

NIST Technical Note
NIST TN 2393

Eave and Vent Experiments (EaVEs)

*Phase B: Characterization of Eave Vents Exposed to
a Full-Scale WUI Fire Source*

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Abstract

This report documents a series of full-scale fire experiments conducted at the National Institute of Standards and Technology (NIST) to characterize the performance of commercially available, wildland-urban interface (WUI) compliant eave vents exposed to fire from a steel shed loaded with wood cribs to simulate stored combustibles. The experiments were conducted indoors under the 20 MW exhaust hood in the National Fire Research Laboratory (NFRL) with the source structure (steel shed with wood cribs) placed at a structure separation distance (SSD) of 5 ft from the target structure. The residential target structure included an assembly of an exterior wall, a roof, and an eave vent. Measurements taken during the experiments included heat release rate and heat flux at the target eaves to quantify the thermal exposure, and temperature at the vent and gas flow velocity in the attic to characterize the vent performance. Embers and flame penetration through the vent were monitored using video and infrared cameras.

Thermal exposures generated by a fuel load typically consisting of six 1-A wood cribs (120 kg $\pm$ 4 kg) within a steel shed were found to be repeatable when quantified in terms of heat release rate and heat fluxes at the target structure. This exposure consistently resulted in eave ignition, with one exception. Eave ignition was governed by flame jetting through the door opening of the shed and sustained peak incident heat flux at the eaves. Eave ignition initiated as glowing combustion at thermally vulnerable sections, including sharp edges, corners, and joints of the wooden rafters.

These experiments were conducted for research purposes to characterize vent behavior under the specific exposure conditions investigated. They were not compliance, certification, qualification, or comprehensive comparative product-performance tests. The test methods and exposure conditions used in this study differ from those currently used to establish WUI compliance or product approval. Accordingly, the results should not be interpreted as validating or invalidating any product's certification, listing, approval, or compliance status, nor as establishing the relative performance of one product or manufacturer compared with another.

The performance of seven different eave vents was characterized in this study. Six vents of different designs were listed as approved for use as wildfire flame and ember resistant vents (WUI-compliant), while one was a simple metal mesh vent (non-WUI-compliant). Flame penetration was observed in vents with net free vent area (NFVA) greater than 323 cm² (50 in²). The investigated baffled and louvered vents generally showed no flame penetration, whereas the mesh-screen vent exhibited flame intrusion. For active vents, intumescence initially blocked flame spread; however, incomplete activation of the intumescence was observed in some cases, allowing flame penetration, especially after eave ignition.

Experiments with Vent A, Vent B, and Vent G recorded maximum attic-side temperatures exceeding 350 °C, suggesting a potential inability to prevent ignition of combustible materials in the attic under prolonged, high-intensity thermal exposures. Lower recorded temperatures on the attic side of the vent and at the plywood substrate indicated effective performance of the other tested vents.

Ember penetration varied by vent design. Embers passing through vents were generally small and extinguished upon landing in the attic plenum. The investigated baffled vents exhibited significantly lower ember penetration compared to the investigated honeycomb and mesh designs. Activation of intumescent coatings substantially reduced ember intrusion. Ember flux through a non-WUI-compliant metal mesh vent was markedly higher than through WUI-compliant vents. Overall, while WUI-compliant vents reduced ember intrusion and, in some cases, moderated attic temperatures, they were unable to prevent flame penetration following eave ignition.

This limited experimental series indicated that vents compliant with ASTM E2886/E2886M-20, which is currently used to establish suitability for WUI use, may not provide equivalent performance under realistic fire exposures that can occur during a WUI fire. ASTM E2886/E2886M-20 evaluates vents under sustained direct flame impingement from a 300 kW burner for 10 min, a thermal exposure that generally results in uniform activation of the vent's intumescent coating. In contrast, real thermal exposures may involve intermittent, spatially non-uniform thermal exposure. These thermal conditions may result in incomplete and non-uniform activation of the intumescent coating, resulting in heat flow into the attic space. Flame penetration can occur through vent cells that remain partially or fully open, especially following eave ignition.

Keywords

attic vents; auxiliary structures; community fire spread; convective heat exposure; eaves; fire; fire-induced flow; gas flow velocity; heat flux measurements; heat release rate; radiant heat exposure; sheds; temperature measurements; vents; wildland fire; wildland-urban interface.

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1. Introduction

Residential structure losses during wildland-urban interface (WUI) fires are often amplified by direct structure-to-structure fire spread or by the proximity of combustible objects commonly found on residential properties that provide pathways for fire spread to adjacent structures. Recent wildfires, including the Tubbs Fire (Santa Rosa, CA, 2017), Camp Fire (Paradise, CA, 2018), Marshall Fire (Louisville, CO, 2021), Lahaina Fire (Lahaina, HI, 2023), and the Eaton Fire (Altadena, CA, 2025) evidenced extensive fire spread among WUI fuels including parcel-level combustibles¹ resulting in extensive loss of residential structures. The location of parcel-level combustibles near structures, within the reach of flames and radiation, increases the hazard for fire spread. Post-fire observations and case studies [1-6] and experimental studies [7-12] have shown that the eaves of a residential structure are a vulnerable link that contributes to structure ignitions.

Eaves are overhanging parts of the roof that extend beyond the exterior wall to provide weather protection and facilitate ventilation. Eave vents mounted on the vertical wall in the eave space, or horizontally on the soffit, provide ventilation paths into the attic to regulate temperature under normal conditions. However, eave vents can become entry points for embers and flames from exterior fire exposures during WUI fires. Ember and/or flame penetration into the attic area through eave vents can compromise the entire residential structure. Therefore, eave vents present a design challenge, needing to be open for ventilation, but closed to reduce fire vulnerability.

Several building codes applicable to structures in WUI locations, including the International Wildland-Urban Interface Code (IWUIC) Sec 504.10.1 and 505.10.1 [13], NFPA 1140 Standard for Wildland Fire Protection Section 25.3.3 [14], and AS 3959 Construction of buildings in bushfire-prone areas Section 5.6.6 [15], include provisions requiring ember and flame-resistant vents. In the IWUIC and NFPA model codes, ember and flame resistance is defined using the methods described in ASTM E2886/E2886M-20 [16] (Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement), which evaluates the response of vents when subjected to ember showers and flames under controlled conditions. With two tests, vents are separately exposed to a simulated ember shower for approximately 3 min and to a direct flaming source (with a heat release rate of 300 kW $\pm$ 10 kW) for 10 min.

WUI vents generally prevent ember and flame penetration via active and/or passive mechanisms. Active mechanisms include vents with an intumescent coating on the mesh, screens, or baffles that activate as a self-closing vent system. The intumescent coating expands (intumesces) when exposed to elevated temperatures (approximately 200 °C). The expansion of the intumescent coating physically blocks the heat, flames, and embers from entering the attic space. Mechanical self-closing vents have spring-loaded or motorized shutters that close when

¹ Such as fences, decks, outdoor furniture, sheds, parked vehicles, vegetation, wood piles, and other combustible items on the parcel.

exposed to high temperatures. These mechanical self-closing vent types were not used in the current experiments.

Passive mechanisms obstruct air flow through the vent using internal baffles or louvers. These components deflect or limit the airflow, thereby trapping embers before they enter the attic space. The flame penetration and heat flow is also obstructed and limited by this design. Some vents include metal shields or external barriers that reflect radiant heat and block direct flame exposure. Metal, or non-combustible, mesh screens are also passive mechanisms for vents that can prevent ember penetration but cannot block the flame or heat penetration alone. Certain vent designs combine both active and passive mechanisms to prevent ember and flame penetration.

The use of vents designed to limit ember intrusion and flame penetration into attic spaces is an important component of hardening homes against WUI fire exposures. Standardized test methods, including ASTM E2886/E2886M-20, provide an important means of evaluating vent performance under specific fire exposure conditions. Previous NIST studies in this series [10-12] have shown that realistic thermal exposures during WUI fires could differ significantly than those specified in the existing test methods for assessing the performance of vents for WUI applications. This report assesses the ignition behavior of eave assemblies and characterizes performance of vents when exposed to controlled radiant and convective thermal exposures from burning of wood cribs in noncombustible steel sheds. The background information for this study and the rationale for the choice of source fire to assess the eave-vent performance is described in the section below.

1.1. Background Research and Rationale

This experimental series is an extension of prior experiments that focused on structure-to-structure ignition from storage sheds to a target residential structure [10-12]. Earlier experiments focused on quantifying thermal exposures from auxiliary structures, specifically residential storage sheds, that may spread fire to a primary residential structure. The effects of shed size, construction material, fuel loading, and separation distance on the ignition of primary dwellings (residential structures) with [11] and without wind [10] were studied. The target structure performance was evaluated in terms of ignition of the eaves/rafters, damage to the exterior layer of the target wall, window performance (frame melting and/or ignition, and breakage of the windowpane), and vent performance (ember and/or flame penetration through the vent, temperature in the attic behind the vent, and efficacy of intumescent coating in closing the vent).

Observations made during previous experiments suggested additional study of the vulnerability of under-eave vents was needed to better understand ignition of the eaves and relevant hardening methods. Subsequent experiments were conducted with a focus on the role of the eave vent [12]. In Phase A, experiments were conducted with a limited number of commercially available vent designs. For the experiments presented in this report, additional vent designs were included to better understand the role of eave vents on the ignition resistance of the target structure when exposed to a realistic WUI fire scenario.

These experiments followed the same set-up and procedure of the prior eave experiments [12]. A noncombustible steel shed (30 ft² (2.8 m²)) with a fuel loading of six 1-A wood cribs [17] was used as the source fire. A structure separation distance (SSD) of 5 ft (1.5 m) was used in all experiments. Performance of six commercially available, WUI-compliant vents and one non-WUI-compliant vent is discussed in this report.

2. Experiments

Phase B experiments focused on assessing the ignition performance of target eaves with different vent types when exposed to flames from wood cribs burning within a noncombustible shed. The exposure source, described in the section below, consistently resulted in eave ignition. The experimental configuration was similar to that used in Phase A experiments [12]. The descriptions of measurement uncertainties are in Appendix A.

These experiments were conducted for research purposes to characterize vent behavior under the specific exposure conditions investigated. They were not compliance, certification, qualification, or comprehensive comparative product-performance tests. The test methods and exposure conditions used in this study differ from those currently used to establish WUI compliance or product approval. Accordingly, the results should not be interpreted as validating or invalidating any product's certification, listing, approval, or compliance status, nor as establishing the relative performance of one product or manufacturer compared with another.

2.1. Exposure Source

Commercially available noncombustible steel sheds were used as the source structure for all experiments. A 5 ft (1.5 m) deep, 6 ft (1.8 m) wide, and 6 ft (1.8 m) tall, traditional shed design with a single door and peaked roof, noted as a "Very Small (VS)" steel shed in previous experiments [10-12], was chosen for this experimental series. Previous experiments showed that the structural integrity of the noncombustible steel sheds remained intact and that the thermal exposure from six 1-A wood cribs (approximately 120 kg of fuel mass and a fuel packing density of 581 MJ/m³) within the VS noncombustible steel shed consistently resulted in ignition of the open-eaves. The measured peak heat release rate was 1.9 MW ± 0.1 MW. Additionally, the results from the outdoor experimental series that assessed the effect of wind on the burning behavior of sheds suggested that the flame jetting from the noncombustible steel sheds was not impacted by wind [11], therefore allowing these experiments to be conducted indoors without wind.

Similar to the previous experiments, the single door of the shed was in a fully open configuration, representing realistic worst-case scenarios if the shed doors were left open or blown open during a WUI fire. Moreover, a fully open-door configuration minimizes complexities arising from reduced ventilation. The ventilation conditions significantly affect fire hazards, such as heat release rate (HRR), fire growth rate, smoke, and CO production. The sheds were positioned with the doorway centered and facing the target structure with a 5 ft (1.5 m) SSD such that the flame from the shed impinged on the vent.

2.2. Target Structure

The target structure used in this experimental series was similar to those constructed previously [10-12] to represent the façade of a single-story residence. The target structure included a roof-wall assembly with open eaves and a vented attic space; a window was not included in the target structure for this experimental series. The target structure was oriented

north to south under a 20 MW capacity calorimetry exhaust hood with the exterior side of the structure facing east. The door opening of the shed faced west. Commercially available WUI eave vents approved for use in WUI locations were installed in the open eaves of the target structure. Vent specifications and the mechanism with which the vent operated is described in Section 2.3 below.

The approximately 13 ft (4 m) tall and 16 ft (4.9 m) wide target wall construction was fire-hardened beyond current WUI building code requirements to prevent ignition of the wall before eave ignition. For additional target wall details, see the Phase A report [12].

A plenum was constructed behind the vent on the attic side of the central rafter bay of the target structure, similar to the one used during previous experiments [10, 12]. The plenum was made of noncombustible drywall along the sides and the floor extended approximately 24 in (60 cm) back from the vent on the attic side.

2.3. Eave Vent Descriptions

Seven eave vents were tested in this experimental series. Six out of seven vents conformed to IWUIC [13], ASTM E2886/E2886M-20 [16], and ASTM E2912-17 [18] requirements (Vents A to F) for use in WUI construction (referred to as WUI-compliant vents). One vent was built in-house and was not in compliance with IWUIC requirements (Vent G). This in-house built vent was used to establish a baseline non-compliant vent performance. Vents with nominal dimensions and descriptions listed in Table 1 were installed in the central rafter bay. Fire-resistant caulking was applied around each vent from the exterior side, as per standard installation practice. Selected vents differed in shapes, sizes, net free vent area (NFVA), and activation mechanisms. NFVA is defined as the effective open area of a vent that allows air to pass through, after accounting for any obstructions such as louvers, baffles, screens, or mesh. NFVA was calculated by multiplying the gross opening area of each vent and the percentage of free opening area. The calculated NFVA values are reported in Table 1. Lower NFVA values correspond to lower air flow rates. Typically, vents with baffles and louvers have lower NFVA values compared to those with screens or mesh only.

Vent A was an active vent with an intumescent-coated metal honeycomb matrix (nominal 5 mm (0.2 in) matrix spacing) sandwiched between metal mesh screens (nominal 1.6 mm (1/16 in) interior mesh screen and nominal 6.4 mm (1/4 in) exterior mesh screen). Vent A had an NFVA of 102 in² (658 cm²). Visual observations during previous experimental series indicated penetration of small embers through Vent A when exposed to a realistic WUI scenario [10-12].

Vent B was an active vent similar to Vent A, but the exterior metal mesh screen had a wire mesh with smaller openings (nominal 3.2 mm (1/8 in)). The NFVA value for Vent B was the same as Vent A (102 in²) (658 cm²).

Vent C had intumescent-coated baffled slots with a metal mesh screen on the interior side of the vent to prevent ember penetration (nominal 1.6 mm (1/16 in) screen opening size). The NFVA for Vent C was significantly lower (27 in²) (174 cm²) compared to Vent A and Vent B.

Vent D was a small circular-shaped vent with no intumescent components. This vent operated passively to prevent ember penetration. Three circular vents with metal mesh on the exterior and attic sides of the vent were installed in the rafter bay. These vents had the lowest NFVA of 2 in² (13 cm²).

Vent E and **Vent F** had similar designs and operated by active mechanism with an intumescent-coated louver. Vent E was smaller with overall vent area of 66 in² (426 cm²) compared to Vent F (84 in² (542 cm²) area). Corresponding NFVA values for Vent E and Vent F were 30 in² (194 cm²) and 42 in² (271 cm²), respectively.

Vent G was a metal mesh-only design, cut in-house to fit in the eave bay. The metal mesh, a perforated metal plate with 0.125 in (1/8 in) diameter holes had a NFVA value of 66 in² (426 cm²).

Table 1. Eave vent descriptions and nominal dimensions (1 in = 2.54 cm).

Vent	Overall Dimensions		Mesh Screen		Intumescent	Notes
	H × W (in)	t (in)	Exposed side (in)	Unexposed side (in)		
A	7.5 × 22	0.75	0.25	0.06	Yes	Rectangle, honeycomb interior, NFVA = 102 in ²
B	7.5 × 22	0.75	0.1	0.06	Yes	Rectangle, honeycomb interior, NFVA = 102 in ²
C	5.5 × 22	1.5	None	0.06	Yes	Rectangle, baffled, NFVA = 27 in ²
D	3 (diam.)	1.5	0.13	0.06	No	Circular, baffled, NFVA = 2 in ²
E	3 × 22	1	None	0.06	Yes	Rectangular, louvered, NFVA = 30 in ²
F	6 × 14	1	None	0.06	Yes	Rectangular, louvered, NFVA = 42 in ²
G	7.5 × 22	0.06	0.14	None	No	Rectangular, mesh only, NFVA = 66 in ²

2.4. Data Acquisition

The thermal exposure to the eaves and vents was quantified with three measurements: HRR, heat flux, and temperature (for additional details and uncertainties see the Phase A report [12]; the repeatability of measured quantities is discussed in Section 3).

The HRR from the source fire (shed with cribs only), was measured using the 20 MW oxygen consumption calorimeter attached to a 13.7 m by 15.2 m (45 ft by 50 ft) exhaust hood in the NFRL. HRR after ignition of the target structure was not included in the analysis of HRR for this

report. The HRR data and videos from these experiments are published in the NIST Fire Calorimetry Database (FCD) [19].

Heat fluxes were measured in the eaves of the target structure using 6 water-cooled Schmidt-Boelter heat flux transducers as described previously in the Phase A report [12] and locations shown below in Fig. 1.

Temperatures were recorded at locations near the vent and in the attic using type K thermocouples. Two thermocouples measured air temperature, one centered on the exposed side of the vent (ETC), and one centered on the attic side of the vent (ATC). An additional thermocouple measured the surface temperature of the plywood roofing material above the vent inside the attic space (PTC).

Fire-induced flow velocity through the vent was measured using three S-type pitot probes (S-probes) located on the attic side of the wall behind the vent within the plenum. The north, central, and south S-probes were noted as VSP1, VSP2, and VSP3, respectively.

Additionally, the experiments were recorded with standard video and infrared cameras.

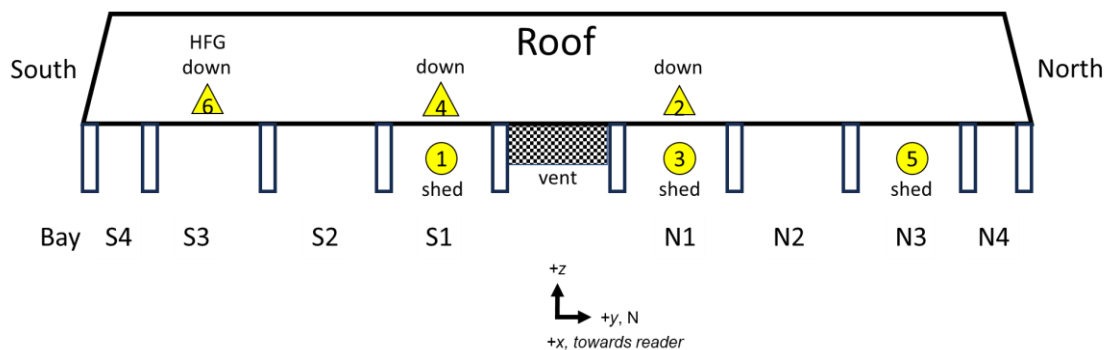


Fig. 1. Locations of the six heat flux gauges in the eaves. Gauges 1, 3, and 5 faced the source structure from the eave bays while Gauges 2, 4, and 6 faced down towards the source structure from the underside of the overhang (figure not to scale).

3. Results and Discussion

Eave ignition and flame penetration into the attic was evaluated in experiments using six different commercially available WUI eave vents with different activation mechanisms when exposed to radiant and convective thermal exposures. One non-WUI eave vent was tested for comparison purposes. The thermal exposure source was generated from burning six 1-A wood cribs in a non-combustible steel shed (30 ft²) (2.8 m²) located 5 ft (SSD) (1.5 m) from the target structure. The thermal performance of the vents was assessed in terms of change in temperatures and airflow on the attic side (unexposed side) of the vent. Ember and flame penetration through the vent was monitored using video and thermal cameras.

Table 2 lists test configurations and a summary of results for each experiment. Experiments listed in Table 2 include two experiments (e18 and e19) from the previous Phase A series and 11 experiments (e37, e43–e52) from the Phase B series. Thermal exposure from burning cribs (average fuel mass of 120 kg ± 4 kg) in a noncombustible steel shed caused ignition of combustible eaves in 12 out of 13 experiments.

Comparison of HRR curves for experiments with and without eave ignition is shown in Fig. 2 below. The HRR curve for experiment e43 shows the peak HRR of 2 MW occurred at about 14 min followed by a sharp peak (2.2 MW) when the eaves ignited. The instantaneous drop in HRR is due to fire suppression using water. The HRR curve for experiment e51 does not show a sharp peak, nor a sharp decrease, since eave ignition did not occur and the fire was not suppressed. The peak HRR for experiment e51 was recorded at 1.8 MW. The wood cribs were allowed to burn until a minimum HRR was achieved and therefore there is a gradual decrease in HRR.

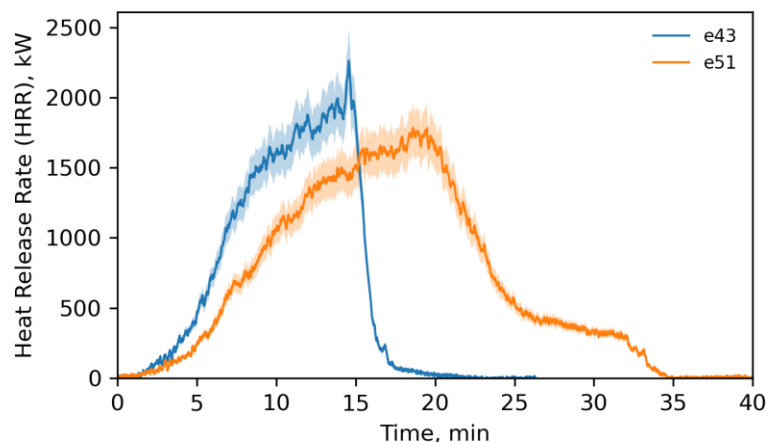


Fig. 2. Comparison of HRR curves for experiments with (e43) and without (e51) eave ignition.

Flame penetration through the vent occurred in 4 out of 13 experiments (Vent A (1), Vent B (2), and Vent G (1)). In most cases, the flame penetration occurred after the eaves ignited on the exterior, except in the case of Vent G, where flame penetration was noticed even before peak HRR was recorded (see temporal data in Table 3). As observed in previous experimental series,

eave ignition started with glowing ignition in thermally vulnerable locations including sharp edges, corners, and joints of the rafters.

Flame penetration occurred in experiments where vents with NFVA values above 50 in² (323 cm²) were used. Typically, vents with baffles and louvers showed no evidence of flame penetration, while vents with a mesh screen with no intumescent coating resulted in flame penetration during the burns. For active vents, flame penetration was blocked by the intumescence; however, partial activation in certain parts of the vent resulted in flame penetration in some experiments.

Table 2. List of test variables and summary of eave and vent performance results.

Eave Vent	Test ID	Fuel Load (crib mass, ± 0.5 kg)	Result Summary		
			Eave Ignition	Vent Closure	Flame Penetration
A	e18	124	Yes	Partial	Yes
	e51	124	No	Partial	No
B	e19	113	Yes	Partial	Yes
	e50	118	Yes	Partial	Yes
C	e37	126	Yes	Yes	No
	e47	121	Yes	Yes	No
D	e45	116	Yes	N/A	No
	e49	118	Yes	N/A	No
E	e44	120	Yes	Yes	No
	e48	119	Yes	Yes	No
F	e43	120	Yes	Yes	No
	e46	116	Yes	Yes	No
G	e52	123	Yes	N/A	Yes

Temporal data for key events during the burn experiments are provided in Table 3 below. For vents with intumescent coatings, vent activation occurred before the peak HRR and eave ignition. Eave ignition often occurred at about the same time or within a minute of peak HRR, after the eaves continued to experience high thermal exposure. Vent activation times for Vent A and Vent B were slightly longer than those for Vent C, Vent E, and Vent F. Vent activation times may vary due to the type of intumescent coating and design used in each vent.

Table 3. Temporal data for key events during burn experiments (± 0.05 min).

Vent	Test ID	Time (min)				
		Vent activation	Peak HRR	Eave Ignition	Flames Through Vent	Suppression
A	e18	10.3	17.9	18.7	18.6	18.9
	e51	10.4	18.6	No	No	32.0
B	e19	9.5	15.5	15.9	16.7	16.9
	e50	6.2	13.5	13.6	13.9	14.3
C	e37	5.7	9.6	9.9	No	10.7
	e47	7.7	13.5	13.6	No	14.1
D	e45	N/A	10.9	12.3	No	12.7
	e49	N/A	14.1	14.1	No	14.6
E	e44	5.1	10.9	10.9	No	11.3
	e48	6.4	11.4	11.9	No	12.4
F	e43	6.2	13.9	14.2	No	14.5
	e46	6.7	10.6	13.4	No	12.9
G	e52	N/A	15.7	16.1	8.9	16.6

3.1. Repeatability of Experiments

Due to the inherent complexity and the cost-prohibitive nature of the large fire experiments in this series, experiments with commercially available vents were repeated only once to identify how sensitive outcomes are to small changes in setup or experimental sample (in this case, the vent). Experiment e52 with the in-house built metal-mesh vent was not repeated.

3.1.1. Repeatability of Thermal Exposure from Source Structure: Peak HRR

The peak heat release rate (peak HRR) and the time at which the peak HRR occurs is often used to characterize the differences in burning behaviors of different materials. The repeatability of thermal exposure from the source structure (Very Small shed filled with an average fuel mass of $120 \text{ kg} \pm 4 \text{ kg}$) at an SSD of 5 ft (1.5 m), with the doors fully opened and facing the target structure, was assessed in terms of peak HRR for 13 experiments. The wood cribs in the noncombustible shed burned with an average peak HRR of $1.9 \text{ MW} \pm 0.1 \text{ MW}$ prior to eave ignition, while the time-to-peak heat release was repeatable within 3 min. The average time to peak HRR was $14 \text{ min} \pm 3 \text{ min}$.

3.1.2. Repeatability of Thermal Exposure from Source Structure: Heat Flux

The repeatability of the thermal exposure from the burning wood cribs in the Very Small shed was quantified using six heat flux gauges (HFG) measuring total heat flux in the eaves of the

target structure. The location of the HFGs is described in Fig. 1 above. An example of HF data plotted as a function of time for experiment e43 is shown in Fig. 3 below.

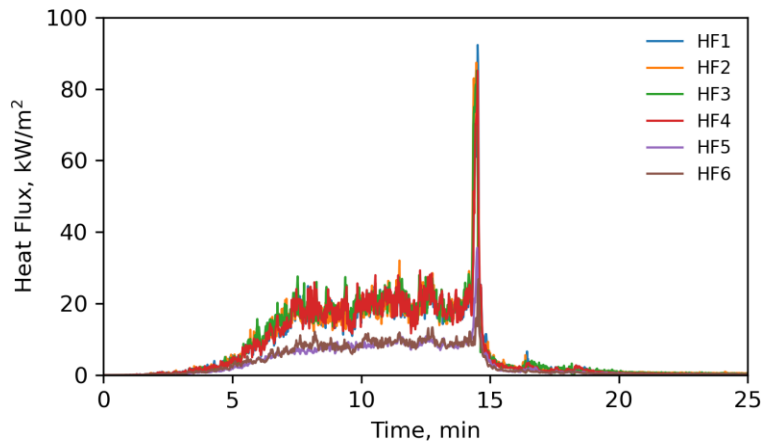


Fig. 3. Temporal profiles of HF data measured in the eaves for experiment e43.

HF data recorded by HF1, HF2, HF3, and HF4, located close to the vent, were higher than those recorded by HF5 and HF6, located towards the ends of the eaves, as noted in previous studies [10-12], due to the alignment of the source fire and the directional flame exposure from the shed doorway. Generally, the HF increased gradually and plateaued around 15 kW/m² for HF gauges located close to the vent until eave ignition occurred and the heat flux rapidly increased. Across the 13 experiments, the thermal exposure was reasonably repeatable, as indicated by the consistent maximum heat flux measurements from HF1 prior to eave ignition, which averaged 23 kW/m² with a standard deviation of ± 6 kW/m².

Fig. 4 shows a comparison of HF1 data with the corresponding HRR curve for experiment e43. The HF and HRR curves have similar time dependencies, with sharp peaks following the eave ignition at approximately 14 min. There is a similar trend for all the experiments except e51 where eave ignition did not occur; the sharp peak in the HF and HRR curve was not noted, see Fig. 5 below.

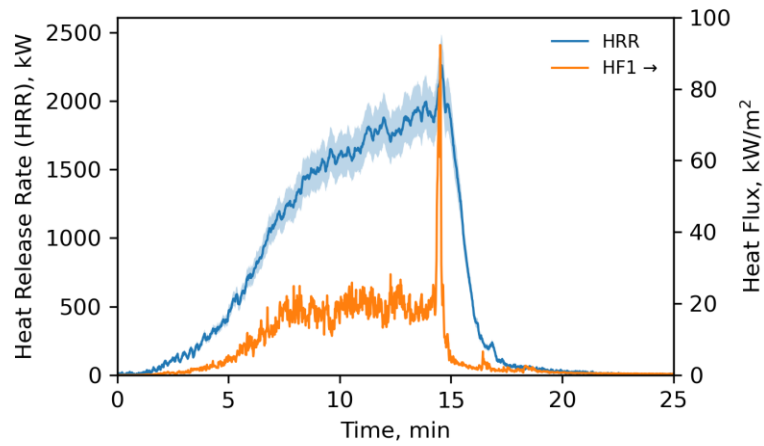


Fig. 4. Temporal profiles of HRR and HF data for experiment e43, including eave ignition followed quickly by suppression.

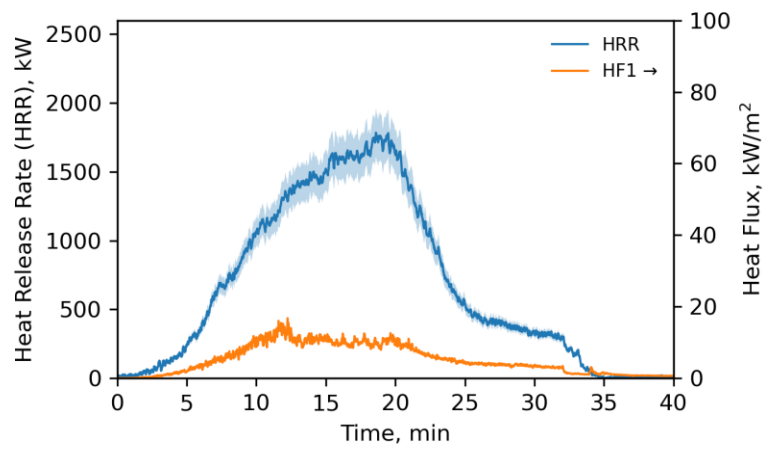


Fig. 5. Temporal profiles of HRR and HF data for experiment e51 without eave ignition.

3.1.3. Repeatability of Thermal Exposure at the Target Structure: Temperature

The repeatability of thermal exposure at the vent was quantified by measuring the temperature of the air at the exposed (eave) side of the vent (ETC). The ETC data followed a similar profile as the HF curves. For the 13 experiments, the temperature at the eaves plateaued around 430 °C before it peaked during eave ignition. The average maximum temperature at the eaves before ignition was 534 °C ± 41 °C for the 13 experiments. This relatively low variability demonstrates consistent thermal conditions prior to ignition, despite the complexities inherent in large-scale testing and associated measurement uncertainties. Temperature data from the unexposed side of the vent (ATC and PTC) were not considered for assessing repeatability since they were a function of vent performance.

3.2. Quantitative Analysis of Vent Performance

Performance of the vents with different protective mechanisms is discussed below and was characterized by monitoring ember penetration through the vent, the airflow, and the temperature on the attic (unexposed) side (ATC) of the vent. Generally, the size of the embers generated from burning the wood cribs was small, and the embers ceased glowing as the convective air currents lifted the embers away from the vent and through the plenum on the attic side of the vent. Thermal exposure at the eaves and vent performance was quantified by measuring heat fluxes in the eaves and temperature at the vent respectively. Measured maximum values are provided in Table 4. Lower maximum temperatures measured on the attic side of the vent (ATC) and at the plywood (PTC) as compared to the eaves side (ETC) indicate effective vent performance.

Table 4. Measured maximum temperature and heat flux data at the target structure before eave ignition (see Appendix A for measurement uncertainties).

Vent	Test ID	Measured Maximum Temperature near the Vent (°C)			Measured Maximum Heat Flux in the Eaves (kW/m ²)					
		Eave Side	Attic Side	Plywood	HF1	HF2	HF3	HF4	HF5	HF6
A	e18	476	401	217	22	NA	15	29	12	13
	e51	464	375	326	17	21	16	23	10	13
B	e19	510	359	203	18	NA	20	23	18	12
	e50	525	431	270	17	26	17	31	11	21
C	e37	590	237	182	31	30	27	37	11	15
	e47	522	74	159	27	23	24	32	10	16
D*	e45	529	25	98	27	29	25	30	11	13
	e49	574	26	96	21	27	19	34	12	23
E	e44	513	NA	147	28	28	25	31	11	14
	e48	594	53	132	19	30	30	33	11	16
F	e43	527	205	126	28	32	28	29	12	13
	e46	579	171	106	28	31	31	28	11	19
G*	e52	540	458	437	14	26	19	23	10	13

*This vent did not have intumescence.

For reference, section 504.10.1 in the IWUIC [13] states that the maximum temperature on the surface of the unexposed side of the vent when tested as per the ASTM E2886/E2886M-20 [16] should not exceed 350 °C for the vent. While the current measurements were not the same as the standardized test, experiments with Vent A, Vent B, and Vent G resulted in maximum attic air temperatures (ATC) above the referenced 350 °C criterion, suggesting potential for the ignition of combustible items in the attic during a relevant WUI fire exposure scenario. The maximum temperature at a single point on the plywood (PTC) in the attic area was also higher than the stated criterion for the vent surface in IWUIC (350 °C). Single-point maximum temperatures on the plywood for Vent A, Vent B, and Vent G suggest that flaming ignition of plywood could occur in the presence of naturally existing convective airflow. However, once the intumescent coating in Vents A and B activated, the airflow and the temperatures on the attic side of the vent dropped significantly. For experiments with Vent C, Vent D, Vent E, and Vent F, the temperatures on the attic side of the vent remained below 250 °C, suggesting the efficacy of the vents in limiting heat flow into the attic. Measured peak temperatures below 250 °C in the attic also suggests that the ignition of cellulosic combustibles would not occur. The operating mechanism of the vents is described below and was quantified by experimental measurements.

3.2.1. Eave Vent with Honeycomb Core with Intumescent Coating (Vent A and Vent B)

Vents A and B had an intumescent-coated metal honeycomb matrix sandwiched between two metal mesh screens. Airflow through the vent was measured using bi-directional probes (e18, e19) and S-probes (e50, e51) on the unexposed attic side of the vent in the plenum. It can be noted from Fig. 6 that the airflow through the vent was generally uniform across the attic side of the vent as the airflow data followed the same temporal profiles measured by the north (VSP1), central (VSP2), and south (VSP3) vent S-probes. The airflow gradually increased as the burning of the wood cribs progressed. Increased wood burning generated stronger buoyancy-driven convective forces, leading to higher airflow through the vent.

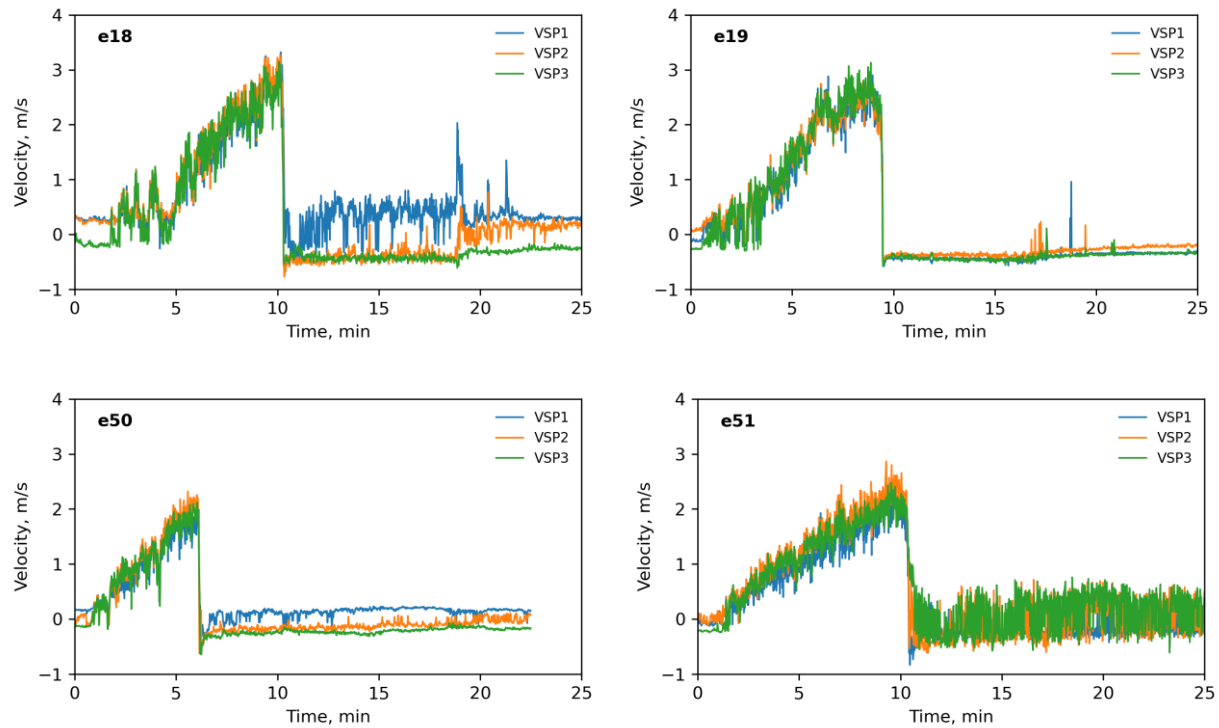


Fig. 6. Temporal profiles of airflow data measured by the north (VSP1), central (VSP2), and south (VSP3) vent S-probes in experiments (a) e18 Vent A, (b) e19 Vent B, (c) e50 Vent B, and (d) e51 Vent A. See Appendix A for measurement uncertainties.

As the temperature on the eave side of the vent (ETC) exceeds the intumescence activation temperature, the intumescent coating undergoes thermally induced expansion thereby closing the vent cells. The airflow through the vent dropped sharply once the intumescent char closed the vent cells. This phenomenon can be clearly noted from Fig. 7 which plots the temporal profile of airflow data (center probe 2), as well as the temporal profiles of temperature data measured on the eave (ETC) and attic (ATC) side of the vent.

Vent performance can also be assessed by comparing the temperature on either side of the vent. The temperature data measured by the eave TC (ETC) and the attic TC (ATC) in Fig. 7 are initially the same. However, once ETC reached the activation temperature of the intumescent coating (at about 6 min), the airflow through the vent dropped significantly. The temperature on the attic side (ATC) of the vent dropped to almost ambient temperature and stayed below 50 °C. The temperature on the eave side (ETC) of the vent remained above the activation temperature until eave ignition occurred. Significantly lower temperatures on the attic side (ATC) of the vent indicate that the vent cells remained closed, thereby blocking the heat from flowing through the vent.

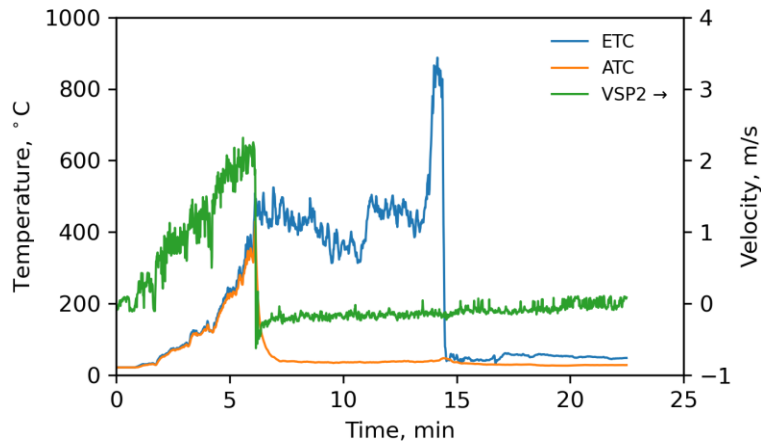


Fig. 7. Temporal profiles of airflow (center vent S-probe VSP2) through the vent and temperature data measured on the eave (ETC) and attic (unexposed) side (ATC) of Vent B in experiment e50.

For Vent A, approximately 30 s before vent activation began (at 10.4 min), many embers were observed passing through the vent (Fig. 8a). However, as mentioned earlier, the size of the embers was small, and the embers ceased glowing as they landed in the plenum. Several minutes after activation, at approximately the peak HRR, fewer embers were observed passing through the vent, and only through the portion of the vent that remained open after vent activation (Fig. 8b).

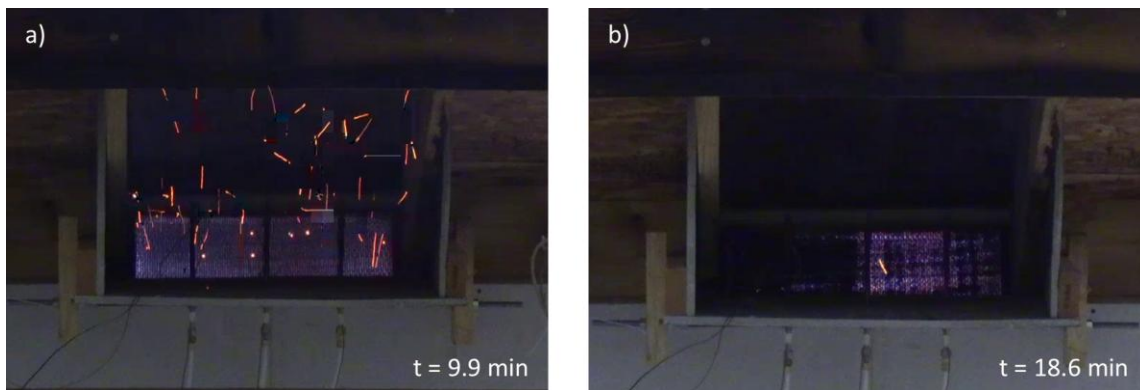


Fig. 8. Images from the attic (unexposed) side of Vent A in experiment e51 showing ember penetration (a) before vent activation at 9.9 min and (b) after vent activation at 18.6 min.

For Vent B, approximately 30 s before vent activation began (at 6.2 min), many embers were observed passing through the vent (Fig. 9a), similar to Vent A. Several minutes after activation, at approximately the peak HRR, fewer embers were observed to pass through the vent, and only through a narrow portion of the vent along the edges that remained open after vent activation (Fig. 9b).

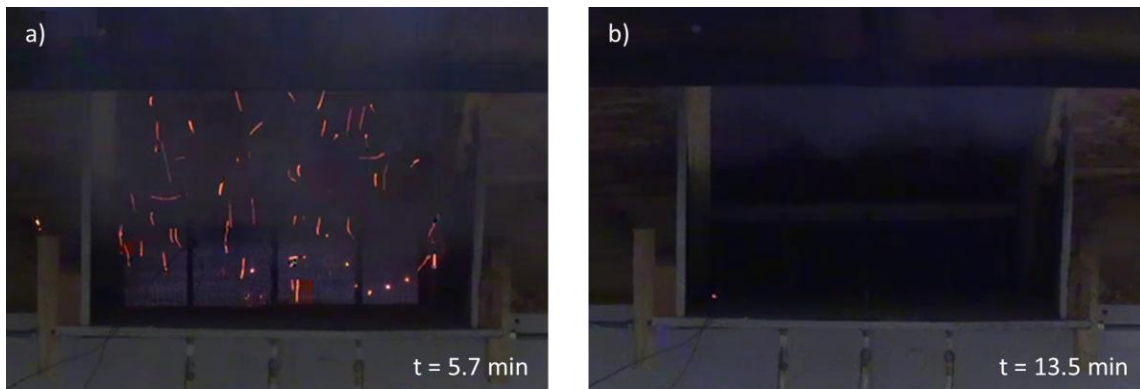


Fig. 9. Images from the attic (unexposed) side of Vent B in experiment e50 showing ember penetration (a) before vent activation at 5.7 min and (b) after vent activation at 13.5 min.

The temperature and airflow data on the attic side of the vent suggest that the intumescent coating in the honeycomb cells was successful in blocking the airflow and heat through the vent, and thus the overall vent performance in blocking the thermal exposure was effective. It can be noted from Fig. 10a that Vent B in e50 closed uniformly, blocking the flames from the exposed side. However, once the eave ignition occurred at 13.9 min, flame penetration was observed from the edges of the vent. Ignition of flammable gases at 14.3 min in the attic area can be noted in Fig. 10b. Visual observations indicated that the ignition of gases in the attic area was not sustained. Flammable gases in the attic area ignited intermittently from the flame that penetrated along the edges of the vent.

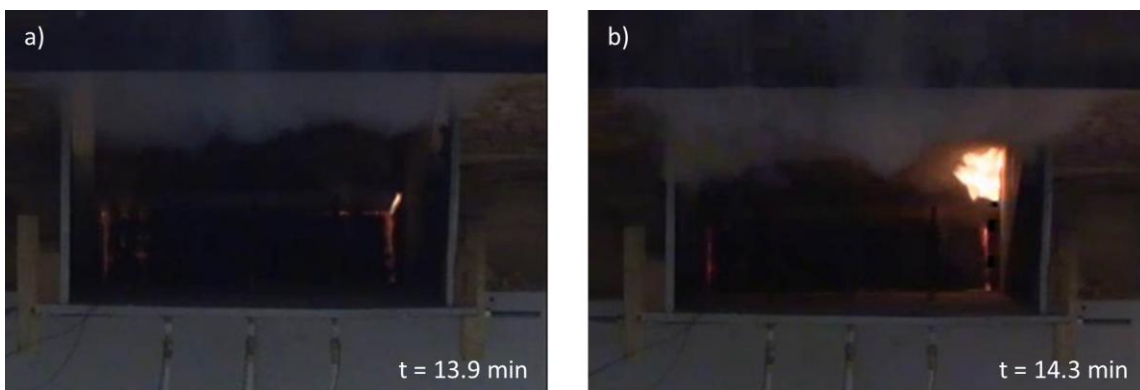


Fig. 10. Images from the attic (unexposed) side of Vent B in experiment e50 showing (a) flame penetration at 13.9 min and (b) ignition of flammable gases at 14.3 min.

3.2.2. Eave Vent with Intumescent-Coated Baffles and Metal Mesh (Vent C, e37 and e47)

The design of Vent C consisted of intumescent-coated baffles with a metal mesh screen (nominal 1.6 mm (1/16 in) screen size) on the attic side of the vent to prevent ember intrusion. Airflow data for experiments e37 and e47 that employed Vent C are shown in Fig. 11. Generally, the airflow measured by the S-probes through Vent C was significantly lower than the airflow through Vent A and Vent B. Although the baffled design and lower NFVA lower the flow rate, the flow through the vents is likely higher than was measured due to the S-probe location downstream of the vent. Comparison of airflow through Vent B and Vent C in experiments e50 and e47 respectively, is shown in Fig. 12.

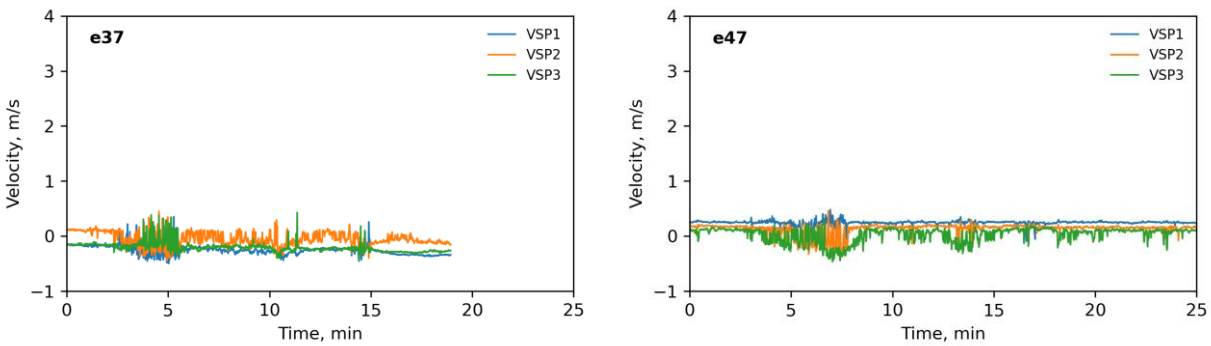


Fig. 11. Temporal profiles of airflow data measured by the north (VSP1), central (VSP2), and south (VSP3) vent S-probes in experiments (a) e37 and (b) e47 using Vent C.

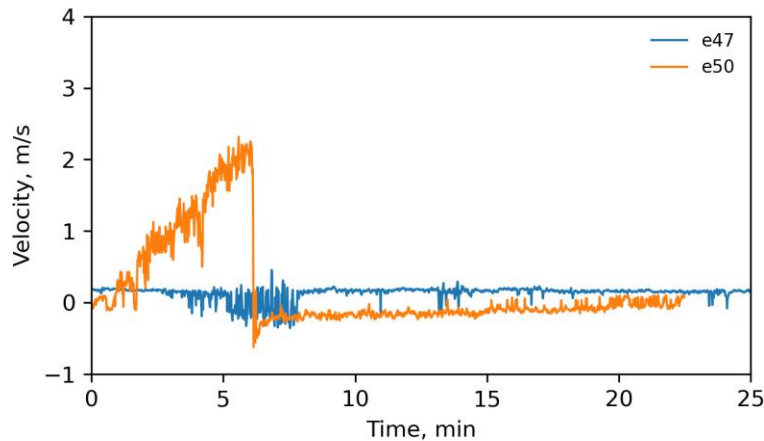


Fig. 12. Comparison of airflow (center vent S-probe VSP2) through Vent B (e50) and Vent C (e47).

The airflow and temperature data for experiment e47 is plotted in Fig. 13. As the temperature on the eave side (ETC) of the vent approached the intumescent activation threshold, a decrease in airflow through the vent was observed (Fig. 13). However, due to significant signal noise during the measurement of low airflow rates, it is difficult to draw definitive conclusions regarding the magnitude of the observed reduction in airflow. However, the vent was effective in blocking the airflow and the heat from entering the attic side of the vent once the intumescent material activated. Also, flame penetration was not observed through the vent even after eave ignition. The air temperature on the attic side (ATC) of the vent remained below 70 °C throughout the experiment.

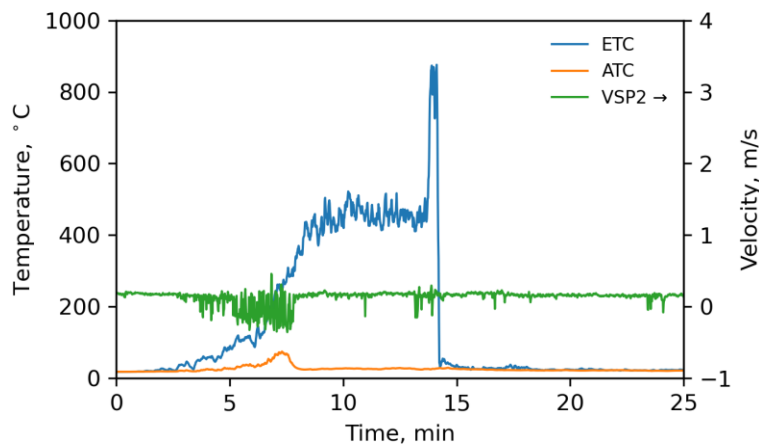


Fig. 13. Temporal profiles of airflow (center vent S-probe VSP2) through Vent C and temperature data measured on eave (ETC) and attic (unexposed) side (ATC) of the vent in experiment e47.

During the experiments with Vent C (e37 and e47), minimal embers were observed passing through the vent when compared to Vent A and Vent B (Fig. 14a). After vent activation, embers or flames were not seen passing through the vent, including during peak HRR and during eave ignition (Fig. 14b).

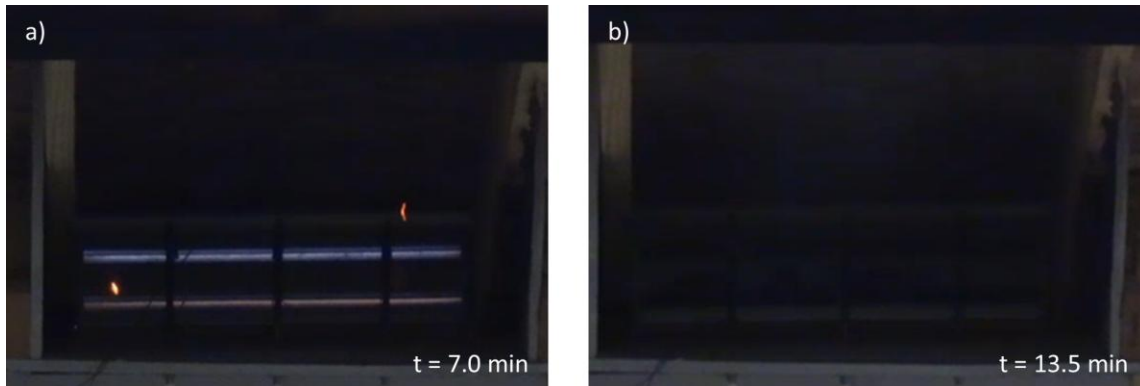


Fig. 14. Two embers passing through Vent C (e47) 30 seconds before vent activation (a) and no embers after vent activation, including during peak HRR (b).

3.2.3. Circular Eave Vent with Metal Mesh without Intumescent Coating (Vent D, e45 and e49)

Circular Vent D used in experiments e45 and e49 was a passive vent with no intumescent coating. A row of three circular vents with metal mesh on both sides of the vent were installed in the rafter bay in the place of the larger rectangular-style vents. This vent had a small NFVA of 2 in² (13 cm²), resulting in lower airflow through the vent. Temporal profiles of airflow data measured in experiments e45 and e49 are shown in Fig. 15a and Fig. 15b, respectively.

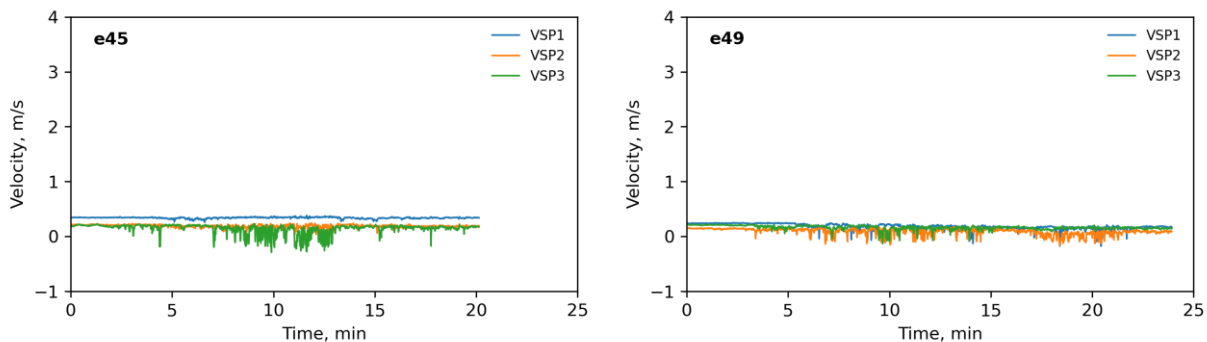


Fig. 15. Temporal profiles of airflow data measured by the north (VSP1), central (VSP2), and south (VSP3) vent S-probes in experiments (a) e45 and (b) e49 using circular Vent D.

Fig. 16 shows a comparison of airflow measurements through Vent C (e47) and Vent D (e45). Excluding the noise in airflow data for Vent C in e47, the airflow rates for Vent C (e47) and Vent D (e45) were comparable, indicating the flow was diverted or slowed down by the vent design and no appreciable air flow was measured by the attic S-probes.

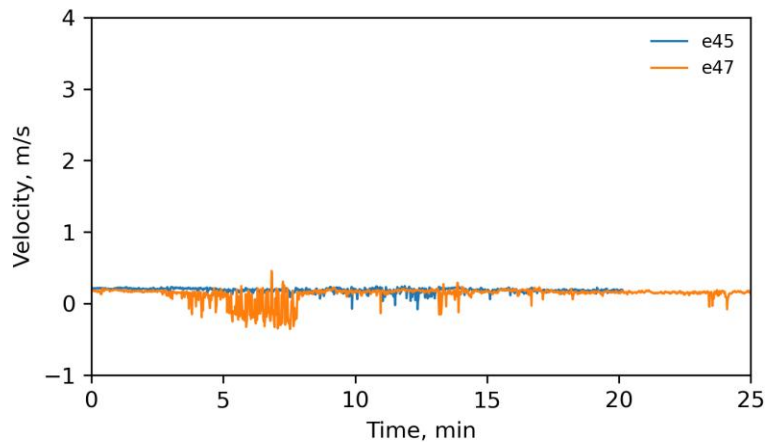


Fig. 16. Comparison of similar airflow (center vent S-probe VSP2) through Vent C (e47) and Vent D (e45).

The performance of circular Vent D can be noted from the temperature and airflow plots in Fig. 17. Temperature on the eave side (ETC) of the vent increased with burning of the wood cribs while the temperature on the attic side (ATC) of the vent remained close to ambient temperature. This was primarily due to a lower NFVA value (2 in^2 (13 cm^2)) resulting in restricted airflow and heat flow through Vent D.

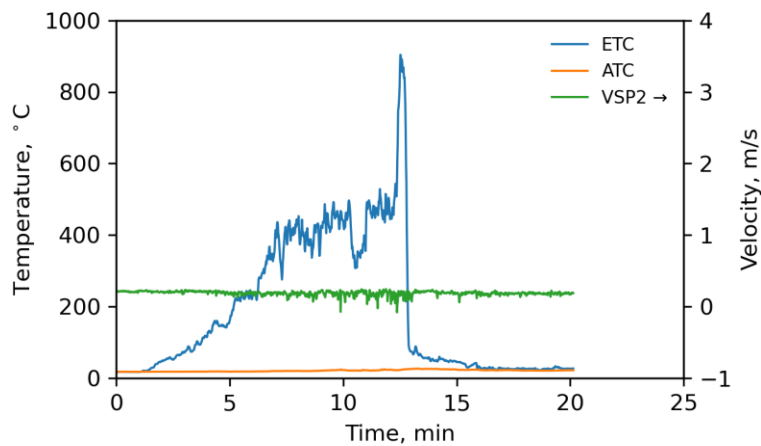


Fig. 17. Temporal profiles of airflow (center vent S-probe VSP2) through Vent D and temperature data measured on the eave (ETC) and attic (unexposed) side (ATC) in experiment e45.

Both experiments with Vent D (e45 and e49) showed small flames flickering within the vent. Following the eave ignition, brief flame penetration on the attic side was noted, however, since sustained flaming was not observed, small flame penetration was considered negligible. Small embers intermittently passed through the vents for the entire duration of wood crib burning

(Fig. 18). As mentioned earlier, the size of the embers was too small and sustained glowing of embers that landed on the attic side of the vent was not observed.

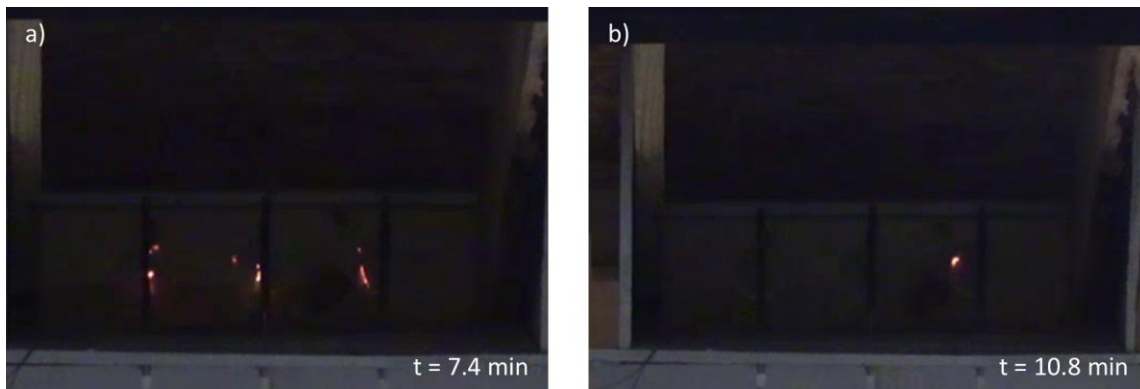


Fig. 18. Embers passing through Vent D (e45) (a) and few embers during peak HRR (b).

3.2.4. Eave Vent with Louvers with Intumescent Strip and Metal Mesh (Vent E and Vent F)

Vent E and Vent F had similar designs and operated by the same combined active/passive mechanism, except that Vent E was smaller in size (3 in by 22 in) (7.6 cm by 56 cm) compared to Vent F (6 in by 14 in) (15 cm by 36 cm). Airflow profiles through the two vents (Vent E and Vent F) are plotted in Fig. 19 and it can be noted that Vent F in e46 had higher airflow by virtue of its size. The performance of Vent E and Vent F can be noted from Fig. 20 and Fig. 21, respectively.

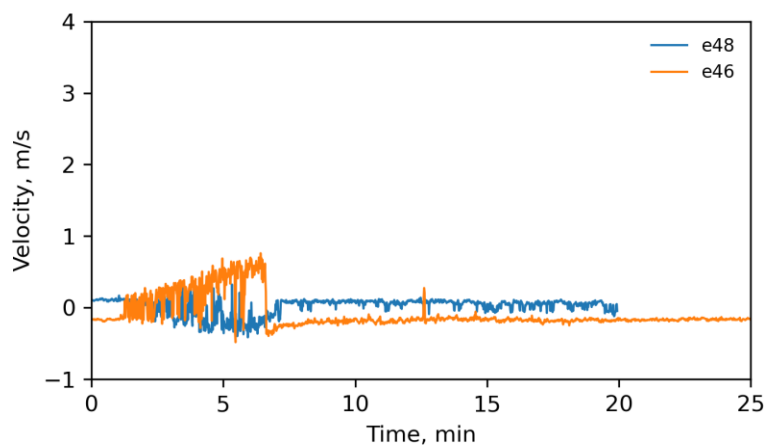


Fig. 19. Comparison of airflow (center vent S-probe VSP2) through Vent E (e48) and Vent F (e46) in the attic plenum.

The airflow through Vent E was limited by the presence of louvers, thereby preventing temperature rise on the attic side (ATC) of the vent. Temperature on the attic side (ATC) of Vent E did not exceed 100 °C at any point during the experiment. The airflow rates were initially low but dropped further as the temperature on the eave side (ETC) increased, suggesting more obstruction of airflow due to activation of intumescent coating on the baffled louvers.

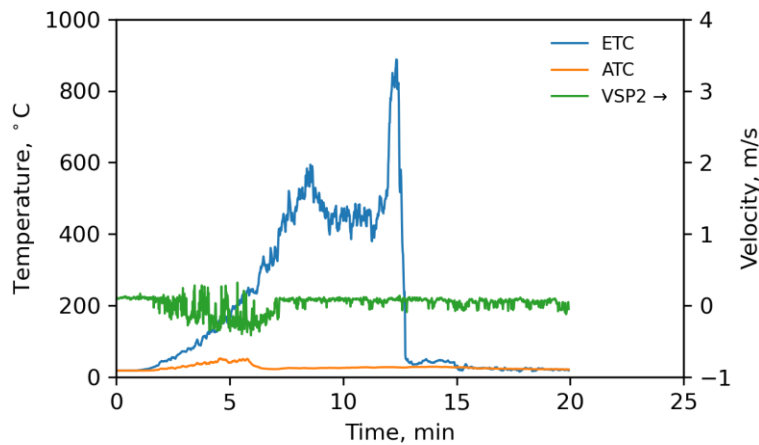


Fig. 20. Temporal profiles of airflow (center vent S-probe VSP2) and temperature data measured on the eave (ETC) and attic (unexposed) side (ATC) of Vent E in experiment e48.

Performance of Vent F can be noted from Fig. 21. The airflow through the vent increased steadily as the burning of the wood cribs progressed. The temperature on the attic side (ATC) of the vent increased to the activation temperature and subsequently dropped to ambient as the intumescence on the baffled louvers activated. The airflow at this point significantly dropped, as noted in Fig. 21, which also corresponds with the drop in temperatures on the attic side (ATC) of the vent. It is clear from the airflow and temperature measurements on the attic side that the vent mechanism operated effectively, preventing the flame and heat penetration to the attic side.

Visual observations confirmed that there was no flame penetration through either Vent E or F before or after the eaves had ignited. Ember penetration was observed for both vents prior to vent activation but was significantly reduced after vent activation. Images showing embers passing through Vent F before vent activation and the absence of glowing embers on the attic side during peak HRR are provided in Fig. 22a and Fig. 22b, respectively.

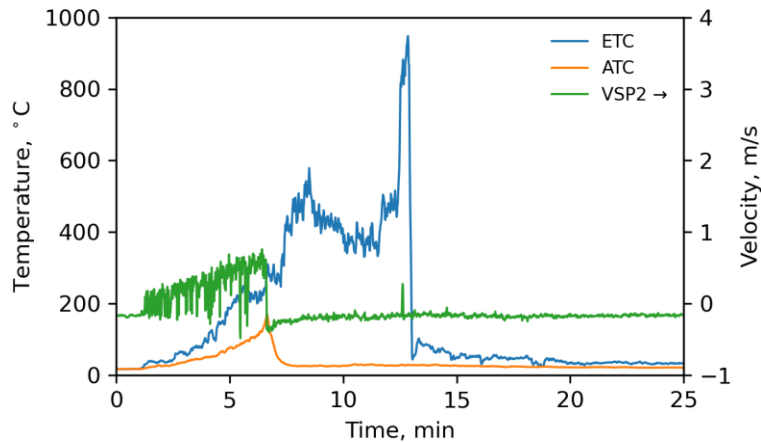


Fig. 21. Temporal profiles of airflow (center vent S-probe VSP2) and temperature data measured on the eave (ETC) and attic (unexposed) side (ATC) of Vent F in experiment e46.

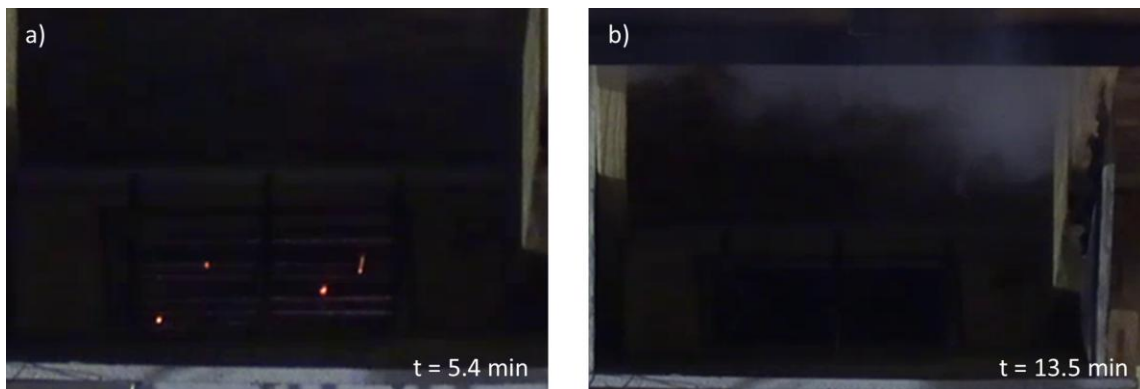


Fig. 22. Embers passing through Vent F(e43) at 5.41 min (a) and no embers during peak HRR (b).

3.2.5. Eave Vent with Metal Mesh without Intumescent Coating (Vent G)

The temporal profiles of airflow measured behind Vent G are plotted in Fig. 23. The airflow across the vent was uniform and the airflow through the vent increased as the wood crib burning in the source structure progressed. The temperature data measured on the eave side (ETC) and on the attic side (ATC) showed similar temperatures on both sides of the vent throughout the duration of the experiment (Fig. 24). Attic side temperatures greater than 350 °C were measured behind Vent G suggesting that this type of vent with no intumescent coating and high NFVA values is ineffective at preventing heat and flame penetration.

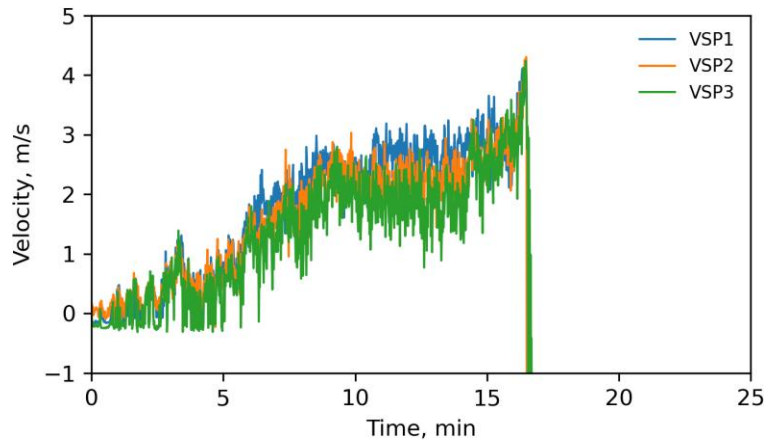


Fig. 23. Temporal profiles of airflow data measured by the north (VSP1), central (VSP2), and south (VSP3) vent S-probes in experiments e52 using metal mesh Vent G.

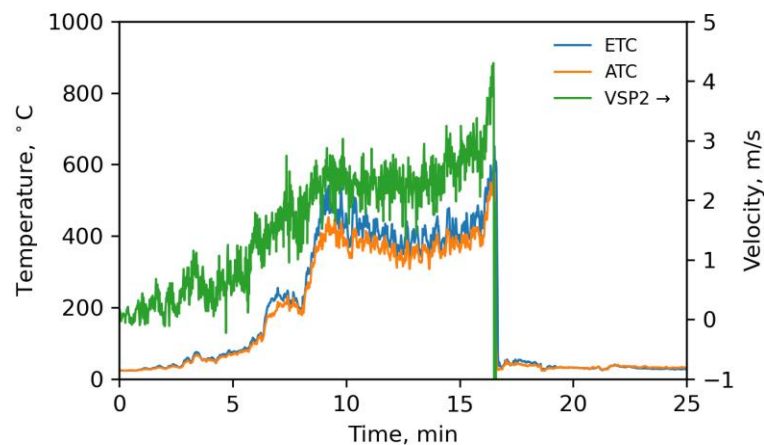


Fig. 24. Temporal profiles of airflow (center vent S-probe VSP2) and temperature data measured on the eave (ETC) and attic (unexposed) side (ATC) of Vent G in experiment e52.

During the experiment (e52), many embers were observed passing through Vent G. The metal mesh prevented penetration of larger embers, but the number of embers passing through the vent increased as the burning wood cribs collapsed. The flames from the source structure reached and passed through the vent as the HRR increased (Fig. 25a). Flame penetration through Vent G was noted much earlier (at 8.9 min), before eave ignition (16.13 min), compared to experiments with other vents. During peak HRR, embers continued passing through the vent prior to eave ignition (Fig. 25b), however the number of embers was reduced significantly.

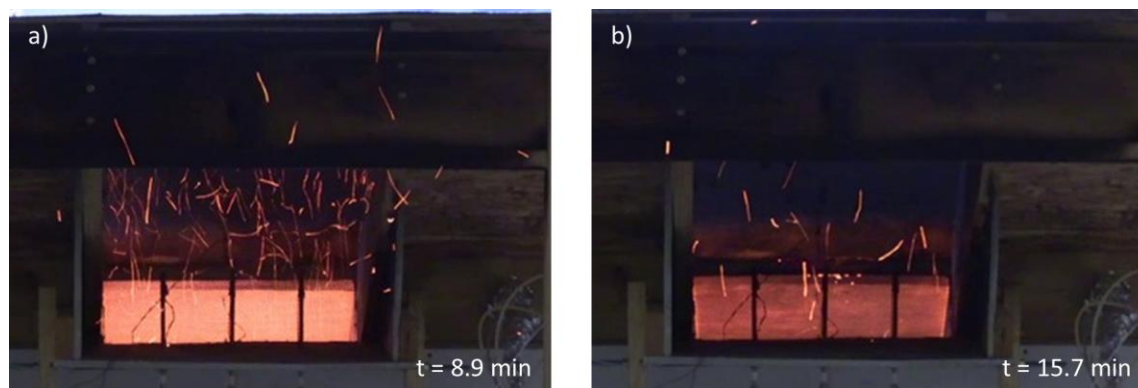


Fig. 25. Many embers passing through Vent G (e52) at 8.9 min just prior to flames observed through the vent (a) and during peak HRR (b) prior to eave ignition.

4. Experimental Limitations and Technical Findings

The experimental data provided in this report serves as guidance for exposure quantification, hazard assessment, and for hazard mitigation. However, the following limitations may affect the usability of the results.

4.1. Source Fire Limitations

1. The experiments only used noncombustible steel sheds with fuel loading of standard 1-A wood cribs as the source fire. Although the wood cribs represented a significant fuel load, due to safety concerns and potential damage to the surroundings, the experiments did not use typical fuels stored in residential sheds that could result in larger heat release rates, longer duration of exposure, or an explosion.
2. The experiments were conducted on flat ground and did not study the effects of topography or wind on flame spread or thermal exposures to the target structure.
3. The experiments were not conducted in the presence of additional fuels between the source fire and the target structure, such as ladder fuels, vegetation, fences, and vehicles.
4. These experiments used only one shed orientation with the open shed doorway facing the target structure wall from five feet away and with the fire plume directed towards the target structure eaves and eave vent. Other shed orientations and fuels could result in different exposure intensities at the target structure.

4.2. Target Structure Limitations

1. The target structure is assumed to be hardened for ember exposures.
2. The experiments only used target structures that complied with the hardening requirements described in the California IWUI code [20] (which is based on the IWUI code [13]) and refers to performance requirements listed in the California State Fire Marshal (SFM) standard 12-7A-1 [21] and ASTM E2886/E2886M-20 [16].
3. The experiments only used single-story target structures.
4. The experiments only used limited types of eave vents installed in one style of eave construction on the target structures.
5. The experiments simulated the target structure as a simple flat wall configuration with no corners or other complex geometries.
6. The experiments did not evaluate the effect of weathering, cracking, deterioration of the target structures, or minor variations in eave vent installation.

4.3. Technical Findings

Given the above-mentioned limitations, the technical findings based on thermal exposures to the target structure are listed below. While these findings are associated with the exposure from an auxiliary structure (residential storage shed), they can also provide guidance on thermal exposures of similar scale.

1 - Thermal exposures from common residential storage sheds (30 ft² (2.8 m²)) loaded with six 1-A wood cribs (120 kg ± 4 kg) were found to be repeatable when quantified in terms of heat release rate (mean absolute error < 60 kW) and heat fluxes (mean absolute error < 1.5 kW/m²). This thermal exposure consistently resulted in eave ignition of the target structure, except in one experiment where eave ignition did not occur.

2 - In the case of noncombustible steel sheds, eave ignition was a function of flame jetting from the door opening and sustained incident peak heat flux at the eaves.

3 - Eave ignition started with glowing ignition in thermally vulnerable locations including sharp edges, corners, and joints in the rafters.

4 - In this experimental series, intumescent-coated baffle vents maintained lower attic temperatures and effectively limited flame penetration throughout the high thermal exposures. Under similar thermal exposures the investigated intumescent coated honeycomb core vents could not limit the heat flow before the activation of the intumescent coating. Flame penetration occurred following eave ignition.

4-a Intumescent-coated honeycomb core vents used in these experiments that complied with ASTM E2886/E2886M-20 [16] and are listed as WUI-code-compliant products were unable to prevent flame penetration after eave ignition in this experimental configuration. Flame penetration was initially blocked by the intumescence in active vents; however, the intumescent structure was not effective in certain parts of the vent, and flame penetration was noted, particularly after eave ignition.

4-b Flame penetration occurred through vents with NFVA values in excess of 50 in² (323 cm²). Vents with baffles and louvers typically showed no evidence of flame penetration, while the vent with only the mesh screen resulted in flame penetration during the burns.

4-c Experiments with Vent A, Vent B, and Vent G recorded maximum attic temperatures in excess of 350 °C before activating the intumescent coating, suggesting that these vents may not be able to prevent ignition of combustible items in the attic in the case of large and prolonged thermal exposures.

4-d Vents C, D, E, and F recorded lower temperatures on the attic side of the vent and at the plywood compared to the temperatures on the eaves side indicating effective vent performance.

5 - The ignition of gases in the attic area did not result in sustained ignitions during these experiments. Flammable gases in the attic area ignited from intermittent flame that penetrated through the vent.

6 - Glowing embers that passed through the vents were generally small and did not cause ignition of combustible structural elements. Visual observations indicated that the embers did not have sufficient thermal energy (combined temperature and mass) to cause ignition of combustible items typically found in the attic.

6-a For vents with baffles, the ember penetration was reduced even before activation of the intumescence.

6-b For vents with intumescent coatings, once the intumescent coating activated, the number of observed embers on the attic side of the vent was significantly reduced.

6-c Ember flux through WUI-non-compliant vent G (metal mesh built in-house) was significantly higher than that observed through WUI-compliant vents.

7 - In several experiments, the eave vent activated and lowered the attic temperature as designed, however once the eave ignited, the vent was unable to prevent flames from penetrating into the attic.

5. Overall Conclusions

This limited experimental series indicates that vents compliant with ASTM E2886/E2886M-20 [16] may not provide equivalent performance under realistic fire exposures. ASTM E2886/E2886M-20 standard test evaluates vents under sustained direct flame impingement from a 300 kW burner for 10 min, a thermal exposure that results in uniform activation of the intumescent coating and closing of vent openings, thereby inhibiting flame penetration. In contrast, realistic thermal exposures involve intermittent, spatially non-uniform flaming. These thermal conditions may result in incomplete and non-uniform activation of the intumescent coating, resulting in continued heat flow into the attic space. Flame penetration can occur through vent cells that remain partially or fully open, especially following eave ignition.

The current eave vent test methods may not adequately expose the eave vents to the full range of possible WUI fire conditions. Additionally, in the event of a real WUI fire, it is important to consider the performance of the entire wall and roof assembly and their combined contributions towards the eventual survivability of the target structure, not just the performance of a single element within the assembly.

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Appendix A. Uncertainty of Measurements

The measurements of heat release rate, heat fluxes, temperatures, times, gas and airflow velocities, and distances have associated uncertainties. Measurement uncertainties have several components that are typically grouped into two categories based on the method used to estimate their value. Type A uncertainties are evaluated by statistical methods, and Type B uncertainties are evaluated by other means, often based on scientific judgement using all available relevant information [22]. The component standard uncertainty includes resolution, calibration, installation, and random errors. The resolution is the minimum change in the data measurement the instrument can exhibit. Calibration error includes uncertainties from sensor calibration. The resolution and calibration uncertainties were derived from instrument specifications (Type B). Uncertainty due to the installation method was estimated based on engineering judgment (Type B) considering misalignment, quality of the sensor mounting method, and previous data.

Given the nature of experiments and hence the singular measurements in this study, the evaluation of Type A uncertainties was not feasible for the majority of measurements. Most uncertainties reported herein are Type B uncertainties, either estimated through scientific judgment or obtained from the literature.

Type K thermocouples used in these experiments have an inherent standard uncertainty for the temperature measurements reported by the manufacturer as $\pm 0.75\%$. Additional uncertainties in measured temperature are primarily due to radiative heating and cooling of the thermocouple bead that causes it to respond to phenomena other than the surrounding gas temperature. Due to the nature of fire testing, the thermal environment surrounding a given thermocouple is difficult to characterize. These uncertainties will overwhelm the inherent uncertainties in the thermocouple described earlier.

The average expanded uncertainty in measuring the heat release rate in the normal operating range of the 20 MW (13.7 m x 15.2 m) hood for generic combustible fuels is 9.8 %. This uncertainty is valid for near steady state fires. Transient events (less than 30 s) may have more significant uncertainty because of system response time. Bryant and Bundy [23] provide detailed information on the NFRL calorimetry measurement system.

The nominal uncertainty for the S-probes is 2 % [24].

The relative expanded uncertainty reported by the manufacturer for the heat flux gauges is $\pm 3\%$ of the gauge sensitivity (the slope of the calibration curve) with a coverage factor of 2. This would result in an uncertainty of about 4 kW/m² for a nominal reading of 140 kW/m². The main sources of uncertainty for the total heat flux measurements are: (1) the uncertainty of the analog/digital conversion, (2) uncertainty in the calibration, and (3) uncertainty due to soot deposition on the sensing surface of the gauge [25].

The uncertainty in the A/D conversion is inherent to the data acquisition system. It is system-specific and is associated with the digitization of the analog signals from the gauge. This type of uncertainty is negligible. The uncertainty due to soot deposition is more challenging to quantify. The amount of soot deposition depends on many parameters, such as the location of the

gauge, the flow field and temperature fields near the gauge, the duration of an experiment, and the soot volume fraction. No attempt will be made to quantify the soot effect on heat flux measurements for these experiments. Additional uncertainty due to flame impingement on the gauges is considered negligible.

The structure separation distances (SSDs) between the target wall and the source structure and the distance between the source structure and instrumentation including the heat flux gauge are measured using a tape measure. Sources of uncertainty include the placement of the tape measure and the ability to adjust the positions of the source structure and sensors accurately. The construction dimensions are rounded to the nearest tenth. The expanded uncertainty for engineering measurements with a confidence level of 95 % was estimated as 1.2 cm (0.5 in). For longer tape measures, the expanded uncertainty was ± 2.54 cm (± 1 in).

The users of this report are advised to be informed that the experimental results presented in this report are either raw data or the statistics of raw data acquired by the measurement systems. Incorporating the measurement uncertainty reported herein into the validation of predictive models is highly recommended.

Appendix B. Experiment Summary Sheets

This appendix includes two-page summary sheets that describe each experiment. The top of each summary includes the shed material and type, fuel loading and mass, and vent ID and type; the objective of the specific experiment; and the status of the vent response. A representative photo is included to visualize the condition of the eaves and the vent installation before the experiment.

Four plots show the complete time history of measured values, including heat release rate (HRR), heat flux at the eaves, temperatures at the vent, and airflow velocity through the vent. Vertical lines indicate when the vent began to activate (Actv) and when suppression was initiated (Supp). The data lines were not smoothed and illustrate the variability of the values as measured at a frequency of 1 Hz.

Tables list values of temperature and heat flux measurements at the time of vent activation. For the three experiments in which the vent did not have intumescence to activate (e45, e49, e52), the maximum measured value prior to eave ignition is listed. Tabulated values were calculated using a 15 s average centered on the activation time. Values were rounded to the nearest whole number.

The time of occurrence of several key events is tabulated, listed in the most frequent order of events:

1. Start of vent activation: defined as the maximum negative rate of change in vent flow velocity measurement (after a 15 s smoothing filter was applied) and verified by visual review of IR video focused on the interior side of the vent.
2. Peak shed HRR (peak HRR): defined as the maximum value of HRR measured before the eave ignition time.
3. Eave ignition: defined as sustained flaming at any point on the eave assembly, determined by visual review of video recordings from the front and side of the wall assembly.
4. Flames through vent: defined as sustained flaming on the interior side of the vent, determined by visual review of video recordings from the back side of the wall focused on the vent.
5. Suppression: defined as the first application of water to terminate the experiment, determined by visual review of video recordings.

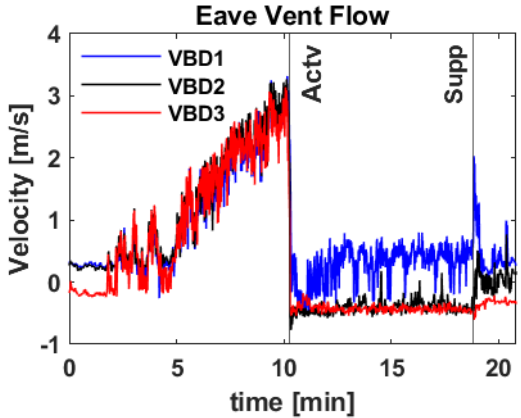
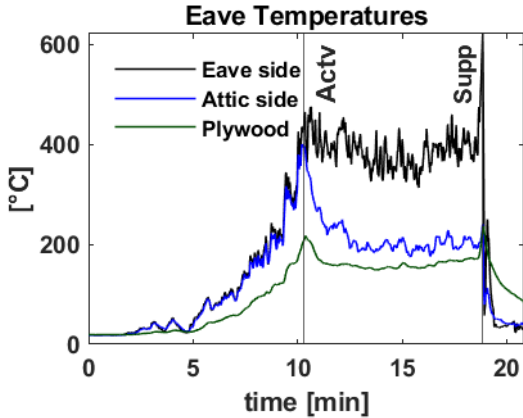
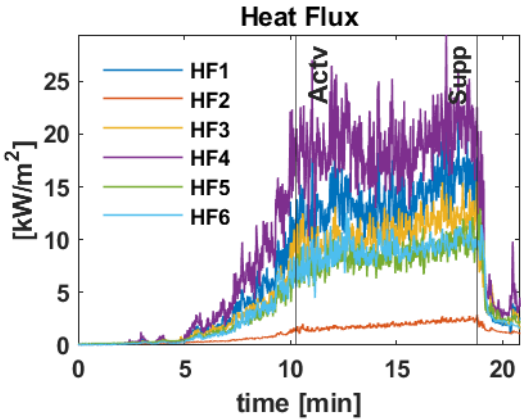
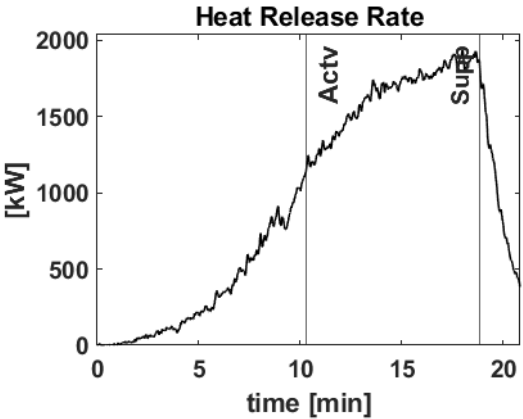
The second page includes more detailed information about observed key events in chronological order: vent activation, eave ignition and flames through the vent. For the beginning of vent activation, a plot is included spanning one minute before and after the beginning of vent activation for ATC and SP2. For eave ignition, an image is included around the moment of eave ignition, and a plot is included spanning one minute before and after eave ignition for ETC and HF1. For flames through the vent, an image is included of flame passing through the vent, and a plot spanning a minute before and after flame penetration for ATC and SP2.

EAVE_Phase_B_e18

WUI Eave Vent ID: A
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Partial Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 124 kg (273.4 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent A and quantify the heat exposure from 6 wood cribs in the very small style steel shed (1 of 2).



Temperature at Vent Activation

Location	(°C)
Vent – eave side	430
Vent – attic side	390
Attic plywood	204

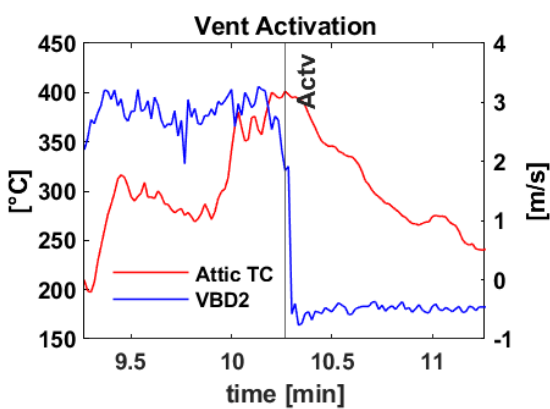
Heat Flux at Vent Activation

Location	(kW/m ²)
HF 1 (S center, out)	7
HF 2 (N center, down)	2
HF 3 (N center, out)	10
HF 4 (S center, down)	18
HF 5 (N, out)	7
HF 6 (S, down)	7

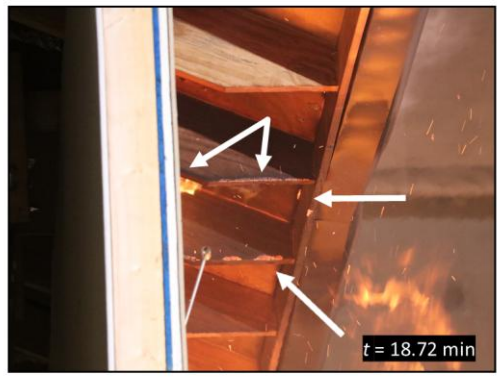
Key Events (time after ignition)

Event	Time (min)
Vent activation begins	10.27
Peak shed HRR	17.98
Eave ignition	18.65
Flames through vent	18.63
Suppression	18.85

Vent activation begins (10.27 min)



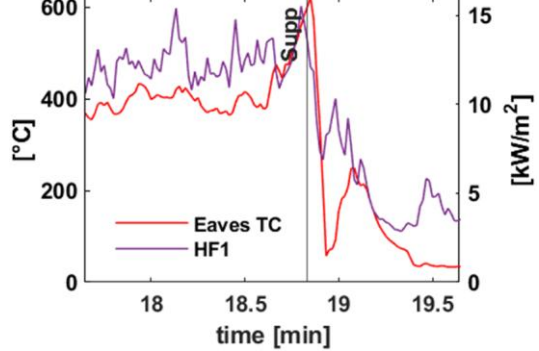
Eave ignition (18.65 min)



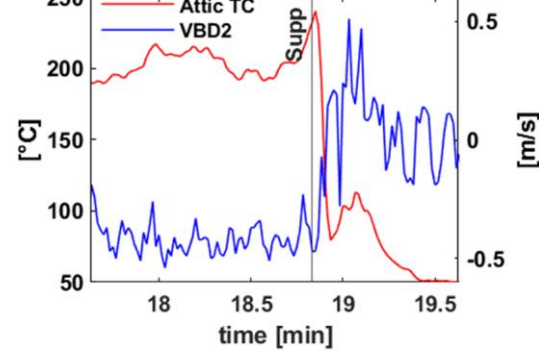
Flames through vent (18.63 min)



Eave Ignition



Flames Through Vent

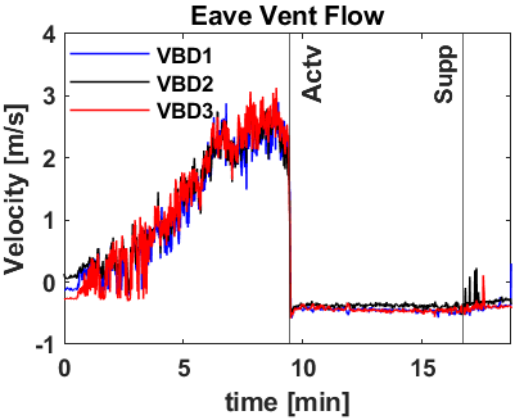
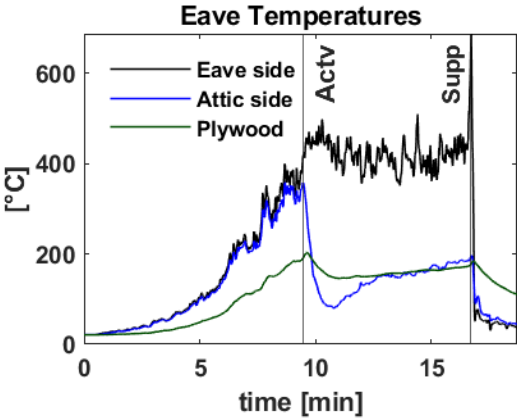
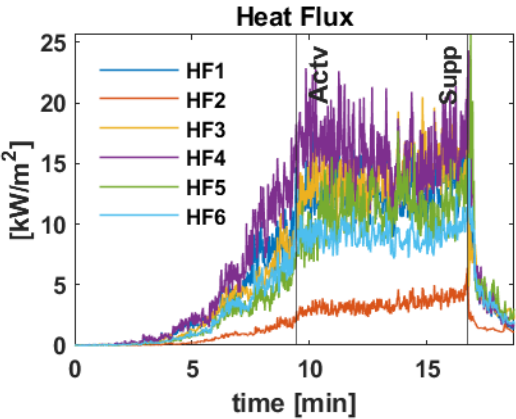
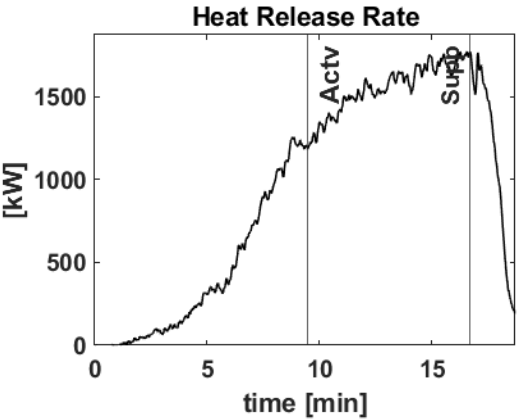


EAVE_Phase_B_e19

WUI Eave Vent ID: B
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Partial closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 112.9 kg (248.9 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent B and quantify the heat exposure from 6 wood cribs in the very small style steel shed (1 of 2).



Temperature at Vent Activation

Location	(°C)
Vent – eave side	402
Vent – attic side	344
Attic plywood	191

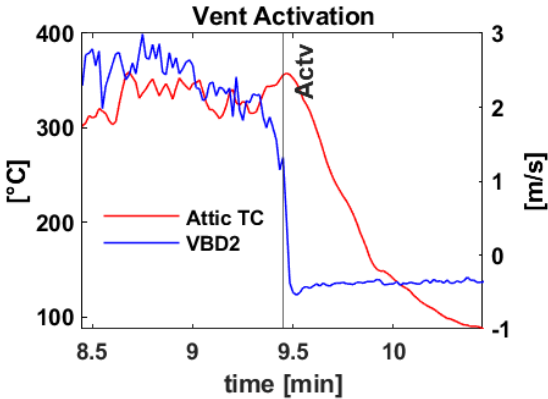
Heat Flux at Vent Activation

Location	(kW/m ²)
HF 1 (S center, out)	7
HF 2 (N center, down)	3
HF 3 (N center, out)	11
HF 4 (S center, down)	16
HF 5 (N, out)	7
HF 6 (S, down)	9

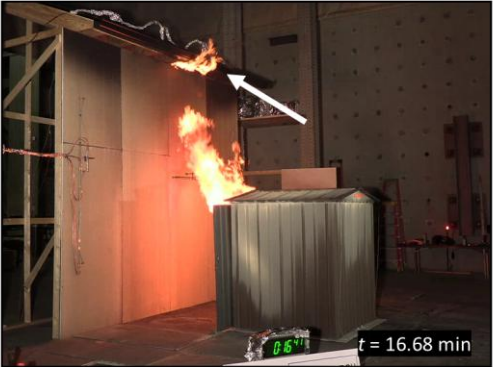
Key Events (time after ignition)

Event	Time (min)
Vent activation begins	9.45
Peak shed HRR	15.53
Eave ignition	15.93
Flames through vent	16.73
Suppression	16.85

Vent activation begins (9.45 min)



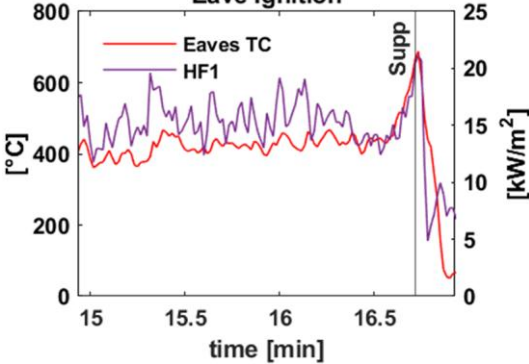
Eave ignition (15.93 min)



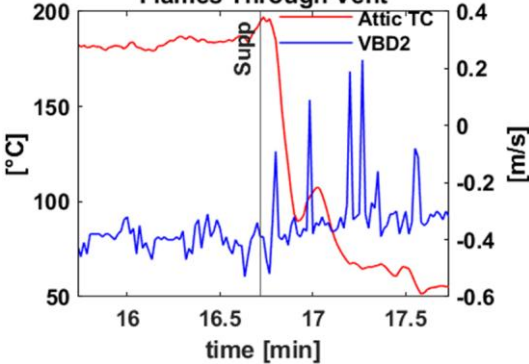
Flames through vent (16.73 min)



Eave Ignition



Flames Through Vent

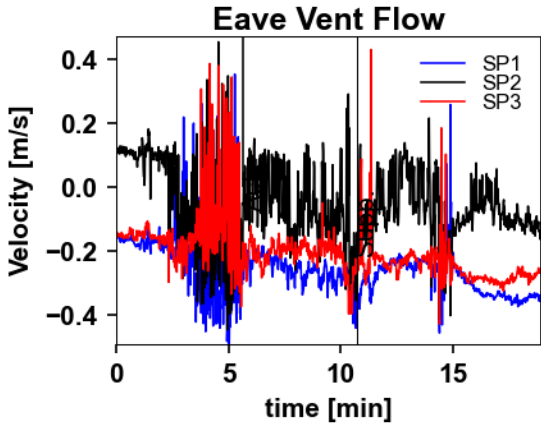
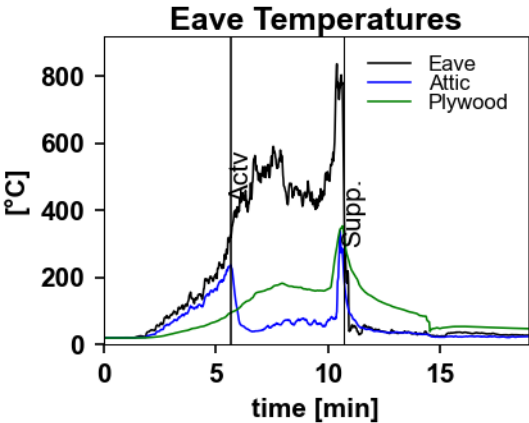
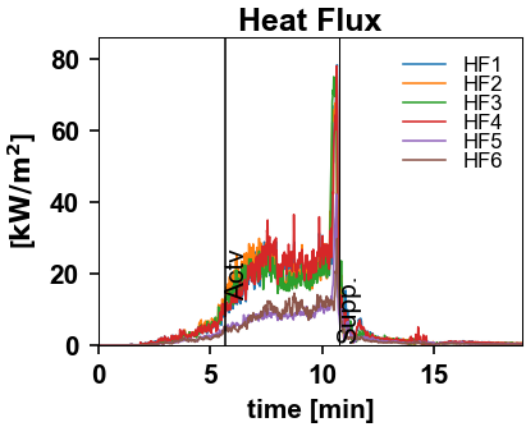
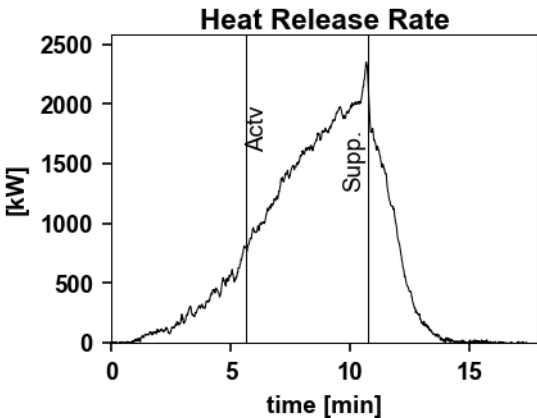


EAVE_Phase_B_e37

WUI Eave Vent ID: C
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (7 × [1-A wood cribs])
Combustible Mass: 125.8 kg (277.3 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of a WUI Eave Vent C and quantify the heat exposure from 7 wood cribs in the very small style steel shed (1 of 2). Seven cribs were used instead of 6 cribs to get the fuel mass into the ‘high’ fuel range based on previous experiments.



Temperature at Vent Activation

Location	(°C)
Vent – eave side	314
Vent – attic side	232
Attic plywood	92

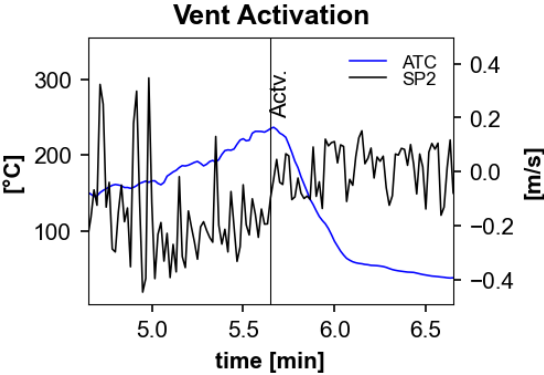
Heat Flux at Vent Activation

Location	(kW/m ²)
HF 1 (S center, out)	10
HF 2 (N center, down)	12
HF 3 (N center, out)	10
HF 4 (S center, down)	10
HF 5 (N, out)	5
HF 6 (S, down)	4

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	5.65
Peak shed HRR	9.57
Eave ignition	9.92
Flames through vent	No
Suppression	10.73

Vent activation begins (5.65 min)



Eave ignition (9.92 min)

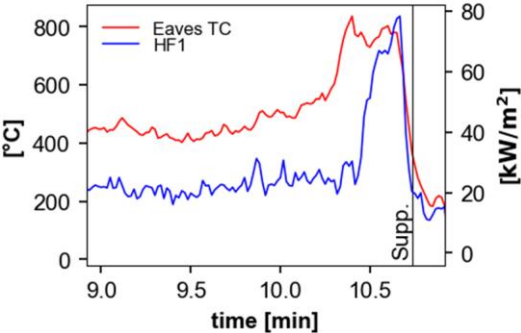


Flames through vent (No min)

n/a



Eave Ignition

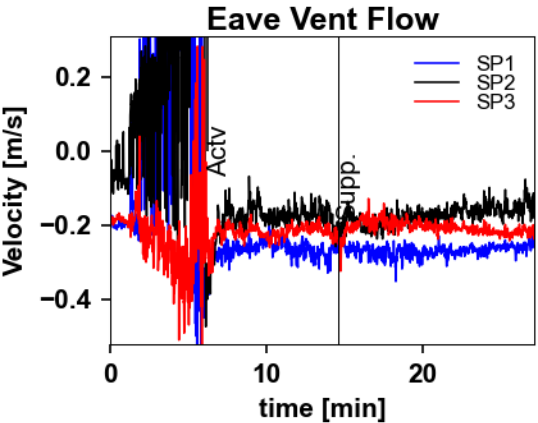
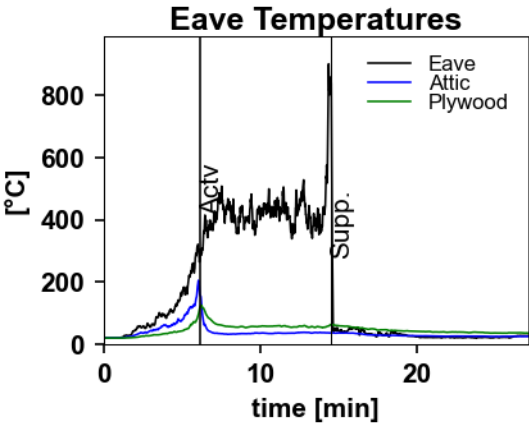
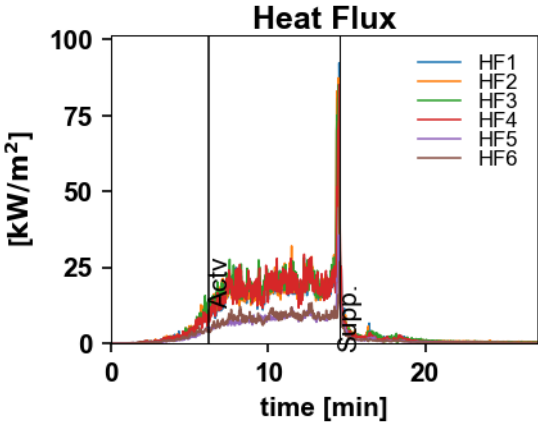
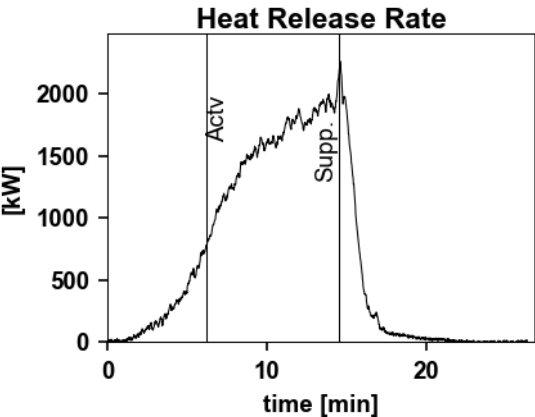


EAVE_Phase_B_e43

WUI Eave Vent ID: F
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 119.6 kg (263.7 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent F and quantify the heat exposure from 6 wood cribs in the very small style steel shed (1 of 2).



Temperature at Vent Activation

Location	(°C)
Vent – eave side	274
Vent – attic side	165
Attic plywood	116

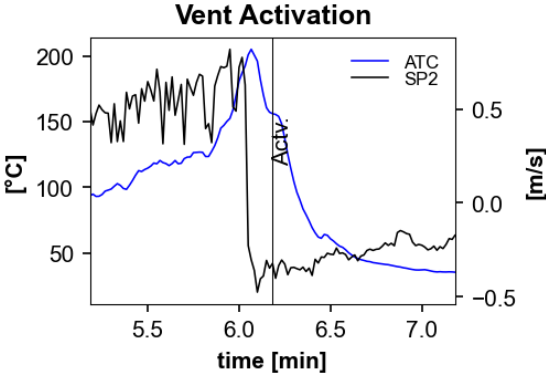
Heat Flux at Vent Activation

Location	(kW/m²)
HF 1 (S center, out)	8
HF 2 (N center, down)	10
HF 3 (N center, out)	9
HF 4 (S center, down)	8
HF 5 (N, out)	4
HF 6 (S, down)	4

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	6.18
Peak shed HRR	13.88
Eave ignition	14.22
Flames through vent	No
Suppression	14.53

Vent activation begins (6.18 min)



Eave ignition (14.22 min)

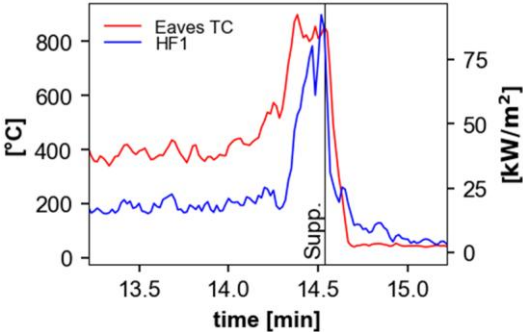


Flames through vent (No min)

n/a



Eave Ignition

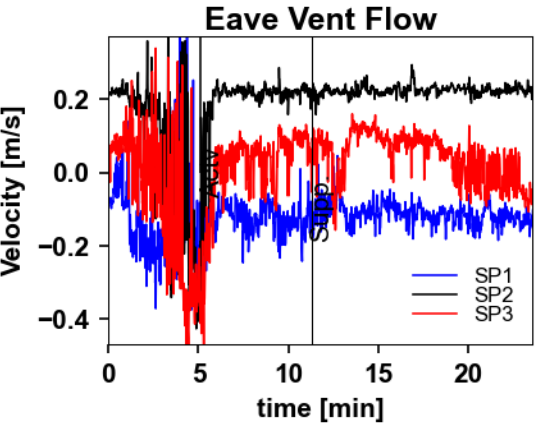
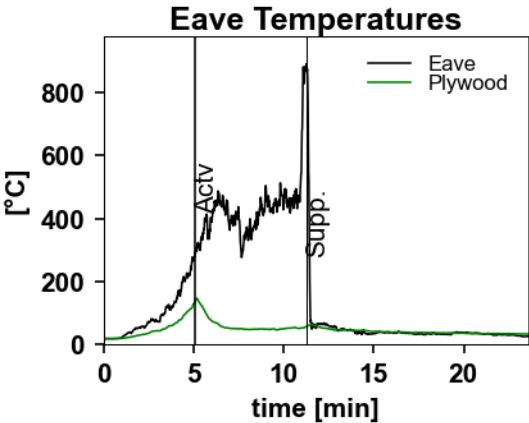
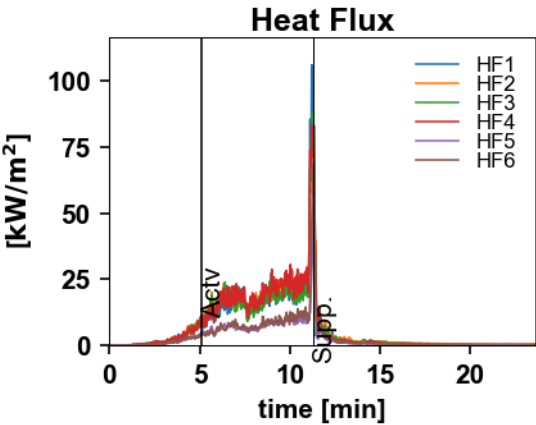
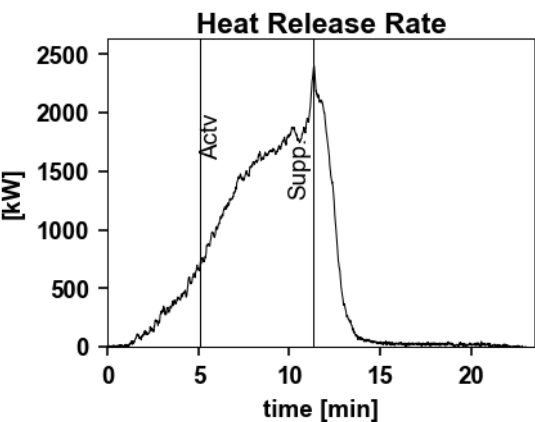


EAVE_Phase_B_e44

WUI Eave Vent ID: E
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 120.1 kg (264.8 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent E and quantify the heat exposure from 6 wood cribs in the very small style steel shed (1 of 2).



Temperature at Vent Activation

Location	(°C)
Vent – eave side	278
Vent – attic side	n/d
Attic plywood	132

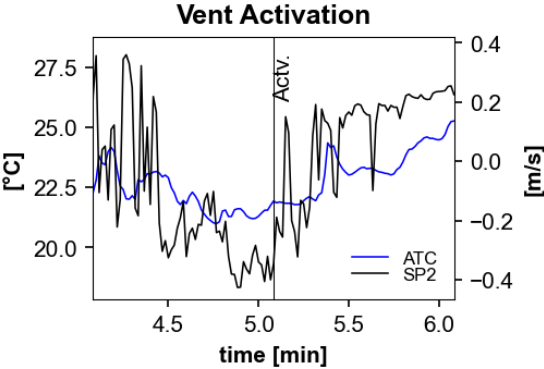
Heat Flux at Vent Activation

Location	(kW/m ²)
HF 1 (S center, out)	9
HF 2 (N center, down)	10
HF 3 (N center, out)	9
HF 4 (S center, down)	10
HF 5 (N, out)	4
HF 6 (S, down)	4

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	5.08
Peak shed HRR	10.93
Eave ignition	10.95
Flames through vent	No
Suppression	11.30

Vent activation begins (5.08 min)



Eave ignition (10.95 min)

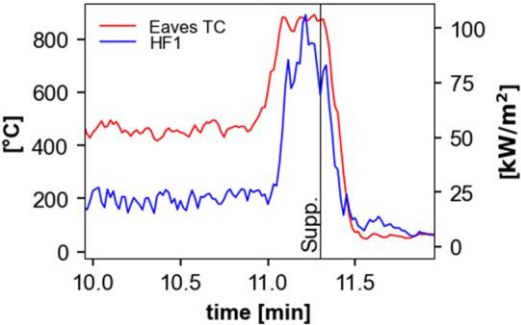


Flames through vent (No min)

n/a



Eave Ignition

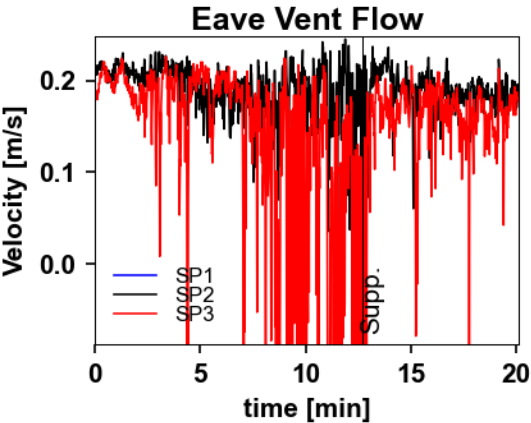
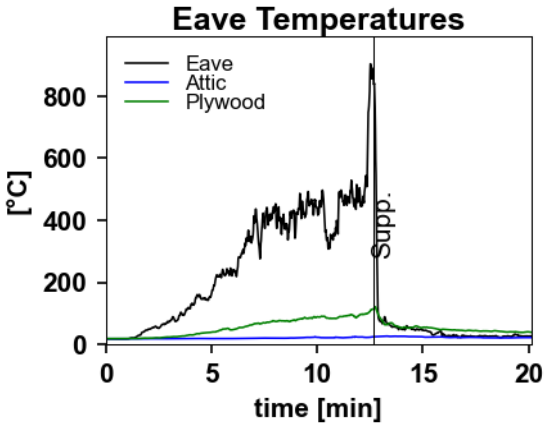
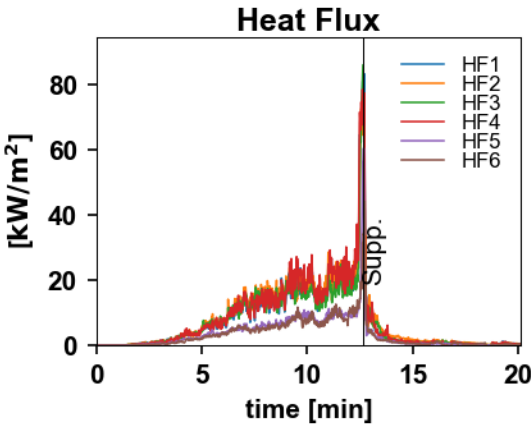
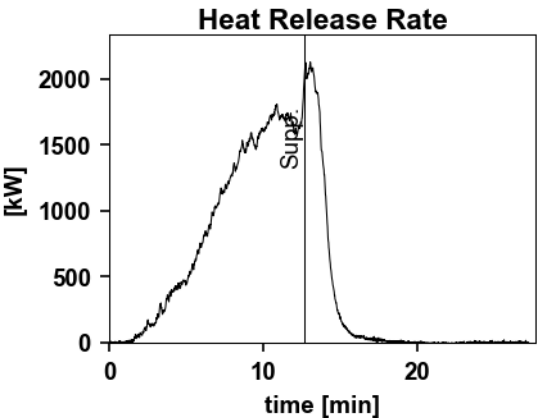


EAVE_Phase_B_e45

WUI Eave Vent ID: D
Eave Ignition: Yes
Vent Type: Passive
Vent Response: n/a

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 116.3 kg (256.4 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent D and quantify the heat exposure from 6 wood cribs in the very small style steel shed (1 of 2).



Max Temperature Prior to Eave Ignition

Location	(°C)
Vent – eave side	529
Vent – attic side	25
Attic plywood	98

Max Heat Flux Prior to Eave Ignition

Location	(kW/m²)
HF 1 (S center, out)	27
HF 2 (N center, down)	29
HF 3 (N center, out)	25
HF 4 (S center, down)	30
HF 5 (N, out)	11
HF 6 (S, down)	13

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	n/a
Peak shed HRR	10.85
Eave ignition	12.27
Flames through vent	n/a
Suppression	12.68

Vent activation begins (n/a min)

n/a

Eave ignition (12.27 min)

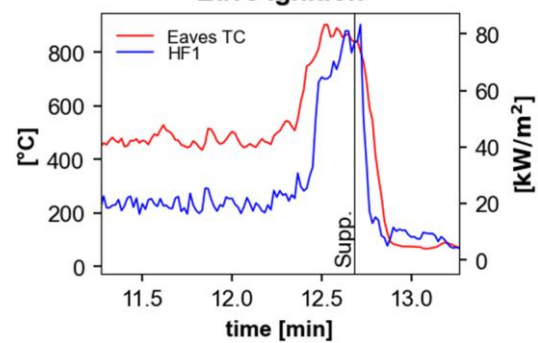


Flames through vent (No min)

n/a



Eave Ignition

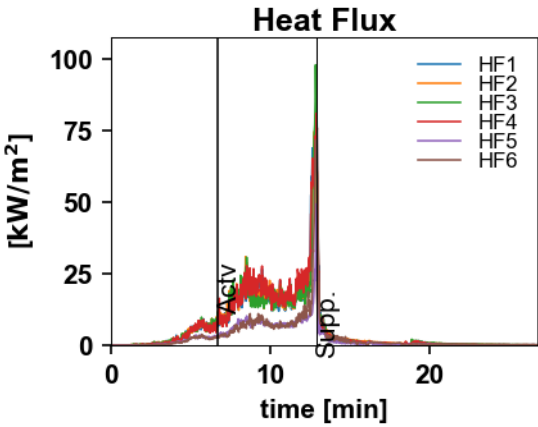
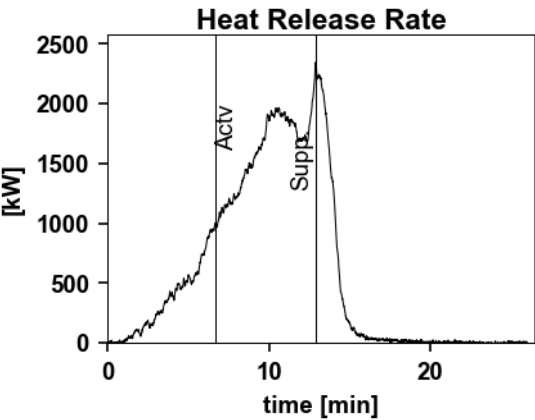


EAVE_Phase_B_e46

WUI Eave Vent ID: F
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 116.2 kg (256.2 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent F and quantify the heat exposure from 6 wood cribs in the very small style steel shed (2 of 2).

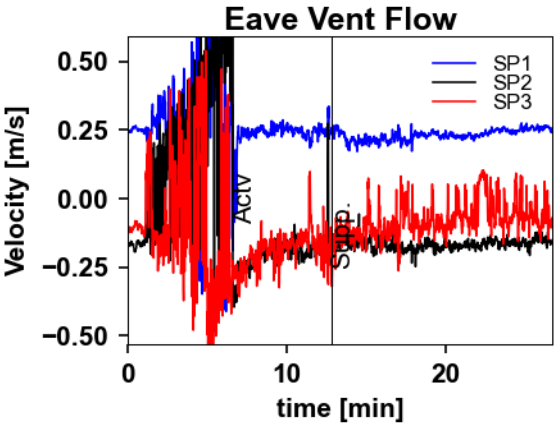
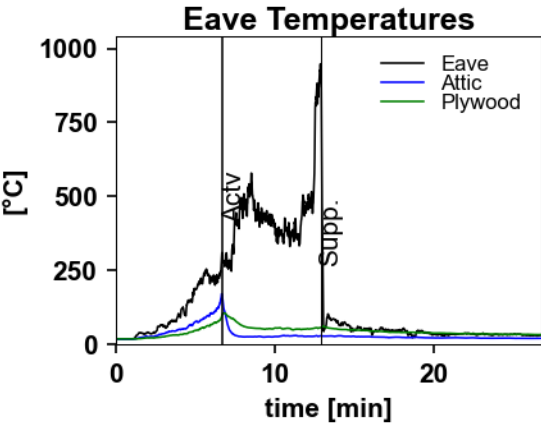


Temperature at Vent Activation

Location	(°C)
Vent – eave side	290
Vent – attic side	165
Attic plywood	94

Heat Flux at Vent Activation

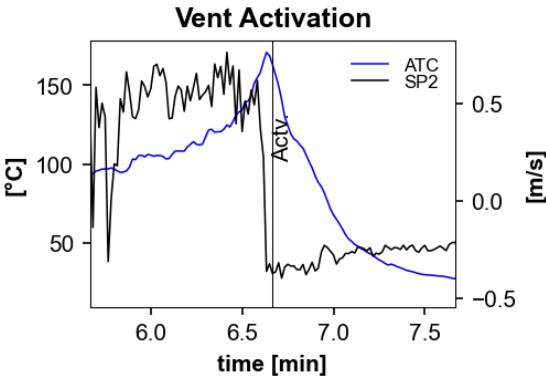
Location	(kW/m²)
HF 1 (S center, out)	9
HF 2 (N center, down)	10
HF 3 (N center, out)	8
HF 4 (S center, down)	8
HF 5 (N, out)	3
HF 6 (S, down)	3



Key Events (time after ignition)

Event	Time (min)
Vent activation begins	6.67
Peak shed HRR	10.62
Eave ignition	12.37
Flames through vent	No
Suppression	12.87

Vent activation begins (6.67 min)



Eave ignition (12.37 min)

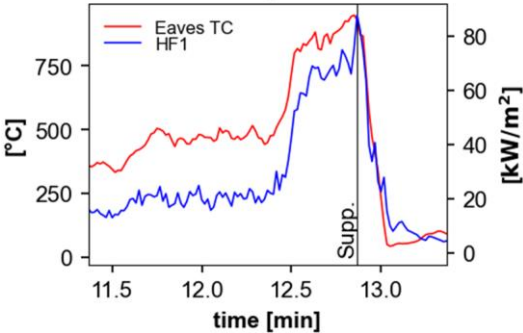


Flames through vent (No min)

n/a



Eave Ignition

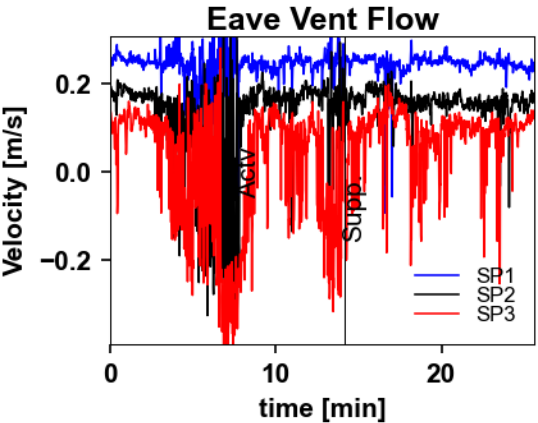
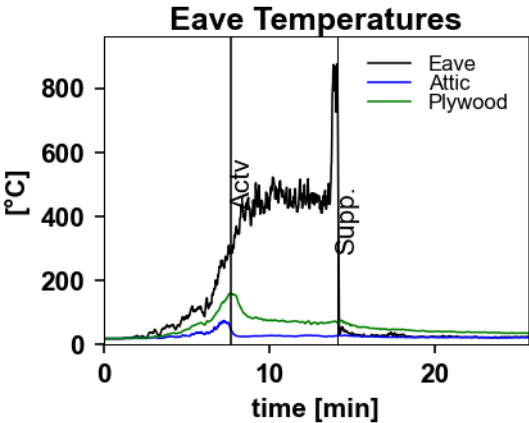
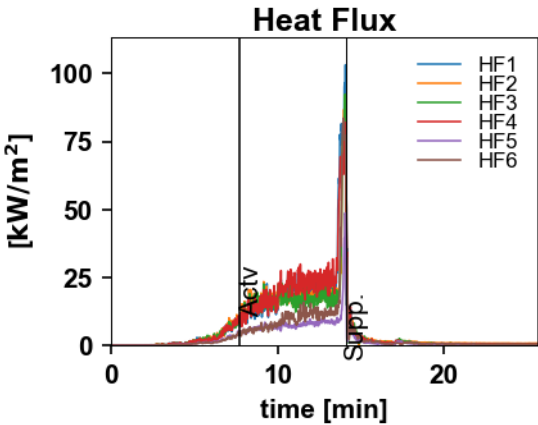
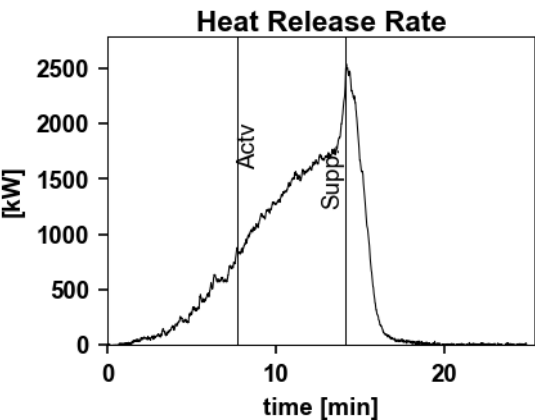


EAVE_Phase_B_e47

WUI Eave Vent ID: C
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 120.5 kg (265.7 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent C and quantify the heat exposure from 6 wood cribs in the very small style steel shed (2 of 2).



Temperature at Vent Activation

Location	(°C)
Vent – eave side	286
Vent – attic side	51
Attic plywood	158

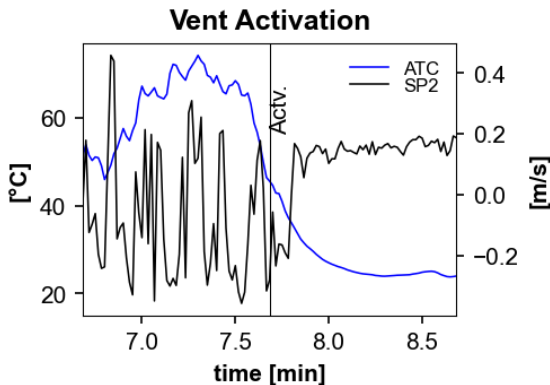
Heat Flux at Vent Activation

Location	(kW/m ²)
HF 1 (S center, out)	9
HF 2 (N center, down)	9
HF 3 (N center, out)	9
HF 4 (S center, down)	10
HF 5 (N, out)	4
HF 6 (S, down)	4

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	7.68
Peak shed HRR	13.47
Eave ignition	13.58
Flames through vent	No
Suppression	14.12

Vent activation begins (7.68 min)



Eave ignition (13.58 min)

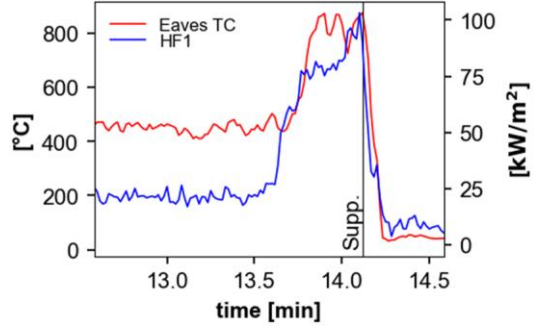


Flames through vent (No min)

n/a



Eave Ignition

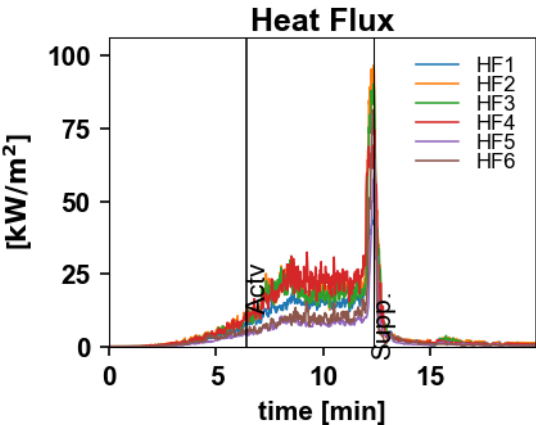
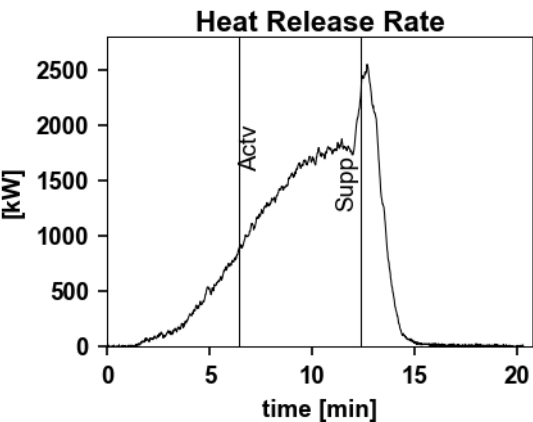


EAVE_Phase_B_e48

WUI Eave Vent ID: E
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Closure

Shed Material: Steel Fuel Loading: High (6 × [1-A wood cribs]) Wind Speed: 0 m/s
Shed Type: Very Small (30 ft²) Combustible Mass: 119 kg (262.3 lb) SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent E and quantify the heat exposure from 6 wood cribs in the very small style steel shed (2 of 2).

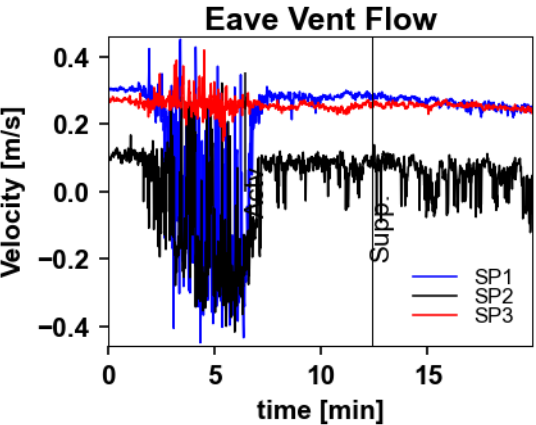
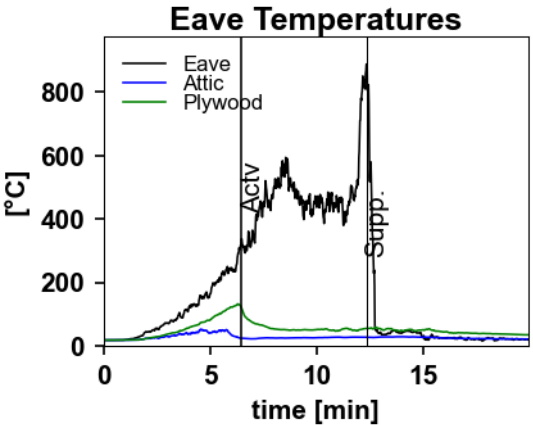


Temperature at Vent Activation

Location	(°C)
Vent – eave side	309
Vent – attic side	25
Attic plywood	128

Heat Flux at Vent Activation

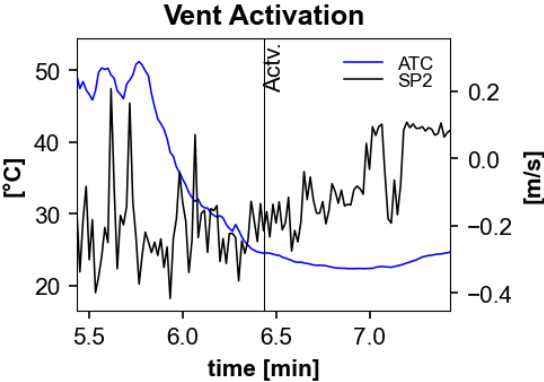
Location	(kW/m ²)
HF 1 (S center, out)	8
HF 2 (N center, down)	11
HF 3 (N center, out)	11
HF 4 (S center, down)	11
HF 5 (N, out)	4
HF 6 (S, down)	5



Key Events (time after ignition)

Event	Time (min)
Vent activation begins	6.43
Peak shed HRR	11.43
Eave ignition	11.88
Flames through vent	No
Suppression	12.37

Vent activation begins (6.43 min)



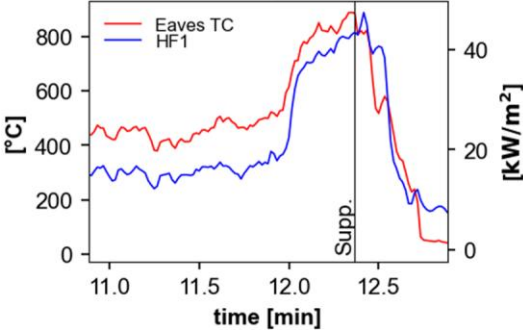
Eave ignition (11.88 min)



Flames through vent (No min)

n/a

Eave Ignition

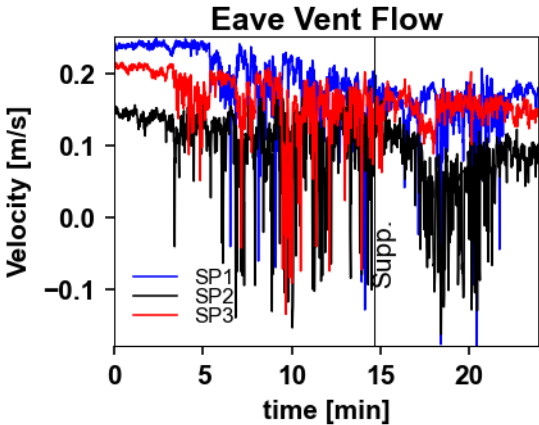
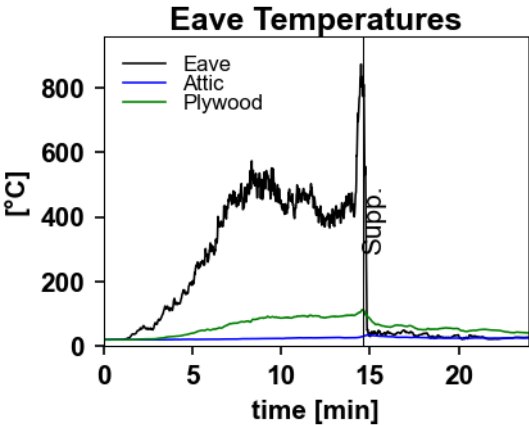
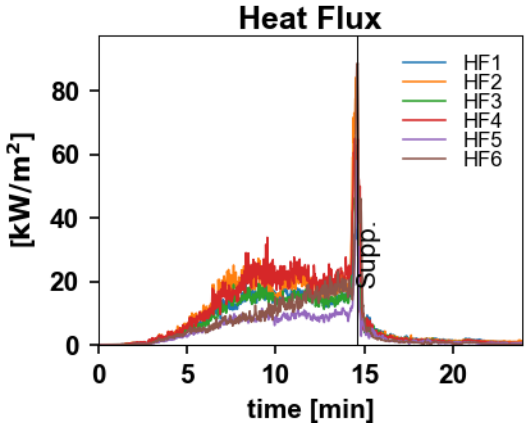
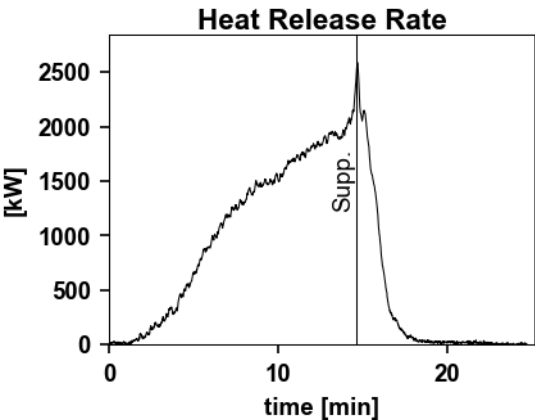


EAVE_Phase_B_e49

WUI Eave Vent ID: D
Eave Ignition: Yes
Vent Type: Passive
Vent Response: n/a

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 118.4 kg (261 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent D and quantify the heat exposure from 6 wood cribs in the very small style steel shed (2 of 2).



Max Temperature Prior to Eave Ignition

Location	(°C)
Vent – eave side	573
Vent – attic side	26
Attic plywood	96

Max Heat Flux Prior to Eave Ignition

Location	(kW/m²)
HF 1 (S center, out)	21
HF 2 (N center, down)	27
HF 3 (N center, out)	19
HF 4 (S center, down)	34
HF 5 (N, out)	12
HF 6 (S, down)	23

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	n/a
Peak shed HRR	14.07
Eave ignition	14.08
Flames through vent	No
Suppression	14.62

Vent activation begins (n/a min)

n/a

Eave ignition (14.08 min)

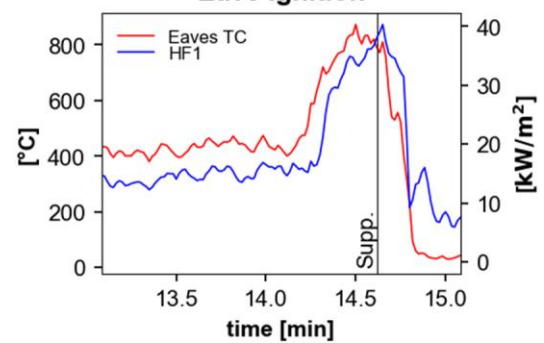


Flames through vent (No min)

n/a



Eave Ignition

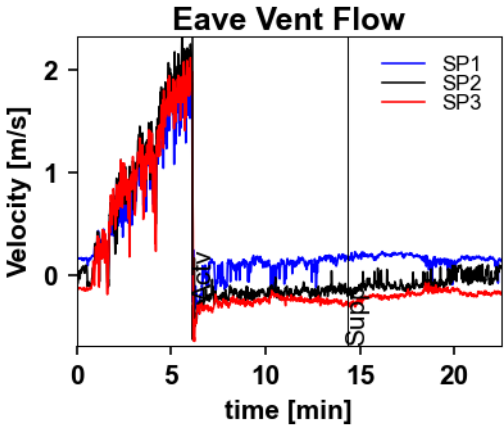
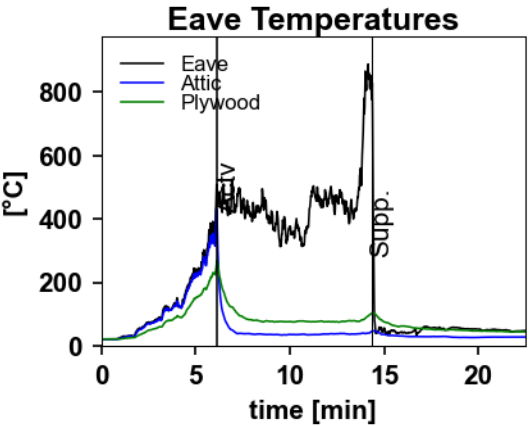
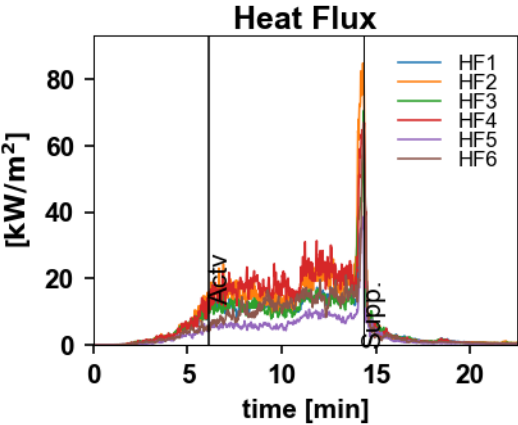
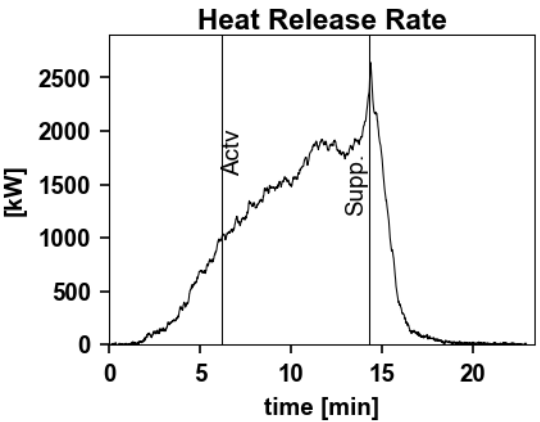


EAVE_Phase_B_e50

WUI Eave Vent ID: B
Eave Ignition: Yes
Vent Type: Intumescent
Vent Response: Partial Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 118.3 kg (260.8 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent B and quantify the heat exposure from 6 wood cribs in the very small style steel shed (2 of 2).



Temperature at Vent Activation

Location	(°C)
Vent – eave side	480
Vent – attic side	400
Attic plywood	258

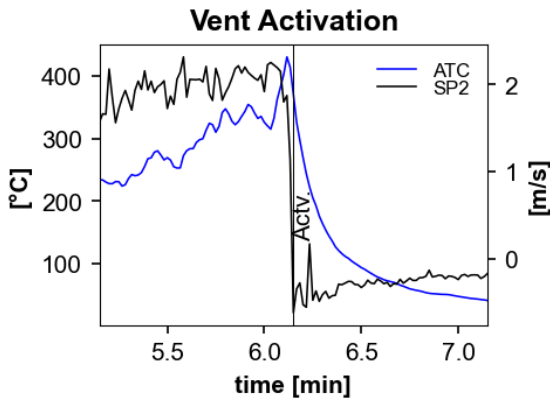
Heat Flux at Vent Activation

Location	(kW/m ²)
HF 1 (S center, out)	11
HF 2 (N center, down)	14
HF 3 (N center, out)	12
HF 4 (S center, down)	14
HF 5 (N, out)	5
HF 6 (S, down)	5

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	6.15
Peak shed HRR	13.52
Eave ignition	13.62
Flames through vent	13.92
Suppression	14.33

Vent activation begins (6.15 min)



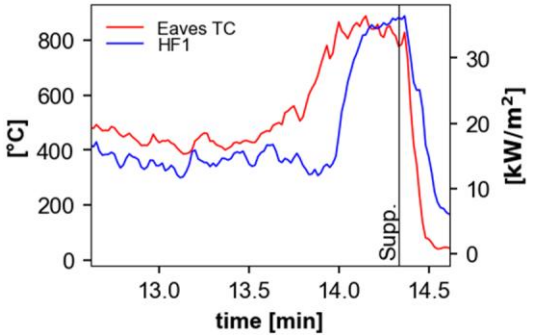
Eave ignition (13.62 min)



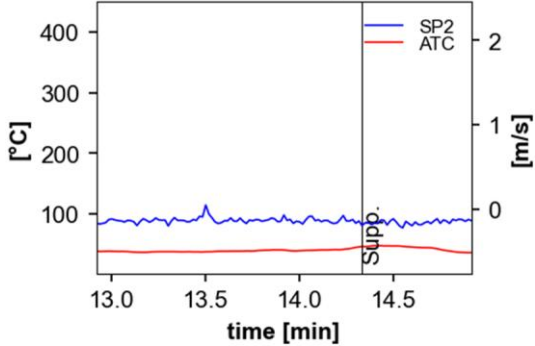
Flames through vent (13.92 min)



Eave Ignition



Flames Through Vent

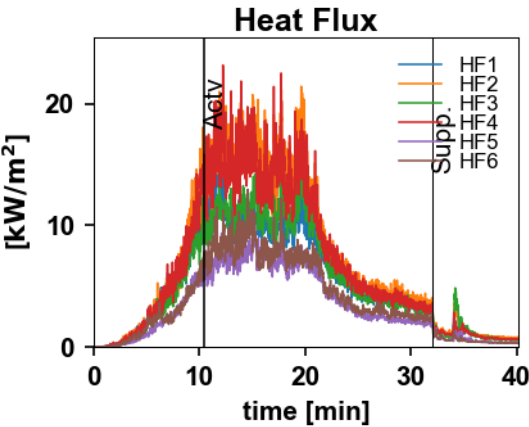
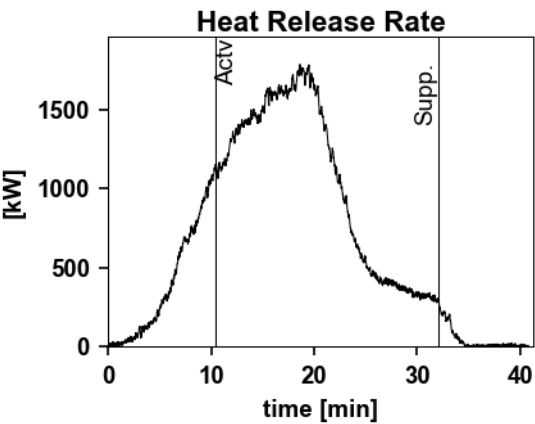


EAVE_Phase_B_e51

WUI Eave Vent ID: A
Eave Ignition: No
Vent Type: Intumescent
Vent Response: Partial Closure

Shed Material: Steel
Shed Type: Very Small (30 ft²)
Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 123.9 kg (273.2 lb)
Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of WUI Eave Vent A and quantify the heat exposure from 6 wood cribs in the very small style steel shed (2 of 2).

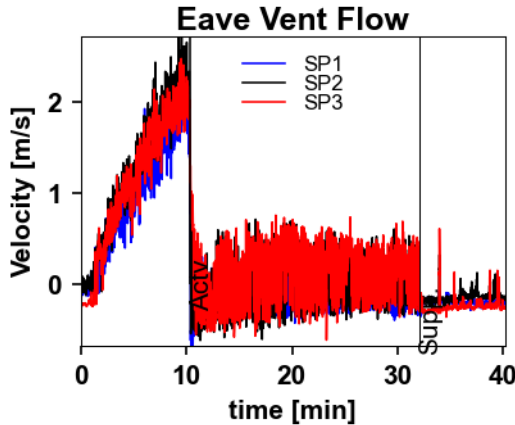
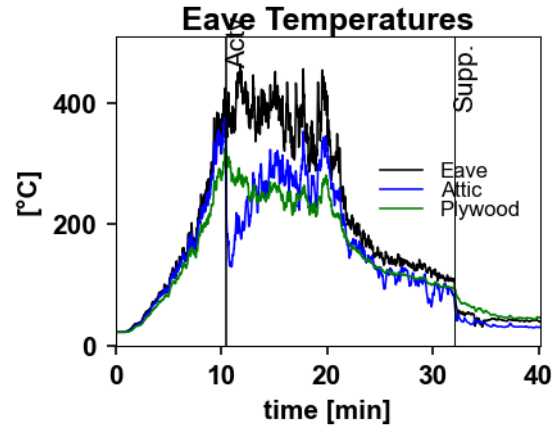


Temperature at Vent Activation

Location	(°C)
Vent – eave side	410
Vent – attic side	358
Attic plywood	322

Heat Flux at Vent Activation

Location	(kW/m ²)
HF 1 (S center, out)	11
HF 2 (N center, down)	14
HF 3 (N center, out)	10
HF 4 (S center, down)	14
HF 5 (N, out)	6
HF 6 (S, down)	7



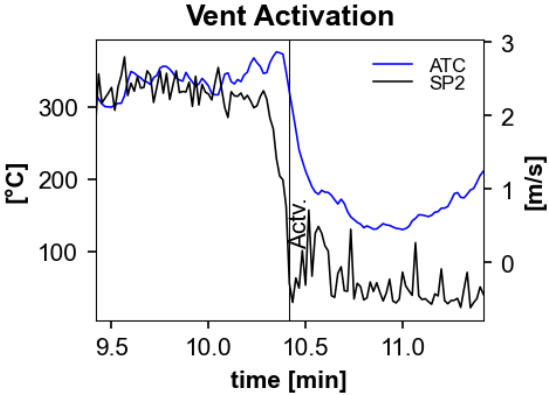
Key Events (time after ignition)

Event	Time (min)
Vent activation begins	10.42
Peak shed HRR	18.60
Eave ignition	No
Flames through vent	No
Suppression	32.03

Vent activation begins (10.42 min)

Eave ignition (No min)

Flames through vent (No min)



n/a

n/a

EAVE_Phase_B_e52

WUI Eave Vent ID: G
Eave Ignition: Yes

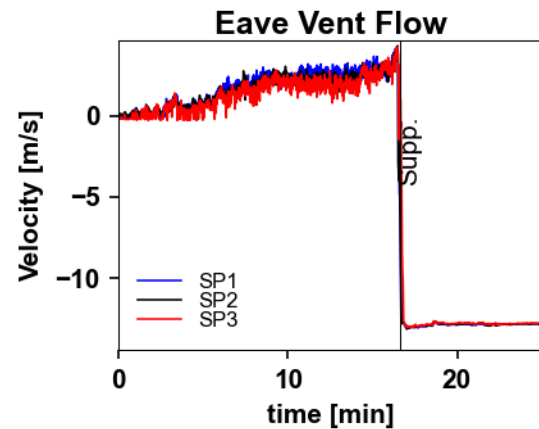
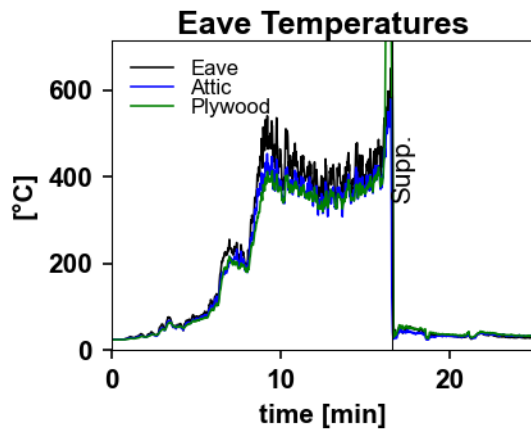
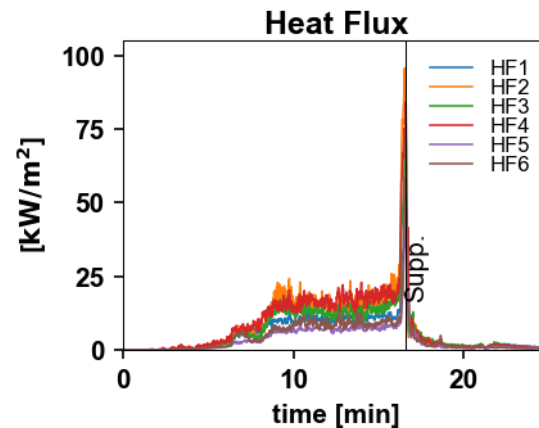
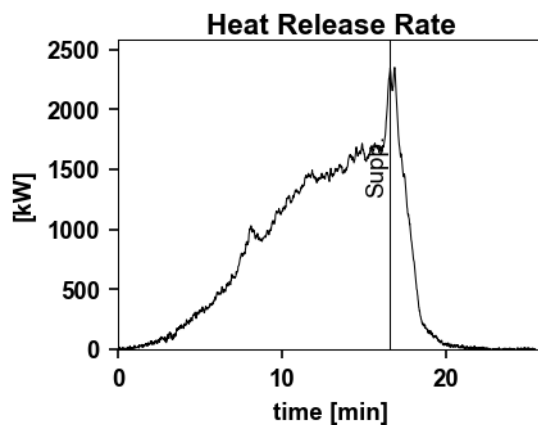
Vent Type: Passive
Vent Response: n/a

Shed Material: Steel
Shed Type: Very Small (30 ft²)

Fuel Loading: High (6 × [1-A wood cribs])
Combustible Mass: 123.2 kg (271.6 lb)

Wind Speed: 0 m/s
SSD: 5 ft

Objective: To assess the performance of mesh Vent G and quantify the heat exposure from 6 wood cribs in the very small style steel shed (1 of 1).



Max Temperature Prior to Eave Ignition

Location	(°C)
Vent – eave side	540
Vent – attic side	458
Attic plywood	437

Max Heat Flux Prior to Eave Ignition

Location	(kW/m ²)
HF 1 (S center, out)	14
HF 2 (N center, down)	26
HF 3 (N center, out)	19
HF 4 (S center, down)	23
HF 5 (N, out)	10
HF 6 (S, down)	13

Key Events (time after ignition)

Event	Time (min)
Vent activation begins	n/a
Peak shed HRR	15.68
Eave ignition	16.13
Flames through vent	8.87
Suppression	16.62

Vent activation begins (n/a min)

n/a

Eave ignition (16.13 min)



Flames through vent (8.87 min)

