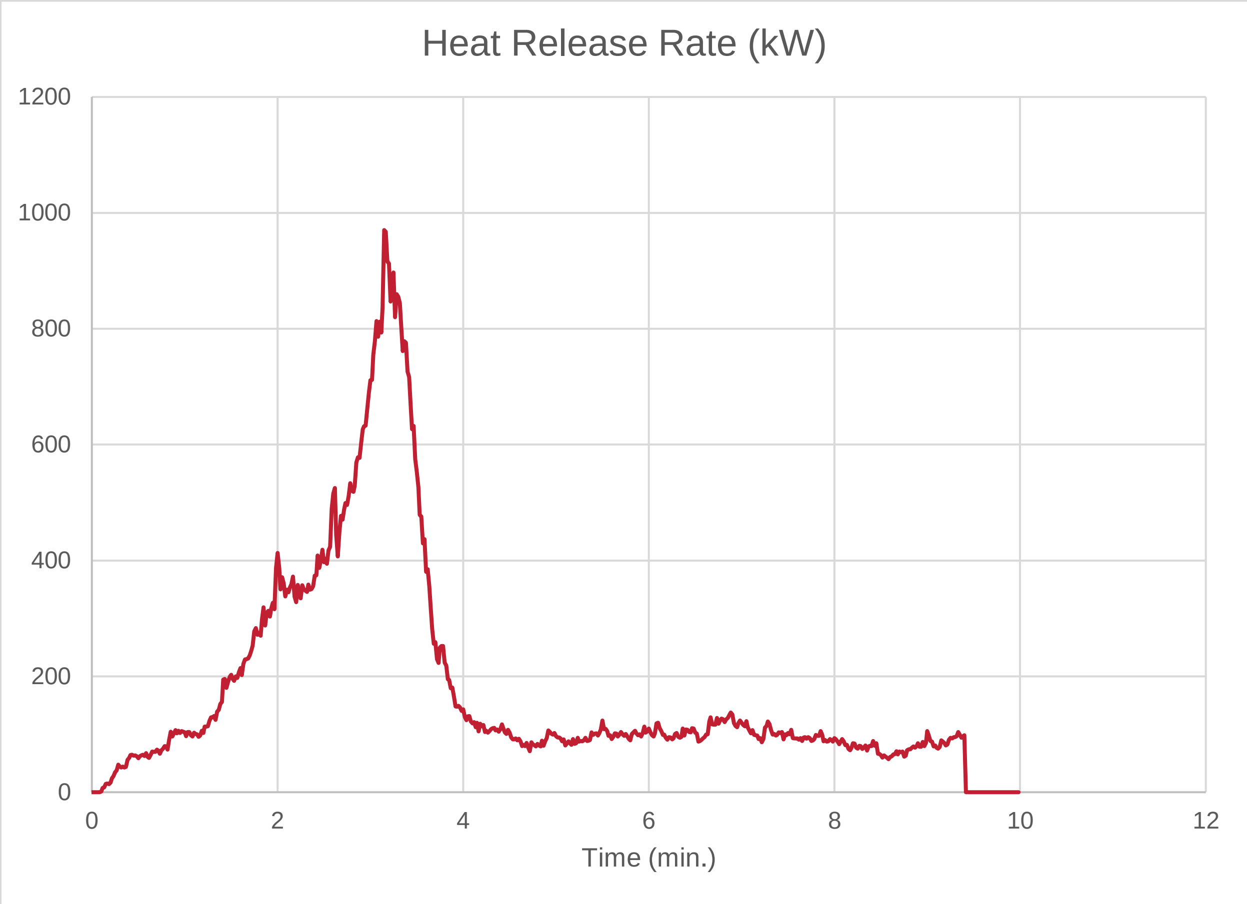


Figure 81 - Test 9 Vinyl Siding/Furring Strips/Foil Polyiso Heat Release Rate

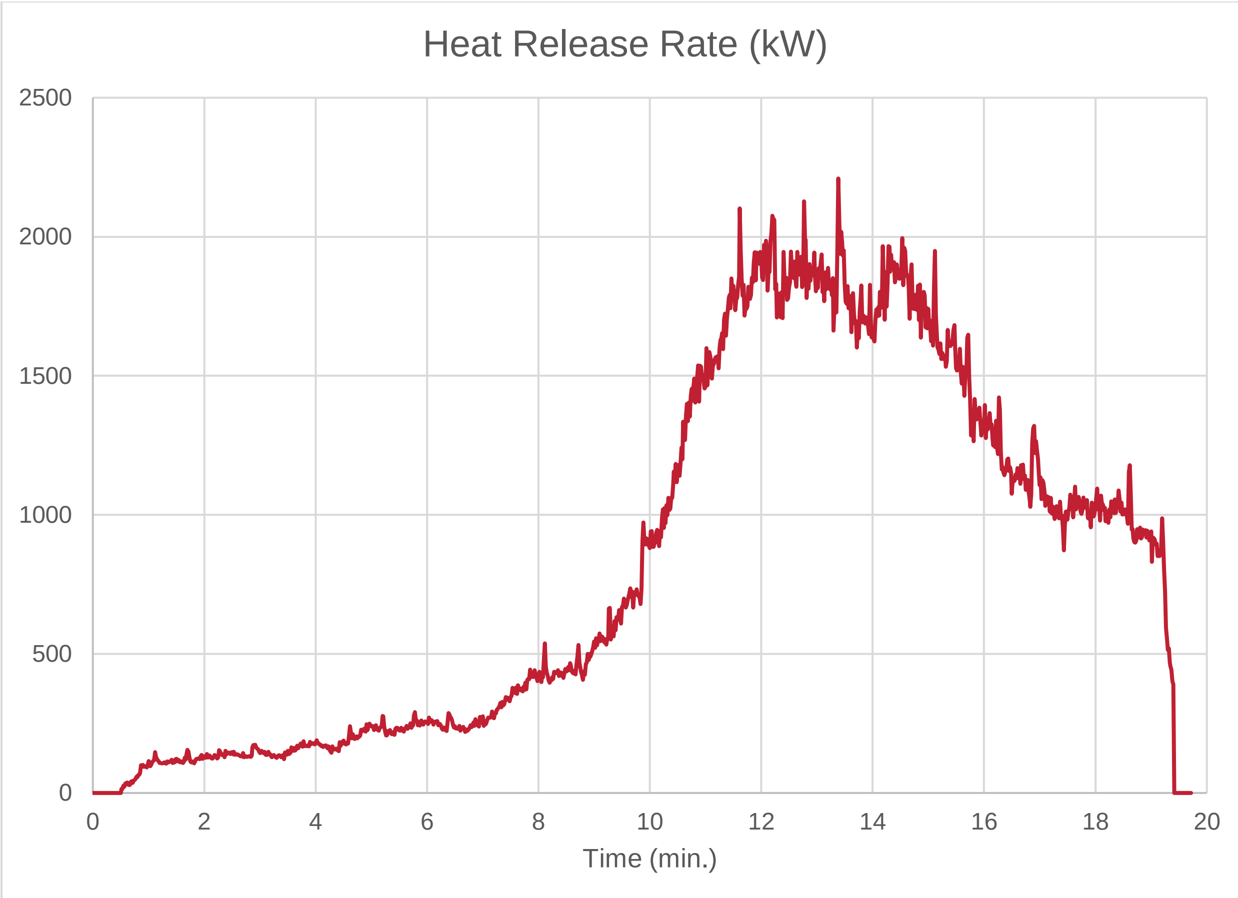


Figure 82 - Test 10 Wood Composite Siding/Furring Strips/Foil Polyiso Heat Release Rate

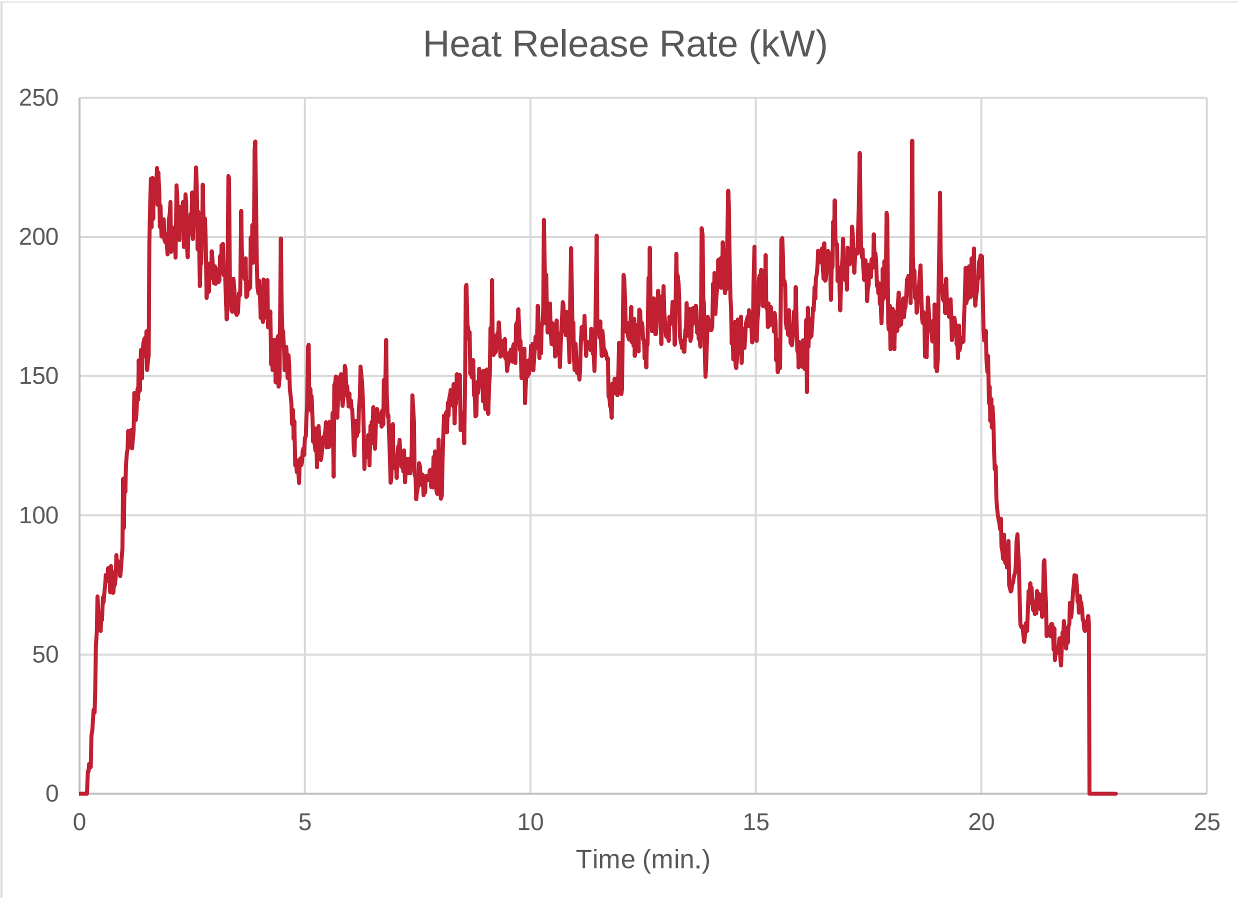


Figure 83 - Test 11 Vinyl Siding/Furring Strips/Mineral Wool Heat Release Rate Plot

Appendix D: Temperature Plots (English Units)

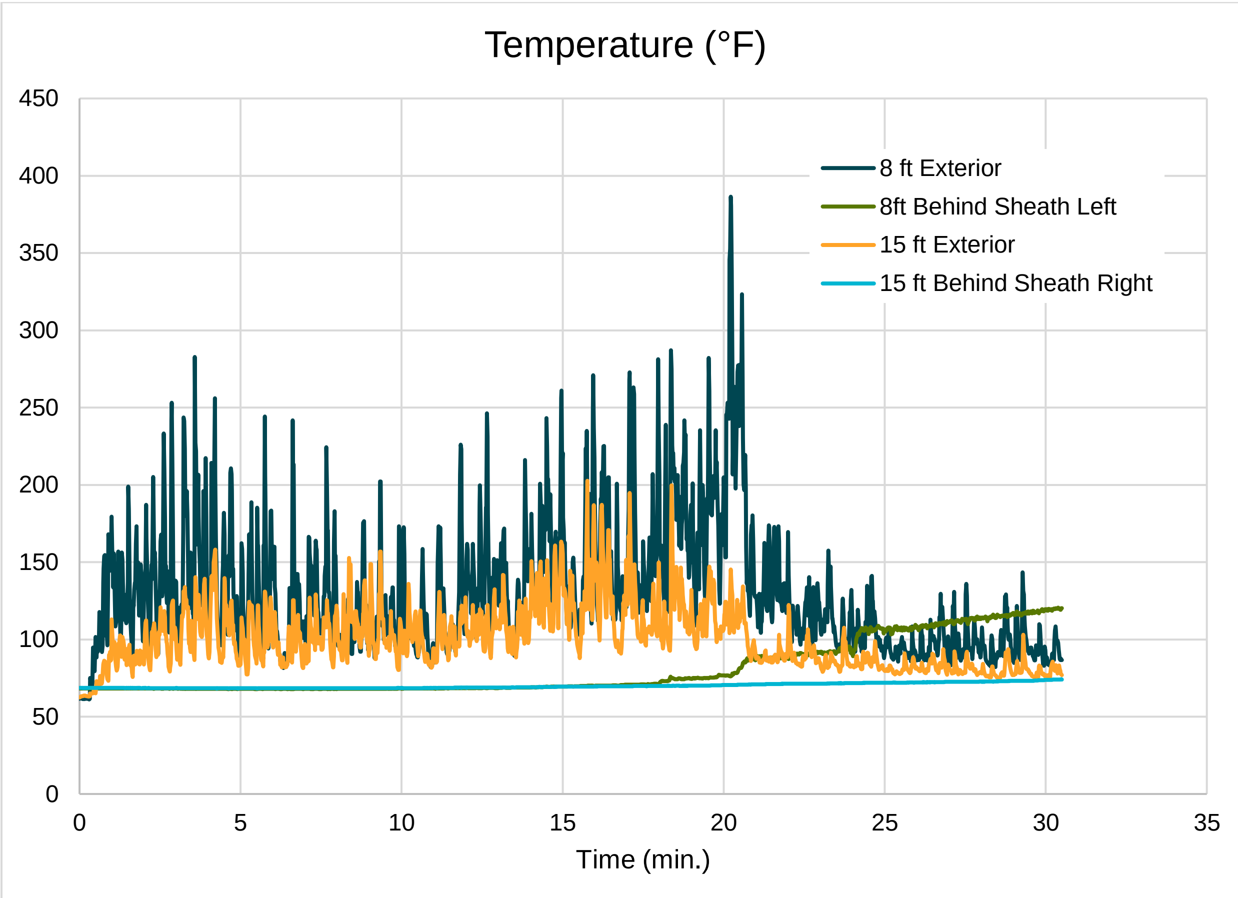


Figure 84 - Test 1 Wood Composite Siding/Asphalt Paper (75 kW) Temperature Plots (English Units)

Note: 8 ft Behind Sheath Right and 15 ft Behind Sheath Left channels were not functioning.

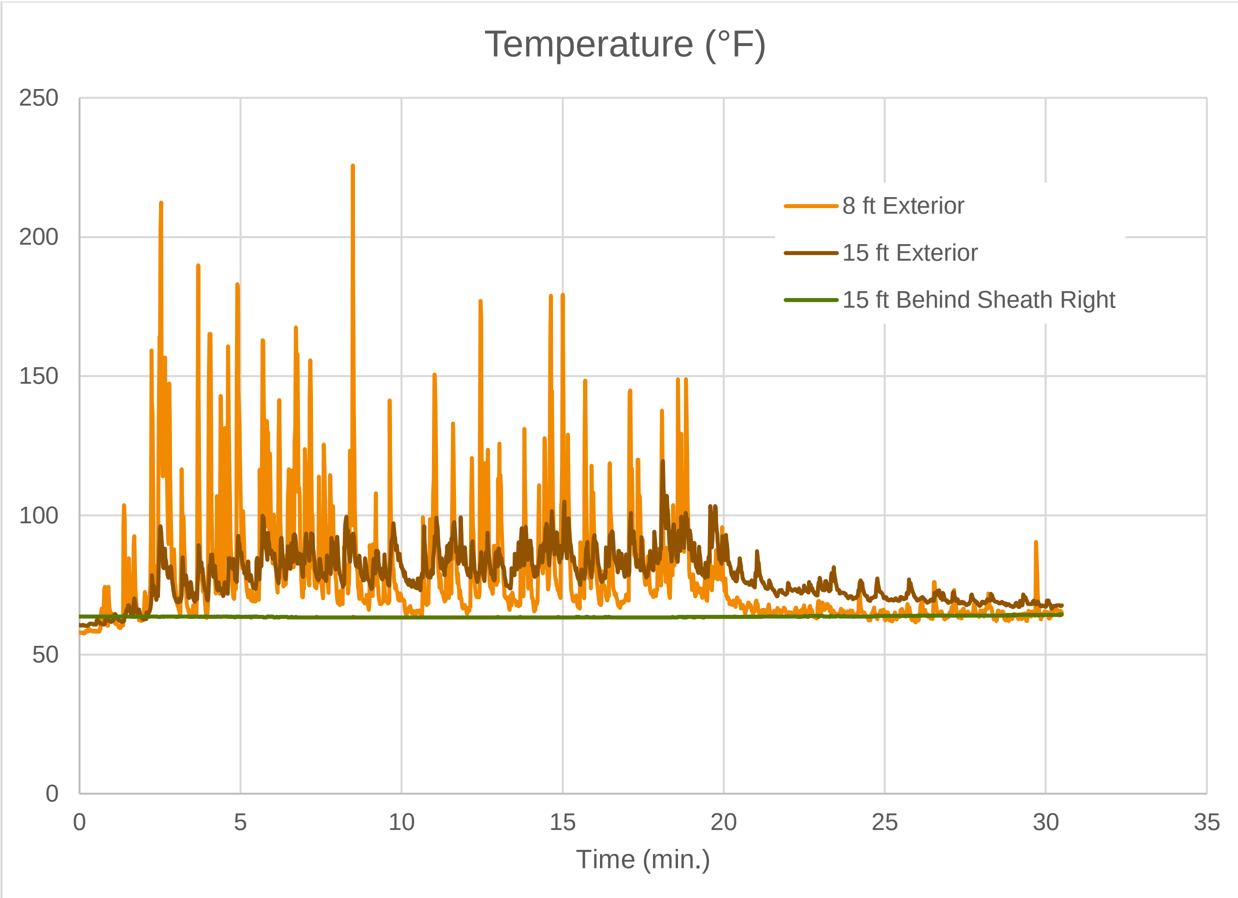


Figure 85 - Test 2 Wood Composite Siding/Asphalt Paper (50 kW) Temperature Plot (English Units)

Note: 8 ft Behind Sheath Right, 8 ft Behind Sheath Left, and 15 ft Behind Sheath Left channels were not functioning.

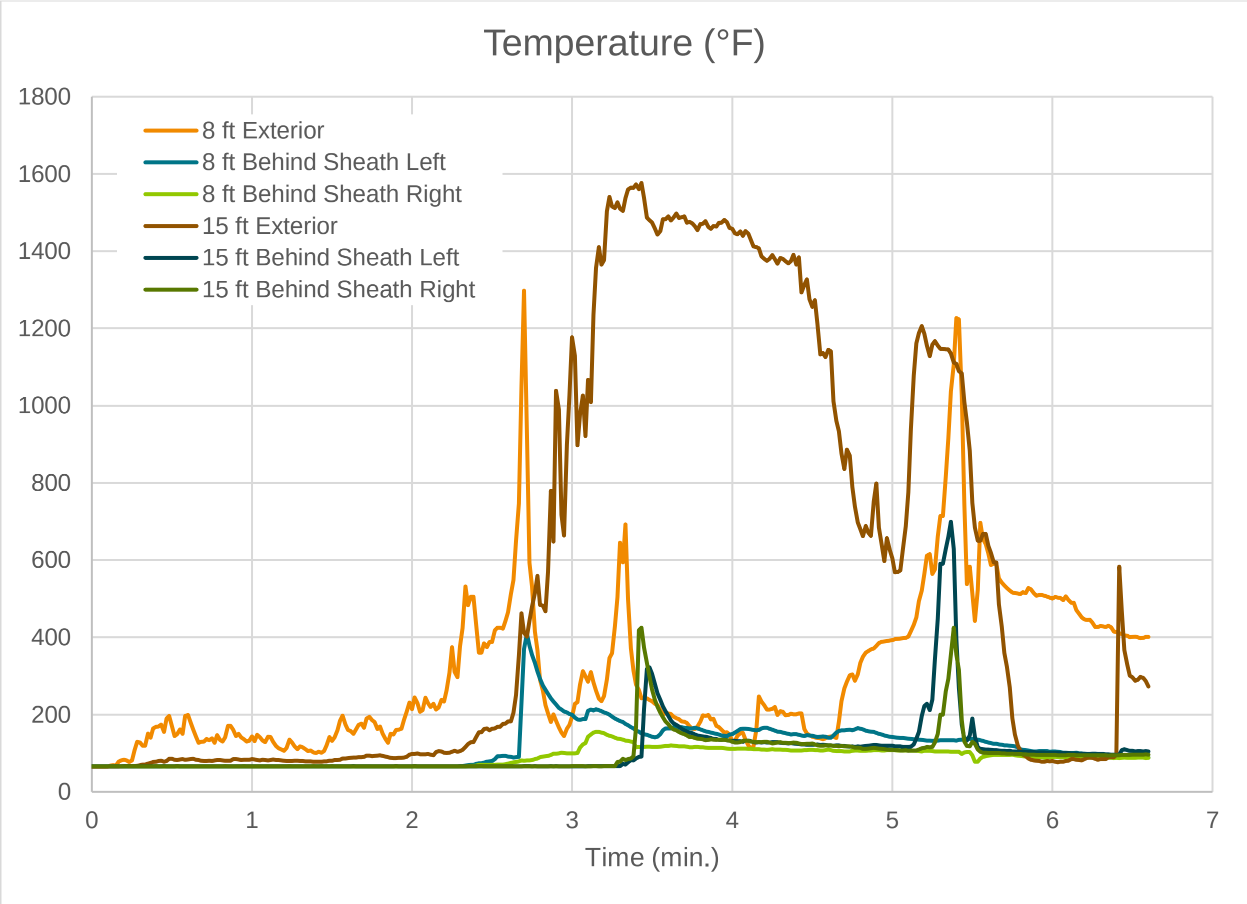


Figure 86 - Test 3 Vinyl Siding/Asphalt Paper Temperature Plot (English Units)

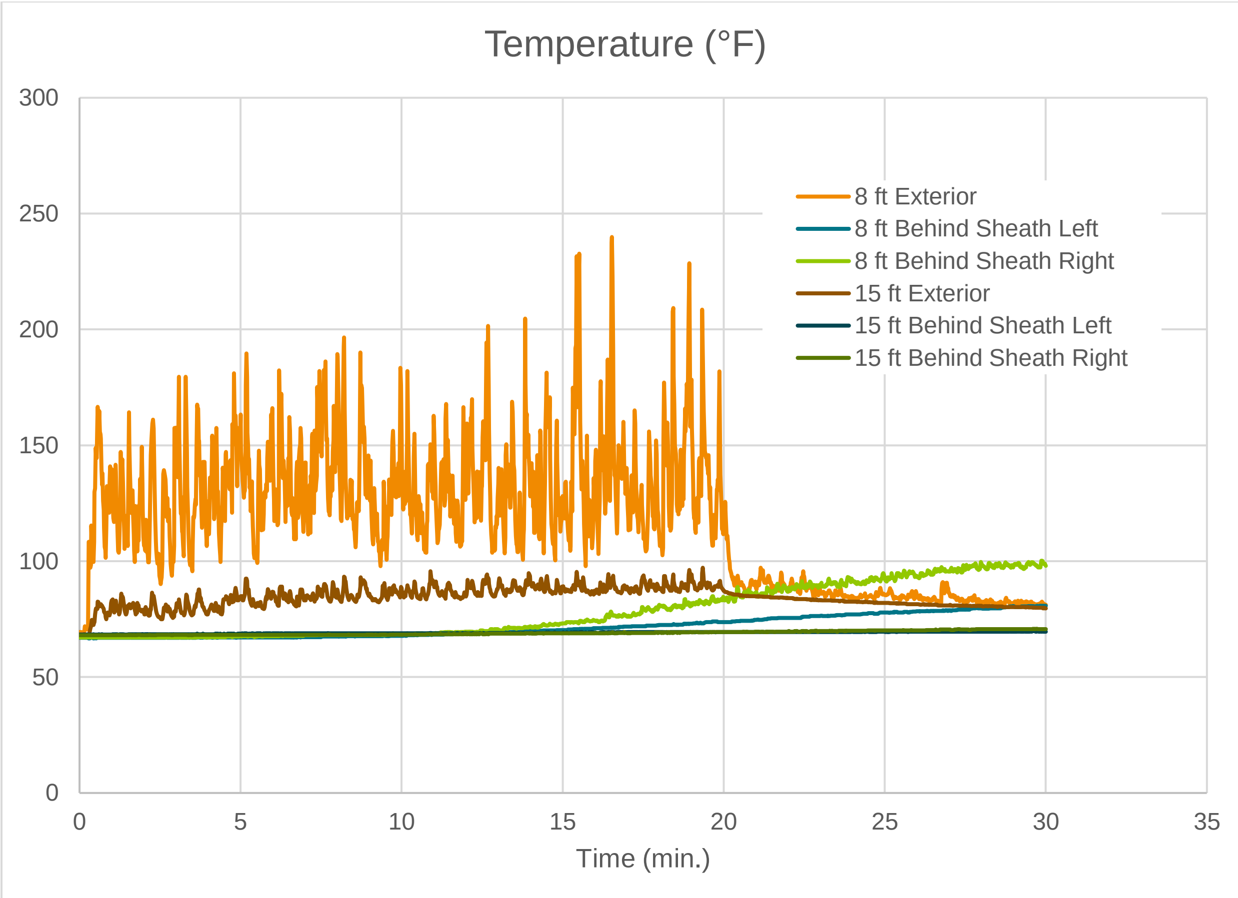


Figure 87 - Test 4 Fiber Cement Siding/Asphalt Paper Temperature Plot (English Units)

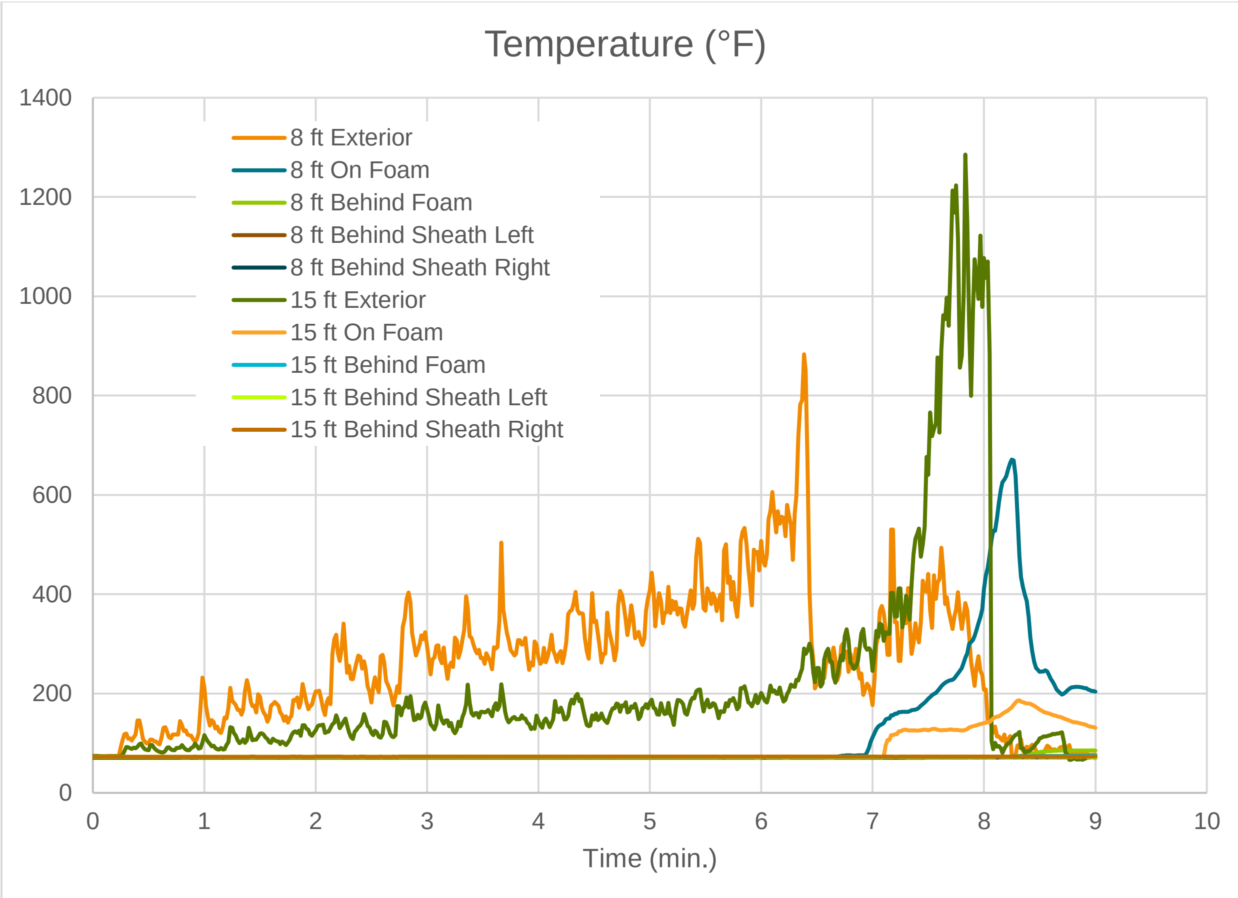


Figure 88 - Test 5 Wood Composite Siding/EPS/Mineral Wool Temperature Plot (English Units)

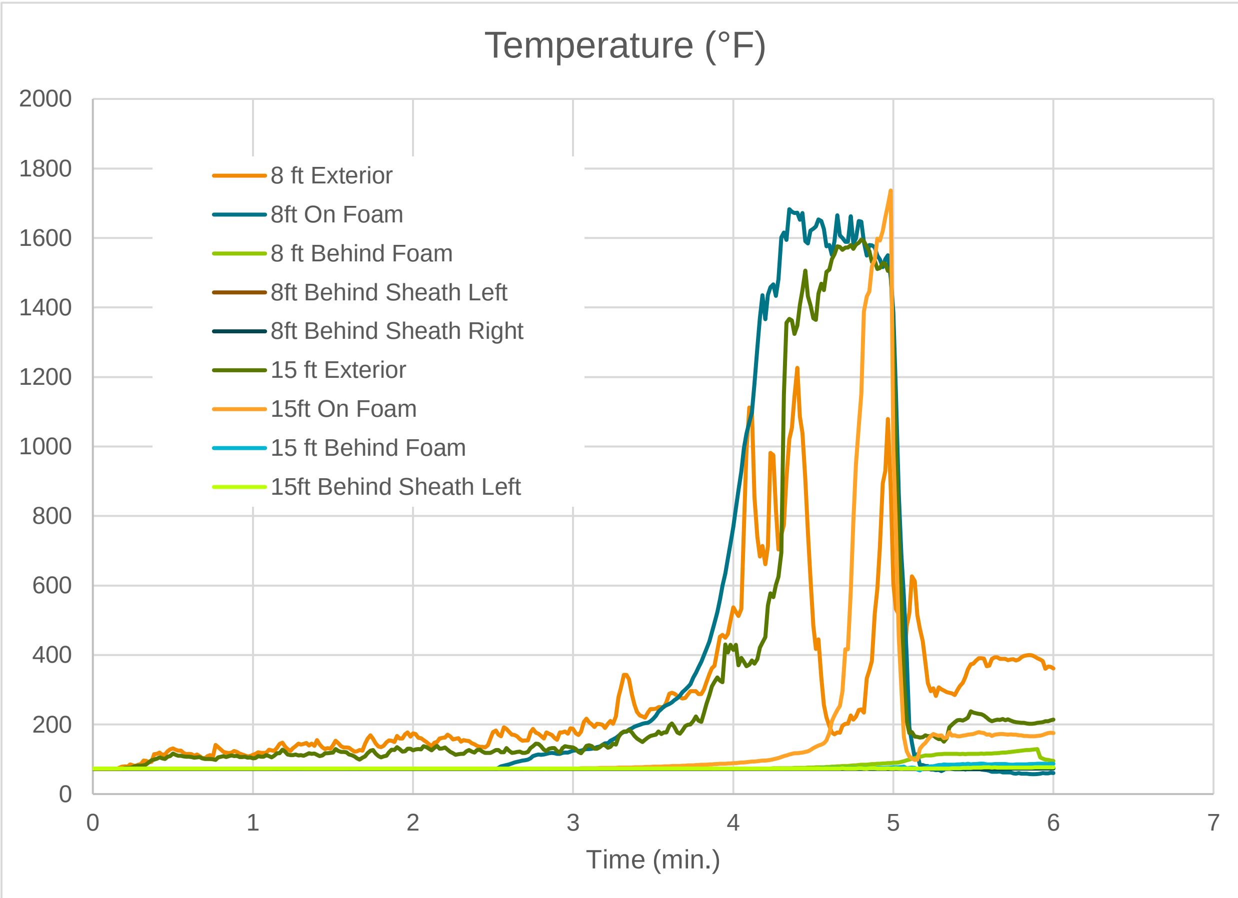


Figure 89 - Test 6 Vinyl Siding/EPS/Mineral Wool Temperature Plot (English Units)

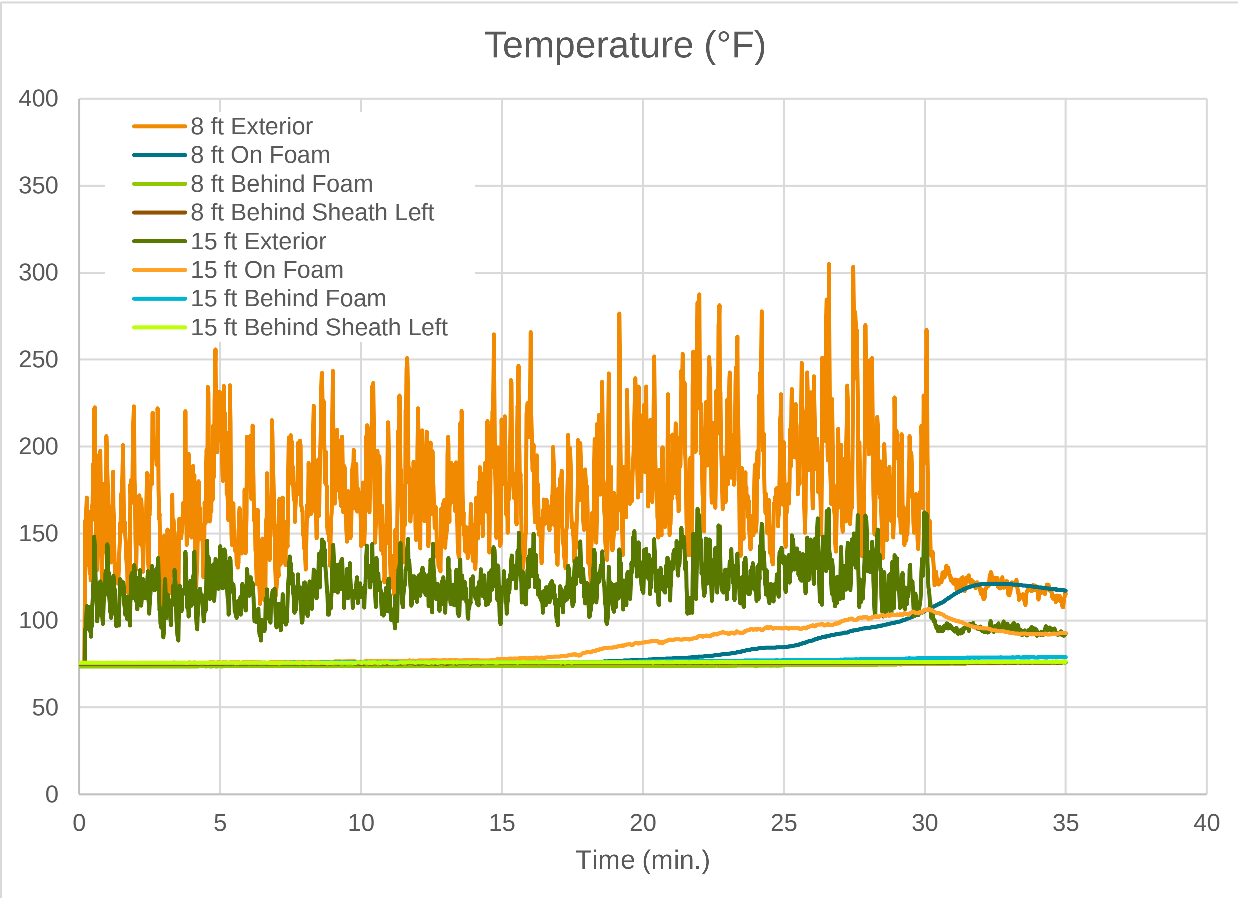


Figure 90 - Test 7 Fiber Cement Siding/EPS/Mineral Wool Temperature Plot (English Units)

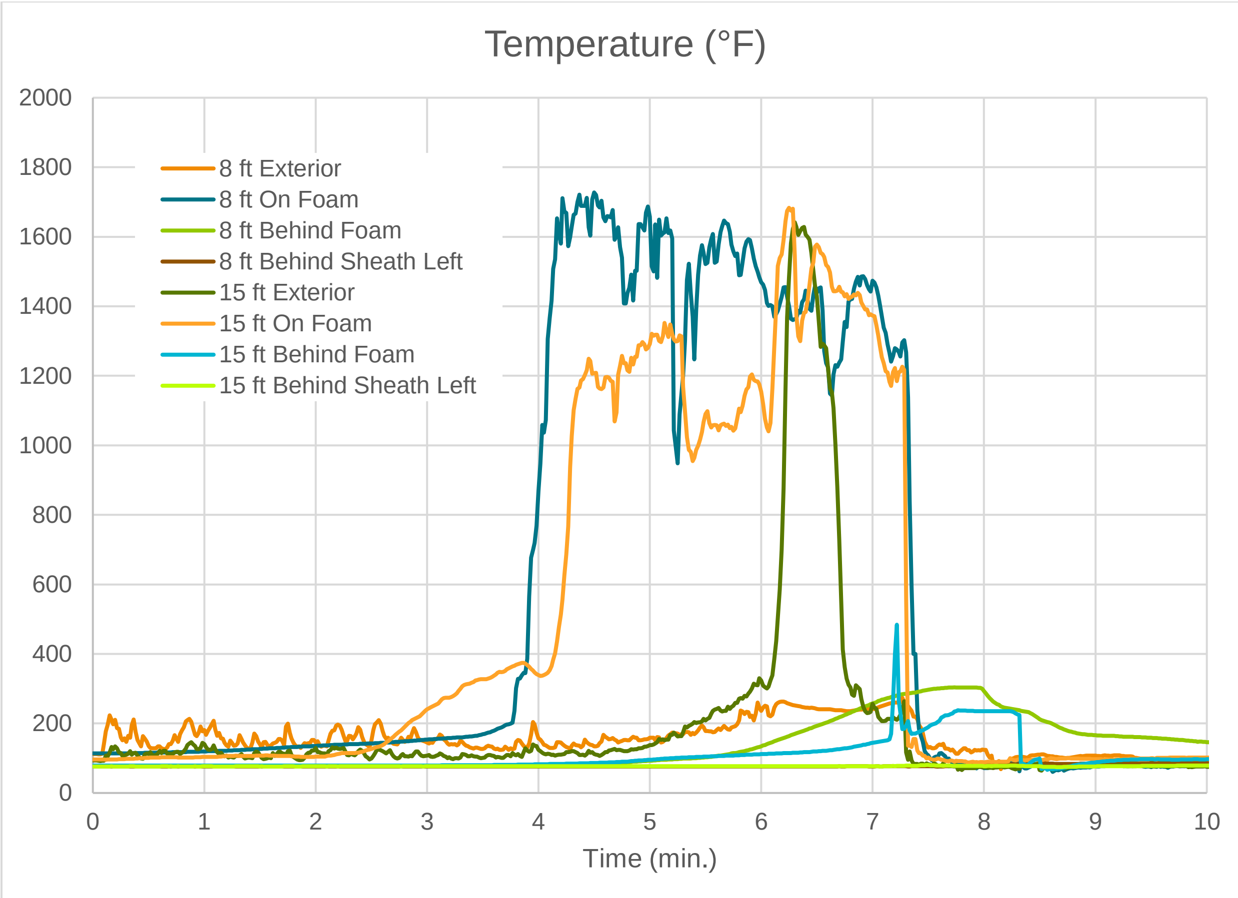


Figure 91 - Test 7 Fiber Cement Siding/EPS/Mineral Wool After Panels Removed Temperature Plot (English Units)

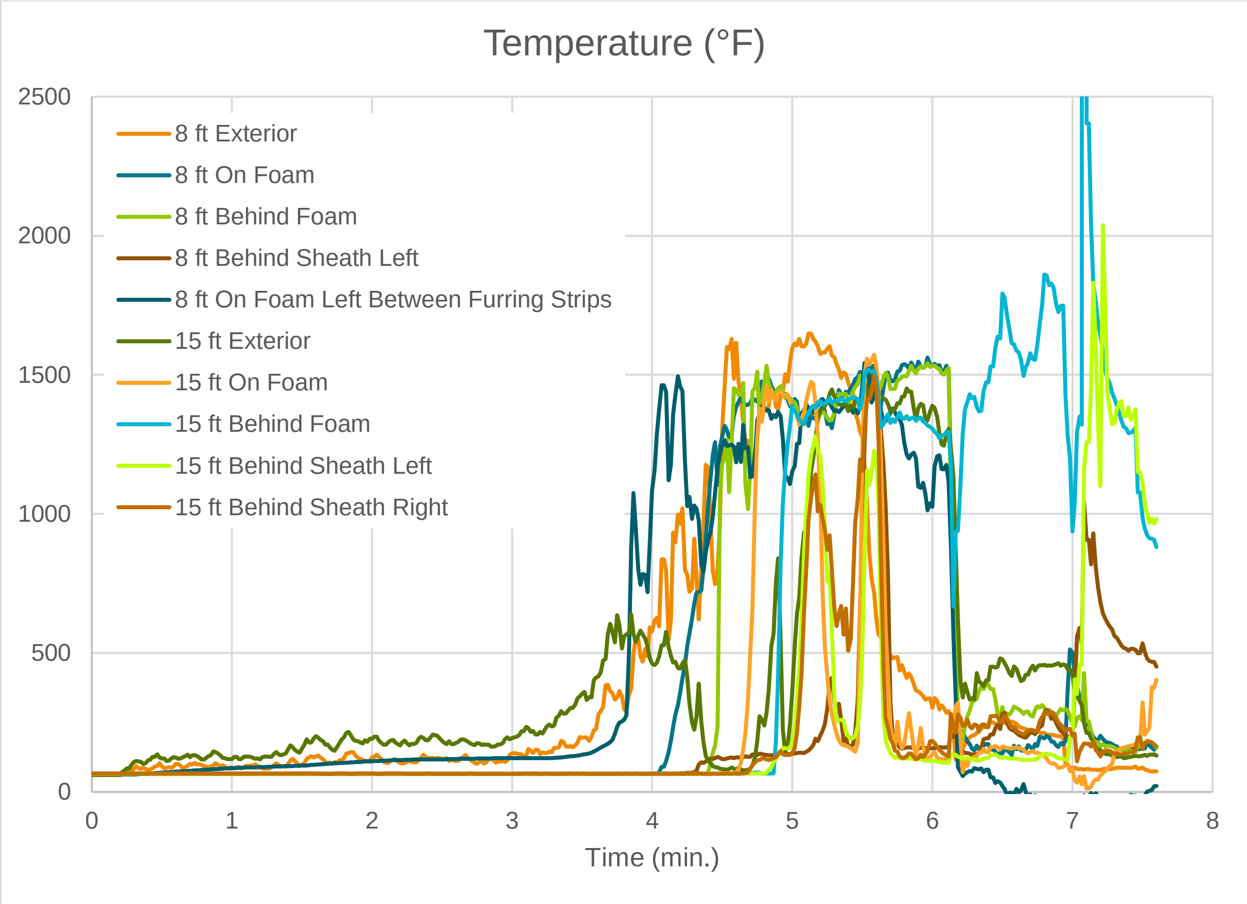


Figure 92 - Test 8 Vinyl Siding/Furring Strips with XPS/XPS Temperature Plot (English Units)

Note: 8 ft Behind Sheath Right channel was not functioning.

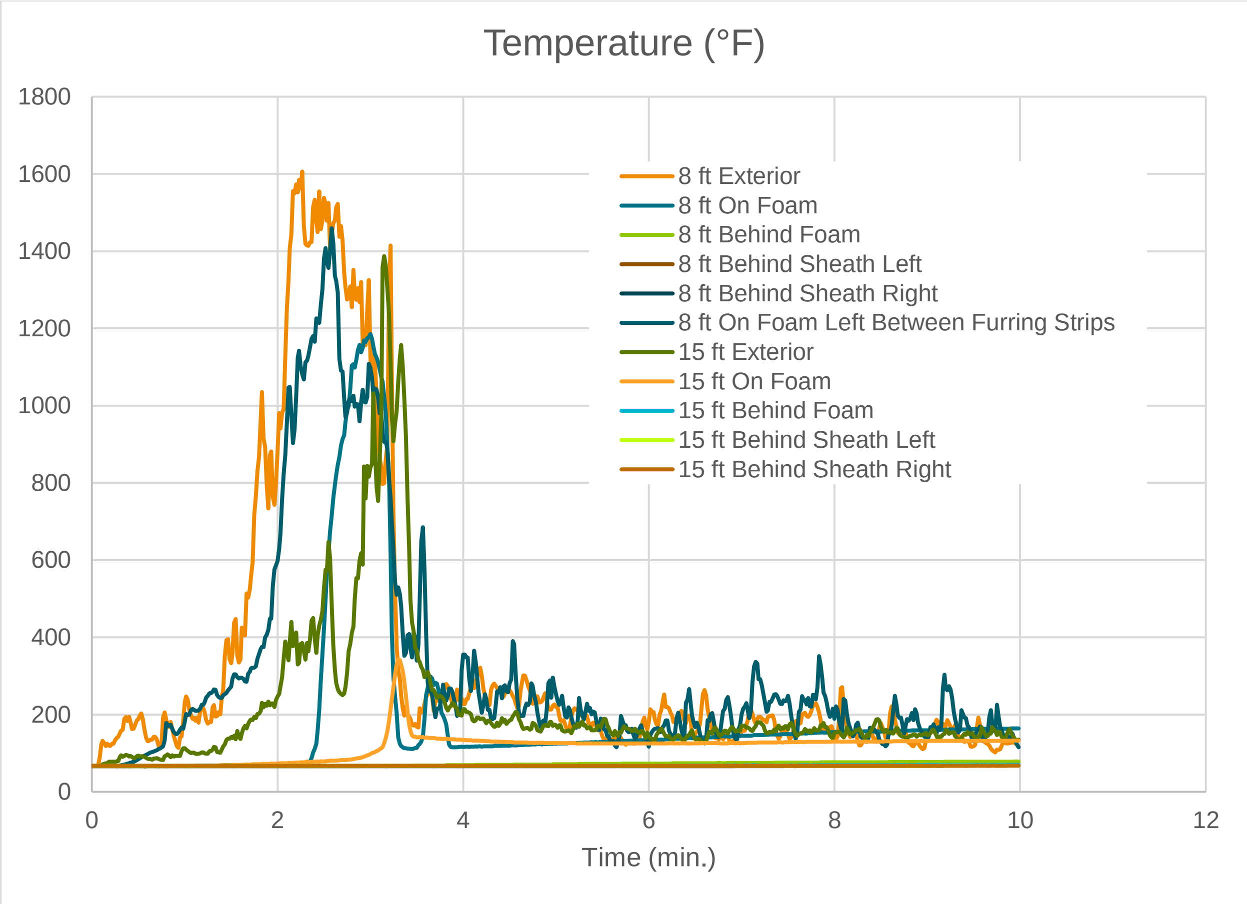


Figure 93 - Test 9 Vinyl Siding/Furring Strips/Foil Polyiso Temperature Plot (English Units)

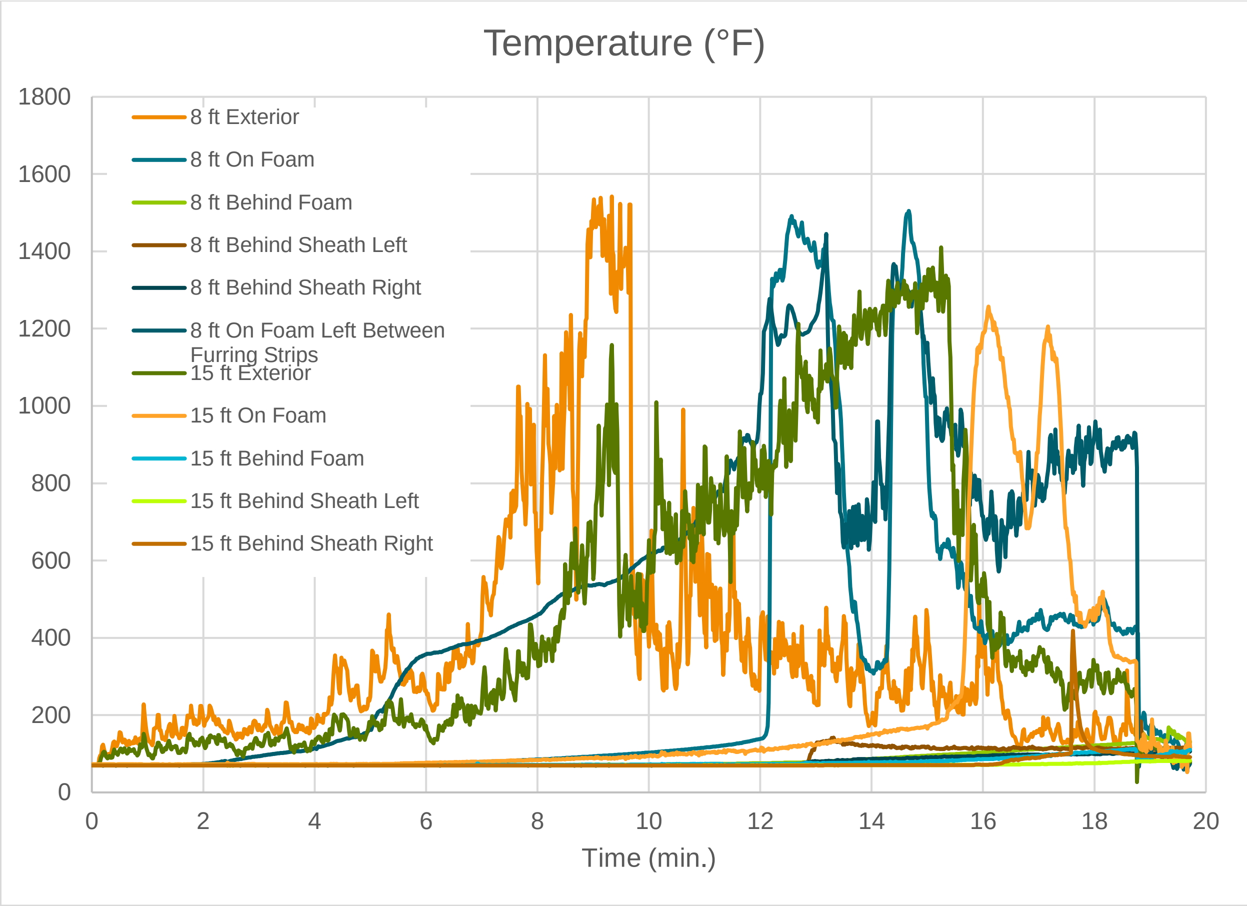


Figure 94 - Test 10 Wood Composite Siding/Furring Strips/Foil Polyiso Temperature Plot (English Units)

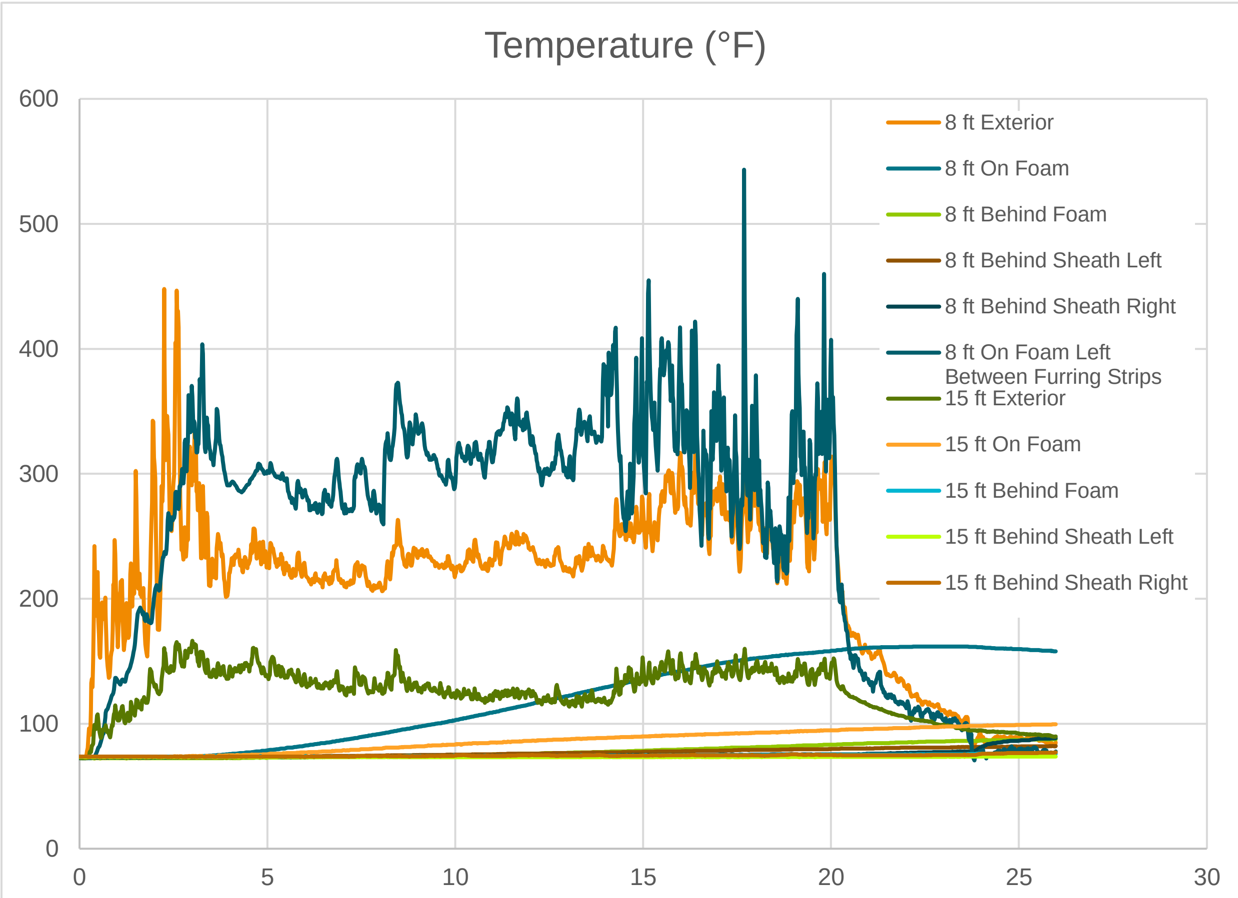


Figure 95 - Test 11 Vinyl Siding/Furring Strips/Mineral Wool Temperature Plot (English Units)

Appendix E: Temperature Plots (Metric Unit)

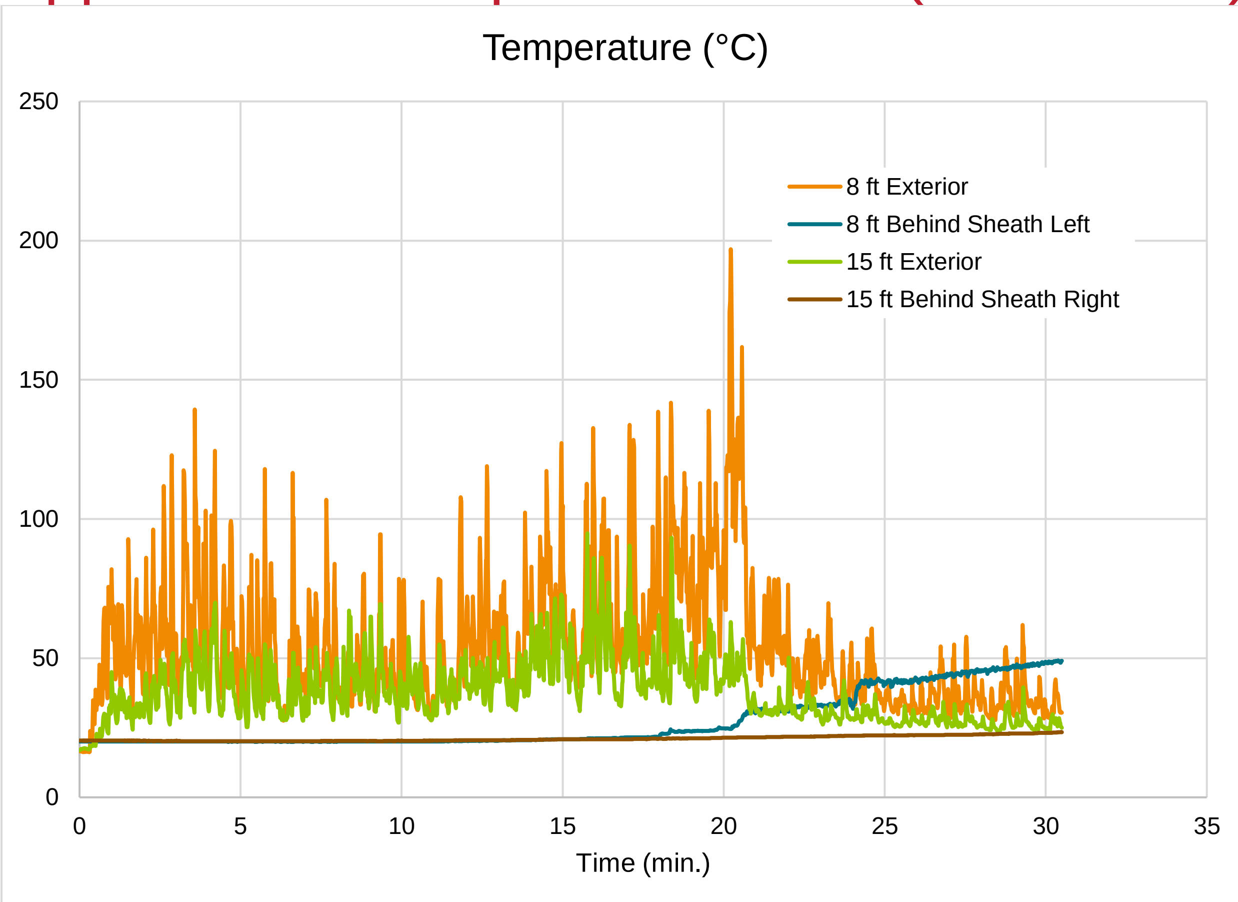


Figure 96 - Test 1 Wood Composite Siding/Asphalt Paper (75 kW) Temperature Plot (Metric Units)

Note: 8 ft Behind Sheath Right and 15 ft Behind Sheath Left channels were not functioning.

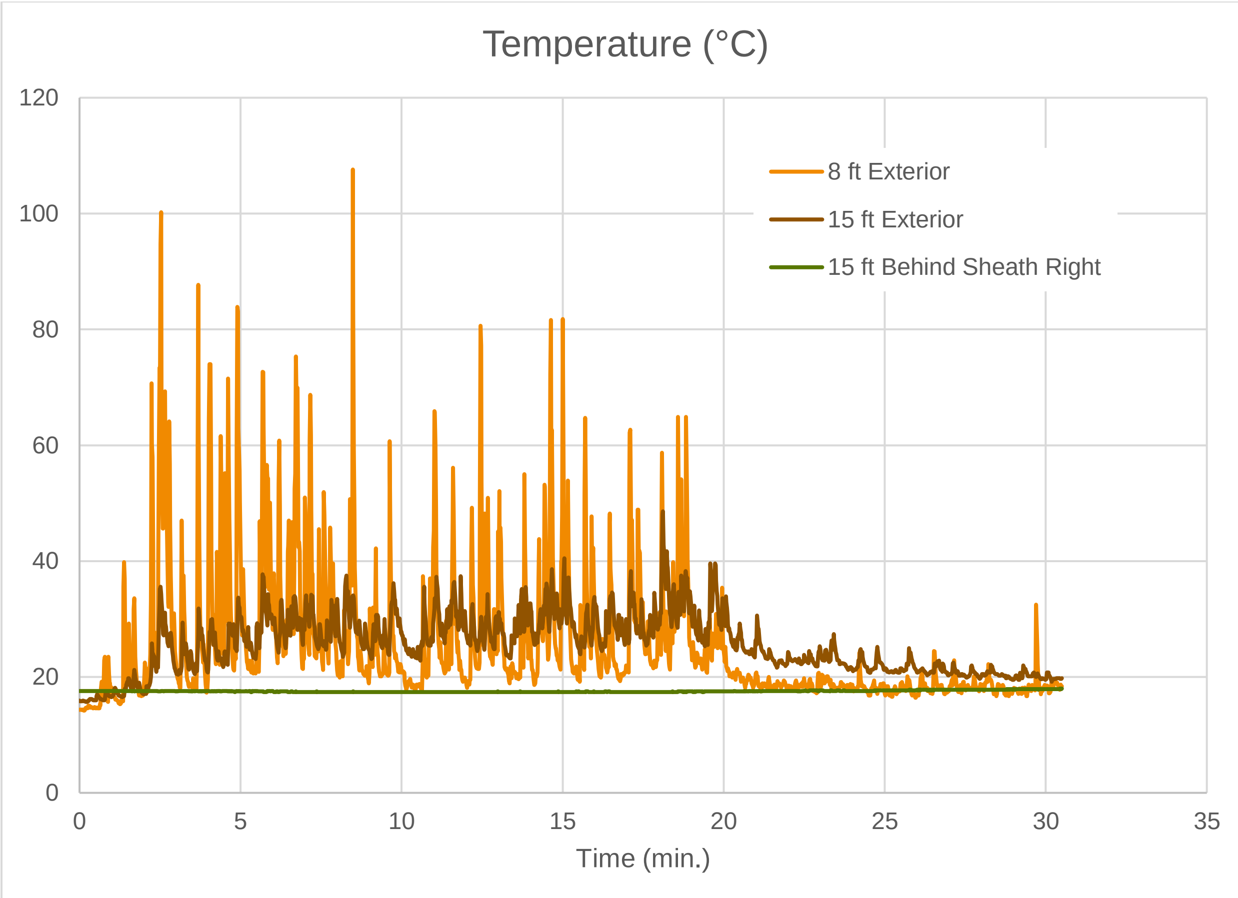


Figure 97 - Test 2 Wood Composite Siding/Asphalt Paper (50 kW) Temperature Plot (Metric Units)

Note: 8 ft Behind Sheath Right, 8 ft Behind Sheath Left, and 15 ft Behind Sheath Left channels were not functioning.

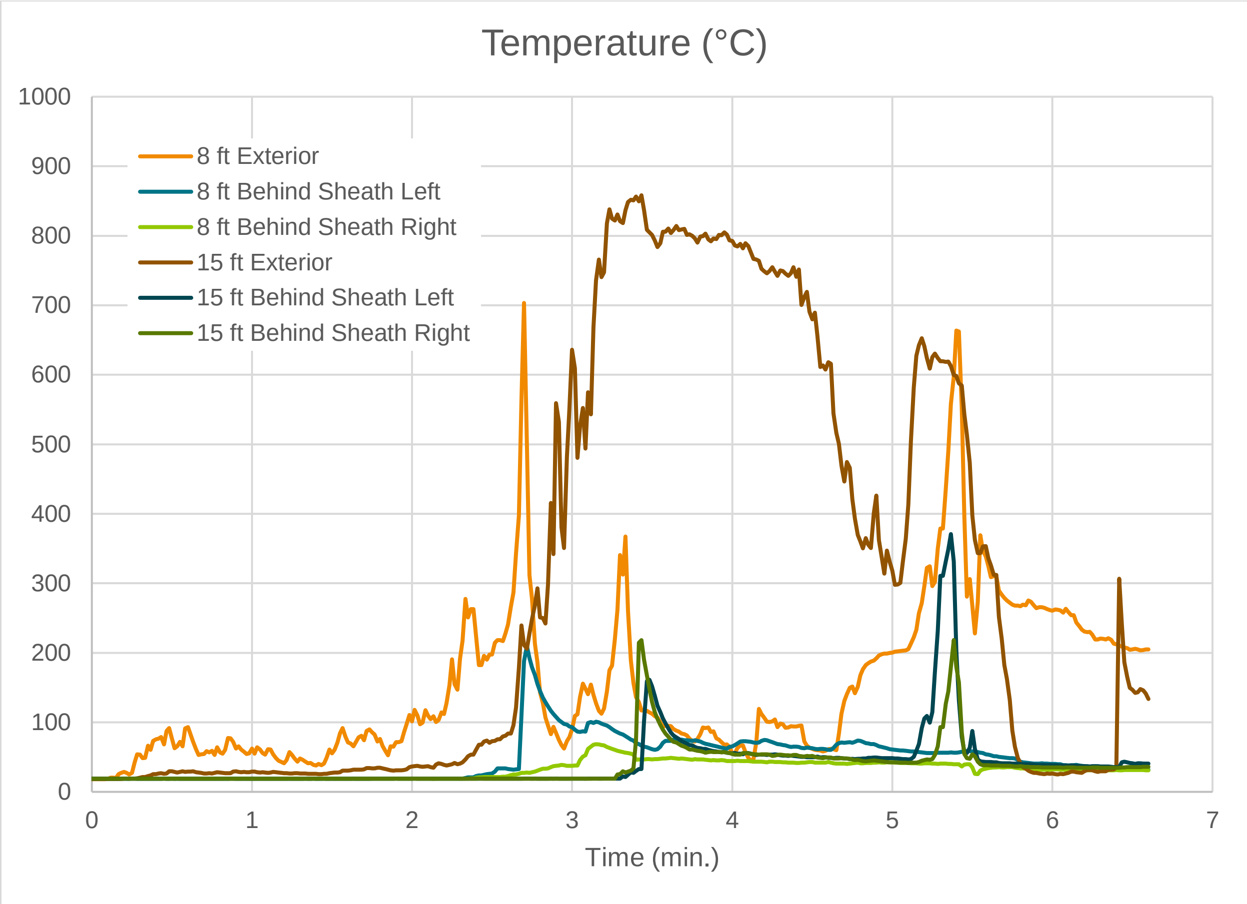


Figure 98 - Test 3 Vinyl Siding/Asphalt Paper Temperature Plot (Metric Units)

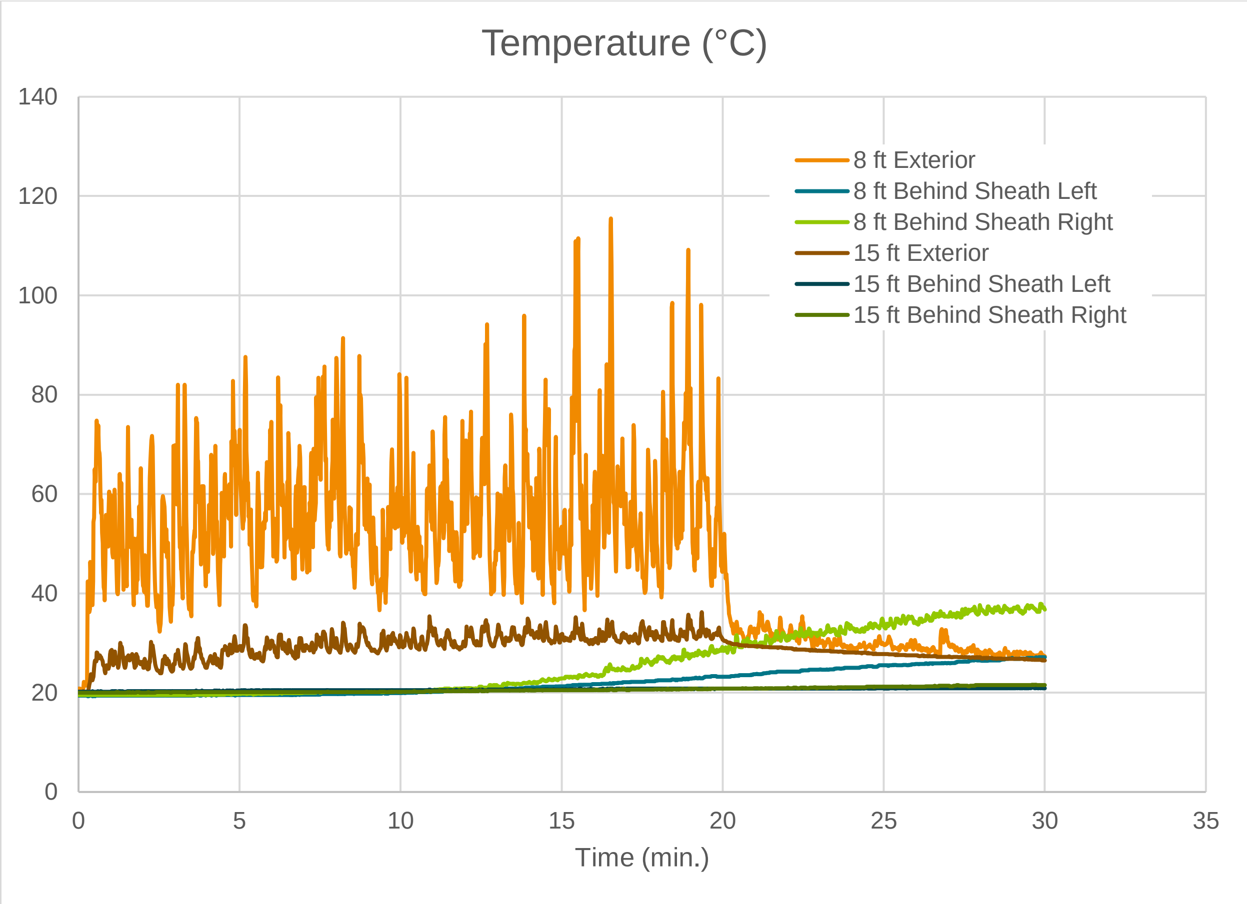


Figure 99 - Test 4 Fiber Cement Siding/Asphalt Paper Temperature Plot (Metric Units)

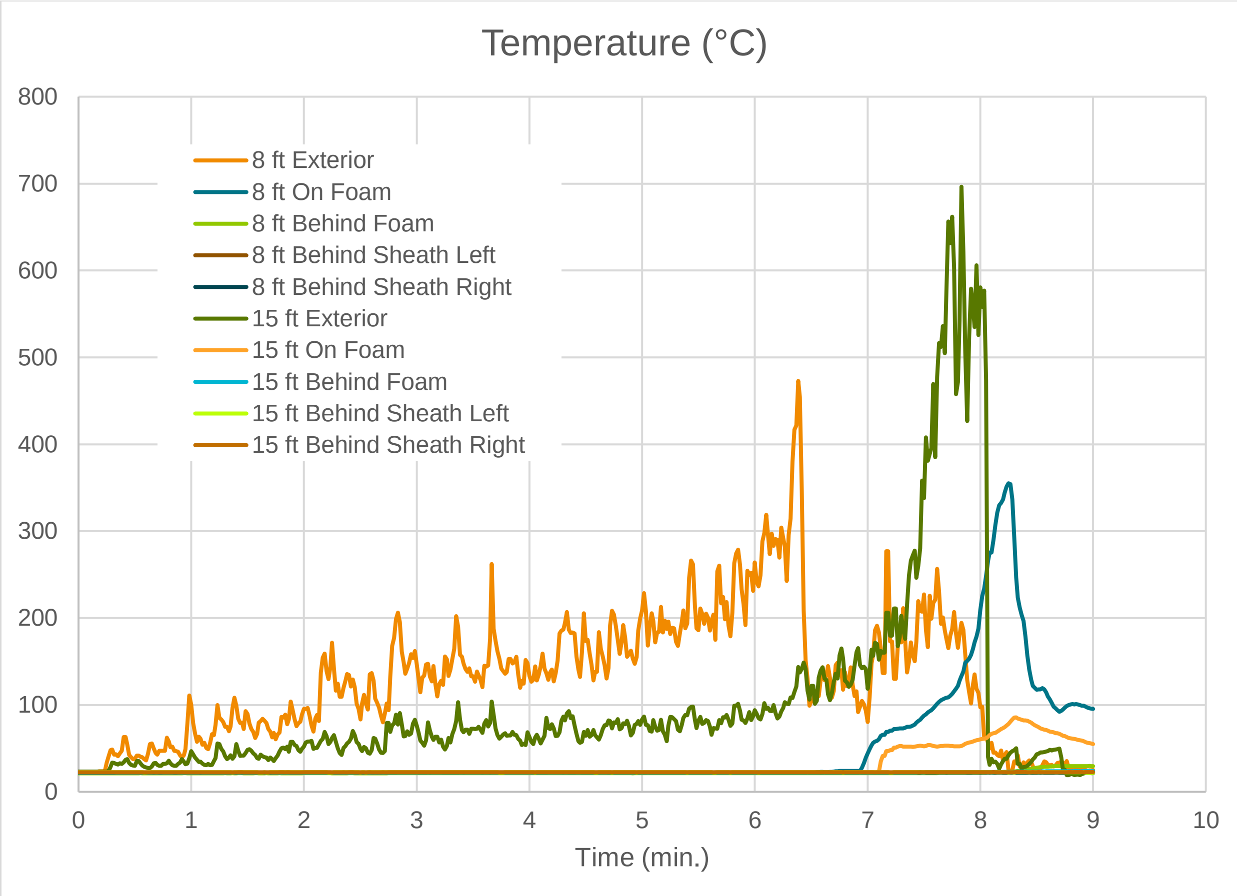


Figure 100 - Test 5 Wood Composite Siding/EPS/Mineral Wool Temperature Plot (Metric Units)

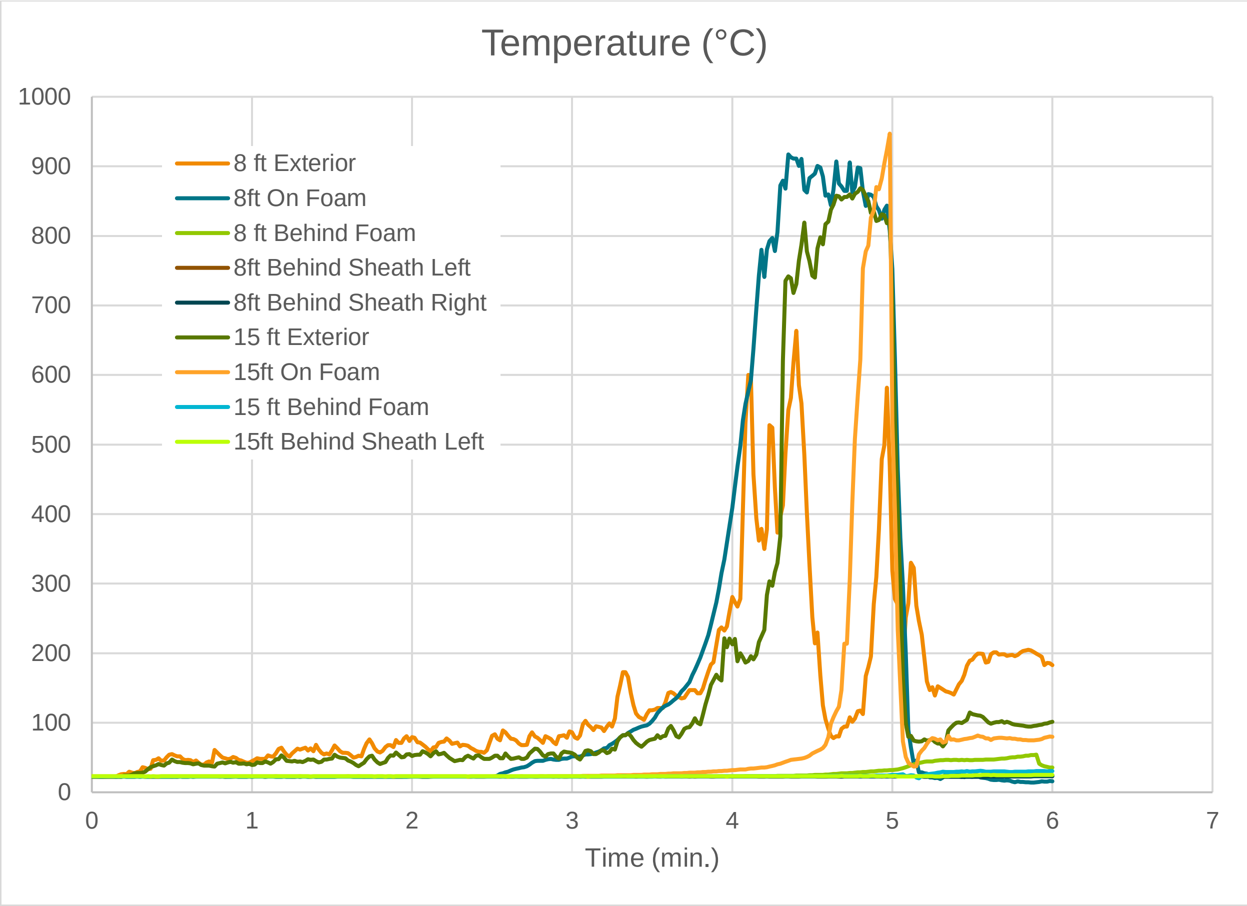


Figure 101 - Test 6 Vinyl Siding/EPS/Mineral Wool Temperature Plot (Metric Units)

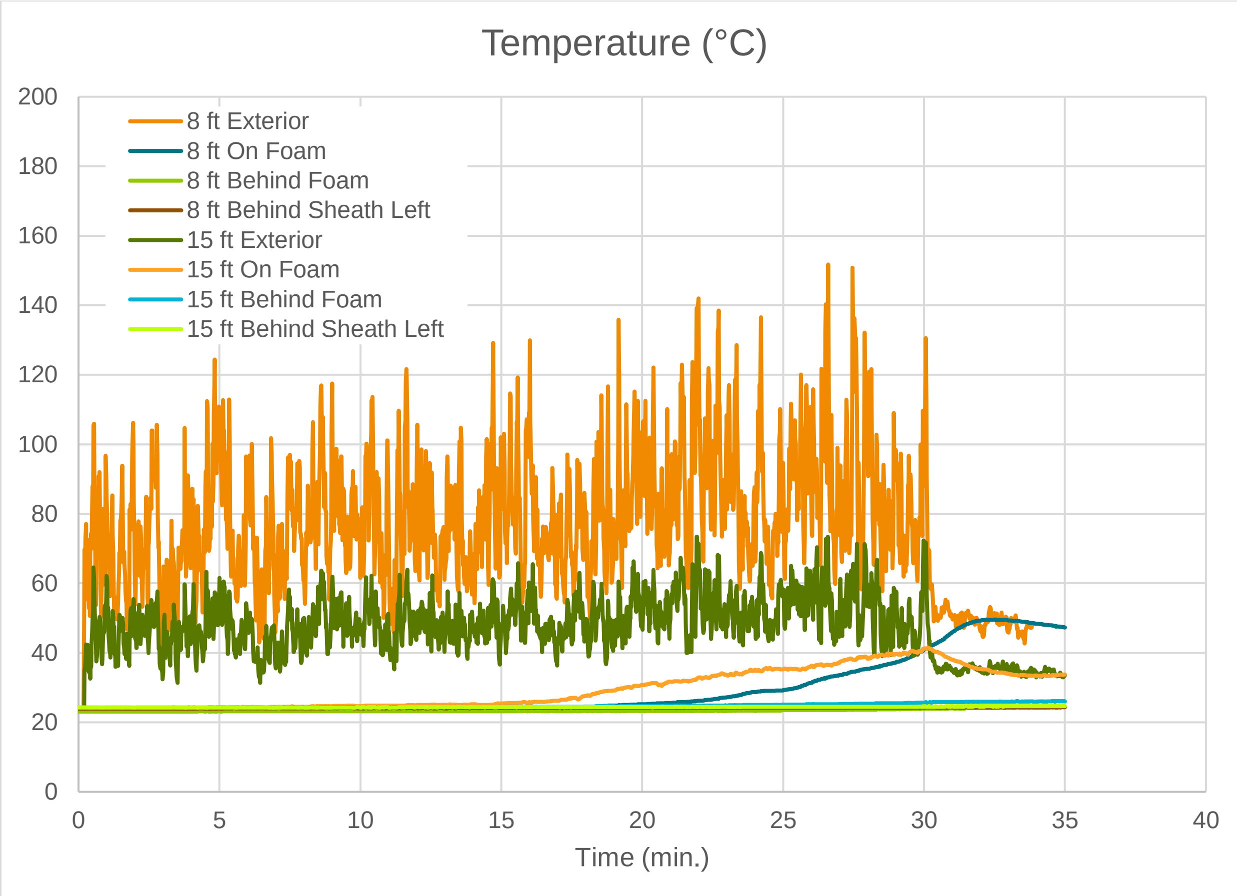


Figure 102 - Test 7 Fiber Cement Siding/EPS/Mineral Wool Temperature Plot (Metric Units)

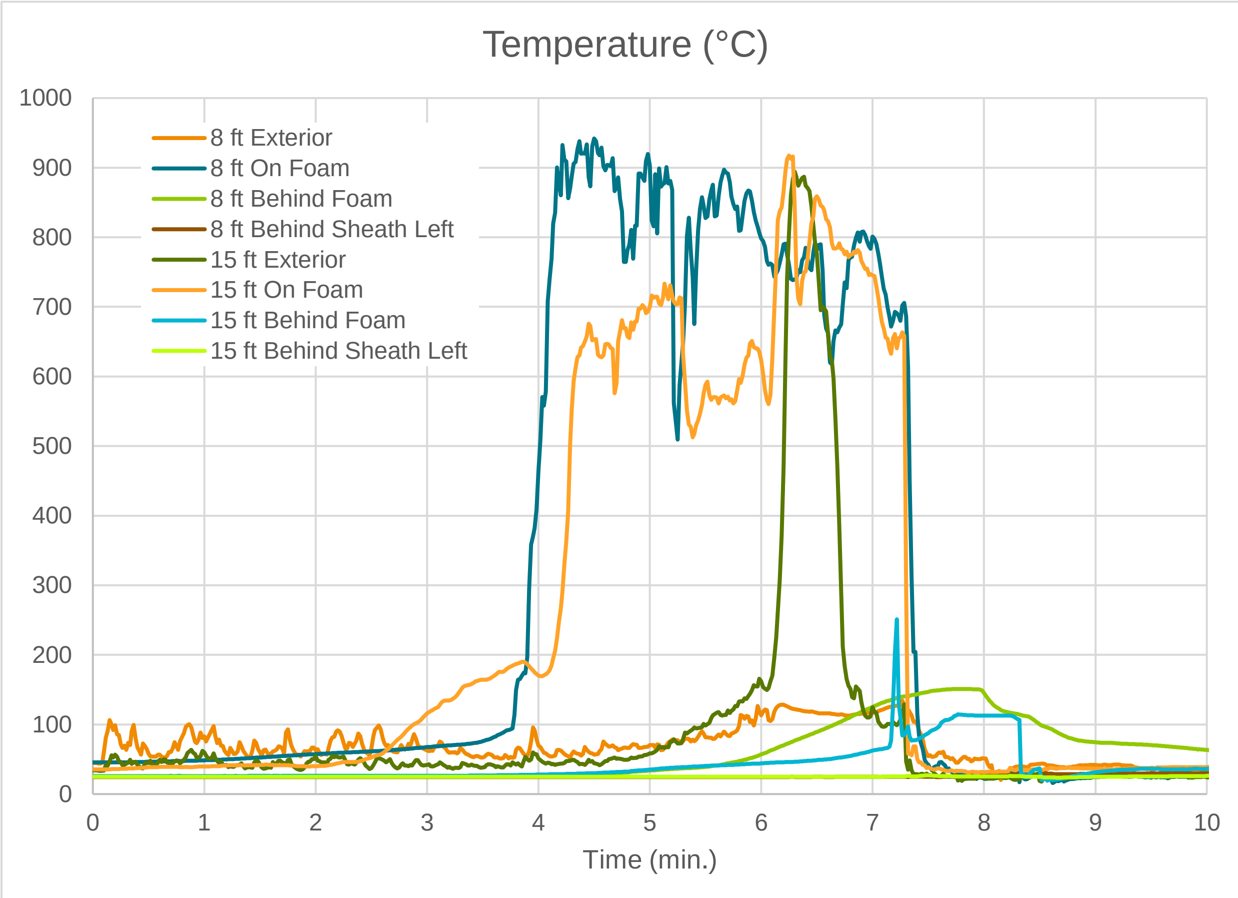


Figure 103 - Test 7 Fiber Cement Siding/EPS/Mineral Wool After Panels Removed Temperature Plot (Metric Units)

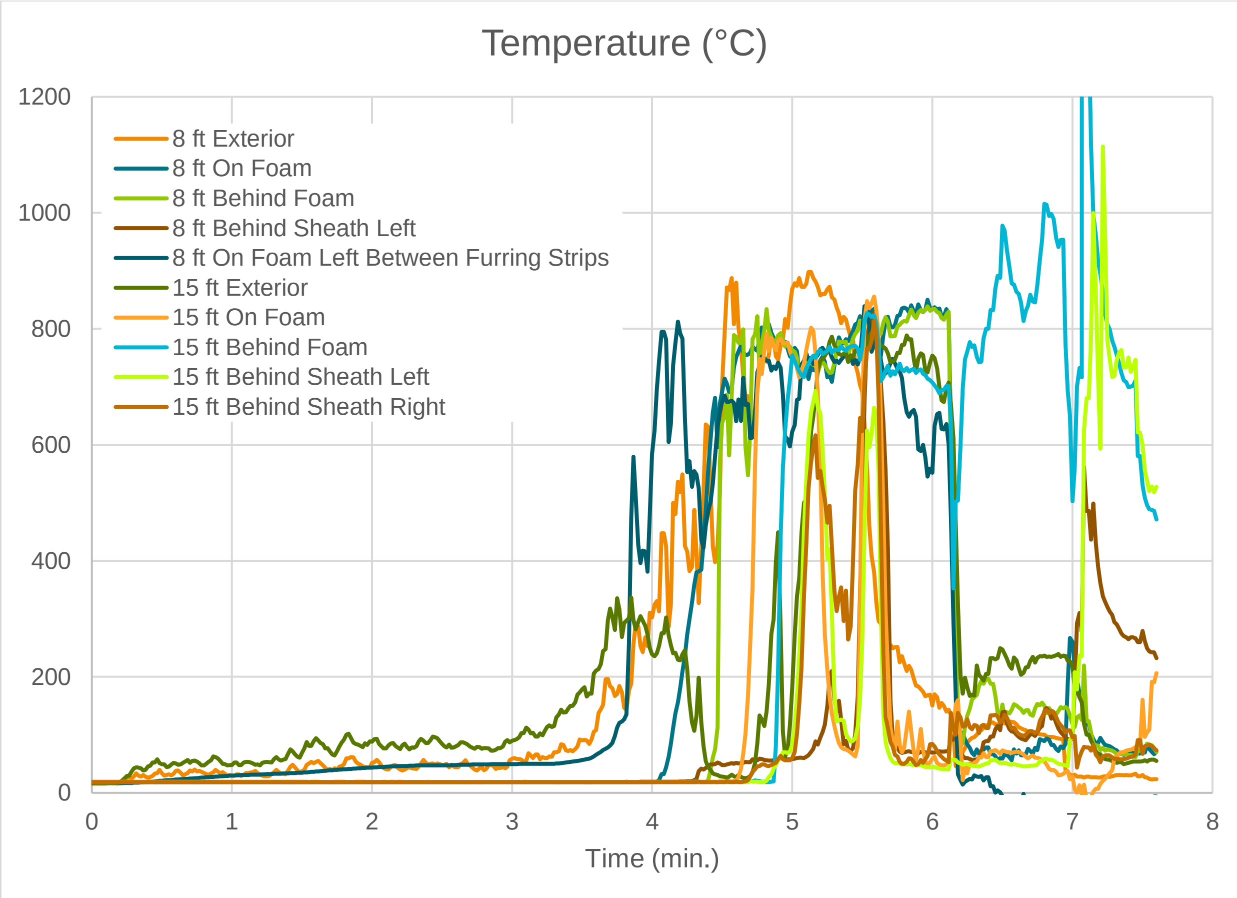


Figure 104 - Test 8 Vinyl Siding/Furring Strips with XPS/XPS Temperature Plot (Metric Units)

Note: 8 ft Behind Sheath Right channel was not functioning.

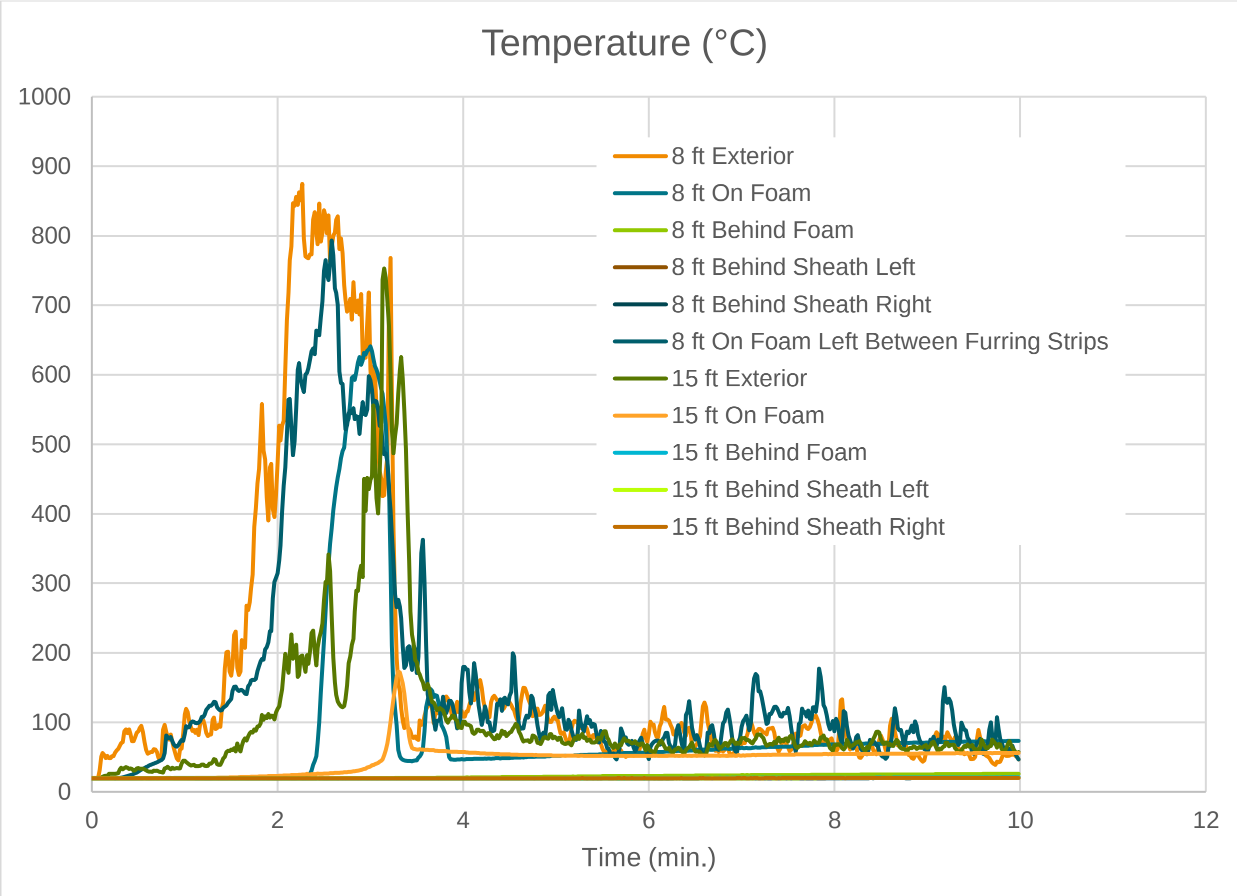


Figure 105 - Test 9 Vinyl Siding/Furring Strips/Foil Polyiso Temperature Plot (Metric Units)

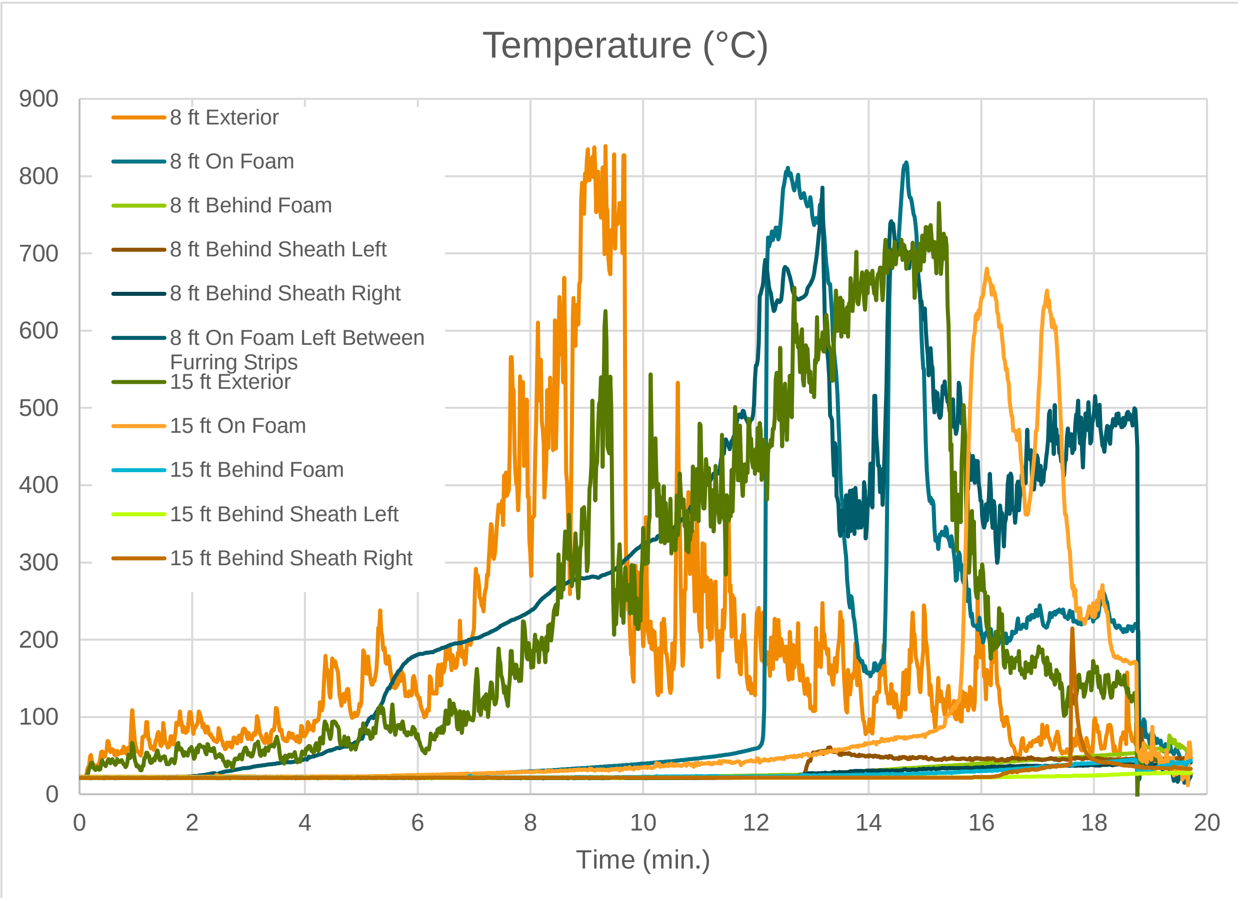


Figure 106 - Test 10 Wood Composite Siding/Furring Strips/Foil Polyiso Temperature Plot (Metric Units)

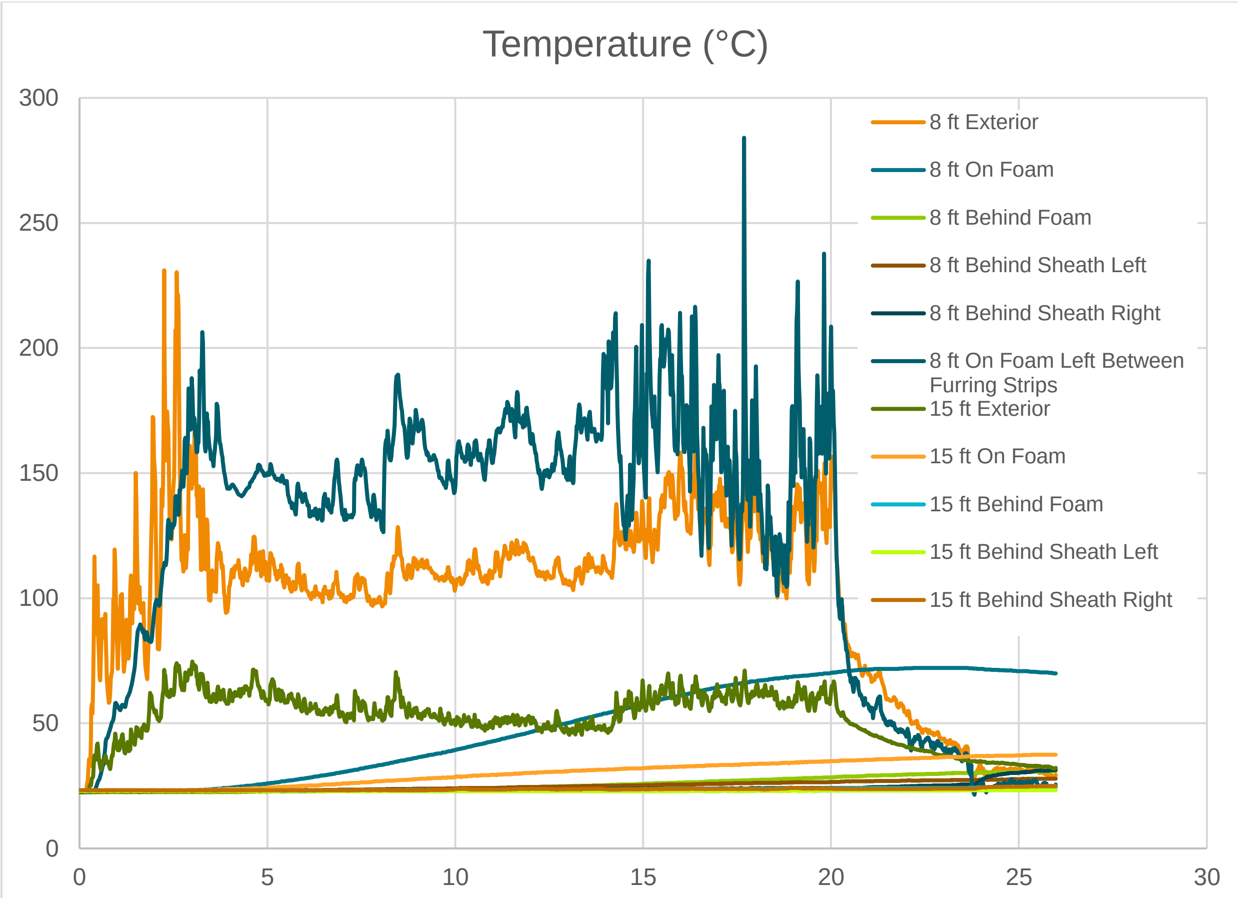


Figure 107 - Test 11 Vinyl Siding/Furring Strips/Mineral Wool Temperature Plot (Metric Units)

Appendix F: Heat Flux Plots

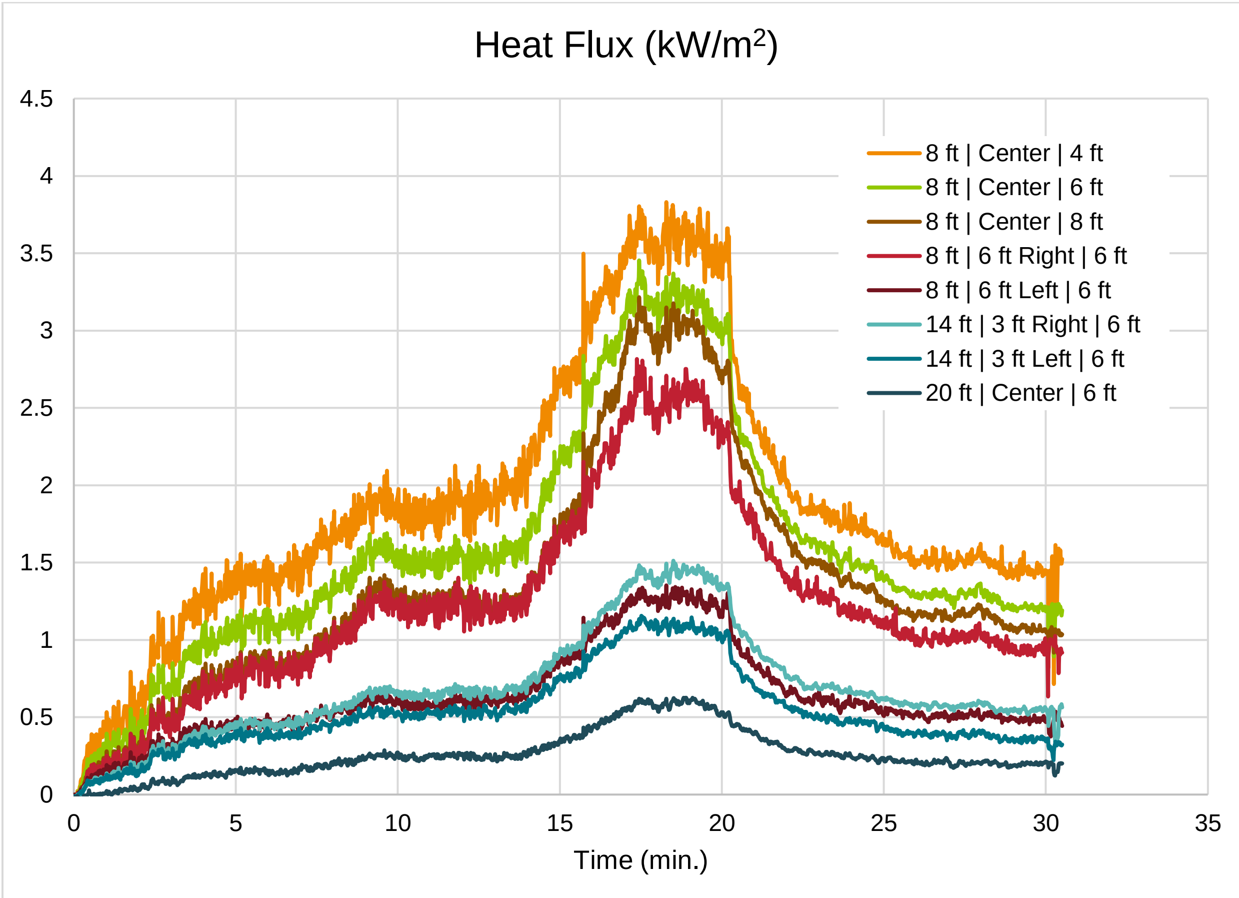


Figure 108 - Test 1 Wood Composite Siding/Asphalt Paper (75 kW) Heat Flux Plot

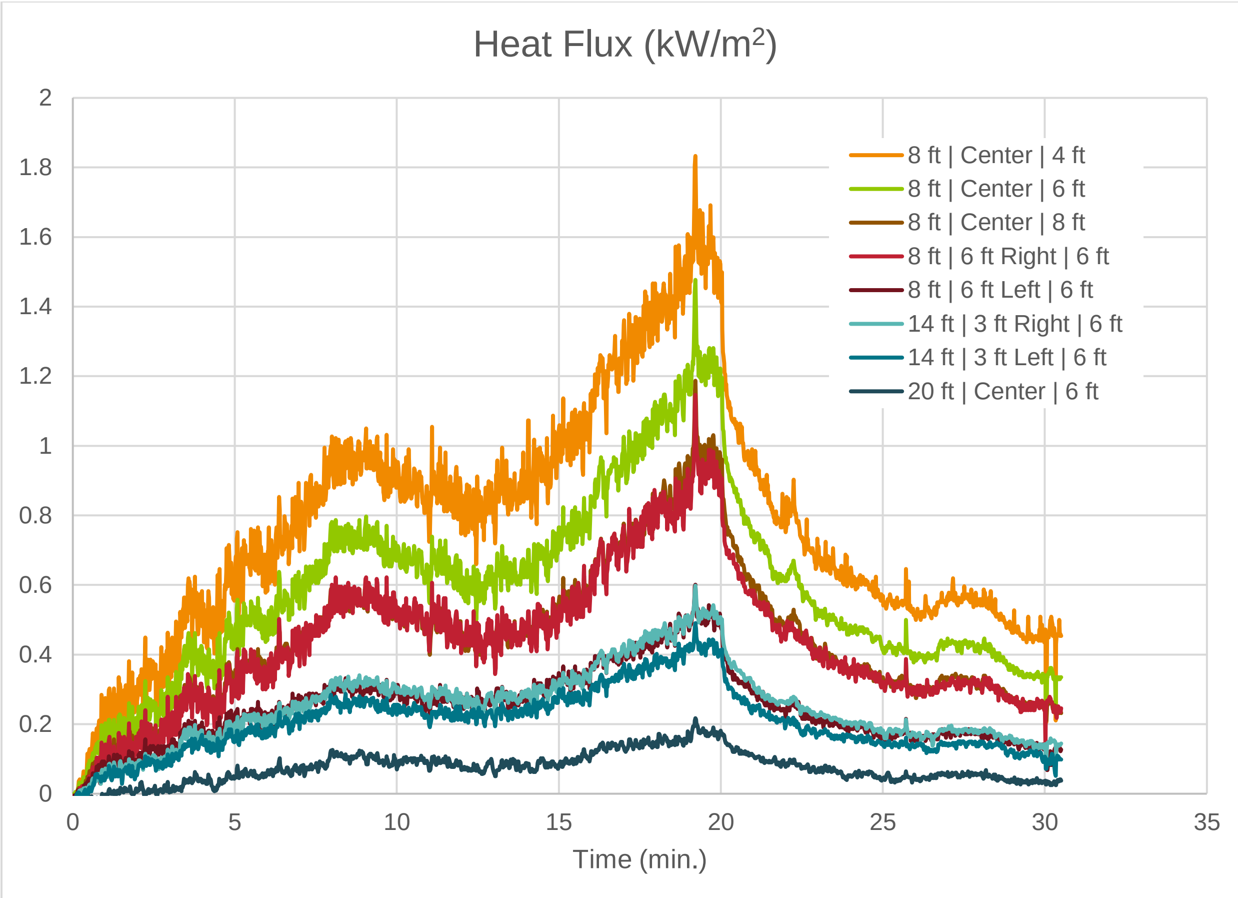


Figure 109 - Test 2 Wood Composite Siding/Asphalt Paper (50 kW) Heat Flux Plot

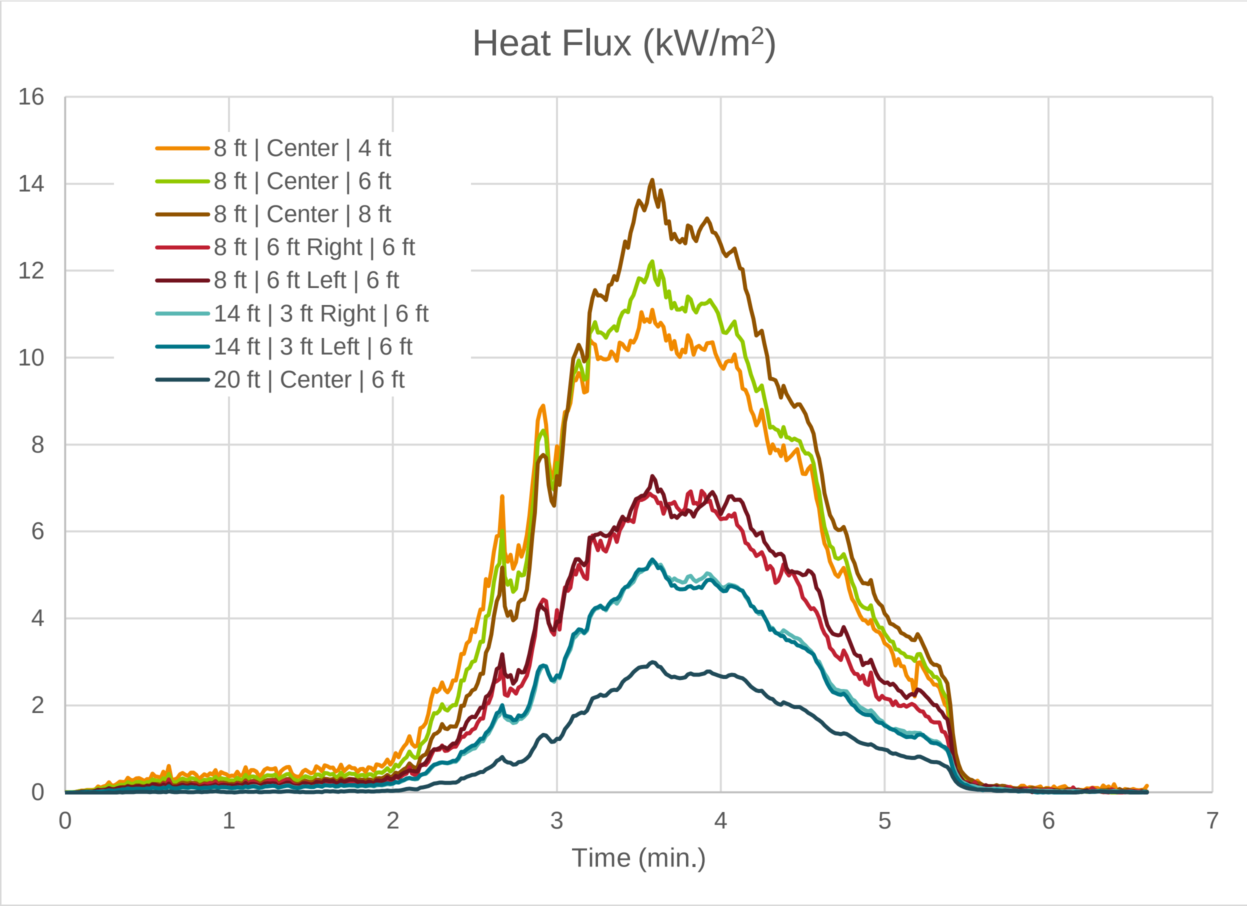


Figure 110 - Test 3 Vinyl Siding/Asphalt Paper Heat Flux Plot

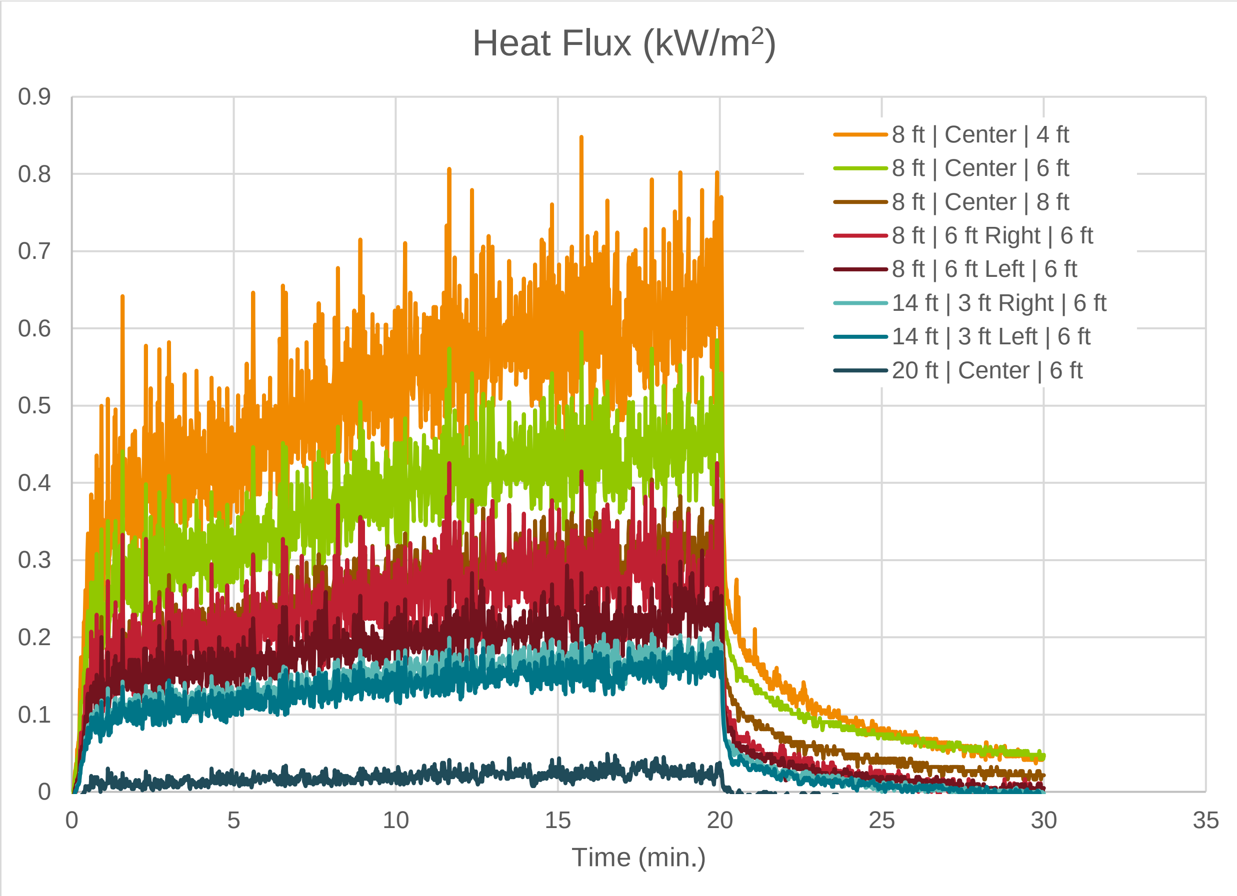


Figure 111 - Test 4 Fiber Cement Siding/Asphalt Paper Heat Flux Plot

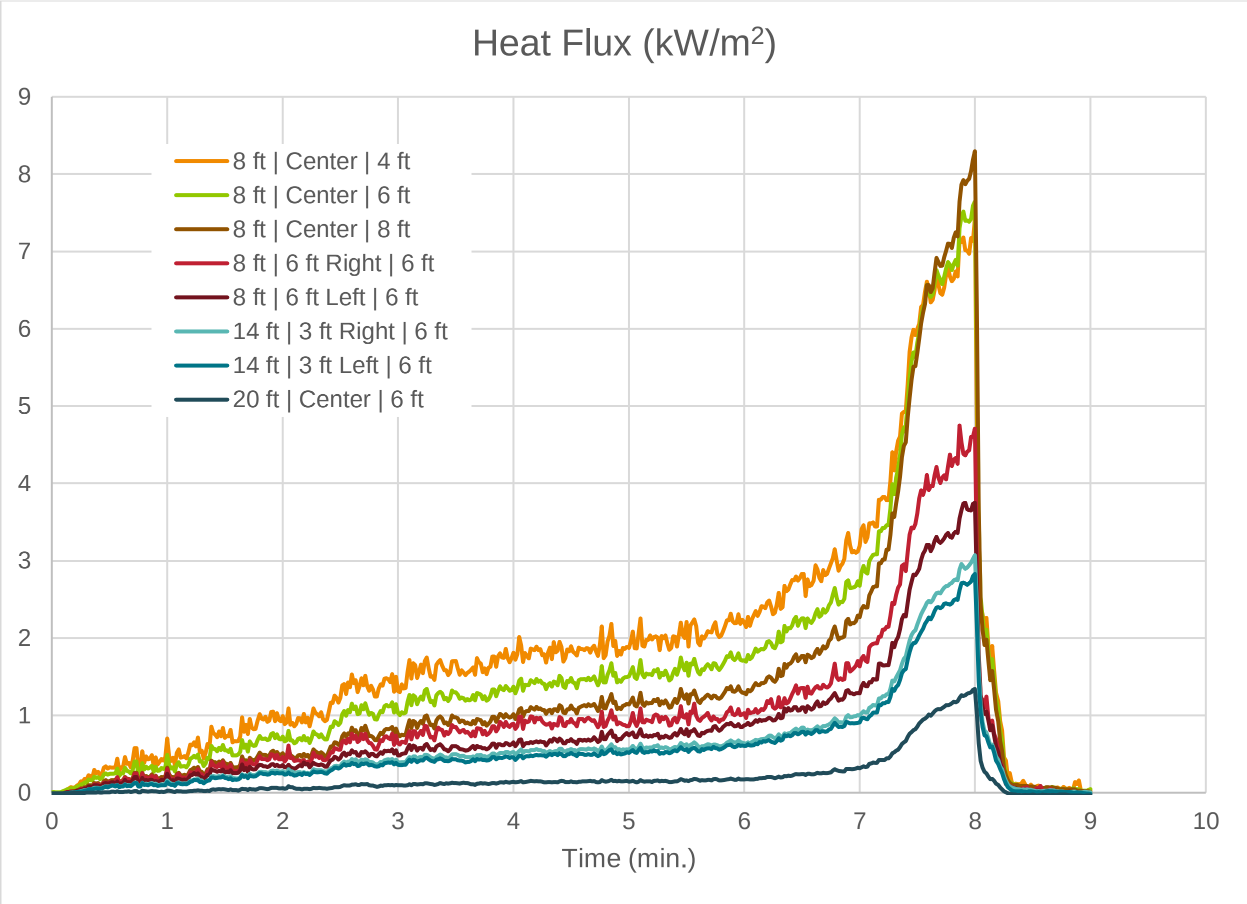


Figure 112: Test 5 Wood Composite Siding/EPS/Mineral Wool Heat Flux Plot

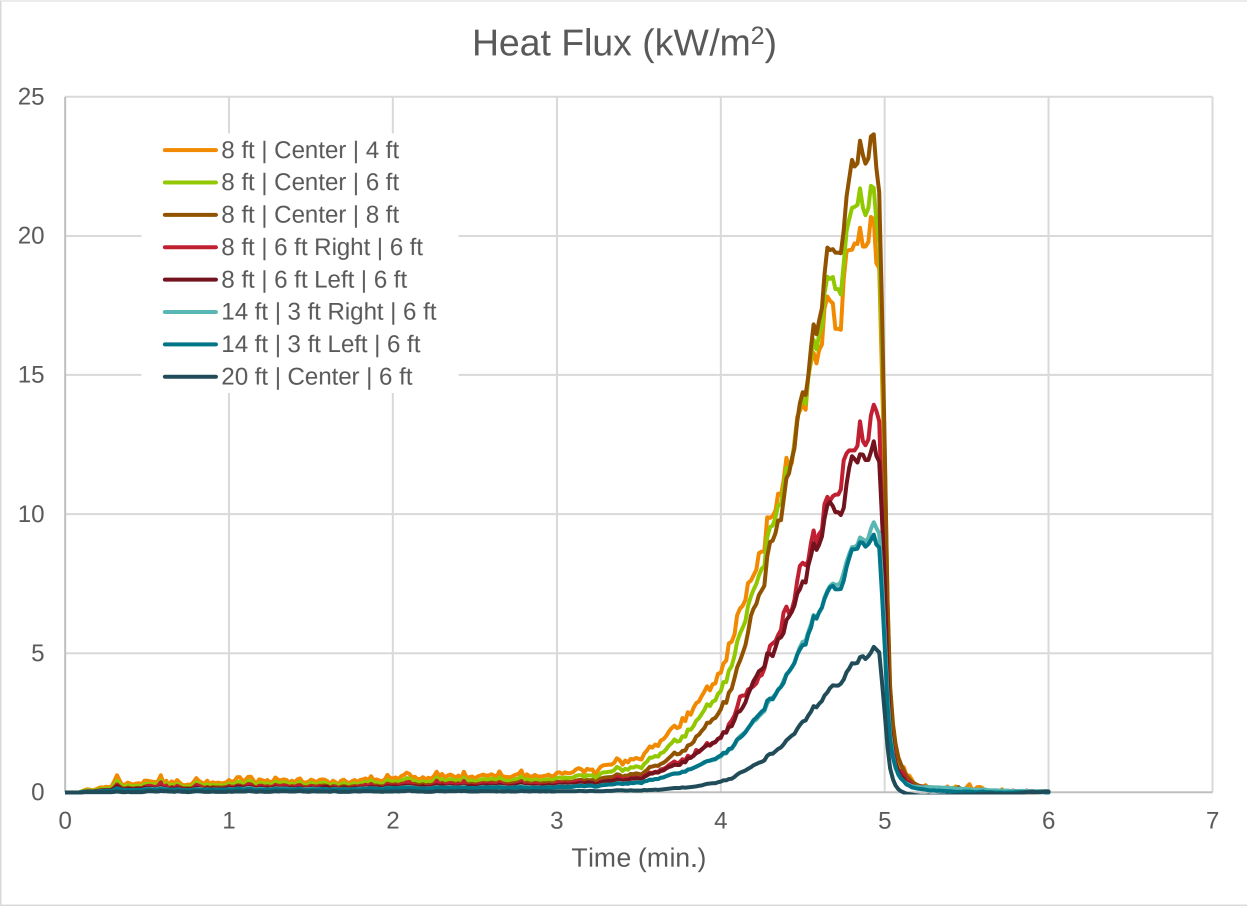


Figure 113 - Test 6 Vinyl Siding/EPS/Mineral Wool Heat Flux Plot

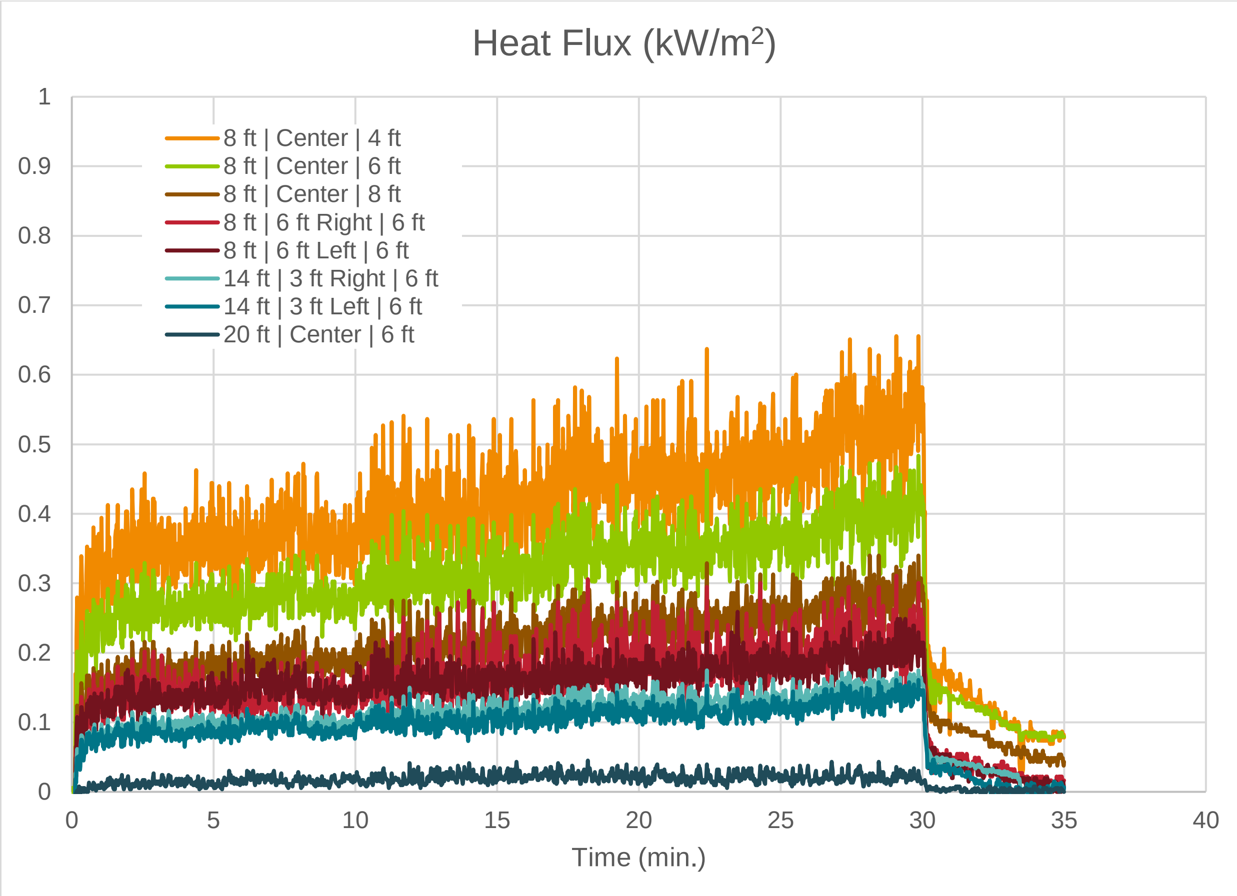


Figure 114 - Test 7 Fiber Cement Siding/EPS/Mineral Wool Heat Flux Plot

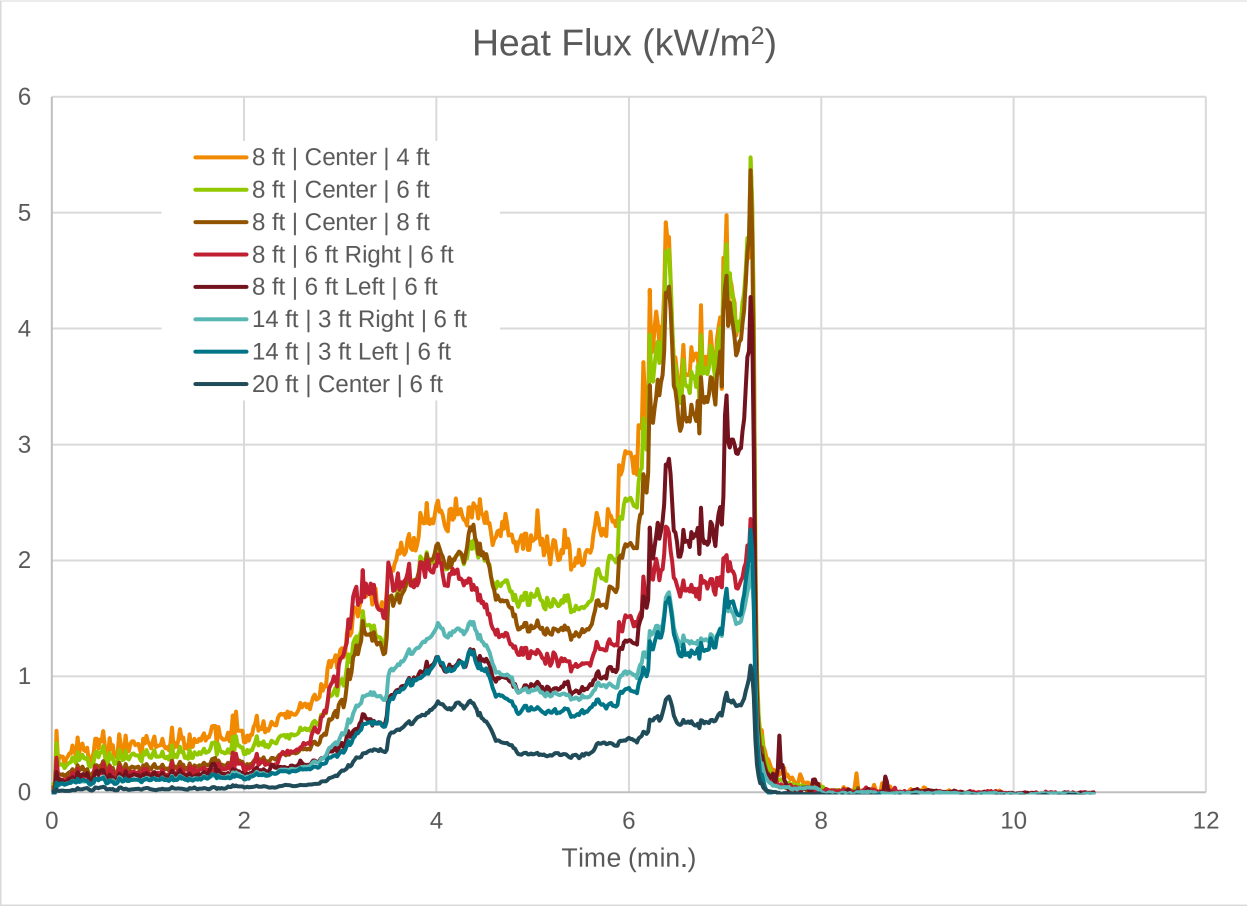


Figure 115 - Test 7 Fiber Cement Siding/EPS/Mineral Wool After Panels Removed Heat Flux Plot

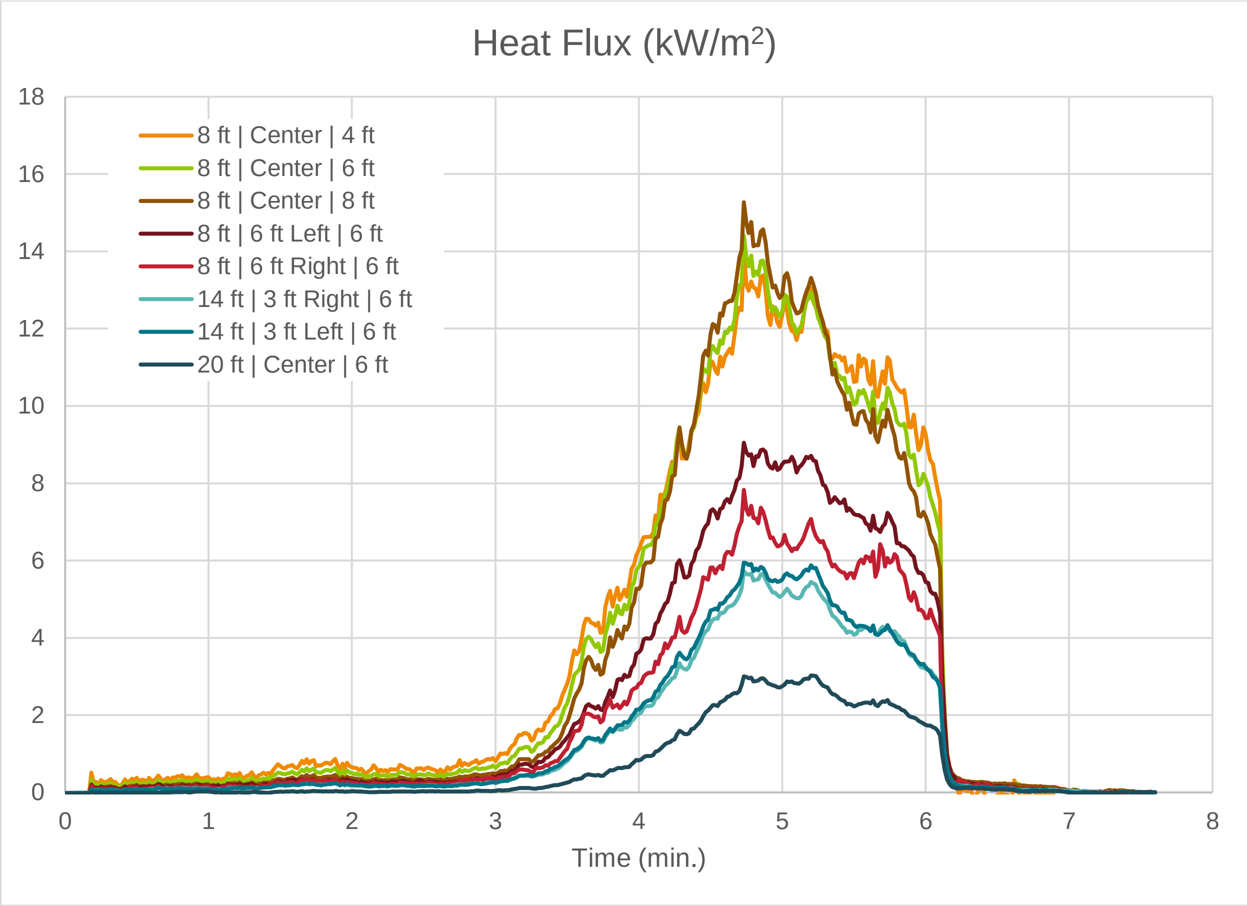


Figure 116 - Test 8 Vinyl Siding/Furring Strips with XPS/XPS Heat Flux Plot

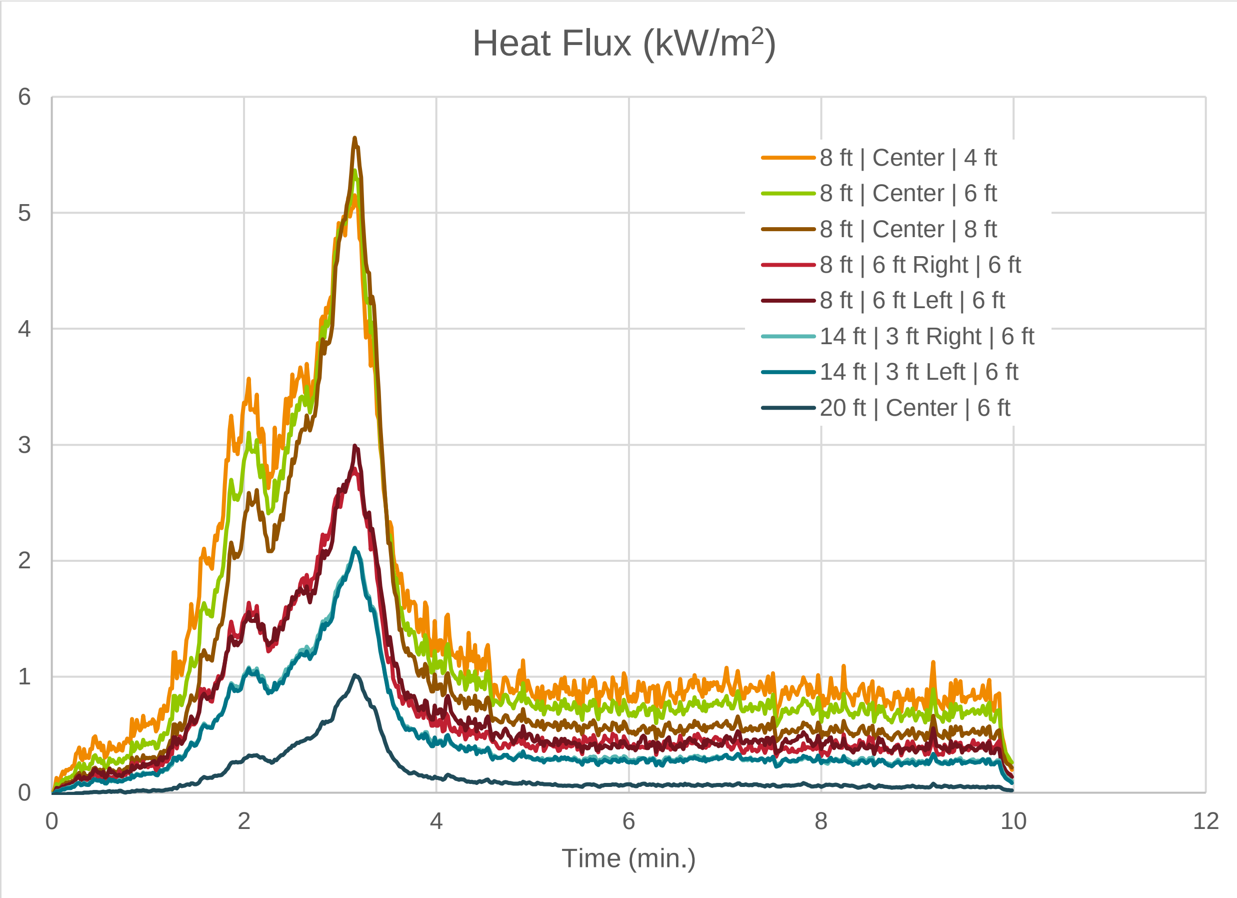


Figure 117 - Test 9 Vinyl Siding/Furring Strips/Foil Polyiso Heat Flux Plot

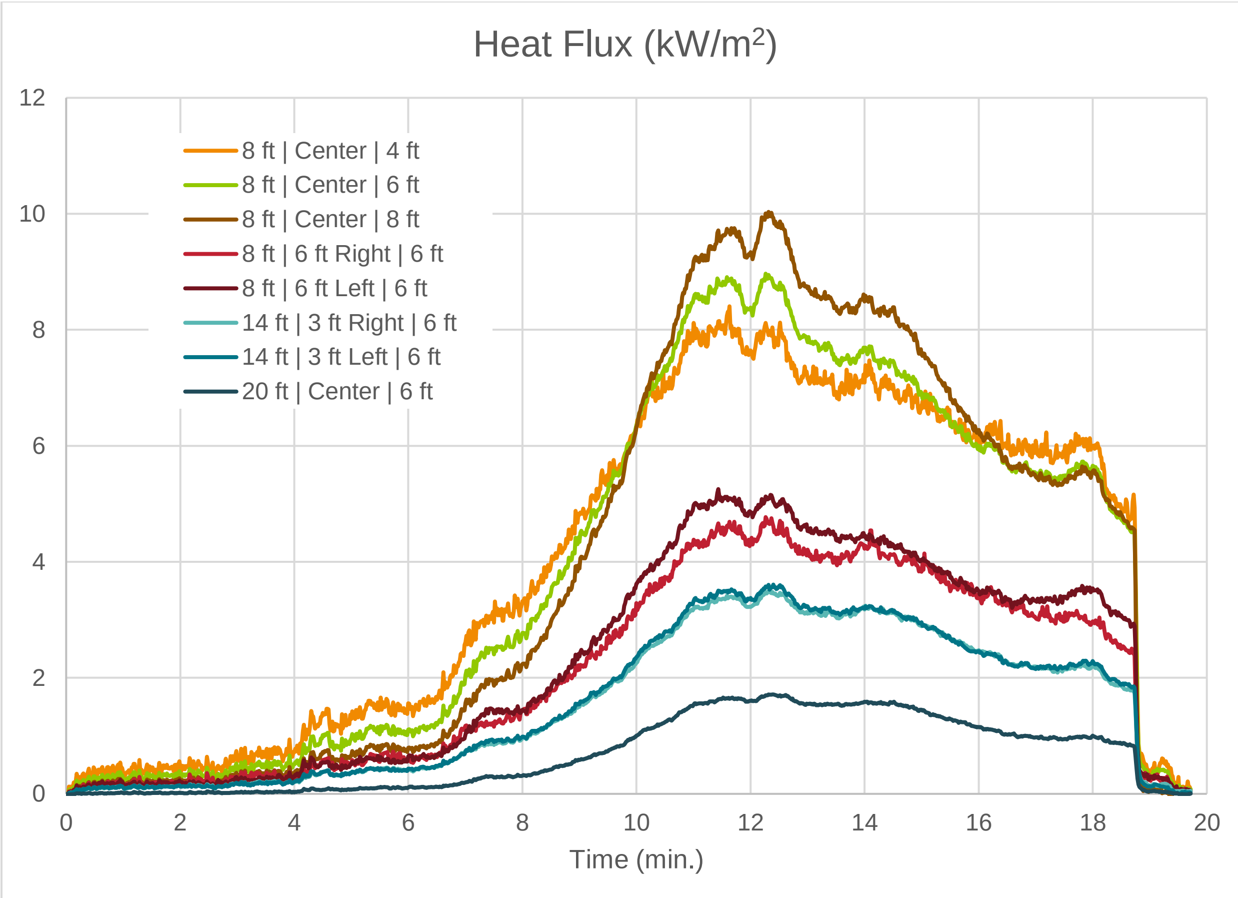


Figure 118 - Test 10 Wood Composite Siding/Furring Strips/Foil Polyiso Heat Flux Plot

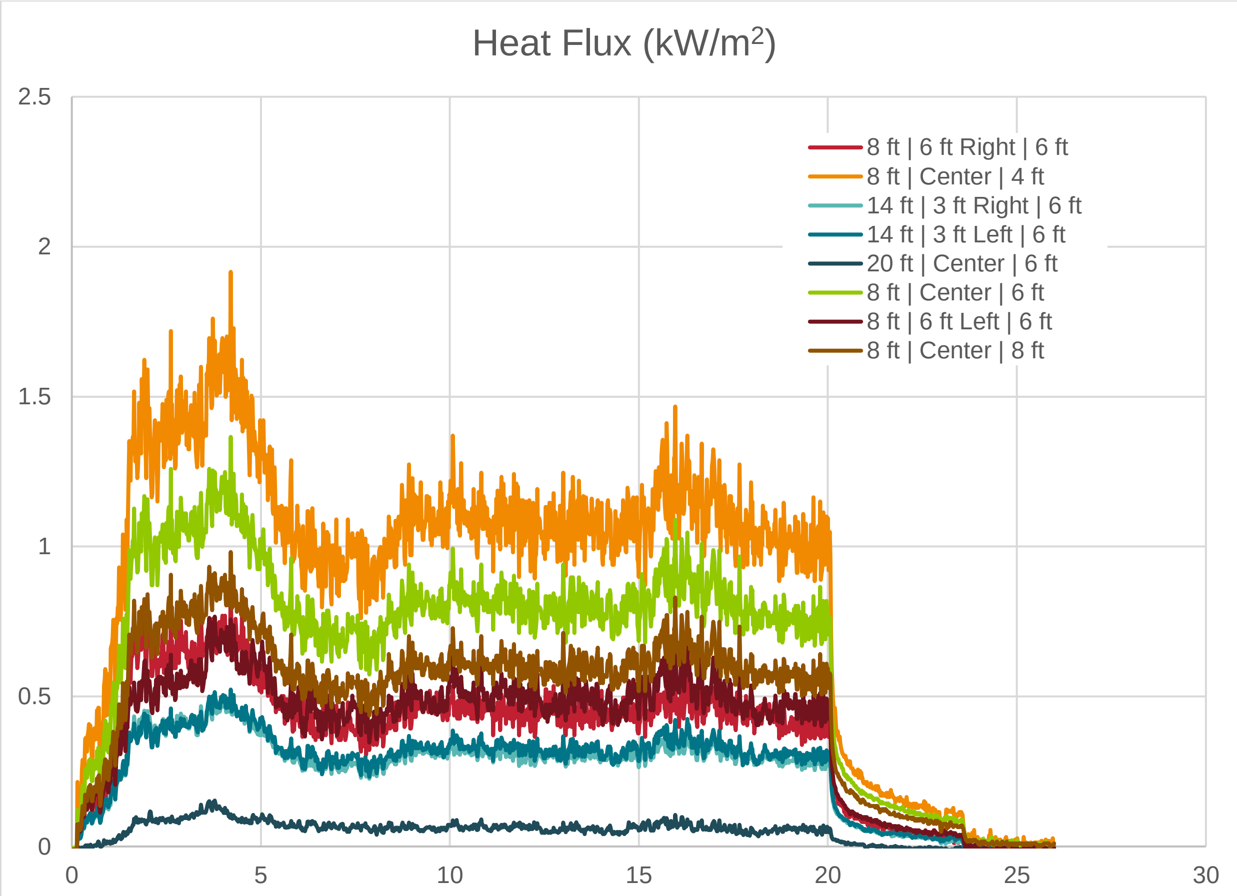


Figure 119 - Test 11 Vinyl Siding/Furring Strips/Mineral Wool Heat Flux Plot