RESEARCH TECHNICAL REPORT

Gravity Smoke Vents in Storage Occupancies

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Disclaimer

Executive Summary

Many FM Global clients are required by local building codes to install smoke and/or heat vents (i.e, smoke vents) in storage occupancies, including in-process storage, which can be high-hazard. These building code requirements are for life safety to maintain tenability in the event of a fire, to assist with the evacuation of the building, and to provide safe access for manual firefighting efforts. However, it is not clear that smoke vents provide a property loss prevention benefit for storage occupancies, and there are concerns that they may adversely impact sprinkler protection. This report presents an assessment of gravity smoke vents in storage occupancies from a property loss prevention perspective, based on full-scale testing and numerical modeling.

Historical tests conducted at FM Global and elsewhere offer some insight into this topic for sprinklered occupancies[1,2] . Smoke vents showed the potential to delay the first sprinkler activation time if the nearest vent is closer to the ignition location than the nearest sprinkler, resulting in a larger fire size at the time of first sprinkler activation. This raised the concern that smoke vents may lead to the failure of an otherwise adequate sprinkler design. However, no full-scale tests using a realistic commodity have demonstrated this concern.

FM Global Property Loss Prevention Data Sheets (i.e., DS) do not recommend the installation of smoke vents and, where required by building codes, provide recommendations intended to ensure that sprinklers activate and control the fire before smoke vents are opened. For adequately designed sprinkler systems, these recommendations may prevent automatic smoke vents from opening at all due to ceiling cooling and fire suppression effects.

Competing positions exist, particularly outside of North America where there are fewer requirements for sprinkler protection and more requirements for compartmentation and smoke venting. The competing position is that smoke vents do not adversely impact sprinklers, and that they offer additional benefits in terms of improved tenability.

This study aims to clarify the behavior of smoke vents in storage occupancies, with a focus on gravity vents and their interactions with sprinkler protection. Nominally sized vents of 3 m^2 (32 ft^2) are considered. Full-scale tests and numerical simulations are used to perform an assessment of smoke vents, incorporating both a probabilistic view (likelihood) and a worst-case scenario view (impact). The

[1] Factory Mutual Engineering Corporation, “Heat Vents and Fire Curtains, Effect in Operation of Sprinklers and Visibility”, FM Global, Technical Memorandum, Project ID 13085, 1956.

[2] G. Heskestad, “Model Study of Automatic Smoke and Heat Vent Performance in Sprinklered Fires”, FM Global, Technical Report, Project ID 21933, 1974.

numerical simulations were performed with FireFOAM, which has been validated for fire growth and suppression dynamics[3,4].

For unsprinklered storage occupancies, this study evaluates the property loss prevention benefit of smoke vents. Two cases were simulated using FireFOAM, with and without smoke vents. The results showed that smoke vent have a negligible impact on fire growth where the combustible load is large and compartmentation/vitiation effects are small. The fast-growing nature of unsprinklered storage fires resulted in widespread flame impingement on the ceiling with/without smoke vents, leading to the rapid onset of structural damage to the building.

For sprinklered storage occupancies, this study evaluates the impact of smoke vents on the sprinkler protection. It is assumed that the largest impact will occur when the smoke vents open before the sprinklers. The removal of heat from the ceiling layer may delay sprinkler activations and result in a fire that is larger than expected for the sprinkler design, potentially increasing losses. This concern is first addressed by using a probabilistic analysis to determine the likelihood of automatic smoke vents opening before the sprinklers. An ensemble of FireFOAM simulations were performed to quantify this likelihood, considering a wide parameter space including commodity type, storage/ceiling height, ignition scenario, and vent and sprinkler thermal element properties. It was found that smoke vents are highly unlikely to activate before sprinklers if the vent activation temperature is equal to or greater than the sprinkler activation temperature. The main reason for this is that there are many more sprinkler thermal elements than smoke vent thermal elements at the ceiling. For example, if the vent thermal element used a higher temperature-rating than the sprinklers (consistent with NFPA 13 recommendations), then there was on average a 2% and 7% chance for vents to open before quick-response ordinary-temperature sprinklers and standard-response high-temperature sprinklers, respectively. A sensitivity analysis was also conducted considering more/less total venting area in the ceiling, but this did not significantly alter the results.

The probabilistic analysis showed that automatic smoke vents are only expected to open before sprinklers if the ignition location is much closer to a smoke vent than the sprinklers. While this likelihood was found to be small, the impact must also be determined to evaluate the overall risk. To this end, a combined modeling and testing effort was conducted that focused on the low-probability event where the ignition occurs directly underneath a smoke vent and as far as possible from the sprinklers. Two conditions with/without smoke vents were considered: 1) cartoned unexpanded plastic (CUP) commodity with a sprinkler design recommended in FM Global DS 8-9, and 2) Class 2 commodity with a representative sprinkler protection that FM Global does not deem to be adequate but exists in the field

[3]N. Ren, J. deVries, X. Zhou, M. Chaos, K.V. Meredith, Y. Wang, “Large-scale fire suppression modeling of corrugated cardboard boxes on wood pallets in rack-storage configurations”, *Fire Safety Journal*, vol. 91, pp. 695-704, 2017.

[4] Y. Wang, K. Meredith, Z. Zhou, P. Chatterjee, Y. Xin, M. Chaos, N. Ren, S. Dorofeev, “Numerical Simulation of Sprinkler Suppression of Rack Storage Fires”, Fire Safety Science, vol 11, pp. 1170-1183, 2014.

and is considered adequate by NFPA 13. This protection options shall be referred to as “marginal sprinkler protection” and was chosen specifically to provide a greater challenge fire to the sprinkler system. The model results were generated using FireFOAM before the testing was performed. This *a priori* approach sets a rigorous validation standard, i.e., the model is not tuned to match the test results. The model results showed that the smoke vent opened before the sprinklers, delaying the first sprinkler activation time and resulting in a larger peak fire size. However, this did not lead to a failure of the sprinkler protection.

To validate these findings, tests were performed in the FM Global Research Campus Large Burn Laboratory (LBL) at the same conditions used in the FireFOAM simulations. The results from the CUP tests with adequate sprinkler protection were consistent with the model results: the smoke vent opened first and delayed the first sprinkler activation time and resulted in a larger peak fire size but did not lead to worse outcomes compared to the unvented cases. Differences existed between the test and the model in terms of sprinkler activation order/pattern, but these differences are attributed to the phenomenon of “sprinkler skipping”, which was not fully captured by the model and is outside the scope of this report. The results from the Class 2 tests with marginal sprinkler protection were also consistent with the model results in terms of the physical trends. Unlike the CUP results, the delay in first sprinkler activation due to the smoke vent increased the total water demand and number of sprinkler activations. This difference is attributed to the marginal sprinkler protection used for the Class 2 cases. The increased water demand was more pronounced in the tests compared to the model, which predicted the correct trend behavior with decreasing water supply but over-predicted suppression at the tested conditions.

The validation tests and modeling focused on the low-probability event where ignition occurs directly underneath a smoke vent and as far as possible from the sprinklers, leading to the smoke vent opening before the first sprinkler, which is considered the “worst-case scenario” in terms of the impact of the smoke vent on the sprinkler protection. In this case, the main conclusions are: 1) smoke vents can delay the first sprinkler activation and result in a larger peak fire size but do not lead to worse outcomes if the sprinkler system is adequately designed, and 2) if the sprinkler protection is marginal, the delay in sprinkler activation time caused by the smoke vents can lead to increased sprinkler activations, potentially exceeding the available water supply and leading to increased losses.

The FireFOAM model was then used to study the sensitivity of the results. Simulations were conducted with an array of always-open smoke vents (‘vent-openings’ as defined in FM Global DS 2-0, combined with a draft curtain and with a vent-to-floor ratio of 3.1%. The results were not significantly different to the baseline (validation) cases, which suggests that the impact of a vent-opening is like that of an automatic smoke vent that opens before the first sprinkler. Parametric variations considering ignition location, ceiling height, clearance above the top of storage array, and commodity type showed consistent findings.

The loss prevention recommendations in FM Global DS 2-0 were evaluated using the FireFOAM model. These recommendations are made for occupancies that are required by local building codes to include smoke vents and are intended to ensure that sprinklers open and control the fire. The recommendations include options to use thermal elements with very high activation temperatures for the smoke vent, smoke vents operated on a 20-minute timer following sprinkler activation, or sprinklers installed on a 1.2 m (4 ft) spacing underneath the smoke vent area. The model results showed that these measures reduced the impact of smoke vents on the first sprinkler activation time but did not qualitatively change the outcome relative to the baseline (validation) test conditions.

Overall, this study finds that automatic gravity smoke vents alone do not provide a property loss prevention benefit for storage occupancies. However, gravity smoke vents are also highly unlikely to adversely impact sprinkler protection that is otherwise adequately designed. For marginal sprinkler protection, the operation of automatic smoke vents can increase the number of sprinkler activations beyond the design limit, although the likelihood for such worst-case scenarios remains small.

Abstract

A study was performed using FireFOAM simulations and full-scale testing to investigate the behavior of gravity smoke and heat vents (smoke vents) in storage occupancies. The FireFOAM model was validated against experiments and used to extend the parameter space to different commodities, ceiling heights, clearance heights, ignition locations, and thermal element settings for the smoke vent and sprinkler. The study considered both sprinklered and unsprinklered occupancies with one or more 3 m^2 (32 ft^2) smoke vents. Simulations were used to quantify the probability of an automatic smoke vent opening before the sprinklers, potentially delaying the sprinkler activation time and increasing the peak fire size. The probability was found to be very low, unless ignition occurs directly underneath a smoke vent and as far as possible from the nearest sprinkler. This 'worst-case scenario' is unlikely, due to the much higher density of sprinkler thermal elements compared to smoke vent thermal elements at the ceiling. A combination of tests and simulations was used to observe the outcomes of the worst-case ignition scenario. The results showed that smoke vents provide no property loss prevention benefit to unsprinklered or sprinklered storage occupancies with an abundance of combustibles. For sprinklered occupancies, the smoke vents can delay the first sprinkler activation time, however the delay is within the normal variation of an accepted sprinkler design. All testing and modeling showed that there is no adverse impact for sprinkler protection that is otherwise adequately designed. Existing risk-improvement recommendations in FM Global DS 2-0 for installing sprinklers in occupancies with smoke vents were evaluated and it is recommended to relax these recommendations for smoke vents that are no larger than 3 m^2 (32 ft^2).

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1. **Introduction**

This report considers the use of gravity smoke and heat vents (smoke vents) in storage occupancies, with a focus on the interaction of smoke vents and sprinklers. Multiple studies have investigated this topic [1], [2], [3], [4], [5], [6], [7] yielding an incomplete picture and a lack of consensus in the academic literature [3], [8] and engineering codes and standards [9], [10], [11]. While some studies have identified a degree of adverse interaction [2], [4] no full-scale study has clearly demonstrated that smoke vents can lead to the failure of an otherwise adequate sprinkler design or that they can sustain tenable conditions for manual firefighting efforts in the absence of sprinklers, but this may be due to the limited test history.

Here, the interaction of smoke vents and sprinklers is revisited. Knowledge gaps from prior literature are identified and numerical simulations and full-scale tests are conducted to clarify the conflicting views that exist on this topic. The conclusions from this study are then used to make recommendations for updating FM Global Property Loss Prevention Data Sheets (*i.e.*, DS).

Firstly, background information on smoke vents and sprinklers is presented in Section 1.1. FM Global's test history is summarized in Section 1.2, a general literature review is presented in Section 1.3, and a summary of existing codes and standards is provided in Section 1.4. Finally, the scope and objective of this project are defined in Section 1.5.

1.1 Background

1.1.1 Smoke Vents

Smoke vents are designed to remove heat and smoke from buildings in the event of a fire. The removal of smoke and heat is intended to aid egress from the building and to assist firefighters in manually extinguishing the fire. In the US, Smoke vents are required to comply with approval standards such as UL 793 [12] and FM Approval Standard 4430 [13].

There are many different types of smoke vents, categorized by two main criteria:

- Automatic vs manual activation. Automatic smoke vents are activated by a thermal element, smoke detector, or any other method that does not require human intervention. Manual smoke vents require human intervention.
- Gravity vs mechanical operation. Gravity vents rely on natural convection driven by thermal stratification – hot products from the fire are less dense than the ambient air and rise through the vent. Mechanical vents use fans to draw gasses out from the building.

Smoke vents can be further distinguished by their size, construction, and actuation mechanism.

Figure 1-1 shows an example of a typical gravity smoke vent installation at the roof level of a building. In this example, each smoke vent has a two-door, spring-loaded, polymer construction that open in the event of a fire. Alternate designs exist that use fewer/more doors, metal construction, or polymer construction where the vent panel shrinks and are dislodged when heated by a fire (these are known as "shrink-out" vents).

Figure 1-1: Example of a typical gravity smoke vent installed in an array at the roof of a building.

A survey of commercially available smoke vents shows that they range from 0.2 m^2 (2.25 ft^2) to 9.3 m^2 (100 ft^2), with a typical size of 1.5-3.7 m^2 (16-40 ft^2) where the vent size is the area of the opening (the geometric free area). Smoke vents are installed at ceiling level in arrays, see Figure 1-1. The number of smoke vents is determined from the individual vent size and the ratio of vented area to floor area, r_V, which is a design parameter. r_V is determined from codes and standards, either as a fixed value or one derived from engineering calculations specific to the occupancy. An r_V value is selected with the intention to maintain tenability within the occupancy for a required duration. Typical values for r_V range from 1% to 3%.

For sufficiently large fire areas, draft curtains are required to partition the ceiling and accumulate a smoke layer, particularly for gravity vents which require thermal stratification. The sizing and placement of draft curtains is designed in accordance with building codes and fire protection standards, e.g., Refs. [14], [15]. Smoke vents may be activated individually or collectively, known as 'ganged' operation. For individual activation, each smoke vent is opened based on a local measurement, e.g., a thermal element. For ganged operation, all smoke vents in a fire area are simultaneously activated if any single vent is activated. The review study by Cooper and Beyler stated that ganged operation may be desired for sprinklered occupancies because cooling of the ceiling prevents the activation of smoke vents that are remote from the fire [3].

Unlike sprinklers, smoke vents have no direct effect on fire spread. A building with smoke vents and no sprinklers relies on manual firefighting alone to extinguish the fire. NFPA 1710 [16] sets a benchmark of 5 minutes, 20 seconds between the detection of smoke/flames and the arrival of firefighters at the building. In reality, response times can be significantly longer [17]. When the time taken to detect and report the fire, and the time taken to enter the building are added, the fire may be very large and prevent firefighters from entering the building. For this reason, smoke vents should not be considered a property protection measure.

1.1.2 Sprinklers

Sprinklers are designed to automatically activate when a fire is detected to prevent it from growing out of control. FM Global distinguishes between storage and non-storage sprinklers. The former are suitable for protecting storage occupancies. These are high hazard because they feature large amounts of combustible materials and continuity of fuel over a large area. FM Global DS 8-9 [18] lists specifications for storage sprinklers used for protecting FM Global standard commodities (defined in FM Global DS 8-1 [19]) and for a range of ceiling heights.

The 'storage' and 'non-storage' nomenclature replaced the older 'control mode' and 'suppression mode' nomenclature [9]. Control mode sprinklers work primarily by pre-wetting the commodity surrounding the seat of the fire, maintaining a sufficient flow of water over the unburnt fuel to prevent the fire from spreading. Suppression mode sprinklers primarily work by delivering water directly to the seat of the fire at its early stage and cooling the surface of the burning material, limiting the generation of flammable gasses and in doing so directly decreasing the size of the fire. The terms 'storage' and 'suppression' are not entirely interchangeable, but most storage sprinklers feature a strong central core of water discharge characteristic of suppression mode sprinklers. NFPA uses the definition early suppression fast response (ESFR) [10]. An ESFR sprinkler features a thermal element with a response time index (RTI) less than 50 $m^{0.5}s^{0.5}$ (90 $ft^{0.5}s^{0.5}$) and is listed for its capability to provide fire suppression for specific high-challenge fire hazards. The terms 'storage' and 'ESFR' are also not entirely interchangeable, but most storage sprinklers fitted with a quick response thermal element would also be considered ESFR sprinklers.

In this study, two types of storage sprinklers are used for two different storage scenarios:

- K240 (K16.8) quick response pendent sprinkler with an activation temperature of 347 K (165°F) with cartoned unexpanded plastic (CUP) [20] commodity under a 9.1 m (30 ft) ceiling.
- K160 (K11.2) quick response upright sprinkler with an activation temperature of 347 K (165°F) with Class 2 [20] commodity under a 9.1 m (30 ft) ceiling.

1.1.3 Interaction of Smoke Vents and Sprinklers

Smoke vents and sprinklers may interact in several ways, both directly and indirectly due to their impact on the fire. These interactions are illustrated in the conceptual model shown in Figure 1-2.

Both the sprinklers and (automatically operated) smoke vents have thermal elements that are heated by the fire. Depending on the relative location of the fire, sprinklers, and smoke vents, as well as the thermal element response time index (RTI) and activation temperature (T_{ACT}), either the smoke vents or the sprinklers may activate first.

If the sprinklers activate first, they will directly impact the smoke vents by cooling the near-ceiling region and potentially spraying water directly onto the smoke vent thermal element. The sprinklers will also indirectly impact the smoke vents by suppressing the fire and reducing the rate of heat transport to the ceiling. This makes it unlikely for smoke vent thermal elements to activate after sprinklers, assuming the sprinkler system is adequately designed and suppresses the fire.

If the smoke vents open first, they will directly impact the sprinklers by removing a portion of heat from the near-ceiling region, potentially resulting in delayed sprinkler interactions. In some cases, the smoke vents may be left open to provide natural ventilation, in which case they will always remove some heat from the near-ceiling region if ignition occurs in the vicinity of the smoke vent. The amount of heat removal and its impact will vary from case to case, depending on vent size, number of vents, proximity of ignition location to sprinklers and vents, if the vent is left open, and the vent and sprinklers thermal element settings.

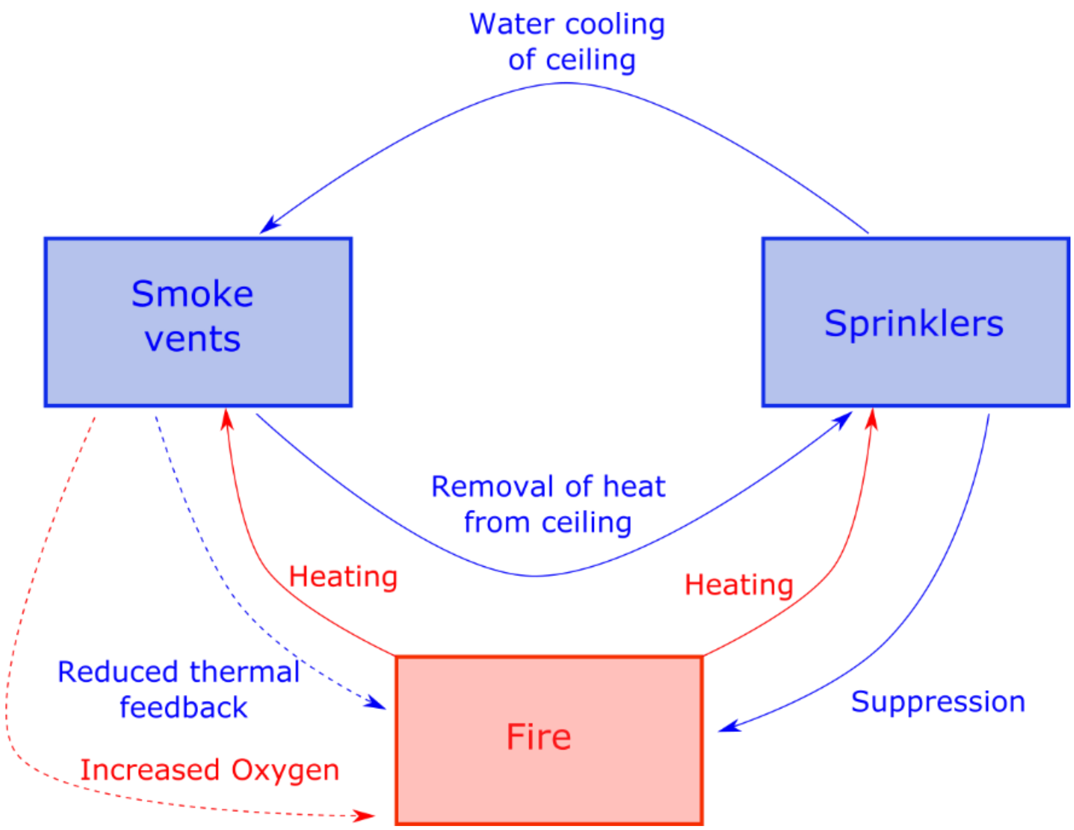


Figure 1-2: Conceptual model of sprinkler and smoke vent interactions. Primary interactions shown with solid arrows, secondary interactions shown with dashed arrows. Cooling/fire-suppressing interactions shown with blue, heating/fire-enhancing interactions shown with red.

Indirect effects of the smoke vents on the sprinklers are also possible, but these are of secondary importance. The smoke vents will increase the air-change-rate in the building, drawing in fresh oxygen and in principle enhancing the fire burning rate. However, storage occupancies are very large, and the oxygen concentration is unlikely to be significantly impacted by the presence/absence of smoke vents unless the fire has already grown out of control. Conversely, the smoke vents may decrease burning rates by cooling the ceiling and decreasing the thermal feedback to the unburnt commodity, although this effect is likely to be very small because most of the thermal feedback to the unburnt fuel occurs in the flames directly surrounding the commodity.

Based on these potential interactions where both sprinklers and smoke vents are installed, a range of outcomes are possible, but it is difficult to know how significant the adverse impacts can be *a priori*. In the next section, a literature review is presented with the main findings from previous investigations on this subject.

1.2 FM Global Test History

FM Global has conducted several studies that directly [1], [2]and indirectly [4], [6] assess the impact of smoke vents on sprinkler systems. This section summarizes this work, which forms the basis for FM Global's current position on smoke vents.

A 1956 study combined a smoke vent, draft curtains, non-storage sprinklers, and a 10 MW gasoline spray-burner fire source and has been summarized in [1] The vent ratio was 1.4% and the smoke vent size was 1.5 to 3 m^2 (16 to 32 ft^2). Six tests were performed varying the presence of draft curtains, presence of smoke vent, size of smoke vent, and sprinkler water density. The results showed that the maximum number of sprinkler activations (48) occurred without a smoke vent or draft curtains and with the lower water density. Any change to this baseline condition reduced the number of sprinkler activations, with the fewest sprinklers activated with the higher sprinkler water density and no smoke vent (15) or with the lower water density and a combination of draft curtains and a smoke vent (24). The lack of coupling between the sprinklers and the fire source implies a scenario in which the sprinkler protection is adequate to control the fire but not to reduce the burning intensity. Under these conditions, the study suggests that the cooling effect of the smoke vents may be expected to decrease the total number of sprinkler activations.

Full-scale tests performed between 1968 and 1975 by FM Global did not include ceiling-level smoke vents, but some tests used eaveline windows that functioned as ventilation in several tests [4]. One such test was performed with rubber tire commodity [4] that reached a controlled steady-state with the eaveline ventilation closed; when the ventilation was opened, the burning intensity increased and the sprinkler system failed to control the fire. In tests like this, the sprinklers were designed to operate in control mode, which partially relies on vitiation effects to reduce the fire intensity. This may explain the link between ventilation and the success/failure of the sprinkler protection. Because ceiling level smoke vents were not included in any tests, no conclusions can be drawn from these studies about the impact of smoke vents on first sprinkler activation time.

A 1974 report from Gunnar Heskestad studied the effect of smoke vents and draft curtains on sprinkler protection using a 1:12.5 scale model based on Froude number analysis [2]. The study considered both piled combustible material and a heptane pool as the fire source, with vented ratios ranging from 1 to

4%. The sprinkler protection was activated in zones, rather than per individual nozzle, and two water densities, 10 and 18 mm/min (0.25 and 0.45 gpm/ft^2), were used for the piled combustible material tests. For the heptane pool fire tests, the presence of smoke vents and draft curtains resulted in a 20% reduction in sprinkler activations. For the piled combustible material tests with 10 mm/min (0.25 gpm/ft^2), the presence of smoke vents and draft curtains increased the number of sprinkler activations where the smoke vents were far from the ignition location, but reduced the number of sprinkler activations where a smoke vent was positioned directly above the ignition location. For the piled combustible material tests with 18 mm/min (0.45 gpm/ft^2), the smoke vents did not operate, and the water demand was about half compared to the unvented case with 10 mm/min (0.25 gpm/ft^2). Several observations are made on these results:

- The heptane pool fire results seem to reproduce the finding from the 1956 full-scale, gasoline spray-fire tests [1] in which the presence of smoke vents and draft curtains was associated with fewer sprinkler activations.
- For the piled combustible material tests with 10 mm/min (0.25 gpm/ft^2), the smoke vents could result in either an increase or decrease in number of sprinkler activations, depending on the position of the smoke vents. Where the vent was positioned directly over the ignition location, the fire plume directly impinged on the vent area, promoting the removal of heat from the ceiling layer, potentially explaining the reduction in sprinkler activations. Where the vents were positioned far from the ignition location, they did not activate until after the sprinklers closer to the fire had activated.
- For the piled combustible material tests with 18 mm/min (0.45 gpm/ft^2), the increase in water density controlled the fire and cooled the ceiling, preventing the smoke vents from opening. No tests at this water density included a smoke vent directly over the ignition location and so it is unclear what effect this would have had on the results.
- The combustible material test results imply that the adequacy of the sprinkler system is more important than the presence/absence of smoke vents.
- The tests assume control mode sprinkler protection where vitiation is expected to reduce the burning intensity and the potential for ventilation to reduce the vitiation effect is of concern. This limits the applicability of these results to modern sprinkler protection designs that do not rely on vitiation.

Another internal FM Global research effort was carried out to investigate the interaction between ESFR sprinklers, smoke vents and draft curtains. The focus of this study was to identify the delay in the first sprinkler activation time caused by smoke vents. The smoke vents activated before the first sprinkler, only when the smoke vent was positioned directly above the ignition location. In this case, the first sprinkler activated at around 100 sec compared to 50 sec in the case with no smoke vent. Measurements of a simulated thermal element for an inactive smoke vent were obtained, and it was determined that a vent activation temperature of 455 K (182°C or 360°F) should prevent the smoke vent from activating in most cases. The total number of sprinkler activations and the outcome of fire tests was not reported, but it was reasoned that the delay in first sprinkler activation induced by the smoke vents would deteriorate the protection of the ESFR sprinkler system, which relies on early detection and suppression of the fire with a relatively small number of sprinkler activations. This concern is distinct from that explored in previous tests conducted with control mode sprinkler protection [1], [4], [6].

A follow-up, full-scale study explored the impact of the delay in first sprinkler activation time on the performance of ESFR sprinkler systems. The tests used K-200 (K-14) ESFR sprinklers at 3.4 bar (50 psi) and with a 347 K (74°C or 165°F) activation temperature. The commodity consisted of a 7 m (23 ft) tall array of cartoned unexpanded plastic in a rack-storage array under a 9.1 m (30 ft) ceiling, and a 1.4 m (4.5 ft) diameter powered (i.e., not gravity driven) vent directly above the ignition location. Ignition occurred in the central flue space, between two sprinklers. The tests included target arrays with a 1.2 m (4 ft) aisle space. The vent caused a 44 sec delay in first sprinkler activation time and a doubling of the convective HRR at the time of first sprinkler activation compared to the unvented case. All six sprinklers were activated, the fire was controlled, target ignition did not occur, and the fire did not spread far along the main array. Ceiling thermocouple data suggested that additional sprinkler activations would have been possible, but with a total number of activations well short of 12, the design limit for the tested scenario. The results were compared against two unvented tests. In the first, one of the between two sprinklers was plugged, simulating a skipped sprinkler. In this case, 11 sprinklers activated and the fire was controlled. In the second test, no sprinklers were plugged, and the fire was controlled with two sprinklers. Overall, the results suggest that the delay in first sprinkler activation caused by the smoke vent can increase the number of sprinkler activations but has less impact than a single skipped sprinkler near the ignition location.

FM Global's test history provides evidence for the following concerns regarding smoke vents:

- For control mode sprinklers operation with marginal water supply, where vitiation effects are important to control the fire, smoke vents can lead to additional sprinkler activations, increased burning intensity, and potentially the loss of control of the fire [1], [4].
- For suppression mode sprinkler operation with adequate water supply, a smoke vent located directly above the ignition location can delay the first sprinkler activation and increase the peak fire size. However, only one full-scale test was conducted at this condition, it was successfully controlled and was not close to meeting any failure criteria.

No tests have been performed combining gravity vents, modern 'storage' sprinklers, and with full-scale test arrays.

1.3 Literature Review

Beyler and Cooper [3] conducted a review of experimental studies relating to the interaction of sprinklers and smoke vents in terms of claims for/against the use of smoke vents in sprinklered occupancies (see Table 1-1). They concluded that venting had no adverse effect on sprinkler performance so long as draft curtains were placed in aisle spaces. They further concluded that automatic smoke vents are unlikely to open before sprinklers due to the sprinklers cooling the ceiling layer and suppressing the fire. Based on these conclusions, Beyler and Cooper recommended that smoke vents be ganged and activated prior to the sprinklers to obtain the benefit of both systems and that draft curtains be placed over aisle spaces.

Heskestad rebutted [8] several aspects of the review by Beyler and Cooper [3]. Table 1-1 summarizes the competing positions on a claim-by-claim basis and with respect to the primary literature.

Heskestad's [8] main criticisms were that:

- Vents do impact the burning rate by increasing the oxygen concentration and that this effect is significant in Refs. [2], [4].
- Ref. [21] does not show a clear benefit of venting.
- There is no cost benefit to installing smoke vents because if the sprinklers fail to operate the smoke vents will not protect the building and if the sprinklers work as designed no or few smoke vents will operate.

Following these claims, Heskestad states that Beyler and Cooper's recommendation for early ganged vent operation should be adjusted so that "…*all sprinklers capable of delivering water to the fire must have operated."* [8]. In other words, any potential benefit of venting must be deferred until after the sprinkler system has controlled the fire.

When considering the impact of smoke vents on burning rate, it is important to note that Heskestad's primary research [2] and his interpretations of Ref. [4] are informed by arguments based on "control mode" sprinklers. Control mode sprinklers are designed to pre-wet the unburnt commodity and to reduce the intensity of the fire through gas-phase cooling and vitiation effects [22]. This contrasts with "suppression mode" sprinklers that apply water directly to the pyrolyzing solid fuel to reduce the burning rate, and do not rely on vitiation [22]. This explains the emphasis Heskestad places on the impact of venting on oxygen concentration (vitiation).

Table 1-1: Summary of claims made for/against installing smoke vents in sprinklered occupancies, summary of conclusions from Beyler and Cooper [3] and rebuttal from Heskestad [8].

Claims Against	Beyler & Cooper Conclusion	Heskestad Rebuttal
Smoke vents enhance burning rates.	Not supported by available literature.	Oxygen concentration in Ref. [4] were increased with open vents. Ref. [21] study was well-ventilated for both vented/unvented cases so effect could not be observed.
Smoke vents delay sprinkler activation.	Only true if fire occurs beneath smoke vent [23].	Review of Ghent study [21] by Gustafsson [24] showed that in vented tests sprinklers near the fire source were delayed or skipped.
Smoke vents increase water demand.	Indeterminate due to conflicting results across studies and test limitations.	Spurious reason was given for discarding Ref. [2] results that show increased water demand.
Smoke vent flow rates are insufficient to realize any benefit.	May have some merit but not clearly supported by literature.	-
Smoke vents are not cost effective.	Indeterminate due to lack of study.	Only marginal improvements in tenability if sprinklers operate as designed.
Claims in Favor	**Beyler & Cooper Conclusion**	**Heskestad Rebuttal**
Smoke vents limit smoke damage.	Using curtains and smoke vents reduces smoke damage outside of curtained area [1], [2], [21].	-
Smoke vents reduce water demand.	Indeterminate due to conflicting results across studies and test limitations.	Reasons stated for discarding Ref. [2] results that show increased water demand are spurious.
Smoke vents aid manual firefighting.	Opened vents help to locate the fire and improve conditions for firefighters, but smoke vents may not open if sprinklers are adequate and vents are far from fire as observed in Ref. [2], [7], [23].	-
Smoke vents are a back-up property protection measure if sprinklers fail.	In the unlikely event of sprinkler failure, manual firefighting will benefit from smoke venting.	Smoke vents will not avert a large loss without sprinklers.

The terms “control mode” and “suppression mode” are no longer used within FM Global to describe sprinklers, they have been replaced with “storage” and “non storage” sprinkler terminology and these terms are not entirely interchangeable. Storage sprinklers are designed for storage and other high-hazard occupancies [10]. They feature moderate to large K-factors, are usually fitted with quick response thermal elements, and are usually designed to operate in the “suppression mode” with a lower number of higher flow-rate sprinklers. Note that this description of storage sprinklers is similar to, but distinct from ESFR sprinklers.

The use of storage sprinklers is deeply embedded in the current FM Global DS 8-9 *Storage of Class 1, 2, 3, 4 and Plastic Commodities* [18] and DS 2-0 *Installation Guidelines for Automatic Sprinklers* [9]. Full-scale rack-storage tests performed under the movable ceilings in the Large Burn Laboratory (LBL) form the basis for the recommendations in FM Global DS 8-9. These tests are conducted in a ventilated building with a large volume of air. The ventilation is located above the unvented movable ceiling. This prevents the ventilation from affecting the flow underneath the ceiling, while simulating a very large building area and minimizing vitiation behavior. For this reason, prior research considering the effects of venting on vitiation and the impact this has on sprinkler protection have limited applicability to modern storage sprinkler designs.

Modern quick response storage sprinklers are typically designed to activate early and deliver water directly to the seat of the fire before it becomes too large to suppress. It should be noted that for such sprinklers with large volume of water flow, exceeding designed number of operations can quickly overtax the water supply. For this reason, it is important to understand what impact smoke vents have on sprinkler activation times, number of sprinkler activations, and successful/failed fire suppression. Unfortunately, the literature available to directly address this subject is very limited. Of the primary studies reviewed by Beyler and Cooper [3], only four [2], [5], [7], [23] included all requisite elements: sprinklers, smoke vents, and fuels that can be extinguished by the sprinklers (non-static fire sources). While still valuable, studies based on fixed fire sources may yield misleading results because sprinkler and vent activations are inextricably linked to fire growth and suppression dynamics. For example, the delayed/skipped sprinklers reported in Gustafsson's analysis [24] of Ref. [21] may be contingent on the static fire source. If a realistic commodity had been used, the delayed/skipped sprinklers would have promoted fire growth and resulted in less sprinkler delay/skipping relative to the observations made using a static fire source. Without considering the dynamic coupling between the fire, sprinklers, and vents, it is not possible to draw robust conclusions on the overall impact of smoke vents on the sprinkler's protection.

The four studies that include smoke vents, sprinkler, and fuels that can be extinguished by the sprinklers are summarized here:

- (1964) Underwriters Laboratories [5] performed a test series with a wooden crib and a second one with piled, palletized storage of cardboard and expanded plastics. The results suggested that open vents (not near the ignition location) can result in fewer sprinkler activations and decreased water demand for a control-mode sprinkler design. It is difficult to draw further conclusions because: 1) the study used non-storage sprinklers with a water supply that is inadequate by modern standards, and 2) no tests were performed with the smoke vent closer to the ignition location than the nearest sprinklers.
- (1974) Factory Mutual Research Corporation (FMRC – the Research arm of FM Global until 2001) performed physical modeling based on Froude number analysis and a 1:12.5 length scale reduction [2]. A test series was performed with cardboard material representing rack-storage commodity. The smoke vents were located far from the ignition source and the sprinklers were activated in zones using simulated links, rather than individual activation mechanisms. Two

water densities were supplied: 11 and 18 mm/min (0.27 and 0.45 gpm/ft^2). They were tested with/without smoke vent and repeat tests were performed for each condition. With 11 mm/min (0.27 gpm/ft^2) sprinkler density, the cases with smoke where 3 or 4 smoke vents opened in each test opened more sprinklers than the case without smoke vents. With 18 mm/min (0.45 gpm/ft^2) sprinkler density, the number of sprinkler activations was significantly reduced both with/without smoke vents and none of the smoke vents opened.

- (1980) The Intra-industry Fire Venting Research Committee conducted repeated sprinklered tests with/without smoke vents and with 4 stacks of 5 wooden pallet (0.6 m (2 ft) high storage) under a 5.2 m (17 ft) ceiling [7]. The relatively small, isolated fuel load limits the applicability of these tests to storage occupancies. The tests had poor reproducibility and no clear impact of the smoke vents was observed.
- (1998) The National Institute of Standards and Technology (NIST) published a study that included a series of full-scale tests with 6.1 m (20 ft) high, cartoned unexpanded plastic commodity under a 7.6-8.2 m (25-27 ft) ceiling with upright, K160 (K11.2) standard response sprinklers with an activation temperature of 347 K (74°C or 165°F) delivering 20 mm/minute (0.5gpm/ft^2) [23]. Tests were performed with/without vents and for a variety of ignition scenarios varying the vent offset from the ignition location and the positioning of the draft curtains. Only one test (P-3) showed an adverse impact, due to the draft curtain placement over the commodity, which resulted in delayed sprinkler activations beyond the draft curtain. In that test, one smoke vent opened (after nearby surrounding sprinklers) and did not adversely impact the sprinkler system. In another test (P-2), where the ignition was located directly underneath a vent and was far from the draft curtains, there was a larger number of sprinklers activated compared to the unvented baseline case. However, this difference cannot be attributed to the smoke vents as the one above the ignition location did not activate – it was 'skipped' due to spray impingement on the thermal element. Another smoke vent beyond the second ring of sprinklers did open, but only after 23 sprinklers had already activated.

Only the NIST study [23] used a realistic representation of a warehouse occupancy with multi-tiered rack storage, continuity of combustibles, and a relatively modern sprinkler design. Yet, even this study did not use adequate sprinkler protection as judged by FM Global DS 8-9. It is therefore notable that even with marginal protection that no significant impact of the smoke vent was observed – the impact due to the draft curtain in case P-3 already being addressed by recommendations found in FM Global DS 1-10 [14] and NFPA 204 [15].

The results in the NIST study [23] may have been sensitive to: 1) the choice of the ignition location, "between 2" instead of "among 4" used in all cases, and 2) the 'skipping' of the vent over the ignition location in case P-2, which could be stochastic and contingent on the selected thermal element used to activate the smoke vents. That is, the worst-case scenario may not have been considered.

The FMRC scale-model study [2] showed increased sprinkler activations with smoke vents only for the cases with the lower water density. For the cases with the higher water density a smaller number of sprinklers were activated and controlled the fire and no vents were opened. Hence, the effect of the smoke vent may be contingent on the inadequate sprinkler protection and not generalizable to occupancies with adequate sprinkler protection. This interpretation of the results is consistent with that of test P-2 from Ref. [23].

The tests analyzed in Ref. [7] showed no clear adverse impacts of the smoke vents on sprinkler activation times or fire outcomes, but are generally regarded as lower-quality due to lack of repeatability and significant deviations in the experimental design compared to modern storage occupancies and modern sprinkler designs.

Additional internal studies by FM Global on the interaction between ESFR sprinklers and smoke vents(discussed in Section 1.2) were not included in the review by Beyler and Cooper [3]. As stated in Section 1.2, these studies showed that smoke vents placed directly above the ignition location could delay the first sprinkler activation but a full-scale test showed that this did not result in the failure of the sprinkler protection.

Overall, it is found that no adequately designed study has observed a clear adverse impact of smoke vents on sprinklers relevant to modern storage occupancies. The strongest arguments made by Heskestad in the rebuttal [8] to Beyler and Cooper [3] are limited to the subjects of: 1) vitiation, which is not very relevant to modern sprinkler designs for storage occupancies, and 2) delayed/skipped sprinklers in a study that lacked coupling between the fire growth and sprinkler protection [24]. Further, in cases where venting was associated with excessive sprinkler activations (e.g., lower water density tests in Ref. [2]), the sprinkler protection was inadequate and the smoke vents only opened after the sprinklers close to the ignition location failed to control the fire. In regards to the benefits of smoke vents aiding manual firefighting, there is indirect evidence in terms of improved tenability in some cases (summarized in Ref. [3]) but these benefits are unlikely to be significant for storage fires which feature abundant and continuous fuel loads: unsprinklered storage occupancies will lead to extremely large fires that could begin damaging the building envelope before manual firefighting intervention can take place, and sprinklered storage occupancies will prevent or impede the automatic operation of gravity vents due to cooling at the ceiling and the suppression of the fire.

Storage occupancies are difficult to generalize given the wide variation in numerous parameters, including but not limited to, commodity type, storage height, storage configuration, aisle spacing, ceiling height, clearance height, ceiling obstructions, and ceiling slope. An exhaustive study demonstrating that smoke vents do not adversely impact sprinklered storage occupancies is not feasible. Worse yet, the prior literature contains few, if any, tests that can be applied to modern storage occupancies and so it is difficult to draw conclusions that are not based on speculation.

The present study attempts to address this knowledge gap. Although an exhaustive study of all possible parameters is not possible, this work covers a wide range of conditions and combines a “worst-case scenario” analysis with a probabilistic analysis that quantifies the likelihood of the worst-case scenario. Numerical modeling and full-scale tests are conducted, including coupled fire growth and suppression dynamics that are necessary for drawing conclusions on this subject.

1.4 Standards

FM Global DS provide engineering guidelines that co-exist with local building and fire safety codes that have additional legal/regulatory requirements focused on life safety. Some jurisdictions require that smoke vents be installed in addition to sprinklers, or occasionally be provided as an alternative to sprinklers. The lack of scientific consensus on the interaction of smoke vents and sprinklers leads to inconsistent recommendations between code and standards bodies. In this section, the current FM Global recommendations on smoke vents are summarized and contrasted against NFPA consensus standards.

Smoke and heat vents are discussed in FM Global DS 2-0 *Installation Guidelines for Automatic Sprinklers* [9] and FM Global DS 1-10 *Interaction of Sprinklers, Smoke and Heat Vents, and Draft Curtains* [14]. DS 2-0 states FM Global's current position on the use of smoke vents in Section 2.5.1.3.1 "*Do not install heat vents or smoke vents in buildings protected by ceiling-level sprinklers. If the installation of heat vents or smoke vents is unavoidable, use the flowchart in Figure 2.5.1.3.1 to determine potential corrective options due to their presence.*", where the flow chart is reproduced in Fig. 1-3.

Figure 1-3 shows that manually operated smoke vents that are not left open (e.g., for the purpose of ventilation) require no action. Both manual and automatic smoke vents that are left open are treated as a "vent opening" and corrective measures are detailed in in Figs. 2.5.1.3.2(a), 2.5.1.3.2(b), and 2.5.1.3.2(c) of DS 2-0. Vent openings smaller than 0.4 m^2 (4 ft^2) require no corrective action. Vent openings larger than 0.4 m^2 (4 ft^2) can be addressed by installing a false ceiling equipped with sprinklers underneath the smoke vent (Fig. 2.5.1.3.2(b)) or by installing sprinklers directly underneath the smoke vents without a false ceiling but with a maximum 1.2 m (4 ft) spacing (Fig. 2.5.1.3.2(c)). Smoke vents in storage occupancies that are automatically operated and are not left open can be treated in three ways:

- Install FM Approved smoke vents with standard response 455 K (182°C or 360°F) thermal links.
- Install FM Approved smoke vents arranged to open 20 minutes after the sprinkler activation. This requires a special control system capable of detecting sprinkler activation and responding by triggering the opening of the vent.
- Install sprinklers underneath the smoke vent in that same manner as recommended for a "vent opening" shown in Figs. 2.5.1.3.2(b) and 2.5.1.3.2(b).

The intent of these recommendations is to guarantee that smoke vents do not open until after the sprinkler system has suppressed the fire. The opening of smoke vents after the suppression of the fire, either manually or automatically, is not intended to be prevented. FM Global DS 1-10 *Interaction of Sprinklers, Smoke and Heat Vents, and Draft Curtains* [14] discusses in greater detail the reasoning for FM Global's position on the use of smoke vents in sprinklered buildings. References are made to the literature presented in Sections 1.2 and 1.3, and the justifications presented for delaying smoke vents until after the sprinklers have suppressed the fire follow the arguments presented by Heskestad [8]. DS 1-10 details the design requirements of draft curtains, most notably that draft curtains be placed over aisle spaces, and that the aisle spaces be sufficiently wide to prevent the draft curtains from obstructing the ceiling jet from activating sprinklers capable of suppressing the fire, which addresses the specific hazard identified in the NIST tests [23].

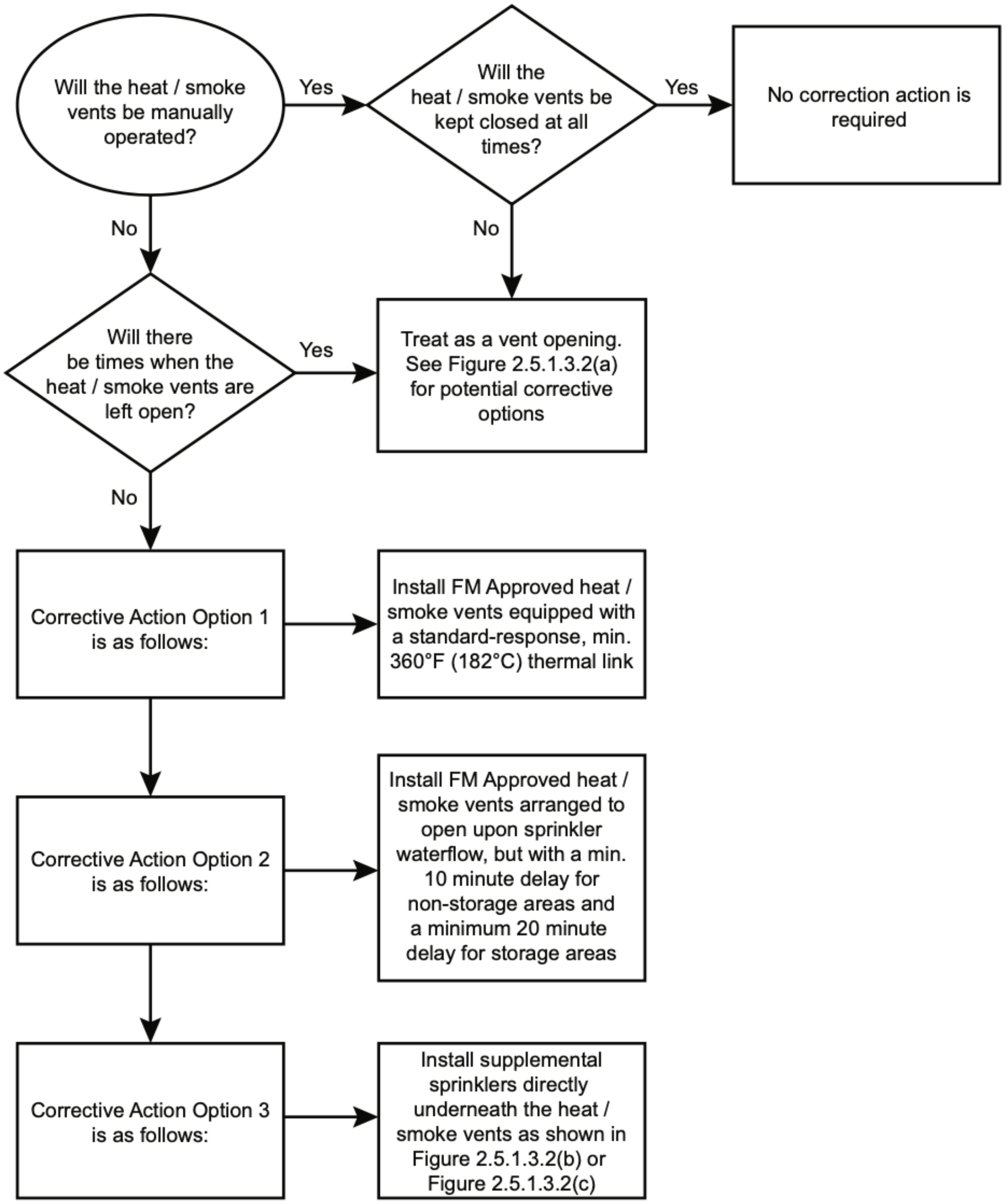


Figure 1-3: Flowchart of corrective options where the installation of smoke vents cannot be avoided. Reproduced from Figure 2.5.1.3.1 in FM DS 2-0 [11].

NFPA 13 *Standard for the Installation of Sprinkler Systems* [10] and NFPA 204 *Standard for Smoke and Heat Venting* [15] are the US consensus standards relevant to the interaction of smoke vents and sprinklers. NFPA 13 is less restrictive compared to FM DS 2-0 on the use of smoke vents in sprinklered occupancies. Section 20.9.5.1 of NFPA 13 states:

> *"Manually operated roof vent or automatic roof vent with operating elements that have a higher temperature classification than the automatic sprinklers shall be permitted."*

Section 20.9.5.2 states:

> *"ESFR sprinklers shall not be used in building with automatic heat or smoke vents unless the vents use a high-temperature rated, standard response operating mechanism."*

This approach, using the vent thermal element to control the order of sprinkler and vent activation, is similar to that in "Corrective Action Option 1" from FM DS 2-0 Fig. 2.5.1.3.1 (see Fig. 1-3 in this report). The main difference is that DS 2-0 requires a standard-response 455 K (182°C or 360°F) vent activation temperature for all sprinkler designs, while NFPA 13 distinguishes between sprinkler type and, in most cases, sets lower activation temperature thresholds for smoke vents. For example, an occupancy with 347 K (74°C or 165°F) sprinkler thermal elements and storage sprinklers would require a 394-422 K [121-149°C (250-300°F)] vent activation temperature according to NFPA 13 compared to the value of 455 K (182°C or 360°F) in DS 2-0. Overall, the recommendations in NFPA 13 and FM DS 2-0 are well aligned.

Chapter 11 in NFPA 204 *Standard for Smoke and Heat Venting* concerns the use of smoke vents in sprinklered occupancies. NFPA 204 Section 11.1 states:

> *"Where provided, the design of venting for sprinklered buildings shall be based on an engineering analysis acceptable to the AHJ, demonstrating that the established objectives are met. (*See Section F.3.*)"*

Section F.3 contains a literature review referencing the same studies discussed in Section 1.3 of this report. As noted in Section 1.3, the literature considered test conditions that were not representative of modern sprinkler design principles for storage occupancies.

NFPA 204 also provides detailed guidance on the design of smoke vent systems, including the sizing and location of draft curtains. The guidance for draft curtains is closely aligned with that presented in FM DS 1-10.

1.5 Scope and Objective

This study is limited to investigating gravity smoke vents in storage occupancies, including in-process storage. The investigation uses a combination of physics-based modeling and full-scale testing. The model is used to explore the parameter space and to identify suitable cases for full-scale testing. The test results are then used to evaluate the model, enabling its application over a larger parameter space than would be feasible with testing alone. This complementary approach of modeling and testing addresses many of the limitations found in past works.

The combination of modeling and testing used in this report is aimed at quantifying the benefits, if any, of smoke vents from a property loss prevention standpoint, and the potential of smoke vents to adversely impact sprinklers. Both unsprinklered and sprinklered occupancies, and both adequate and marginal sprinkler protection are to be considered. The risk improvement recommendations from FM DS 2-0 are to be evaluated. Questions of tenability and life safety are not directly addressed.

2. Test Methodology

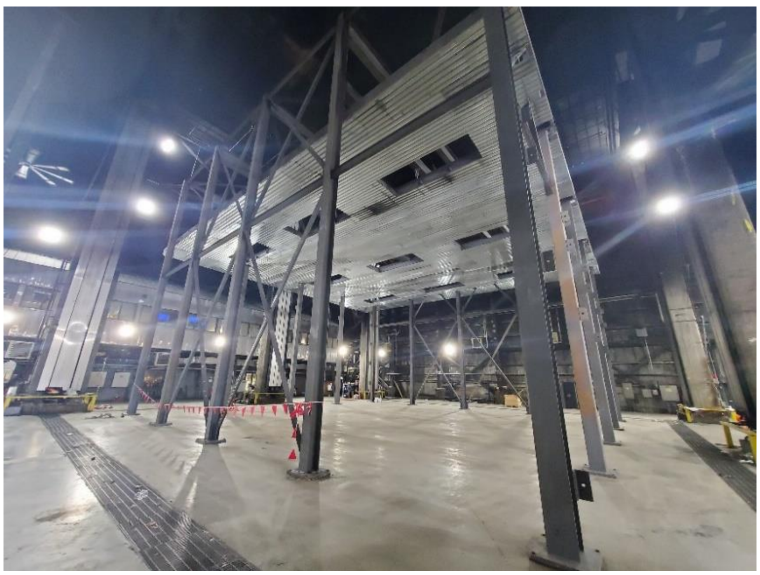
Exploratory FireFOAM rack-storage simulations identified where automatic smoke vents have the greatest potential to impact sprinkler protection, as judged by the delay in first sprinkler activation time. This occurs where: ignition is located on the floor in the longitudinal flue space with cartoned commodity, ignition is directly underneath the smoke vent thermal element and centered among four sprinklers, and for storage configurations with the minimum 1.5 m (5 ft) clearance between the top of the commodity and the ceiling. This leads to a narrower fire plume with a higher peak temperature that impinges on the center of the vent and is as far as possible from the nearest sprinklers. This promotes the activation of the smoke vent before the first sprinkler, even where the smoke vent's thermal element has a slower thermal response and a higher activation temperature. Two commodities were selected at this condition: 1) cartoned unexpanded plastic (CUP) [20] which is a higher-hazard commodity that produces a faster growing fire, and 2) Class 2 [20], which is a lower-hazard commodity which produces a slower growing fire. Seven full-scale fire tests were conducted to evaluate the FireFOAM model, see Table 2-1 for summary of test parameters. Three baseline tests were conducted without the smoke vents, while three additional tests were conducted using the same test configurations but with the smoke vents open. This methodology was selected in order to assess the effect of smoke vents on sprinkler performance protection. One test was also conducted using a different ignition location. The following sections describe the details of these tests, including the ceiling structure, instrumentation, commodity, and its configuration as well as the vent activation mechanisms.

Table 2-1: Summary of test parameters for the seven large scale tests.

Test #	1	2	3	4	5	6	7
Vent active	No	Yes	No		Yes	No	Yes
Test site	South movable ceiling of LBL						
Test commodity	CUP					Class 2	
Array size (main)	2 x 8 x 5						
Array size (targets)	1 x 4 x 5						
Storage height m (ft)	7.6 m (25 ft)						
Ceiling height m (ft)	9.1 m (30 ft)						
Aisle width m (ft)	1.2 m (4 ft)						
Ignition location (WRT sprinklers)	B2	A4					
Ignition location (WRT vent)	Offset 1.5 m (5 ft)	U1					
Ignition location (WRT commodity)	Central flue-space						
Sprinkler orientation	Pendent					Upright	
Sprinkler K-factor lpm/bar$^{0.5}$ (gpm/psi$^{0.5}$)	240 (16.8)					160 (11.2)	
Sprinkler temperature rating K (°F)	347 (165)						
Discharge pressure barg (psig)	2.4 (35)					1.7 (25)	
Discharge density mm/min (gpm/ft^2)	41 (1.0)					23 (0.56)	
Vent temperature rating K (°F)	414 (285)						
Vent RTI m$^{0.5}$s$^{0.5}$ (ft$^{0.5}$s$^{0.5}$)	80 (145)						

2.1 Ceiling Structure

A ceiling structure was constructed for the purpose of carrying out full-scale fire tests to investigate the interaction between smoke vents and sprinklers. Figure 2-1 (a) shows the skeleton of the ceiling structure and 2-1(b) shows the test setup under the ceiling structure. The ceiling had an overall dimension of 18.3 m × 18.3 m (60 ft × 60 ft), and had sixteen columns and five purlins along with numerous beams, trusses, brackets, and braces as part of the support structure. The ceiling was made of corrugated steel with a layer of gypsum board at the bottom. The ceiling structure had provision for nine smoke vents, but only one in the center was used in this study. Figure 2-2 shows the layout of the ceiling structure. The smoke vent used in this test series measured 2.4 m × 1.2 m (8 ft × 4 ft) and was located at the center of the ceiling. The wider edge of the smoke vent was aligned in the East-West direction.



(a)

(b)

Figure 2-1: Pictures of the ceiling structure: (a) skeleton of the steel structure and (b) Test setup under the ceiling structure.

Six sprinkler pipes were installed on the ceiling in the North-South direction as shown in Figure 2-3. The spacing between the pipes was 3 m (10 ft). A total of 36 sprinklers were installed on the ceiling for each test. For Tests 1-5, the sprinkler protection consisted of FM Approved K240 (K16.8) pendent quick response sprinklers with a 74°C (165°F) thermal element. The distance between the ceiling and the thermal element of the sprinkler was maintained at 33 cm (13 in.). For Tests 6 and 7, the sprinkler protection was provided by FM Approved K11.2 upright quick response sprinklers with a 74°C (165°F) thermal element. The pressure was maintained at 2.4 bar (35 psi) that provided a design density of 41 mm/min (1.0 gpm/ft^2) for Tests 1-5 and at 1.7 bar (25 psi) that provided a design density of 23 mm/min (0.56 gpm/ft^2) for Test 6-7. The distance between the ceiling and the thermal element of the sprinkler was maintained at 30 cm (12 in.).

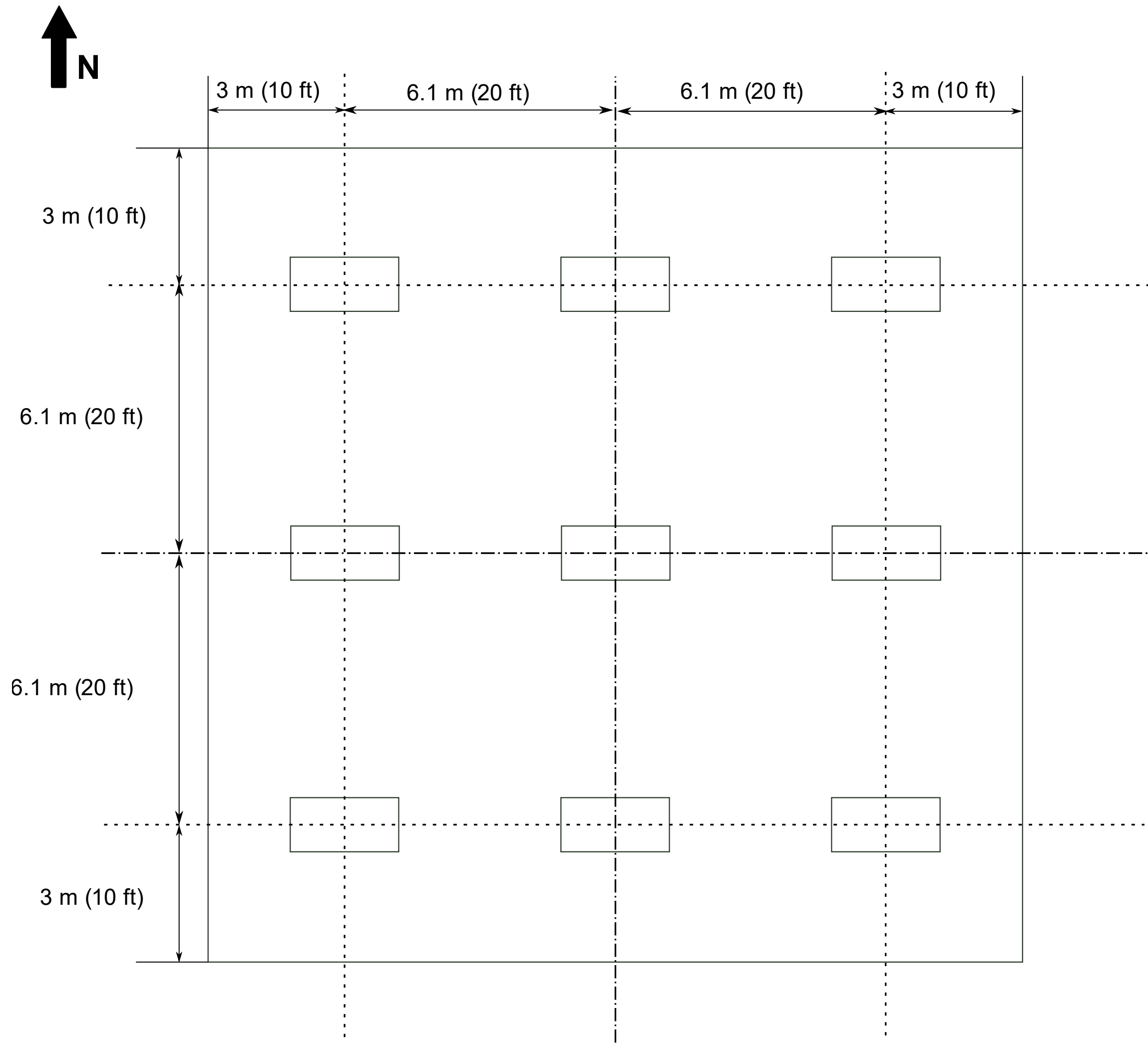


Figure 2-2: Plan view of the ceiling structure.

2.2 Instrumentation

The following instrumentation was included for the present work:

- Bare-bead, 0.8-mm (20-gauge), thermocouples installed 15 cm (6 in.) below the ceiling at numerous locations as shown in Figure 2-4. The thermocouples had a Response Time Index (RTI) of 8 $(m\text{-}s)^{1/2}$ [14.5 $(ft\text{-}s)^{1/2}$].
- Thermocouples embedded in two 6.35-mm (0.25-in.) thick steel angles, made from two 1.2-m (4-ft) long pieces, North and South of the smoke vent. The thermocouples were embedded at the center of the steel angles.

- A simulated thermal element (STE) with an RTI value of 80 $(m\text{-}s)^{1/2}$ [145 $(ft\text{-}s)^{1/2}$] installed at the center of the ceiling. It was placed 15 cm (6 in.) below the ceiling and was used to determine the time for opening the smoke vent.
- Electrical circuits on each sprinkler to determine individual sprinkler activation times.
- Flow meters and pressure controllers to monitor and control the sprinkler system.

Gas analyzers for O_2, CO, CO_2 and total hydrocarbons (THC) concentrations in the exhaust duct to obtain the chemical energy release.

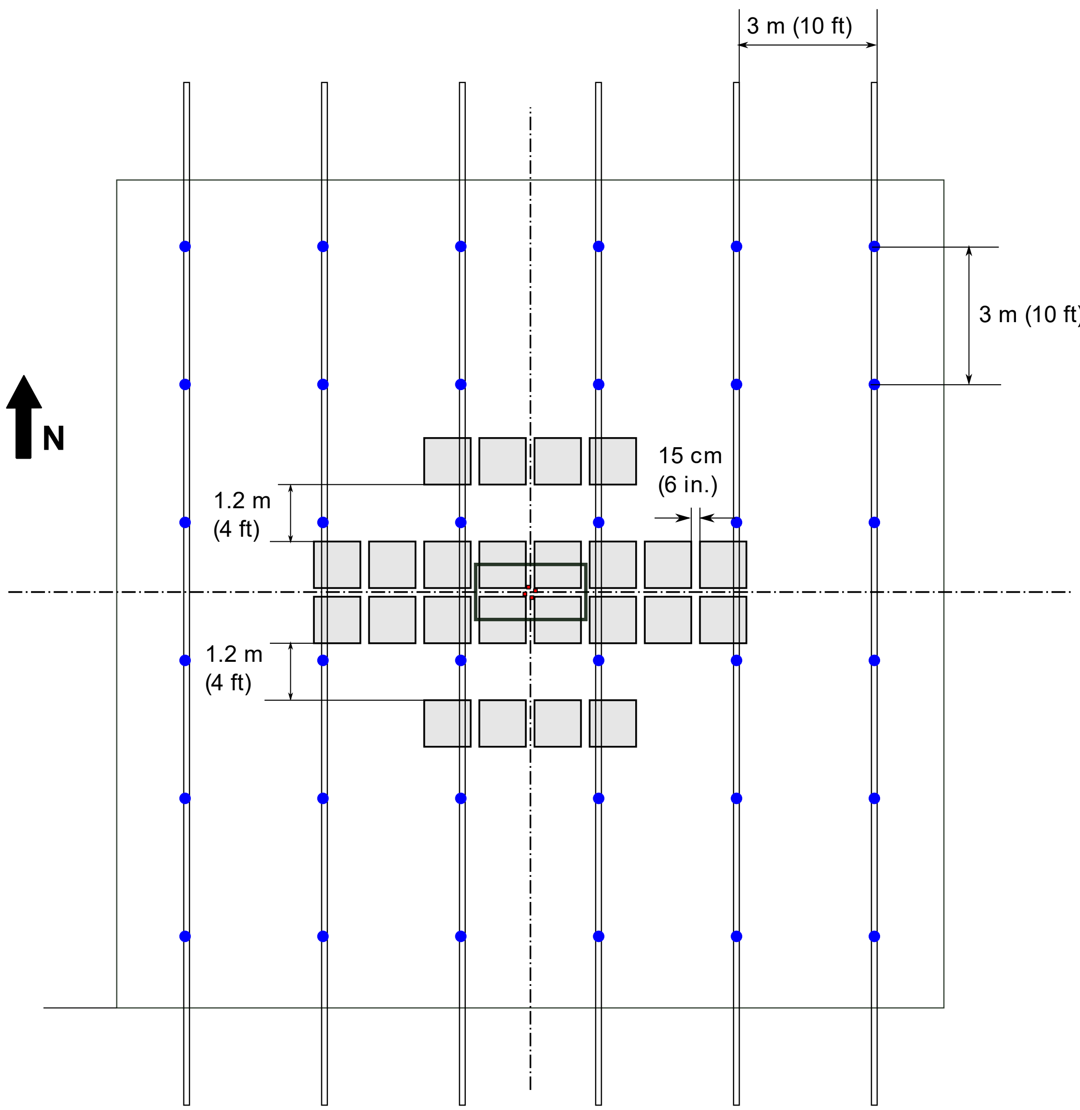


Figure 2-3: Pipes and sprinkler layout.

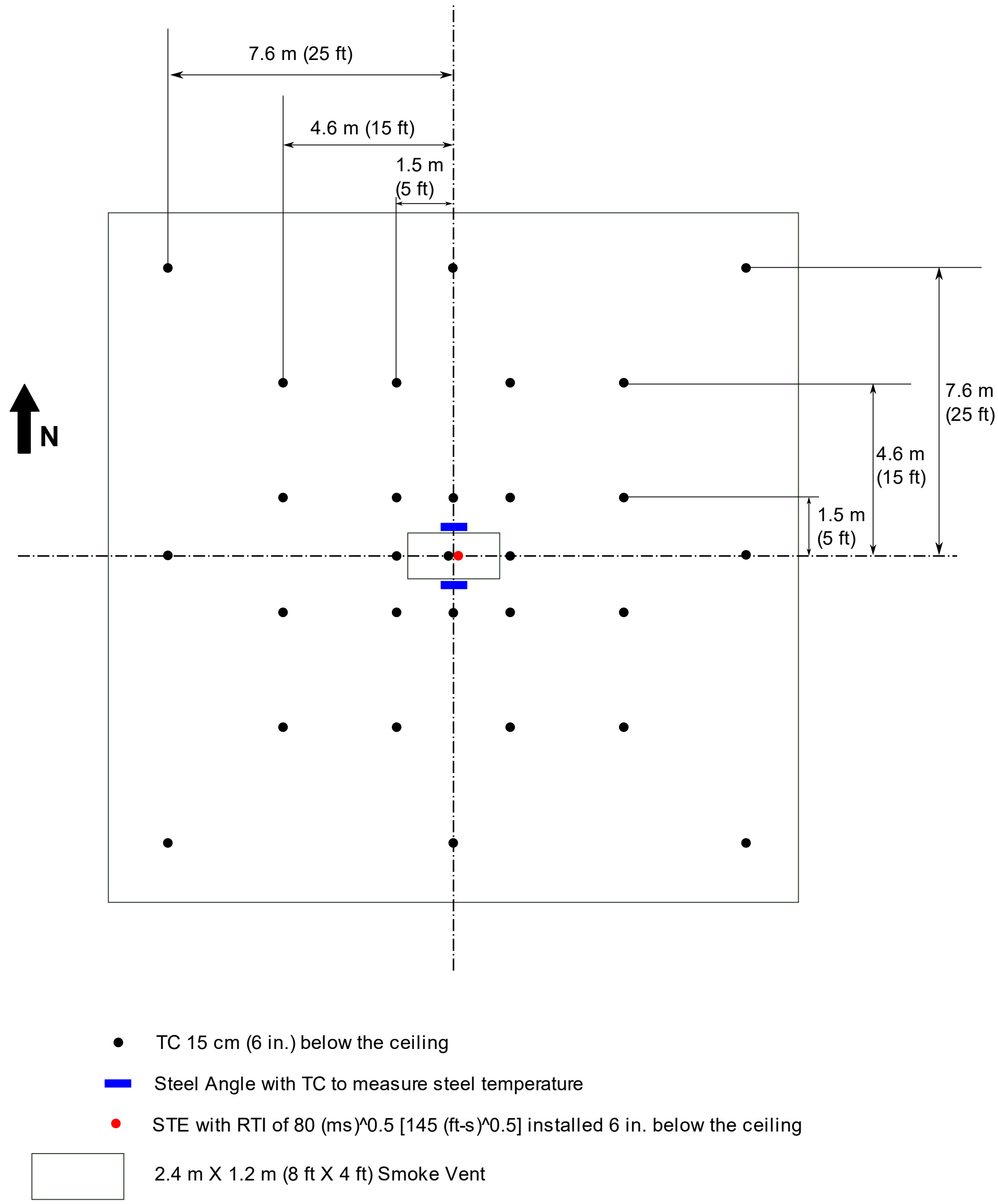


Figure 2-4: Figure showing instrumentation on the ceiling.

2.3 Commodity Configuration

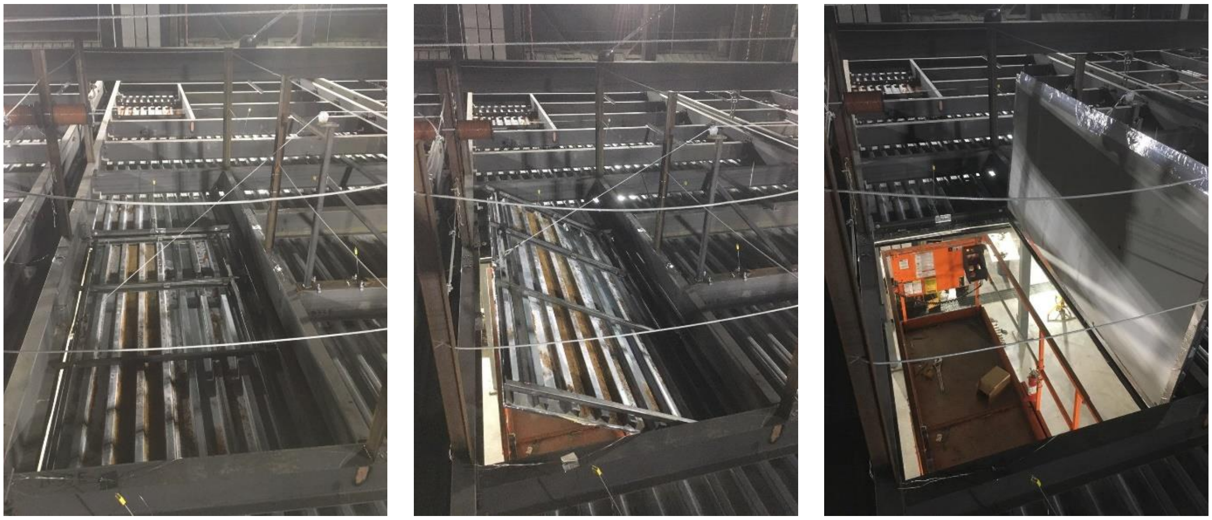
CUP and Class 2 standard commodities were used for Tests 1-5 and Tests 6-7, respectively [20]. The storage arrangement for each full-scale fire test consisted of a main array using double-row open-frame racks and two target arrays using single-row open-frame racks. The main array ran East-West and was two-pallet-load wide and eight-pallet-load long. The target arrays were one-pallet-load wide, and four-pallet-loads long. They were placed to the North and South of the main array with an aisle width of 1.2 m (4 ft). All the longitudinal and transverse flues were nominally 15 cm (6 in.). The storage height for all seven tests was nominally 7.6 m (25 ft), *i.e.*, 5 tiers. Figure 2-1 (b) shows a photograph of the test array in Test 2 and Figure 2-3 show the plan view of the test setup with respect to the smoke vents and sprinklers.

For Tests 2-7, ignition was achieved using four standard FM Global half igniters, which are cylinders of rolled cellucotton, each soaked with 113 ml (4 oz) of gasoline. The igniters were positioned at the base of the bottom tier, in the center of the main array. This conforms to an 'among-four' centered ignition scenario, which was found to produce the greatest impact of smoke vents on sprinkler operations in modeling studies. In Test 1, the igniters were shifted one pallet load to the West of the center of the main array and, therefore, resulted in a scenario like 'between-two' centered ignition. Therefore, results from Test 1 should be interpreted in a different manner from those results for the 'among-four' ignition scenario.

2.4 Smoke Vent Activation Mechanism

The smoke vent was simulated in this test series through mechanical activation. The activation mechanism consisted of a crankshaft, cable, and pulley assembly to open the ceiling vents (see Figures 2-4 and 2-5). The crankshaft was located on one of the columns near the lab floor and was operated manually when the threshold temperature was reached. A Simulated Thermal Element (STE) with an RTI of 80 $(m\text{-}s)^{1/2}$ [145 $(ft\text{-}s)^{1/2}$] was installed at the center of the ceiling. It was placed 15 cm (6 in.) below the ceiling and was used to determine the activation time for the smoke vent. To simulate a smoke vent equipped with a thermal element, ideally, it would have to be opened very rapidly when the thermal element reached the activation temperature. Since the activation mechanism used in this work could not provide fast opening of the smoke vent, the goal in current testing work was to have the vent half-way open (45°) upon the trigger of the temperature threshold. Several trials were performed to determine the time to open the vent fully using the crankshaft, which showed that an average of 9 sec was needed to fully open the smoke vent and about 4 sec to open it by half. Therefore, in subsequent tests where the smoke vent had to be opened, the manual activation would start 4 sec prior to the time when the STE was expected to reach the activation temperature of 141°C (286°F). This timing shift was determined using the STE data from the tests in which the smoke vents had not been opened. For example, in Test 6, without smoke vent open, the STE reached a temperature of 141°C (286°F) at 66 sec. Four seconds prior to this event, the STE temperature was 77°C (170°F). Therefore, in Test 7, which was the same test configuration but with smoke vent open, the manual activation began when the STE reached a temperature of 77°C (170°F), resulting in half opening by the time the STE would reach the activation temperature.

Figure 2-5: Crankshaft for smoke vent activation.



(a) Fully closed (b) Partially open (c) Fully open

Figure 2-6: Smoke vent activation mechanism.

3. **Model Methodology**

3.1 FireFOAM

The simulations are performed using FireFOAM [25], a solver developed within OpenFOAM [26] for simulating fire dynamics, including fire growth and suppression. FireFOAM has been validated for rack storage fire growth and suppression of cartoned commodities, including cartoned unexpanded plastic (CUP) [27] and Class 2 [28].

FireFOAM uses a multi-region approach where separate computational domains are solved for gas-phase physics, liquid surface films, and solid pyrolysis. In the gas-phase domain, governing equations are solved for mass, momentum, energy, and species mass fraction conservation using the large eddy simulation (LES) method. In the liquid surface-film domain, two-dimensional governing equations are solved for mass, momentum, energy, and film surface height. In the solid pyrolysis domain, one-dimensional governing equations are solved for species mass fraction and energy conservation. The regions are coupled via boundary conditions for temperature, species mass fractions, velocity, and, via source terms for mass and energy transfer due to pyrolysis, spray impingement, evaporation, etc. A complete description of this approach can be found in Refs. [28], [29]. The present study uses version fireFoam-v1912, compiled against the OpenFOAM-v1912 release from ESI-OpenCFD [30].

The new model feature necessary for this study is the dynamic boundary condition used to represent the opening of a smoke vent. The smoke vent is represented by a surface that behaves as a wall when the smoke vent is closed and as a cyclic boundary (i.e., no obstruction) when the smoke vent is open. A probe location, representing the smoke vent thermal element, solves a response time index (RTI) equation identical to that used for the sprinkler elements, see Equation 3-1 where T_L is the thermal element temperature, T_G is the gas temperature surrounding the thermal element, T_∞ is the solid far field temperature in thermal contact with the link, U_G is the gas velocity, S_{RAD} is the radiation source term, and S_{H_2O} is a water cooling term. From left to right, the terms on the right-hand side of Equation 3-1 represent convection, conduction, radiation, water cooling. A full description of these terms is available in Ref. [28]. When the probe temperature exceeds the activation temperature T_{ACT} the boundary condition is switched from wall-type to cyclic-type. The cyclic boundary condition allows for seamless mass/heat transfer across the open vent boundary, see Figure 3-1.

$$\frac{dT_L}{dt} = \frac{\left(\sqrt{U_G} \cdot (T_G - T_L)\right)}{RTI} - C \cdot (T_L - T_\infty) + S_{RAD} - S_{H_2O} \qquad \text{3-1}$$

All other model boundary conditions, governing equation, and sub-model closures are identical to those documented in Refs. [28], [29].

3.2 Computational Mesh

The computational domain is represented with multiple levels of mesh refinement zones, each of which is discretized with hexahedral orthogonal cells. Figure 3-2 shows an example cross section of the mesh where the coarsest level is 0.4 m (16 in.) and the finest level is 0.025 m (1 in.), which is concentrated around the rack-storage array and plume region centered above the ignition location. The mesh resolution in the ceiling layer (including the sprinkler locations) is 0.05 m (2 in.). The commodity (boxes and pallets) has a 0.025 m (1 in.) surface mesh coupling the gas, surface film, and pyrolysis regions. The surface film is represented by a 2-D surface mesh covering the commodity and ground which exchanges water droplets with the gas-phase mesh through spray impingement, splashing, and dripping processes. The pyrolysis mesh consists of a 1-D extruded mesh for each face on the surface mesh. The mesh generation process is consistent with prior validation studies [27], [28].

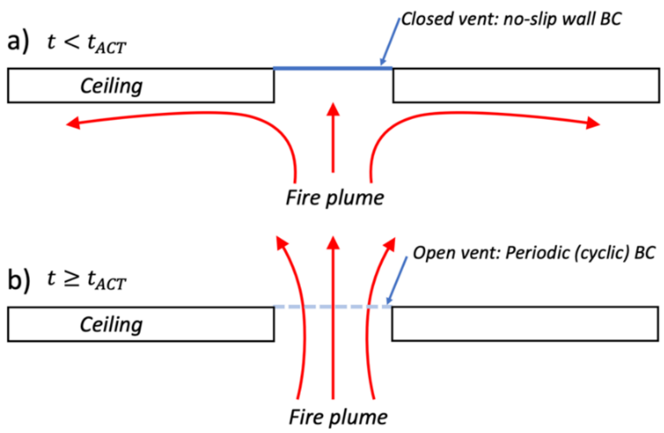


Figure 3-1: Illustration of vent boundary condition a) before, and b) after vent activation.

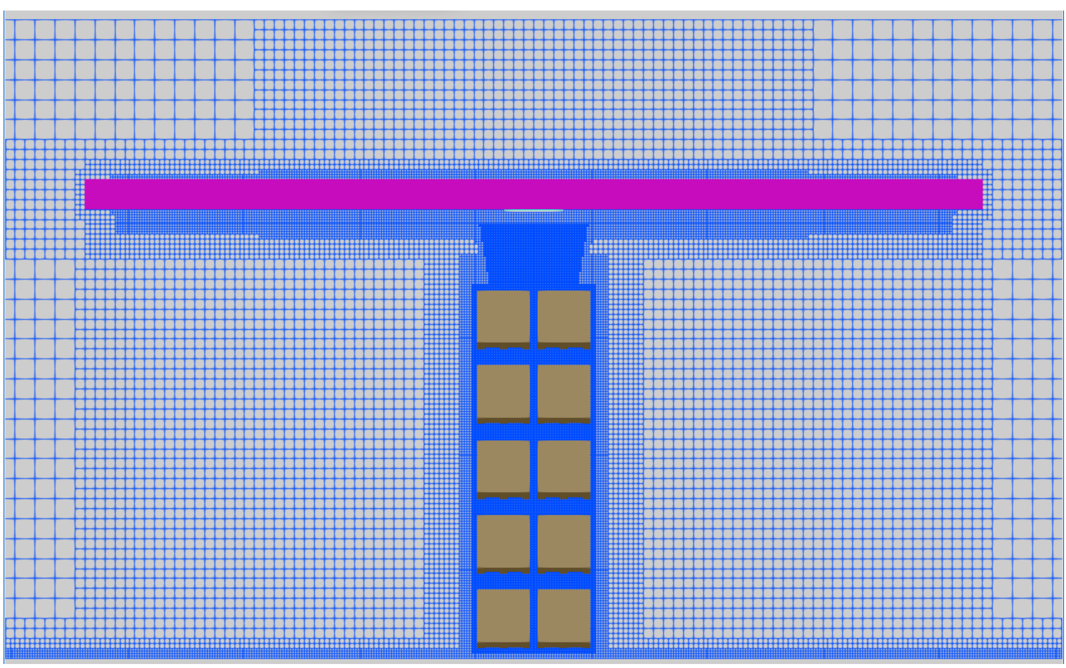


Figure 3-2: Visualization of the computational mesh. 2-D slice in the transverse direction, centered at the ignition location. Wireframe shows triangulated computational mesh. Ceiling (magenta), cartoned commodity (tan), pallets (dark brown) also shown.

Figure 3-3 shows a visualization of the smoke vent, viewed from inside the building near the rack storage array. The smoke vent "door" is represented by a 2-D plane in line with the ceiling. The mesh in and surrounding the vent has a 0.05 m (2 in.) resolution.

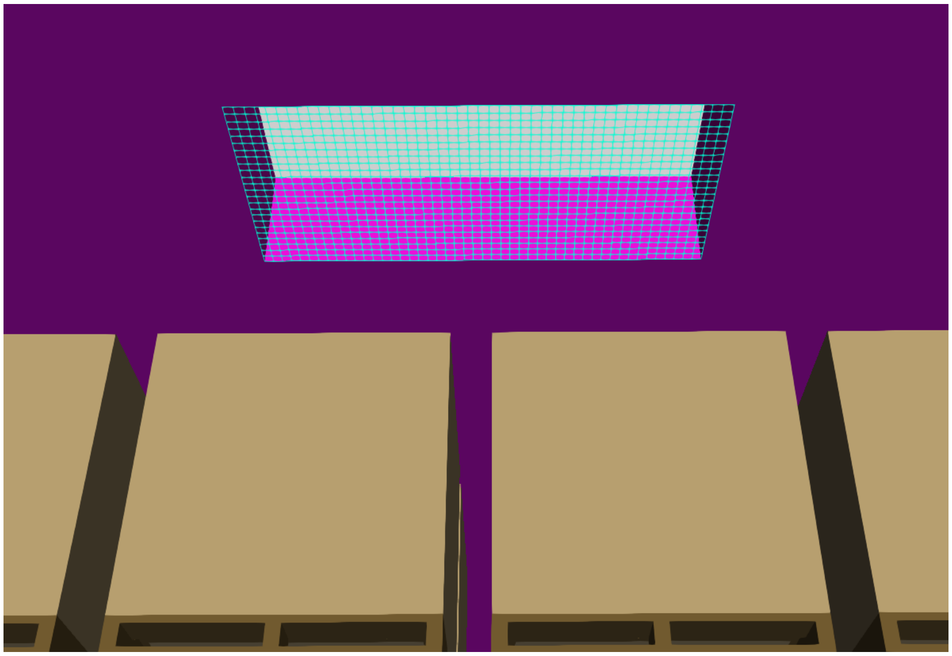


Figure 3-3: View of smoke vent from below the ceiling (blue mesh shows location of vent door). Ceiling (magenta), cartoned commodity (tan), pallets (dark brown) also shown.

4. Smoke Vents in Unsprinklered Storage Occupancies

Before considering the impact of smoke vents on sprinklered occupancies, the effect of smoke vents in unsprinklered storage occupancies is examined using FireFOAM. The purpose of this analysis is to evaluate the benefit, if any, of smoke vents on limiting fire spread and property loss in the absence of sprinkler protection. Questions of tenability and egress are not directly addressed. In order to maximize the potential benefits of smoke vents, the assumption is that they are always fully open, and the vented ratio is large (3.1%).

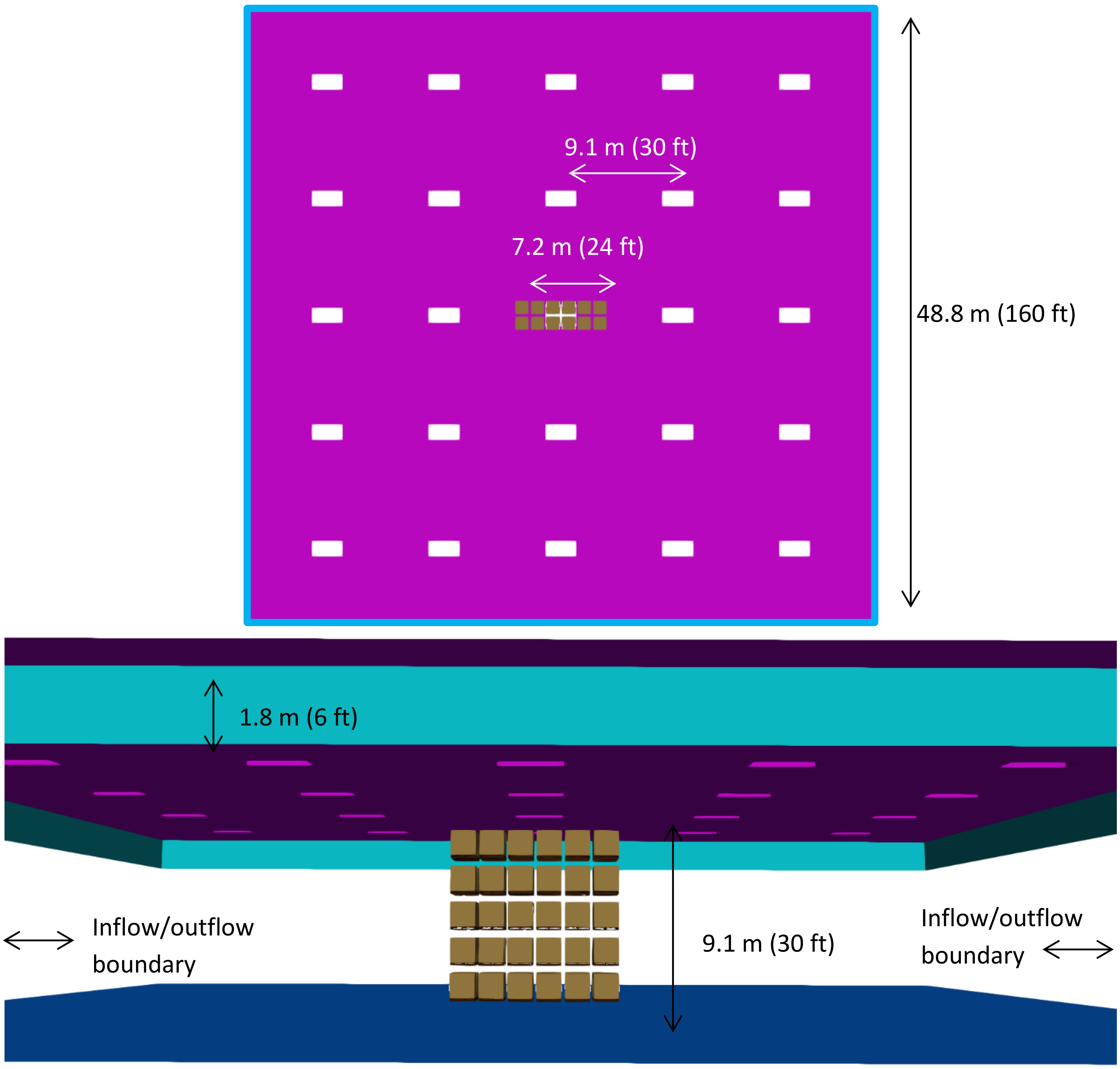


Figure 4-1: (top) Plan view of simulated domain, ceiling with vent array shown in pink, cyan border is the draft curtain, commodity array shown in tan. (bottom) Side view of domain, ground shown in dark blue.

4.1 Case Configuration

Figure 4-1 shows a plan view (top) and side view (bottom) of the simulation domain for cases U-1 and U-2 (vents are closed for case U-1). The domain has a 48.8 x 48.8 m (160 x 160 ft) footprint and the ceiling is 9.1 m (30 ft) above the ground. The ceiling extends to the edge of the simulation domain which has an inflow/outflow boundary to allow for the outward flow of combustion products and the inward flow of fresh gasses, either through the vent openings in the ceiling or through the sides of the domain. A draft curtain is present that extends from the ceiling 20% of the height from the ceiling to the ground [15], 1.8 m (6 ft). The draft curtain helps to contain the heat and smoke from the fire and to develop the smoke layer under the ceiling for the gravity smoke vents. A double-row rack of CUP commodity, 6 pallet loads wide, 5 pallet loads high, is used for the fuel array. Ignition occurs in the central flue space of the storage array, directly underneath an open smoke vent for case U-2.

Table 4-1 summarizes cases U-1 and U-2. The main difference between the cases is the absence/ presence of the smoke vent array in case U-1/U-2.

Table 4-1: Matrix of unsprinklered cases.

Case Name	Commodity	Storage/ceiling height	Ignition location	Draft curtain depth	Smoke vents
U-1	CUP	7.6/9.1 (25/30)	Center	1.8 m (6 ft)	None
U-2	CUP	7.6/9.1 (25/30)	Center	1.8 m (6 ft)	2.4x1.2 m (8x4 ft) vent 5x5 array, r_V=3.1%

4.2 Results

For both the unvented (U-1) and vented (U-2) case, the fire grows rapidly out of control, with widespread flame impingement on the ceiling that would lead to rapid structural damage, impeding manual firefighting efforts. Simulated steel temperatures at the ceiling indicate that exposed steel elements would exceed FM Global's test failure criteria of 922 K (1200 °F) within 4 minutes of ignition for both the vented and unvented ceilings. The abundant and continuous supply of fuel promotes the rapid fire growth, and the presence of the smoke vents has essentially no impact on the resulting fire size. This is clear from Figures 4-2 and 4-3, which show fire growth measured by HRR and visualization snapshots, respectively. In both cases, the fire spreads to the ends of the array within 2 minutes and exceeds 150 MW within 3 minutes after ignition. The fire would have continued to spread further if the simulations had included additional commodity.

For case U-1, the ceiling contains the fire within the building. For case U-2, soon after ignition (>30 sec) the fire grows to reach the ceiling level and a portion of the gaseous fuel is vented and burnt on the outside of the building. In Figure 4-2 the dashed blue line shows the HRR inside the building and the solid blue line shows the total HRR for case U-2 and the orange line shows the total HRR for case U-1.

The difference between the blue curves shows that the smoke vents cause about 30-40% of the gaseous fuel to be removed from the building prior to burning. Yet, the difference between the solid lines shows only a small (<5%) difference, indicating that the smoke vents have essentially no impact on the overall fire growth rate. This apparent contradiction can be resolved by analyzing the main energy flows in vented, unsprinklered storage fires, including the heat transfer processes that lead to flame spread and fire growth.

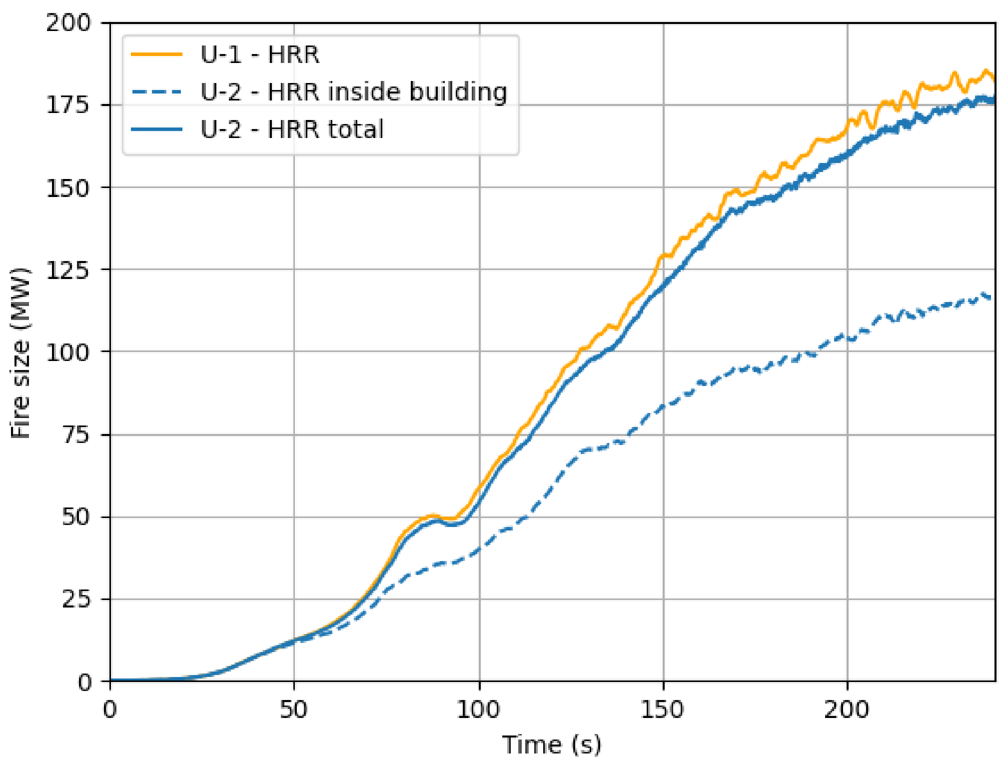


Figure 4-2: Comparison of fire size for unvented (U-1, orange) and vented (U-2, blue) CUP cases.

The flow chart in Figure 4-4 shows the fate of the gaseous fuel (pyrolysate) for case U-2. The fuel is either vented from the building or consumed inside the building. The energy from the fuel burnt inside the building is then either radiated within the building or transported within or outside the building as hot product gasses (convection). Figure 4-5 plots the fire size alongside vented and unvented energy flows for case U-2. Approximately one third of the energy in the pyrolysate is vented as unburnt fuel, the remainder is combusted within the building, of which half is retained within the building in the form of radiation or convection, and half is vented as a convective heat loss through the smoke vents.

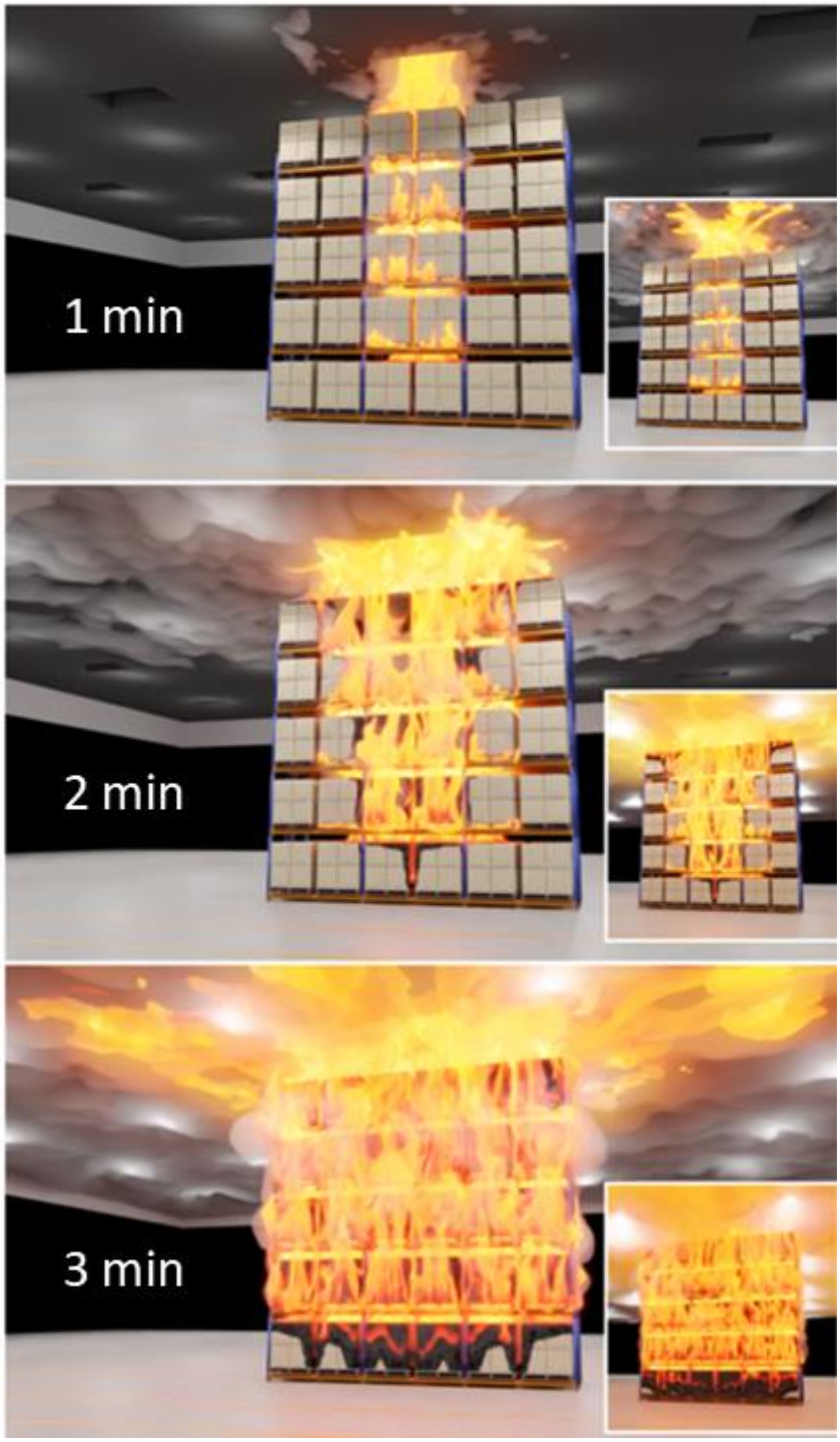


Figure 4-3: Snapshots of vented case U-2 (main images) with unvented comparison case U-1 (inset images) at 1 minute (top), 2 minutes (middle), and 3 minutes (bottom) post ignition.

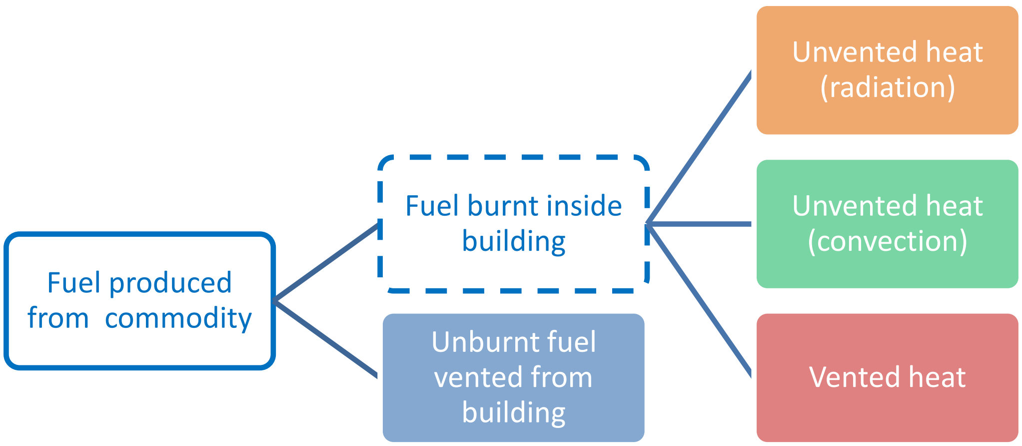


Figure 4-4: Energy flows for vented storage fire.

It is significant that, during the 4 minutes after ignition, two thirds of the total energy produced from the solid fuel is removed from the building by the smoke vents (Note: this is assuming that the smoke vents are always open, ignition occurs directly beneath a vent, and that there is a large vent ratio). The removal of this energy from the building will have a short-term impact on the amount of heat and smoke trapped within the building. However, the duration of this benefit will be limited to when the fire is small and before the building envelope is damaged, at which point the presence/absence of smoke vents will be an insignificant factor. The exact time at which this point is reached will vary from occupancy to occupancy. For the case simulated here, exposed 6 mm steel members located at the ceiling above ignition location, exceeded the threshold value of 811 K (538°C or 1000°F) within 4 minutes of ignition.

However, it is the flame-spread dynamics and total fire size that are important from a property loss prevention perspective, and for the longer-term tenability within the building. Flame spread is determined by the heat transfer to the unburnt solid fuel. This has two main components, convective and radiative thermal feedback from the gas-phase. The convective component is determined by the temperature adjacent to the unburnt solid fuel and so the presence of smoke vents at the ceiling level has no impact on this process. The radiative component depends on the view-factor between the flames and the solid fuel. Most of the commodity is not facing the ceiling and, therefore, the potential for venting to attenuate the radiative feedback to the commodity array is also small. Only the top surface of the top tier of the array is facing the ceiling, and so any impact of venting on flame spread via radiative heat transfer would be limited to that portion of the commodity.

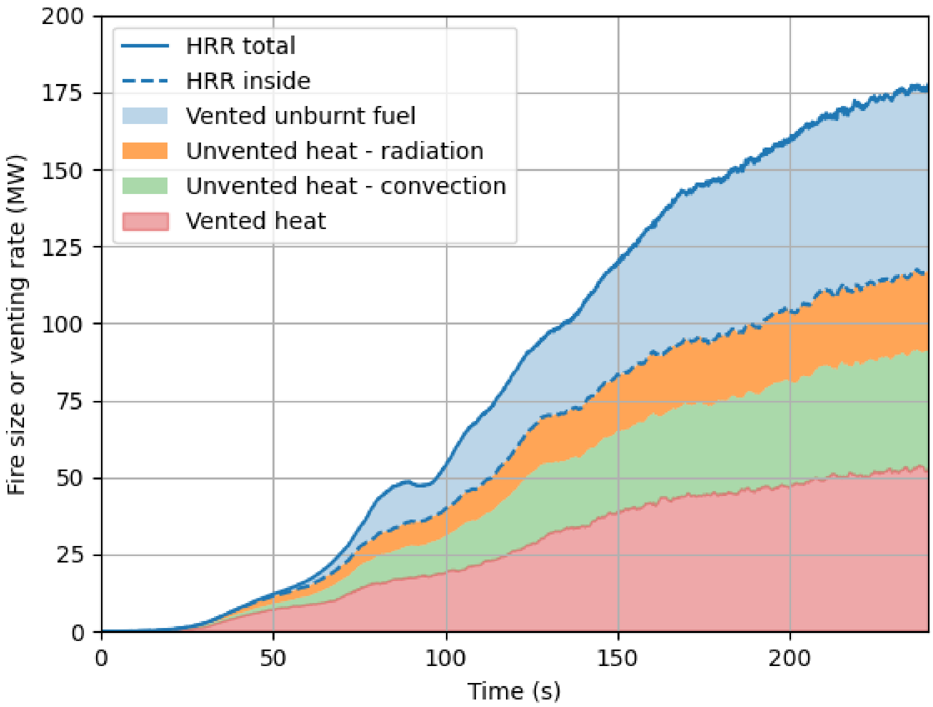


Figure 4-5: Total (solid line) and inside (dashed line) HRR for vented case U-2. Shaded areas show vented and non-vented components.

Case U-2 also demonstrated the sensitivity of the smoke vent as a function of distance from the ignition location. Figure 4-6 shows the total amount of heat vented from the first, second, and third ring of smoke vents (left) and the average heat vented by a smoke vent in each ring (right). The performance of an individual smoke vent decreases rapidly with increasing distance from the ignition location. The smoke vents that are not positioned directly over the ignition location do not have a significant impact on the results within the first 100 sec when the first set of sprinkler activations would occur in a sprinklered occupancy. Note that the negative heat venting value briefly observed for the third ring of smoke vents is due to the inflow of replacement ambient air from the exterior of the building in response to the consumption of fresh gasses within the building by the fire. The ambient air is slightly above the reference thermodynamic temperature, which briefly results in a net flow of energy into the building.

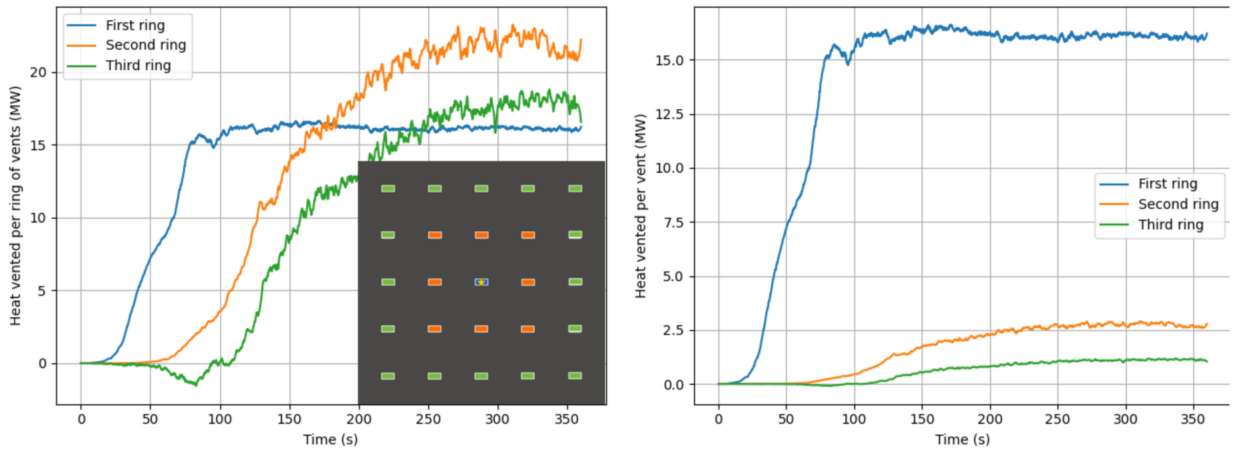


Figure 4-6: (left) Total heat vented per ring of smoke vents. Inset image shows plan view of ceiling with first (blue), second(orange), third (green) rings of smoke vents, ignition location (yellow star). (right) Average heat vented for an individual vent in each ring of smoke vents.

This analysis leads to the following observations for the use of gravity smoke vents in unsprinklered storage occupancies:

1. Flame spread and fire growth are dominated by the heat transfer processes directly surrounding the commodity and are not very sensitive to the effects of the smoke vents which are limited to the near-ceiling region.
2. The small decrease in total HRR observed in case U-2 compared to U-1 may be explained by the decrease in radiative heat transfer to the top surface of the commodity array.
3. There is likely to be some benefit in terms of tenability and egress resulting from the smoke vents, but this benefit will be limited by the rapid fire-growth typical of storage occupancies. The duration and magnitude of any ~~life safety~~ benefit would be occupancy-specific and depend upon the abundance and continuity of combustibles, the type of commodity, and the ability of the ceiling to resist thermal assault. For the storage scenario considered here, simulated steel temperatures exceeded FM Global's failure criteria within 4 minutes of ignition for both the unvented and vented cases, due to the widespread flame impingement on the ceiling. This implies that rapid structural damage to the building will occur, likely before manual firefighting can commence and so no property loss prevention benefit should be expected from automatic smoke vents in unsprinklered storage occupancies.
4. The effectiveness of gravity smoke vents decreases rapidly as a function of distance from the ignition location. Smoke vents positioned directly above the ignition location are more effective because the fire plume directly impinges on the smoke vent area, while any other smoke vent location can only influence a smaller portion of the ceiling layer.

Any realistic change to the current conditions (e.g., lower vented-ratio, use of automatic vents, use of non-ganged vents, different ignition location) would further reduce the already marginal impact that the smoke vents have on the outcome of the fire.

5. **Smoke Vents in Sprinklered Storage Occupancies**

In Section 4, it was found that gravity smoke vents should not be considered a property loss prevention measure as they do not prevent/delay fire growth or building structural damage. However, smoke vents may be required in some jurisdictions and may be used in conjunction with sprinklers, so their impact must also be considered for sprinklered occupancies.

The activation of smoke vents and sprinklers are interdependent (see Figure 1-2). If the smoke vent activates first, a portion of the plume/ceiling jet will be diverted out of the building, delaying the activation of the sprinklers. If the sprinklers activate before the smoke vent, the fire size will be reduced and the ceiling will be cooled, preventing the smoke vent from activating when the sprinkler protection is adequate. Of these two scenarios, the activation of the vents before the sprinklers is of greater concern because the delay in sprinkler activation could result in a larger peak fire size, potentially beyond the conditions for which the sprinkler system was designed. The activation of the sprinklers before the smoke vents may also be of concern, as the sprinklers may prevent the smoke vents from automatically activating due to cooling effects. This concern does not have significant property loss prevention implications and is not the focus of this study.

In the following analysis, it is assumed that the smoke vents have the largest impact on the sprinkler performance when they open before the sprinklers. The scenario where sprinklers open before the smoke vents is not the focus of this study. The likelihood of the smoke vents opening first depends on the ignition scenario, storage configuration, and details of the sprinkler and smoke vent systems. A probabilistic analysis is presented in Section 5.1 that quantifies this likelihood over a broad parameter-space assuming that the smoke vents are activated by thermal elements. The scenario most likely to activate the smoke vent before the sprinklers is deemed to be the “worst-case scenario”, because it maximizes the potential delay in the first sprinkler activation time. A series of full-scale tests and model simulations are presented in Section 5.2 to determine the impact of the worst-case scenario on the sprinkler protection. An analysis is also performed in Section 5.3 for smoke vents that are always left open, “vent openings”, which is also applicable to ganged smoke vent systems with very early activation (e.g., via smoke detection). A sensitivity study is also performed in Section 5.3 to evaluate the generality/conservativeness of the baseline results. Lastly, existing recommendations from FM Global DS 2-0 are evaluated in Section 5.4.

5.1 Probability of Automatic Smoke Vents Activating Before Sprinklers

Smoke vents and sprinklers that are automatically operated both rely on the detection of the fire by a thermal element that is heated to the activation temperature. In general, thermal elements that are closer to the ignition location will be exposed to higher heating rates and are expected to be activated earlier.

The probability of the smoke vents opening before the sprinklers, $P_{V,S}$, is calculated using FireFOAM simulations. A range of commodities, storage heights, clearance heights, ignition scenarios, and thermal link properties are considered. The probabilities are presented as functions of smoke vent and sprinkler activation temperatures. For each case, probabilities are calculated for both quick response, ordinary temperature (QR-OT) and standard response, high temperature (ST-HT) sprinklers.

5.1.1 *Probability Definition*

The probability of the smoke vents opening before the sprinklers depends on several factors:

1. The relative density of sprinklers and smoke vent thermal elements at the ceiling.
2. The location of the ignition with respect to the sprinklers.
3. The location of the ignition with respect to the smoke vents.
4. The location of the smoke vents with respect to the sprinklers.

$P_{V,S}$ is defined as the weighted-average probability of the smoke vents opening before the sprinklers for a random ignition location ($\overrightarrow{x_R}$) with respect to the sprinklers. Equation 5-1 presents an approximation for this weighted-average value that considers three ignition locations with respect to the sprinklers: “among four” (A4), “between two” (B2), and “under one” (U1). The derivation of Equation 5-1 is given in Appendix H.

$$P_{V,S}(\overrightarrow{x_R}) = w_{A4}P_{V,S}(\vec{x}_{A4}) + w_{B2}P_{V,S}(\vec{x}_{B2}) + \; w_{U1}P_{V,S}(\vec{x}_{U1}) \qquad 5\text{-}1$$

The weight values w_{A4}, w_{B2}, w_{U1} represent the probability of ignition occurring in a particular location with respect to the sprinklers and the values $P_{V,S}(\vec{x}_{A4}),\; P_{V,S}(\vec{x}_{B2}),\; P_{V,S}(\vec{x}_{U1})$ represent the corresponding probability of the smoke vents opening before the sprinklers for A4, B2, and U1 ignition scenarios. The calculation method is documented in Appendix I.

Table 5-1: Matrix of simulated cases testing vent and sprinkler activation times.

Case	Commodity	Ignition location		Height	
		W.R.T Sprinklers	W.R.T Commodity	Storage m^2 (ft^2)	Ceiling m^2 (ft^2)
P-1	Class 2	U1*/ B2^/ A4+	Offset	7.6 (25)	9.1 (30)
P-2	CUP	U1/ B2/ A4	Offset	7.6 (25)	9.1 (30)
P-3	UUP	U1/ B2/ A4	Offset	7.6 (25)	9.1 (30)
P-4	CUP	U1/ B2/ A4	Center	7.6 (25)	9.1 (30)
P-5	Class 2	U1/ B2/ A4	Offset	4.6 (15)	9.1 (30)
P-6	Class 2	U1/ B2/ A4	Offset	13 (45)	15 (50)
P-7	Class 2	U1/ B2/ A4	Offset	11 (35)	15 (50)
P-8	CUP	U1/ B2/ A4	Offset	4.6 (15)	9.1 (30)
P-9	CUP	U1/ B2/ A4	Center	4.6 (15)	9.1 (30)
P-10	CUP	U1/ B2/ A4	Offset	13 (45)	15 (50)
P-11	CUP	U1/ B2/ A4	Offset	11 (35)	15 (50)
P-12	CUP	U1/ B2/ A4	Offset	7.6 (25)	9.1 (50)
P-13	UUP	U1/ B2/ A4	Offset	4.6 (15)	9.1 (30)

5.1.2 Matrix of Simulated Cases

Table 5-1 presents the matrix of simulated cases for which $P_{V,S}$ is evaluated. These cases consider several independent effects:

1. Commodity type: Class 2, CUP, and UUP [20];
2. Ceiling height: 9.1 m (30 ft), and 15 m (50 ft);
3. Clearance height: 1.5 m (5 ft), 4.6 m (15 ft), 7.6 m (25 ft); and
4. Central vs offset ignition within the rack-storage array.

5.1.3 Sources of Uncertainty

There are several sources of uncertainty that influence the calculation of $P_{V,S}$. In particular, the sprinkler and vent thermal element properties and location, the vented ratio, and the vent size are site-specific variables. To account for the variation of these parameters, a realistic range of values are used to bound the probability calculations. This results in a probability range prediction for each condition.

5.1.3.1 Sprinkler and smoke vent thermal element properties

Sprinkler and smoke vent thermal elements are simulated using Equation 5-2, neglecting water cooling due to the lack of sprinkler spray. When T_L exceeds the activation temperature, T_{ACT}, the thermal element is activated.

$$\frac{dT_L}{dt} = \frac{\sqrt{U_G}}{RTI}(T_G - T_L) - C(T_L - T_\infty) \qquad \text{5-2}$$

Two types of sprinkler thermal elements are considered:

1. Quick response, ordinary temperature (QR-OT). Quick response sprinklers have an RTI value under 50 $m^{0.5}s^{0.5}$ (90 $ft^{0.5}s^{0.5}$). Ordinary temperature sprinklers have an activation temperature between 330 and 350 K (135 and 170°F).
2. Standard response, high temperature (SR-HT). Standard response sprinklers have an RTI value typically over 80 $m^{0.5}s^{0.5}$ (145 $ft^{0.5}s^{0.5}$). High temperature sprinklers have an activation temperature between 394 and 422 K (250 and 300°F).

Values of $P_{V,S}$ are calculated for a wide range of smoke vent activation temperatures, as the recommendations in codes and standards can differ significantly [9] [10]. The smoke vent RTI is assumed to be 175 $m^{0.5}s^{0.5}$ (315 $ft^{0.5}s^{0.5}$), in line with previous full-scale testing [23]. All thermal elements are assumed to have a C value of 0.5 s^{-1} (the results are not very sensitive to this value).

Table 5-2 summarizes the thermal element properties for the sprinklers and smoke vents used in this section.

Table 5-2: Thermal element properties for simulations P-1 to P-13.

	RTI	**C**	**T_{ACT}**
	$m^{0.5}s^{0.5}$ ($ft^{0.5}s^{0.5}$)	s^{-1}	K (°F)
QR-OT Sprinkler	40 (72)	0.5	347 (165)
SR-HT Sprinkler	100 (181)	0.5	414 (285)
Smoke Vents	175 (315)	0.5	320 – 500 (115 – 440)

5.1.3.2 Sprinkler and smoke vent thermal element ceiling offset distance

Thermal element activation times are sensitive to the vertical offset distance from the ceiling. Figure 5-1 shows a sketch of a typical fire plume and ceiling jet layer close to the first sprinkler activation time. The fire plume rises above the ignition location and impinges on the ceiling, where it is deflected into a ceiling jet. The ceiling jet results in very steep thermal stratification; locations inside (outside) the ceiling jet are subject to significant (insignificant) convective heating. $P_{V,S}$ values will therefore be sensitive to the relative locations of the sprinkler and smoke vent thermal elements.

To provide conservative estimates for $P_{V,S}$, the sprinkler thermal elements are assumed to be at the maximum distance from the ceiling permitted by FM DS 2-0 (lowest possible heating, later activation) and the smoke vent thermal elements are assumed to be close to the ceiling (highest possible heating, earlier activation). This corresponds to measuring the sprinkler thermal elements at 0.33 m (13 in.) from the ceiling and measuring the vent thermal element 50 mm (2 in.) from the ceiling, which is the location of the peak, mean, gas-phase temperature below the ceiling in the FireFOAM simulations.

In general, the sprinkler thermal elements can be closer to the ceiling and the vent thermal element may not be exposed to the hottest sub-layer of the ceiling jet, so these assumptions will ensure that the probability calculations are very conservative.

The vented ratio typically ranges from 2% to 4% for storage occupancies, with the exact value determined according to local standards and building codes. Here, a vented ratio of $r_v = 3\%$ is assumed, but the range of 2% to 4% is used to quantify the sensitivity of $P_{V,S}$ to r_v.

Typical smoke vent sizes range from $A_{V0} =$ 1.5 to 4.5 m^2 (16 to 48 ft^2). A representative value of $A_{V0} =$ 3 m^2 (32 ft^2) is selected, which corresponds to the 1.2 by 2.4 m (4 by 8 ft) smoke vent design available from most manufacturers.

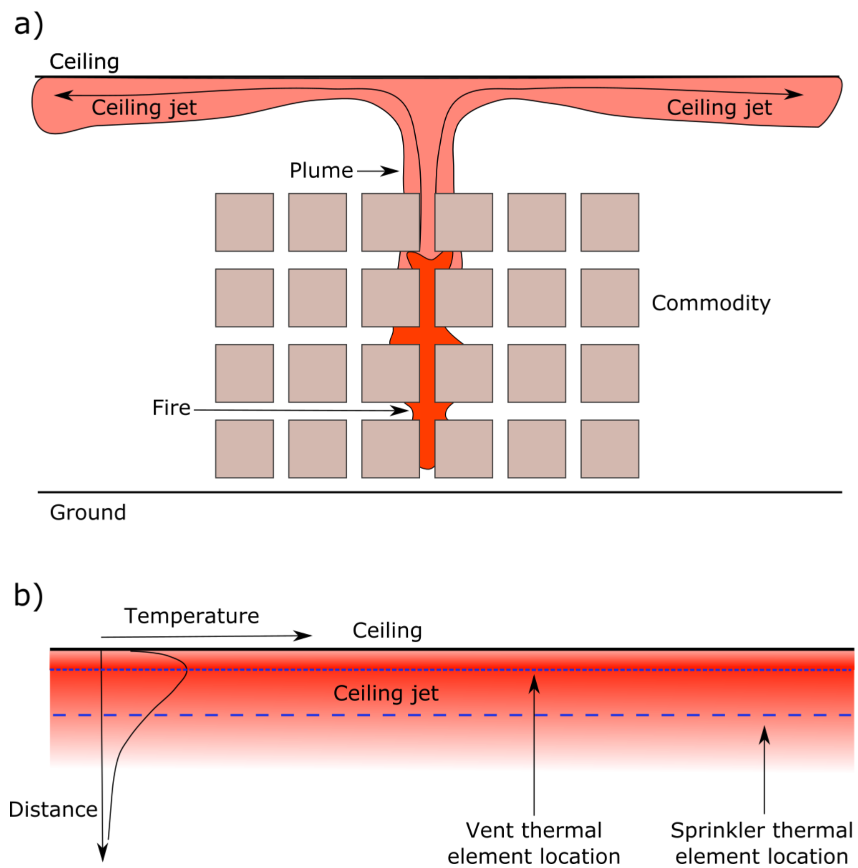


Figure 5-1: a) Sketch of rack storage fire plume and ceiling jet. B) Sketch of thermal stratification below ceiling and the location of sprinkler and vent simulated thermal elements.

5.1.4 Results

Table 5-3 presents the $\mathrm{P}_{\mathrm{V,S}}$ values for cases P-1 to P-13 evaluated for QR-OT and SR-HT sprinklers and for a range of $T_{ACT,V}$ values. These cases cover a wide range of commodity types, storage heights, clearance heights, and ignition locations within the fuel array. Overall, the results show that the smoke vents are highly unlikely to operate before the sprinklers if $T_{ACT,V}$ is equal to or greater than $T_{ACT,S}$. The results depend on multiple parameters which will be discussed here. The methodology used to generate these calculations is presented in Appendix I. Where test data are available, the calculated probability values compare favorably with experimental observations and this analysis is presented in Appendix K.

From Table 5-3 it is apparent that $\mathrm{P}_{\mathrm{V,S}}$ decreases with increasing $T_{ACT,V}$, as expected. The strong link between these two parameters is made clearer by plotting $\mathrm{P}_{\mathrm{V,S}}$ as a function of $T_{ACT,V}$ for a given case and sprinkler thermal element setting in Figure 5-2. Where $T_{ACT,V}$ is less than $T_{ACT,S}$, $\mathrm{P}_{\mathrm{V,S}}$ increases steeply with decreasing $T_{ACT,V}$. Where $T_{ACT,V}$ is greater than $T_{ACT,S}$, $\mathrm{P}_{\mathrm{V,S}}$ approaches zero with increasing $T_{ACT,V}$. Considering the three thresholds in Table 5-3:

- Where $T_{ACT,V} = T_{ACT,S}$, the mean value of $\mathrm{P}_{\mathrm{V,S}}$ is 4% for QR-OT sprinklers and 14% for SR-HT sprinklers, respectively.
- Where $T_{ACT,V}$ has a higher temperature rating than the sprinklers (NFPA 13 [10]), the mean value of $\mathrm{P}_{\mathrm{V,S}}$ is 2% for QR-OT sprinklers and 7% for SR-HT sprinklers, respectively.
- Where $T_{ACT,V}$ is equal to 455 K (182°C or 360°F) (FM DS 2-0), the mean value of $\mathrm{P}_{\mathrm{V,S}}(\vec{\mathrm{x}}_R)$ is <1% for QR-OT sprinklers and 2% for SR-HT sprinklers, respectively.

There are additional trends in the results as a function of clearance height, ceiling height, commodity type, and ignition location. Overall, the value of $\mathrm{P}_{\mathrm{V,S}}$ increases as the fire plume becomes narrower and more concentrated in the center of the vent. This occurs where mixing of fresh gasses into the fire plume is minimized and where the fire plume is symmetrical. This condition is favored where:

- The clearance height and storage height are minimized, as this reduces the distance over which mixing occurs.
- The commodity is cartoned, as this produces a narrower plume bound by the flue-space between the boxes, compared to the enhanced mixing arising from the open geometry of UUP.
- Ignition is centered in the array, as this produces a symmetrical plume centered over the vent area, in contrast to the tilted plume that arises from the asymmetrical offset ignition scenario.

A detailed analysis of these sensitivities is presented in Appendix J.

Table 5-3: Probability of smoke vents opening before sprinklers. Bold numbers assume $r_v = 3\%$, lower- and upper-bounds assume $r_v = 2\%$ and $r_v = 4\%$, respectively. +Vent activation temperature equal to sprinkler activation temperature. *NFPA 13 recommendation for higher activation-temperature than sprinkler. #FM DS 2-0 recommendation 455 K (360F). ^ Ultra-high temperature rating of 544 K (520 F).

Case *Commodity* Storage/Ceiling Height m (ft)	**Sprinkler Thermal Link Settings**					
	Quick Response Ordinary Temperature RTI 40 ms$^{1/2}$ (72 fts$^{1/2}$) T_{ACT} 347 K (165 F)			**Standard Response High Temperature** RTI 100 ms$^{1/2}$ (181 fts$^{1/2}$) T_{AC} 414 K (285 F)		
	Vent Activation Temperature RTI 175 ms$^{1/2}$ (317 fts$^{1/2}$)			**Vent Activation Temperature** RTI 175 ms$^{1/2}$ (317 fts$^{1/2}$)		
	347K / 165F Sprinkler+	366K / 200F NFPA*	455K / 360F FM#	414K / 285F Sprinkler	455K / 360F NFPA / FM	544K / 520F Ultra-High^
P-1 *Class 2* 7.6/9.1 (25/30)	**8%** (5-10%)	**4%** (2-5%)	**<1%** (<1-<1%)	**20%** (13-25%)	**11%** (7-15%)	**4%** (3-6%)
P-2 *CUP (offset)* 7.6/9.1 (25/30)	**9%** (6-12%)	**5%** (3-6%)	**<1%** (<1-<1%)	**18%** (12-24%)	**10%** (7-14%)	**4%** (3-6%)
P-3 *UUP* 7.6/9.1 (25/30)	**9%** (6-12%)	**4%** (2-5%)	**0%** (0-0%)	**7%** (5-10%)	**3%** (2-3%)	**<1%** (<1-<1%)
P-4 *CUP (central)* 7.6/9.1 (25/30)	**10%** (7-14%)	**6%** (4-7%)	**<1%** (<1-<1%)	**26%** (18-35%)	**16%** (11-22%)	**7%** (5-9%)
P-5 *Class 2* 4.6/9.1 (15/30)	**4%** (3-6%)	**2%** (1-3%)	**0%** (0-0%)	**15%** (10-19%)	**7%** (5-9%)	**1%** (1-1%)
P-6 *Class 2* 13/15 (45/50)	**1%** (1-2%)	**0%** (0-0%)	**0%** (0-0%)	**9%** (6-12%)	**5%** (3-7%)	**2%** (1-2%)
P-7 *Class 2* 11/15 (35/50)	**0%** (0-0%)	**0%** (0-0%)	**0%** (0-0%)	**7%** (5-9%)	**1%** (1-1%)	**0%** (0-0%)
P-8 *CUP (offset)* 4.6/9.1 (15/30)	**4%** (3-5%)	**1%** (1-2%)	**0%** (0-0%)	**14%** (10-19%)	**7%** (5-9%)	**1%** (1-1%)
P-9 *CUP (central)* 4.6/9.1 (15/30)	**2%** (2-3%)	**0%** (0-0%)	**0%** (0-0%)	**20%** (14-27%)	**11%** (7-15%)	**3%** (2-3%)
P-10 *CUP* 13/15 (45/50)	**2%** (1-3%)	**<1%** (<1-<1%)	**0%** (0-0%)	**10%** (7-13%)	**6%** (4-8%)	**2%** (1-3%)
P-11 *CUP* 11/15 (35/50)	**0%** (0-0%)	**0%** (0-0%)	**0%** (0-0%)	**8%** (5-10%)	**1%** (1-1%)	**0%** (0-0%)
P-12 *CUP* 7.6/15 (25/50)	**0%** (0-0%)	**0%** (0-0%)	**0%** (0-0%)	**4%** (3-5%)	**<1%** (<1-<1%)	**0%** (0-0%)
P-13 *UUP* 4.6/9.1 (15/30)	**10%** (7-14%)	**4%** (2-5%)	**0%** (0-0%)	**14%** (9-19%)	**5%** (3-7%)	**0%** (0-0%)
Average	**4%**	**2%**	**<1%**	**14%**	**7%**	**2%**

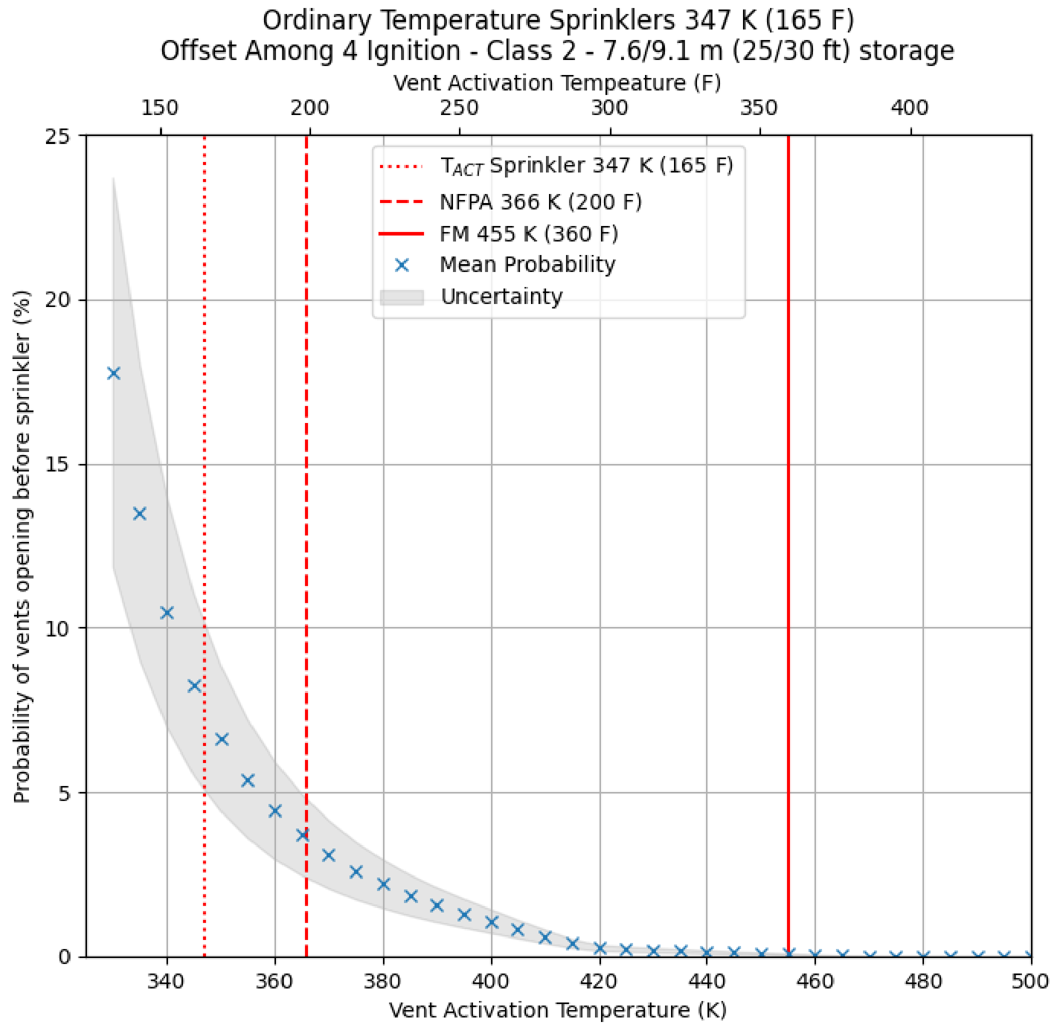


Figure 5-2: Sensitivity to vent activation temperature for A4 offset ignition with QR-OT sprinklers for case P-2.

5.1.5 Discussion

The results show that automatic smoke vents are very unlikely to open before sprinklers if the vent activation temperature is equal to or greater than the sprinkler activation temperature. The main reason for this is that there is a much higher density of sprinkler thermal elements compared to vent thermal elements. The conditions that are relatively more likely to lead to vents activating before sprinklers (absolute probability remains small) involve cartoned commodities, small clearances, lower ceiling heights, and center ignition. These conditions favor a narrower and hotter fire plume that can potentially activating smoke vents before the sprinklers, although the probability remains low. Factors that increase entrainment into the fire plume: increasing clearance height, increasing ceiling height, open-structured commodity (e.g., UUP), result in a wider fire plume with a lower peak temperature that has a high probability of activating sprinklers before smoke vents.

5.2 Impact of Automatic Smoke Vents Activating Before Sprinklers

In Section 5.1, the probability of smoke vents activating before sprinklers was quantified using FireFOAM simulations over a wide range of sprinklered storage scenarios. It was found that the probability was very low, but in special “worst-case scenarios” it is possible for the smoke vents to operate before the sprinklers, potentially impacting the sprinkler performance.

In this section, a worst-case scenario analysis is conducted by selecting conditions that are most likely to result in automatic smoke vents opening before sprinklers. FireFOAM simulations were performed to identify these worst-case scenario conditions, as judged by the delay in first sprinkler activation caused by the smoke vents for a realistic combination of sprinkler and smoke vent settings. Full-scale tests were then performed and used to evaluate the FireFOAM model. Both recommended (DS 8-9) and marginal sprinkler protection points were considered. The model was then used to extend the analysis to vents that are always left open (“vent openings”) and to a wide parameter space of commodity type, ceiling/storage height, ignition scenario, and vent location.

Seven tests were performed in the LBL (see Table 2-1 for details) using a false ceiling suspended underneath the movable ceiling, attached to a temporary steel structure, see Figure 2-1. The false ceiling contains a 2.4 x 1.2 m (8 x 4 ft) manually actuated smoke vent in the center of the ceiling. A 3 x 3 m (10 x 10 ft) array of quick response K240 (K16.8) pendent sprinklers at 2.4 bar (35 psi) activated at 347 K (74°C or 165°F) for the CUP tests, and K160 (K11.2) upright sprinklers at 1.7 bar (25 psi) for the Class 2 tests. The ignitor was placed in the central flue space, with the rack centered among four sprinklers. This ignition scenario was selected as the one most likely to open the smoke vent before the sprinklers, which is supported by the analysis in Section 5.1.

The tests targeted two scenarios:

- CUP 7.6/9.1 m (25/30 ft) storage with FM Global DS 8-9 recommended sprinkler protection and NFPA-13 guidance for the automatic smoke vent (standard response, high-temperature thermal element).
- Class 2 7.6/9.1 m (25/30 ft) storage with marginal sprinkler protection and NFPA-13 guidance for the automatic smoke vent.

Table 2-1 summarizes the full-scale tests. They are grouped by: commodity type, Tests 1-5 use CUP, Tests 6-7 use Class 2; venting, Tests 1, 3-4, 6 do not have a smoke vent, Tests 2, 5, 7 do have a smoke vent; and ignition location with respect to the sprinklers, Test 1 is between two sprinklers, Tests 2-7 are among four sprinklers. Note that the CUP tests were repeated due to the prominence of sprinkler skipping, which was not a significant factor for the Class 2 tests. A complete specification of the test conditions has been presented in Section 2.

Six FireFOAM simulations, cases V-1 to V-6 were performed and evaluated against the tests. Cases V-1 and V-2 used the CUP commodity, cases V-3 and V-4 used the Class 2 commodity, and cases V-5 and V-6 used the Class 2 commodity with a reduced water pressure. The correspondence between the simulated cases and the tests is summarized in Table 5-4.

Table 5-4: FireFOAM simulation case matrix summary.

Case Name	Corresponding Test	Note
V-1	T-3 and T-4	Repeat tests due to sprinkler skipping
V-2	T-2 and T-5	Repeat tests due to sprinkler skipping
V-3	T-6	-
V-4	T-7	-
V-5	T-6	Decreased pressure K160 (K11.2) @ 0.5 bar (7 psi)
V-6	T-7	Decreased pressure K160 (K11.2) @ 0.5 bar (7 psi)

5.2.1 Tests and Simulations at DS 8-9 Recommended Protection Options

5.2.1.1 Unvented CUP Tests

Tests T-3 and T-4 were performed at nominally identical conditions without a smoke vent. Figure 5-3 shows the sprinkler activation map and extent of fire damage in the two tests.

In Test T-3, two diagonally-opposite, first-ring sprinklers opened at 55 and 56 sec. The fire was not suppressed by these two sprinklers, it gradually recovered and spread along the main array. Two of the first-ring sprinklers were skipped due to the cooling effect from the two open sprinklers. Eight (8) sprinklers in the second and third rings activated before a third sprinkler in the first ring activated at 762 sec. After the three sprinklers in the first ring were opened, the fire was brought under control and the remaining first-ring sprinkler never activated. A total of 12 sprinklers opened, which is the design limit in FM Global DS 8-9. The fire did not reach either end, aisle jump did not occur, and the ceiling steel temperatures were far below failure thresholds.

While Test T-3 was successfully controlled, the total number of sprinklers (12) was at the design limit which includes a 50% safety factor. Sprinkler skipping played a large role in the outcome of the test as the first two sprinklers were insufficient to control the fire but delayed/prevented the remaining two first-ring sprinklers from opening. A repeat test (T-4) was performed due to the prominence of sprinkler skipping, which is a highly stochastic phenomenon.

In Test T-4, the same two diagonally-opposite, first-ring sprinklers opened at 47 and 51 sec. As with Test T-3, these two sprinklers were insufficient to control the fire, which gradually recovered and spread along the main array. Unlike in T-3, in Test T-4 a third first-ring sprinkler was only moderately delayed and activated at 229 sec, preventing the fire from spreading any further in that direction. The fourth sprinkler to open was in the second ring at 248 sec, skipping the remaining first-ring sprinkler. The fire spread very gradually in the direction of the skipped first-ring sprinkler, but was halted by the active second-ring sprinkler. The remaining first-ring sprinkler eventually opened at 1767 sec, but the fire was already under control at this point.

Test T-4 had a total of 5 sprinkler activations compared to 12 in T-3 and the fire damage area was approximately 40% lower. Sprinkler skipping was observed in both T-3 and T-4, but was more prominent in T-3. The tests showed that three open sprinklers in the first ring are sufficient to control the fire and that the outcome of the tests is very sensitive to the degree of sprinkler skipping.

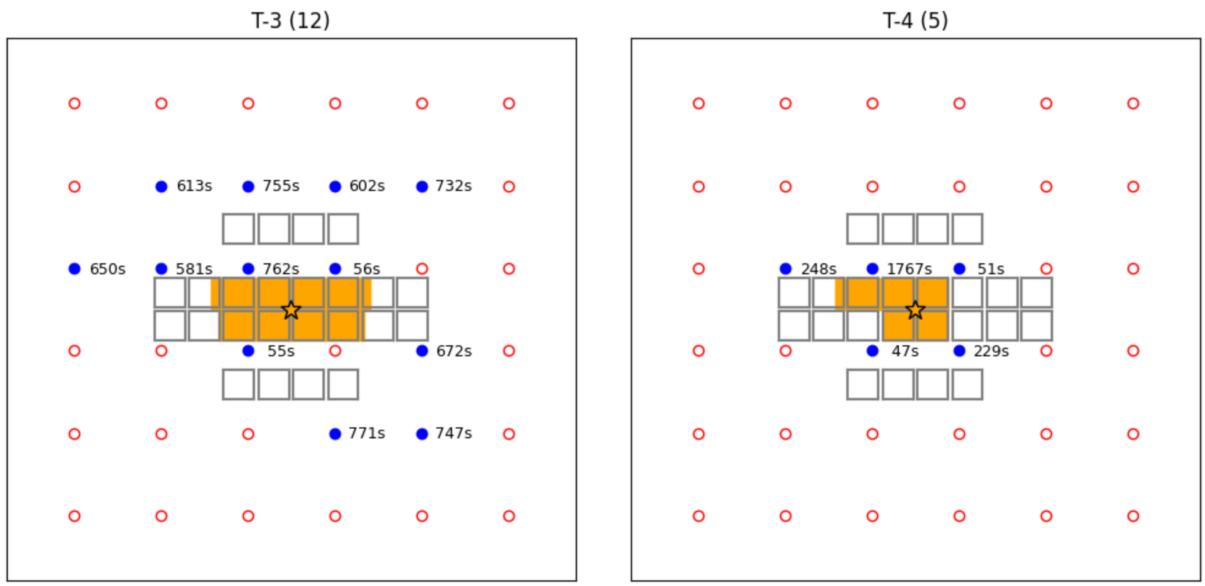


Figure 5-3: Sprinkler activation map and fire damage (orange shading) for unvented Tests T-3 (left) and T-4 (right).

5.2.1.2 Vented CUP Tests

Tests T-2 and T-5 were performed with a smoke vent centered over the ignition location at nominally identical conditions. Figure 5-4 shows the sprinkler activation map and extent of fire damage for the two cases.

In Test T-2, the smoke vent was activated, going from fully closed at 50 sec to fully opened at 59 sec. Three first ring sprinklers opened at 93, 96, and 109 sec. The fourth first-ring sprinkler was delayed until 130 sec, just after two second-ring sprinklers activated. The fire was controlled with a total of 6 sprinkler activations, with a similar fire damage area as the unvented cases. Sprinkler skipping did not play an important role in Test T-2, but based on the observations of unvented Tests T-3 and T-4, a repeat test (T-5) was also performed.

In Test T-5, the smoke vent opened between 42 and 51 sec. While the vent was opening, one first-ring sprinkler (SW of ignition) opened. A second first-ring sprinkler (NE of ignition) opened at 88 sec.

Sprinkler skipping was more significant in this test compared with T-2. The remaining two first-ring sprinklers were skipped, with 5 sprinkler activations occurring in the second and third rings before the sprinklers NW and SW of ignition opened at 315 and 321 sec, respectively. This increase in sprinkler skipping resulted in more sprinkler activations and a larger fire damage compared to Test T-2. Although the first sprinkler activated earlier in Test T-5 compared to T-2, this may have contributed towards sprinkler skipping, which resulted in a more challenging fire.

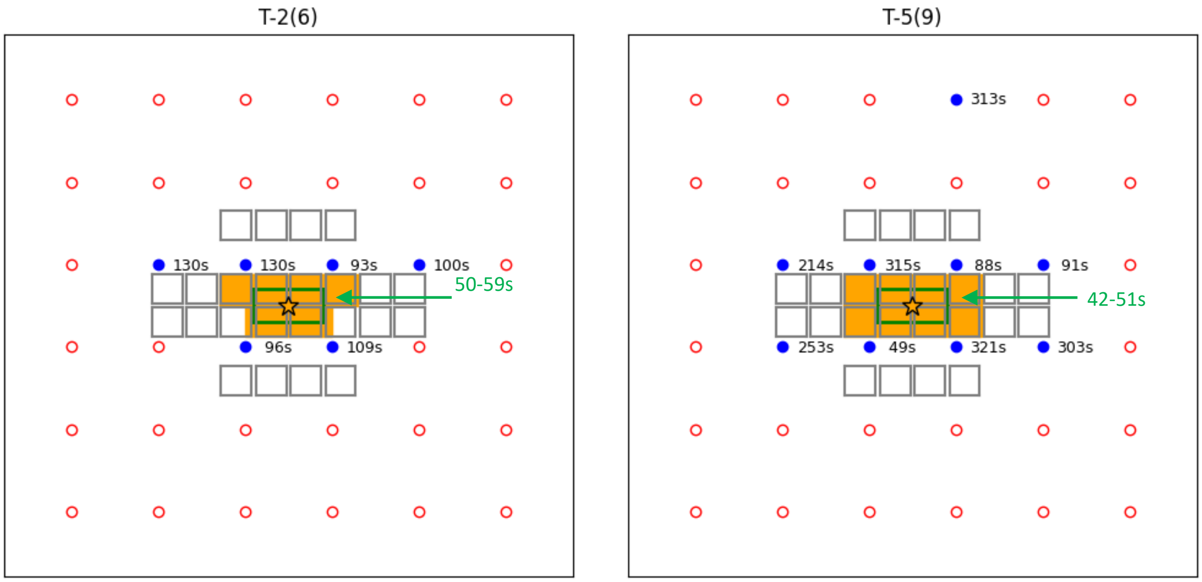


Figure 5-4: Sprinkler activation map and extend of fire damage (orange shading) for Tests T-2 (left) and T-5 (right). Green rectangle, arrow, and text refer to smoke vent location and opening time.

5.2.1.1 Effect of Smoke Vent on Test Outcome

Figure 5-5 shows snapshots of Tests T-2 (vented) and T-3 (unvented) at 50 sec (just before smoke vent opens in T-2), 55sec (just after the first sprinkler opens in T-3), and 93 sec (just after the first sprinkler opens in T-2). At 50 sec, the fire has grown vertically with direct flame impingement on the ceiling in both cases, which activated the smoke vent in T-2. At 55 sec, the fire plume is passing through the open smoke vent in T-2; in T-3, the fire plume remains under the ceiling and activates the first sprinkler. By 93 sec, the fire in T-2 has spread laterally and the plume is no longer contained within the vent area, leading to the first sprinkler activation. At the same time in T-3, two sprinklers are opened but the fire is not yet suppressed.

In Test T-5, the first sprinkler activation is not delayed by the smoke vent because the first sprinkler opens nearly simultaneously. The combined cooling of the smoke vent and first open sprinkler delays subsequent sprinkler activations. This allows the fire to recover and gradually spread, but all first-ring sprinklers are activated and control the fire. Figure 5-5 summarizes the sprinkler and vent activation times and fire outcomes for Tests T-2 to T-5. All tests are successfully controlled. In no case did the fire reach or approach the end of the main array. The fire did not jump the aisle space in any case. The ceiling steel temperatures did not reach or approach failure. The only failure criterion that was approached (but not exceeded) was the number of sprinkler activations in the unvented Test T-3. The largest number of sprinklers activated in a vented case was 9.

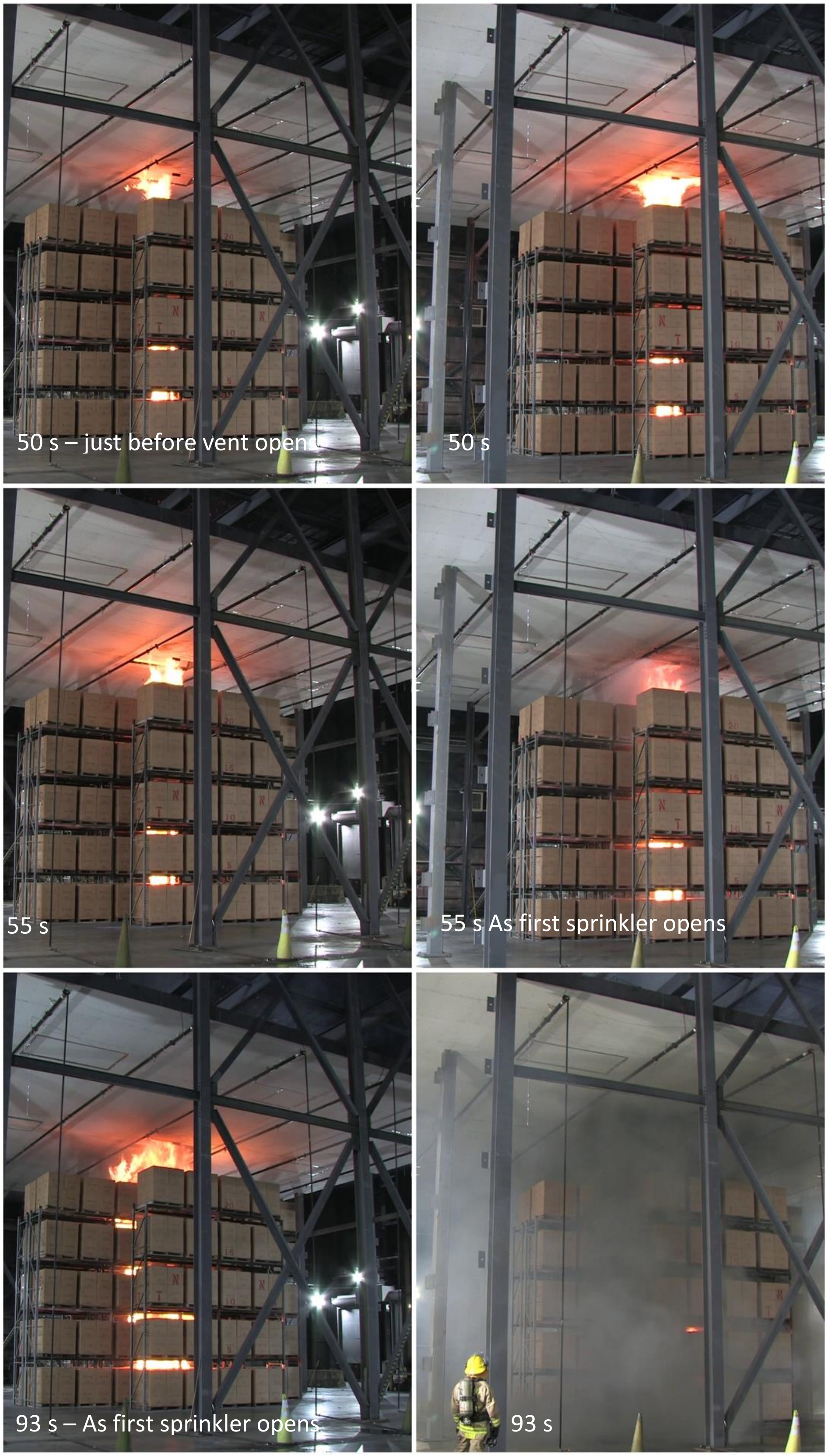


Figure 5-5: Comparison of vented Test T-2 (left column) and unvented Test T-3 (right column).

Table 5-5: Summary of CUP test results and evaluation of failure criteria.

Case Name	Vent (sec)	First sprinkler (sec)	Sprinkler activations	Exceed failure criteria?			
				Fire spread main array	Fire spread aisle jump	Ceiling steel temperature	Activation # (limit 12)
T-2	50-59	93	6	No	No	No	No
T-3	-	55	12	No	No	No	No (Borderline)
T-4	-	47	5	No	No	No	No
T-5	42-51	49	9	No	No	No	No

Tests T-2 to T-5 provided no evidence to support the claim that automatic smoke vents have an adverse impact on the performance of an adequately designed sprinkler system. While it is possible for the first sprinkler activation to be delayed, this did not lead to worse outcomes. The test-to-test variation at nominally identical conditions was larger than any difference between the vented and unvented tests. The test-to-test variation is attributed to the phenomenon of sprinkler delay/skipping which is addressed in Section 5.2.1.2.

5.2.1.2 Effect of First Ring Sprinkler Delay/Skipping on Test Results

In all CUP tests, the fire is controlled when 3-4 first-ring sprinklers are opened. The tests with the longest delay before opening three first-ring sprinklers, T-5 (vented) and T-3 (unvented), are the closest to failing due to number of sprinklers activations, 9 and 12, respectively. To understand this behavior and any dependence of the presence of smoke vents, the delay/skipping of the first-ring sprinklers is analyzed in this section. Figure 5-6 quantifies the first-ring sprinkler delay/skipping that occurred in Tests T-2 to T-5 by plotting first-ring sprinkler activations versus total sprinkler activations (top) and first-ring sprinkler activations versus time (bottom).

For the unvented tests (T-3 and T-4 shown in orange in Figure 5-6), the first two sprinklers are opened within 1 minute of ignition, but the third first-ring sprinkler does not activate until 4 minutes (T-4) or 12 minutes (T-3) and the fourth first-ring sprinkler is delayed until 29 minutes (T-4) or never opens (T-3). For the vented tests (T-2 and T-5 shown in blue in Figure 5-6), the first two sprinklers are opened approximately 40 sec later compared to the unvented cases because of the smoke vent. However, all four first-ring sprinklers open within 6 minutes of ignition. Overall, the delay/skipping of first-ring sprinklers does not appear to have a strong correlation with the presence/absence of an open smoke vent directly above the ignition location. While the first 1-2 sprinklers in the first ring are likely to be slightly delayed due to the smoke vent, the remaining first-ring sprinklers are less likely to be delayed/skipped. This behavior may be due to the larger fire size at the time of first sprinkler activation for the vented cases (see Figure 5-5), which could make it less likely to delay/skip additional first-ring sprinklers. This interaction is expected to decrease significantly when the ignition does not occur directly underneath a smoke vent.

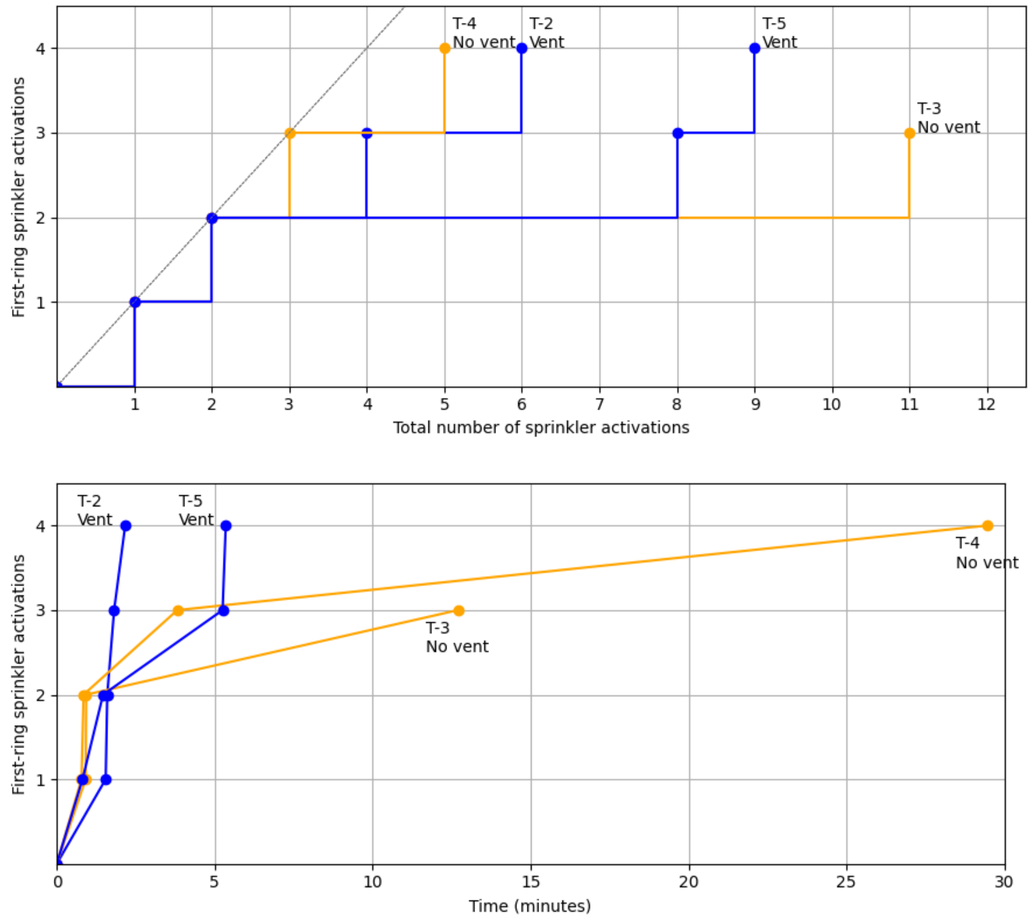


Figure 5-6: Number of first-ring sprinkler activations versus total activations (top) and versus time (bottom).

5.2.1.3 Model Results

Simulations were run using FireFOAM at conditions matching the vented Tests T-2 and T-5, and the unvented Tests T-3 and T-4. The unvented simulation is case V-1 and the vented simulation is V-2.

Figure 5-7 shows the HRR and sprinkler and vent activation times. Figure 5-8 shows the sprinkler activation map and fire damage area for cases V-1 (unvented) and V-2 (vented). For case V-1, the first sprinkler activation occurs at 35 sec and all four first-ring sprinklers are open by 37 sec. Soon after, the HRR curve peaks at about 9 MW and starts to decrease, with two additional sprinkler activations occurring by 50 sec. The HRR continues to decrease until it reaches 3 MW by 90 sec. For case V-2, the smoke vent opens at 31 sec, delaying the first sprinkler activation until 51 sec when the HRR is 12 MW. By 56 sec all four first-ring sprinklers are open and the fire size has peaked at 13 MW. The HRR then decreases until it converges with case V-1 by 90 sec as a 3 MW fire. For both cases, the fire size gradually increases from this point as the timber pallets are ignited and continue to burn where dry patches exist underneath the pallet loads. The fire does not spread along the main array and there is minimal flaming in the aisle space. No target array is included in these simulations, but aisle jump is very unlikely to have occurred based on these results. In both cases V-1 and V-2, sprinkler delay/skipping was not observed which is a departure from the test results that will be discussed in Section 5.2.1.4.

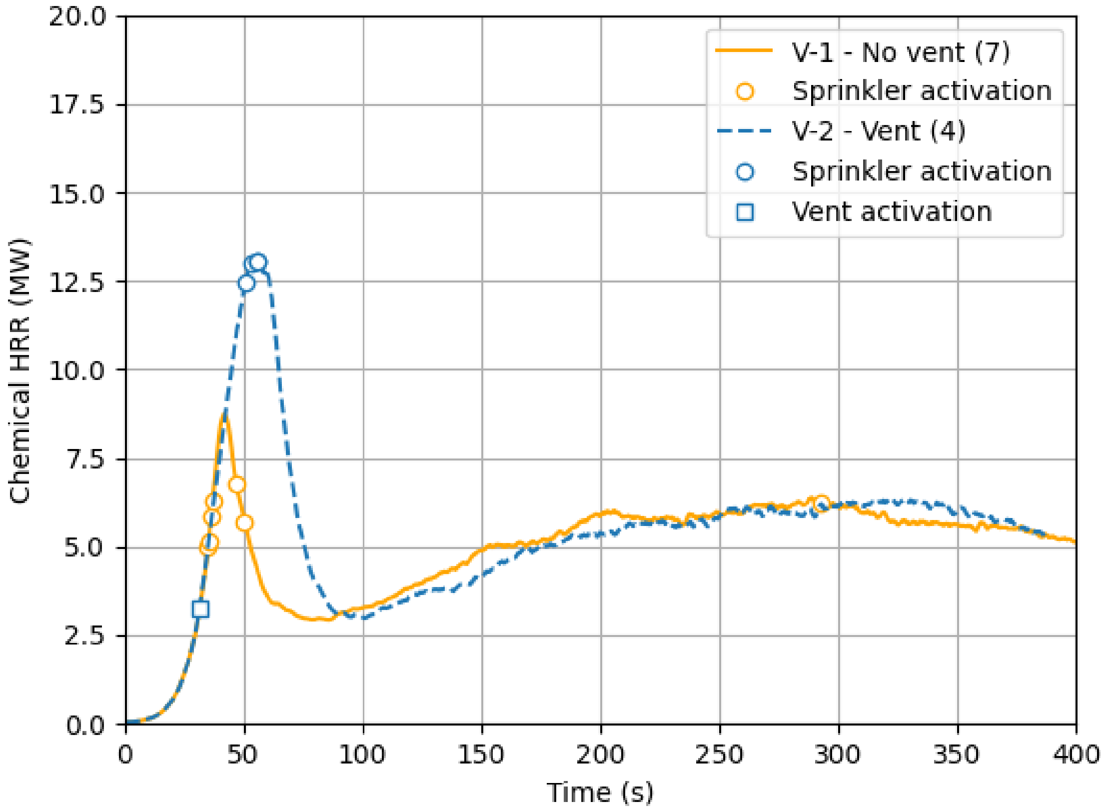


Figure 5-7: HRR and sprinkler and vent activation times for cases V-1 and V-2.

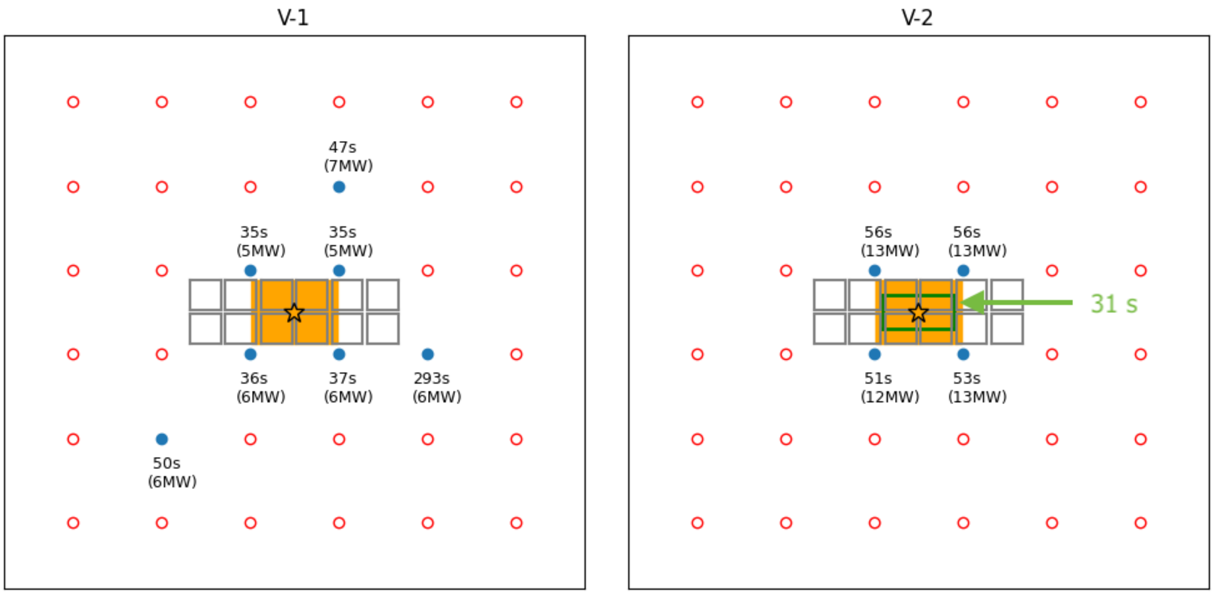


Figure 5-8: Sprinkler activation map and fire damage (orange shading) for unvented case V-1 (left) and vented case V-2 (right). Green rectangle, arrow, and text indicated vent location and activation.

To better understand the dynamic interaction between the sprinklers and the smoke vent, the sprinkler thermal element temperature histories are presented in Figure 5-9. For case V-2, the smoke vent opens shortly before the first sprinkler activation would have occurred. This creates a 20 sec delay for the first-ring sprinkler activations (shown in purple) compared to the unvented case. The open smoke vent also slows the heating of the second-ring sprinklers. After the first-ring sprinklers have opened the fire is controlled and the ceiling cooled, preventing additional activations. For the unvented case, three second-ring sprinklers are opened despite the lower peak fire. The additional activations are due to the lack of a smoke vent, resulting in higher temperatures in the ceiling layer.

Figure 5-10 plots the fire size, vented sensible enthalpy, and vented unburnt fuel (left) and the vented sensible enthalpy as a fraction of the heat release rate within the occupancy (right). After the smoke vent opens, but before the sprinklers open, about 60-70% of the heat released from the fire is vented outside of the building. There is also a small fraction of unburnt fuel that is vented and burns outside of the building. After the sprinklers open, the vented fraction rapidly decreases to about 20-25%. The decrease in vented fraction is due to downward momentum of the sprinkler spray, which opposes the fire plume and pushes the fire product gasses away from the smoke vent.

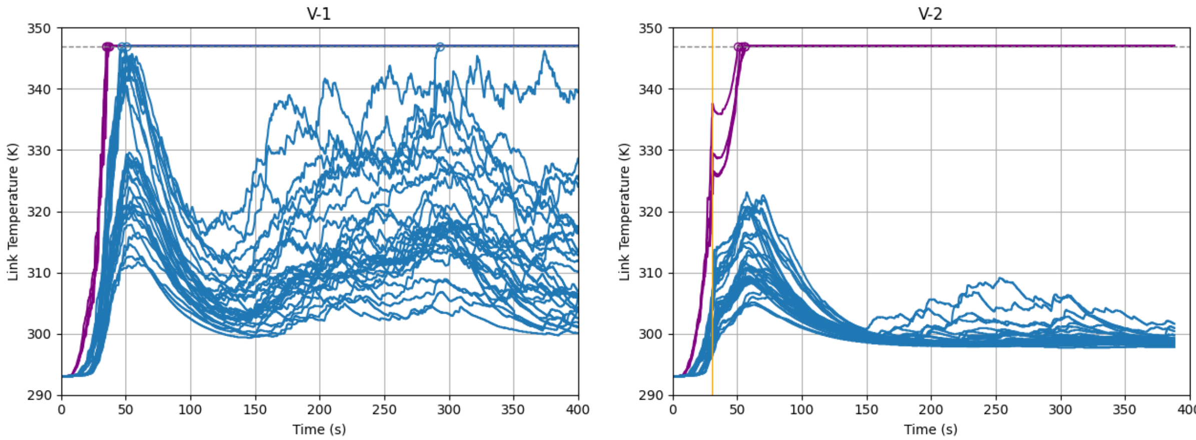


Figure 5-9: Sprinkler thermal element temperature history for vented case V-2 (right) and unvented case V-1 (left). Purple traces are the first-ring sprinklers, blue traces are the second- and third-ring sprinklers. The dashed horizontal line is the sprinkler activation temperature. The orange vertical line is the vent activation time for case V-2.

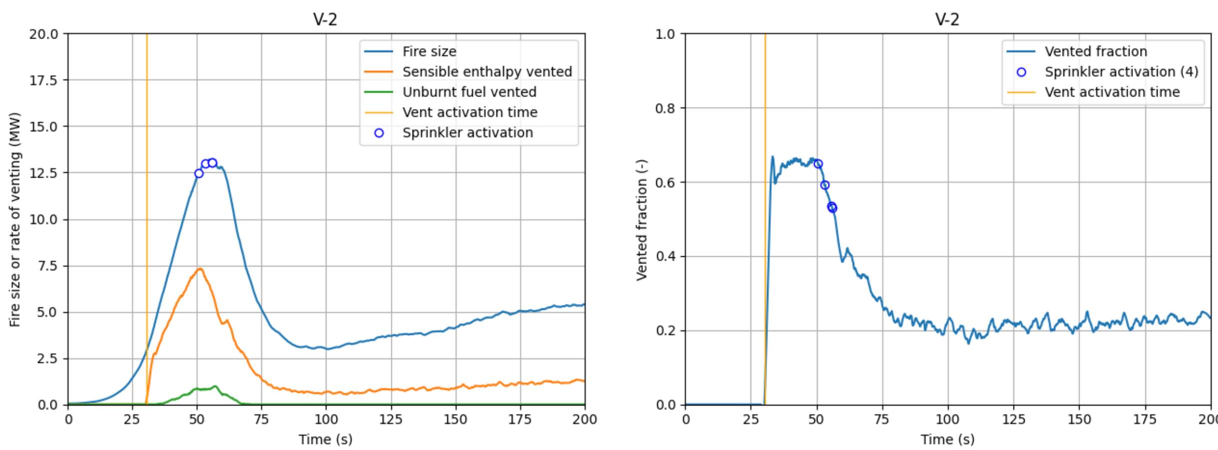


Figure 5-10: (left) Fire size and rate of sensible enthalpy and unburnt fuel venting. (right) Fraction of heat released inside building that is vented.

Figure 5-11 shows a visual comparison of cases V-1 and V-2 at key times: 31 sec, just before smoke vent activation in case V-2; 35 sec, just after first sprinkler activation in case V-1; and 51 sec, just after first sprinkler activation in case V-2. Each image shows the flame surface in the red-yellow scale, with the color, transparency, and emission based on the flame surface temperature. The smoke is represented by a volume rendering of the region exceeding a certain CO_2 mass-fraction threshold. The sprinkler spray is represented by particle data, where the size and orientation of each particle is derived from the particle diameter and velocity. The water film is extracted as a surface exceeding a film thickness threshold of 0.1 mm. The char layer is extracted as a surface colored by char mass-fraction. The sprinkler pipes, sprinklers, and the racking structure are shown for visualization purposes only and are not present in the FireFOAM simulations.

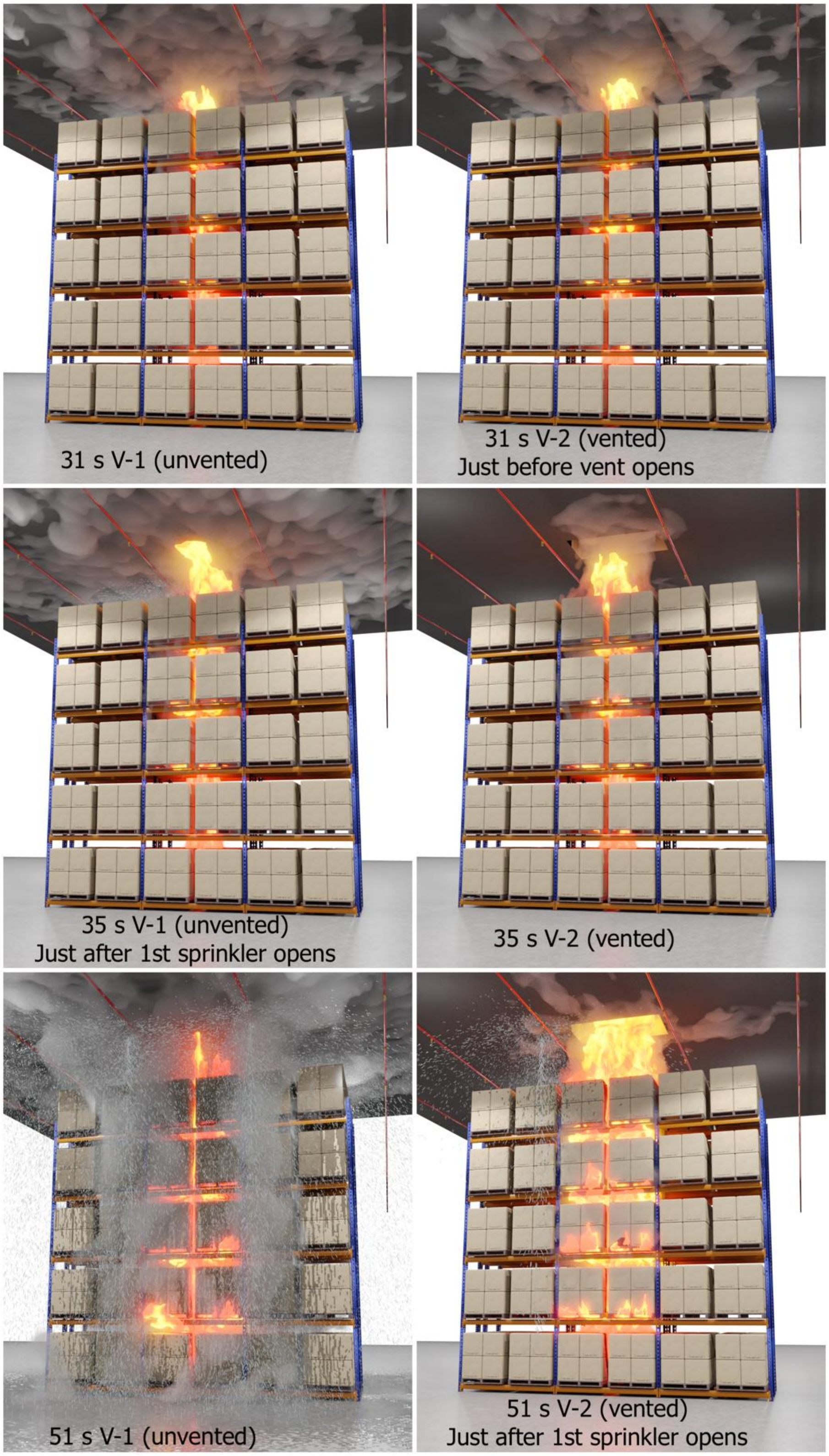


Figure 5-11: Comparison of vent and sprinkler activation sequence for vented (left column) and unvented (right column) cases. Top row shows 31 sec, middle row 35 sec, bottom row 54 sec post ignition.

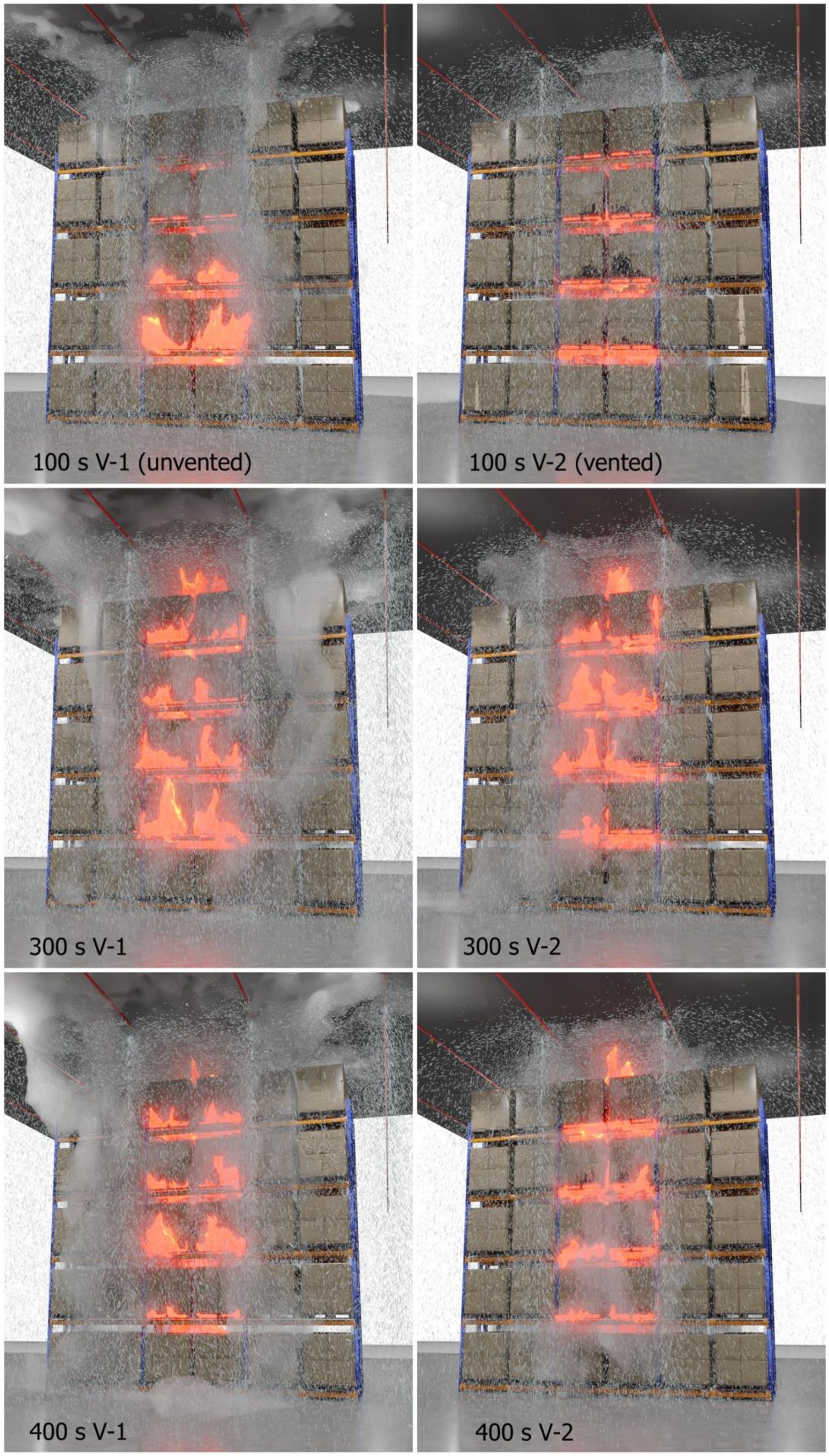


Figure 5-12: Un-vented case V-1 (left) and vented case V-2 (right) at 100, 200, and 400 sec post ignition.

At 31 sec, the fire has grown vertically and is starting to impinge on the ceiling, leading to vent activation in case V-2. At 35 sec, the open smoke vent in case V-2 has significantly reduced the hot gasses in the ceiling layer compared to the unvented case V-1 which has one open sprinkler. By 51 sec, the fire in case V-2 has significantly increased in size and spread laterally, resulting in the fire plume not being completely contained within the vent area and leading to sprinkler activation. By this time six sprinklers are open for case V-1 and the fire size is significantly reduced. Figure 5-12 shows a visual comparison of cases V-1 and V-2 at 100, 300, and 400 sec after ignition. In both cases, the fire does not spread far from the ignition location and there is only limited flaming in the aisle space.

5.2.1.4 Model and Test Comparison

The model and test results are generally in good agreement:

- The automatic smoke vent can open before the sprinklers and delay the first sprinkler activation, resulting in a larger peak fire size.
    - The relative timing of vent and sprinkler activations, and the impact on the apparent fire size is consistent, see Figure 5-13.
    - Once 3-4 first-ring sprinklers are open, the fire is suppressed.
- In all tests and simulations, the fire was successfully controlled by the sprinkler design.
    - The fire does not spread towards the end of the array or jump the aisle space (significant flaming in aisle space not observed in simulations which did not include a target array).
    - Ceiling steel temperatures are far from failure.
    - Number of sprinkler activations does not exceed design.
- Slightly more sprinklers are activated in the unvented case (tests – 12 and 5, model – 6) compared to the vented case (tests – 6 and 9, model – 4).

The main difference between the tests and the simulations is related to sprinkler delay/skipping in the first-ring sprinklers, which was prominent in the tests but not in the simulations. This explains the higher number of sprinkler activations in the tests. The skipping/delay behavior in the tests was not due to the presence of a smoke vent, in fact skipping/delay was less prominent in the vented cases, potentially due to the larger fire size at first sprinkler activation.

It is not clear why the simulations did not predict sprinkler skipping/delay, but it may be due to the inherent symmetry in the ignition scenario and perturbations which exist in the test but not in the model, e.g., asymmetric entrainment of ambient air, sprinkler-to-sprinkler variations, non-idealities in the ignition location, etc. In the simulation, the entrainment pattern, ignitor position, and sprinkler system, is perfectly symmetrical and so a staggered sprinkler activation is less likely. Without a staggered sprinkler activation sequence, sprinkler delay/skipping due to droplet impingement on neighboring thermal elements is less likely.

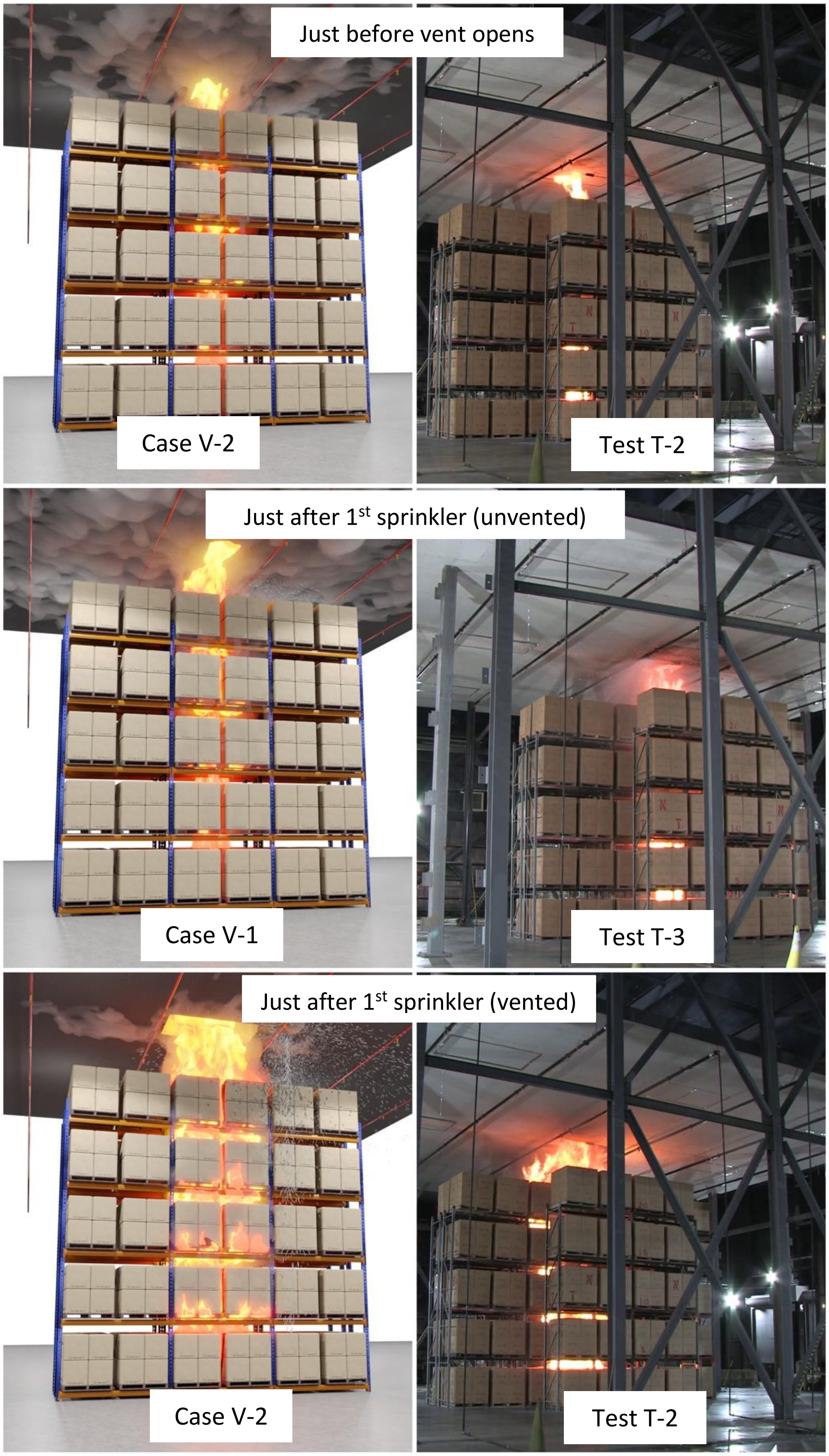


Figure 5-13: Snapshots of model (left) and test (right) key times for vented and unvented conditions.

Overall, the comparison between the tests and simulations validates the model in terms: I) predicting the success/failure of the main fire suppression dynamics in an unvented case, and, II) predicting the impact of the smoke vent on the fire suppression relative to the unvented case. The full-scale tests and the simulations lead to a consistent set of conclusions regarding the interaction of smoke vents and sprinklers:

- For a worst-case ignition scenario, it is possible for automatic smoke vents to open before first sprinkler activation, delaying that activation and increasing the peak fire size.
- However, this does not lead to a worse outcome. The fire is controlled with a similar or smaller number of sprinkler activations.

5.2.2 Tests and Simulations at Marginal Protection Point

5.2.2.1 Unvented and Vented Test Results

The unvented (T-6) and vented (T-7) Class 2 tests are presented together in this section. These tests were conducted with Class2 commodity protected by K160 (K11.2) upright sprinklers at 1.7 bar (25 psig). Figure 5-14 shows the sprinkler activation maps and fire damage areas for both cases. In T-6, 10 sprinklers activated and controlled the fire, in Test T-7 18 sprinklers opened and controlled the fire. Since the design limit for this condition is 20 sprinklers in NFPA 13 [10], based on number of sprinkler activations T-6 was a success. However, T-7 would be considered a failure since it does not offer an acceptable safety margin between the number of sprinklers that operated in an idealized laboratory setting and the protection option. The protection option is 20 sprinklers and, therefore, no more than 13 sprinklers (13 + 50 % × 8 = 19.5) should operate during the test. In both cases, the fire did not spread to the end of the main array or spread to the far side of the target array, although aisle jump occurred in T-7 on both the North and South. The ceiling steel temperatures did not approach the failure criteria. Table 5-6 summarizes the key events and the failure criteria for both cases.

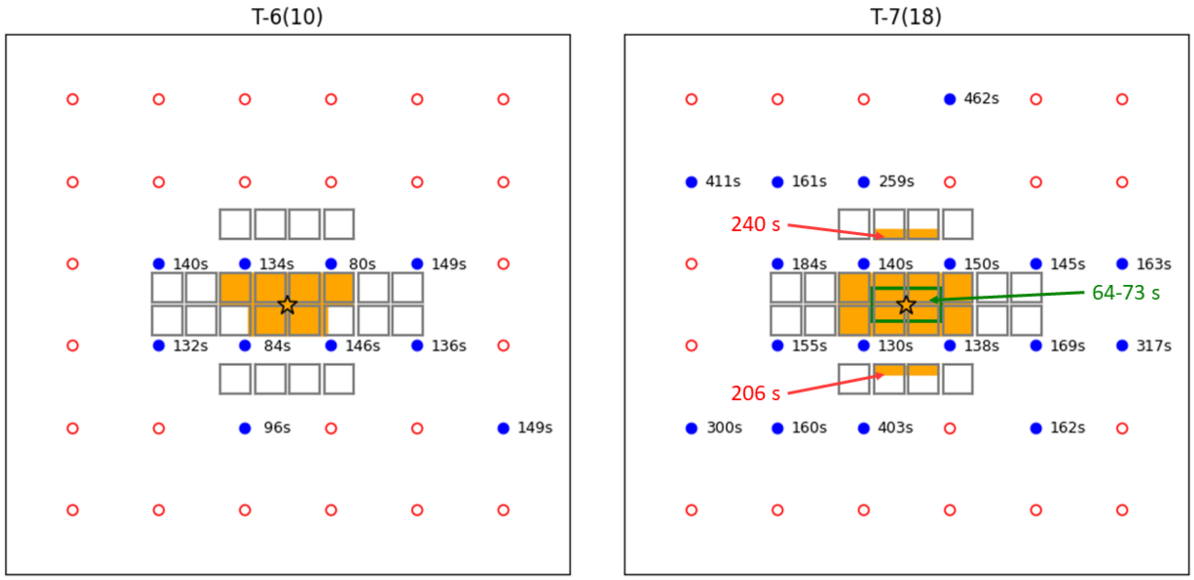


Figure 5-14: Sprinkler activation map and fire damage area (orange shading) for unvented Test T-6 (left) and vented Test T-7 (right). Green rectangle, arrow and text indicate vent location and activation time. Red arrow and text indicate target ignition time.

Repeat tests were not performed for the following reasons:

- Unlike the CUP tests, sprinkler skipping did not play an important role in the outcome of T-6 or T-7. In both tests, the first-ring sprinklers opened before, or within 40 sec of any second-ring sprinkler.
- The lower priority of the marginal Class 2 condition relative to the CUP tests.

Table 5-6: Key events and evaluation of failure criteria for Class 2 Tests T-6 and T-7.

Case Name	Vent time (sec)	First sprinkler time (sec)	# of Sprinkler activations	Exceed failure criteria?			
				Fire spread main array	Fire spread target array	Ceiling steel temperature	Activation # (limit 10)
T-6	-	80	10	No	No	No	No (Borderline)
T-7	64-73	130	18(12*)	No	No	No	Yes

5.2.2.2 Effect of Smoke Vent on Test Results

Figure 5-15 presents snapshots of Tests T-6 (left) and T-7 (right) at key times (relative to ignition): 64 sec, just before when the smoke vent opens in Test T-7; 77 sec, just before the first sprinkler opens in Test T-6; and 130 sec, just before the first sprinkler opens in Test T-7. At 64 sec after ignition, the fire has grown vertically in the central flue space and flames are just visible above the storage array (see inset pictures taken from a different video camera). By 77 sec, significant flaming is observed above the storage array. The fire plume passes through the open vent for T-7, but impinges on the ceiling for T-6, triggering the first sprinkler activation. By 130 sec after ignition, the fire in T-7 has spread laterally until the fire plume is no longer contained within the vent area, leading to increased heating in the ceiling layer and the first sprinkler activation in T-7. The dynamics of early fire growth, vent activation, and first sprinkler activation delay, are essentially the same as described in Section 5.2.1 for the CUP tests.

For T-6, following the first sprinkler activation, the fire gradually spreads, activating nine more sprinklers before the fire is contained and brought under control. For T-7, the larger fire size at first sprinkler activation, combined with the borderline sprinkler protection (as seen in Test T-6), leads to an increase in fire damage area and number of sprinkler activations. The larger fire ignited the South and North target arrays at 206 and 240 sec, respectively, and activated a total of 18 sprinklers (12 occurred before target ignition).

These results show that, for a case where the sprinkler protection is marginal, the delay in first sprinkler activation can increase the fire damage area and number of sprinkler activations. The increase in number of sprinkler activations classifies Test T-7 as a failure, although the fire was successfully controlled due to the adequate water supply in the LBL.

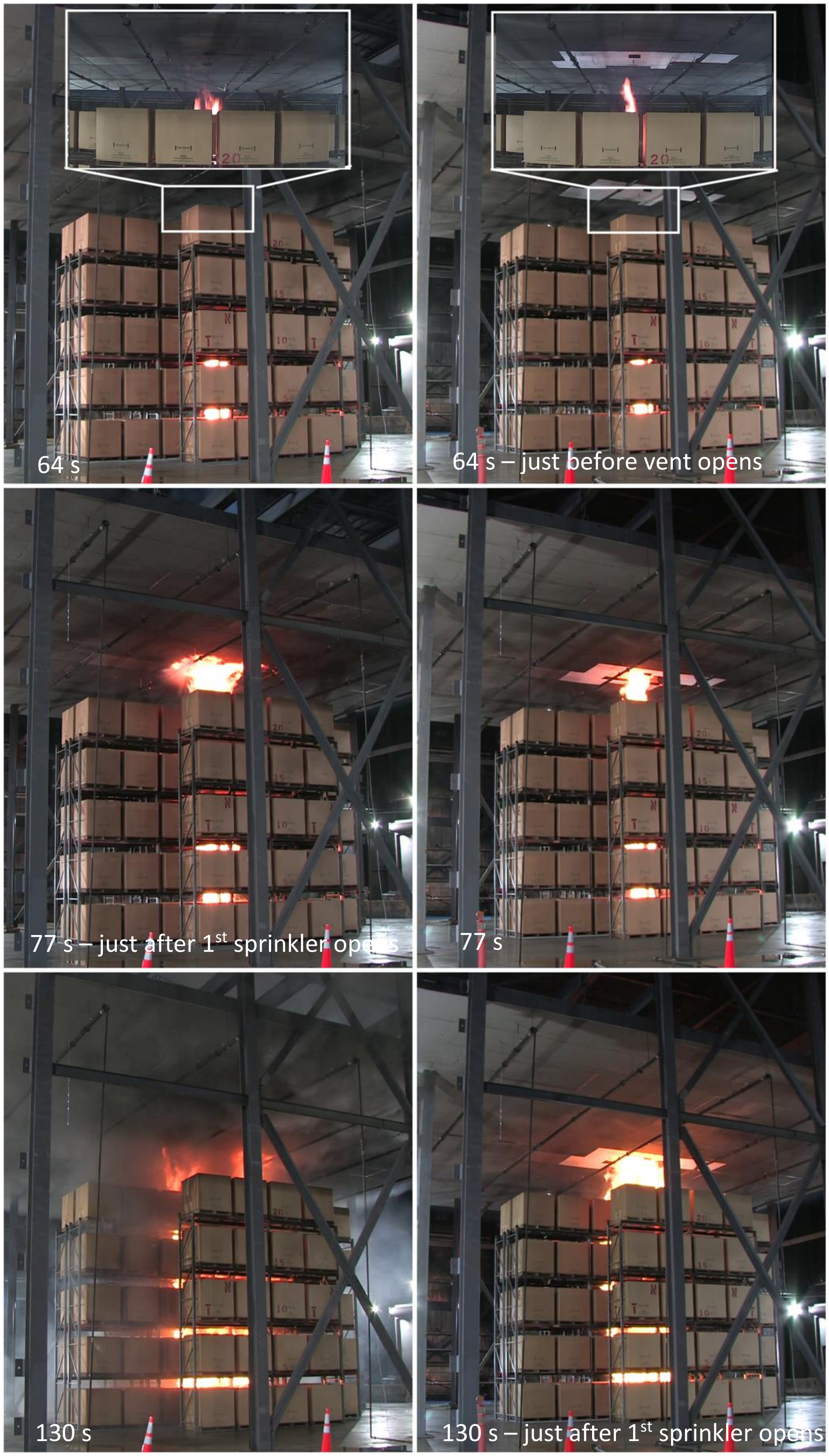


Figure 5-15: Snapshots of unvented Test T-6 (left) and vented Test T-7 (right) at key times.

5.2.2.3 Model Results

Figure 5-16 shows the fire size and timing of the sprinkler and vent activations for the model cases V-3 (unvented) and V-4 (vented). Figure 5-17 presents visualizations of cases V-3 and V-4 at first sprinkler activation and vent activation. For case V-3, the first sprinkler activated at 84 sec when the fire emerged above the rack-storage array and the HRR was approximately 2 MW. Two sprinklers activated and successfully controlled the fire which was below 0.5 MW after 150 sec. The simulation was ended at 180 sec as the fire was highly unlikely to recover. For case V-4, the smoke vent activated at 80 sec, just before the first sprinkler would have activated. The smoke vent removed heat from the ceiling layer, delaying the first sprinkler activation until 142 sec and allowing the fire to grow to a peak of 11 MW before all four first-ring sprinklers activated. These sprinklers reduced the fire below 2 MW by 200 sec, containing it to the concealed spaces between pallet loads, near the ignition location. From 200 to 400 sec, the fire size gradually increased due to the ignition of the timber pallets in the concealed spaces, but did not spread away from the ignition location. From 400 sec onwards, the fire size gradually decreased due to a lack of dry, unburnt fuel.

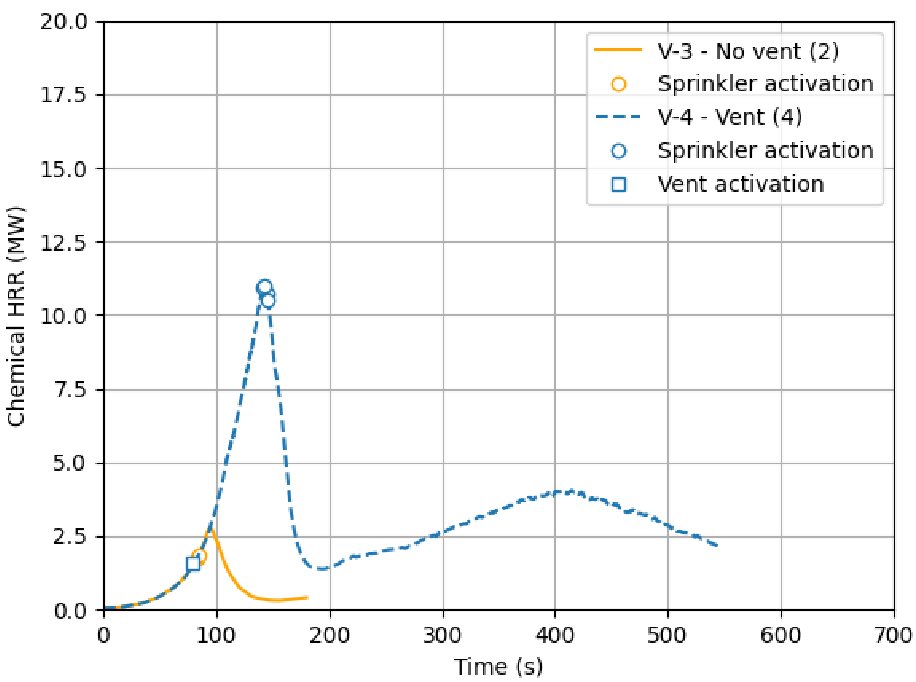


Figure 5-16: Fire size and sprinkler (circle) and vent (square) activations for cases V-3 and V-4. Number of sprinkler activation in legend parenthesis.

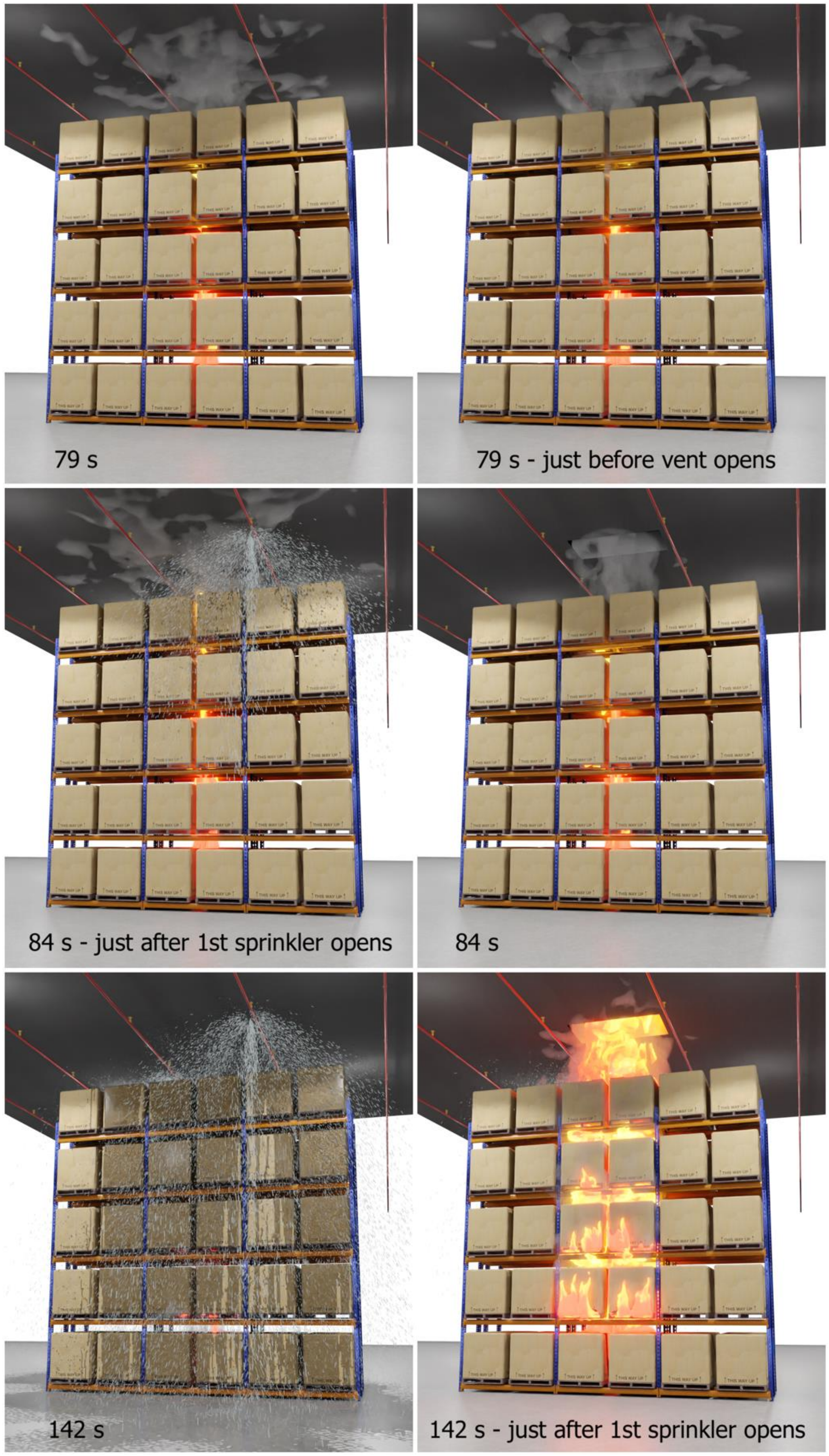


Figure 5-17: Visualization of model results from unvented case V-3 (left column) and vented case V-4 (right column) at key times (see annotations).

Figure 5-18 shows the sprinkler activation maps and extent of fire damage and Figure 5-19 shows the sprinkler link temperature histories. For case V-3, the two first-ring sprinklers that did not activate were very close to opening but were quickly cooled by the two open sprinklers and prevented from opening. For case V-4, the fire was significantly larger at the time of first sprinkler activation (11 MW vs 2 MW for case V-3). This activated all four first-ring sprinklers, but the cooling effects of the vent and open sprinklers prevented any additional sprinkler activations.

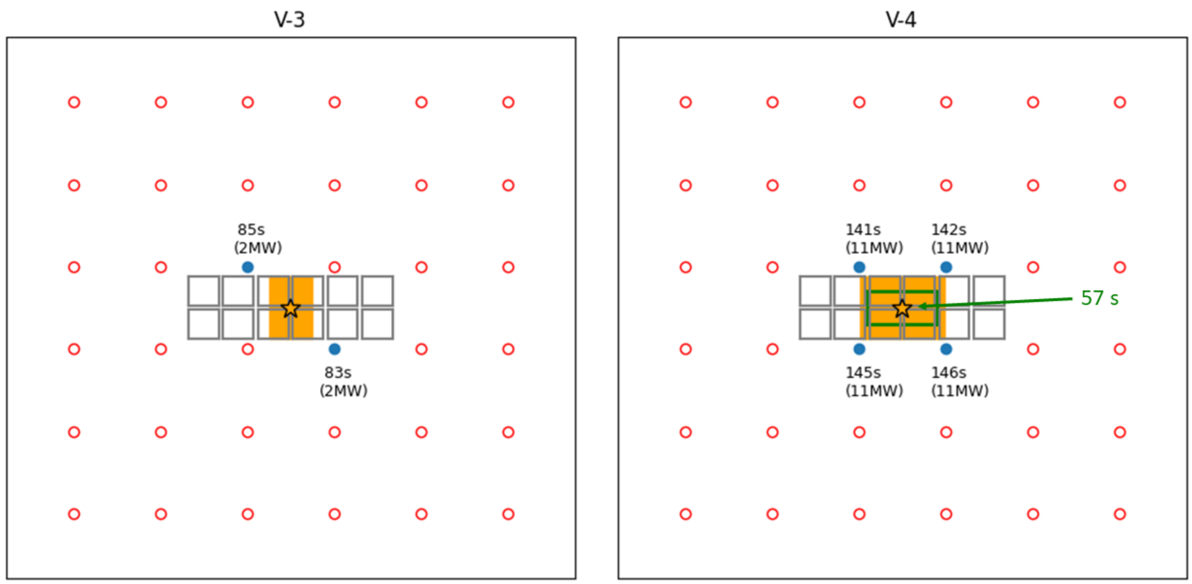


Figure 5-18: Sprinkler activation map and fire damage area (orange shading) for Class 2 validation cases. Green rectangle, arrow and text indicate vent location and activation time.

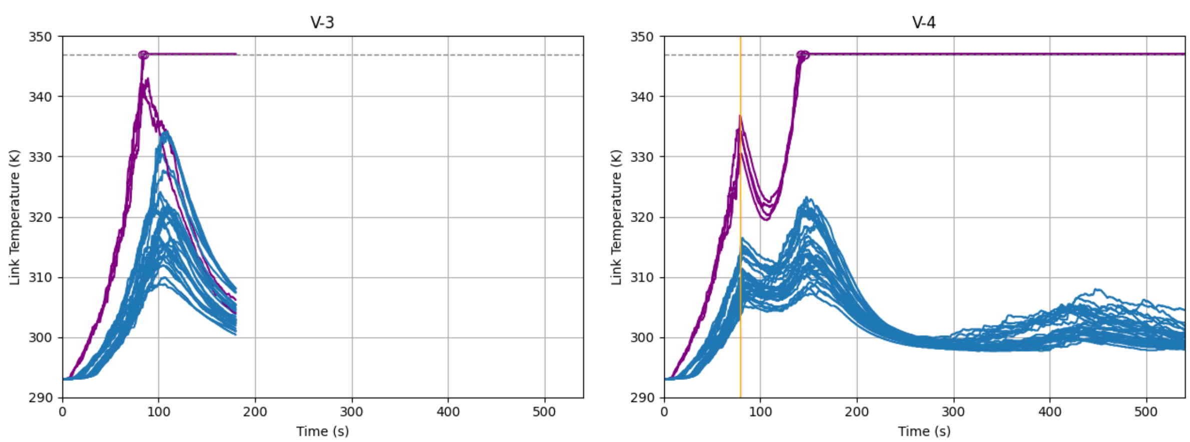


Figure 5-19: Temperature history of sprinkler thermal elements. First-ring sprinklers in purple, other sprinklers in blue. Vertical orange line is vent activation time for V-4. Dashed gray line is sprinkler activation temperature. Circles show sprinkler activation times.

Figure 5-20 shows the heat removed from the building by the smoke vent for case V-4. The behavior is essentially the same as reported for case V-2 with CUP commodity. Between the vent and first sprinkler activations, the smoke vent removes approximately two thirds of the heat from the fire, after the sprinkler activations, the fraction of heat removed by the vent reduces to approximately one fifth.

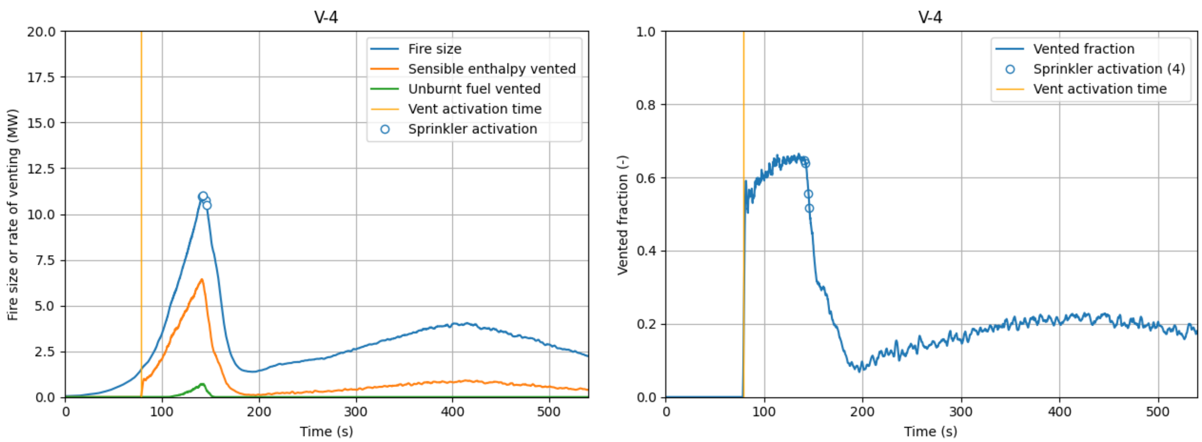


Figure 5-20: (left) Total HRR, rate of vented sensible enthalpy and unburnt fuel. (right) Fraction of HRR within building vented.

Cases V-3 and V-4 used the same water pressure, but over-predicted suppression, compared to the corresponding tests. This may be due to the inherent difficulty in predicting cases on the border between successful and failed suppression without model tuning, and/or the uncertainties of model inputs/parameters. Additional cases V-5 and V-6 were simulated at 0.5 barg (7 psig) to test the model sensitivity with decreasing water supply and to see if the model has the correct trend compared to the test.

Figure 5-21 presents the HRR and sprinkler activation times for case V-5 (unvented) and case V-6 (vented). For case V-5, the fire reaches 2 MW before activating all four first-ring sprinklers. The open sprinklers reduce the fire size, but significant burning remains due to the lower water density compared to case V-3. The fire gradually recovers, peaking at 3 MW, but does not activate additional sprinklers or spread along the array due to the pre-wetting of adjacent commodities. For case V-6, like case V-4, the vent opens and delays the first sprinkler activation until the fire exceeds 11 MW. All four first-ring sprinklers open nearly simultaneously, reducing the fire size to 3 MW by 200 sec. As with case V-5, the fire recovers due to the insufficient water density, reaching 8 MW by 420 sec. Unlike case V-5, the fire gradually spreads along the array and activates an additional eight sprinklers between 500 and 600 sec. After this time, the fire size gradually decreases due to the lack of dry commodity near the ignition location, but the fire continues to slowly spread along the array. It is possible that the fire would reach the end of the array and activate additional sprinklers, but the simulation was not run longer than 700 sec.

Cases V-5 and V-6 have a good qualitative agreement with Tests T-6 and T-7 in terms of the impact of the smoke vent. For both the model and test results, the smoke vent delays sprinkler activation and results in a significantly higher number of sprinkler activations and a larger fire damage area. This result shows that, although the model over-predicts suppression for this scenario, the trend is in good agreement with the test results. Furthermore, comparing simulations V-3 and V-4, with simulations V-5 and V-6, and Tests T-6 and T-7, in terms of the impact of the smoke vent, the conclusions are consistent: for storage occupancies with marginal sprinkler protection, in the worst-case ignition scenario (which has a very low probability of occurring) the smoke vents can delay the first sprinkler operation, lead to a larger peak fire size, and result in a larger number of sprinkler activations.

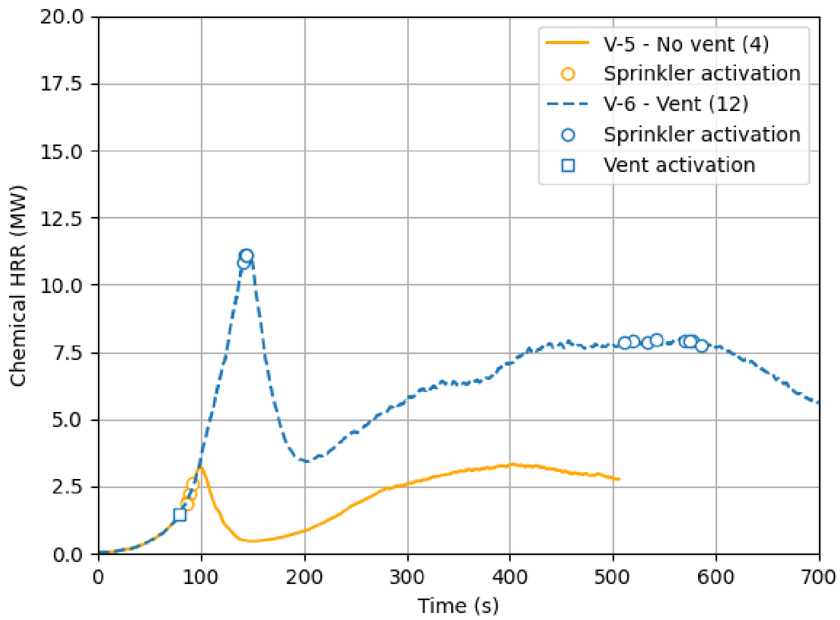


Figure 5-21: Fire size and sprinkler (circle) and vent (square) activations for cases V-5 and V-6. Number of sprinkler activation in legend parenthesis.

5.2.2.4 Comparison of Model and Test Results

The model and test results both show that marginally-protected Class 2 commodity with an automatic smoke vent placed over the ignition location can result in delayed first sprinkler activation, a larger peak fire size, an increased number of sprinkler activations, and increased fire damage. However, when the model was run at the same nominal conditions as the tests, the effect of the vent and the difficulty in suppressing the fire were significantly underpredicted. This indicates that caution is needed when applying the model to marginally-protected conditions. The additional simulations performed at a lower water pressure showed that the model could predict the correct trend. In that case, the model correctly showed that the delay in the sprinkler activation time and the larger peak fire size resulted in significantly more sprinkler activations and fire spread along the commodity array. Despite the discrepancy between the model and test, the dynamics of the vent and sprinkler activations are essentially the same as observed for the CUP commodity in Section 5.2.1 and are adequately captured by the model.

5.3 Impact of Always-Open Vents on Sprinklers

Additional cases were simulated where the smoke vents were always open. This was done to: 1) consider the case where smoke vents are left open for building ventilation (creating a "vent opening" as defined in FM Global DS 2-0), and 2) maximize the impact of smoke vents on sprinklers.

The cases presented in this section are simulated for shorter durations compared to the validation cases, due to the larger number of cases and the limited computational resources. Each case was simulated until 2 minutes post ignition.

5.3.1 Array of Always-Open Vents with Draft Curtain

Simulations were performed with a draft curtain surrounding a 45.7 x 45.7 m (150 x 150 ft) fire area, with a 5 x 5 array of 3 m^2 (32 ft^2) always-open smoke vents, resulting in a vented ratio of 3.1%. The ceiling height was 9.1 m (30 ft) and the draft curtain depth was 20% of the ceiling height. All tests used 7.6 m (25 ft) storage height of CUP commodity protected by K240 (K16.8) sprinklers at 2.4 bar (35 psi), which matches the validation condition in Section 5.2.1. Table 5-7 summarizes the simulated cases.

Table 5-7: Matrix of simulations with array of always-open vents and a draft curtain.

Case Name	Ignition location with respect to rack	Ignition location with respect to sprinklers	Vent offset distance from ignition
O-1	Center	A4	No vent
O-2	Center	A4	0 m (0 ft)
O-3	Center	A4	3 m (10 ft)
O-4	Center	B2	No vent
O-5	Center	B2	0 m (0 ft)
O-6	Center	B2	3 m (10 ft)
O-7	Offset	A4	No vent
O-8	Offset	A4	0 m (0 ft)

Figure 5-22 shows the chemical HRR and sprinkler activations for all cases. In all cases, enough sprinklers activate to reduce the fire size below 5 MW by 2 minutes post ignition, consistent with the validation cases in Section 5.2.1. Additional activations are possible, but the results are qualitatively consistent with the validation case that had a single, automatically operated smoke vent and no draft curtains. For the first 2 minutes simulated in these cases, fewer sprinkler activations were observed with the smoke vent directly above the ignition location compared to the unvented cases and the cases with the 3 m (10 ft) offset. The reason for this is that the smoke vents remove a portion of the heat from the ceiling layer which, when combined with the suppression effect from the first ring of sprinklers, prevents additional sprinkler activations within the first 2 minutes post-ignition.

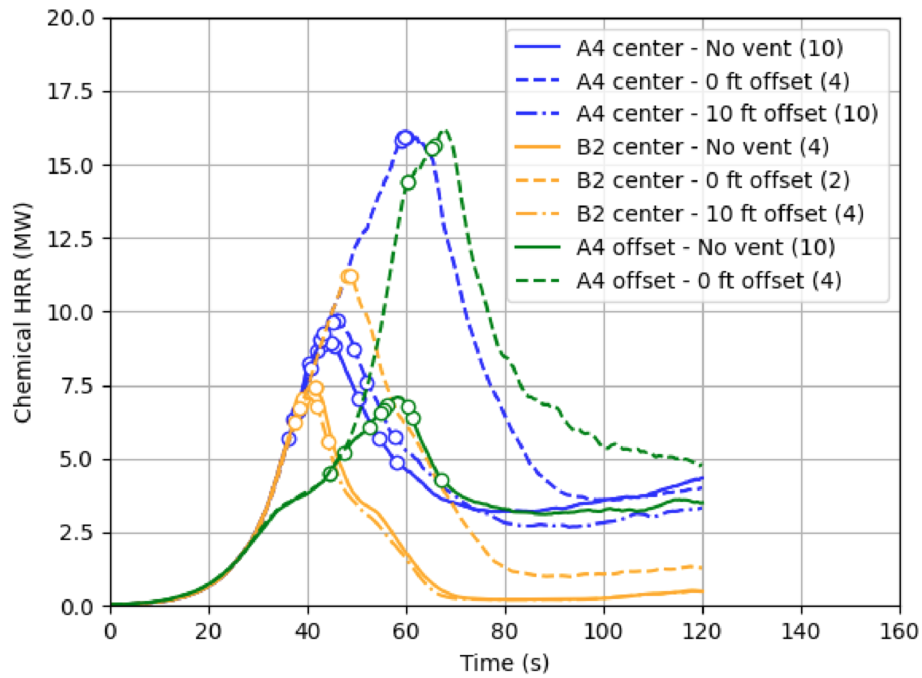


Figure 5-22: HRR and sprinkler activations for cases O-1 to O-8. Sprinkler activations marked with circles.

Figure 5-22 shows that the effect of the smoke vent is not very sensitive to the details of the ignition scenario. Comparing A4 and B2, and comparing center and offset ignition, the smoke vent results in a delay of about 20 sec for the first sprinkler activation. This leads to a peak fire size that is about 50% larger than the unvented case but, once the first ring sprinklers are activated, the fire size of the vented and unvented cases quickly converge. Due to the relative location of the A4 and B2 sprinklers, the peak fire size is larger for the A4 cases. The fire initially grows slower for the offset ignition case, but the effect of the smoke vent is very similar.

The effect of the smoke vent quickly decreases with increasing offset distance for both A4 and B2 ignition. With increasing offset distance, the fire plume does not impinge on the vent area and so a much smaller fraction of heat is removed from the ceiling layer. This results in an identical number of sprinkler activations, and nearly identical HRR curves for the unvented cases compared to the 3 m (10 ft) offset cases (solid and dot-dashed curves in Figure 5-22, respectively).

Figure 5-23 shows the sprinkler activation maps for cases O-1 to O-8. These maps support the observation that a smoke vent directly above the ignition location will delay the first ring of sprinklers, resulting in a larger peak fire, but that the fire will still be controlled and that there is likely to be fewer sprinkler activations overall due to the removal of some heat from the ceiling layer. When the smoke vent is offset, the sprinkler activation pattern in the second ring may change, but the same number of sprinklers open compared to the unvented case and the protection remains effective.

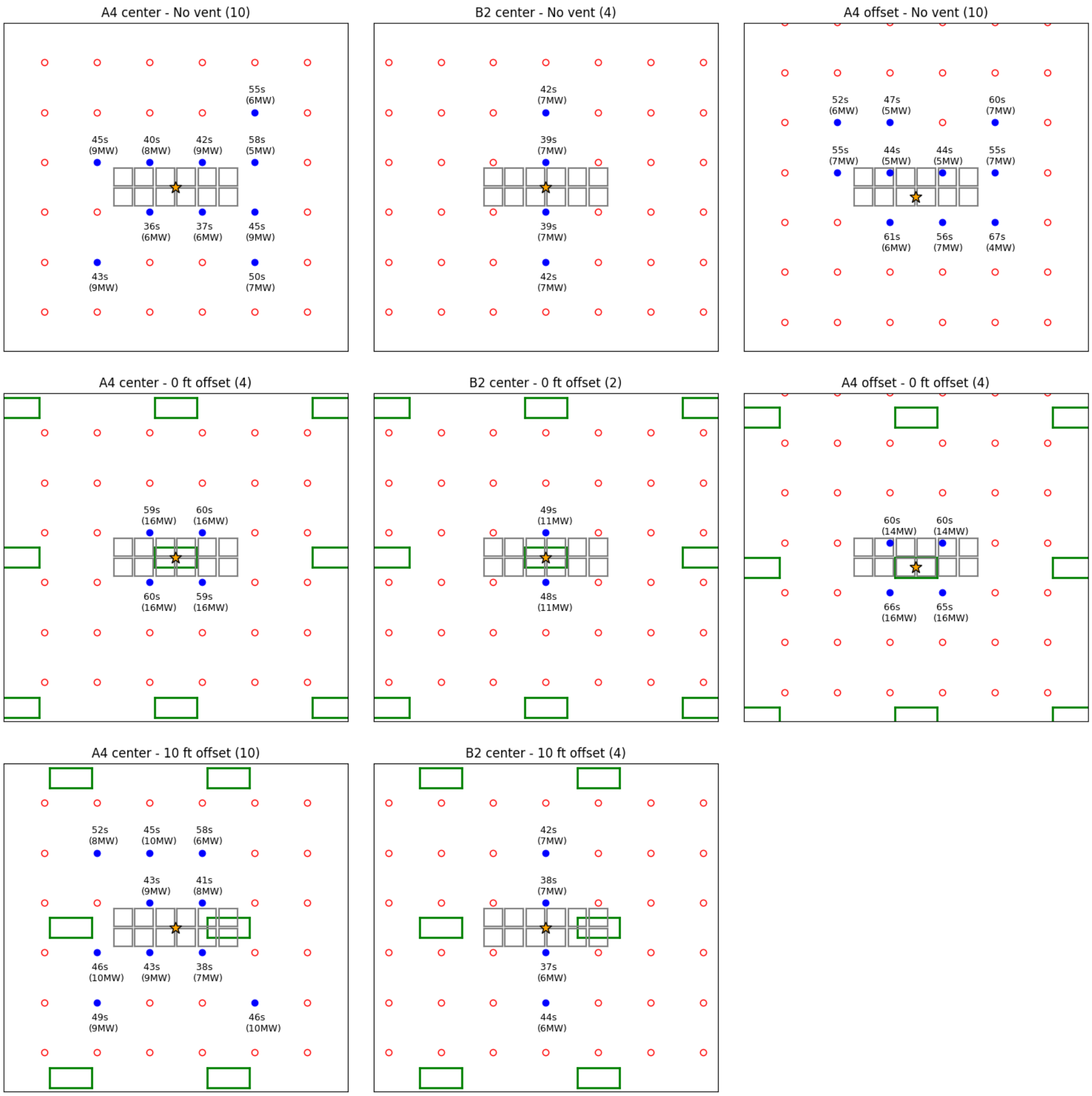


Figure 5-23: Sprinkler activation maps for A4 center ignition (left column), B2 center ignition (middle column), and A4 offset ignition (right column). Yellow star is the ignition location, green rectangles are the vent locations, red/blue circles are inactive/active sprinklers, respectively. Text adjacent to active sprinklers states time and HRR when activation occurs.

Directly comparing cases O-1 and O-2 to the validation cases V-1 and V-2 in Figure 5-24, the effect of an always open vent is like that of an automatic smoke vent which opens before the first sprinkler. The peak fire size is about 10% larger with an always open vent, due to a slightly longer delay in first sprinkler activation compared to the case with an automatic smoke vent, but in both cases the sprinkler protection is adequate to suppress the fire. There are differences in number of sprinkler activations, but these do not alter the conclusions drawn from the validation cases. The difference in number of sprinkler activations for the unvented cases O-1 and V-1 are due to the presence of draft curtains in case O-1, where case V-1 has no draft curtains and a much smaller ceiling section, like the movable ceiling in the LBL. These differences impact the development of the ceiling layer and therefore the number of sprinkler activations.

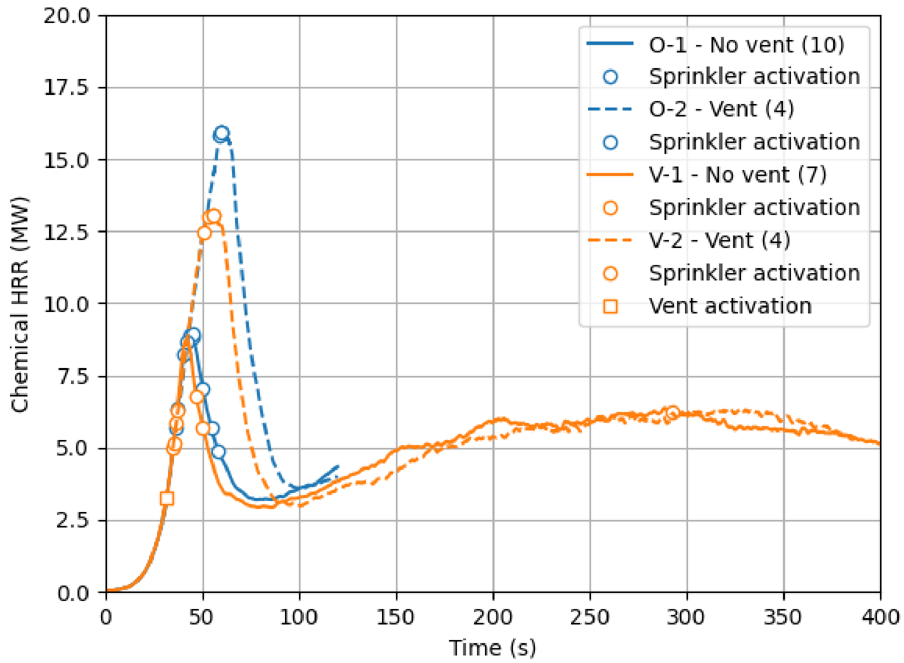


Figure 5-24: HRR and sprinkler activation comparison for cases O-1 and O-2 (blue) and validation V-1 and V-2 (orange). Sprinkler activations marked with circles. Case O-2 has an always open vent, case V-2 has an automatic vent (open time marked with square).

5.3.2 Parametric Variation of Test Conditions with Always-Open Vent

A second set of simulations was performed with always-open smoke vents, using a single smoke vent and a smaller ceiling section without a draft curtain, matching the ceiling configuration used in Tests T-1 to T-7 in the LBL. The purpose of these cases was to explore a wide range of commodity types, ceiling/storage heights and ignition scenarios and to make comparisons with the baseline, tested conditions.

Each case is simulated until first sprinkler activation and the impact of the smoke vent on the delay in first sprinkler activation times and vented heat is compared to the baseline condition. Table 5-8 summarizes the cases considering several parametric variations:

- Commodity type
    - Cases O-9 (CUP), O-10 (Class 2), O-16 (UUP) at 7.6/9.1 m (25/30 ft).

- Storage height
  - Cases O-11 (10.7 m (35 ft)) and O-12 (4.6 m (15 ft)) with CUP under a 12.2 m (40 ft) ceiling.
  - Cases O-15 (4.6 m (15 ft)) and O-16 (7.6 m (25 ft)) with UUP under a 9.1 m (30 ft) ceiling.
- Ceiling height
  - Cases O-9 (9.1 m (30 ft)) and O-11 (12.2 m (40 ft)) with CUP and 1.5 m (5 ft) clearance.
- Ignition location
  - Cases O-9 (center) and O-13 (offset) with CUP at 7.6/9.1 m (25/30 ft).
- Vent offset
  - Cases O-9 (0 m (0 ft)) and O-14 (1.5 m (5 ft)) with CUP at 7.6/9.1 m (25/30 ft).

Cases O-9 and O-10 correspond to the vented validation model cases V-2 and V-4, respectively, but with an always-open vent in place of an automatically opened vent.

Table 5-8: Matrix of cases with single, always open vent and no draft curtains.

Case Name	Commodity	Ignition Scenario	Vent offset distance from ignition
O-9	CUP (25/30 ft)	A4 Center	0 m (0 ft)
O-10	Class 2 (25/30 ft)	A4 Center	0 m (0 ft)
O-11	CUP (35/40 ft)	A4 Center	0 m (0 ft)
O-12	CUP (15/40 ft)	A4 Center	0 m (0 ft)
O-13	CUP (25/30 ft)	A4 Offset	0 m (0 ft)
O-14	CUP (25/30 ft)	A4 Center	1.5 m (5 ft)
O-15	UUP (15/30 ft)	A4 Offset	0 m (0 ft)
O-16	UUP (25/30 ft)	A4 Offset	0 m (0 ft)

Table 5-9 summarizes the results for each case. Cases O-9 and O-10 are essentially identical to cases V-2 and V-4 in terms of peak vented fraction, fire size at first sprinkler activation, and the delay in first sprinkler activation. This suggests that the impact of the vent opening before the sprinkler is not very sensitive to the vent activation time, since a smoke vent that is always open produces a similar effect to one that opens just before the sprinklers would have activated. Cases O-11 to O-16 show that changes to the baseline, tested conditions in terms of the commodity type, ceiling height, storage height, ignition location, and vent offset, reduce the impact of the smoke vent on the peak fire size and the sprinkler protection:

- Increasing ceiling height with fixed clearance height (O-11 vs O-9) slightly decreases the vented fraction and the delay in first sprinkler activation.

- Increasing the clearance height with fixed ceiling height (O-11 vs O-12) decreases the vented fraction and nearly eliminates the delay in first sprinkler activation time.
- Moving the ignition to rack-offset from rack-center (O-13 vs O-9) slightly decreases the vented fraction and halves the delay in first sprinkler activation time.
- Moving the smoke vent 1.5 m (5 ft) from the ignition location (O-14 vs O-9) halves the vented fraction and nearly eliminates the delay in first sprinkler activation time.
- Using UUP commodity compared to cartoned commodity (O-15 and O-16 compared to O-9 and O-10) significantly lowers the vented fraction and has a similar delay in first sprinkler activation.

Table 5-9 also reports that the vented sprinkler activation time is increased by a factor of 1 to 1.9 relative to the unvented case. This is consistent with the full-scale tests, in which the vents increased the first sprinkler activation time by a factor of 1.4 for the CUP tests (averaged over repeat tests) and a factor of 1.6 for the Class 2 tests. These delay factors should be compared to simulations O-9 (CUP) and O-10 (Class 2) which had a delay factor of 1.7 and 1.9, respectively. The larger delay factor in the simulation results is expected because they used vent openings whereas the tests used automatic smoke vents.

Table 5-9: Summary of results for cases O-9 to O-16.

Case Name	Commodity Storage / ceiling (ft)	Ignition	Vent offset (ft)	Vent Open				No Vent		Relative delay in first sprinkler activation due to smoke vent
				Peak Vented %	HRR @1st Sprink. (MW)	aHRR @1st Sprink. (MW)	First Sprink. Act. (sec)	HRR @1st Sprink. (MW)	First Sprink. Act. (sec)	
O-9	CUP 25/30	A4 Center	0	67%	15	5.5	57	4.6	34	1.7
O-10	Class 2 25/30	A4 Center	0	67%	11	3.5	141	1.8	75	1.9
O-11	CUP 35/40	A4 Center	0	63%	19	7.5	53	5	34	1.6
O-12	CUP 15/40	A4 Center	0	52%	8	5.1	54	4.1	52	1.0
O-13	CUP 25/30	A4 Offset	0	65%	9.2	4.0	54	4.5	44	1.2
O-14	CUP 25/30	A4 Center	5	33%	5.8	4.3	36	4.6	34	1.1
O-15	UUP 15/30	A4 Offset	0	47%	6.9	3.4	173	3.9	150	1.2
O-16	UUP 25/30	A4 Offset	0	37%	8.0	4.5	179	4.2	151	1.2

There are other sources of variability in sprinkler system design that impact sprinkler activation times, such as RTI, activation temperature, orientation, distance from ceiling etc. For context, the delay in sprinkler activation times due to smoke vents is commensurate with that expected due to the accepted variability in sprinkler RTI values. FM Approval Standard 2000 [20] defines QR sprinklers as having an RTI value less than 50 $m^{0.5}s^{0.5}$ (90 $ft^{0.5}s^{0.5}$), and FM Approval Standard 2008 [31] defines ESFR sprinklers (which use QR thermal elements) to have an RTI from 19 to 36 $m^{0.5}s^{0.5}$ (35 to 65 $ft^{0.5}s^{0.5}$), implying a factor of 1.9-2.6 variability. Ref. [31] also defines SR sprinklers to have an RTI between 80 and 350 $m^{0.5}s^{0.5}$ (145 and 635 $ft^{0.5}s^{0.5}$), a factor of 4.4 variability. Since the sprinkler activation time is inversely proportional to the RTI for a constant heating rate, the acceptable variability in first sprinkler activation time due to variations in the RTI value alone is commensurate with the worst-case effect of the vent opening. Additional sources of variation in sprinkler activation time due to accepted ranges of activation temperature and accepted variations in ceiling construction should also be considered. The worst-case delay in sprinkler activation time observed in this study due to the presence of a gravity smoke vent is no greater than what is expected from these other sources.

Overall, the results show that the tested conditions can be generalized to variations in ceiling height, clearance height, commodity type, ignition location, and vent offset distance. Changes to any of these parameters result in a similar or significantly lower impact of the smoke vent in terms of energy vented from the ceiling and delay of first sprinkler activation time.

5.4 Evaluation of FM Global DS 2-0 Recommendations

FM Global DS 2-0 contains three recommendations for the installation of sprinklers in occupancies with smoke vents (see Section 1.4 for details):

1. Install automatic smoke vents with standard response thermal elements that activate at 455 K (182°C or 360°F).
2. Delay smoke vent activation 20 minutes post first sprinkler activation.
3. Install additional sprinklers on 1.2 x 1.2 m (4 x 4 ft) density underneath the smoke vent (or underneath a false ceiling installed underneath the smoke vent).

These measures are intended to guarantee that the sprinklers closest to the ignition location are activated. In this section, options 1 (455 K (182°C or 360°F) smoke vent links) and 3 (sprinklers installed underneath the smoke vent) are evaluated at the same condition considered in the validation tests: CUP 7.6/9.1 m (25/30 ft) storage protected with K240 (K16.8) sprinklers at 2.4 bar (35 psi). Based on the available test and simulation data, option 2 is not analyzed because it is clear from all other tests and simulations that smoke vents opening 20 minutes after the first sprinkler activation will not significantly impact the fire growth or suppression dynamics.

Table 5-10: Summary of simulated cases for the evaluation of FM Global DS 2-0 recommendations.

Case Name	Baseline comparison case	Additional protection measures from FM Global DS 2-0
FM-1	V-2	Sprinklers installed under vent
FM-2	V-2	455 K (182°C or 360°F) vent activation temperature

Figure 5-25 plots the HRR and sprinkler and vent activation times for cases FM-1, FM-2, and the baseline validation cases V-1 (unvented) and V-2 (vented). Figure 5-26 plots the sprinkler activation map and fire damage areas for cases FM-1 and FM-2. For case FM-1, one sprinkler underneath the smoke vent activates at 28 sec when the HRR is 2.5 MW, suppressing the fire and reducing the HRR to 1 MW by 60 sec. The fire gradually increased back to 2.5 MW before activating the second sprinkler. After 2 minutes the fire was suppressed by the two open sprinklers. The opening of the in-vent sprinklers prevented the smoke vent from opening in case FM-1. For case FM-2, the smoke vent is activated at 34 sec compared to 31 sec for the baseline case V-2. The open smoke vent delays the first sprinkler activation until 46 sec compared to 51 sec for case V-2, and all four first-ring sprinklers are opened by 59 sec. The HRR peaks at 11 MW before it decreases to 3 MW by 90 sec, at which point the simulation was ended.

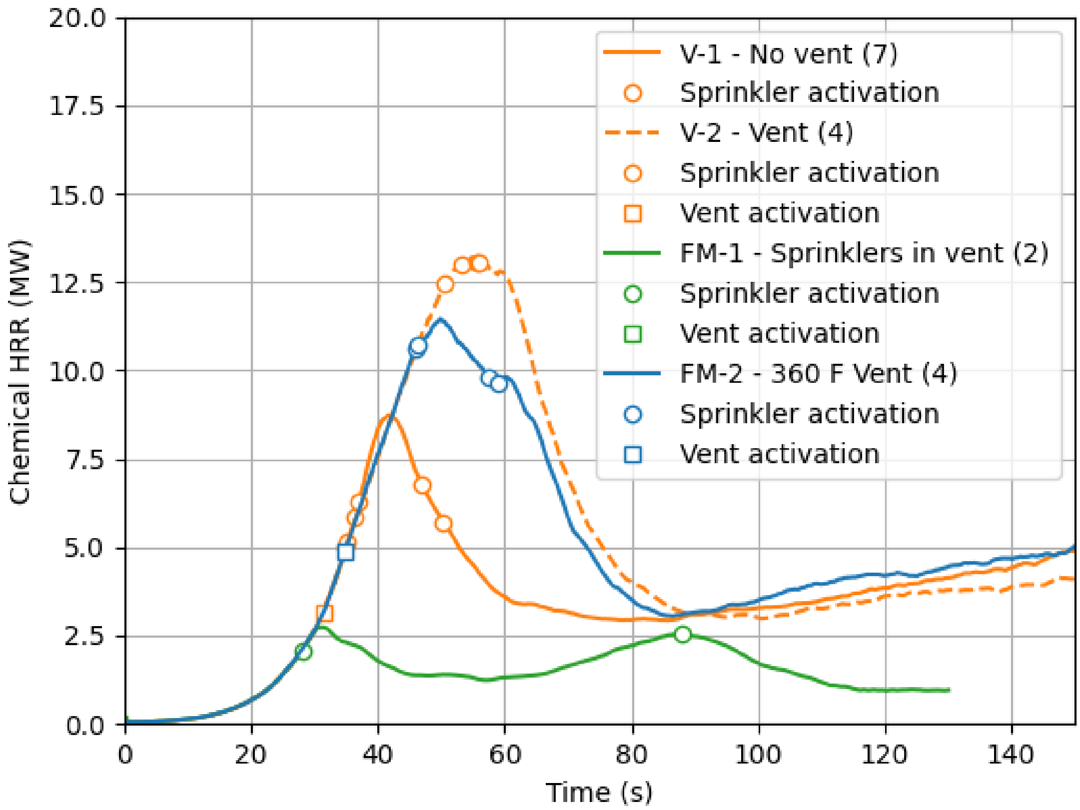


Figure 5-25: Fire size and sprinkler and vent activation times for cases with 455 K (182°C or 360°F) vent activation temperature (FM-2, green) and sprinklers installed under the vent (FM-1, blue) compared to baseline validation unvented (V-1, orange, solid line) and vented (V-2, orange, dashed line) cases. Circles indicate sprinkler activation time, squares vent activation times. Note: no vent activation for case FM-1.

The sprinkler link temperature histories are plotted in Figure 5-27 for cases FM-1 and FM-2. For case FM-1, the first open sprinkler is insufficient to suppress the fire, causing the second sprinkler under the vent to activate. Case FM-1 resembles an U1 ignition scenario where the proximity of the fire plume to the sprinkler leads to early activation when the fire is small. Once activated, the sprinkler spray pattern has a strong core which is directed to the seat of the fire. For case FM-2, the smoke vent opens just before the first sprinkler would have opened, resulting in a smaller delay in first sprinkler activation compared to the baseline condition outlined in Section 5.2.1.2, but it does not prevent the smoke vent from opening before the sprinklers. The smoke vent thermal element is heated very rapidly when placed directly above the ignition location, which explains why results are not very sensitive to vent activation temperature. If the ignition location had been moved, the smoke vent would not have opened.

Overall, the results show that placing sprinklers directly underneath the smoke vent results in earlier first sprinkler activation, a smaller peak fire size, no smoke vent activation, and few sprinkler activations. This is because this configuration is very similar to an U1 ignition scenario, which is less challenging for sprinkler protection, especially when the sprinkler spray pattern features a strong core. The results also show that increasing the vent activation temperature to 455 K (182°C or 360°F) may not significantly change the outcome compared to using an activation temperature consistent with NFPA 13 guidelines. In this case, the smoke vent activated slightly before the first sprinkler, but slightly perturbed conditions could have resulted in the smoke vent not opening and an outcome similar to the unvented baseline condition (case V-1).

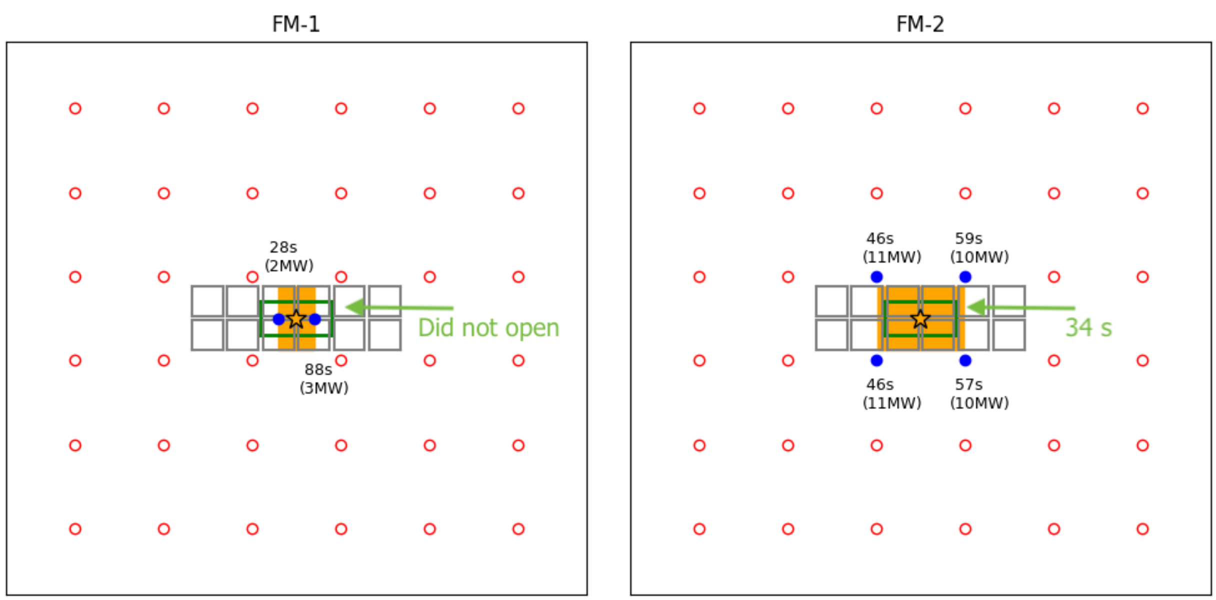


Figure 5-26: Sprinkler activation maps and fire damage extent for cases FM-1 (sprinklers in vent, left) and FM-2 (455 K (182°C or 360°F) vent link, right). Green rectangle, arrow and text indicated vent location and activation time.

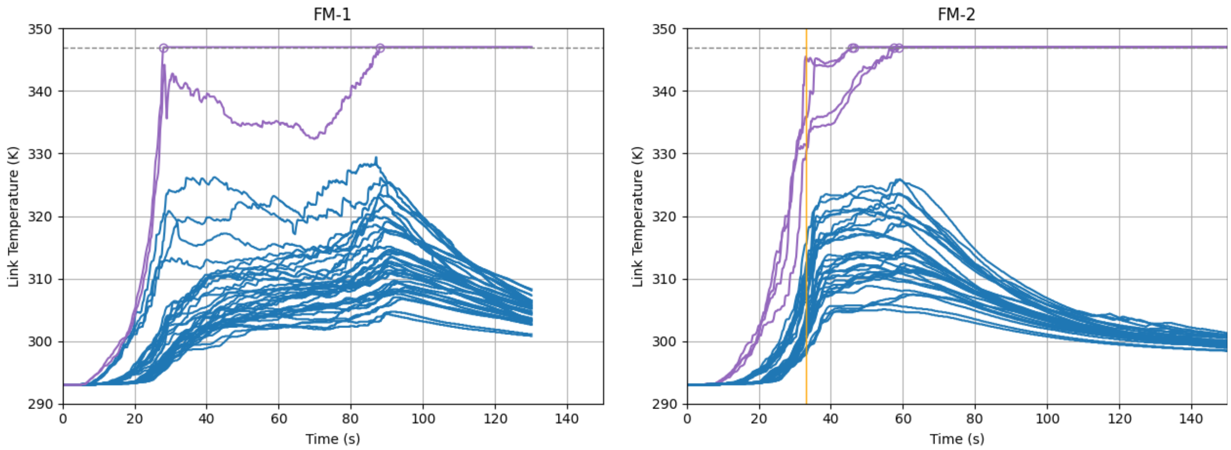


Figure 5-27: Sprinkler thermal element temperature histories for case FM-1 (sprinklers in vent, left) and case FM-2 (455 K (182°C or 360°F) vent link, right). First-ring sprinklers in purple, other sprinklers in blue. Vertical orange line is vent activation time for V-4. Dashed gray line is sprinkler activation temperature. Circles show sprinkler activation times.

6. Discussion

For unsprinklered storage occupancies, the results show that gravity smoke and heat vents (smoke vents) do not significantly reduce smoke and fire damage or significantly delay structural damage to the building. This is because smoke vents do not prevent flame spread or reduce the fire growth rate, and storage occupancies have an abundant and widespread supply of fuel. For both the vented and unvented cases, exposed steel elements at the ceiling are heated beyond FM Global's failure criteria within 4 minutes of ignition due to the rapid fire-growth and widespread flame impingement on the ceiling [20]. For this reason, smoke vents are not expected to aid manual firefighting in unsprinklered storage occupancies or to offer a property loss prevention benefit.

For sprinklered storage occupancies, the concern is that the smoke vents may impair the sprinkler protection, given that smoke vents provide essentially no property protection benefit *per se*. Both the tests and simulations show that, in a worst-case scenario (ignition directly beneath a smoke vent and as far as possible from the nearest sprinklers), the smoke vents can open first and delay the first sprinkler activation and result in a larger peak fire size, consistent with historical scale-model [2] and full-scale tests. However, for an adequately designed sprinkler system, e.g., one consistent with the recommendations in FM DS 8-9, no adverse impact was observed in terms of the sprinkler system performance as judged by the number of sprinkler activations and the extent of fire damage, which is in line with the limited historical testing discussed in Section 1.2. For a marginal sprinkler protection system, a moderate adverse impact was observed with increased sprinkler activations and fire damage area. This central finding, that smoke vents do not adversely impact adequately designed sprinkler systems, but can adversely impact marginal or deficient sprinkler systems, is consistent with the historical literature [2], [23].

The worst-case scenario analysis assumes a very unlikely combination of factors leading to the automatic smoke vent opening before the sprinklers: ignition directly below vent, ignition centered among four sprinklers, and a minimal clearance between the storage and ceiling. The probability analysis in Section 5.1 showed that this combination of factors is highly unlikely to occur and that in most cases the sprinklers will open before the smoke vents, suppress the fire (assuming an adequate sprinkler design) and prevent the smoke vent from automatically opening.

The main impact of smoke vents on sprinklers for the worst-case scenario, observed across most tests and simulations, is the delay in first sprinkler activation and resulting increase in peak fire size. The first sprinkler activation is delayed by a factor of 1.9 or less compared to the unvented case (see Table 5-9). This delay factor is within the range associated with the accepted variability in sprinkler design and ceiling construction (see Section 5.3.2).

The observations that 1) the worst-case scenario is highly unlikely, and 2) there was little impact of the smoke vents in the worst-case scenario, suggest that automatic smoke vents do not represent a significant hazard to adequately designed sprinkler protection systems.

The results from additional simulations, considering vents that are always open ('vent openings') were not significantly different from the results based on automatically opening smoke vents. So long as the smoke vent opens before the sprinkler, it can divert most of the heat in the fire plume out of the ceiling layer at early times (assuming ignition is directly beneath a smoke vent) and the sprinklers will not open until the fire has spread laterally and the fire plume has extended outside of the vent area. This has two implications. Firstly, that vent openings are not significantly more hazardous than automatic smoke vents. Secondly, that the risk posed by both automatic smoke vents and vent openings is expected to increase with vent size. The sensitivity to the smoke vent size is expected to be insignificant for small differences in smoke vent area (e.g. <20% area variations) but significantly larger smoke vents may pose a larger risk.

The evaluation of FM Global DS 2-0 risk improvement recommendations for occupancies with smoke vents (increase vent activation temperature, delay vent activation, and place sprinklers underneath the vent) showed:

- Increasing the vent activation temperature is the least likely to alter the outcome of the worst-case ignition scenario, because the smoke vent activation time is not very sensitive to the activation temperature when the vent link is placed directly over the ignition location. Nonetheless, in most cases, the 455 K (182°C or 360°F) activation temperature is expected to prevent the smoke vent from opening before the sprinklers in most cases.
- Placing sprinklers underneath the smoke vent on a 1.2 m (4 ft) spacing will prevent an automatic smoke vent from opening due to the early suppression of the fire and the cooling of the ceiling at the smoke vent location.
- Delaying the sprinklers 20 minutes after the first sprinkler activation will prevent the smoke vents from playing a significant role in the fire growth and suppression dynamics.

The results presented in this research show that these measures are unnecessary for vents 3 m^2 (32 ft^2) or smaller if the sprinkler system is otherwise adequately designed.

7. Conclusions

An assessment of gravity smoke and heat vents (smoke vents) in storage occupancies was conducted with a combined computer modeling and full-scale testing approach aimed to address gaps identified in prior work. For this work, FireFOAM simulations directed the full-scale testing effort and provided insight over a wider range of conditions than would have been possible with testing alone. The test results were used to evaluate the FireFOAM model and to provide an independent data set for drawing conclusions and making recommendations. Although there were some differences, the model predicted the correct physical trends and dynamic interactions between the fire, sprinklers, and gravity smoke vents. The conclusions independently drawn from testing and modeling were consistent and support the following statements:

1. Gravity smoke vents provide no property protection benefit to unsprinklered storage occupancies.
    a. Smoke vents do not slow vertical or horizontal flame spread.
    b. Smoke vents will not significantly delay the onset of structural damage. The fire will grow out of control due to the abundance and continuity of combustible material and flames will directly impinge on the ceiling, rapidly heating it to failure. E.g., simulated ceiling steel temperatures exceeded FM Global's failure criteria within 4 minutes for both the vented and unvented cases.
2. Gravity smoke vents are ineffective in sprinklered occupancies because sprinklers cool the ceiling layer and push down the smoke.
3. Gravity smoke vents, when individually limited to 3 m^2 (32 ft^2) do not significantly reduce the effectiveness of ceiling-level sprinkler protection. The worst-case ignition scenario for buildings with both smoke vents and sprinklers, in terms of the potential for the smoke vent to adversely impact the sprinkler system performance, is when the ignition occurs directly beneath a smoke vent and as far as possible from the nearby sprinklers. In this case, the following conclusion apply:
    a. The smoke vent can open before the first sprinkler, even when the vent activation temperature is higher than the sprinkler activation temperature. This can result in a delay in the first sprinkler activation time and a larger peak fire size.
        i. Where the sprinkler protection was adequate, e.g., if it complies with FM Global DS 8-9, no adverse impact was observed in terms of total number of sprinkler activations or fire damage.
        ii. Where the sprinkler protection was marginal, an adverse impact was observed in terms of the total number of sprinkler activations and fire damage area.
    b. If the smoke vent opens before the first sprinkler:
        i. It will initially remove most of the heat from the ceiling layer due to the fire plume directly impinging on the vented area. The exact amount of heat removed by the smoke vent will depend on fire plume shape, which in turn depends on many factors including the clearance height, ceiling height, and commodity type.

Lower ceiling heights with minimal clearance and storage arrays of cartoned commodity result in a narrower fire plume and more heat removed from the ceiling layer.

ii. Once the sprinklers activate, the smoke vent is far less effective at removing heat and smoke from the building due to the momentum of the sprinkler spray pushing the fire plume down and the cooling in the ceiling layer reducing the buoyancy of the fire products.

iii. The larger fire size at first sprinkler activation may reduce the sprinkler delay/skipping tendency for the other sprinklers located close to the ignition location.

iv. The removal of heat from the ceiling layer by the smoke vent may reduce the number of sprinkler activations far from the ignition location, if the sprinkler protection is otherwise adequately designed.

4. A probabilistic analysis was performed to determine the likelihood of the worst-case ignition scenario occurring. The analysis considered variations in commodity type, ceiling height, storage height, sprinkler and vent location, sprinkler and vent thermal link parameters, and ignition location. The following conclusions are made:
    a. Automatic smoke vents are highly unlikely to activate before the first sprinkler if the vent activation temperature is equal to or greater than the sprinkler activation temperature.
    b. Following NFPA 13 guidelines for the vent thermal element, there is a ~2% chance for smoke vents to open before quick response, ordinary temperature sprinklers and a ~7% chance for smoke vents to open before standard response, high temperature sprinklers, averaged across all cases and assuming a vent-to-floor ratio of 3%.
5. The impact of gravity smoke vents that are always open (‘vent openings’) was assessed and was found to be similar to the case where automatic smoke vents open before the first sprinkler activation. Having the smoke vent open at early times when the fire was small did not significantly alter the results compared to the baseline, tested conditions.
6. A sensitivity analysis was performed relative to the baseline, tested conditions. It was found that the results could be generalized across a wide range of ceiling heights (up to 12.2 m (40 ft)), clearance heights (1.5 to 7.6 m (5 to 25 ft)), commodity types (Class 2, CUP, and UUP), and ignition scenarios.
7. Simulations were performed to assess the recommendations in FM Global DS 2-0 for installing sprinklers in occupancies with smoke vents. It was found that these recommendations are not necessary for gravity smoke vents up to the 3 m^2 (32 ft^2) size used in this study.

Nomenclature

Glossary

Among four ignition – ignition location directly in the middle of four sprinklers.

Automatic smoke vent – a smoke vent that is initially closed and opens automatically in response to a fire, usually based on a thermal element.

Between two ignition– ignition location directly in the middle of two sprinklers.

Center ignition – ignition location in the central flue space of the rack storage array.

Class 2 – FM Global commodity consisting of inert metal box inside three double-layer cardboard boxes, stacked on a wooden pallet.

Control mode sprinkler – a sprinkler designed to prevent or limit the spread of fire without necessarily suppressing the fire, relying chiefly on pre-wetting the unburnt commodities.

Cartoned unexpanded commodity – FM Global standard commodity consisting of unexpanded Styrofoam plastic cups and cardboard partitions inside a single-layer cardboard box, stacked on a wooden pallet.

Early suppression fast response – referring to sprinklers with a quick response thermal element and suitable for high-hazard commodities.

First-ring sprinkler(s) – the closest 1, 2, or 4 sprinkler(s) to the ignition location for under one, between two, and among four ignition scenarios, respectively.

Non-storage sprinkler – a sprinkler not suitable for storage occupancies.

Offset ignition – ignition location in the transverse flue space of the rack storage array.

Quick response – a thermal element with a response time index (RTI) under 50 $m^{0.5}s^{0.5}$ (90 $ft^{0.5}s^{0.5}$).

Rack centered ignition – rack positioned such that the central flue space is centered underneath the ceiling.

Rack offset ignition – rack positioned such that the ignition location is centered underneath the ceiling.

Storage sprinkler – a sprinkler suitable for storage occupancies.

Suppression mode sprinkler – a sprinkler designed to deliver water directly to the seat of the fire, cool the burning commodity and suppress the fire.

Under one ignition– ignition location directly underneath a sprinkler.

Uncartoned unexpanded plastic – FM Global standard commodity consisting of eight high-density polyethylene pallets.

Vent offset distance – the distance from the ignition location to the center of the vent.

Vent opening – a smoke vent that is left open for any period of time, e.g., to provide natural ventilation in a hot climate.

Abbreviations

A4 – Among four (ignition location)
B2 – Between two (ignition location)
CUP – Cartoned, unexpanded plastic
DS – (FM Global) Data Sheet
HT – High temperature (thermal element)
OT – Ordinary temperature (thermal element)
QR – Quick response (thermal element)
RTI – Response time index (thermal element)
SR – Standard response (thermal element)
U1 – Under one (ignition location)
UUP – Uncartoned, unexpanded plastic

Latin Symbols

A m^2 (ft^2) – Area
C s^{-1} – Thermal element heat conduction constant
HRR MW – Heat release rate
K $lpm/bar^{1/2}$ ($gpm/psi^{1/2}$) – Sprinkler K-factor
p_I m^{-2} (ft^{-2}) – Probability per unit area of ignition occurring at location
P – Probability
RTI $m^{1/2}s^{1/2}$ ($ft^{1/2}s^{1/2}$) – Response time index for convective heating of thermal element
t sec – Time
T K (F) – Temperature
U $m \cdot s^{-1}$ ($ft \cdot s^{-1}$) – Velocity
w – Weighting factor
x – Position vector

Subscripts

$_{A4}$ – Among four (ignition location)

$_{ACT}$ – Activation

$_{B2}$ – Between two (ignition location)

$_{I}$ – Ignition (location)

$_{L}$ – Thermal element

$_{G}$ – Gas phase

$_{P}$ – Periodic (area)

$_{R}$ – Random (ignition location)

$_{V,S}$ – Vent activation before sprinkler activation

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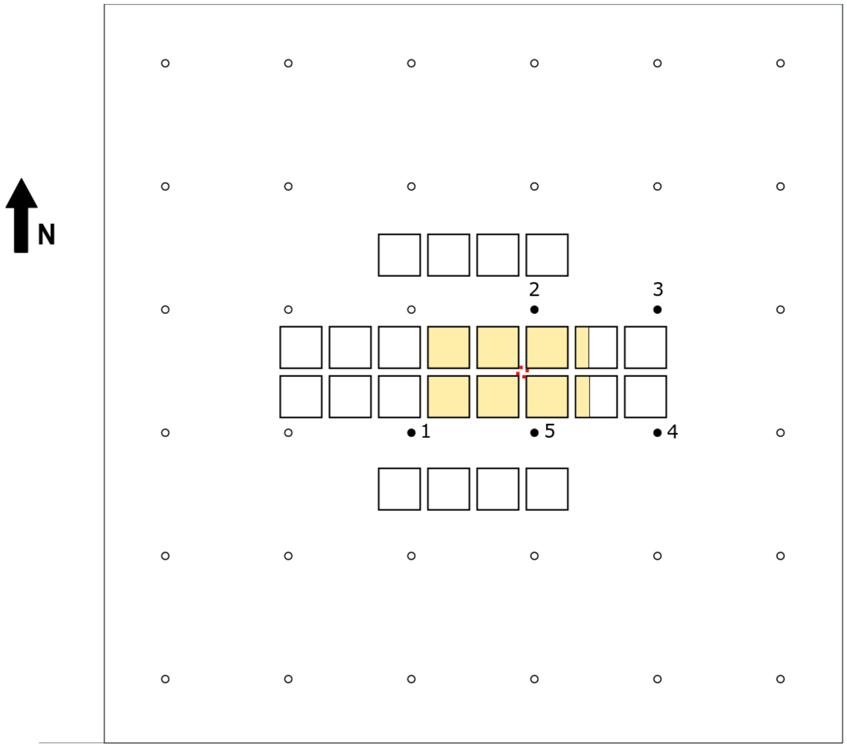
Appendix A. Test 1

A.1 Summary

Test 1 was conducted on November 5, 2021 under the smoke vent structure built below the South movable ceiling of the Large Burn Laboratory. The parameters of Test 1 were chosen to match those of one of the simulations, to help in acquiring data to validate the model. The commodity was a rack-storage arrangement of CUP. The main array consisted of a 2 × 8 × 5 high double-row open-frame rack, with standard 1.5 m (5 ft) tiers and nominal 15 cm (6 in.) flues. The main array was aligned so the longitudinal flue was in the East-West direction. There were two target arrays in this test. They consisted of 1 × 4 × 5 high single row open frame racks, with standard 1.5 m (5 ft) tiers nominal 15 cm (6 in.) flues. The single row target arrays were aligned North and South of the main array, with a 1.2 m (4 ft) aisle. The sprinkler protection consisted of FM Approved K240 (K16.8) pendent QR sprinklers installed on a 3 m × 3 m (10 ft × 10 ft) spacing. The distance between the sprinkler link and the ceiling was maintained at 33 cm (13 in.). The system discharge pressure of 2.4 bar (35 psi) resulted in a flow rate of 379 lpm (100 gpm) per sprinkler, and a 41 mm/min (1.0 gpm/ft^2) density based on the sprinkler spacing. This protection option is the current FM Global recommendation for storage of CUP under a 9.1 m (30 ft) ceiling.

The ignition for this test was planned to be among four sprinklers at the center of the main array. However, a misplaced ignitor led to a test condition that was close to a between-two ignition scenario as shown in Figure A-1. This test was eventually repeated with among-four ignition location and is discussed in Appendix C (Test 3).

After ignition, the flames were seen impinging on the ceiling at 35 sec. The sprinkler activation sequence and damage assessment are shown in Figure A-1. This appendix also provides a detailed fire chronology and representative data plots. The first three sprinklers opened in quick succession between 37 and 39 sec after ignition. Two additional sprinklers operated between 43 and 53 sec. Following the activation of these sprinklers, the fire subsided. Infrared imaging revealed sustained flames in the bottom three tiers of the main array but were limited to the area around ignition. The fire did not spread to either ends of the ends of the main array or to the target arrays. The maximum ceiling steel temperature was 49°C (121°F). This is well below the threshold value of 538°C (1000°F), beyond which the risk of roof collapse becomes significant. All the test evaluation criteria were satisfied, and the sprinkler protection was adequate in controlling the fire.



Sprinkler Activation	Time (m:s)
1	0:37
2	0:39
3	0:39
4	0:43
5	0:53

Figure A-1: Sprinkler activation sequence and damage assessment in Test 1.

A.2 Fire Chronology

Table A-1: Fire chronology for Test 1.

Time (min:sec)	Observations
0:00	Ignition was achieved
0:10	Flames were seen above the first tier boxes, 1.5 m (5 ft)
0:16	Flames were seen above the second tier boxes, 3 m (10 ft)
0:20	Flames were seen above the third tier boxes, 4.6 m (15 ft)
0:28	Flames were seen above the top of the main array, 7.6 m (25 ft)
1:20	Flames were seen impinging on the ceiling
0:37 – 0:39	First three sprinklers operated
0:43 – 0:53	Two more sprinklers operated
1:20	Visibility of the array was obscured by smoke
1:20 – 30:00	Infrared imaging revealed flames were seen sustained in bottom three tiers of the main array but limited to the area around ignition
30:00	Test Terminated

A.3 Representative Data

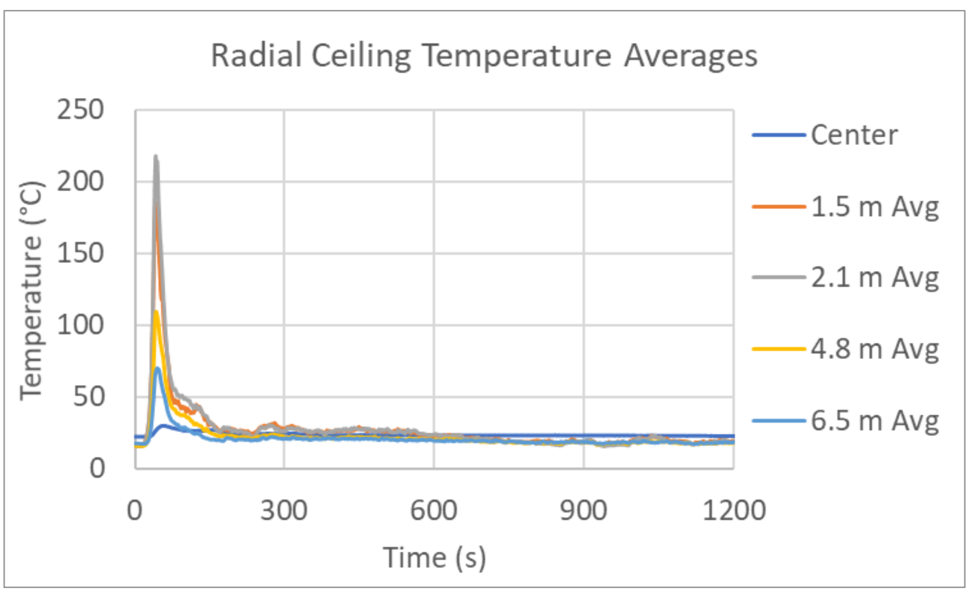


Figure A-1: Radial ceiling temperature averages in Test 1.

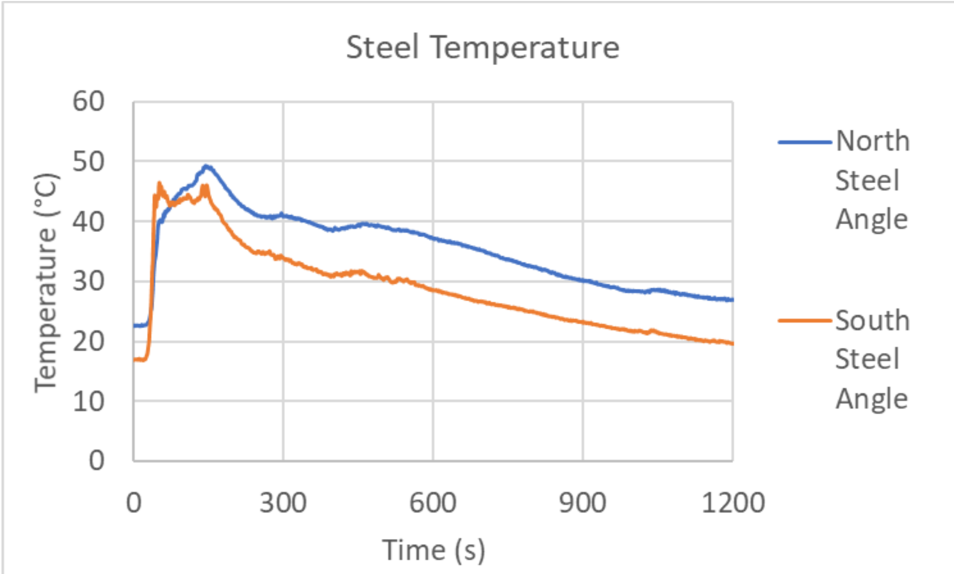


Figure A-2: Temperatures of steel angles in Test 1.

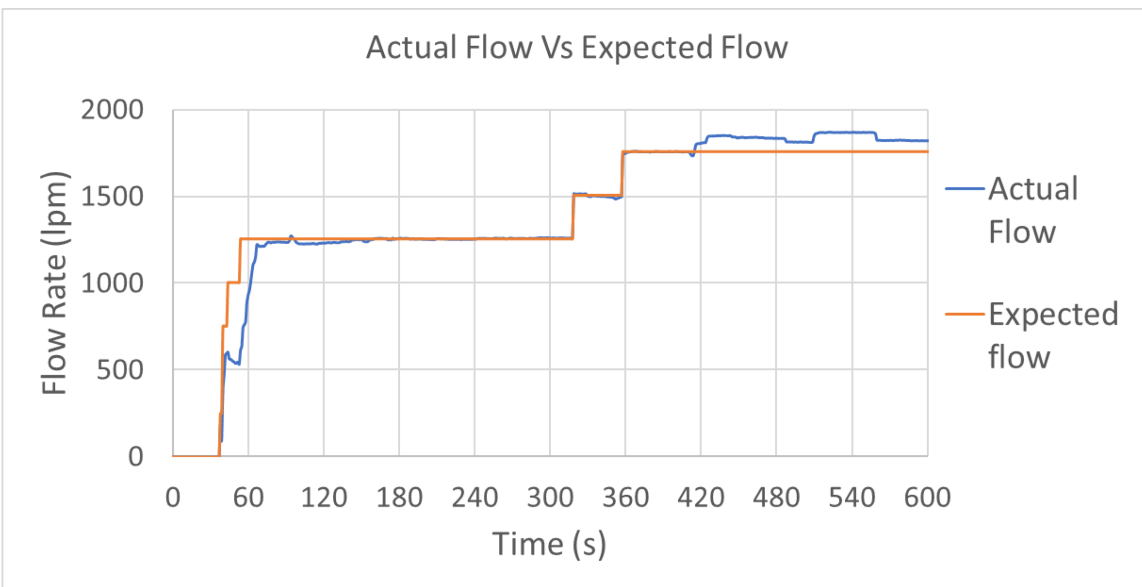


Figure A-3: Flow Rate through all the sprinklers in Test 1.

Appendix B. Test 2

B.1 Summary

Test 2 was conducted on November 11, 2021 under the ceiling structure with a smoke vent. A single smoke vent directly above ignition was opened during the test. The purpose of Test 2 was to evaluate the effect of the presence of a smoke vent on sprinkler performance. The test parameters were the same as those intended in Test 1 with only one change: the smoke vent was made operational. The criterion for opening the smoke vent is described in Section 2.5. The STE temperature from Test 1 was used to determine the time for opening the smoke vent in Test 2. This was very close to the criterion obtained from STE data of Test 3 (less than half a second difference), and therefore, this test can be used as a direct comparison with Test 3.

The sprinkler activation sequence and damage assessment have been shown in Figure 5-4. This appendix contains a detailed fire chronology and representative data plots. After ignition, flames were seen impinging on the ceiling at 49 sec. At 50 sec, the STE temperature reached a value of 71°C (160°F) and opening of the smoke vent was initiated. This ensured that the vent was half open by 54 sec, when the STE was expected to reach the activation temperature. For the next 40 sec, flames were seen exiting the smoke vent with no sprinkler activations. The first sprinkler opened at 1 min 33 sec followed by another 3 sec later. Both were close to ignition. A third sprinkler farther away from ignition opened at 1 min 40 sec. A fourth sprinkler close to ignition operated at 1 min 49 sec. At 2 min 10 sec, two more sprinklers operated along with one of the four closest sprinklers. With all four core sprinklers operational, the fire subsided. Flames could be seen in the bottom three tiers of the main array that gradually reduced in intensity towards the end of the test at 30 min. The fire was limited to the area around ignition and did not spread to the ends of the main array or the target arrays. The maximum steel temperature was 65°C (149°F). All the test evaluation criteria were satisfied, and the sprinkler protection was adequate in controlling the fire.

B.2 Fire Chronology

Table B-1: Fire Chronology for Test 2

Time (min:sec)	Observations
0:00	Ignition was achieved.
0:13	Flames were seen above the first tier boxes, 1.5 m (5 ft).
0:36	Flames were seen above the second tier boxes, 3 m (10 ft).
0:43	Flames were seen above the third tier boxes, 4.6 m (15 ft).
0:45	Flames were seen above the top of the main array, 7.6 m (25 ft).
0:49	Flames were seen impinging on the ceiling.
0:50	The STE temperature reached a temperature of 71°C (160°F) and the smoke vent manual activation was begun. The smoke vent was half open by 54 sec and fully open by 59 sec.
0:50 – 1:30	Flames on top of the main array seen exiting the smoke vent with minimal impingement on the rest of the ceiling.
1:33 – 1:36	First two sprinklers operated.
1:40 – 1:49	Two more sprinklers operated.
2:10	Two additional sprinklers operated.
2:30	Visibility of the array was obscured by smoke.
2:30 – 30:00	Infrared imaging revealed flames were seen sustained in bottom three tiers of the main array but limited to the area around ignition. The flames gradually reduced in size towards the end of the test at 30 min.
30:00	Test Terminated.

B.3 Representative Data

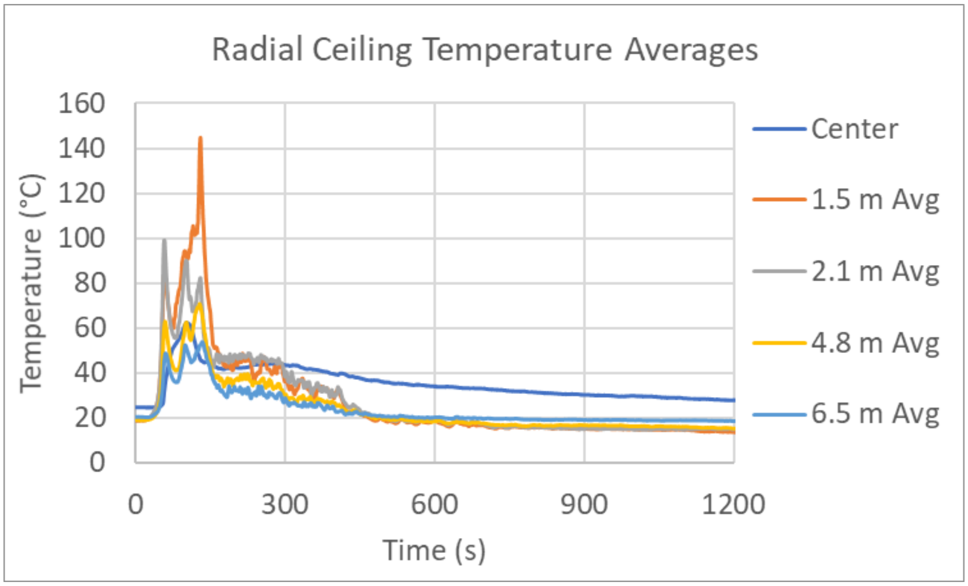


Figure B-1: Radial ceiling temperature averages in Test 2.

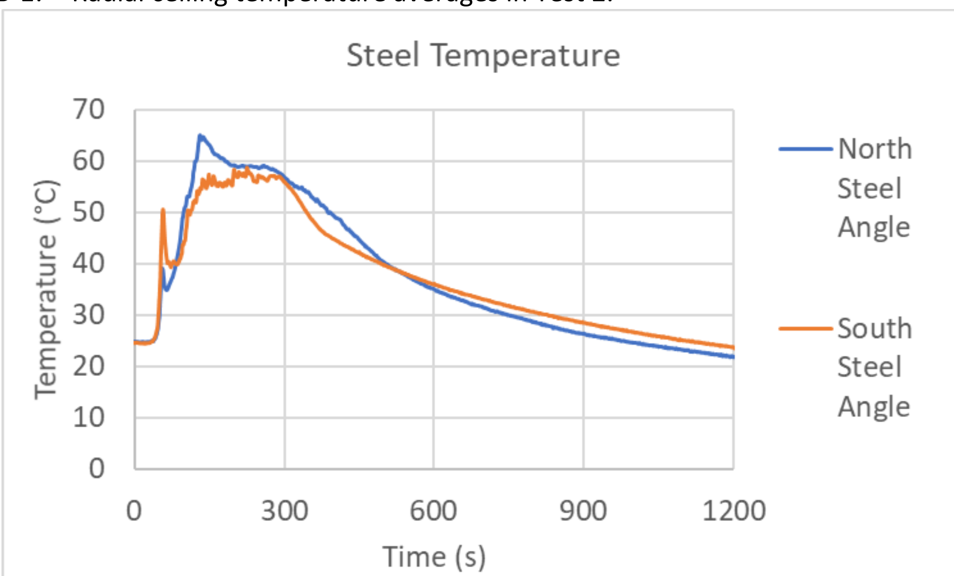


Figure B-2: Temperatures of steel angles in Test 2.

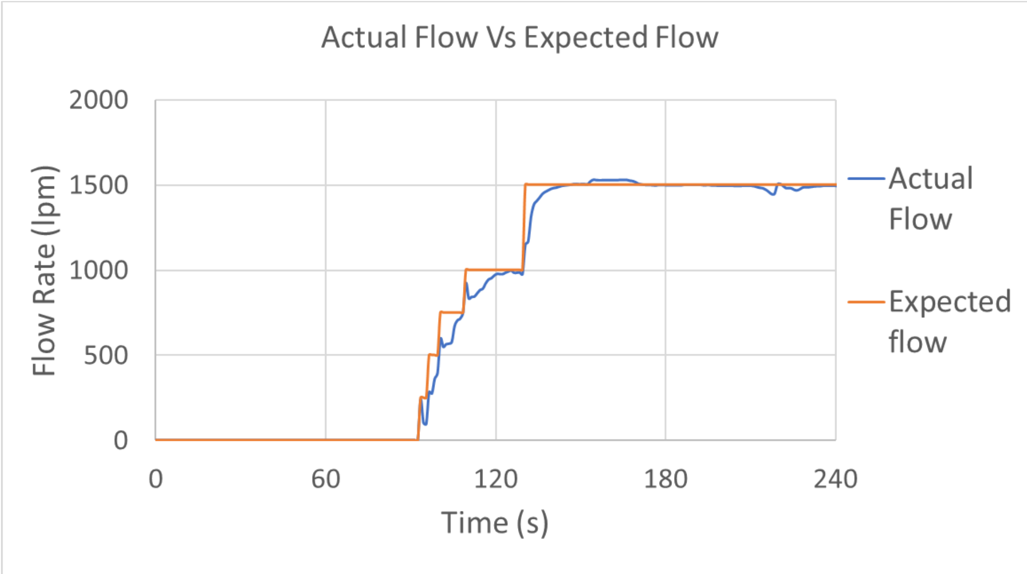


Figure B-3: Flow Rate through all the sprinklers in Test 2.

Appendix C. Test 3

C.1 Summary

Test 3 was conducted on November 17, 2021 under the ceiling structure. This test had the same parameters as Test 2 except the smoke vent was kept closed, which provided a direct comparison with Test 2 to evaluate the effect of smoke vent on sprinkler performance.

The sprinkler activation sequence and damage assessment have been shown in Figure 5-3. This appendix contains a detailed fire chronology and typical data plots. After ignition, flames were seen impinging on the ceiling at 51 sec. The first two sprinklers close to ignition operated at 55 and 56 sec. During the next five minutes, flames reduced in intensity with only two sprinklers activated. However, flames intensified and reached the top of the main array at 8 min. This led to operation of additional sprinklers. A total of twelve sprinklers operated by 12 min 51 sec. Most of these sprinklers were far from the ignition location and did not contribute significantly to controlling the fire. It was not until the operation of the eleventh sprinkler at 12 min 42 sec that the fire reduced in intensity. The test was terminated at 30 min when the fire was limited to the bottom two tiers of the main array near the ignition location. The fire did not spread to the ends of the main array or the target arrays. The maximum steel temperature was 86°C (188°F). All the test evaluation criteria were satisfied, and the sprinkler protection was adequate in controlling the fire.

C.2 Fire Chronology

Table C-1: Fire Chronology for Test 3

Time (min:sec)	Observations
0:00	Ignition was achieved.
0:15	Flames were seen above the first tier boxes, 1.5 m (5 ft).
0:36	Flames were seen above the second tier boxes, 3 m (10 ft).
0:46	Flames were seen above the third tier boxes, 4.6 m (15 ft).
0:48	Flames were seen above the top of the main array, 7.6 m (25 ft).
0:51	Flames were seen impinging on the ceiling.
0:55 – 0:56	First two sprinklers operated.
1:00 – 6:00	Flames subsided to the bottom three tiers and the visibility was partially obscured by the smoke.
6:00 – 8:00	Flames gradually intensified and reached the top of the main array at 8 min.
9:41 – 12:51	Flames intensified and ten more sprinklers opened.
13:00 – 30:00	The fire gradually subsided, and the ceiling temperatures reduced to near ambient conditions. Infrared imaging revealed flames were seen present in bottom three tiers of the main array and limited to the bottom two tiers towards the end of the
30:00	Test Terminated.

C.3 Representative Data

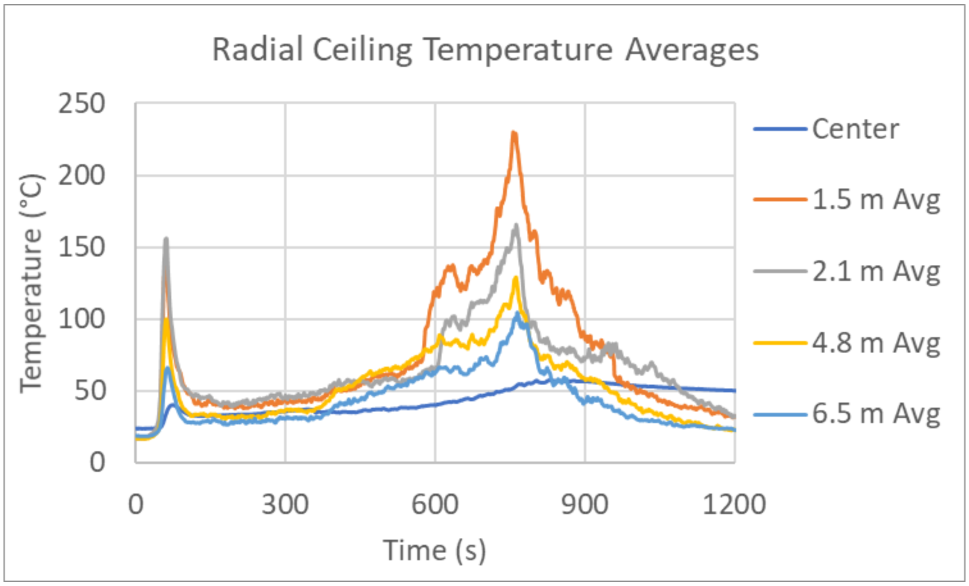


Figure C-1: Radial ceiling temperature averages in Test 3.

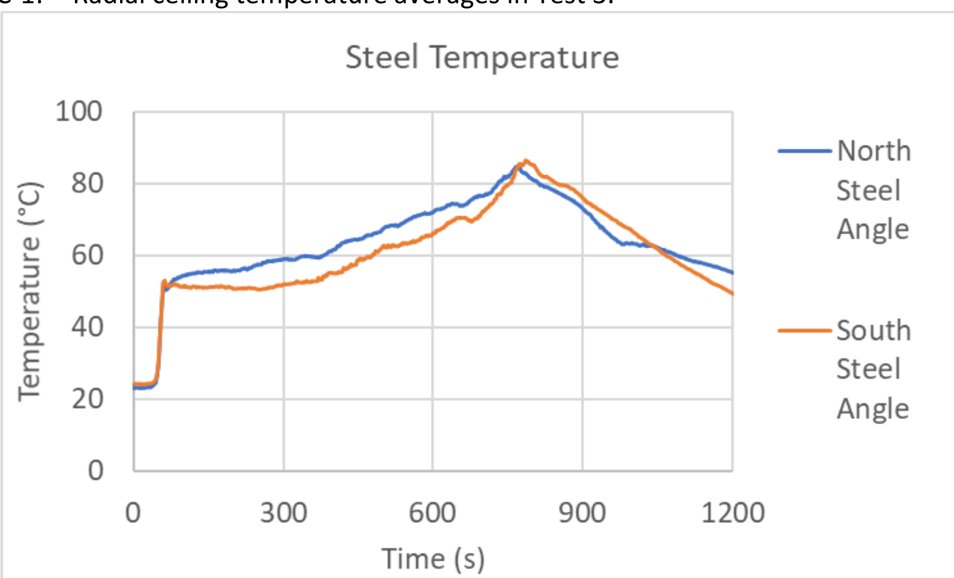


Figure C-2: Temperatures of steel angles in Test 3

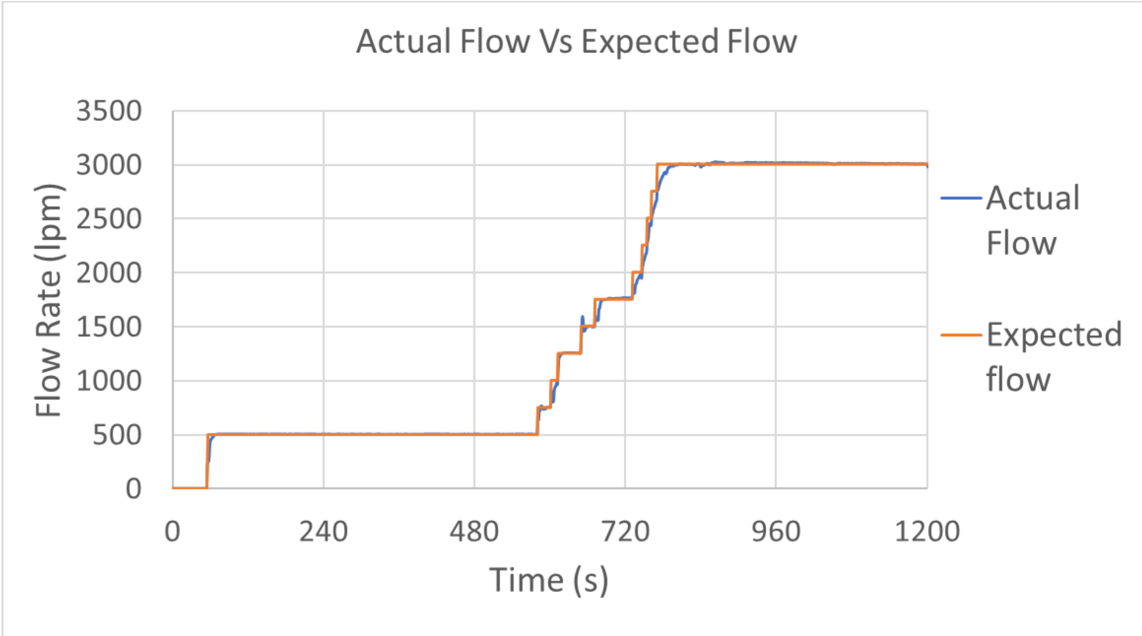


Figure C-3: Flow Rate through all the sprinklers in Test 3.

Appendix D. Test 4

D.1 Summary

Test 4 was conducted on November 30, 2021. It was a repeat of Test 3, which showed a pattern of sprinkler skipping. Sprinkler skipping is a stochastic process and may occur under certain conditions that can lead to conclusions that require careful examination. Therefore, Test 3 was repeated to assess the effect of sprinkler skipping on the test outcome.

The sprinkler activation sequence and damage assessment have been shown in Figure 5-3. This appendix contains a detailed fire chronology and typical data plots. After ignition, flames were seen impinging on the ceiling at 42 sec. The first two sprinklers, both close to ignition operated at 47 and 51 sec. Flames reduced in intensity but gradually intensified, which led to operation of two additional sprinklers, one of which was close to ignition. With the operation of this third first-ring sprinkler, flames were reduced to the bottom three tiers of the main array. At 29 min 27 sec, a fifth sprinkler operated. The test was extended by five minutes following this late sprinkler operation and terminated at 35 min. The fire did not spread to the ends of the main array or the target arrays. The maximum steel temperature was 69°C (157°F). All the test evaluation criteria were satisfied, and the sprinkler protection was adequate in controlling the fire.

D.2 Fire Chronology

Table D-1: Fire Chronology for Test 4

Time (min:sec)	Observations
0:00	Ignition was achieved.
0:15	Flames were seen above the first tier boxes, 1.5 m (5 ft).
0:31	Flames were seen above the second tier boxes, 3 m (10 ft).
0:38	Flames were seen above the third tier boxes, 4.6 m (15 ft).
0:40	Flames were seen above the top of the main array, 7.6 m (25 ft).
0:42	Flames were seen impinging on the ceiling.
0:47 – 0:51	First two sprinklers operated.
0:51 – 1:30	Flames subsided to the bottom three tiers of the main array.
1:30 – 3:30	Flames gradually intensified reaching the top of the main array.
3:49 – 4:08	Two more sprinklers operated.
4:08 – 17:00	Flames remained intense and visible on the bottom three tiers of the main array.
17:00 – 29:00	Visibility of the array was obscured by smoke. Infrared imaging revealed flames were seen sustained in bottom three tiers of the main array.
29:27	Fifth sprinkler activated. Test was extended by five minutes.
35:00	Test Terminated.

D.3 Representative Data

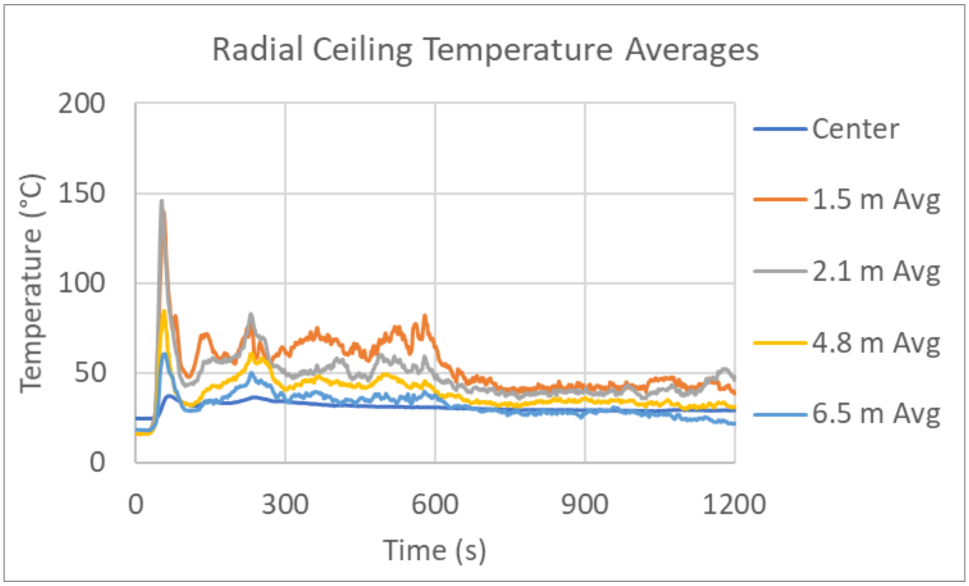


Figure D-1: Radial ceiling temperature averages in Test 4.

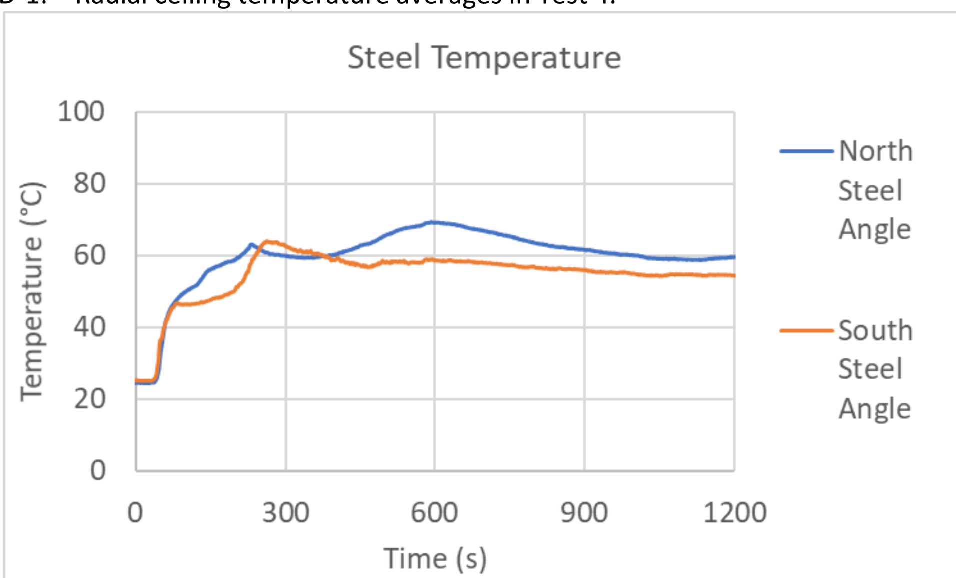


Figure D-2: Temperatures of steel angles in Test 4.

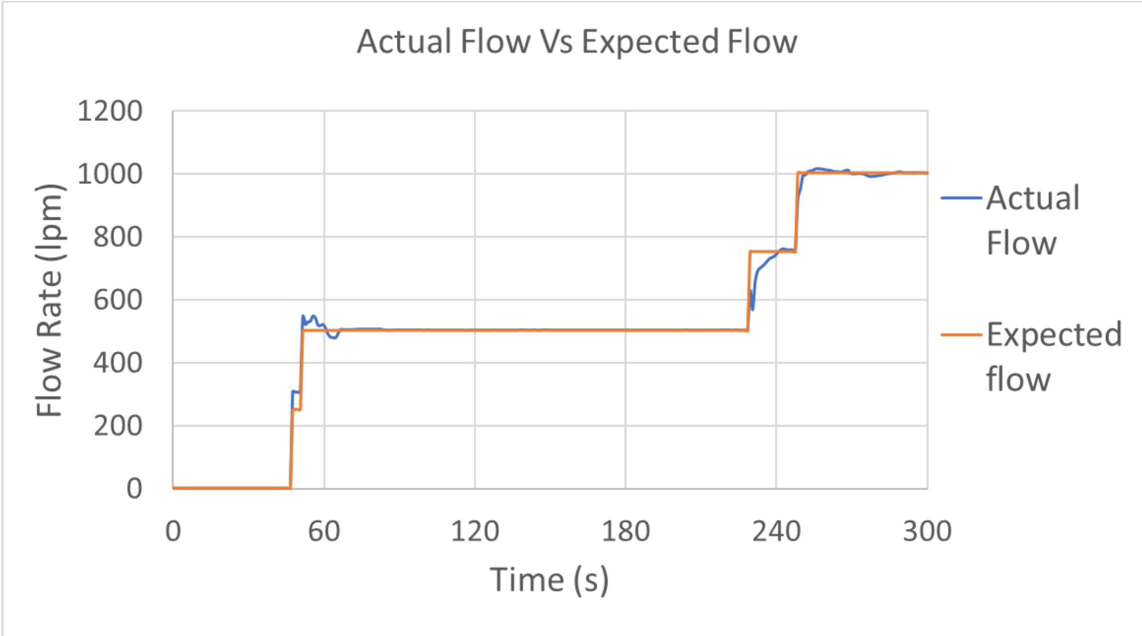


Figure D-3: Flow Rate through all the sprinklers in Test 4.

Appendix E. Test 5

E.1 Summary

Test 5 was conducted on December 8, 2021. It as a repeat of Test 2. Since the stochastic process of sprinkler skipping was seen as a significant contributor to the outcome, the conditions of Test 2 were repeated to get a better understanding of the effect of smoke vents on sprinkler performance.

The sprinkler activation sequence and damage assessment have been shown in Figure 5-4. This appendix contains a detailed fire chronology and typical data plots. After ignition, flames were seen impinging on the ceiling at 42 sec. At 42 sec, the STE temperature reached a value of 71°C (160°F) and opening of the smoke vent was initiated. This temperature was based on STE temperature data from Test 4 and turned out to be very close to the criterion used in Test 2. Therefore, the Test 2 criterion was used. This made sure that the vent was half open by 46 sec, when the STE was expected to reach the activation temperature if the smoke vent had not opened. The first sprinkler operated at 49 sec, while the smoke vent was being opened. Fire intensified and two additional sprinklers operated at 1 min 28 sec and 1 min 31 sec. One of them was close to ignition. With only two core sprinklers operational, the fire intensified leading to opening of additional sprinklers until two additional core sprinklers operated at 5 min 15 sec and 5 min 21 sec. A total of nine sprinklers operated. Once all four core sprinklers opened, the fire gradually subsided and the test was terminated at 30 min. The fire did not spread to the ends of the main array or the target arrays. The maximum steel temperature was 77°C (170°F). All the test evaluation criteria were satisfied, and the sprinkler protection was adequate in controlling the fire.

E.2 Fire Chronology

Table E-1: Fire Chronology for Test 5

Time (min:sec)	Observations
0:00	Ignition was achieved.
0:13	Flames were seen above the first tier boxes, 1.5 m (5 ft).
0:27	Flames were seen above the second tier boxes, 3 m (10 ft).
0:37	Flames were seen above the third tier boxes, 4.6 m (15 ft).
0:40	Flames were seen above the top of the main array, 7.6 m (25 ft).
0:42	Flames were seen impinging on the ceiling.
0:42	The STE temperature reached a temperature of 71°C (160°F) and the smoke vent manual activation was begun. The smoke vent was half open by 46 sec and fully open by 51 sec.
0:49	First sprinkler operated.
1:28 – 1:31	Fire intensified and two more sprinklers operated.
1:50	Visibility of the array was obscured by smoke.
3:34 – 4:13	Two additional sprinklers operated.
4:15 – 5:00	Fire intensified and involved bottom four tiers of the main array.
5:03 – 5:21	Four sprinklers operated including two core sprinklers and one perimeter sprinkler.
5:30 – 30:00	Infrared imaging showed flames persisted in the bottom four tiers of the main array but subsided gradually.
30:00	Test Terminated.

E.3 Representative Data

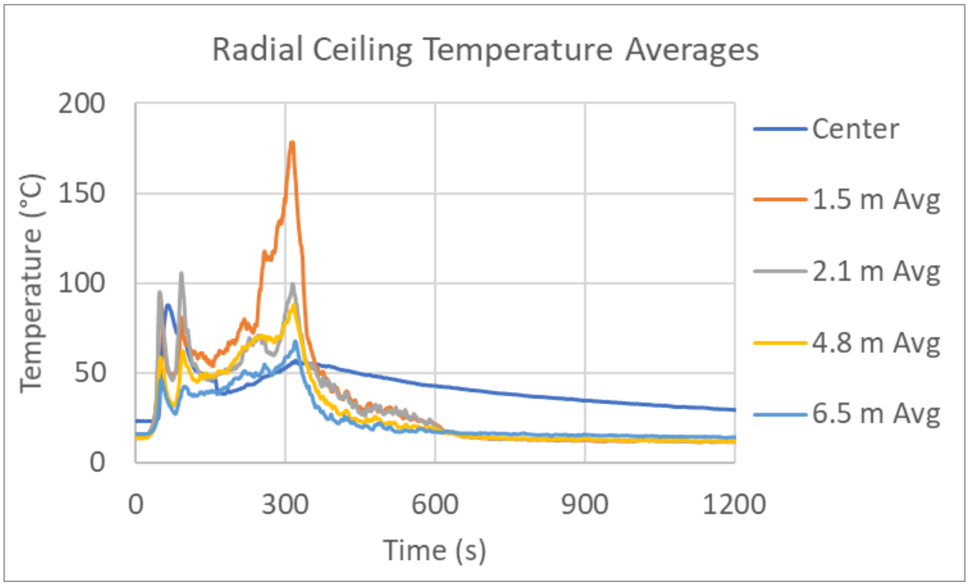


Figure E-1: Radial ceiling temperature averages in Test 5.

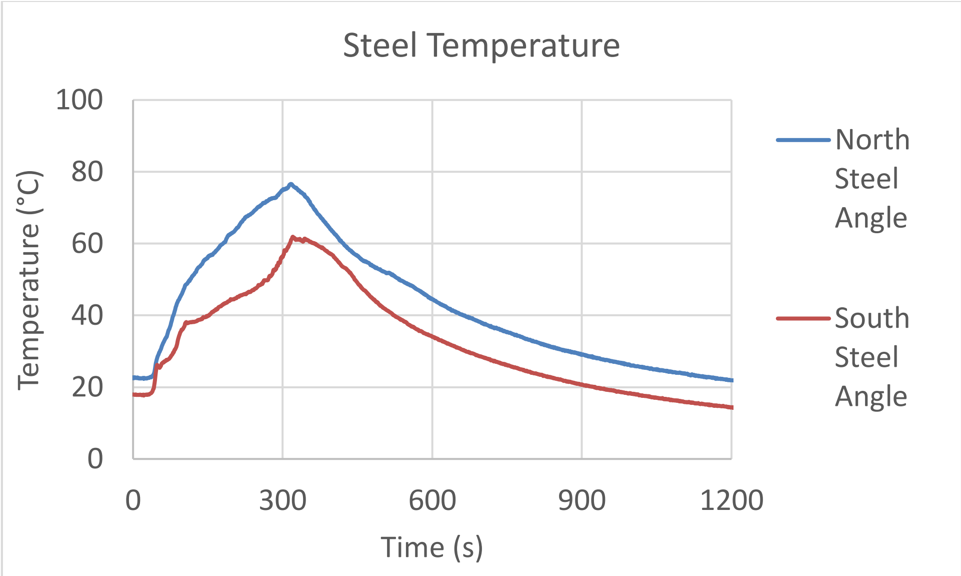


Figure E-2: Temperatures of steel angles in Test 5.

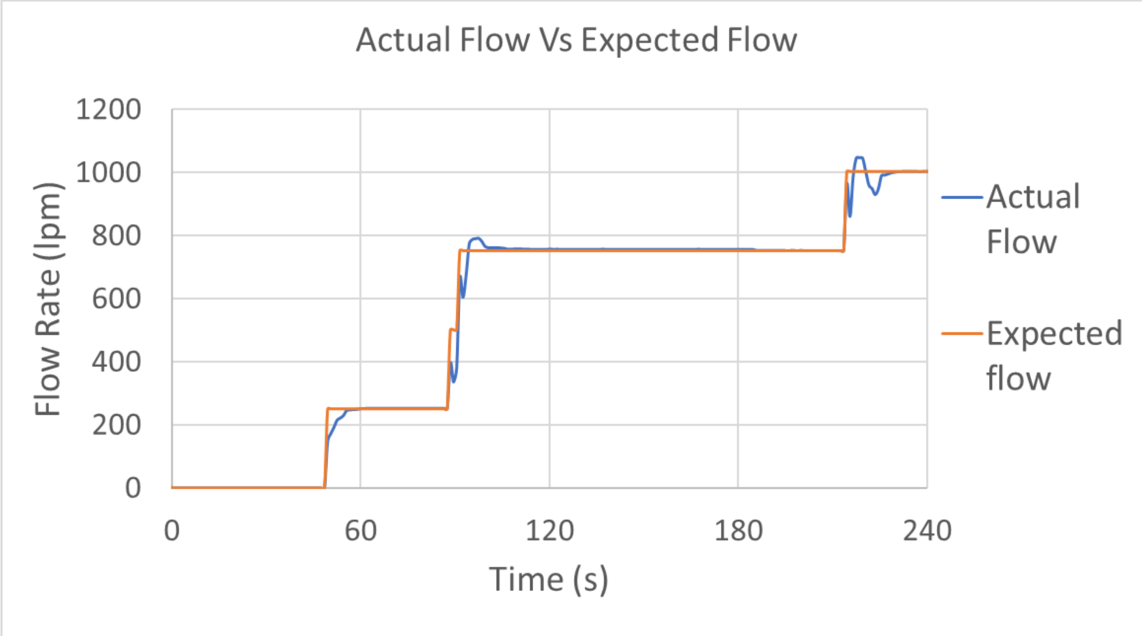


Figure E-3: Flow Rate through all the sprinklers in Test 5.

Appendix F. Test 6

F.1 Summary

Test 6 was conducted on December 12, 2021. The commodity used in this test was Class 2. The arrangement was the same as in the previous tests with CUP commodity. The sprinkler protection consisted of FM Approved K160 (K11.2) upright QR sprinklers installed on a 3 m × 3 m (10 ft × 10 ft) spacing. The distance between the sprinkler link and the ceiling was maintained at 30 cm (12 in.). The system discharge pressure of 1.7 bar (25 psi) resulted in a flow of 211 lpm (56 gpm) per sprinkler, and a 23 mm/min (0.56 gpm/ft^2) density based on the sprinkler spacing. The protection option for this test is a representative sprinkler protection that FM Global does not deem to be adequate but exists in the field and considered adequate by NFPA 13. These test conditions were chosen to provide a more challenging fire, where the effect of smoke vents on sprinkler performance could be more significant.

The sprinkler activation sequence and damage assessment have been shown in Figure 5-14. This appendix contains a detailed fire chronology and typical data plots. After ignition, flames were seen impinging on the ceiling at 1 min 12 sec. This led to the operation of ten sprinklers in quick succession between 1 min 20 sec and 2 min 29 sec. Following the activation of these sprinklers, the fire gradually reduced in intensity over the remainder of the test. The test was terminated at 30 min with small flames in the bottom two tiers of the main array. The fire did not spread to the ends of the main array or the target arrays. The maximum steel temperature was 78°C (173°F). All the test evaluation criteria were satisfied, and the sprinkler protection was adequate in controlling the fire. It should be noted that the NFPA 13 protection option requires a design for 20 sprinklers, and therefore, based on the number of sprinkler activations, this protection option is considered adequate.

F.2 Fire Chronology

Table F-1: Fire Chronology for Test 6.

Time (min:sec)	Observations
0:00	Ignition was achieved.
0:08	Flames were seen above the first tier boxes, 1.5 m (5 ft).
0:43	Flames were seen above the second tier boxes, 3 m (10 ft).
0:59	Flames were seen above the third tier boxes, 4.6 m (15 ft).
1:07	Flames were seen above the top of the main array, 7.6 m (25 ft).
1:12	Flames were seen impinging on the ceiling.
1:20 – 2:29	Ten sprinklers operated in quick succession. The fire subsided to the bottom four tiers of the main array.
2:30 – 30:00	Fire gradually reduced in size.
30:00	Test Terminated.

F.3 Representative Data

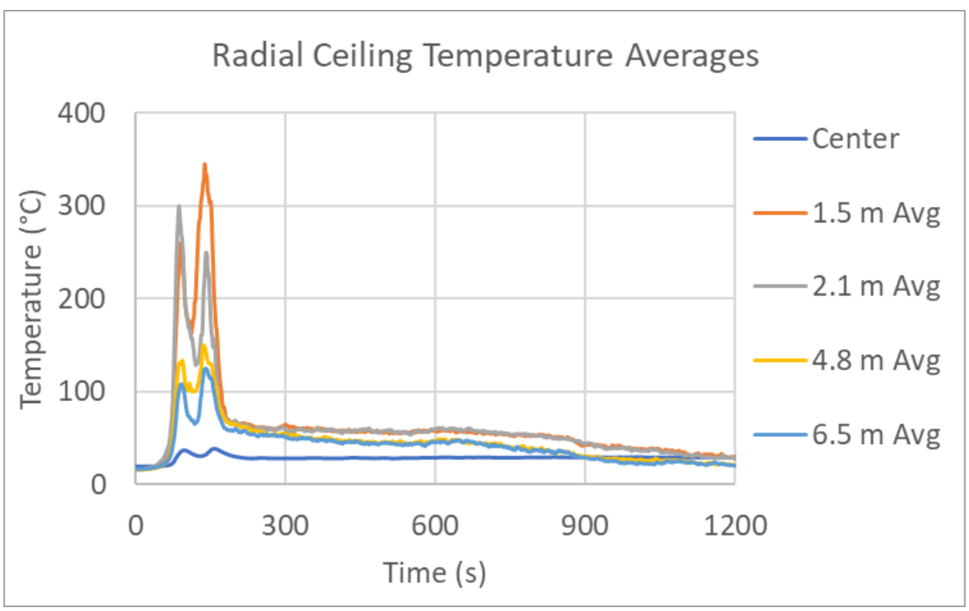


Figure F-1: Radial ceiling temperature averages in Test 6.

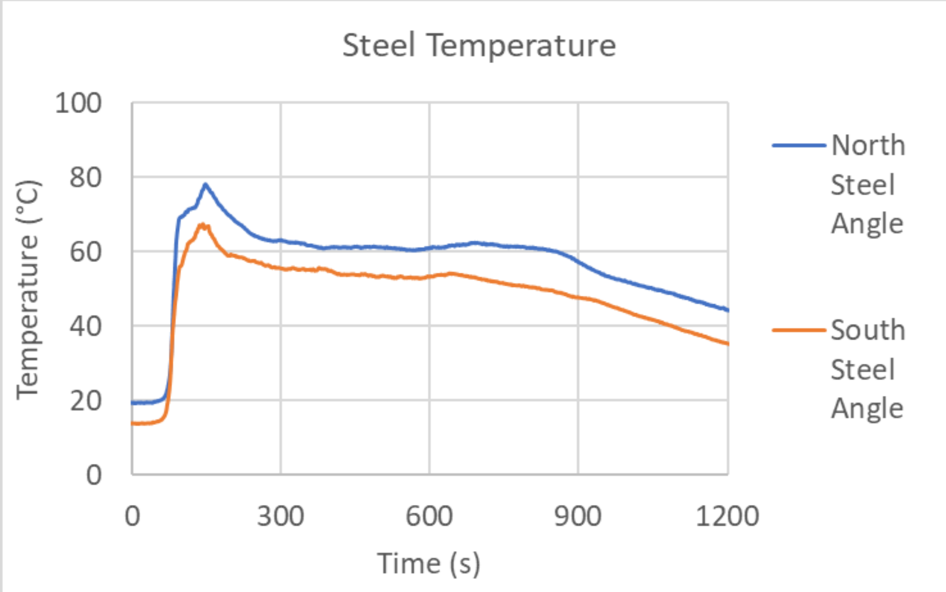


Figure F-2: Temperatures of steel angles in Test 6.

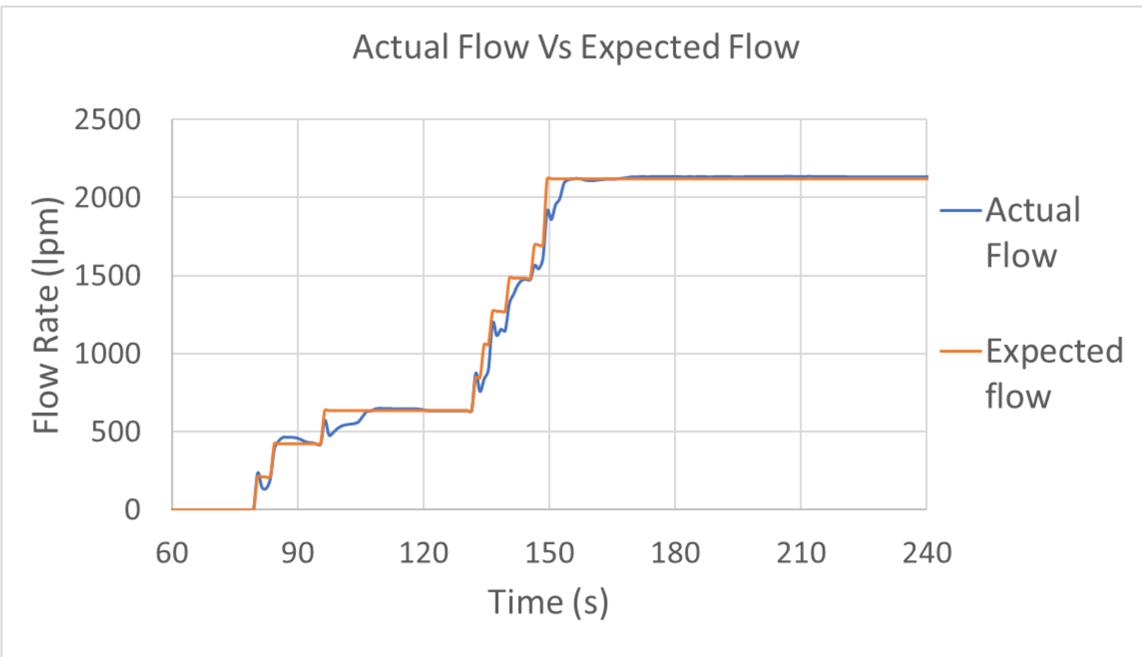


Figure F-3: Flow Rate through all the sprinklers in Test 6.

Appendix G. Test 7

G.1 Summary

Test 7 was conducted on January 10, 2022. A single smoke vent directly above ignition was opened during the test. The purpose of Test 7 was to evaluate the effect of using a smoke vent on sprinkler performance by comparing its outcome with that of Test 6. The parameters were the same as those in Test 6 with only one change: the smoke vent was made operational. The criterion for opening the smoke vent has been described in Section 2.5. The STE temperature from Test 6 was used to determine the time for opening the smoke vent in Test 2.

The sprinkler activation sequence and damage assessment have been shown in Figure 5-14. This appendix contains a detailed fire chronology and typical data plots. After ignition, flames were seen impinging on the ceiling at 1 min 3 sec. At 50 sec, the STE temperature reached a value of 77°C (170°F) and opening of the smoke vent was initiated. This made sure that the vent was half open by 1 min 8 sec, when the STE was expected to reach the activation temperature. For the next one minute, flames were seen exiting the smoke vent with no sprinkler activations. Between 2 min 10 sec and 2 min 30 sec, five sprinklers including the four first-ring sprinklers activated. This did not control the fire and seven additional sprinklers operated during the next 30 sec. The fire spread to both the target arrays by 4 min. The larger fire led to operation of six more sprinklers by 7 min 42 sec bringing the total number of sprinkler operations to eighteen. In the next few minutes, fire was gradually reducing in intensity and the ceiling temperatures stabilized. The test was terminated at 10 min 12 sec to avoid excessive damage to the ceiling structure.

A total of eighteen sprinklers operated during the test. The fire spread to the target arrays but did not reach to their backside, which would have been considered a failure of the sprinkler protection option. The fire did not spread to the ends of the main array. The ceiling steel temperature was 83°C (182°F), which was well within acceptable limits. Based on the number of sprinkler operations, this sprinkler protection would be considered inadequate since it does not offer an acceptable safety margin between the number of sprinklers that operated in an idealized laboratory setting and the protection option. The protection option in NFPA 13 [10] is 20 sprinklers and, therefore, no more than 13 sprinklers (13 + 50 % × 8 = 19.5) should operate during the test. The larger fire size and a larger number of sprinkler operations were the main differences observed between Tests 6 and 7.

G.2 Fire Chronology

Table G-1: Fire chronology for Test 7.

Time (min:sec)	Observations
0:00	Ignition was achieved.
0:15	Flames were seen above the first tier boxes, 1.5 m (5 ft).
0:45	Flames were seen above the second tier boxes, 3 m (10 ft).
1:00	Flames were seen above the third tier boxes, 4.6 m (15 ft).
1:03	Flames were seen above the top of the main array, 7.6 m (25 ft).
1:04	The STE temperature reached a temperature of 77°C (170°F) and the smoke vent manual activation was begun. The smoke vent was half open by 1 min 8 sec and fully open by 1 min 13 sec.
2:10 – 2:30	First five sprinklers including all four first-ring sprinklers operated.
2:35 – 3:04	Fire intensified further and seven additional sprinklers operated.
3:26	Fire spread to the South target array.
4:00	Fire spread to the North target array
4:19 – 7:42	Six more sprinklers operated bringing the total number of operations to eighteen.
7:43 – 10:00	The fire gradually subsided and ceiling temperatures reduced.
10:12	Test was terminated to avoid any excessive damage to the ceiling structure.

G.3 Representative Data

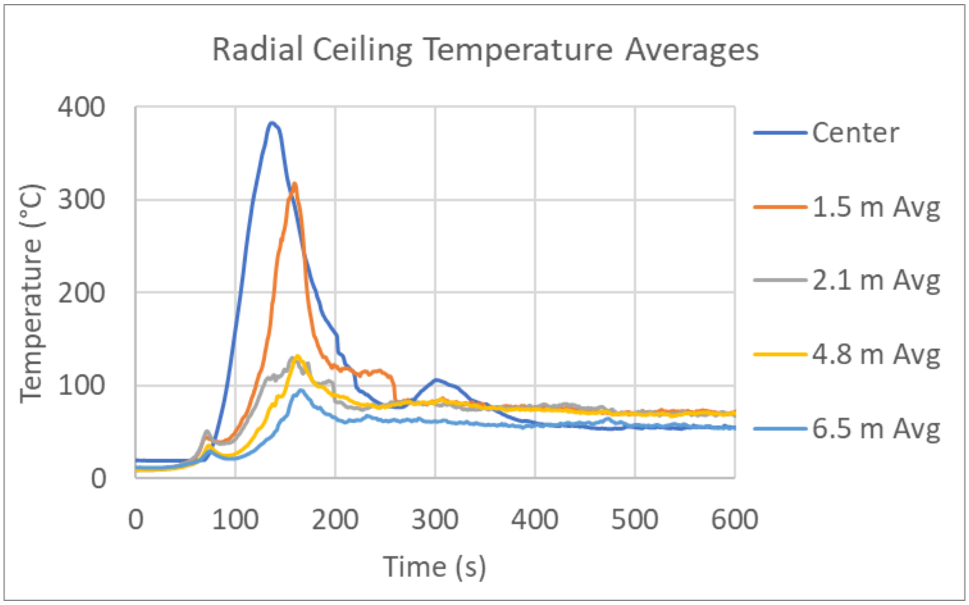


Figure G-1: Radial ceiling temperature averages in Test 7.

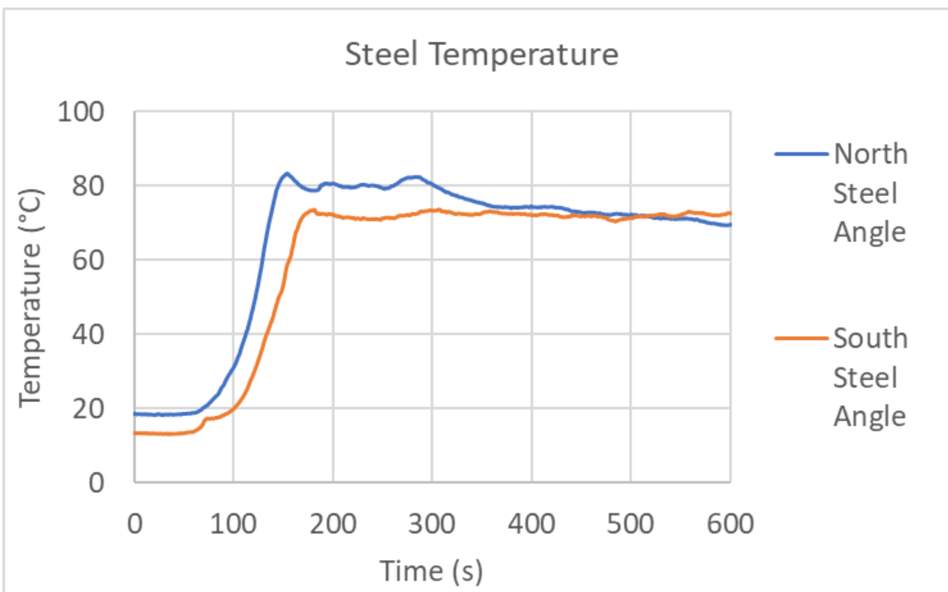


Figure G-2: Temperatures of steel angles in Test 7.

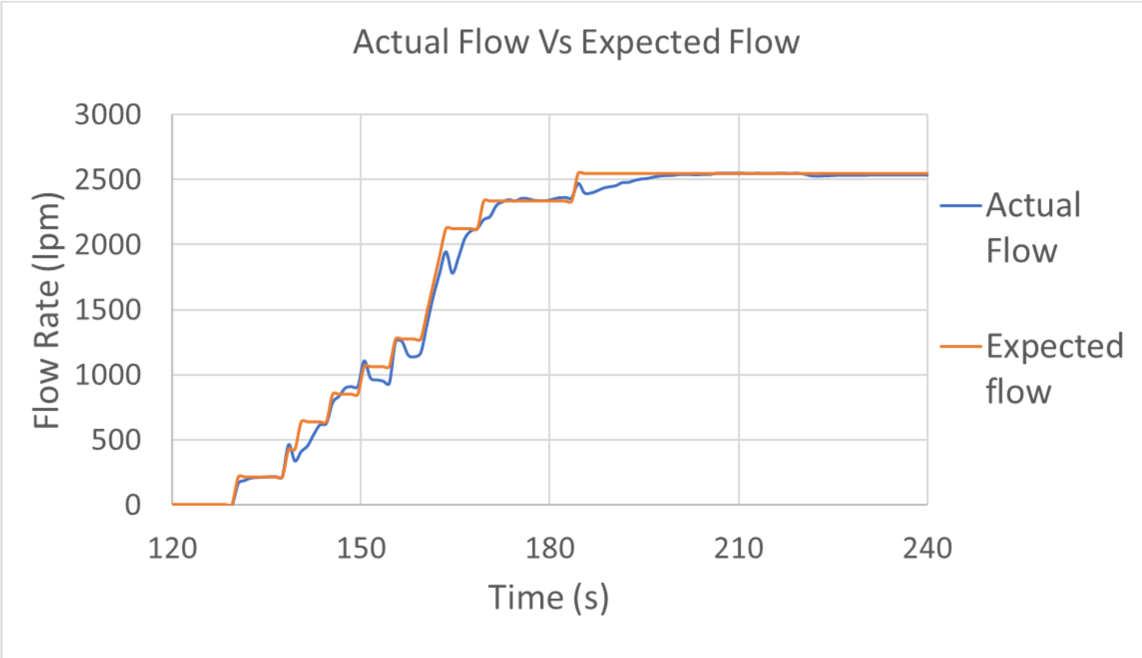


Figure G-3: Flow Rate through all the sprinklers in Test 7.

Appendix H. Probability Derivation for Smoke Vent Opening Before Sprinklers

For a given ratio of vented area to ceiling area, r_v, and a given vent size, A_{V0}, a periodic area, A_P, can be defined as $A_P = A_{V0}/r_v$ which represents the ceiling area closest to any individual vent, see the red shaded area in Figure H-1.

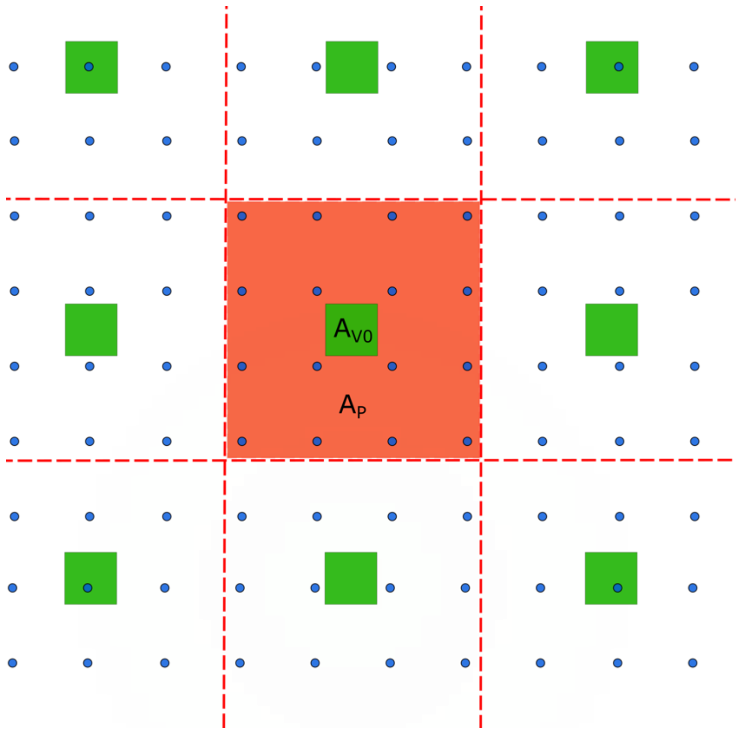


Figure H-1: Periodic vent and sprinkler spacing. Red shaded area is portion of ceiling closest to the central vent. Green squares show individual vents and blue circles show individual sprinklers.

The area in which vents can activate before sprinklers can be calculated from FireFOAM simulations. For a given ignition location with respect to the sprinklers, $\vec{x}$, the vent and sprinkler thermal links are simulated and the area where the vent thermal link would have activated before the sprinklers, $A_{V,S}(\vec{x})$, is calculated. Figure H-2 shows a sketch of $A_{V,S}$ for a particular ignition location, the red shaded region is where a smoke vent thermal link would have activated before the first sprinkler.

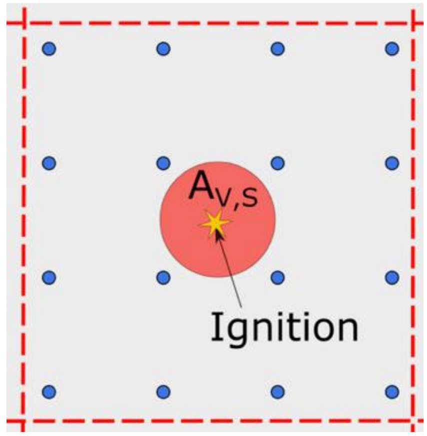


Figure H-2: The area where a vent thermal link would have activated before the sprinklers, $A_{V,S}$, is shown in red shading. The blue circles show the sprinkler locations and the red dashed lines bound the periodic area A_P.

The value of $P_{V,S}$ conditioned on a particular ignition location $\vec{x}$ in A_P, is denoted as $P_{V,S}(\vec{x})$ and can be calculated as $P_{V,S}(\vec{x}) = {A_{V,S}(\vec{x})}/{A_P}$. To calculate the value of $P_{V,S}$ for any random ignition location in A_P, we make three assumptions about the ignition location and the installation locations of the smoke vents and sprinklers.

- The ignition location has a uniform, random distribution.
- The relative location of the smoke vents and sprinklers has a uniform, random distribution, i.e., the smoke vents could be installed in any periodic configuration, independent of the sprinklers.
- There is no correlation between the ignition location and the relative locations of the sprinklers and smoke vents.

Taking these assumptions, $P_{V,S}$ for any random ignition location, $P_{V,S}(\overrightarrow{x_R})$, can be calculated by integrating the product of $p_I(\vec{x})$ and $P_{V,S}(\vec{x})$ over the periodic area A_P, where $p_I(\vec{x})$ is the probability per unit area of ignition occurring at location $\vec{x}$ in A_P. As $p_I(\vec{x})$ is assumed to be uniform over A_P, $P_{V,S}(\overrightarrow{x_R})$ can be expressed by Equation H-1.

$$P_{V,S}(\overrightarrow{x_R}) = \frac{\oint P_{V,S}(\vec{x})dA}{A_P} \qquad \text{H-1}$$

Equation H-1 is simplified by considering only three ignition scenarios with respect to the sprinklers:

- Among four, $\vec{x}_{A4}$,
- Between two, $\vec{x}_{B2}$, and
- Under one, $\vec{x}_{U1}$.

The probability of ignition occurring under each scenario, is approximated by considering the geometry of an idealized occupancy. Figure H-3 discretizes a warehouse ceiling using a 9x9 repeating grid and then dividing the grid into three equal sections between each pair of sprinklers. Doing so shows that a 6x6 grid area is approximated by U1 ignition (yellow shading), a 6x6 grid area is approximated by a B2 ignition (gray shading), and a 3x3 grid area is approximated by a A4 ignition (yellow shading). Based on this argument, weightings $\boldsymbol{w_{U1}}, \boldsymbol{w_{B2}}, \boldsymbol{w_{A4}}$ can be assigned that represent the probability of U1, B2, and A4 ignition scenarios, respectively.

$$
\begin{aligned}
1 = \oint p_I(\vec{x})dA = \oint p_I(\vec{x}_{U1})dA + \oint p_I(\vec{x}_{B2})dA \\
+ \oint p_I(\vec{x}_{A4})dA \\
\boldsymbol{w_{U1}} = \oint p_I(\vec{x}_{U1})dA = \frac{36}{81} = \frac{4}{9} \\
\boldsymbol{w_{B2}} = \oint p_I(\vec{x}_{B2})dA = \frac{36}{81} = \frac{4}{9} \\
\boldsymbol{w_{A4}} = \oint p_I(\vec{x}_{A4})dA = \frac{9}{81} = \frac{1}{9}
\end{aligned}
\quad \text{H-2}
$$

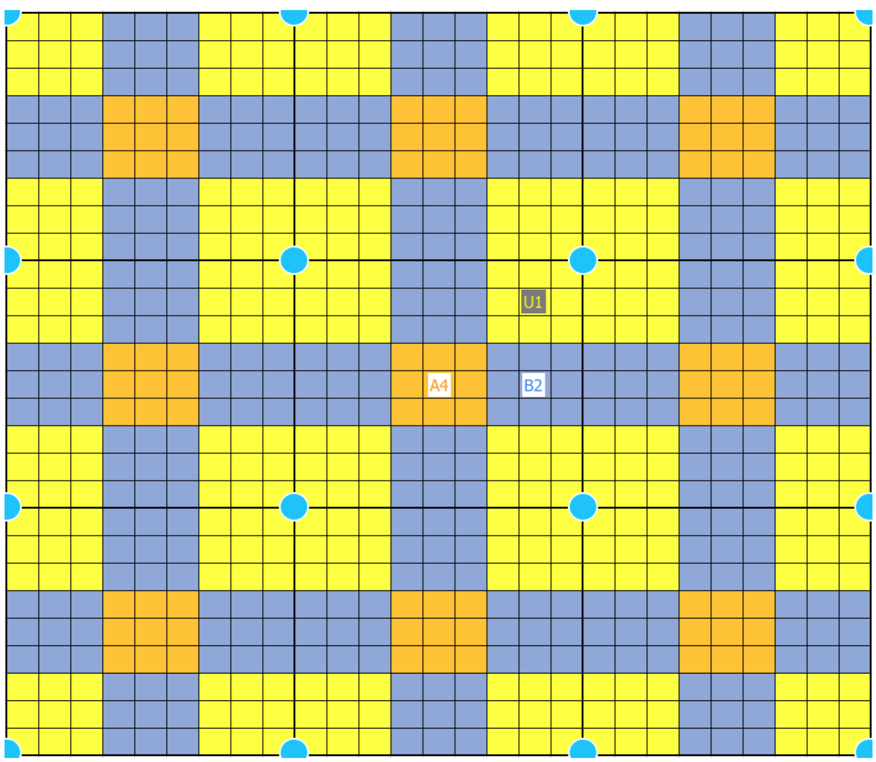


Figure H-3: Map of ignition location probability. Yellow shading – U1, gray shading – B2, orange shading – A4. Blue circles represent sprinkler locations.

Using the ignition location weightings presented in Equation Set H-2, $P_{V,S}(\overrightarrow{x_R})$ can be approximated with Equation H-3.

$$P_{V,S}(\overrightarrow{x_R}) = w_{A4}P_{V,S}(\vec{x}_{A4}) + w_{B2}P_{V,S}(\vec{x}_{B2}) + w_{U1}P_{V,S}(\vec{x}_{U1}) \quad \text{H-3}$$

Appendix I. Example Calculation for Probability of Smoke Vent Opening Before Sprinklers

An example calculation of $P_{V,S}(\overrightarrow{x_R})$ is presented for storage occupancy with 7.6 m (25 ft) of CUP under a 9.1 m (30 ft) ceiling, corresponding to case P-2. The simulated thermal elements for the smoke vents, and QR-OT and SR-HT sprinklers are calculated within the FireFOAM freeburn simulation using Equation 5-2.

$P_{V,S}(\overrightarrow{x_R})$ is calculated as a function of smoke vent activation temperature using the following procedure:

- Activation times for QR-OT and SR-HT sprinkler thermal elements are extracted from the FireFOAM simulation for U1, B2, and A4 ignition scenarios.
- The areas $A_{V,S}(\vec{x}_{A1})$, $A_{V,S}(\vec{x}_{B2})$, and $A_{V,S}(\vec{x}_{A4})$ are calculated for each sprinkler activation time in step 1 by integrating the region where the simulated smoke vent thermal element has exceeded the activation temperature.
- A_P is calculated by assuming values for A_{V0} and r_v. As the value of A_P is site-specific, upper- and lower-estimates are obtained by varying r_v from 2% (less venting, lower bound estimate of $\mathrm{P}_{V,S}(\vec{x}_R)$) to 4% (more venting, upper bound estimate of $\mathrm{P}_{V,S}(\vec{x}_R)$), named A_{P_L} and A_{P_H}, respectively.
- $P_{V,S}(\vec{x}_{U1}), P_{V,S}(\vec{x}_{B2}), P_{V,S}(\vec{x}_{A4})$ are calculated using the results from steps 2 and 3 for A_P, A_{P_L} and A_{P_H}.
- $\mathrm{P}_{V,S}(\vec{x}_R)$ is calculated from step 4 using Equation H-3.

Table I-1 presents all intermediate quantities and $\mathrm{P}_{V,S}(\vec{x}_R)$ values for the QR-OT and SR-HT sprinklers assuming a higher-rated vent activation temperature, in line with NFPA 13 guidance. As expected, values for $\mathrm{A}_{V,S}$ increase from U1 to B2 to A4 ignition scenarios due to the increasing distance between the ignitor and the closest sprinkler, which is illustrated in Figure I-1.

Table I-1: Example calculation of probability for case P2. $P_{V,S}(\vec{x}_R)$ value in bold based on A_P, the lower- and upper-bounds in parenthesis are based on A_{P_L} and A_{P_H}, respectively.

Quantity	**QR-OT Sprinklers**			**SR-HT Sprinklers**		
	RTI 40 $ms^{1/2}$ (72 $fts^{1/2}$) T_{ACT} 347 K (165 F)			RTI 100 $ms^{1/2}$ (181 $fts^{1/2}$) T_{AC} 414 K (285 F)		
	Vent Activation Temperature			**Vent Activation Temperature**		
	366 K (200 F)			455 K (360 F)		
	Ignition Location			**Ignition Location**		
	U1	B2	A4	U1	B2	A4
	Intermediate Quantities					
$t_{S,ACT}$ **(sec)**	24	38	44	32	58	61
$A_{V,S}$ **m^2 (ft^2)**	0 (0)	6.6 (71.0)	16.0 (171.8)	0 (0)	16.9 (181.9)	25.5 (274.5)
A_{P_L} **m^2 (ft^2)**	133 (1434)					
A_P **m^2 (ft^2)**	**100 (1067)**					
A_{P_H} **m^2 (ft^2)**	67 (721)					
$P_{V,S}(\vec{x}_i)$	**0%** (0-0%)	**7%** (5-10%)	**16%** (12-24%)	**0%** (0-0%)	**17%** (13-30%)	**26%** (19-38%)
w	4/9	4/9	1/9	4/9	4/9	1/9
	Result					
$P_{V,S}(\vec{x}_R)$	**5%** (3-6%)			**10%** (7-14%)		

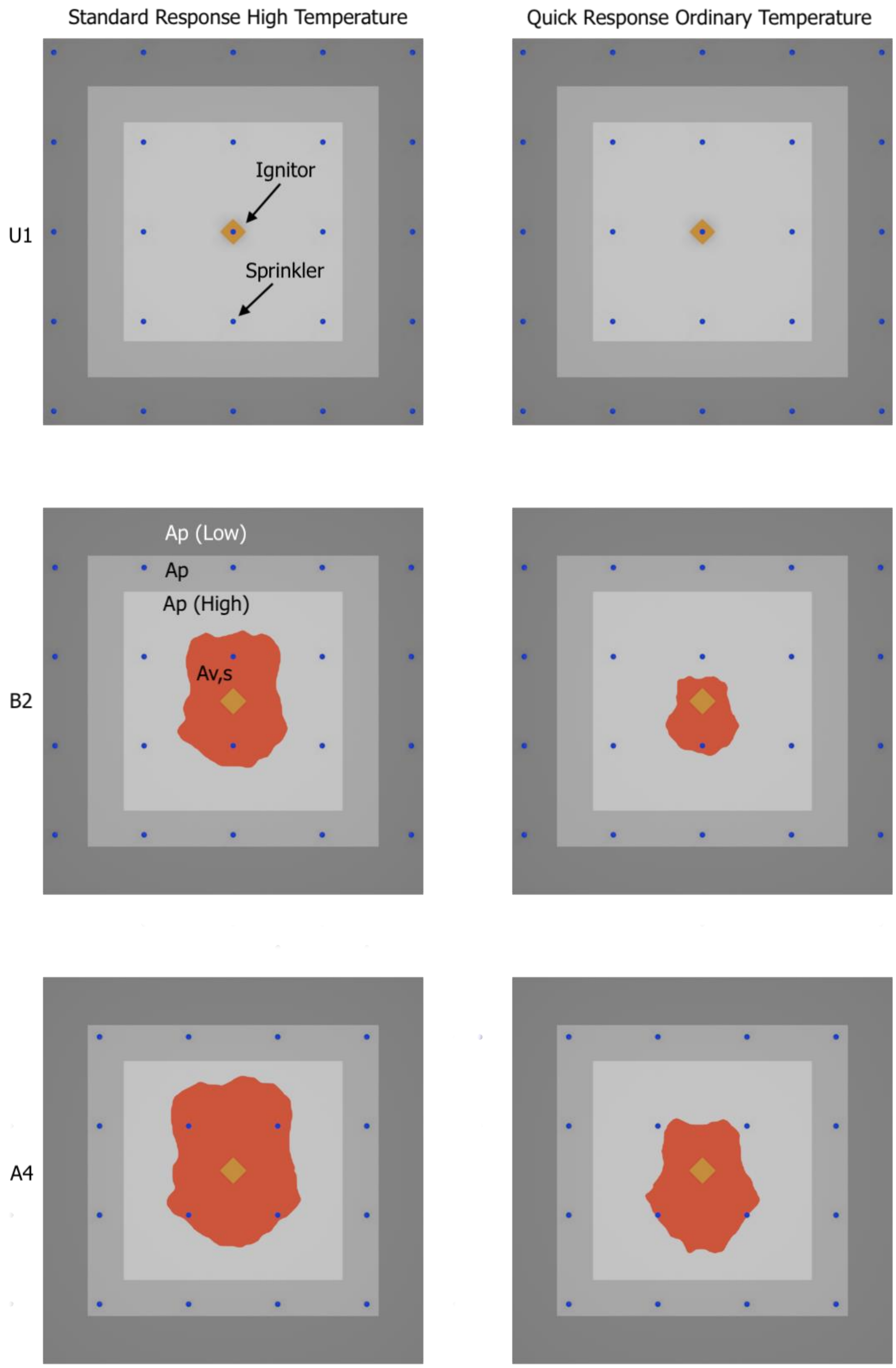


Figure I-1: Vent activation areas for case P2. SR-HT (left column) and QR-OT (right column) sprinklers in under 1 (upper row), between 2 (middle row), and among 4 (lower row). Red shaded area is $A_{V,S}$, yellow diamond is the ignitor location, blue circles are sprinklers, gray areas are A_{P_L}, A_P and A_{P_H} ordered larger to smaller (and darker to lighter gray shading).

Appendix J. Sensitivity Analysis of Probability of Smoke Vent Opening Before Sprinklers

The results presented in Table 5-3 demonstrated multiple sensitivities that were not exhaustively addressed in the main report, and which are detailed here.

J.1 Sprinkler Thermal Element Settings

$\mathrm{P}_{\mathrm{V,S}}(\vec{\mathrm{x}}_R)$ values are consistently and significantly higher for SR-HT sprinklers compared to QR-OT sprinklers. This sensitivity is due to two factors: 1) the SR-HT sprinklers activate later, and 2) the smoke vents are subjected to higher convective heating rates than the sprinklers due to the relative location of their thermal elements, see Figure 5-1. The later activation of the SR-HT sprinklers provides additional time for the vent thermal links to reach their activation temperature compared to the QR-OT sprinklers, resulting in higher $\mathrm{P}_{\mathrm{V,S}}(\vec{\mathrm{x}}_R)$ values.

J.2 Clearance/Storage Height

$\mathrm{P}_{\mathrm{V,S}}(\vec{\mathrm{x}}_R)$ decreases (increases) with increasing (decreasing) clearance (storage) height. For a fixed ceiling height, increasing (decreasing) the clearance (storage) height has two main effects:

- Vertical fire growth rates are reduced after the fire reaches the top of the array, and
- The plume exiting from the top of the array has a longer distance to entrain ambient air, resulting in a wider plume with a lower temperature profile.

Figure J-1 demonstrates this behavior by plotting the radial average-temperature profiles at the smoke vent and sprinkler thermal element heights and at the time of first SR-HT sprinkler activation for A4 ignition for cases P-10, P-11, and P-12 with CUP and 1.5 m (5 ft), 4.6 m (15 ft), and 7.6 (25 ft) clearance under a 15 m (50 ft) ceiling. With increasing clearance height, the temperature profiles decrease, particularly within 2.5 m (8 ft) of the ignition location. This results in lower heating rates for the smoke vents and lower values of $A_{V,S}$, as plotted in Figure J-1. for $T_{ACT,V}$=414 K. There is a competing effect, the increased entrainment with clearance height also delays the first sprinkler activation which provides a longer time for the vent link to be heated. Overall, the effect is to decrease $\mathrm{P}_{\mathrm{V,S}}(\vec{\mathrm{x}}_R)$ with increasing clearance height as the delay in sprinkler activation does not offset the decreased heating rate of the smoke vent thermal element.

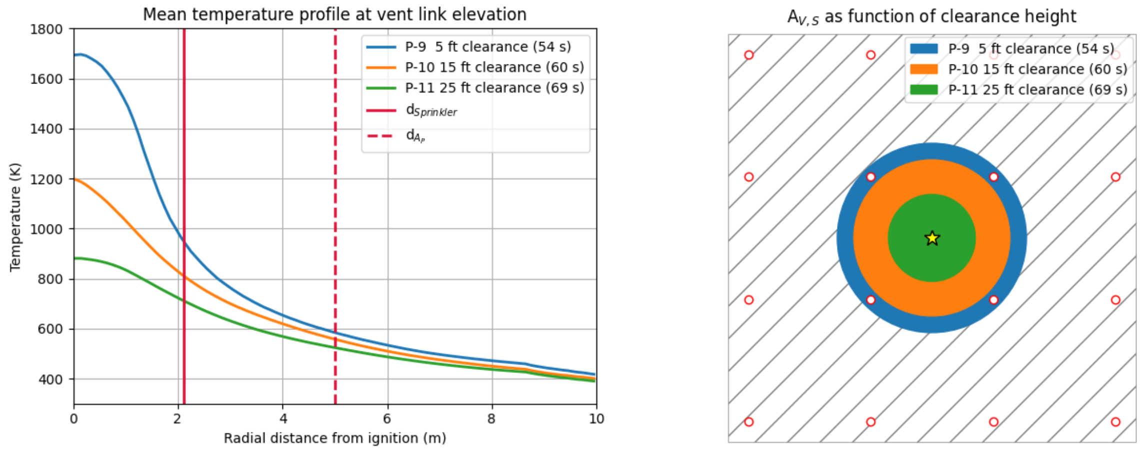


Figure J-1: (left) Azimuthally- and time-averaged (5 sec window) temperature profiles with A4 ignition and SR-HT sprinklers for CUP cases P-9 (blue), P-10 (orange), and P-11 (green) under a 15.24 m (50 ft) ceiling with 1.5 m (5 ft), 4.6 m (15 ft), and 7.6 (25 ft) clearance, respectively, evaluated at vent link elevation. Red solid line is distance from ignition to nearest sprinklers, red dashed line is distance to A_p. Corresponding azimuthally-averaged $A_{V,S}$ values. Cross-hatched area is A_P assuming r_V=3%, yellow star is ignition location.

J.3 Ceiling Height

$P_{V,S}(\vec{x}_R)$ decreases for fixed clearance height and increasing ceiling height comparing both P-2 and P-10 (CUP) and P-1 and P-6 (Class 2). This can be explained with a similar argument from Section J.2 for clearance/storage height – increasing the vertical distance from the ignition location to the ceiling increases the entrainment of ambient air, resulting in a wider fire plume with a lower peak temperature. This makes it less likely for a localized hot spot to form in the ceiling layer between the sprinklers and, therefore, less likely for a smoke vent to be activated before the sprinklers.

J.4 Commodity Type

$P_{V,S}(\vec{x}_R)$ is sensitive to commodity type, with the cartoned commodities having a similar or higher probabilities than UUP, and CUP having slightly higher probabilities than Class 2. To understand this result, the difference in fire growth rates and the difference in entrainment between the commodities must be considered.

Figure J-2 shows the fire growth rates for Class 2 (P-1), CUP (P-2), and UUP (P-3) from ignition until first activation time for offset, A4 ignition and with SR-HT sprinkler links. The commodities are ordered CUP (61 sec), Class 2 (129 sec), UUP (192 sec) in terms of first $t_{ACT,S}$ and CUP, UUP, Class 2 in terms of peak fire growth rate prior to first sprinkler activation.

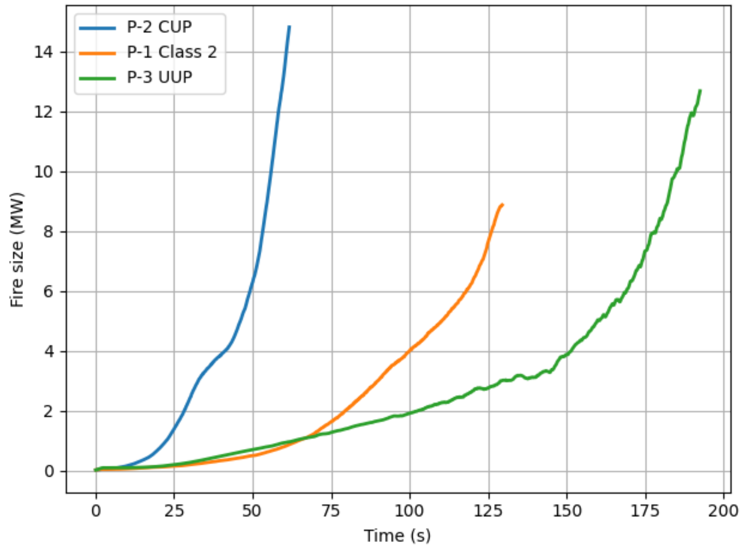


Figure J-2: Fire growth for each commodity type with 7.6/9.1 m (25/30 ft) storage from ignition to first sprinkler activation for A4 ignition and SR-HT sprinkler links.

Figure J-3 shows the azimuthally averaged radial temperature profiles at the vent elevation at first $t_{ACT,S}$ (left). Comparing the cartoned to uncartoned commodities, UUP has an open structure that enhances mixing in the fire plume, entraining more air and lowering the near-ceiling temperature – the cartoned commodities fires are confined within the flue spaces resulting in a narrow plume, less mixing, and higher temperatures beneath the ceiling. Comparing the CUP and Class 2 commodities there is stronger burning at the top of the commodity array for CUP, releasing combustion products that do not mix/cool significantly over the short distance to the ceiling.

The differences in near-ceiling temperature profile and first $t_{ACT,S}$ explain the differences in $A_{V,S}$ between the commodities. Figure J-3 shows the azimuthally-averaged $A_{V,S}$ per commodity (right). Class 2 and CUP have similar $A_{V,S}$, this is because the higher temperature profile for CUP is offset by the longer heating duration for Class 2. UUP has a lower $A_{V,S}$ than Class 2, because the increase in first $t_{ACT,S}$ does not offset the lower temperature profile.

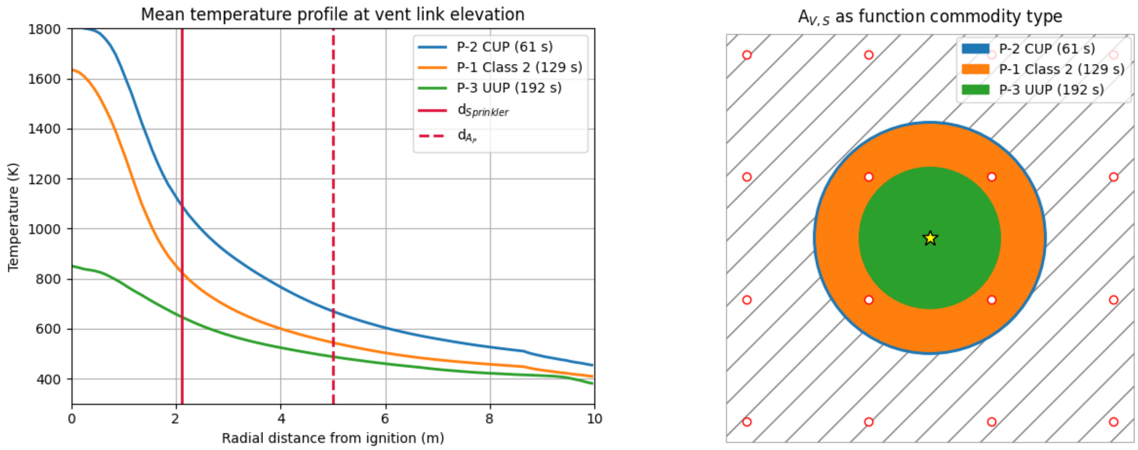


Figure J-3: (left) Azimuthally- and time-averaged (5 sec window) temperature profiles at time of first sprinkler activation for A4 ignition and SR-HT sprinklers with 7.6/9.1 m (25/30 ft) storage of CUP P-2 (blue), Class 2 P-1 (orange), and UUP P-3 (green) commodities evaluated at vent link location. Red solid line is distance from ignition to nearest sprinklers, red dashed line is distance to A_p. (right) Corresponding azimuthally-averaged $A_{V,S}$. Cross-hatched area is A_P assuming r_V=3%, yellow star is ignition location.

J.5 Ignition Location

Cases P-2 and P-4 compare offset and center ignition location for 7.6/9.1 m (25/30 ft) CUP storage. The same comparison is made for 4.6/9.1 m (15/30 ft) CUP storage in cases P-8 and P-9. The $P_{V,S}(\vec{x}_R)$ values are higher for the center ignition cases, except for the 4.6/9.1 m (15/30 ft) storage case with QR-OT sprinklers which are slightly lower for center ignition. Overall, the results are not highly sensitive to the ignition location, but center ignition is associated with higher $P_{V,S}(\vec{x}_R)$ in most cases. Case P-4 (center ignition with 1.5 m (5 ft) clearance) has the largest $P_{V,S}(\vec{x}_R)$ of all simulated cases.

The main reason why center ignition has generally higher $P_{V,S}(\vec{x}_R)$ values is due to the shape of the fire plume. Figure J-4 compares the temperature at the sprinkler link elevation at first sprinkler activation time with A4 ignition for cases P-2 (left) and P-4 (right). For center ignition, the plume is symmetrical, centered as far as possible from the A4 sprinklers. For offset ignition, the plume is biased towards the center of the rack (North) due to the asymmetric flame spread and air entrainment. This results in earlier sprinkler activation when the fire is smaller, reducing the potential for the vents to open before the sprinklers.

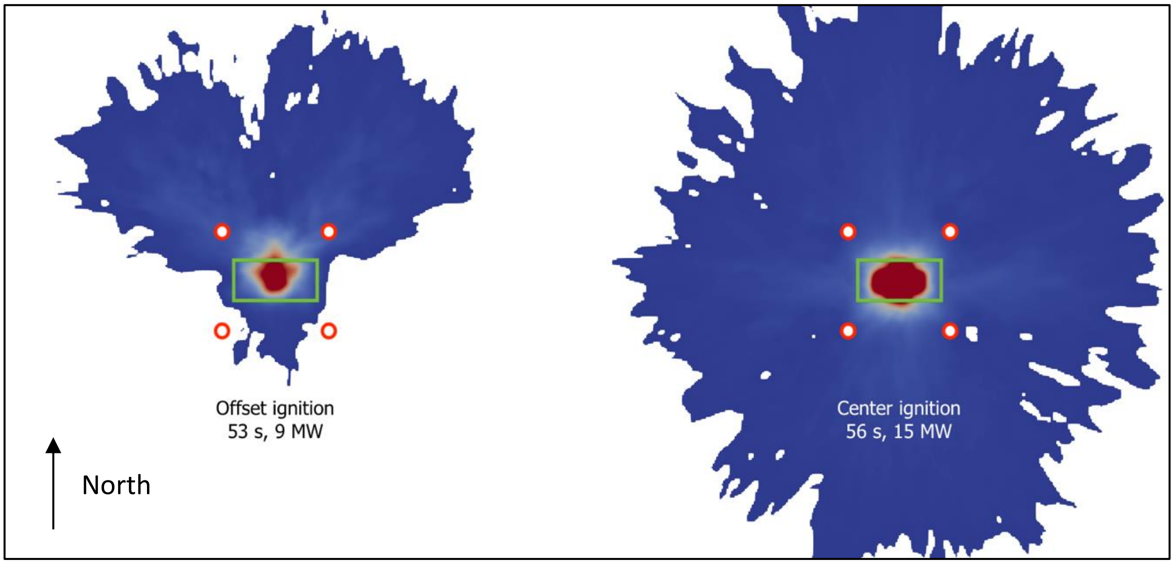


Figure J-4: Time average (5 sec window) temperature at sprinkler link elevation at first sprinkler activation time with A4 ignition for offset ignition case P-2 (left) and center ignition case P-4 (right). Colormap: dark blue is lower limit of 320 K (47°C or 116°F), dark red is upper limit of 1000 K (727°C or 1340°F). Regions below lower limit are transparent. Red circles are A4 sprinkler locations, green rectangle indicates worst-case vent location (vent is not present in these simulations).

Appendix K. Comparison of Calculations and Test Observations for the Probability of Smoke Vents Opening Before Sprinklers

In Section 5.1, the probability of an automatic smoke vent opening before the sprinklers, $P_{V,S}$, was calculated based on FireFOAM simulations. In this section, the results from Tests T-1 to T-7 are compared against these calculations to check the consistency with the model predictions. Note that, while Tests T-1, T-3, T-4, and T-6 did not have an active smoke vent, the same simulated thermal element was always present and so the vent activation time can be determined for every case.

Table K-1 summarizes the vent and sprinkler activation time from the tests and compares the predictions from the model to the outcome from the tests in terms of the order of activation. For all A4 ignition Tests T-2 to T-6, the smoke vent opened, or would have opened, before the first sprinkler. In all vented tests apart from Test T-5, the smoke vent delayed the first sprinkler activation compared to the unvented tests. The smoke vent activates 3-5 seconds before the first sprinkler activated, or would have activated, but this is sufficient to cool the ceiling layer and delay the first sprinkler activation in every test except T-5. For T-5, the first sprinkler is not significantly delayed by the smoke vent, but the combination of the vent and first sprinkler delay subsequent sprinkler activations. For the B2 ignition Test T-1, the smoke vent and first sprinkler activations would have been nearly simultaneous.

The model predictions and test outcomes are aligned for every case, providing confidence in the probabilistic calculations presented in Section 5.1. Automatic smoke vents are likely to open before sprinklers only when positioned directly above the ignition location and B2 or A4 sprinklers. Even small offset distances between the ignition and smoke vent locations will result in sprinklers activating before the smoke vents.

Table K-1: Summary of vent and sprinkler activation order in tests. * Unvented cases where activation time is based on simulated thermal element. ^ Class 2 model cases used offset ignition; central ignition was not simulated. # Ignitor placed in incorrect position in Test T-1.

Test name	Model case name	Ignition scenario	Test Vent (sec)	Test 1st sprinkler (sec)	Test activation order outcome	Model Activation order prediction
T-1	**P-4**	B2# Vent 4ft offset	37*	37	Nearly simultaneous	Nearly simultaneous
T-2	**P-4**	A4	54	93	Vent first	Vent first
T-3	**P-4**	A4	51*	55	Vent first	Vent first
T-4	**P-4**	A4	44*	47	Vent first	Vent first
T-5	**P-4**	A4	46	49	Vent first	Vent first
T-6	**P-1^**	A4	71*	80	Vent first	Vent first
T-7	**P-1^**	A4	68	130	Vent first	Vent first