RESEARCH TECHNICAL REPORT

Sprinkler Performance under Sloped and Obstructed Ceilings

Sprinkler Performance under Sloped and Obstructed Ceilings

Prepared by

Prateep Chatterjee

FM Global
1151 Boston-Providence Turnpike
Norwood, MA 02062

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Executive Summary

The goal of this project is to develop loss prevention guidance for FM Global standards and support the National Fire Protection Association (NFPA) 13[a] Technical Committee on Sprinkler System Discharge in the development of new protection requirements addressing sprinkler design requirements for storage under sloped and obstructed ceilings. The present study has been conducted in partnership with the Fire Protection Research Foundation (FPRF) and the Property Insurance Research Group (PIRG). The study was in three phases with the current Phase 3 aiming to develop fire protection guidelines by carrying out sprinklered, large-scale fire tests.

In the first two phases of the project, numerical modeling using the computational fluid dynamics (CFD) code FireFOAM[b,c] identified the sensitivity of sprinkler activation times and spray dynamics to ceiling slope, sprinkler orientation (deflector parallel-to-floor or parallel-to-ceiling), and obstructed ceiling construction (e.g., purlins and girders). As input to the large-scale test planning, the modeling studies identified a maximum ceiling inclination angle of 18° or a slope of 0.333 (4 in 12), and an acceptable purlin (or a similar vertical ceiling structural member) depth in the range of 150-460 mm (6-18 in.). Modeling and recent cold-flow measurements[d] have shown that the parallel-to-floor sprinkler deflector orientation provides better water distribution on top of the stored commodity compared to the parallel-to-ceiling orientation. Based on the numerical modeling results[e,f,g], a testing proposal was developed in Phase 2 of the project[h].

Large-scale, sprinklered fire tests were conducted in Phase 3 to evaluate the performance of ceiling sprinklers using the FM Global standard Cartoned Unexpanded Plastic (CUP) commodity (equivalent to the NFPA 13 cartoned, nonexpanded Group A plastic commodity) placed in a rack-storage arrangement under sloped ceilings. Obstructed ceiling construction (see definition in the FM Global Property Loss Prevention Data Sheet (DS) 2-0, *Installation Guidelines for Automatic Sprinklers*[i]) in the form of purlins

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[a] "NFPA 13: Standard for the Installation of Sprinkler Systems," National Fire Protection Association, 2016.

[b] Y. Wang, P. Chatterjee, and J. L. de Ris, "Large Eddy Simulation of Fire Plumes," *Proceedings of the Combustion Institute*, vol. 33, no. 2, pp. 2473-2480, 2011.

[c] FireFOAM. [Online]. http://www.fmglobal.com/modeling. Accessed September 15, 2019.

[d] S. J. Jordan and N. L. Ryder, "Phase III - Spray Dispersion Measurements," Fire Protection Research Foundation, Technical Report, 2018.

[e] P. Chatterjee and K. V. Meredith, "Numerical Modeling of Sprinkler Activations and Spray Transport Under Sloped Ceilings," FM Global, Technical Report 3055093, 2015.

[f] P. Chatterjee and J. A. Geiman, "Numerical Simulations of Sprinkler Activations and Spray Transport under Obstructed, Sloped Ceilings," FM Global, Technical Report 3059743, 2017.

[g] P. Chatterjee, "Sprinkler Performance under Non-Sloped Obstructed Ceiling Construction," FM Global, Technical Report 3059742, 2018.

[h] J. A. Geiman and N. L. Ryder, "Protection of Storage Under Sloped Ceilings - Phase 2 - Full Scale Test Matrix," Fire Protection Research Foundation, Technical Report, 2017.

[i] "FM Global Property Loss Prevention Data Sheet 2-0, Installation Guidelines for Automatic Sprinklers," FM Global, January 2014.

and girders was included. All the tests were conducted under a sloped ceiling structure installed in the Large Burn Laboratory (LBL) at the FM Global Research Campus in West Glocester, RI.

Based on the simulation results from Phases 1 and 2[e,f] and spray tests[d], the maximum ceiling slope selected for the tests was 18°, the largest depth for purlins considered was 460 mm (18 in.) and the ceiling clearance above the longitudinal flue of the main array was kept at 3 m (10 ft). Sprinkler deflector orientation was maintained as parallel-to-floor, except for one test conducted with the parallel-to-ceiling orientation. Seven sloped ceiling tests were conducted, and their performance was compared against that in a baseline (non-sloped, unobstructed ceiling) test.

From the range of conditions explored in large-scale testing as well as the previous numerical modeling and spray test results the following conclusions can be drawn:

- Compared to the three sprinkler activations in the CUP baseline test, one to four additional sprinklers activated when the ceiling was inclined at 10° and four to seven additional activations occurred when the ceiling was inclined at 18°. In these tests, fire spread was successfully controlled. The 18° tests were found to be more challenging from a sprinkler protection standpoint, especially the unobstructed ceiling test in which ten sprinklers activated.
- Presence of obstructed ceiling construction (purlins and girders) was generally found to cause early activation of sprinklers compared to the baseline test and mitigated the biased ceiling jet flow caused by the ceiling slope (the ceiling jet tends to move toward the upslope). However, it was found that deeper purlins could confine the ceiling jet within the purlin channels causing several sprinklers to activate far away from the fire source. Closing the purlin channels at the girder locations (the gap above the girders) was found to mitigate the ceiling jet channeling effect, reducing the unwanted activation of sprinklers along the purlin channels. This strategy was found to be effective for purlin depths of 460 mm (18 in.) at 10° inclination and 300 mm (12 in.) at 18° inclination.
- At 10° ceiling inclination, current tests showed limited effect of sprinkler deflector orientation on suppression effectiveness; however, in the parallel-to-ceiling orientation test, the sprinkler spray cores moved away from the ignition region and a larger amount of commodity was consumed during the test (300% increase in total energy release compared to the baseline test whereas only 30% increase was recorded for the parallel-to-floor test). For other storage scenarios besides the tested configuration (4-tier CUP arrays, 10 ft ceiling clearance), the adverse effects of parallel-to-ceiling orientation on the sprinkler suppression performance can be more pronounced. Spray tests[d] and numerical modeling[e,f] have shown inferior spray distribution for the parallel-to-ceiling orientation for ceilings inclined at 18°.

The following general recommendations are made toward updates of FM Global DS 2-0[i] and NFPA 13[a] sprinkler protection designs for storage under sloped ceilings in the presence of obstructed ceiling construction:

1. For ceiling inclinations up to 10° (slope of 2 in 12), a parallel-to-floor sprinkler deflector orientation is preferred as it provides a higher water flux to the ignition area compared to the parallel-to-ceiling orientation. In addition, when purlin depths are less than or equal to 300 mm (12 in.), ceilings of inclination up to 10° can be considered non-sloped, unobstructed type[a,i]. For purlin depths greater than 300 mm (12 in.) and less than or equal to 460 mm (18 in.), purlin channels at girder locations should be closed to prevent ceiling jet channeling which could result in undesired activations far away from the fire location causing the water demand to be exceeded.
2. For ceiling inclinations greater than 10° and less than or equal to 18° (slope of 4 in 12), sprinkler deflectors should be kept parallel-to-floor. In addition, for purlins up to 300 mm (12 in.) depth, the gaps above the girders should be closed to prevent ceiling jet channeling. Purlins deeper than 300 mm (12 in.) when ceiling inclination is greater than 10° are deemed challenging for ceiling sprinklers installed on their normal spacing due to delays in downslope sprinkler activations. For ceiling inclinations greater than 10°, additional protection recommendations, e.g., In-Rack Automatic Sprinklers (IRAS) and/or false-/drop-ceilings[i], would need to be implemented in order to provide an acceptable level of fire control.
3. For ceiling inclinations over 10° and up to 18° (slope of 4 in 12), consideration should be given toward adjusting the ceiling sprinkler design obtained from large-scale fire testing conducted under non-sloped, unobstructed ceilings to account for the impact of ceiling slope and, when present, obstructed ceiling construction.
4. When the purlin depth exceeds the sprinkler's maximum allowable vertical distance[a,i] below the ceiling, it is recommended that sprinklers be placed below the purlins on a plane parallel to the ceiling with the sprinkler deflectors in a parallel-to-floor orientation. The maximum distance of the plane should be 150 mm (6 in.) from the purlins. This recommendation is valid for a maximum purlin depth of 460 mm (18 in.) for ceilings with up to 10° inclination. For ceilings with inclinations greater than 10° and less than or equal to 18°, the maximum purlin depth should be 300 mm (12 in.). Sprinkler spacing on the ceiling level should be selected such that no spray obstruction occurs at girder locations.

Abstract

Seven large-scale, sprinklered fire tests were conducted to evaluate the performance of ceiling sprinklers under sloped ceilings. In the tests, 4-tier-high rack-storage arrays of the FM Global Cartoned Unexpanded Plastic (CUP) commodity were used. Tests were conducted with ceiling inclinations of 10° (slope of 2 in 12) and 18° (4 in 12). One test was conducted with an unobstructed ceiling and six tests were conducted with obstructed ceiling construction in the form of purlins and girders attached to the sloped ceiling. Purlin depths of 300 mm (12 in.) and 460 mm (18 in.) were considered with separation distance of 1.5 m (5 ft). The girder depth considered was 610 mm (24 in.) with separation distances of 7.6 m (25 ft) and 12.2 m (40 ft). Suppression performance of each test was compared against results from a baseline test (non-sloped, unobstructed ceiling). Compared to the three sprinkler activations in the baseline test, one–four additional sprinkler activations occurred when the ceiling was inclined at 10° and four–seven additional activations occurred when the ceiling was inclined at 18°. In these tests, fire spread was successfully controlled. The 18° tests were found to be more challenging from a sprinkler protection standpoint. The role of sprinkler deflector orientation (parallel-to-floor or parallel-to-ceiling) was also investigated and it was determined that the parallel-to-ceiling orientation would result in additional challenges to sprinkler protection design. Presence of obstructed ceiling construction was generally found to cause early activation of sprinklers and mitigated the biased ceiling jet flow caused by the ceiling slope (toward the upslope). However, it was found that deeper purlins could cause the ceiling jet to confine within the purlin channels resulting in several sprinklers to activate far away from the fire source. Based on the present test results along with those from previously conducted numerical modeling studies and spray testing, recommendations toward updates to existing protection guidelines have been developed.

Acknowledgments

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1. Introduction

The goal of this project is to develop loss prevention guidance for FM Global standards and support the National Fire Protection Association (NFPA) 13 [1] Technical Committee on Sprinkler System Discharge in the development of new protection requirements addressing sprinkler design requirements for storage under sloped ceilings. The present study has been conducted in partnership with the Fire Protection Research Foundation (FPRF) and the Property Insurance Research Group (PIRG). The study was in three phases with the current Phase 3 aiming to develop fire protection guidelines by carrying out sprinklered, large-scale fire tests.

In the first two phases of the project, numerical modeling using the computational fluid dynamics (CFD) code FireFOAM [2] [3] identified the sensitivity of sprinkler activation times and spray dynamics to ceiling slope, sprinkler orientation (deflector parallel-to-floor or parallel-to-ceiling), and obstructed ceiling construction (e.g., purlins and girders). As input to the large-scale test planning, the modeling studies identified a maximum ceiling inclination angle of 18° or a slope of 0.333 (4 in 12) [4], and an acceptable purlin (or a similar vertical ceiling structural member) depth in the range of 150-460 mm (6-18 in.) [5]. Modeling also showed that the parallel-to-floor sprinkler deflector orientation provides better water distribution on top of the stored commodity compared to the parallel-to-ceiling orientation [4] [5]. Based on the numerical modeling results, a testing proposal was developed by the FPRF contractor Fire and Risk Alliance (FRA) in Phase 2 of the project [6]. Recent cold-flow measurements have also demonstrated that a parallel-to-floor sprinkler deflector orientation provides superior water distribution below the sprinkler with negligible impact on the distribution pattern due to the sloped ceiling [7].

Large-scale, sprinklered fire tests were conducted in Phase 3 to evaluate the performance of ceiling sprinklers using the FM Global standard Cartoned Unexpanded Plastic (CUP)[a] commodity stored in a rack-storage arrangement under sloped ceilings. The current study has considered scenarios involving fast-growing fires and the use of quick-response, ordinary temperature (QR/OT) sprinklers. Several kinds of obstructed ceiling construction are used in warehouses, e.g., beams, metallic purlins and girders, and concrete tees. However, for this study, All Metal Building Structure (AMBS) type construction is considered. AMBS construction is commonly found in North American warehouses. In AMBS, purlins and girders are primarily present below the ceiling. Obstructed ceiling construction (see definition in the FM Global Property Loss Prevention Data Sheet (DS) 2-0, *Installation Guidelines for Automatic Sprinklers* [8]) in the form of purlins and girders was included. Figure 1-1 shows an industrial building with a sloped ceiling and presence of obstructed ceiling construction (purlins and girders). Obstructed ceiling construction tends to keep the flow of hot combustion products originating from fires confined in the

[a] FM Global standard CUP commodity is equivalent to the NFPA Cartoned, Non-expanded Group A Plastic commodity.

purlin channels, possibly causing delays in sprinkler activations. All the tests were conducted in the Large Burn Laboratory (LBL) at the FM Global Research Campus in West Glocester, RI.

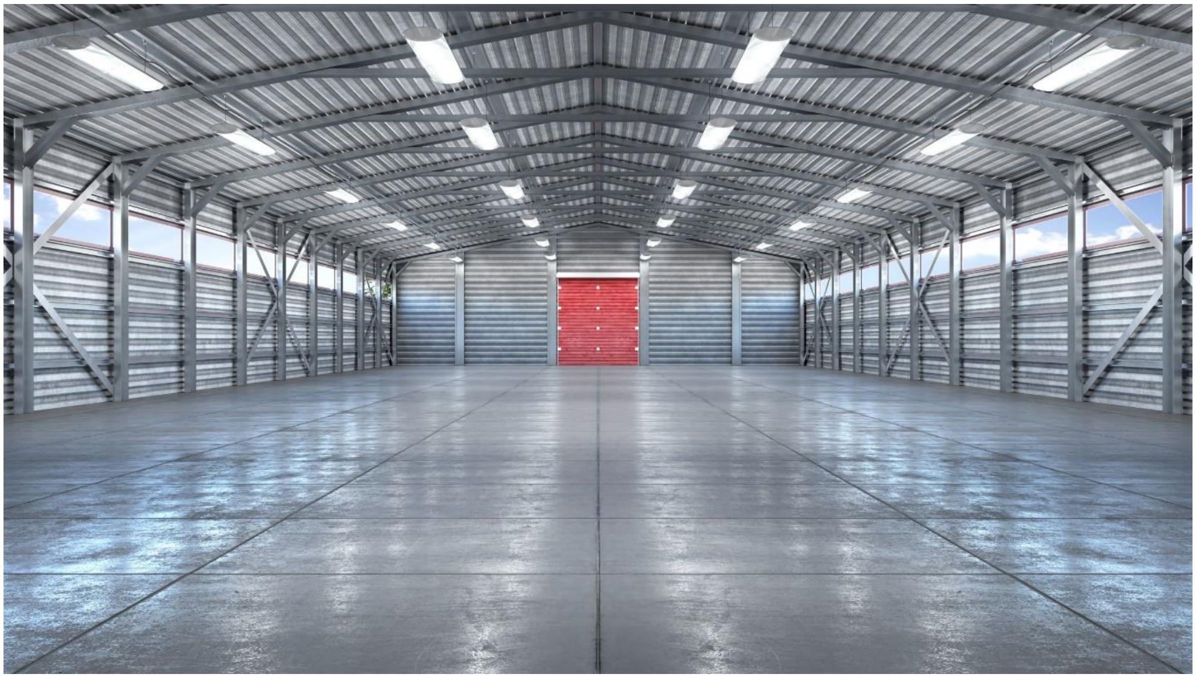

Figure 1-1: Sloped ceiling with obstructed ceiling construction (e.g., purlins and girders) [9].

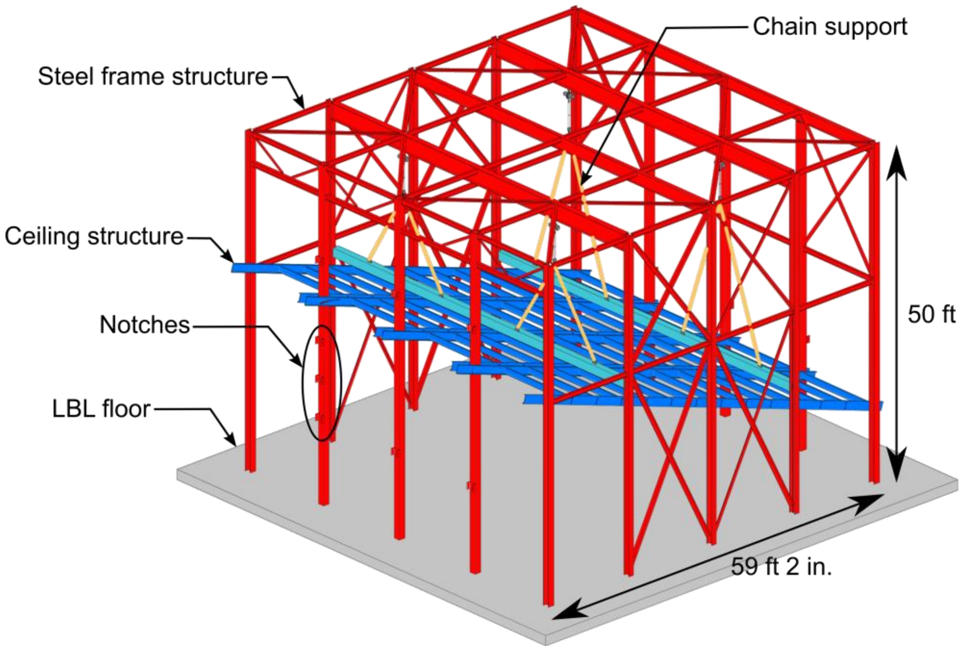

Figure 1-2: Design of the sloped ceiling structure.

A sloped ceiling structure was constructed and installed in the LBL at the FM Global Research Campus. Figure 1-2 shows the 18 m × 18 m (59 ft × 59 ft) wide and 15 m (50 ft) tall steel frame designed to support the ceiling. Figure 1-3 shows the ceiling structure being installed. The sloped ceiling was placed on notches at two ends and supported by vertical chains. The notches located at different heights allowed testing under ceiling slopes of 0.167 or 2 in 12 (10°) and 0.333 or 4 in 12 (18°). The ceiling was fitted with non-combustible materials (fire-rated gypsum sheetrock) for protection of the steel structure, sheet-metal purlins and girders, sprinkler pipes and instrumentation (sprinkler timing wires, thermocouples and bi-directional probes).

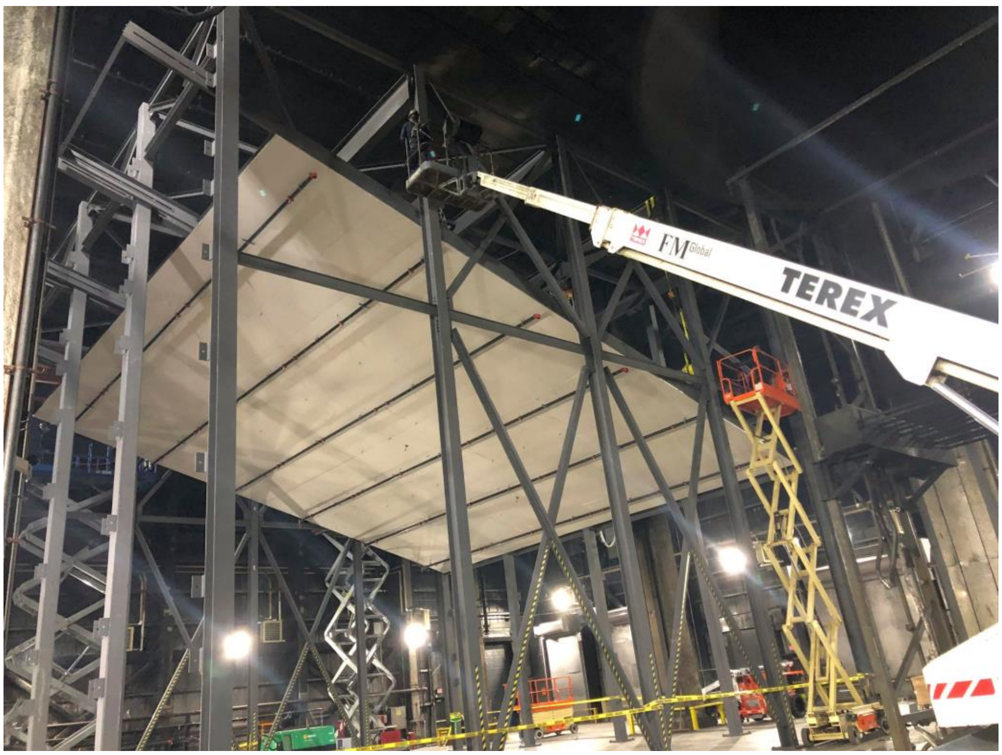

Figure 1-3: Sloped ceiling structure being assembled on the LBL floor.

Based on the simulation results from Phases 1 and 2 [4] [5] and spray tests conducted by FRA [7], the maximum ceiling inclination selected for the tests was 18°, the largest depth for purlins was kept at 460 mm (18 in.) for the 10° inclination tests and the ceiling clearance above the longitudinal flue of the main CUP rack-storage array was kept at 3 m (10 ft). For the 18° inclination, purlin depths greater than 300 mm (12 in.) are deemed challenging for protection design due to delays in downslope sprinkler activations [5]. Additional protection recommendations, e.g., In-Rack Automatic Sprinklers (IRAS) and/or false-/drop-ceilings [8], are implemented when such steep inclinations are encountered in warehouses. Therefore, for the 18° inclination tests, the maximum purlin depth was selected to be 300 mm (12 in.). Sprinkler deflector orientation was maintained as parallel-to-floor, except for one test conducted with the parallel-to-ceiling orientation. A baseline test (non-sloped, unobstructed ceiling) was conducted under the south moveable ceiling of the LBL. Seven sloped ceiling tests were conducted, and individual test performance was compared against that in the baseline test. Based on the large-scale tests, modeling results [4] [5] and spray test outcomes [7], recommendations have been developed for updates to NFPA 13 [1] and DS 2-0 [8].

2. **Large-Scale Fire Suppression Tests**

Seven large-scale fire suppression tests were conducted under the installed sloped ceiling structure. To compare results of the sloped ceiling tests, a baseline test (non-sloped, unobstructed ceiling) was also carried out. Sloped ceiling Tests #3-6 were conducted at a 10° inclination and Tests #1-2 and #7 with the ceiling inclined at 18°. Test setup details are first presented followed by results from the baseline test and the sloped ceiling tests.

2.1 Commodity

The FM Global standard CUP commodity was used in all the tests. The CUP commodity consists of rigid crystalline polystyrene cups (empty, 0.46 l or 16 oz.), packaged, face down and in a single-wall corrugated containerboard carton. The cups are individually compartmented, each layer separated by a corrugated containerboard pad arranged in five layers of 25 cups per layer, yielding a total of 125 cups per carton. Eight 530 mm (21 in.) cubic cartons are placed in a 2 × 2 × 2 arrangement for a total dimension of 1.07 m × 1.07 m × 1.07 m (3.5 ft × 3.5 ft × 3.5 ft), supported on an ordinary, two-way, slatted deck hardwood pallet. Total combustible weight of one pallet load is ~73.8 kg (162.8 lb), consisting of the commodity – corrugated containerboard (~19.8 kg or 43.7 lb) and plastic cups (~31.6 kg or 69.7 lb), along with the hardwood pallet supporting the commodity (~22.4 kg or 49.4 lb). A photograph of the CUP commodity is shown in Figure 2-1.

Figure 2-1: FM Global standard CUP commodity

2.2 Storage Arrangement

The storage arrangement for all tests consisted of a double row, open frame rack main array and two single row open frame target arrays. The main array ran north – south and was two pallet loads wide and six pallet loads long (eight pallet loads long in the baseline test). The main array was aligned with the purlin channels on the sloped ceiling as this is the typical orientation of rack storage found in warehouses with sloped ceilings. The target arrays were one pallet load wide and four pallet loads long. They were placed to the east and west of the main array with an aisle width of 1.2 m (4 ft). All the longitudinal and transverse flues were a nominal 150 mm (6 in.). The ceiling height above the longitudinal flue of the main array was kept at 9.1 m (30 ft) and the storage height was nominal 6.1 m or 20 ft (four pallet loads high) for all the tests.

2.3 Ignition

For all the tests, ignition was achieved using two standard FM Global half igniters, which are cylinders made of rolled cellucotton soaked in 113 ml (4 oz.) of gasoline. The igniters were positioned at the base of the lower tier, in the center of the flue space separating two pallets. In the sloped ceiling tests, the ignition location was among four sprinklers, offset within the rack 0.61 m (2 ft) from the centerline of the longitudinal flue toward the east, as shown in Figure 2-10(b). In the baseline test, the ignition location was offset toward the west, as can be seen in Figure 2-4(a).

2.4 Recording and Instrumentation

Documentation for the tests included video (visible and infrared), still photographs, and audio recordings of observations. The video recordings included several High-Definition (HD) digital video cameras, “bullet” video cameras, and an elevated ceiling-level GoPro video camera. The following instrumentation was available during the tests:

- Bare-bead, 0.8 mm (20 gauge), Chromel-Alumel (k-type) thermocouples installed 165 mm (6.5 in.) perpendicular distance below the sloped ceiling at thirty-one (31) locations, shown in Figure 2-2 by the black circles. The thermocouples had a Response Time Index (RTI) of 8.0±1.5 $(m\text{-}s)^{0.5}$ (14.5±2.7 $(ft\text{-}s)^{0.5}$). Contour plots of ceiling jet gas temperatures developed from the thermocouple array are included in Appendix C.
- Three bi-directional probes were installed to measure the ceiling jet velocities in the sloped ceiling tests. Locations of the probes are shown by the green rectangles in Figure 2-2. One probe was placed at 150 mm (6 in.) perpendicular distance from the ceiling in the north – south direction (inside the purlin channel above the main rack-storage array’s longitudinal flue space). A second probe was located on the upslope side of the main rack-storage array at 150 mm (6 in.) perpendicular distance below the bottom of the purlins for the rest of the tests. A third probe was placed on the downslope end with similar perpendicular distances as the upslope probe. Measured velocity data are shown in Appendix D.
- Two heat flux gages were placed at the upslope side and along the main array’s longitudinal flue direction in the sloped ceiling tests. Heat flux at these two locations was monitored to maintain the integrity of the ceiling structure.
- Flow meters and pressure controllers to monitor and control water flow in the sprinkler system.
- Electrical circuits on each sprinkler to determine individual sprinkler activation times.
- In the baseline test, thermocouples embedded in a cross-shaped steel angle at the ceiling center measured steel temperatures. Thermocouples were embedded at the center and at 150 mm

(6 in.) intervals along the length of each of the four legs (steel thickness of 6.4 mm and total cross-leg length of 0.61 m or 2 ft).

- For the sloped ceiling tests, a FLIR A655sc camera was used for infrared (IR) imaging. This camera utilizes an uncooled Vanadium Oxide (VoX) microbolometer detector measuring wavelengths between 7.5 µm and 14 µm (far infrared) at a resolution of 640 x 480 pixels. A 25° Field of View (FOV) germanium lens (aperture of f/1.0) was attached to the camera to capture the ceiling jet temperatures. False-color images for visualizing the IR spectra (wavelength range outside the visual range) are reported below.

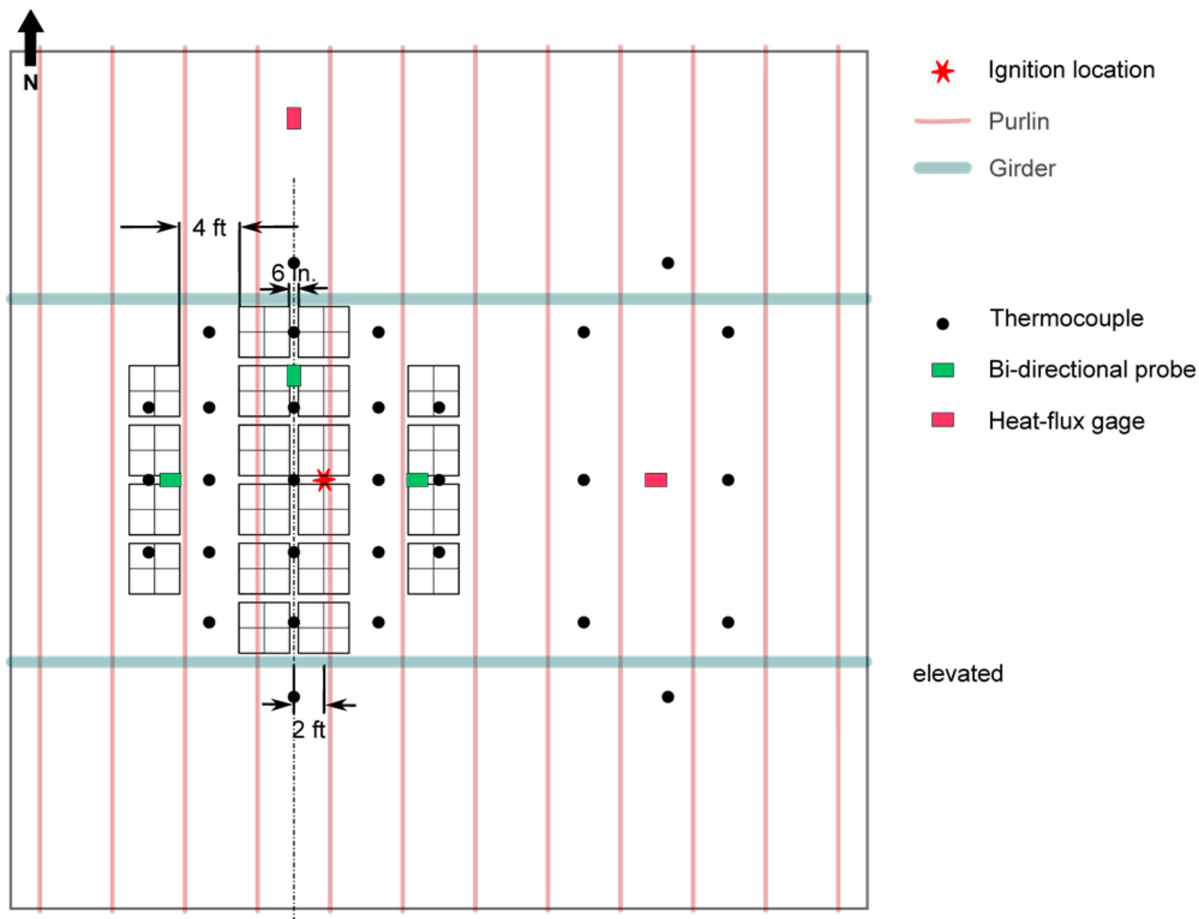

Figure 2-2: Plan view of the test setup showing the instrumentation locations relative to the rack-storage arrays. Thermocouples, bi-directional probes and heat flux gages were installed.

2.5 Test Evaluation Criteria

The results of the sloped ceiling large-scale fire tests were evaluated using the following conditions:

- Ideally, the same number of sprinkler operations should occur in the presence of ceiling slope and/or obstructed ceiling construction compared to the baseline test (non-sloped, unobstructed ceiling). In practical terms, a total number of activations of the same of order of magnitude (within 2-4 operations) would be acceptable.
- No perimeter sprinkler activations, indicating that further activation of sprinklers would not occur if the ceiling was larger and additional sprinklers were present[b].
- Extent of fire spread – ideally, the fire spread should be similar to the observed spread in the baseline test. At worst, the fire should not spread to either end of the main array. Target ignition is acceptable but the fire should not propagate to the back of the target commodity.
- Steel temperatures encountered in the tests should be in the range observed during the baseline test and the peak steel temperature should not exceed 538°C (1000°F)[c].

2.6 Automatic Sprinkler Protection

An FM Approved quick-response (QR) pendent sprinkler with a link rated temperature of 74°C (165°F) was used in this series of tests. Details of the sprinkler properties are summarized in Table 2-2. In the sloped ceiling tests, the K240 (K16.8) sprinklers were installed on nominal 76 mm (3 in.) diameter steel piping at a spacing of 3 m × 3 m (10 ft × 10 ft) along the ceiling surface (actual spacing projected on the floor plane varied depending on the ceiling inclination). The water pressure was set to 2.4 barg (35 psig) providing a nominal design density of 41 mm/min (1.0 gpm/ft^2) for all tests. The deflectors of the pendent, K240 (K16.8) sprinklers were placed parallel to the floor in Tests #1-3 and #5-7 and kept parallel to the ceiling in Test #4. The deflector perpendicular distance from the ceiling varied depending on the purlin depth. Following the calculation method in FM Global DS 2-0 [8], obstruction to spray by ceiling structures (e.g., purlins) was estimated. To avoid spray impingement, the purlins are not permitted to cross to the region below the checkerboard area shown in Figure 2-3. The calculations were conducted for a ceiling inclined at 18° and a purlin depth of 460 mm (18 in.). See Section 2.2.3.5.1 in FM Global DS 2-0 [8] for calculation details. To avoid obstructing the sprinkler's umbrella discharge pattern, the deflectors were placed 150 mm (6 in.) below the purlins on a plane parallel to the ceiling. When the deflector is placed at this distance, the purlins are not expected to obstruct the sprinkler's discharge pattern as shown in Figure 2-3(b). In contrast, some spray impingement would be expected if the deflectors were to be placed on a plane passing through the bottom of the purlins, see Figure 2-3(a). Numerical modeling results [5] showed that up to 150 mm (6 in.) distance below the purlins would be an

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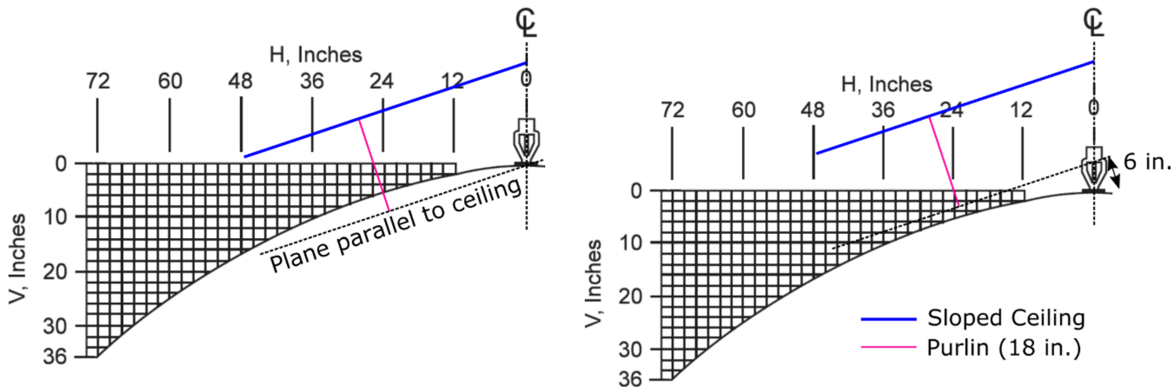
[b] It should be noted that the sloped ceiling structure had smaller dimensions (18 m x 18 m or 59 ft x 59 ft) compared to the baseline test conducted under a 24 m x 24 m (80 ft x 80 ft) structure. The perimeter sprinklers in the sloped ceiling tests were on the third ring compared to the fourth ring for the baseline test.

[c] A steel angle was not installed below the sloped ceiling. Instead, a model was applied for the estimation of the steel temperature. The model details are included in Appendix G.

acceptable distance with minimal delays in the sprinkler activation times. The ceiling to sprinkler link perpendicular distance was, therefore, set to 330 mm (13 in.) in the baseline test and sloped ceiling Test #1 (unobstructed ceiling tests) and 460 mm (18 in.) in Tests #2-4 and #7 (purlin depth of 300 mm or 12 in.) and to 610 mm (24 in.) in Tests #5-6 (purlin depth of 460 mm or 18 in.).

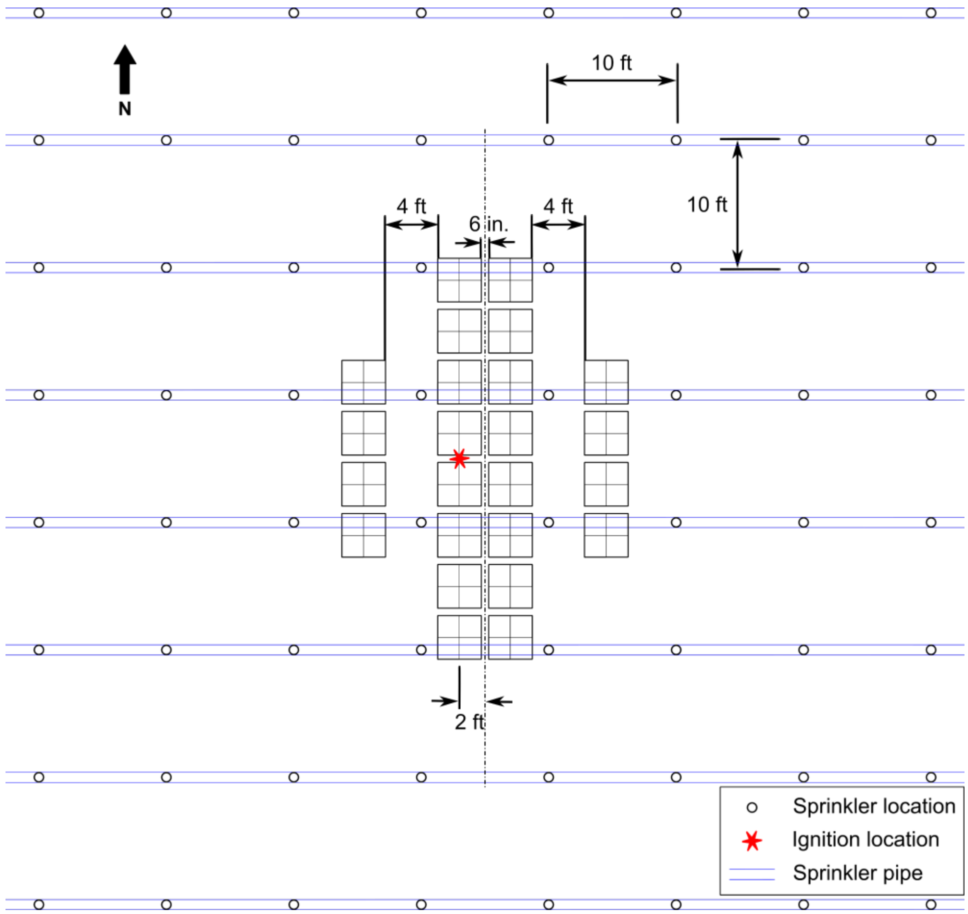


(a) Deflector aligned with bottom of purlin (b) Deflector 150 mm (6 in.) below purlin

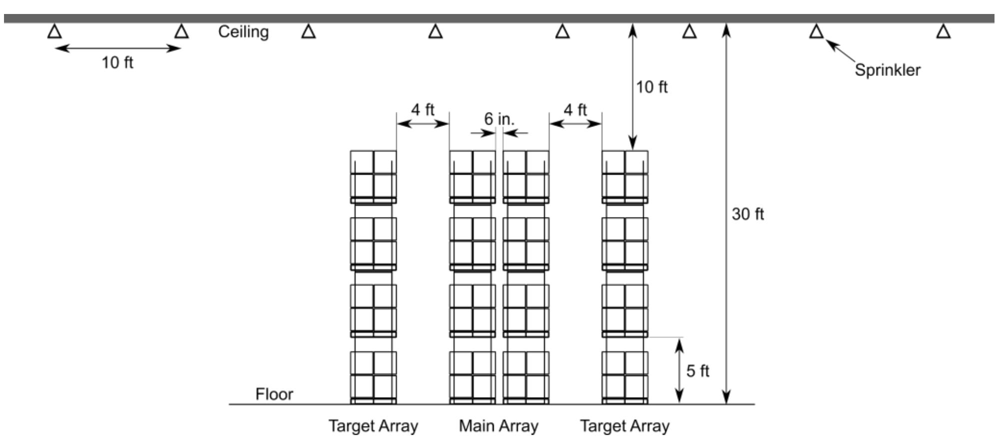
Figure 2-3: Storage sprinkler discharge pattern for a sloped ceiling inclined at 18° in presence of 460 mm (18 in.) deep purlins for two scenarios: (a) deflector aligned with bottom of the purlin, and (b) deflector placed at a 150 mm (6 in.) distance below the purlin. No spray impingement takes place when the purlin does not extend into the region below the checkerboard area.

2.7 Baseline Test

A single baseline test was conducted for 4-tier-high rack storage of CUP commodity under a non-sloped, unobstructed ceiling. The test used K240 (K16.8) QR pendent sprinklers operating at 2.4 barg (35 psig), a protection option offered in both NFPA 13 [1] and FM Global Property Loss Prevention Data Sheet (DS) 8-9, *Storage of Class 1, 2, 3, 4 and Plastic Commodities* [10]. The baseline suppression performance is used for comparison against sloped ceiling test results. Figure 2-4 shows the plan and elevation views of the test setup with the location of sprinklers relative to the test arrays. Figure 2-5 shows a photograph of the test array.



(a) Plan view



(b) Elevation view

Figure 2-4: The baseline test CUP main and target arrays shown in (a) plan and, (b) elevation views. Ignition was offset 0.61 m (2 ft) from the centerline toward the west.

Figure 2-5: Photograph of the CUP arrays for the baseline test.

2.7.1 Summary of Test Results

Test results are summarized in Table 2-1. All times stated are from the start of the fire test (i.e., ignition) and are expressed as min:s unless otherwise noted.

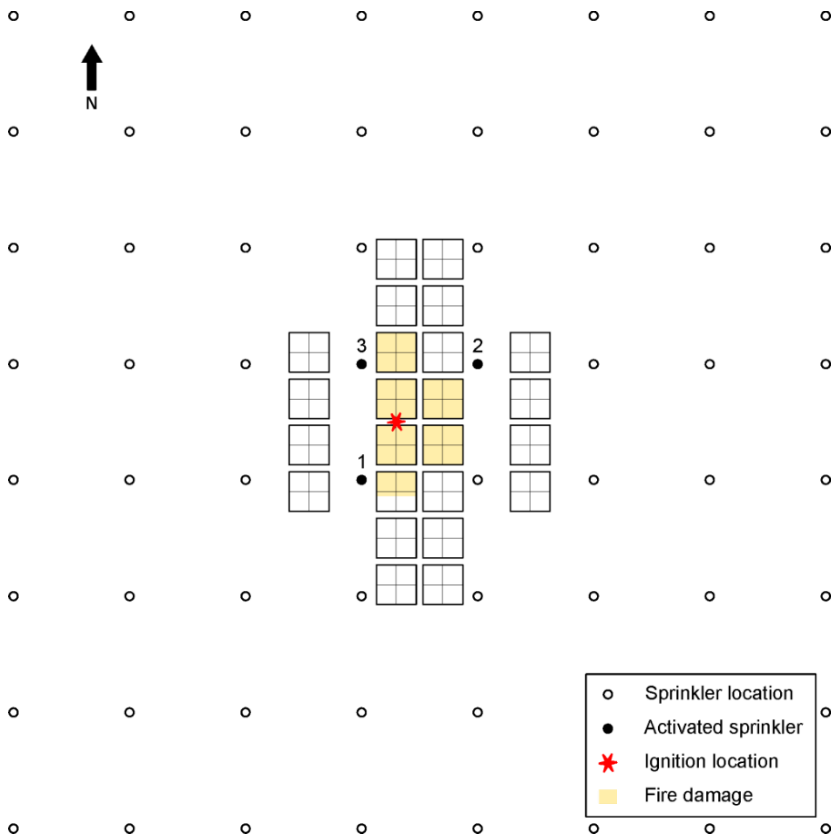
2.7.2 Test Highlights, Results and Damage Assessment

A detailed description of fire chronology and a few selected photographs from the test are provided in Sections A.1 and E.1 of Appendix A and Appendix E, respectively. The flame reached the top of the fourth tier 44 s after ignition. The first sprinkler activated at 1 min 22 s followed by two additional activations between 1 min 23 s and 1 min 25 s. Flames were reduced to below the third tier and white smoke descended to the floor level partially obscuring the array at 1 min 35 s. The fire gradually became less intense and ceiling temperatures decreased below 32°C (90°F) after 2 min 40 s. The test was terminated at 25 min.

Figure 2-6 shows the sprinkler operation pattern and the plan view of the damage assessment. The fire neither reached the ends of the main array nor the target arrays. Figure 2-7 shows the damage to the east and west faces of the main array. Damage was restricted to a small area adjacent to the ignition region. The peak steel temperature was 48°C (118°F), occurred ~2 min after ignition (see Figure 2-8) and was found to be within acceptable limits. Water pressure in the sprinkler pipes was maintained within acceptable bounds as shown in Figure 2-9.

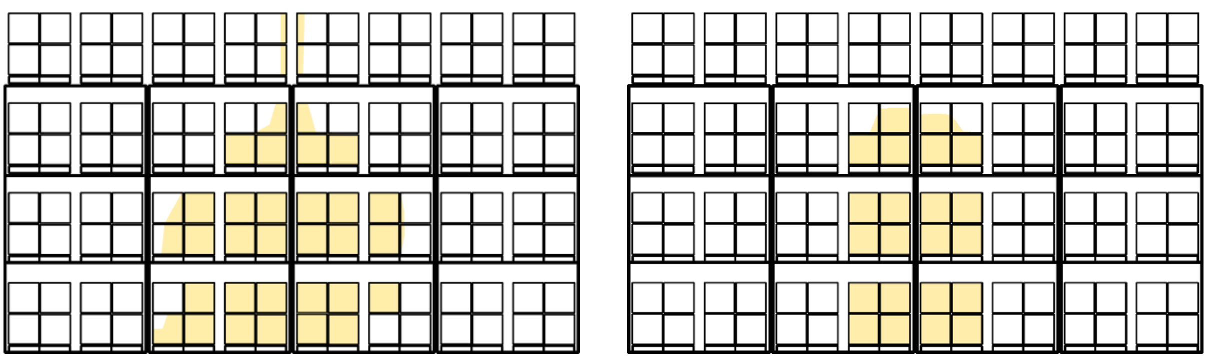
Table 2-1: Summary of baseline test parameters and results.

TEST PARAMETERS	**Test date**	02/27/2018
	Test site	South moveable ceiling of LBL
	Test commodity	CUP
	Array size (main)	2 × 4 × 8
	Array size (target)	1 × 4 × 4
	Nominal storage height [m (ft)]	6.1 (20)
	Nominal ceiling clearance [m (ft)]	3.0 (10)
	Ceiling height [m (ft)]	9.1 (30)
	Aisle width [m (ft)]	1.2 (4)
	Ignition location	Offset, among four
	Sprinkler orientation	Pendent
	Sprinkler K-factor [lpm/bar$^{0.5}$ (gpm/psi$^{0.5}$)]	240 (16.8)
	Sprinkler temperature rating [°C (°F)]	74 (165)
	Nominal RTI [(m-s)$^{0.5}$ ((ft-s)$^{0.5}$)]	34 (62) – QR
	Sprinkler spacing [m (ft)]	3.0 × 3.0 (10 × 10)
	Distance of sprinkler deflector from ceiling [mm (in.)]	330 (13)
	Discharge pressure [barg (psig)]	2.4 (35)
	Discharge density [mm/min (gpm/ft^2)]	41 (1.0)
TEST RESULTS	**First sprinkler operation** (min:s)	1:22
	Last sprinkler operation (min:s)	1:25
	Total number of sprinkler operations	3
	Perimeter sprinkler operations	No
	Peak ceiling gas temperature [°C (°F)]	380 (723)
	Peak steel temperature [°C (°F)]	48 (118)
	Fire to ends of main array	No
	Aisle jump	No
	Total duration (min)	25



Sprinkler Sequence	
#	Time (min:s)
1	1:22
2	1:23
3	1:25

Figure 2-6: Baseline test sprinkler operation pattern and top view of damage assessment.



(a) West face of the main array

(b) East face of the main array

Figure 2-7: Baseline test damage assessment.

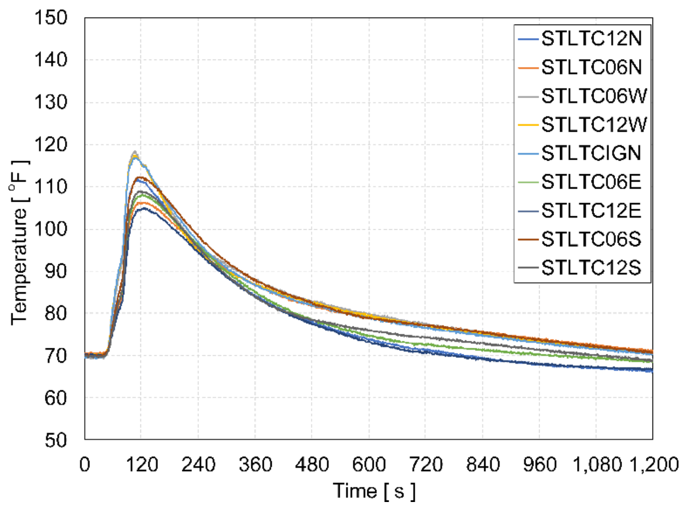


Figure 2-8: Baseline test temperatures of the ceiling steel angle. The thermocouples on the steel angle are named with a prefix of STLTC (Steel Thermocouple), followed by their placement relative to the ignition location (e.g., IGN stands for thermocouple above the ignition location, 06E means the thermocouple was offset by 6 in. towards the East, etc.)

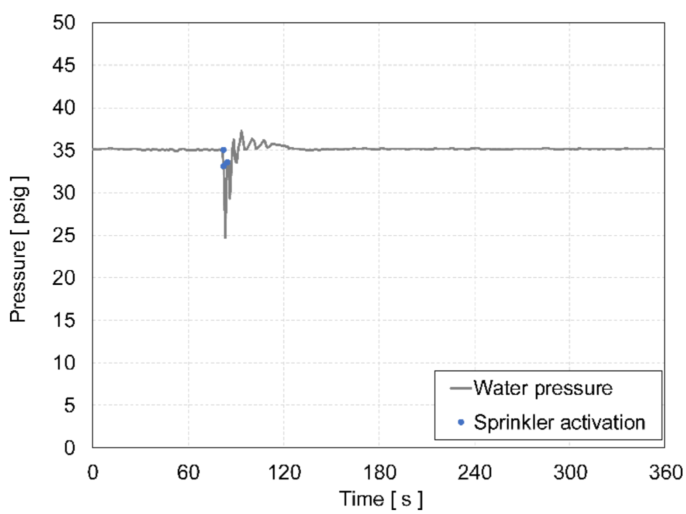


Figure 2-9: Baseline test water pressure measured at the main water supply header duct.

2.8 Sloped Ceiling Tests

Large-scale sloped ceiling tests were designed based on the results from the numerical modeling studies [4] [5], from large-scale testing involving non-sloped ceilings with obstructed ceiling construction [11] and from the baseline testing conducted under a non-sloped, unobstructed ceiling. The test parameters and results are presented below.

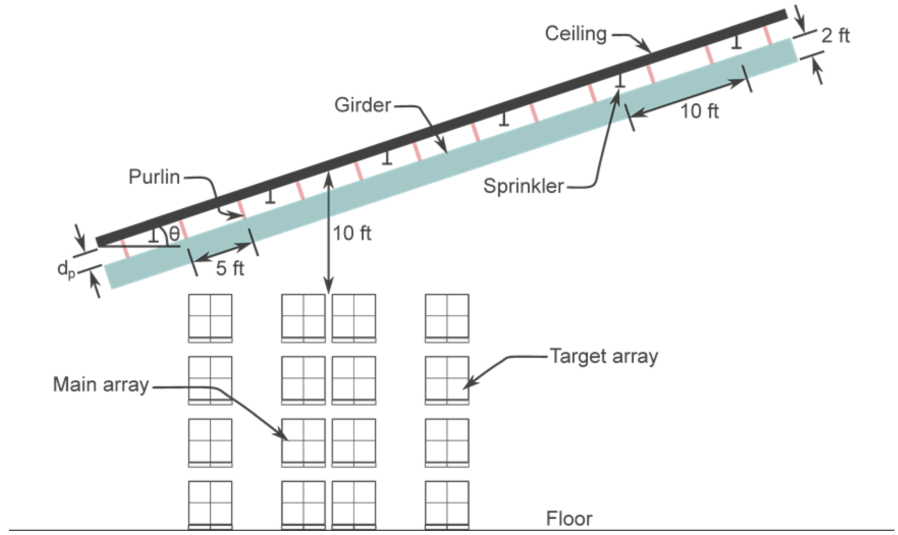
2.8.1 Test Parameters

A total of seven tests were conducted with 4-tier-high rack storage of the CUP commodity under the sloped ceiling. A single test was conducted in the absence of purlins and girders (i.e., unobstructed, sloped ceiling). Six tests were additionally conducted with obstructed ceiling construction included. The obstructed ceiling construction attached to the sloped ceiling was composed of 610 mm (24 in.) deep girders and purlins of a depth of 300–460 mm (12–18 in.). The girders were separated by 7.6 m (25 ft) for Tests #1-5 and 12.2 m (40 ft) for Tests #6-7, and purlins were separated by 1.5 m (5 ft) in all tests. The purlins and girders were constructed using sheet metal. The testing methodology followed the baseline test conducted under the unobstructed, non-sloped ceiling. Summary of all the test parameters are included in Table 2-2 and details of each specific test are available in Tables 2-3 and 2-5.

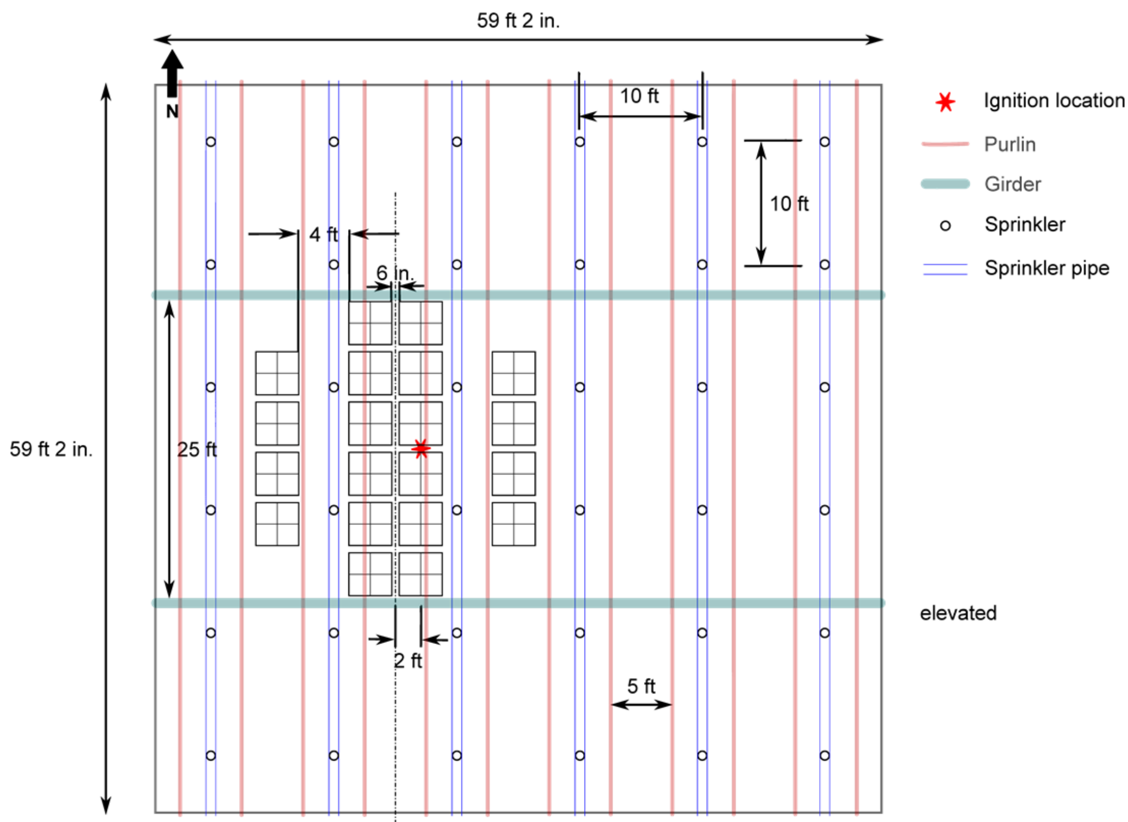
Figure 2-10(a) shows the test setup with the sloped ceiling located above a 4-tier-high rack-storage arrangement of the CUP commodity. The main array was offset by 3 m (10 ft) from ceiling center toward the downslope direction. This was done to ensure that more sprinklers would be present on the upslope side making it possible to investigate biased sprinkler activation patterns caused by preferred ceiling jet direction toward the upslope. Figure 2-10(b) shows a plan view of the locations of purlins and girders relative to the sprinkler, piping and the CUP commodity. Twelve purlins and two girders were attached to the sloped ceiling. The sprinkler branch lines were oriented along the purlins, perpendicular to the slope to maintain water pressure at 2.4 barg (35 psig) at every height. Table 2-2 provides details of the dimensions and sprinklers used in the tests. Figure 2-11 shows photographs of the CUP test arrays from Tests #1 and #3.

Table 2-2: Parameters used in the sloped ceiling tests.

Fire plume source	4-tier-high rack storage of CUP
Ceiling inclination	10° (2 in 12 slope), 18° (4 in 12 slope)
Ceiling clearance	3 m (10 ft) from top of the main array's longitudinal flue
Purlin depth (d_p)	300 mm (12 in.), 450 mm (18 in.)
Purlin spacing	1.5 m (5 ft)
Girder depth	610 mm (24 in.)
Girder spacing	7.6 m (25 ft), 12.2 m (40 ft)
Sprinklers	Pendent, quick-response sprinklers with link temperature of 74°C (165°F), K-240 lpm/bar$^{0.5}$ (K-16.8 gpm/psi$^{0.5}$) at 2.4 barg (35 psig) water pressure (380 lpm or 100 gpm per sprinkler), spaced 3 m × 3 m (10 ft × 10 ft)

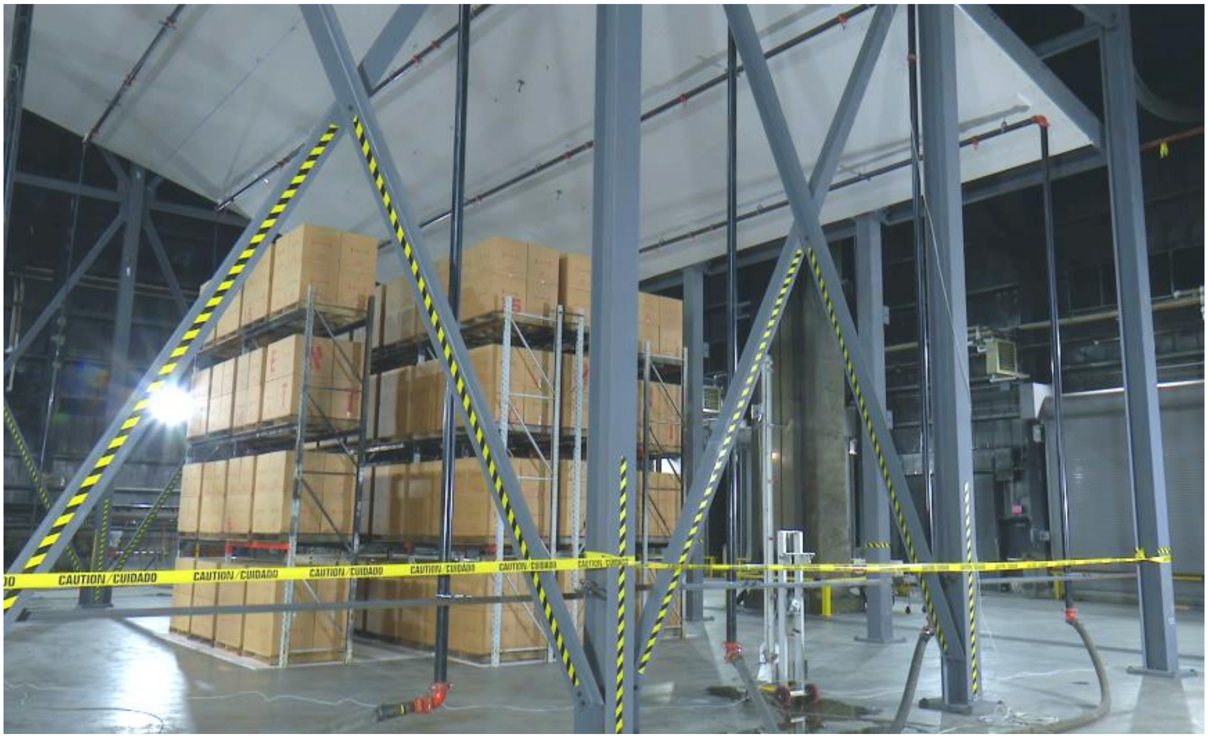


(a) Elevation view

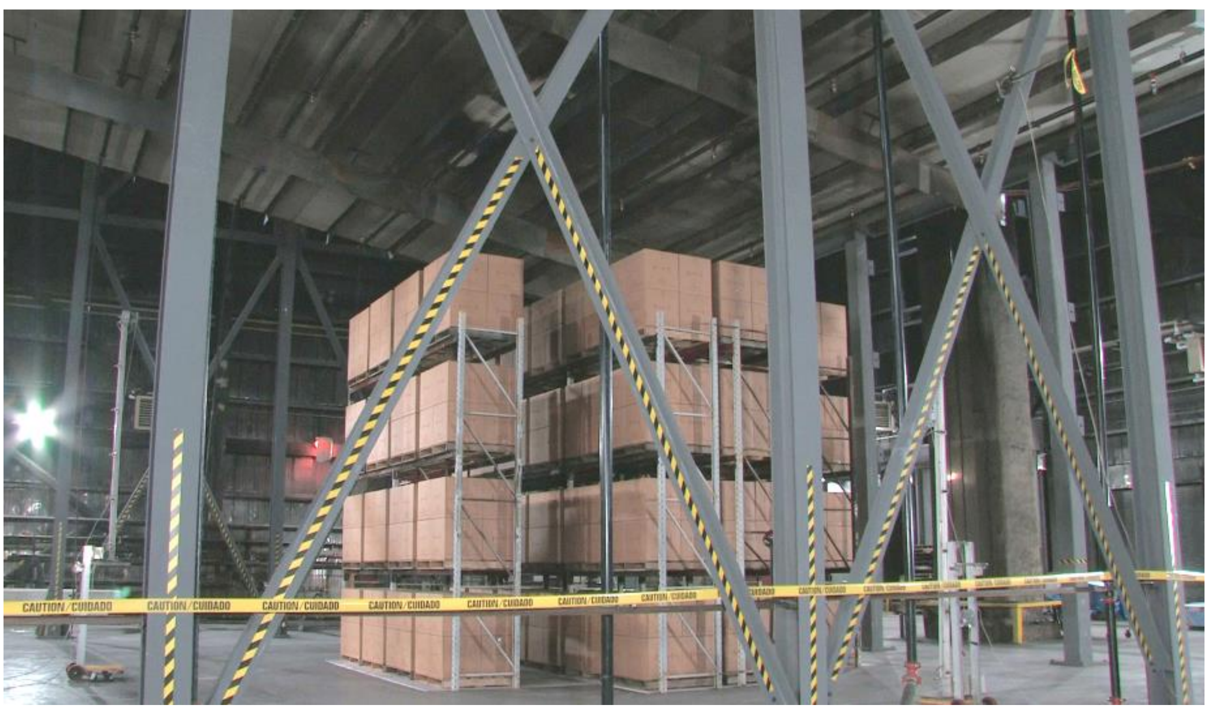


(b) Plan view

Figure 2-10: Sloped ceiling test setup: (a) elevation view showing the 4-tier-high CUP rack-storage array as a fire source with two target arrays located below a ceiling inclined at θ degrees from the horizontal, and (b) plan view showing the main and target arrays, sprinklers and their pipes and obstructed ceiling construction (purlins and girders). The east side of the ceiling was elevated.



(a) Unobstructed ceiling (Test #1)



(b) Obstructed ceiling (Test #3)

Figure 2-11: Photographs of CUP main and target arrays under the sloped ceiling for Test (a) #1 (18°, unobstructed ceiling), and (b) #3 (10°, 300 mm or 12 in. purlins).

2.8.2 10° Inclination Tests

In this section, results are presented for four tests conducted with the ceiling inclined at 10°. For each test, a brief chronology of events is provided followed by presentation of damage assessment to the rack-storage arrays and reporting of maximum values for the ceiling-jet temperature and estimated structural steel temperatures. Appendices A-E provide detailed fire chronologies (Appendix A), water pressure variation in the sprinkler supply pipes (Appendix B), ceiling jet temperature contours (Appendix C) and velocities (Appendix D), and selected photographs from the tests (Appendix E).

2.8.2.1 Summary of Test Results

Summaries of test parameters and results are provided below in Table 2-3. All times stated are from the start of the fire test (i.e., ignition) and are expressed as min:s unless otherwise noted.

Table 2-3: Summary of test parameters and results for the 10° inclination tests.

TEST PARAMETERS	**Test #**	3	4	5	6
	Test date	03/14/2019	03/21/2019	04/05/2019	04/19/2019
	Test site	Large Burn Laboratory			
	Test commodity	CUP			
	Array size (main)	2 × 4 × 6			
	Array size (target)	1 × 4 × 4			
	Number of storage levels	4			
	Nominal storage height [m (ft)]	6.1 (20)			
	Nominal ceiling clearance [m (ft)]	3.0 (10)			
	Ceiling height [m (ft)]	9.1 (30)			
	Aisle width [m (ft)]	1.2 (4)			
	Purlin depth [mm (in.)]	300 (12)	300 (12)	460 (18)	460 (18)
	Purlin separation distance [m (ft)]	1.5 (5)			
	Purlin channel open/closed at girders	Open	Open	Closed	Closed
	Girder depth [mm (in.)]	610 (24)			
	Girder separation distance [m (ft)]	7.6 (25)			12.2 (40)
	Ignition location	Offset, among four			
	Sprinkler orientation	Pendent			
	Deflector orientation, parallel to	Floor	Ceiling	Floor	Floor
	Sprinkler K-factor [lpm/bar$^{0.5}$ (gpm/psi$^{0.5}$)]	240 (16.8)			
	Sprinkler temperature rating [°C (°F)]	74 (165)			
	Nominal RTI [(m-s)$^{0.5}$ ((ft-s)$^{0.5}$)]	34 (62) - QR			
	Sprinkler spacing [m (ft)]	3.0 × 3.0 (10 × 10) on ceiling level			
	Discharge pressure [barg (psig)]	2.4 (35)			
	Discharge density [mm/min (gpm/ft^2)]	41 (1.0)			
	Distance of sprinkler deflector from ceiling [mm (in.)]	460 (18)	460 (18)	610 (24)	610 (24)
TEST RESULTS	**First sprinkler operation (min:s)**	01:22	01:16	01:37	01:23
	Last sprinkler operation (min:s)	01:41	02:32	10:47	01:34
	Total number of sprinkler operations	6	4	9	7
	Perimeter sprinkler operations	No	No	No	No
	Peak ceiling gas temperature [°C (°F)]	400 (745)	270 (511)	380 (712)	370 (699)
	Peak estimated steel temperature [°C (°F)]	53 (128)	71 (159)	200 (384)	67 (153)
	Fire to ends of main array	No	No	Yes	No
	Aisle jump	Yes	No	Yes	No
	Fire reached back end of target arrays	No	No	No	No
	Total duration (min)	30	30	20	30

2.8.2.2 Test #3 (300 mm [12 in.] purlins, deflectors parallel-to-floor)

Test #3 was conducted with 300 mm (12 in.) deep purlins (1.5 m or 5 ft separation distance) with 600 mm (24 in.) deep girders attached to the bottom of the purlins (7.6 m or 25 ft separation distance). FM Approved K240 (K16.8) pendent QR sprinklers were installed such that the perpendicular distance between the ceiling and the sprinkler link was 460 mm (18 in.). Sprinkler deflectors were kept parallel to the floor.

Highlights

The flames reached above the rack-storage array 54 s after ignition. The first sprinkler operated at 1 min 22 s. Figure 2-12 shows an image of the test arrays after first sprinkler operation with the fire visible on the east face of the main array. Five additional sprinklers operated between 1 min 35 s and 1 min 41 s. At 1 min 55 s white smoke descended to the floor completely obscuring the array. In the test, a peak ceiling temperature of 400°C (746°F) was reached at 1 min 37 s. Although the ceiling jet developed along the central purlin channel, enough flow reached adjacent channels to cause four sprinkler operations around the ignition region. The ceiling jet also tended to move toward the upslope, causing two additional activations. After the sprinklers operated, the ceiling jet temperatures were brought down quite rapidly; and 120 s after the first sprinkler activation, almost ambient conditions were observed. This reduction in ceiling jet temperature can be observed in Figure 2-13 which includes a sequence of infrared images of the fire plume and ceiling jet (time interval of 80-110 s after ignition) indicating peak temperatures were close to ambient at 110 s. Figure 2-14 shows the gas-phase temperatures for thermocouples located in the vicinity of the ignition region. The rapid decrease in temperature immediately after the peak confirms the suppression effectiveness of the activated sprinklers. The ceiling temperatures decreased to 27°C (80°F) after 3 min. The test was terminated at 30 min.

Results and Damage Assessment

Figure 2-15 shows the sprinkler operation pattern and the plan view of the damage assessment. A total of six sprinklers operated during the test. None of the perimeter sprinklers operated. The fire did not reach the ends of the main array. The west face of the east target ignited but the fire did not reach the east face. Figure 2-16 shows the damage to the main array and the west face of the east target array. The peak steel temperature was estimated to be 53°C (128°F) and was within acceptable limits (see Appendix G for estimation details). Compared to the baseline test, three additional sprinklers operated. One additional activation occurred in the first ring compared to the baseline test and two upslope sprinklers also activated. The damage area was comparable to the observed area for the baseline test, except for the ignition of the east target array where the fire was suppressed rapidly. Overall, test suppression performance was comparable to the baseline test.

Figure 2-12: Test #3 fire on east face of main array at 1 min 30 s after ignition.

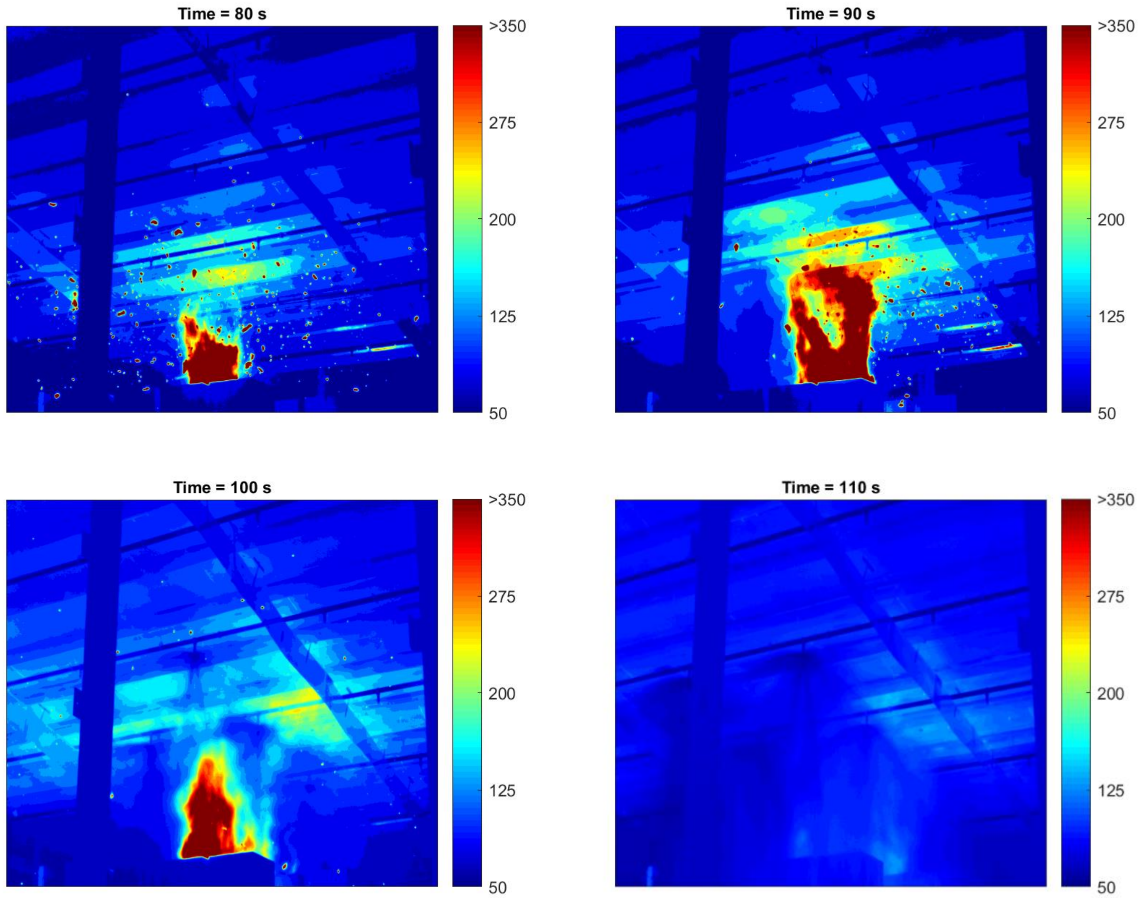


Figure 2-13: False color infrared images captured during Test #3 of the fire plume and ceiling jet near the plume impingement region. Temperatures are in °F.

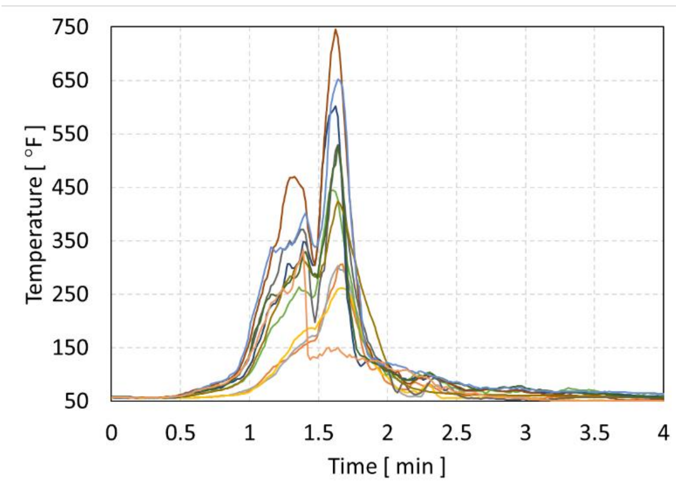
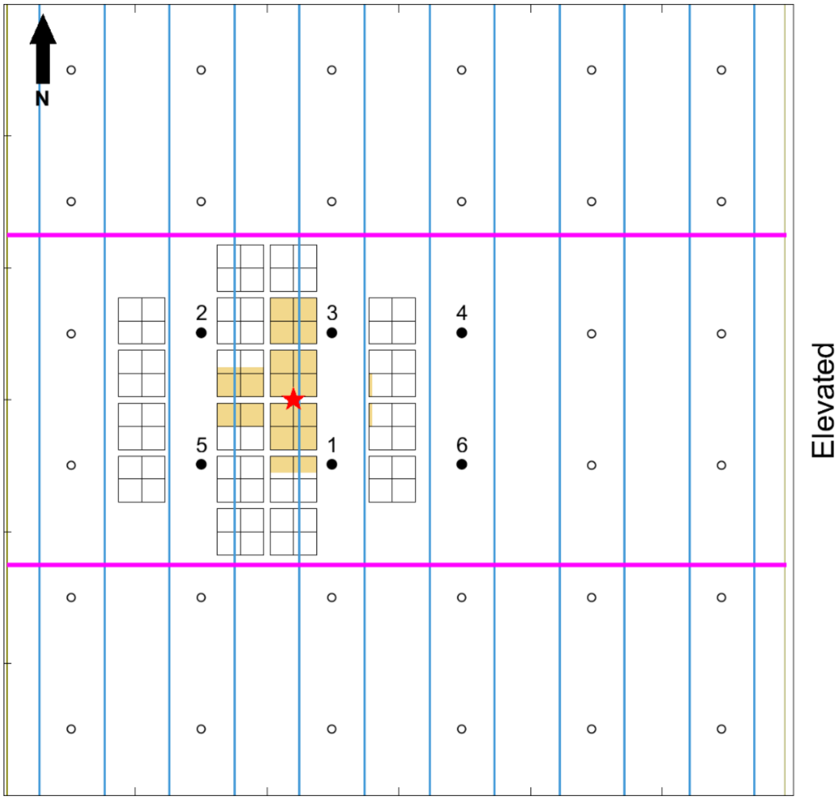


Figure 2-14: Test #3 gas-phase temperature measured 165 mm (6.5 in.) perpendicular distance below the ceiling. Temperature distributions are shown for thermocouples close to the ignition region.



Sprinkler sequence	
#	Time (min:s)
1	1:22
2	1:35
3	1:37
4	1:38
5	1:41
6	1:41

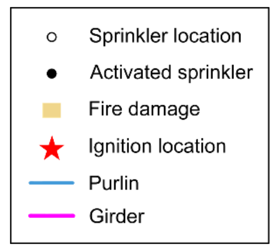
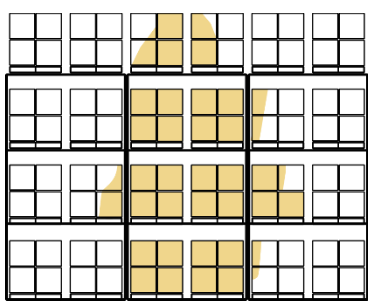
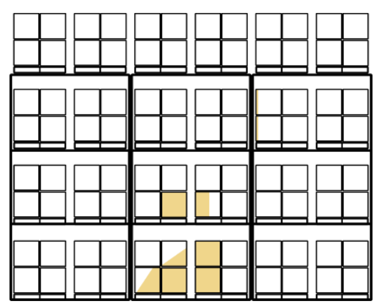


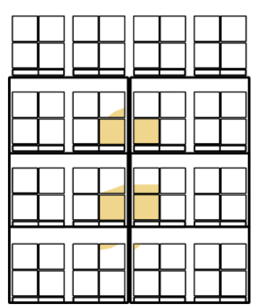
Figure 2-15: Sprinkler operation pattern and top view of damage assessment for Test #3.



(a) East face of the main array



(b) West face of the main array



(c) West face of the east target array

Figure 2-16: Damage assessment on the main array and the east target array for Test #3.

2.8.2.3 Test #4 (300 mm [12 in.] purlins, deflectors parallel-to-ceiling)

Test #4 used the same configuration as Test #3, but the sprinkler deflector orientation was changed. The purpose of this test was to compare suppression performance with Test #3 results. All other parameters were identical to Test #3. The sprinklers were installed such that the perpendicular distance between the links and the ceiling was 460 mm (18 in.), but the deflectors were kept parallel to the ceiling.

Highlights

The flames reached the top of the rack-storage array 42 s after ignition. Two sprinklers closest to the ignition location on the upslope end operated at 1 min 16 s. Figure 2-17 shows an image (looking south) of the fire above the main array at 1 min 30 s after ignition. The spray core from the two upslope sprinklers can be seen to fall on the east target array. Between 2 min 27 s and 2 min 32 s, two additional sprinklers operated on the downslope end.

Figure 2-17: Test #4 – fire above the main array at 1 min 30 s after ignition. Two sprinklers in the upslope direction were operating.

Compared to Test #3, the peak ceiling temperature was lower, 270°C (512°F), occurring at 2 min 33 s. However, unlike Test #3, in which higher temperatures were recorded for only about 1 min, the ceiling jet temperatures remained high for over a 2 min duration. Figures 2-18 and 2-19 show the infrared images of the ceiling jet and gas-phase thermocouple measurements, respectively. In Figure 2-18, at 150 s, the ceiling jet is spread around the plume impingement region with peak temperatures above 79°C (175°F). At about 150 s, two additional sprinklers operated causing the ceiling temperatures to reduce, as can be seen in Figure 2-19. After 180 s, the temperatures lowered to almost ambient conditions until the end of the test. Ceiling temperatures were below 43°C (110°F) after 5 min. Flames were visible on the east face of the third tier until 9 min when smoke descended to the floor and visibility of the main test array was obscured. At 12 min, the ceiling temperatures were below 20°C (68°F). The test was terminated at 30 min.

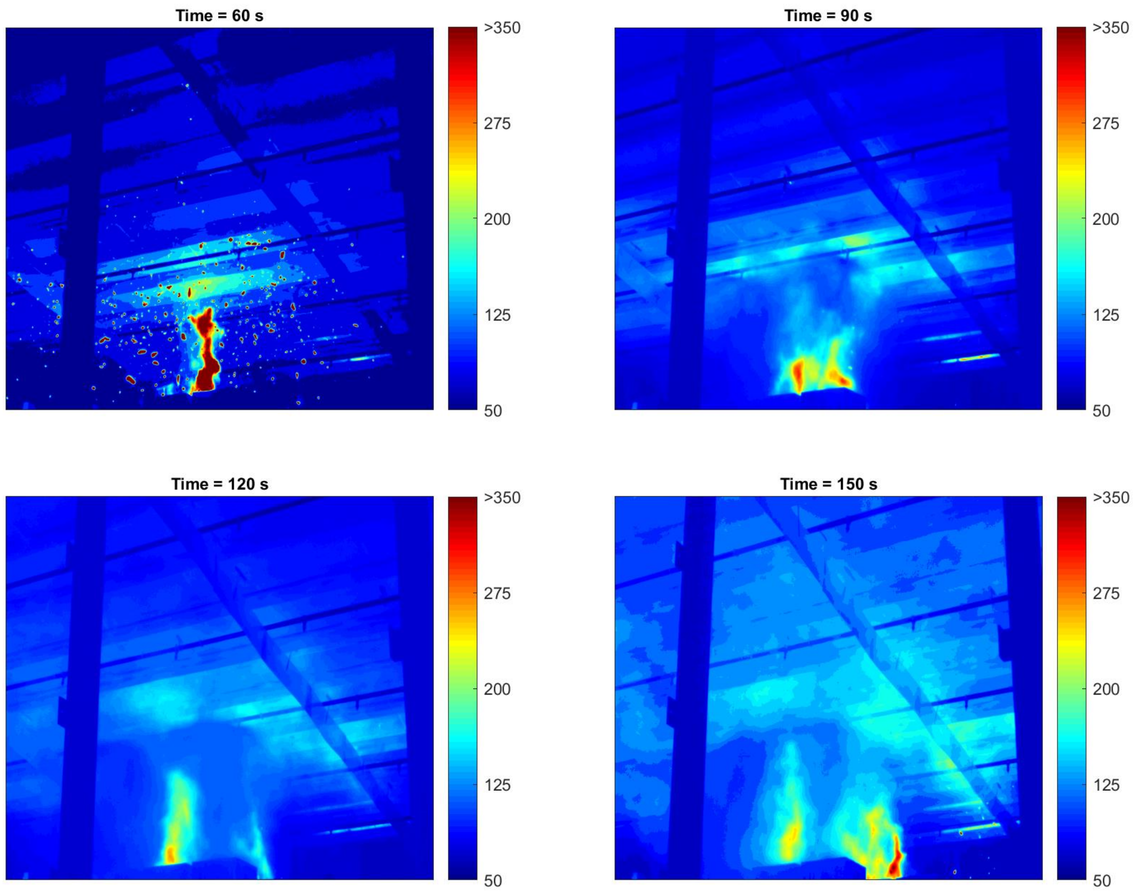


Figure 2-18: False color infrared images captured during Test #4 of the fire plume and ceiling jet near the plume impingement region. Temperatures are in °F.

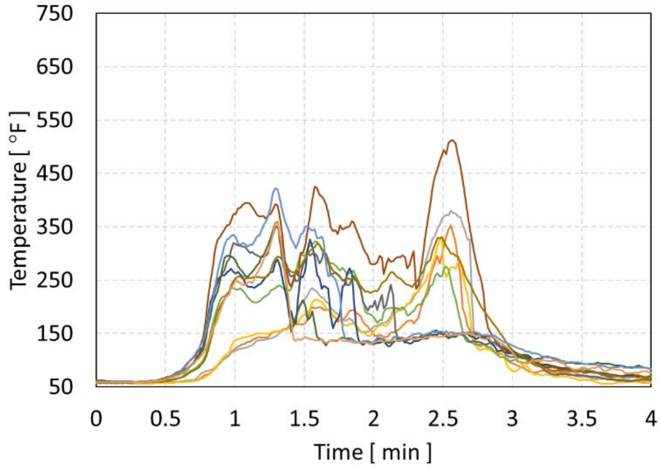
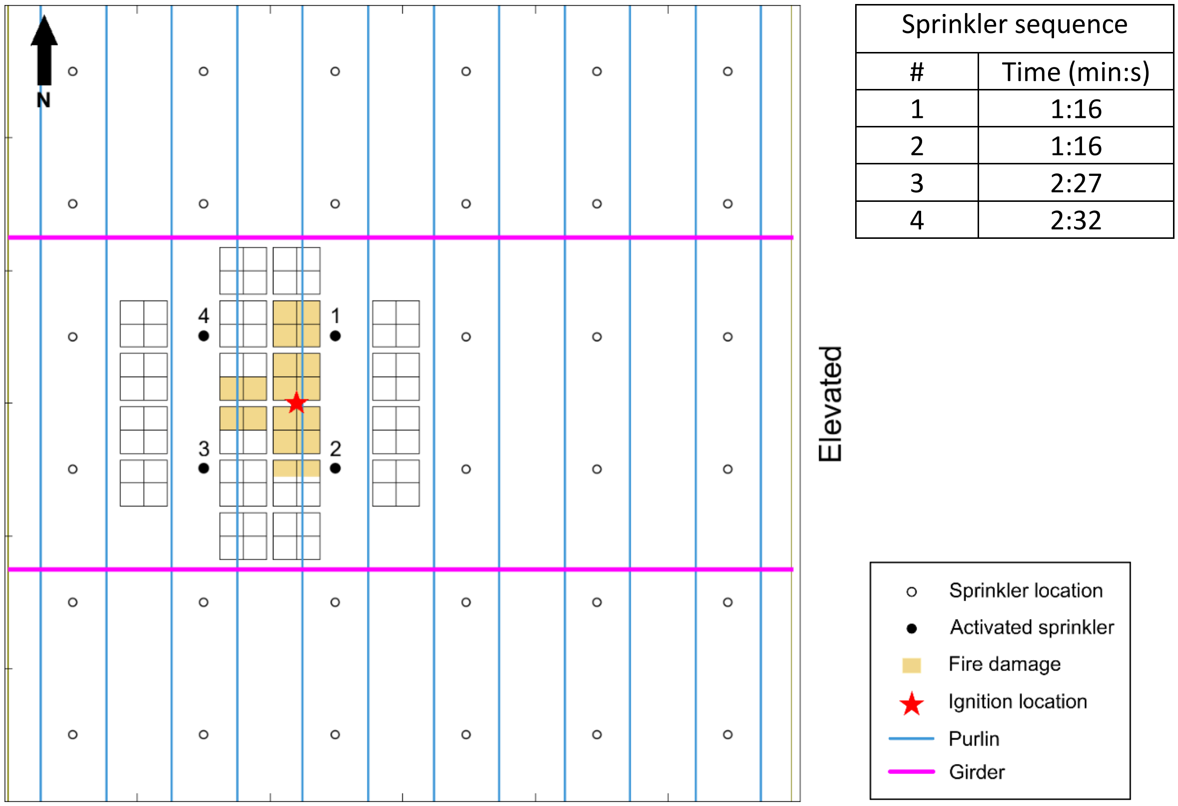


Figure 2-19: Test #4 gas-phase temperature measured 165 mm (6.5 in.) perpendicular distance below the ceiling.

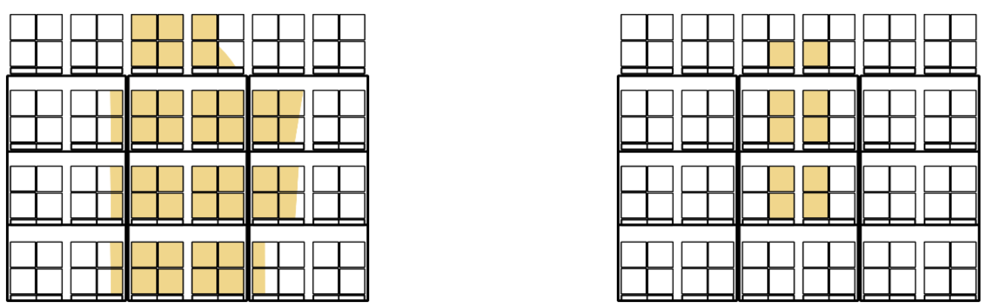
Results and Damage Assessment

Figure 2-20 shows the sprinkler operation pattern and the plan view of the damage assessment. A total of four sprinklers operated during the test. The fire neither reached the ends of the main array nor the target arrays. Figure 2-21 shows the damage to the main array. The peak steel temperature was estimated to be 71°C (159°F) and was within acceptable limits. Compared to the baseline test, one additional sprinkler operated. Suppression performance was comparable to that of the baseline and Test #3. Differences observed with Test #3 were: 1) larger quantity of commodity was consumed due to longer burn time (visual observations and verification by integrating released combustion energy), 2) spray core from upslope operating sprinklers fell on the adjacent east target array, and 3) ceiling jet temperatures remained high for a longer duration. In different scenarios (e.g., higher slope, or different ignition location relative to the sprinklers), it is likely that the difference in suppression performance would be more pronounced as indicated in previous modeling and flow testing [4] [5] [7].



Sprinkler sequence	
#	Time (min:s)
1	1:16
2	1:16
3	2:27
4	2:32

Figure 2-20: Sprinkler operation pattern and top view of damage assessment for Test #4.



(a) East face of the main array (b) West face of the main array

Figure 2-21: Damage assessment on the main array for Test #4.

2.8.2.4 Test #5 (460 mm [18 in.] purlins, deflector parallel-to-floor, closed purlin channels, 7.6 m [25 ft] girder separation distance)

Test #5 used the same configuration as Test #3, but the purlin depth was increased to 460 mm (18 in.) and the purlin channels were closed at the girders which were separated by 7.6 m (25 ft). Figure 2-22 shows the test arrays below the inclined ceiling. Purlins and girders are attached to the flat part of the ceiling with the purlin channels closed at the two girders. Numerical modeling has shown that closing the purlin channels at the girder locations prevents the hot combustion products from continuing to flow along the channels (confinement of the ceiling jet or flow channeling effect) [11]. By preventing the ceiling jet channeling effect, which occurs in the presence of deeper purlins (e.g., purlin depths of greater than 460 mm or 18 in. for non-sloped ceilings [11]), sprinklers located farther away from the ignition region do not activate early, avoiding scenarios where the water demand could be exceeded. Section 3.2.2 in Ref. [11] provides details of the ceiling jet channeling effect. The purpose of Test #5 was to evaluate the effect of closing the purlin channels at the girders to alleviate flow channeling caused by 460 mm (18 in.) purlins for the 10° inclined ceiling. The sprinklers were installed such that the distance between the links and the ceiling was 610 mm (24 in.). The deflectors were kept parallel to the floor.

Figure 2-22: Ceiling structure for Test #5 showing 460 mm (18 in.) purlins and 610 mm (24 in.) girders attached to the flat part of the ceiling. Purlin channels at girders are closed.

Highlights

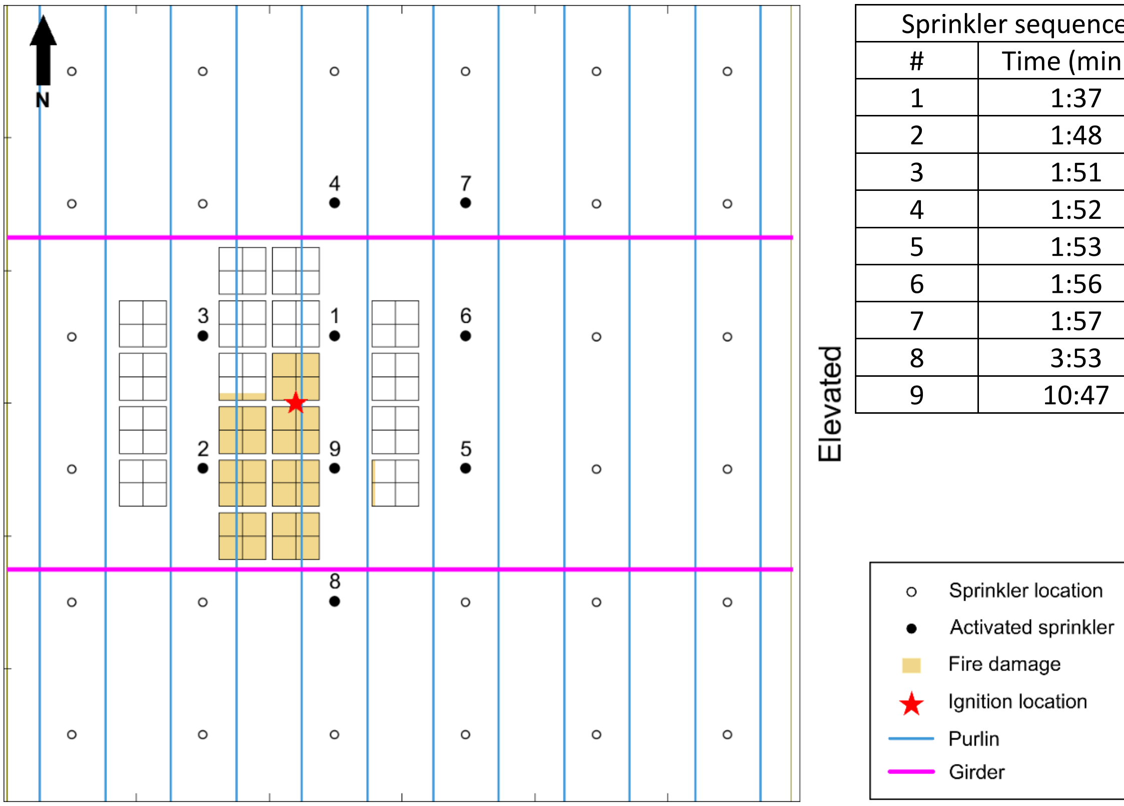
The flames reached above the rack-storage array 1 min 2 s after ignition. The first sprinkler operated on the upslope at 1 min 37 s. Figure 2-23 shows the fire on the east face of the main array after first sprinkler operation. Between 1 min 48 s and 1 min 51 s, two sprinklers operated on the downslope, followed by five sprinkler operations on the upslope between 1 min 52 s and 1 min 57 s. White smoke descended to the floor partially obscuring the array at 2 min. Two additional sprinklers operated on the south side of the main array at 3 min 53 s and 10 min 47 s; however, intense burning was observed on the south side of the main array until 20 min when the test was terminated (see Figure 2-24). The peak temperature recorded during the test was 390°C (727°F) at 1 min 51 s. Compared to the other sloped ceiling tests, during Test #5, higher ceiling jet temperatures were recorded in the range of 150-320°C (300-600°F) until about 14 min after ignition. This was due to the lateral fire spread to the south end of the main array. Overall, nine sprinklers operated during the test.

Results and Damage Assessment

Figure 2-25 shows the sprinkler operation pattern and the plan view of the damage assessment. The fire reached the south end of the main array and the west face of the east target array ignited. Figure 2-26 shows the damage to the main array and the west face of the east target array. The fire reached the south end of the array since spray from the nearest sprinkler was obstructed by the neighboring girder and no pre-wetting of the commodity took place. The peak steel temperature was estimated to be 200°C (384°F) and was within acceptable limits. Due to the fire reaching the south end of the main array, Test #5 failed to satisfy one test evaluation criterion. The abovementioned reason of sprinkler spray obstruction by girders was determined to be the cause of the failure.

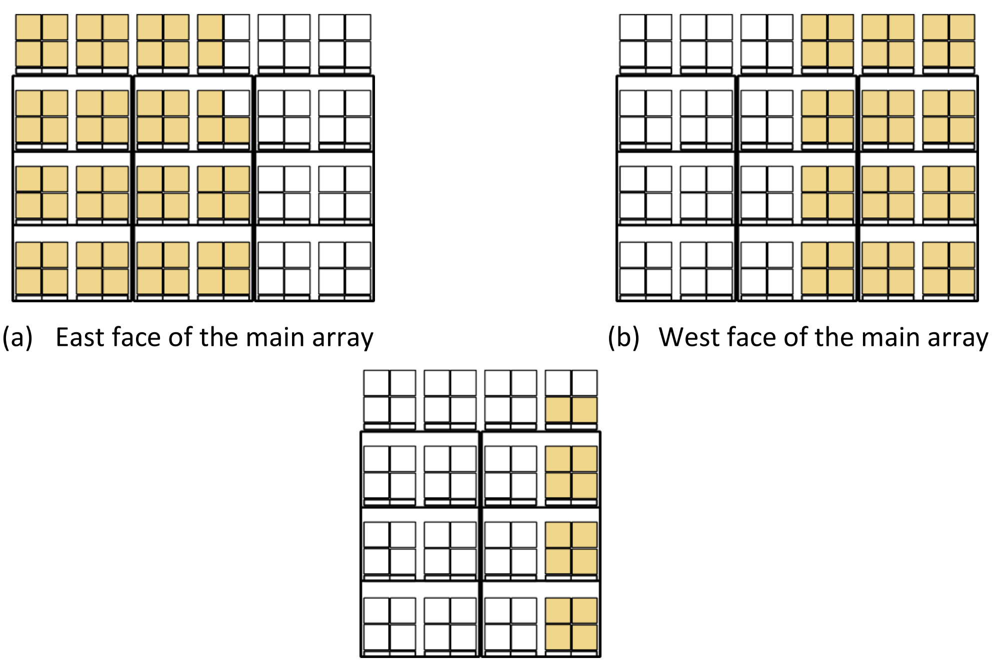
Figure 2-23: Fire on the east side of the main array visible for Test #5 after 1 min 45 s with one sprinkler operating.

Figure 2-24: Test #5 side view of the south end of the main array 4 min after ignition. Intense burning of the commodity can be observed. Spray from the closest sprinkler is obstructed by the adjacent girder.



Sprinkler sequence	
#	Time (min:s)
1	1:37
2	1:48
3	1:51
4	1:52
5	1:53
6	1:56
7	1:57
8	3:53
9	10:47

Figure 2-25: Sprinkler operation pattern and top view of damage assessment for Test #5.



(a) East face of the main array

(b) West face of the main array

(c) West face of the east target array

Figure 2-26: Damage assessment on the main and east target arrays for Test #5.

2.8.2.5 Test #6 (460 mm [18 in.] purlins, deflectors parallel-to-floor, closed purlin channels, 12.2 m [40 ft] girder separation distance)

Test #6 used the same configuration as Test #5, but the girder spacing was increased to 12.2 m (40 ft) to ensure sprinklers were not located in proximity of the girders preventing spray obstruction[d]. All other parameters were identical to those in Test #5. As in Test #5, the sprinklers were installed such that the perpendicular distance between the links and the ceiling was 610 mm (24 in.). The deflectors were kept parallel to the floor.

Highlights

The flames reached above the rack-storage array 45 s after ignition. Five sprinklers operated on the upslope of the ignition location between 1 min 23 s and 1 min 26 s. At 1 min 34 s, two additional sprinklers operated on the downslope. At 1 min 43 s, white smoke descended to the floor obscuring the array. Figure 2-27 shows the fire on the main array at 1 min 30 s and 1 min 45 s after ignition – rapid suppression can be observed to be occurring in the short 15 s interval. The peak ceiling temperature of 380°C (716°F) was recorded at 1 min 26 s. Ceiling temperatures were below 79°C (175°F) after 3 min. The fire gradually became less intense and ceiling temperatures decreased to 52°C (125°F) at 6 min. The peak ceiling temperatures were below 22°C (72°F) after 22 min. The test was terminated at 30 min.

Results and Damage Assessment

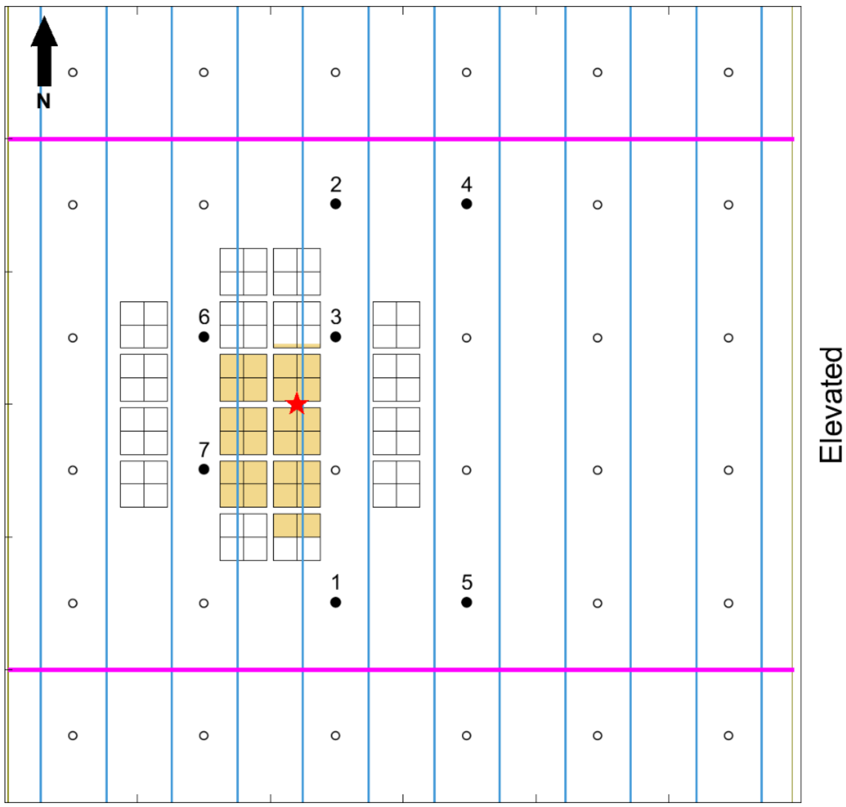
Figure 2-28 shows the sprinkler operation pattern and the plan view of the damage assessment. A total of seven sprinklers operated during the test. The fire neither reached the ends of the main array nor the target arrays. Figure 2-29 shows the damage to the main array. The peak steel temperature was estimated to be 67°C (153°F) and was within acceptable limits. As in the case of Test #5, closing the purlin channels caused the ceiling jet to be confined between the girders, which can be observed from the infrared images in Figure 2-30. However, unlike Test #5, during which spray obstruction occurred, in Test #6 sprinklers were not present in proximity of the girders (due to changed girder spacing) and, therefore, spray obstruction was avoided. The result, in contrast to Test #5, was the fire not spreading to the ends of the main array. Compared to the baseline test, four additional sprinklers operated.

[d] An alternate approach of changing the sprinkler spacing (e.g., to 2.4 m x 3 m or 8 ft x 10 ft) to reduce spray obstruction at the girders was also possible but its implementation would have significantly affected the testing schedule.

(a) Fire visible above array at 1 min 30 s after ignition

(b) Same view at 1 min 45 s

Figure 2-27: Test #6 – view from the elevated end of the ceiling at (a) 1 min 30 s, and (b) 1 min 45 s after ignition. The fire is rapidly suppressed in the short 15 s interval.



Sprinkler sequence	
#	Time (min:s)
1	1:23
2	1:23
3	1:25
4	1:25
5	1:26
6	1:34
7	1:34

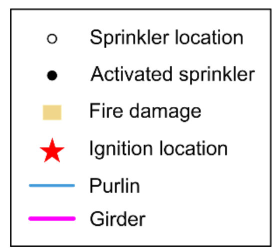
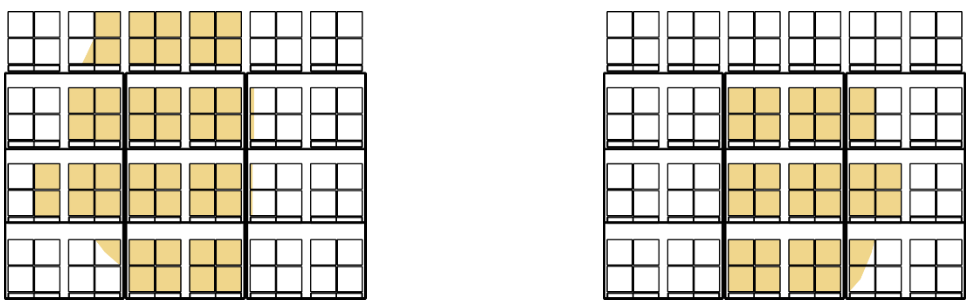


Figure 2-28: Sprinkler operation pattern and top view of damage assessment for Test #6.



(a) East face of the main array (b) West face of the main array

Figure 2-29: Damage assessment on the main array for Test #6.

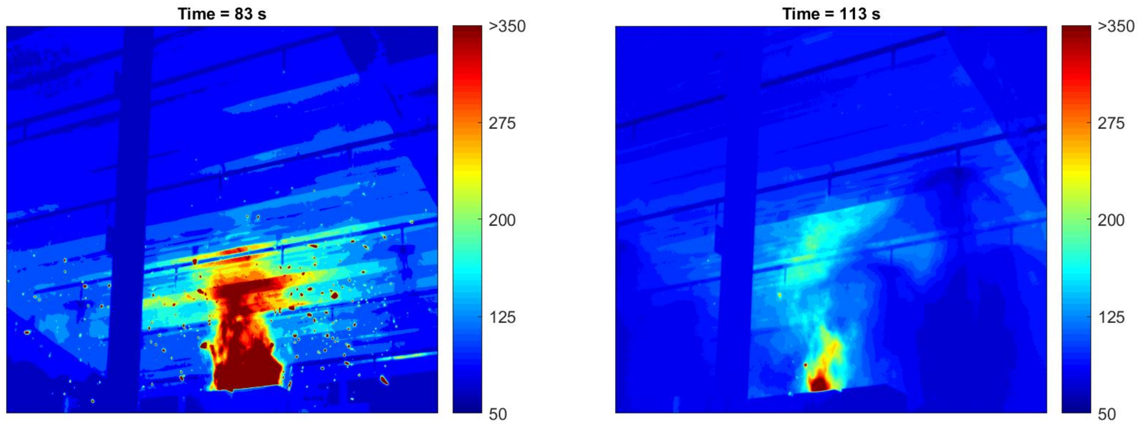


Figure 2-30: Test #6 infrared images showing the ceiling jet when the first sprinkler activated and 30 s after the first activation.

2.8.2.6 Test Performance and Comparison against Baseline Test Results

Four sloped ceiling tests were conducted with the 10° inclination. Tests #3 and #4 compared sprinkler performance for different sprinkler deflector orientation using 300 mm (12 in.) purlins. Results showed limited effect of deflector orientation (parallel-to-floor in Test #3 and parallel-to-ceiling in Test #4) on overall suppression performance for this test configuration. However, key issues were identified from Test #4 – larger quantity of commodity was consumed due to longer burn time (see below for comparison with lower released combustion energy in Test #3), the spray core from upslope operating sprinklers was observed to move away from the adjacent main array and instead fall on the east target array, and the ceiling jet temperatures remained high for a longer duration. All these issues could potentially affect suppression performance in other storage scenarios that were not tested (e.g., higher slope, or different ignition location relative to the sprinklers).

Tests #5 and #6 results were used to verify the effect of closing the purlin channels (purlin depth of 460 mm or 18 in.) at the girders to reduce ceiling jet channeling due to confinement of the hot gases between purlins. Test #5 results, however, were affected by the sprinkler spray obstruction caused by proximity to the girders. This resulted in reduced suppression effectiveness and caused the fire to spread to the south end of the main array. In Test #6, girder spacing was changed to ensure that the sprinkler spray was not obstructed. Sprinkler suppression performance in this test was found to be acceptable.

Total chemical energy release in gigajoule (GJ) during each test is estimated following the methodology described in Appendix F. The integrated energy release is shown in Figure 2-31. The energy is plotted against purlin depth and captions are included to describe the key parameters for each test. Compared to the baseline test (1.4 GJ), in Test #3 (300 mm or 12 in. purlins, deflectors parallel-to-floor) 1.8 GJ was released. Overall, Test #3 had similar performance as the baseline test (29% higher release). In Test #4 (300 mm or 12 in. purlins, deflectors parallel-to-ceiling), significantly higher energy release (4.2 GJ) was estimated, an increase of 200% compared to the baseline test. Increasing the purlin depth to 460 mm (18 in.) and keeping the purlin channels closed at girders separated by 7.6 m (25 ft), the total energy release in Test #5 was 9.2 GJ, an increase of approximately 560% compared to the baseline test. Alleviating spray obstruction at the girder locations (made possible by spacing the girders at 12.2 m or 40 ft) and therefore improving suppression effectiveness, Test #6 had 4.3 GJ of energy released, 53% less comparing to Test #5 or 210% more than the baseline test.

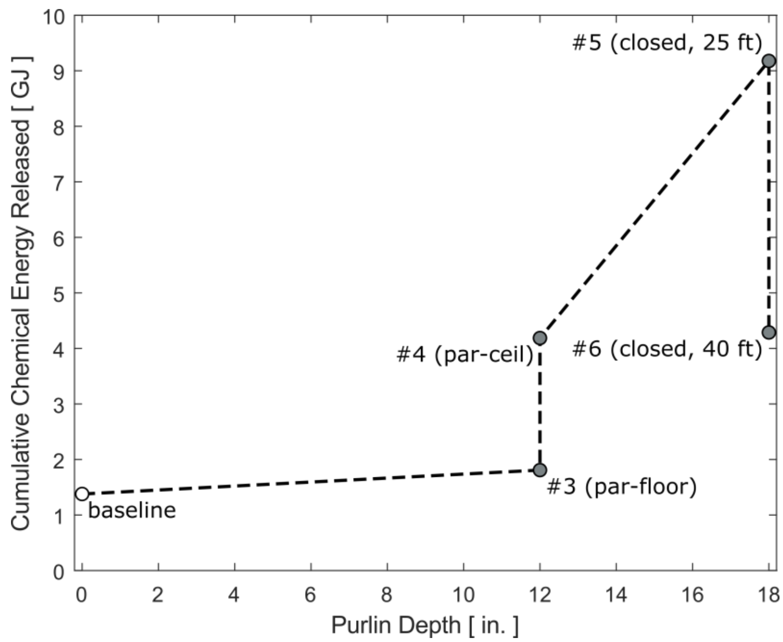


Figure 2-31: Cumulative chemical energy released during the baseline and 10° sloped ceiling tests plotted against purlin depth.

Sloped ceiling results for the 10° inclination tests are compared against results from the baseline test (non-sloped, unobstructed ceiling). Performance of the tests against the baseline test is summarized in Table 2-4. Results from Test #5 are included in the table but are not discussed further as the sprinkler spacing relative to the girders was found to cause spray obstruction affecting test performance. The repeat test (#6) is instead used for comparison against the baseline test. Between four and seven sprinkler operations took place in the sloped ceiling tests compared to three in the baseline test. The number of activations were 1-4 greater than the baseline test which is within the observed testing variability. Additionally, no perimeter sprinkler operations occurred. The fire damage was similar compared to the observed damage in the baseline test. Estimated ceiling steel peak temperatures in the four tests remained well below 538°C (1000°F), which was also the case in the baseline test.

It can be concluded that, for storage under ceilings with up to 10° inclination and maximum purlin depth of 300 mm (12 in.), protection design for non-sloped, unobstructed ceilings can be implemented without additional modifications. Even though an unobstructed ceiling test was not conducted at 10° inclination, it can be concluded that sprinkler performance will be similar to the test conducted with the 300 mm (12 in.) purlins. In the presence of the 300 mm (12 in.) purlins, significant ceiling jet confinement (flow channeling) was not observed and the ceiling jet also developed toward the upslope and downslope directions. In the absence of the purlins, therefore, the ceiling jet is not expected to only develop in the upslope direction for 10° inclination, as was also concluded by the numerical modeling study conducted earlier [4]. For purlin depths greater than 300 mm (12 in.) and up to 460 mm (18 in.), the non-sloped, unobstructed ceiling protection designs could be implemented, but the purlin channels will need to be closed at the girder locations which will prevent water demand to be exceeded. Sprinkler spacing on the ceiling level should be selected such that no spray obstruction occurs at girder locations.

Table 2-4: Test performance comparison between baseline and 10° sloped ceiling tests (#3–6). Sprinkler deflectors kept parallel-to-floor, unless otherwise stated.

Test Number	Purlin Depth [mm (in.)]	Purlin Channels	Girder Spacing [m (ft)]	Total Sprinklers Activated	Perimeter Activations	Extent of Damage	Steel Temp [°C (°F)]	Released Energy (GJ)
Baseline	–	–	–	3	No	Acceptable	48 (118)	1.4
3	300 (12)	Open	7.6 (25)	6	No	Acceptable	53 (128)	1.8
4*	300 (12)	Open	7.6 (25)	4	No	Acceptable	71 (159)	4.2
5	460 (18)	Closed	7.6 (25)	9	No	Not acceptable	200 (384)	9.2
6	460 (18)	Closed	12.2 (40)	7	No	Acceptable	67 (153)	4.3

*Deflectors parallel-to-ceiling

2.8.3 18° Inclination Tests

In this section, results are presented for three tests conducted with the ceiling inclined at 18°. For each test, a brief chronology of test events is provided, followed by presentation of damage assessment to the rack-storage arrays, and reporting of maximum temperatures recorded for the ceiling-jet temperature and estimated for a structural steel angle. Other details are available in appendices at the end of the document.

2.8.3.1 Summary of Test Results

Results from the three tests are summarized in this section. Summaries of test parameters and results are provided below in Table 2-5. All times stated are from the start of the fire test (i.e., ignition) and are expressed as min:s unless otherwise noted.

Table 2-5: Summary of test parameters and results for the 18° inclination tests.

TEST PARAMETERS	**Test #**	1	2	7
	Test date	02/25/2019	03/06/2019	05/01/2019
	Test site	Large Burn Laboratory		
	Test commodity	CUP		
	Array size (main)	2 × 4 × 6		
	Array size (target)	1 × 4 × 4		
	Number of storage levels	4		
	Nominal storage height [m (ft)]	6.1 (20)		
	Nominal ceiling clearance [m (ft)]	1.5 (5)		
	Ceiling height [m (ft)]	7.6 (25)		
	Aisle width [m (ft)]	1.2 (4)		
	Purlin depth [mm (in.)]	–	300 (12)	
	Purlin separation distance [m (ft)]	–	1.5 (5)	
	Purlin channel open/closed at girders		Open	Closed
	Girder depth [mm (in.)]	–	610 (24)	
	Girder separation distance [m (ft)]	–	7.6 (25)	12.2 (40)
	Ignition location	Offset, among four		
	Sprinkler orientation	Pendent		
	Deflector orientation, parallel to	Floor		
	Sprinkler K-factor [lpm/bar$^{0.5}$ (gpm/psi$^{0.5}$)]	240 (16.8)		
	Sprinkler temperature rating [°C (°F)]	74 (165)		
	Nominal RTI [(m-s)$^{0.5}$ ((ft-s)$^{0.5}$)]	34 (62) - QR		
	Sprinkler spacing [m (ft)]	3.0 × 3.0 (10 × 10) on ceiling level		
	Discharge pressure [barg (psig)]	2.4 (35)		
	Discharge density [mm/min (gpm/ft^2)]	41 (1.0)		
	Distance of sprinkler deflector from ceiling [mm (in.)]	330 (13)	460 (18)	460 (18)
TEST RESULTS	**First sprinkler operation (min:s)**	01:18	01:14	01:13
	Last sprinkler operation (min:s)	03:30	03:06	03:53
	Total number of sprinkler operations	10	13	7
	Perimeter sprinkler operations	Yes (1)	Yes (3)	No
	Peak ceiling gas temperature [°C (°F)]	590 (1095)	500 (936)	300 (571)
	Peak estimated steel temperature [°C (°F)]	120 (239)	140 (285)	98 (208)
	Fire to ends of main array	No	No	No
	Aisle jump	Yes	Yes	No
	Fire reached back end of target arrays	No	No	No
	Total duration (min)	20	20	30

2.8.3.2 Test #1 (unobstructed ceiling, deflectors parallel-to-floor)

The purpose of Test #1 was to determine if a ceiling inclination of 18° (in the absence of obstructed ceiling construction) would have a significant impact on the performance of the ceiling sprinklers compared to the baseline test conducted with the non-sloped ceiling. The sprinklers were installed such that the perpendicular distance between the ceiling and the links was 330 mm (13 in.). Sprinkler deflectors were kept parallel to the floor.

Highlights

The flames reached above the rack-storage array 48 s after ignition (Figure 2-32(a) shows the fire 1 min after ignition). At 1 min, the ceiling jet developed toward the upslope of the ignition location, but also moved toward the downslope region, as is evident in Figure 2-33. Ceiling level gas temperature reached 270°C (511°F) at 1 min 14 s after ignition. The first two sprinklers on the upslope operated between 1 min 18 s and 1 min 19 s. After the first two sprinkler activations, the ceiling jet weakened (as can be observed in Figure 2-33 at 120 s) and was observed to extend toward the upslope as shown in Figures 2-32(b). White smoke descended to the floor after 2 min 55 s, partially obscuring the array. The fire intensity increased after 3 min making the ceiling jet hotter and extending the flow almost uniformly around the ignition region, as can be seen in Figure 2-33. The maximum ceiling temperature of 590°C (1095°F) was recorded at 3 min 19 s. Eight additional sprinklers operated between 3 min and 3 min 30 s including downslope activations causing the ceiling jet to weaken (see Figure 2-33 image for 240 s). The fire gradually became less intense and ceiling temperatures decreased to 140°C (275°F) after 5 min. At 16 min, peak ceiling temperatures were below 38°C (100°F). The test was terminated at 20 min.

Results and Damage Assessment

Figure 2-34 shows the sprinkler operation pattern and the plan view of the damage assessment. A total of ten sprinklers, including two perimeter sprinklers, operated during the test. The fire did not reach the ends of the main array; however, the east face of the west target array ignited although the fire did not reach the west face of the target array. Figure 2-35 shows the damage to the main array and the east face. The peak steel temperature was estimated to be 120°C (239°F) and was within acceptable limits. Compared to the baseline test (three sprinkler activations), seven additional sprinklers activated. The sprinkler protection scheme was found to be adequate for preventing fire spread. The perimeter activation on the downslope is not a cause for concern since the ceiling jet is weak in this direction meaning further sprinkler activations would not occur for a larger ceiling. In the absence of purlins, the unconfined ceiling jet initially spread in all directions. However, the sideways flow eventually ceased, and the ceiling jet was observed to move toward the upslope direction. This phenomenon was also observed in numerical modeling results [4]. Therefore, for larger ceilings, further activations of sprinklers in the north and south directions is not expected.

None of the perimeter sprinklers on the upslope end of the ceiling activated reducing concerns of water demand being exceeded. Overall, suppression performance was comparable to the baseline test for the fire damage area, but several additional sprinklers activated.

(a) Fire visible on the east face and above the main array 1 min after ignition

(b) Ceiling jet in the upslope direction 1 min 45 s after ignition

Figure 2-32: Test #1 images showing (a) fire 1 min after ignition, and (b) ceiling jet at 1 min 45 min after ignition.

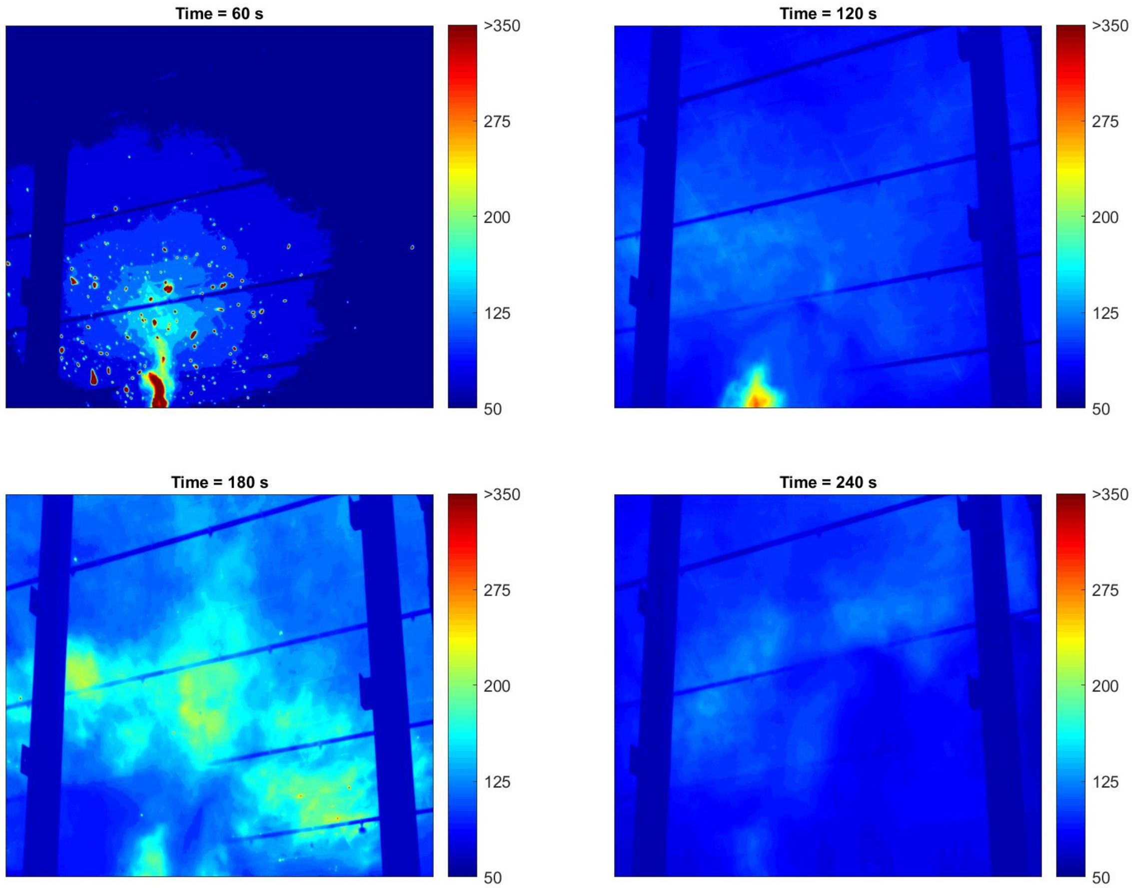
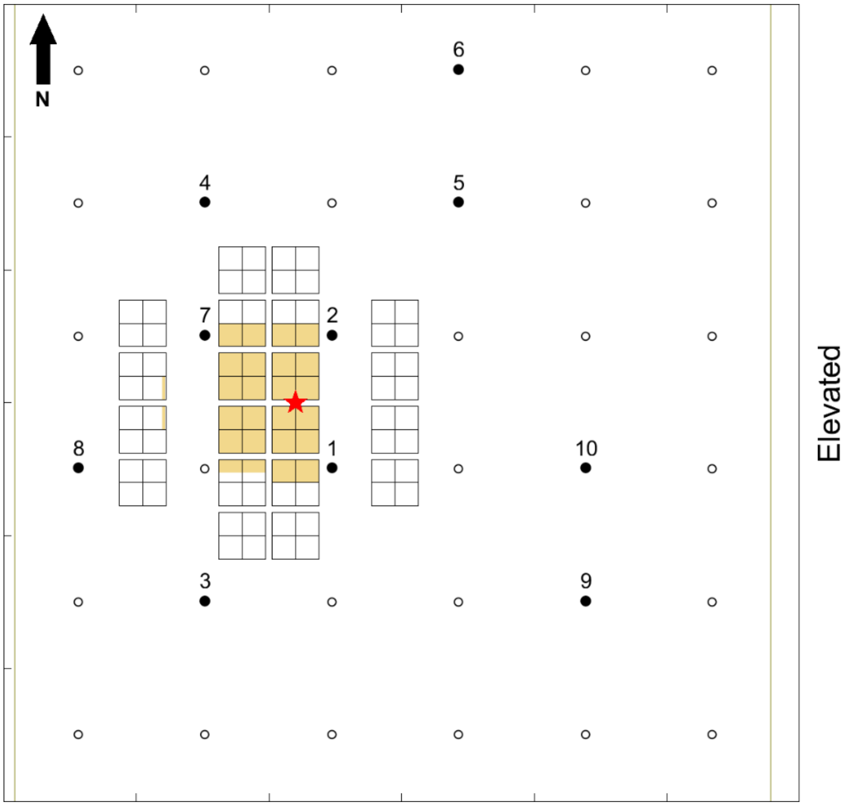
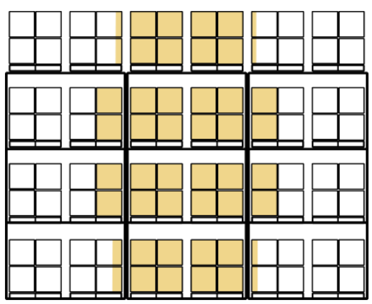


Figure 2-33: False color infrared images captured during Test #1 of the fire plume and ceiling jet near the plume impingement region. Temperatures are in °F.

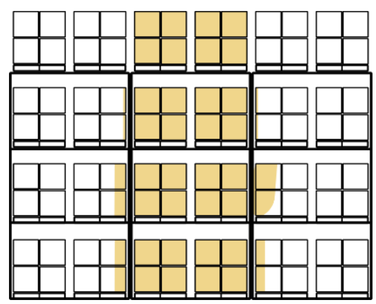


#	Time (min:s)
1	1:18
2	1:19
3	3:00
4	3:03
5	3:11
6	3:17
7	3:17
8	3:22
9	3:23
10	3:30

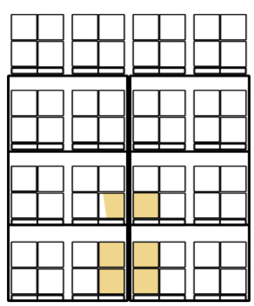
Figure 2-34: Sprinkler operation pattern and top view of damage assessment for Test #1.



(a) East face of the main array



(b) West face of the main array



(c) East face of the west target array

Figure 2-35: Damage assessment on the main array and west target array for Test #1.

2.8.3.3 Test #2 (300 mm [12 in.] purlins, deflectors parallel-to-floor)

Test #2 used the same configuration as Test #1, with the inclusion of 300 mm (12 in.) deep purlins spaced 1.5 m (5 ft) apart and 610 mm (24 in.) girders with a spacing of 7.6 m (25 ft). The sprinklers were installed such that the perpendicular distance between the ceiling and the links was 460 mm (18 in.). Sprinkler deflectors were kept parallel to the floor.

Highlights

The flames reached above the rack-storage array 39 s after ignition. The first upslope sprinkler operated at 1 min 14 s. Four additional sprinklers operated between 1 min 27 s and 1 min 39 s (see Figure 2-36 for an image of the fire 1 min 30 s after ignition). After the activations, white smoke descended to the floor partially obscuring the array. The ceiling jet after the initial set of activations was confined in the central purlin channels, as can be observed from the infrared image at 90 s in Figure 2-37. This confinement caused additional activations along the channel closest to ignition on the upslope end. The channeling effect was observed for another minute (see Figure 2-37: image at 120 s). A peak ceiling temperature of 680°C (1258°F) occurred at 3 min 4 s. Overall, eight additional sprinklers operated between 2 min 29 s and 3 min 6 s. The fire gradually became less intense and ceiling temperatures decreased to 79°C (175°F) after 4 min. After 11 min, peak ceiling temperatures were below 38°C (100°F). The test was terminated at 20 min.

Figure 2-36: Test #2 fire on the east face and above the main array 1 min 30 s after ignition

Results and Damage Assessment

Figure 2-38 shows the sprinkler operation pattern and the plan view of the damage assessment. A total of thirteen sprinklers operated during the test including three perimeter sprinklers. The fire did not reach the ends of the main array; however, both the east and west target arrays ignited, although minor damage to the target arrays was observed post-test. Figure 2-39 shows the damage to the main array and the target arrays. The peak steel temperature was estimated to be 140°C (285°F) and was within acceptable limits. Compared to the baseline test, ten additional sprinklers activated. Furthermore, three perimeter sprinklers operated primarily because of the confinement of the ceiling jet along the 300 mm (12 in.) purlin channels. As numerical modeling results have shown [5], the ceiling jet channeling effect is pronounced at higher ceiling inclinations, i.e., for 300 mm (12 in.) purlins at 18° inclination, the ceiling jet tends to stay confined in the central purlin channels compared to a 10° ceiling with 460 mm (18 in.) purlins. This would cause limited extension of the ceiling jet in the downslope direction, resulting in delayed sprinkler activations and potential for greater fire damage. The above-mentioned observations indicate the ceiling sprinkler performance was significantly different than that observed in the baseline test.

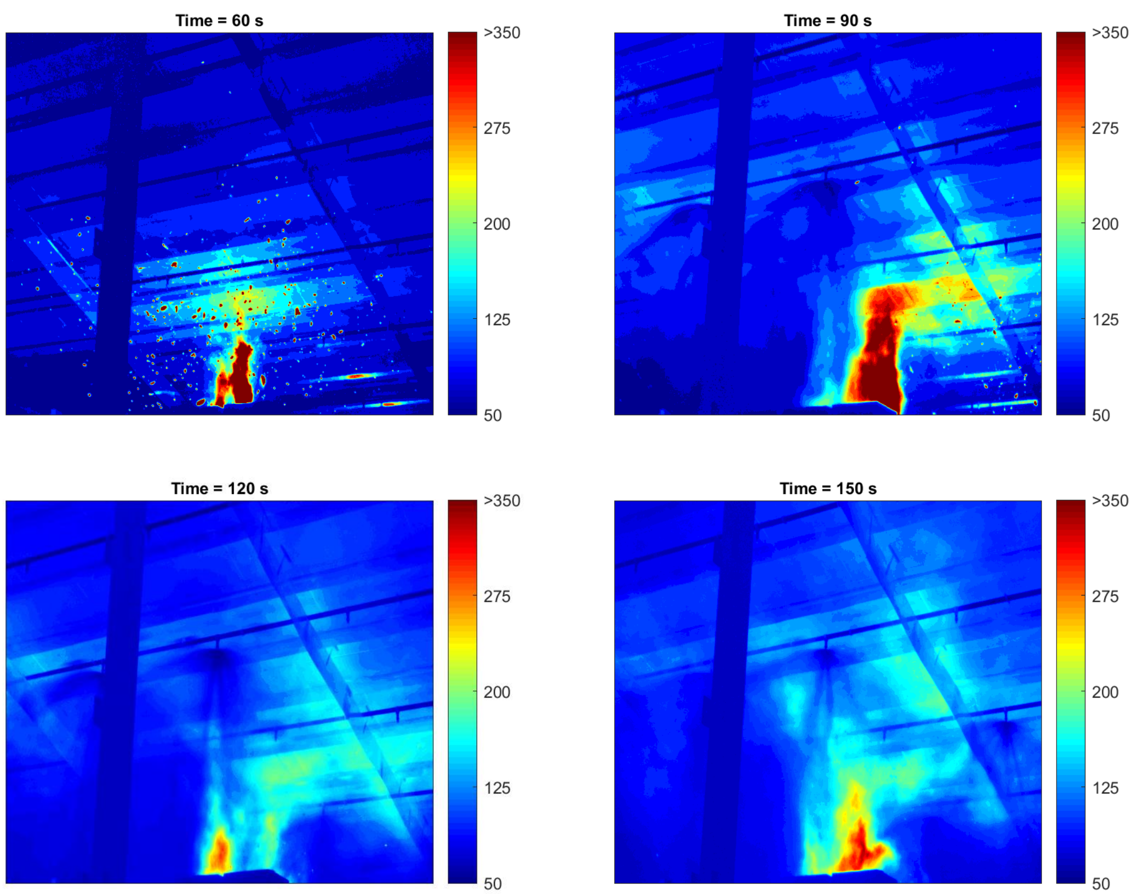
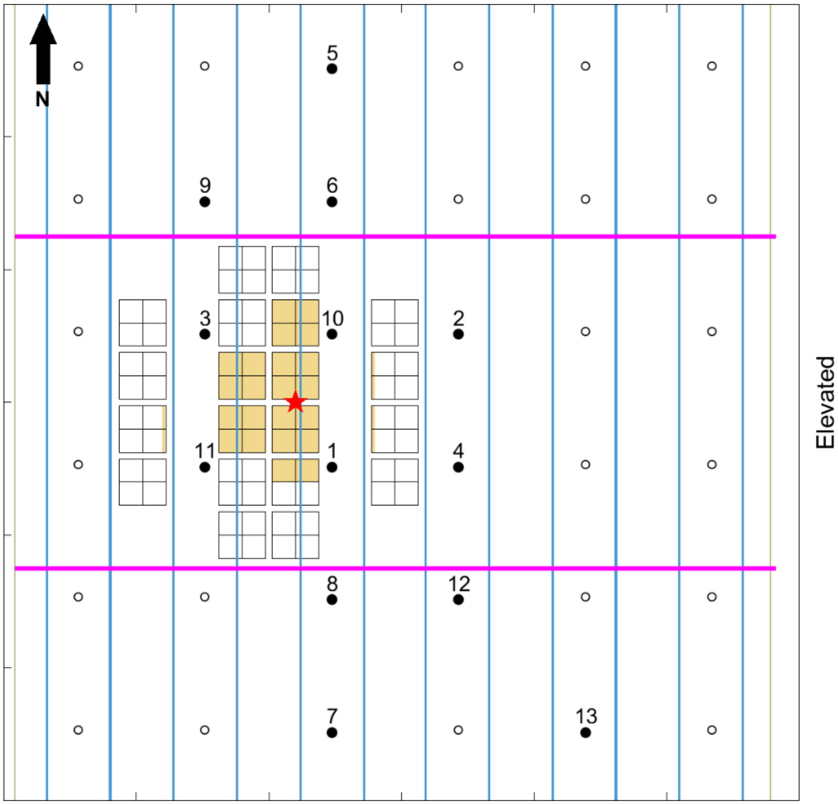


Figure 2-37: False color infrared images captured during Test #2 of the fire plume and ceiling jet near the plume impingement region. Temperatures are in °F.



Sprinkler sequence	
#	Time (min:s)
1	1:14
2	1:27
3	1:28
4	1:28
5	1:39
6	2:29
7	2:49
8	2:52
9	3:01
10	3:03
11	3:04
12	3:05
13	3:06

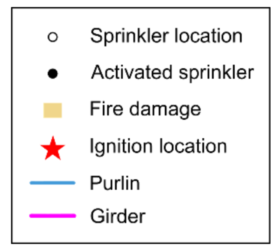
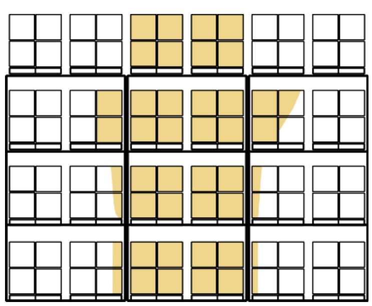
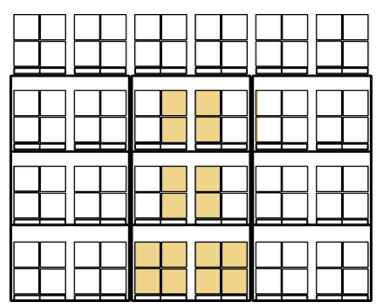


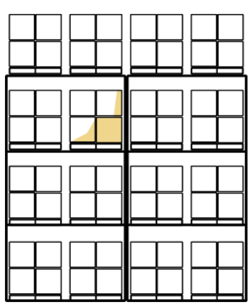
Figure 2-38: Sprinkler operation pattern and top view of damage assessment for Test #2.



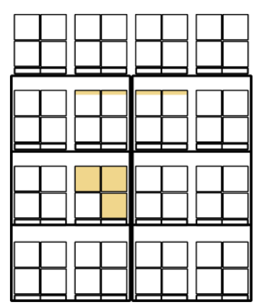
(a) East face of the main array



(b) West face of the main array



(c) East face of the west target array



(d) West face of the east target array

Figure 2-39: Damage assessment on the main array and target arrays for Test #2.

2.8.3.4 Test #7 (300 mm [12 in.] purlins, deflectors parallel-to-floor, closed purlin channels)

Test #7, a repeat of Test #2, was conducted to evaluate the effect of closing the purlin channels to prevent confinement of the ceiling jet (flow channeling) for 300 mm (12 in.) purlins. The purlin channels were closed at the girders spaced 12.2 m (40 ft) apart. As in the case of Test #6, the girder spacing was selected to ensure sprinklers were not placed close to the girders thus avoiding spray obstruction. The sprinklers were installed such that the distance between the links and the ceiling was 460 mm (18 in.). Sprinkler deflectors were kept parallel to the floor.

Highlights

The flames reached above the rack-storage array 42 s after ignition. Between 1 min 13 s and 1 min 15 s, three sprinklers operated upslope of the ignition location followed by one downslope operation at 1 min 32 s. Ceiling jet temperature above the ignition region reached 290°C (561°F) at 1 min 30 s. Figure 2-40 shows the fire on the main array and sprays from the three activated sprinklers at 1 min 20 s. Two sprinklers, out of the first three activations, were adjacent to the girders. The ceiling jet was confined in the deep purlin channels, as can be observed in Figure 2-41, and the closed girders prevented activations of the perimeter sprinklers. After 1 min 50 s, white smoke descended to the floor obscuring the array. Three additional sprinklers operated between 3 min 20 s and 3 min 53 s. A peak temperature of 310°C (589°F) was recorded at 3 min 48 s. The fire gradually became less intense and ceiling temperatures decreased to 93°C (200°F) after 5 min. After 15 min, peak ceiling temperatures were below 21°C (70°F). The test was terminated at 30 min.

Figure 2-40: Test #7 fire on the east face and above the main array 1 min 20 s after ignition

Results and Damage Assessment

Figure 2-42 shows the sprinkler operation pattern and the plan view of the damage assessment. A total of seven sprinklers operated during the test. The fire neither reached the ends of the main array nor the target arrays. Figure 2-43 shows the damage to the main array. The peak steel temperature was estimated to be 98°C (208°F) and was within acceptable limits. As in the case of Test #6 (10°, 460 mm or 18 in. purlins), closing the purlin channels at the girder locations reduced the ceiling jet channeling effect considerably and sprinklers outside the girders did not operate. Compared to the baseline test, four additional sprinklers operated. Sprinkler protection effectiveness was found to be comparable to that of the baseline test for fire damage area.

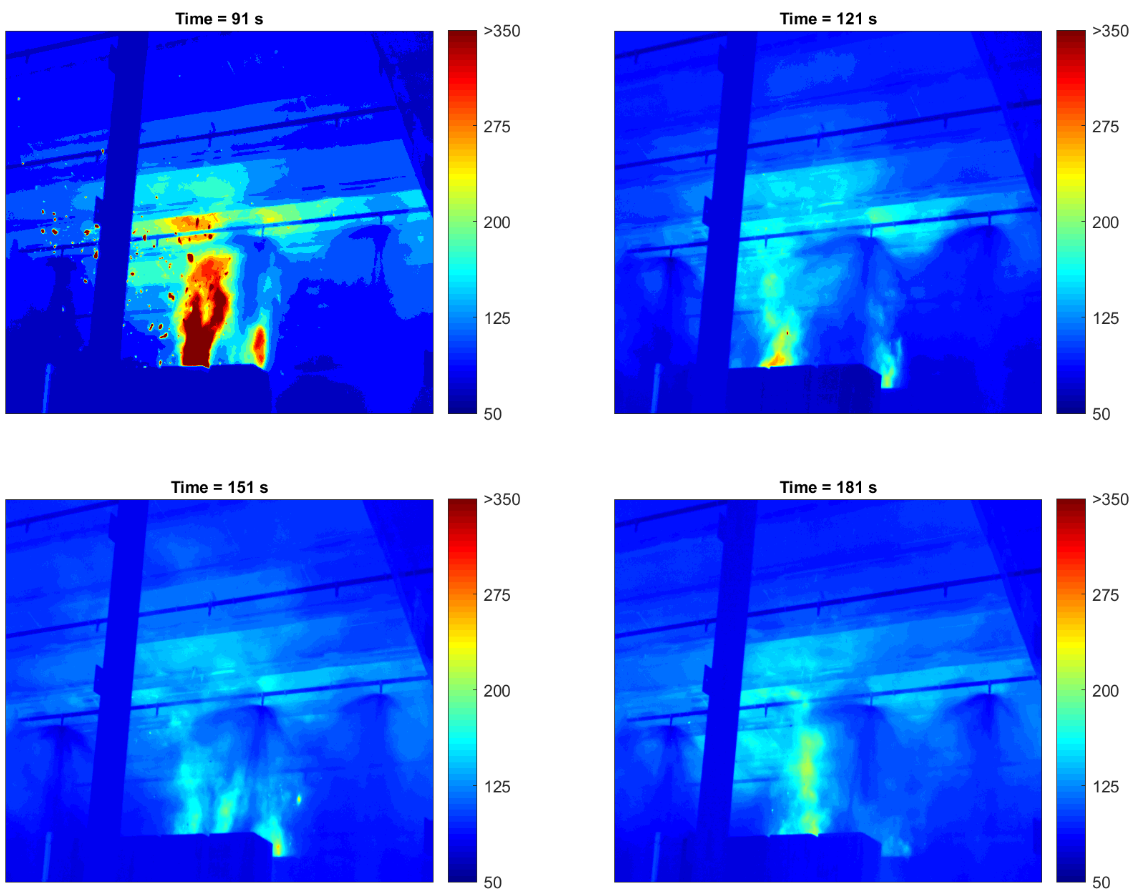
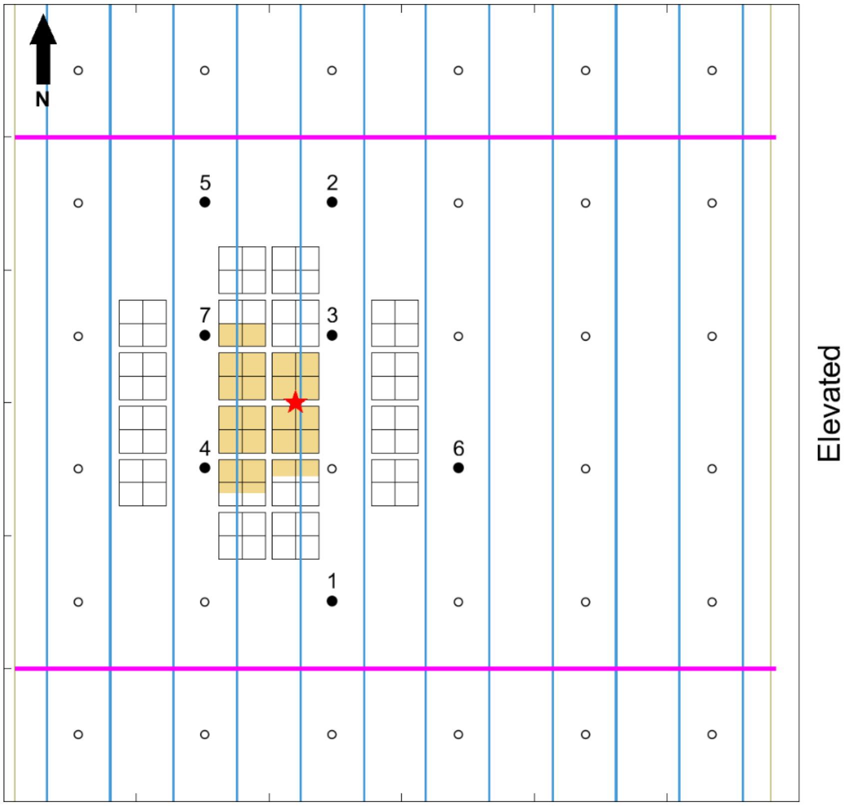


Figure 2-41: False color infrared images captured during Test #7 of the fire plume and ceiling jet near the plume impingement region. Temperatures are in °F.



Sprinkler sequence	
#	Time (min:s)
1	1:13
2	1:13
3	1:15
4	1:32
5	3:20
6	3:33
7	3:53

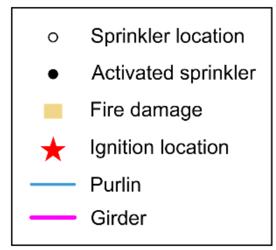
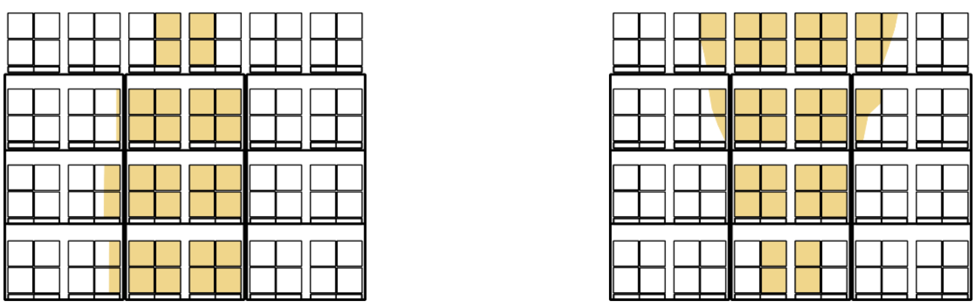


Figure 2-42: Sprinkler operation pattern and top view of damage assessment for Test #7.



(a) East face of the main array

(b) West face of the main array

Figure 2-43: Damage assessment on the main array for Test #7.

2.8.3.5 Test Performance and Comparison against Baseline Test Results

A total of three sloped ceiling tests were conducted with an 18° inclination. Test #1 evaluated sprinkler performance for an unobstructed ceiling. Test #2 was conducted with 300 mm (12 in.) purlins showing unacceptable performance compared to the baseline test. Test #7 was conducted with the same purlin depth but with the purlin channels closed at the girders and showed improved performance compared to Test #2.

Chemical energy released during each test is shown by the blue triangles in Figure 2-44. In Test #1 (unobstructed ceiling), 5.3 GJ of chemical energy was released which is 280% higher than the baseline test. With 300 mm (12 in.) purlins, in Test #2, 6.3 GJ of chemical energy was released. Compared to Test #2, which had open purlin channels, Test #7 had the purlin channels closed at girders spaced 12.2 m (40 ft) apart. A total of 5.8 GJ was released in Test #7, an 8% decrease compared to Test #2 with open channels, indicating the fire spread was not affected significantly (closing the channels reduced the number of sprinkler activations). Compared to the baseline test, up to 350% increase in total chemical energy released was recorded providing an indication that the ceiling sprinkler performance is significantly different than that observed in the baseline test.

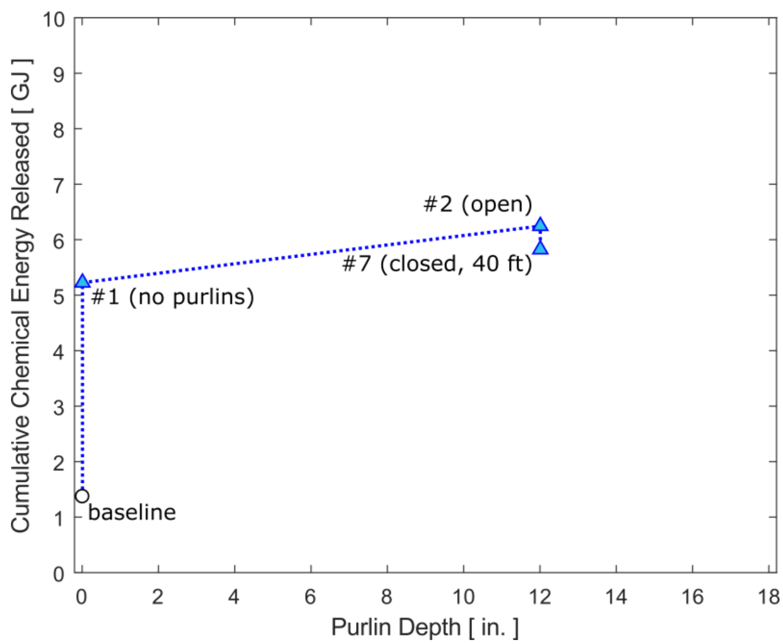


Figure 2-44: Cumulative chemical energy released during the baseline and 18° sloped ceiling tests plotted against purlin depth.

Performance of the sloped ceiling tests against the baseline test is summarized in Table 2-6. Results from Test #2 are included in the table but are not discussed further as Test #7 was found to mitigate the issue of excessive sprinkler activations due to flow channeling observed in Test #2. Between seven and ten sprinkler operations took place in Tests #1 and #7. The number of activations were 4-7 greater than the baseline test. For other storage scenarios not investigated here, the 18° inclination may provide greater challenges and the protection design may not adhere to the existing guidelines. Two perimeter sprinklers operated in Test #1, out of which one was on the downslope side where the ceiling jet is known to be weak [4] [12]. The other perimeter sprinkler operated on the side: the ceiling jet initially traveled sideways, but video evidence pointed to it turning toward the upslope (this was shown in numerical modeling results as well [4]). Since the sloped ceiling structure was 18 m x 18 m (59 ft x 59 ft) wide, only three sprinkler rings were installed. Therefore, compared to the baseline test which had four sprinkler rings, in conjunction with the knowledge that the ceiling jet tended to move toward the upslope, the perimeter sprinkler operation on the side was deemed to be less important. No perimeter sprinklers operated on the upslope end during any of the three tests. In all the tests fire damage was similar compared to the observed damage in the baseline test. Estimated ceiling steel peak temperatures remained well below 538°C (1000°F), which was also the case in the baseline test.

As discussed above, the results of tests conducted with the 18° ceiling inclination demonstrated a ceiling sprinkler performance that is significantly different than that observed in the baseline test. A possible resolution could be a stipulated percent increase to the number of ceiling sprinklers in the protection design for over 10° and up to 18° ceiling inclination and purlin depths of 300 mm (12 in.) or less. For deeper purlins, numerical modeling has shown that the ceiling jet will stay confined in the purlin channels and will have limited extent in the downslope direction, which would delay sprinkler activations [5] and adversely affect fire spread.

Although the issue of deflector orientation was only investigated with testing when the ceiling was inclined at 10°, it can be reasonably concluded that the deflector parallel-to-floor orientation should be used for higher inclinations. This conclusion is supported by the deficiencies recorded during the 10° inclination test conducted with parallel-to-ceiling deflector orientation (discussed above). Additionally, at 18° ceiling inclination and parallel-to-ceiling deflector orientation, spray tests conclusively showed that the spray-core moves toward the upslope direction [7], demonstrating a potential of poor suppression performance. The spray tests conducted at a 18° ceiling inclination showed that this trend was observed for different sprinklers, water pressure and standoff distance of the sprinklers from the ceiling [7]. Modeling results using both pendent and upright sprinklers (various K-factors modeled) and different sprinkler arrangements around the ignition locations (ignition below a sprinkler and among four sprinklers) showed that, when the deflector orientation was kept parallel-to-ceiling, a reduction of up to 25% water flux over the fire region was recorded compared to the parallel-to-floor orientation [4] [5].

Table 2-6: Test performance comparison between baseline and 18° sloped ceiling tests (#1, #2, #7). Sprinkler deflectors kept parallel-to-floor.

Test Number	Purlin Depth [mm (in.)]	Purlin Channels	Girder Spacing [m (ft)]	Total Sprinklers Activated	Perimeter Activations	Extent of Damage	Steel Temp [°C (°F)]	Released Energy (GJ)
Baseline	–	–	–	3	No	Acceptable	48 (118)	1.4
1	–	–	–	10	Yes*	Acceptable	120 (239)	5.3
2	300 (12)	Open	7.6 (25)	13	Yes	Acceptable	140 (285)	6.3
7	300 (12)	Closed	12.2 (40)	7	No	Acceptable	98 (208)	5.8

*Downslope and side perimeter operations are of less concern

2.8.4 Summary

From the seven large-scale tests conducted under the sloped ceiling and comparison with the non-sloped, unobstructed ceiling baseline test results, the following can be summarized:

- For 10° ceiling inclination
  - K240 (K16.8) pendent QR sprinklers operating at 2.4 barg (35 psig) – a discharge density of 41 mm/min (1.0 gpm/ft^2) per sprinkler – is adequate to protect CUP commodity stored to a height of 6.1 m (20 ft) in absence of, or in the presence of obstructed ceiling construction with purlin depths less than or equal to 460 mm (18 in.).
  - Compared to three sprinkler activations in the baseline test, one–four additional activations occurred in the successful sloped ceiling tests.
  - When purlin channels at the girder locations are closed for a purlin depth of 460 mm (18 in.), the ceiling jet channeling effect is reduced leading to a smaller number of sprinkler activations. This would help reduce water demand.
  - The conclusions drawn from investigating the effect of deflector orientation in the numerical modeling studies [4] [5] and the cold flow spray tests [7] were confirmed by the tests conducted – during the test conducted with parallel-to-ceiling deflector orientation, spray core was observed to move in the upslope direction, high ceiling jet temperatures were recorded to occur for a longer duration and a larger amount of chemical energy was released compared to the parallel-to-floor test. These effects could adversely affect test outcomes in a more pronounced way for other slopes and storage scenarios.

- For 18° ceiling inclination
  - K240 (K16.8) pendent QR sprinklers operating at 2.4 barg (35 psig) is adequate to protect CUP commodity stored to a height of 6.1 m (20 ft) in the absence of, or in the presence of obstructed ceiling construction with purlin depths less than or equal to 300 mm (12 in.).
  - Compared to three sprinkler activations in the baseline test, four–seven additional activations occurred in the successful sloped ceiling tests. This increase in the number of activations demonstrates that the ceiling sprinkler performance is significantly different

than that observed in the baseline test. Adjusting the number of sprinklers in protection designs may be a possible remedy for such challenging fire hazard scenarios.

- When purlin channels at the girder locations are closed for a purlin depth of 300 mm (12 in.), the ceiling jet channeling effect is reduced leading to a smaller number of sprinkler activations.

The abovementioned observations are valid for CUP commodity in a 4-tier-high rack-storage arrangement with a ceiling clearance of 3 m (10 ft). Scenarios that were not investigated in the large-scale tests, but would be relevant to practical applications, include other commodities (e.g., Uncartoned Unexpanded Plastic or UUP), taller storage arrays and different ceiling clearances. Though extension of the results from the present study to other conditions should ideally be validated by targeted testing and/or computer simulations, reasonable estimates of expected behavior can be made based on previous work as discussed below.

Large-scale testing using the UUP commodity [11] has shown that the ceiling jet channeling effect is stronger because of the initially weaker plume generated from a slow growing fire. This effect is mitigated by closing the purlin channels at the girder locations, as was evident from numerical modeling results [11]. Closing of the purlin channels was also found to mitigate the flow channeling effect in the sloped ceiling tests. While developing sprinkler protection guidance, consideration should be given to the possibility of greater channeling when UUP like commodities are used.

For taller storage arrays, the activation trends should follow the predictions from numerical modeling [4] [5] and differences in activation patterns are not expected to significantly affect suppression performance. The conclusions of this study should, therefore, be generally still applicable.

For higher ceiling clearances, skewed activation patterns causing delays on the downslope side are expected to reduce. The fire plume would be wider for higher clearances, as shown by numerical modeling for a 6.1 m (20 ft) clearance case [4], when compared to the 3 m (10 ft) clearance scenario considered in the testing. The wider plume impinging on the ceiling would cause more symmetric sprinkler activation patterns to develop around the ignition location, reducing activation delays on the downslope side compared to the upslope activations [4]. As for the case of changes in array height, the conclusions of this study should be generally still applicable.

3. **Conclusions and Recommendations**

From the range of conditions explored in large-scale testing as well as the previous numerical modeling [4] [5], and spray test results [7], conclusions are presented below followed by protection recommendations for storage in warehouses with sloped ceilings. In general, they apply to a 4-tier-high CUP rack-storage scenario with a ceiling clearance of 3 m (10 ft).

3.1 Conclusions

- Compared to the three sprinkler activations in the CUP baseline test, one to four additional sprinkler activations occurred when the ceiling was inclined at 10° and four to seven additional activations occurred when the ceiling was inclined at 18°. In these tests, fire spread was successfully controlled. The 18° tests were found to be more challenging from a sprinkler protection standpoint, especially the unobstructed ceiling test in which ten sprinklers activated.
- Presence of obstructed ceiling construction (purlins and girders) was generally found to cause early activation of sprinklers compared to the baseline test and mitigated the biased ceiling jet flow caused by the ceiling slope (the ceiling jet tends to move toward the upslope). However, it was found that deeper purlins could cause the ceiling jet to confine within the purlin channels causing several sprinklers to activate far away from the fire source. Closing the purlin channels at the girder locations (the gap above the girders) was found to mitigate the ceiling jet channeling effect, reducing the unwanted activation of sprinklers along the purlin channels. Closing the channels was found to be effective for purlin depths of 460 mm (18 in.) at 10° inclination and 300 mm (12 in.) at 18° inclination.
- At 10° ceiling inclination, current tests showed limited effect of sprinkler deflector orientation on suppression effectiveness; however, in the parallel-to-ceiling orientation test, the sprinkler spray cores moved away from the ignition region and a larger amount of commodity was consumed during the test (300% increase in total energy release compared to the baseline test whereas only 30% increase was recorded for the parallel-to-floor test). For other storage scenarios besides the tested configuration (4-tier CUP arrays, 10 ft ceiling clearance), the adverse effects of parallel-to-ceiling orientation on the sprinkler suppression performance can be more pronounced. Spray tests [7] and numerical modeling [4] [5] have shown inferior spray distribution for the parallel-to-ceiling orientation for ceilings inclined at 18°.

3.2 Recommendations

Analyzing the results from the large-scale tests, the modeling studies [4] [5] and the spray test results [7], the following general recommendations are made toward updates of NFPA 13 [1] and FM Global DS 2-0 [8] sprinkler protection designs for storage under sloped ceilings in the presence of obstructed ceiling construction:

1. For ceiling inclinations up to 10° (slope of 2 in 12), a parallel-to-floor sprinkler deflector orientation is preferred as it provides a higher water flux to the ignition area compared to the parallel-to-ceiling orientation. In addition, when purlin depths are less than or equal to 300 mm (12 in.), ceilings of inclination up to 10° can be considered non-sloped, unobstructed type [1] [8]. For purlin depths greater than 300 mm (12 in.) and less than or equal to 460 mm (18 in.), purlin channels at girder locations should be closed to prevent ceiling jet channeling which could result in undesired activations far away from the fire location causing the water demand to be exceeded.
2. For ceiling inclinations greater than 10° and less than or equal to 18° (slope of 4 in 12), sprinkler deflectors should be kept parallel-to-floor. In addition, for purlins up to 300 mm (12 in.) depth, the gaps above the girders should be closed to prevent ceiling jet channeling. Purlins deeper than 300 mm (12 in.) when ceiling inclination is greater than 10° are deemed challenging for ceiling sprinklers installed on their normal spacing due to delays in downslope sprinkler activations. For ceiling inclinations greater than 10°, additional protection recommendations, e.g., In-Rack Automatic Sprinklers (IRAS) and/or false-/drop-ceilings [8], would need to be implemented in order to provide an acceptable level of fire control.
3. For ceiling inclinations over 10° and up to 18° (slope of 4 in 12), consideration should be given toward adjusting the ceiling sprinkler design obtained from large-scale fire testing conducted under non-sloped, unobstructed ceilings to account for the impact of ceiling slope and, when present, obstructed ceiling construction.
4. When the purlin depth exceeds the sprinkler's maximum allowable vertical distance [1] [8] below the ceiling, it is recommended that sprinklers be placed below the purlins on a plane parallel to the ceiling with the sprinkler deflectors in a parallel-to-floor orientation. The maximum distance of the plane should be 150 mm (6 in.) from the purlins. This recommendation is valid for a maximum purlin depth of 460 mm (18 in.) for ceilings with up to 10° inclination. For ceilings with inclinations greater than 10° and less than or equal to 18°, the maximum purlin depth should be 300 mm (12 in.). Sprinkler spacing on the ceiling level should be selected such that no spray obstruction occurs at girder locations.

References

1. "NFPA 13: Standard for the Installation of Sprinkler Systems," National Fire Protection Association, 2016.

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Appendix A. Fire Chronology

A.1 Baseline Test

Time (min:s)	Observations
0:00	Ignition was achieved
0:18	Flames reached the top of 1st tier
0:36	Flames reached the top of 2nd tier
0:41	Flames reached the top of 3rd tier
0:44	Flames reached the top of the array
1:22	First sprinkler activation was observed
1:23 – 1:25	Two additional sprinklers activated
1:26	Ceiling temperature over the ignition briefly reached 370°C (700°F)
1:35	Flames were reduced to below the 3rd tier. White smoke descended to the floor partially obscuring the array
2:20	Visibility of the main test array completely obscured by smoke
2:40 – 25:00	Peak ceiling temperatures were below 32°C (90°F)
25:00	Test was terminated

A.2 Test #1

Time (min:s)	Observations
0:00	Ignition was achieved
0:24	Flames reached the top of 1st tier
0:39	Flames reached the top of 2nd tier
0:42	Flames reached the top of 3rd tier
0:48	Flames reached the top of the array
1:18 – 1:19	First two upslope sprinklers closest to ignition activated
2:55	Flames on the east face of the main array were reduced below 3rd tier. White smoke descended to the floor on the upslope ceiling side partially obscuring the array
3:00 – 3:17	Five additional sprinklers activated
3:19	Ceiling temperature over ignition briefly reached 590°C (1095°F). Flames on the west face of the main array were observed to be impinging on the ceiling
3:22 – 3:30	Three additional sprinklers activated
3:35	Flames on the west face of the main array were reduced to below the 4rd tier. Visibility of the main test array completely obscured by smoke
5:00 – 16:00	Peak ceiling temperatures were below 140°C (275°F)
16:00 – 20:00	Peak ceiling temperatures were below 38°C (100°F)
20:00	Test was terminated

A.3 Test #2

Time (min:s)	Observations
0:00	Ignition was achieved
0:16	Flames reached the top of 1st tier
0:27	Flames reached the top of 2nd tier
0:33	Flames reached the top of 3rd tier
0:39	Flames reached the top of the array
1:14	First upslope sprinkler near ignition activated
1:27	Ceiling temperature over ignition briefly reached 500°C (936°F). Flames on the west face of the main array were observed to be impinging on the ceiling
1:27 – 1:39	Four additional sprinklers activated
1:50	White smoke descended to the floor partially obscuring the array
2:29 – 3:06	Eight additional sprinklers activated
3:05	Ceiling temperature over array briefly reached 680°C (1250°F).
4:00 – 11:00	Peak ceiling temperatures were below 79°C (175°F)
11:00 – 20:00	Peak ceiling temperatures were below 38°C (100°F)
20:00	Test was terminated

A.4 Test #3

Time (min:s)	Observations
0:00	Ignition was achieved
0:22	Flames reached the top of 1st tier
0:41	Flames reached the top of 2nd tier
0:49	Flames reached the top of 3rd tier
0:54	Flames reached the top of the array
1:20	Ceiling temperature over ignition briefly reached 240°C (465°F)
1:22	First upslope sprinkler near ignition activated
1:35 – 1:41	Five additional sprinklers activated
1:37	Ceiling temperature over array briefly reached 400°C (745°F)
1:55	White smoke descended to the floor obscuring the array
3:00 – 10:00	Peak ceiling temperatures were below 27°C (80°F)
10:00 – 30:00	Ceiling temperatures reached ambient conditions, below 16°C (60°F)
30:00	Test was terminated

A.5 Test #4

Time (min:s)	Observations
0:00	Ignition was achieved
0:19	Flames reached the top of 1st tier
0:30	Flames reached the top of 2nd tier
0:36	Flames reached the top of 3rd tier
0:42	Flames reached the top of the array
0:52 – 2:00	Ceiling temperatures were in the range of 150-220°C (300-420°F)
1:16	Two upslope sprinklers near ignition activated
2:27 – 2:32	Two downslope sprinklers activated
2:35	Ceiling temperature over array briefly reached 270°C (511°F)
3:00	White smoke descended to the floor obscuring the array
5:00 – 12:00	Peak ceiling temperatures were below 43°C (110°F)
12:00 – 30:00	Ceiling temperatures reached ambient conditions, below 20°C (68°F)
30:00	Test was terminated

A.6 Test #5

Time (min:s)	Observations
0:00	Ignition was achieved
0:38	Flames reached the top of 1st tier
0:52	Flames reached the top of 2nd tier
0:56	Flames reached the top of 3rd tier
1:02	Flames reached the top of the array
1:37	First upslope sprinkler near ignition activated
1:48	Second sprinkler downslope of ignition activated
1:51	Ceiling temperature over array briefly reached 380°C (712°F)
1:51 – 1:57	Five sprinklers activated
2:00	White smoke descended to the floor obscuring the array
3:34 – 11:05	Peak ceiling temperatures over array were in the range of 260-320°C (500-600°F)
3:53 – 10:47	Two additional sprinklers activated
14:00 – 20:00	Peak ceiling temperatures were below 150°C (300°F)
20:00	Test was terminated

A.7 Test #6

Time (min:s)	Observations
0:00	Ignition was achieved
0:24	Flames reached the top of 1st tier
0:33	Flames reached the top of 2nd tier
0:41	Flames reached the top of 3rd tier
0:45	Flames reached the top of the array
1:23 – 1:26	Five upslope sprinklers activated
1:28	Ceiling temperature over array briefly reached 370°C (699°F)
1:34	Two additional downslope sprinklers activated
1:43	White smoke descended to the floor obscuring the array
3:00 – 6:00	Peak ceiling temperatures were below 79°C (175°F)
6:00 – 22:00	Peak ceiling temperatures were below 52°C (125°F)
22:00 – 30:00	Ceiling temperatures reached ambient conditions, below 22°C (72°F)
30:00	Test was terminated

A.8 Test #7

Time (min:s)	Observations
0:00	Ignition was achieved
0:16	Flames reached the top of 1st tier
0:31	Flames reached the top of 2nd tier
0:36	Flames reached the top of 3rd tier
0:42	Flames reached the top of the array
1:13 – 1:15	Three upslope sprinklers activated
1:32	One downslope sprinkler activated
1:33	Ceiling temperature over array briefly reached 290°C (549°F)
1:50	White smoke descended to the floor obscuring the array
3:20 – 3:33	Two additional sprinklers activated
3:47	Ceiling temperature over array briefly reached 300°C (571°F)
3:53	One additional sprinkler activated
5:00 – 15:00	Peak ceiling temperatures were below 93°C (200°F)
15:00 – 30:00	Peak ceiling temperatures were below 21°C (70°F)
30:00	Test was terminated

Appendix B. Water Pressure

Water supply to sprinklers installed below the sloped ceiling structure was provided by six branch lines, with each branch line accommodating six sprinklers spaced 3 m (10 ft) apart. The following figures show the water pressure in individual branch lines for the seven sloped ceiling tests. For each test, pressure distribution as a function of time is shown for branch lines which had at least one activated sprinkler.

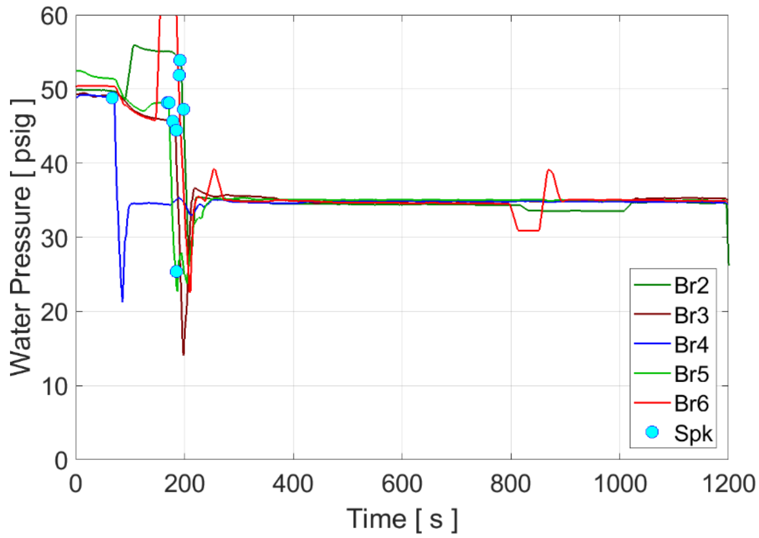


Figure B-1: Water pressure measured at the water supply header ducts for Test #1.

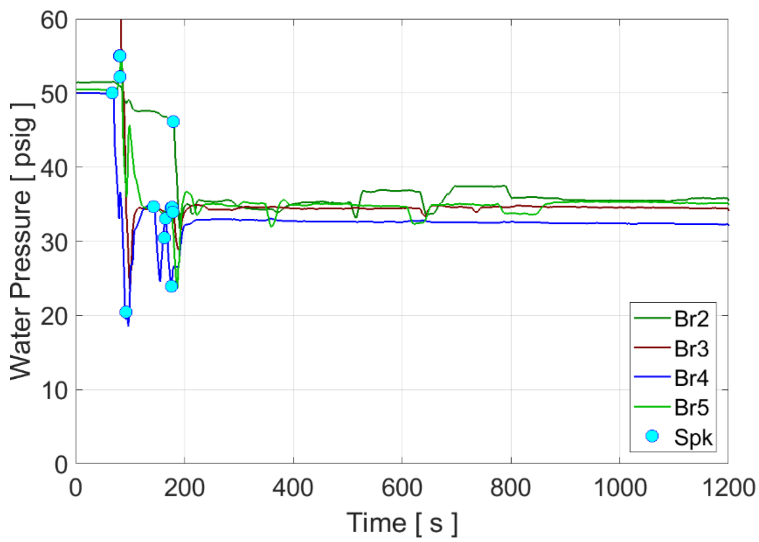


Figure B-2: Water pressure for Test #2.

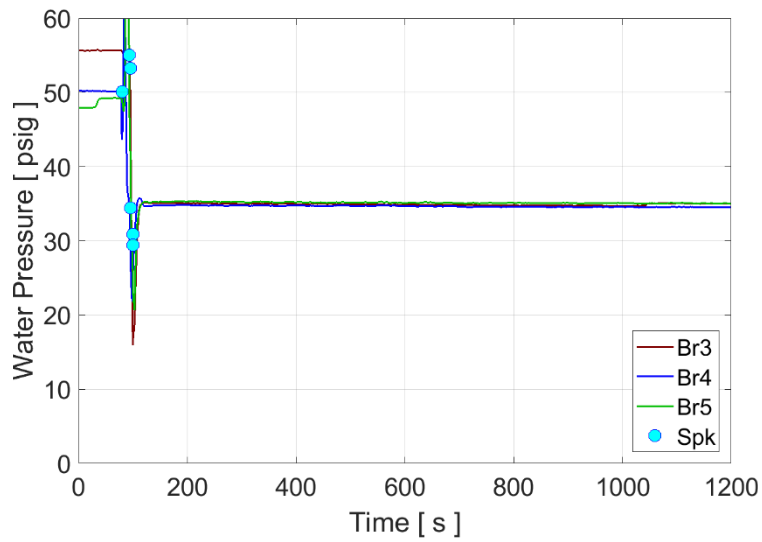


Figure B-3: Water pressure for Test #3.

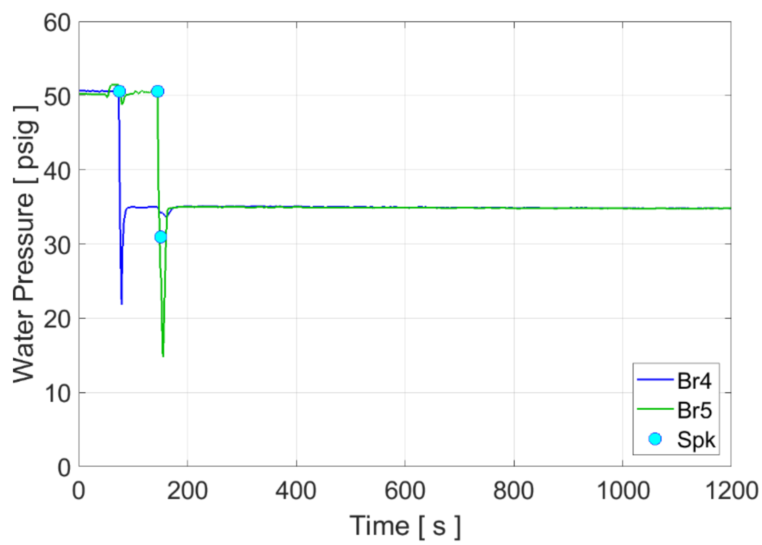


Figure B-4: Water pressure for Test #4.

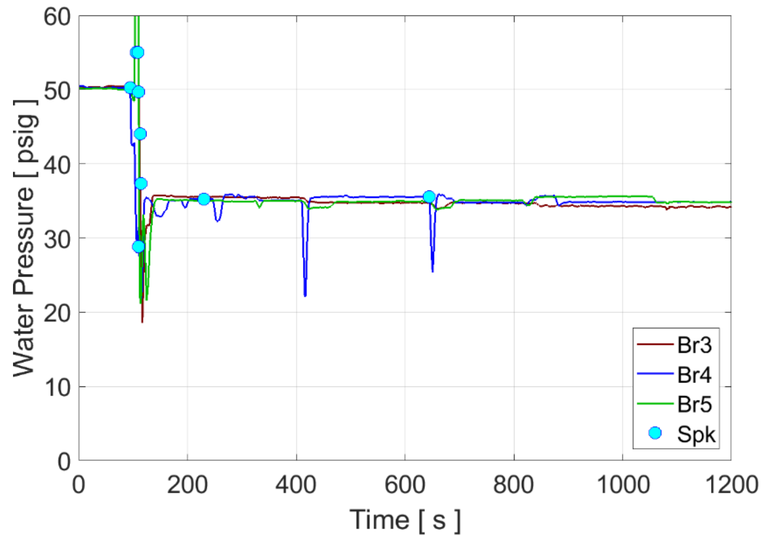


Figure B-5: Water pressure for Test #5.

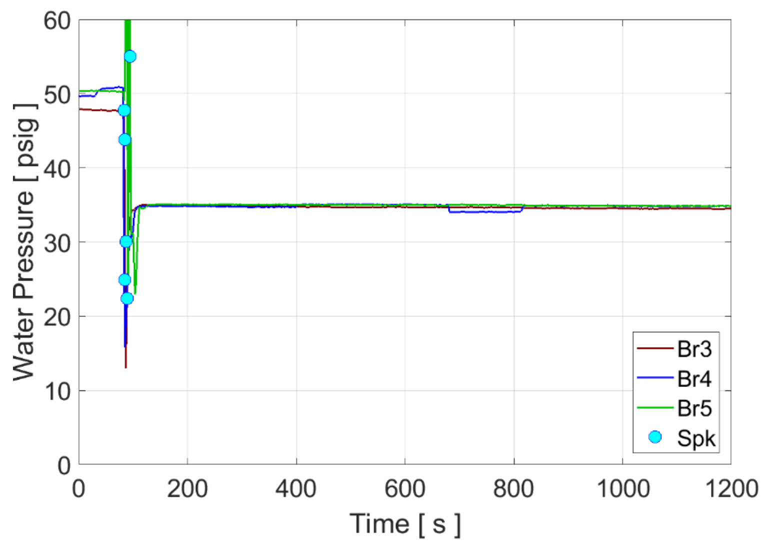


Figure B-6: Water pressure for Test #6.

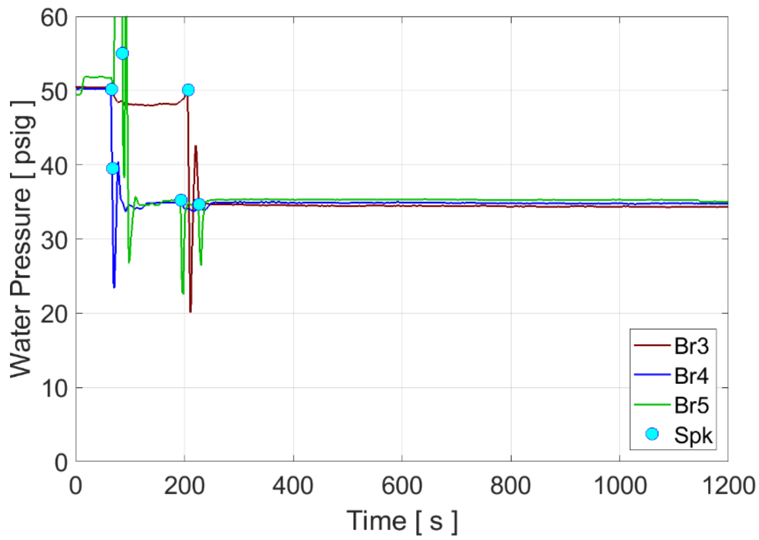
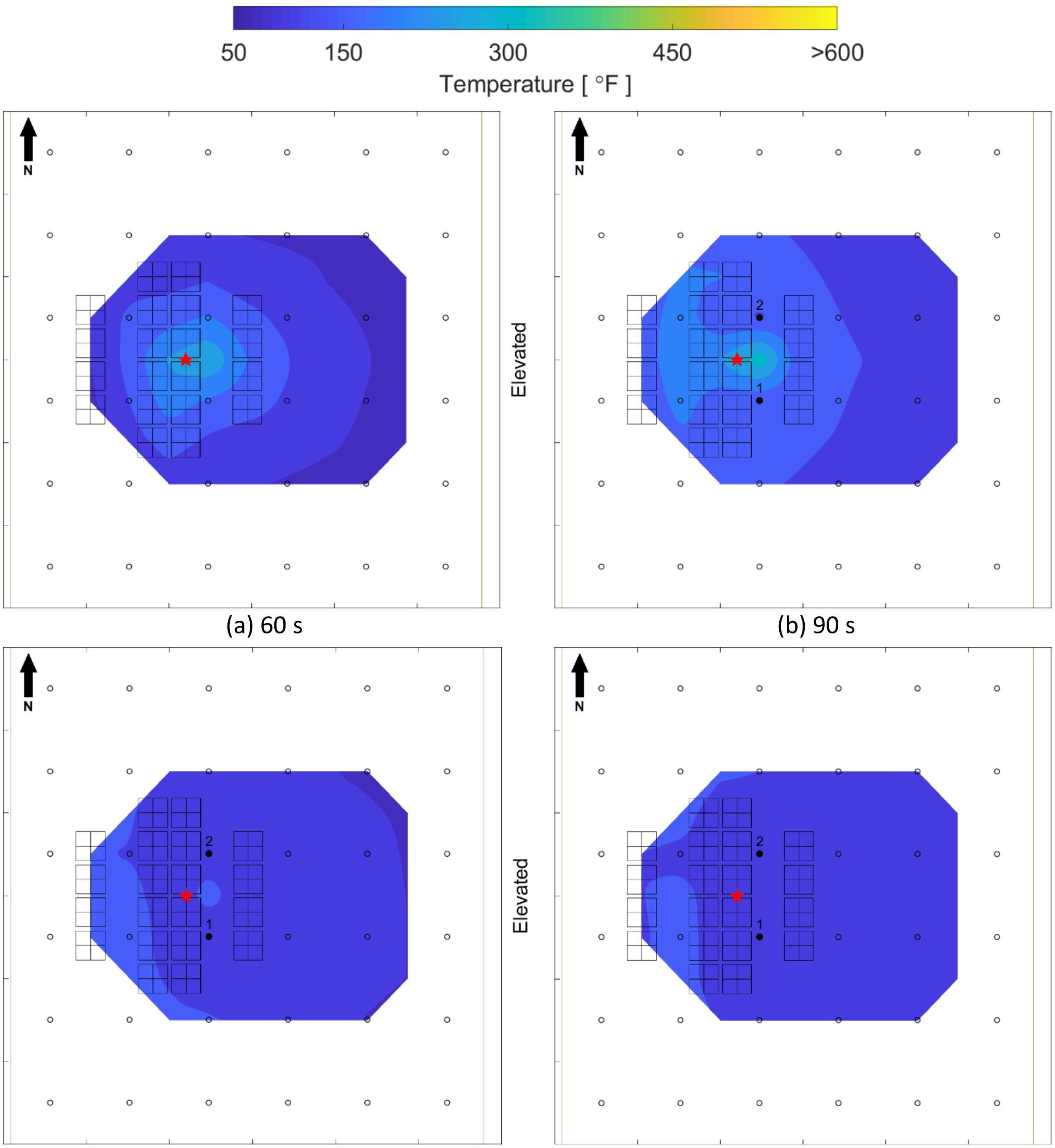


Figure B-7: Water pressure for Test #7.

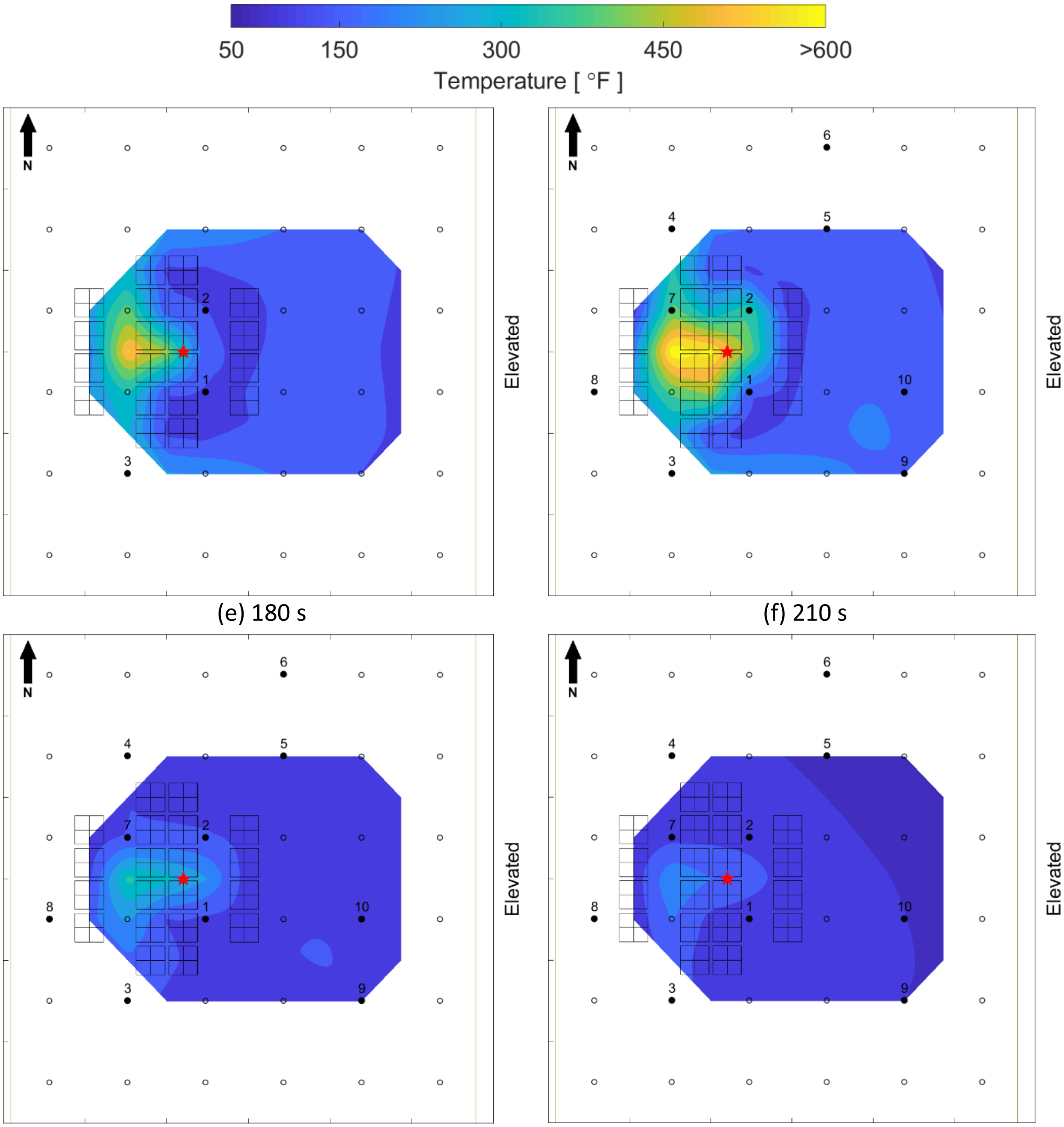
Appendix C. Ceiling Level Gas Temperatures

C.1 Test #1



(a) 60 s
(b) 90 s
(c) 120 s
(d) 150 s

Figure continues on following page

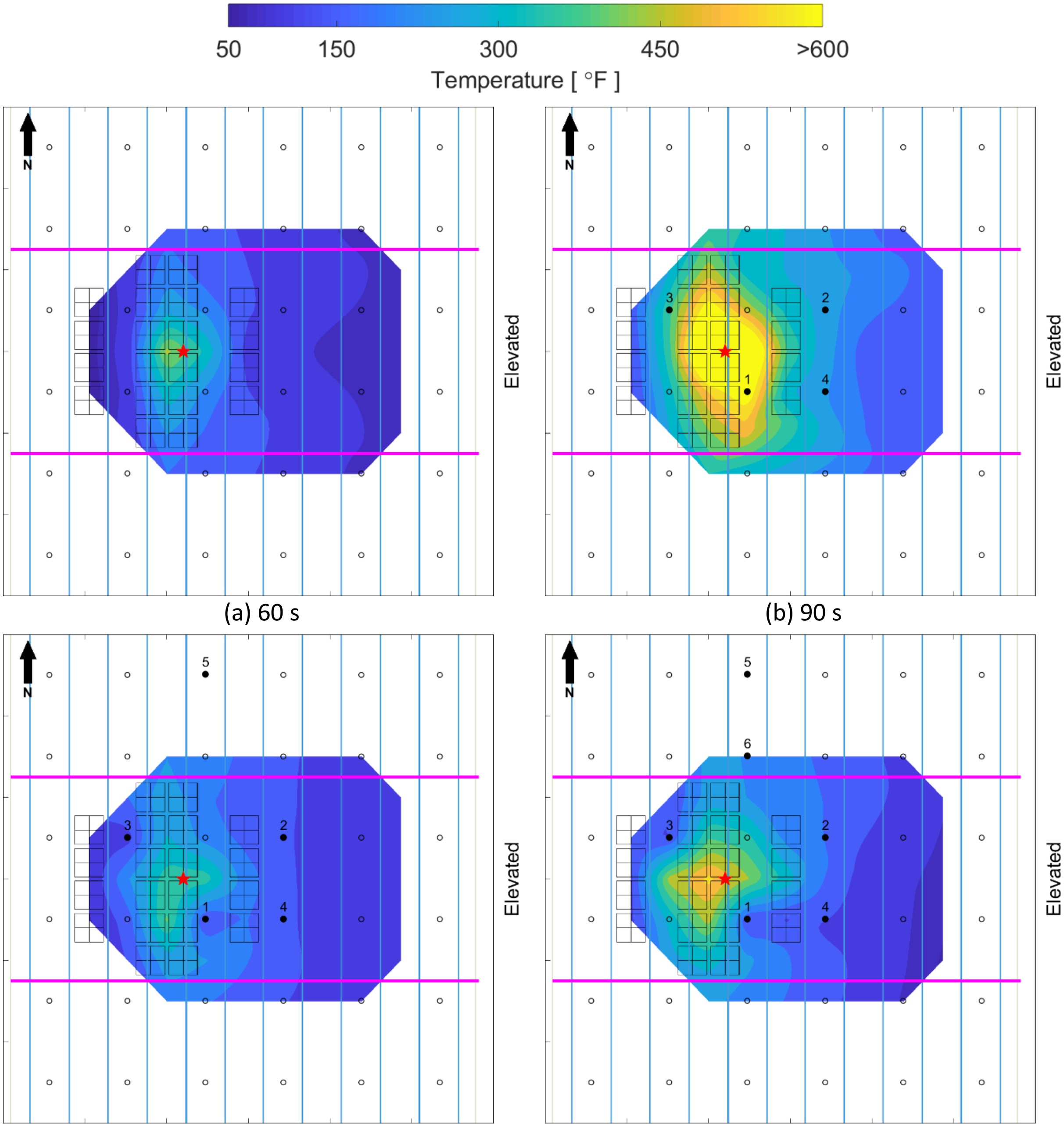


(e) 180 s (f) 210 s

(g) 240 s (h) 300 s

Figure C-1: Test #1 ceiling temperature contours shown from 60 s to 300 s.

C.2 Test #2



(a) 60 s

(b) 90 s

(c) 120 s

(d) 150 s

Figure continues on following page

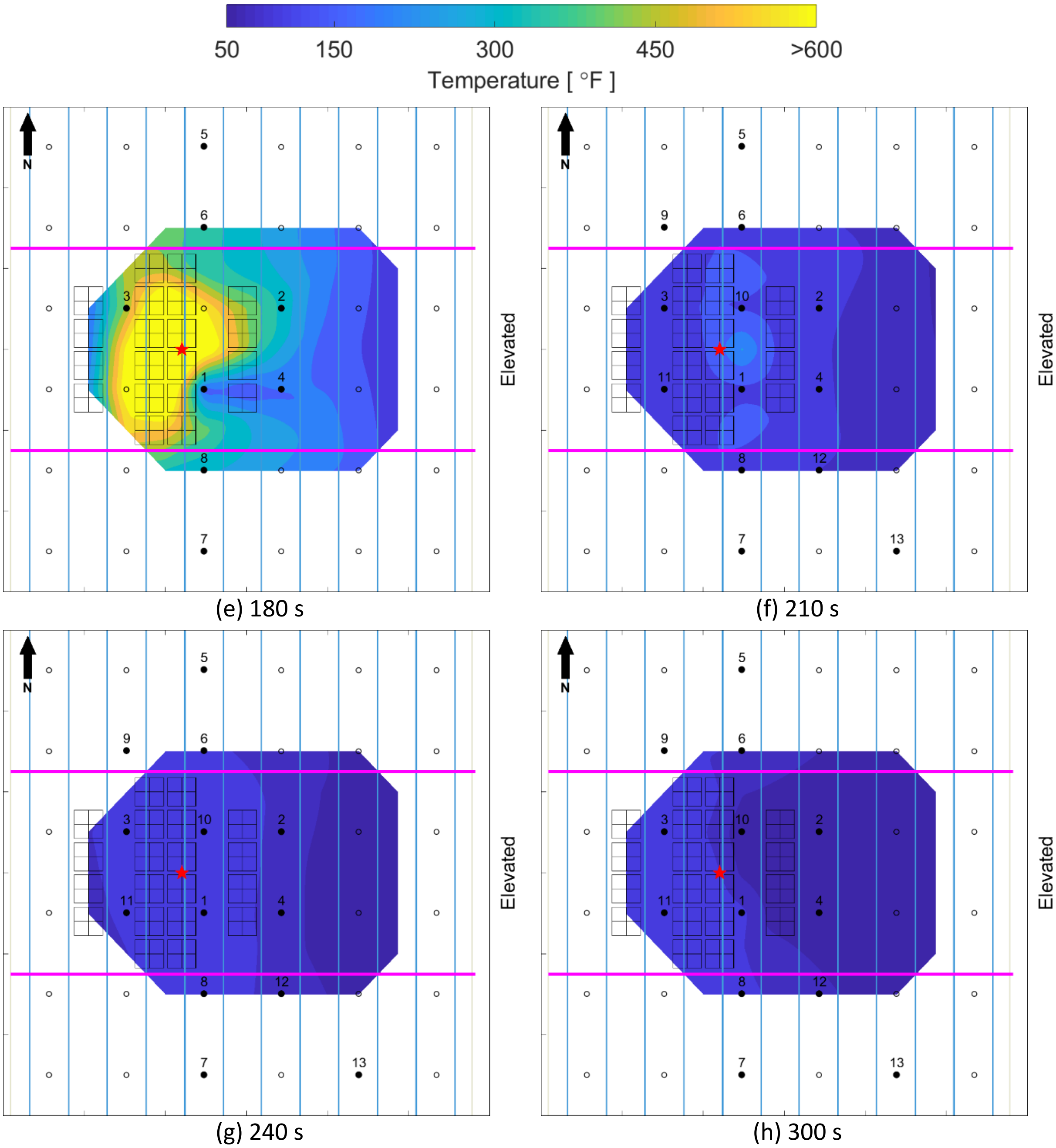
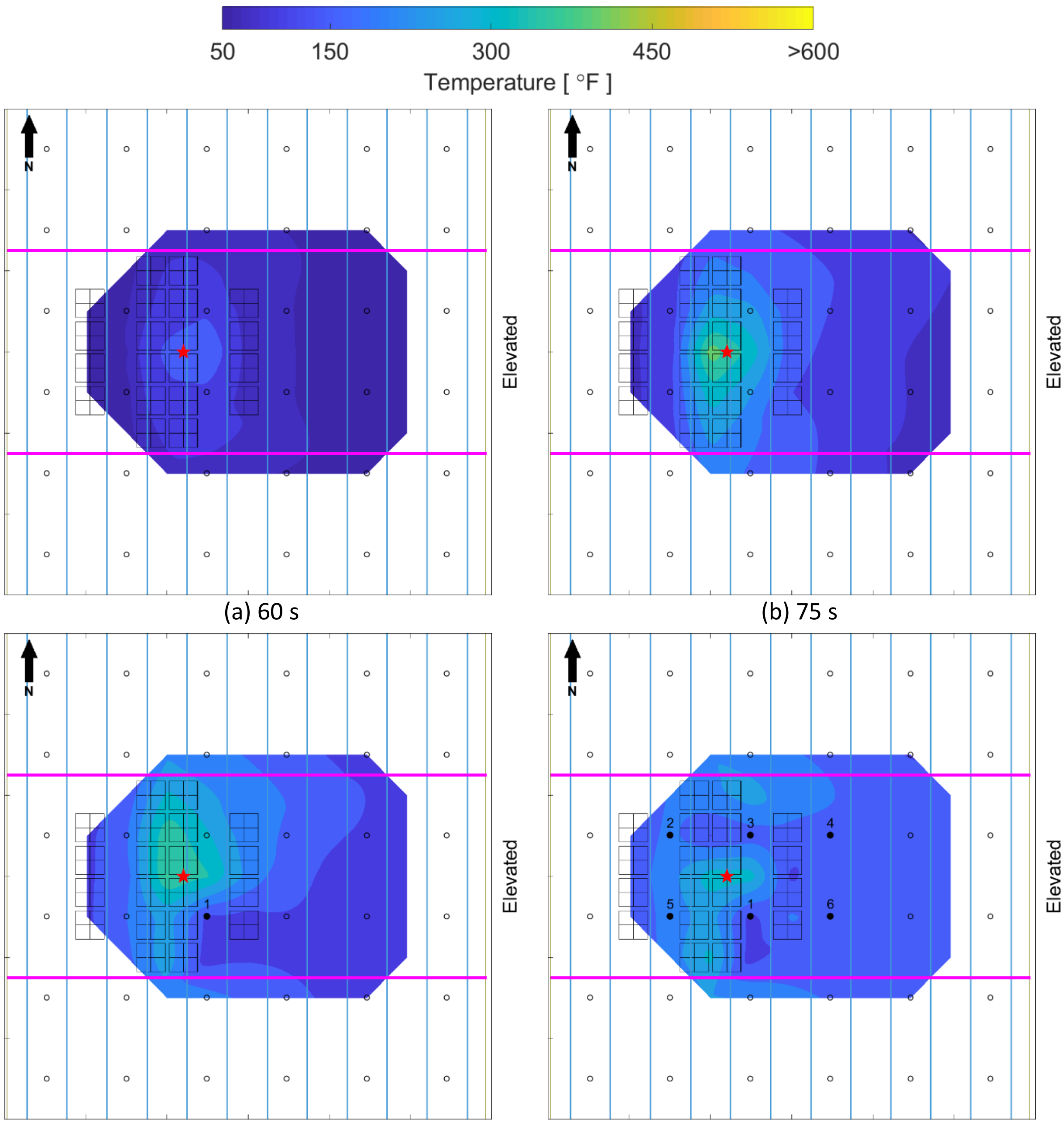


Figure C-2: Test #2 ceiling temperature contours shown from 60 s to 300 s.

C.3 Test #3



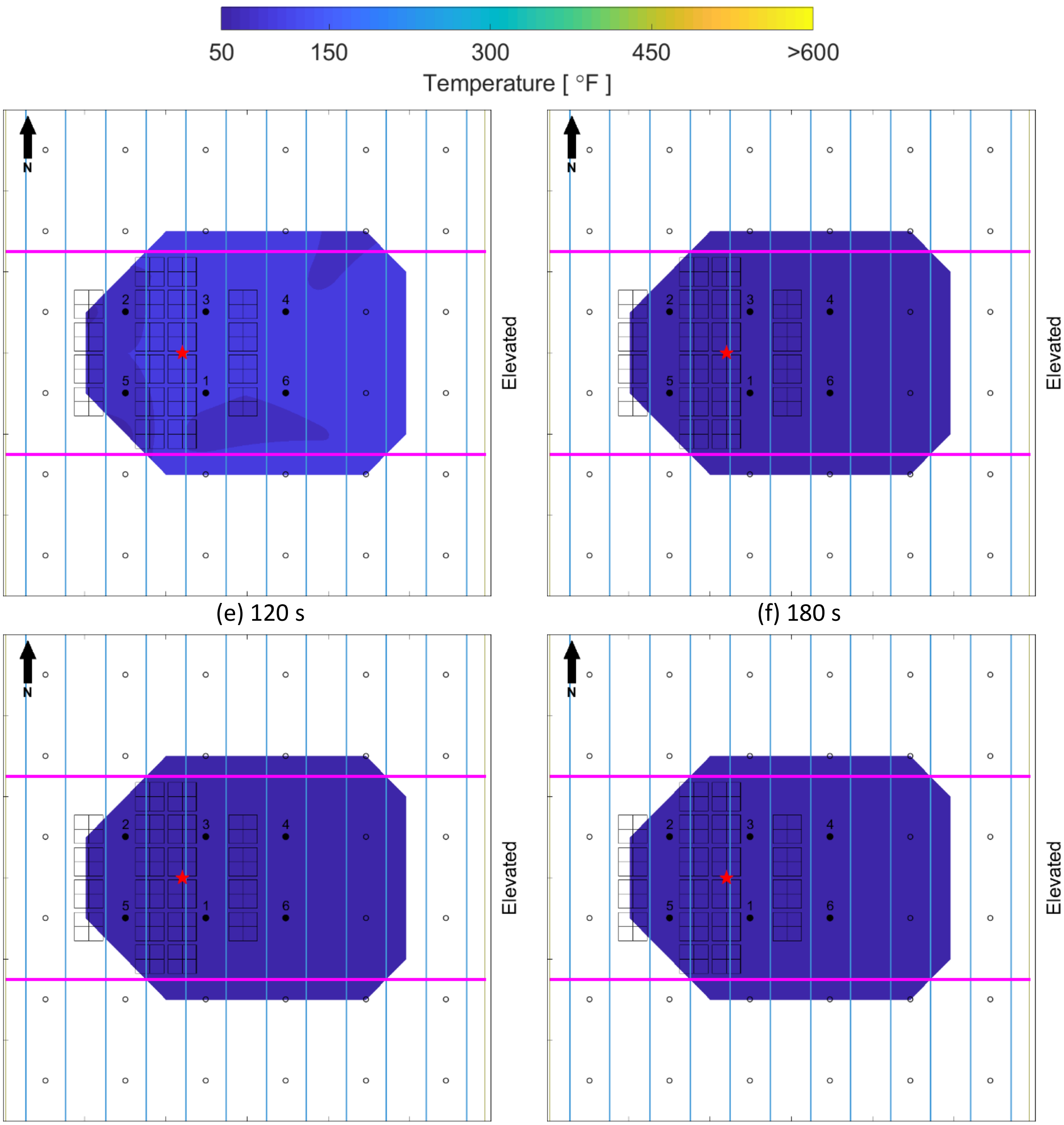
(a) 60 s

(b) 75 s

(c) 90 s

(d) 105 s

Figure continues on following page



(e) 120 s

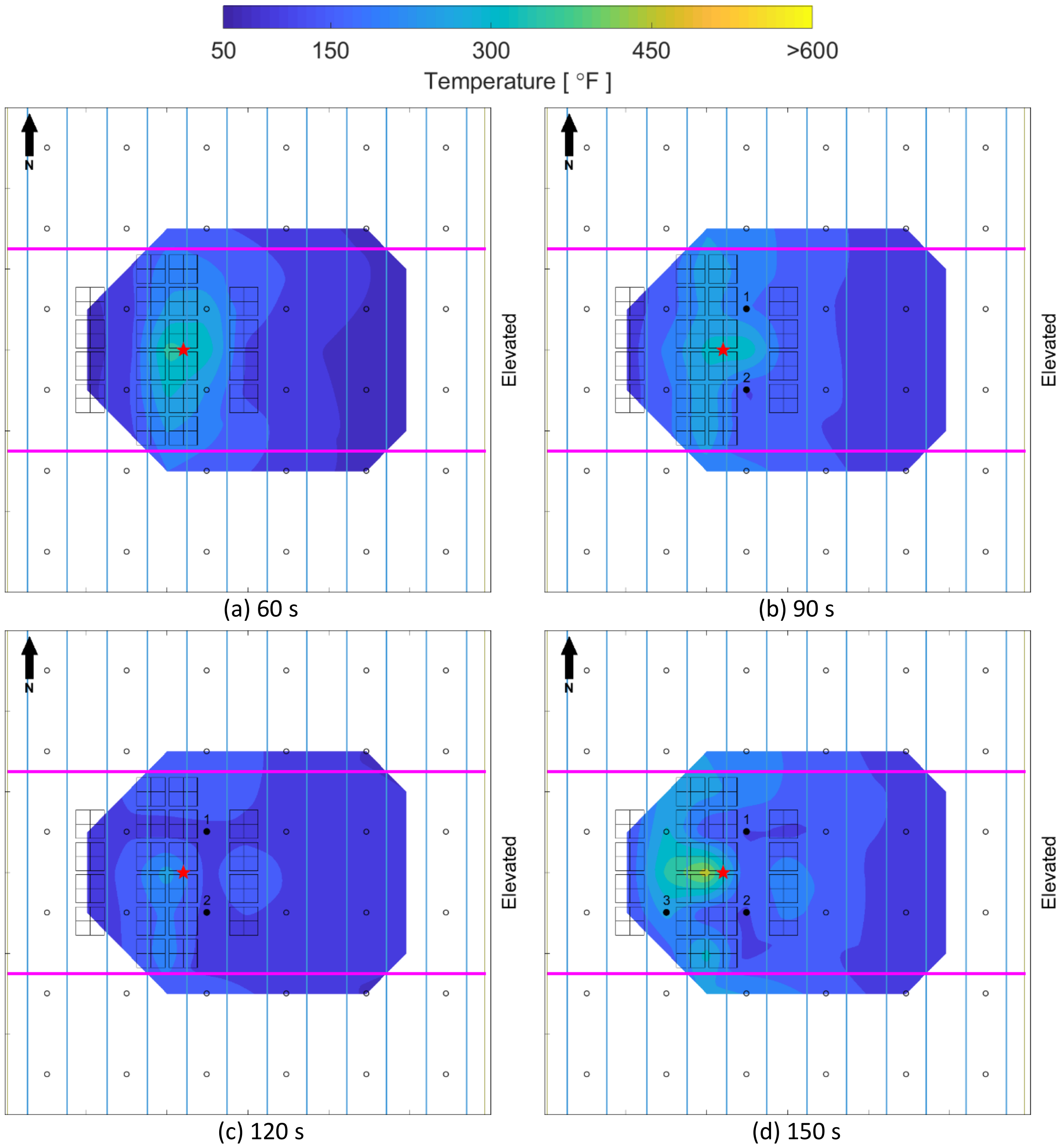
(f) 180 s

(g) 240 s

(h) 300 s

Figure C-3: Test #3 ceiling temperature contours shown from 60 s to 300 s.

C.4 Test #4



(a) 60 s
(b) 90 s
(c) 120 s
(d) 150 s

Figure continues on following page

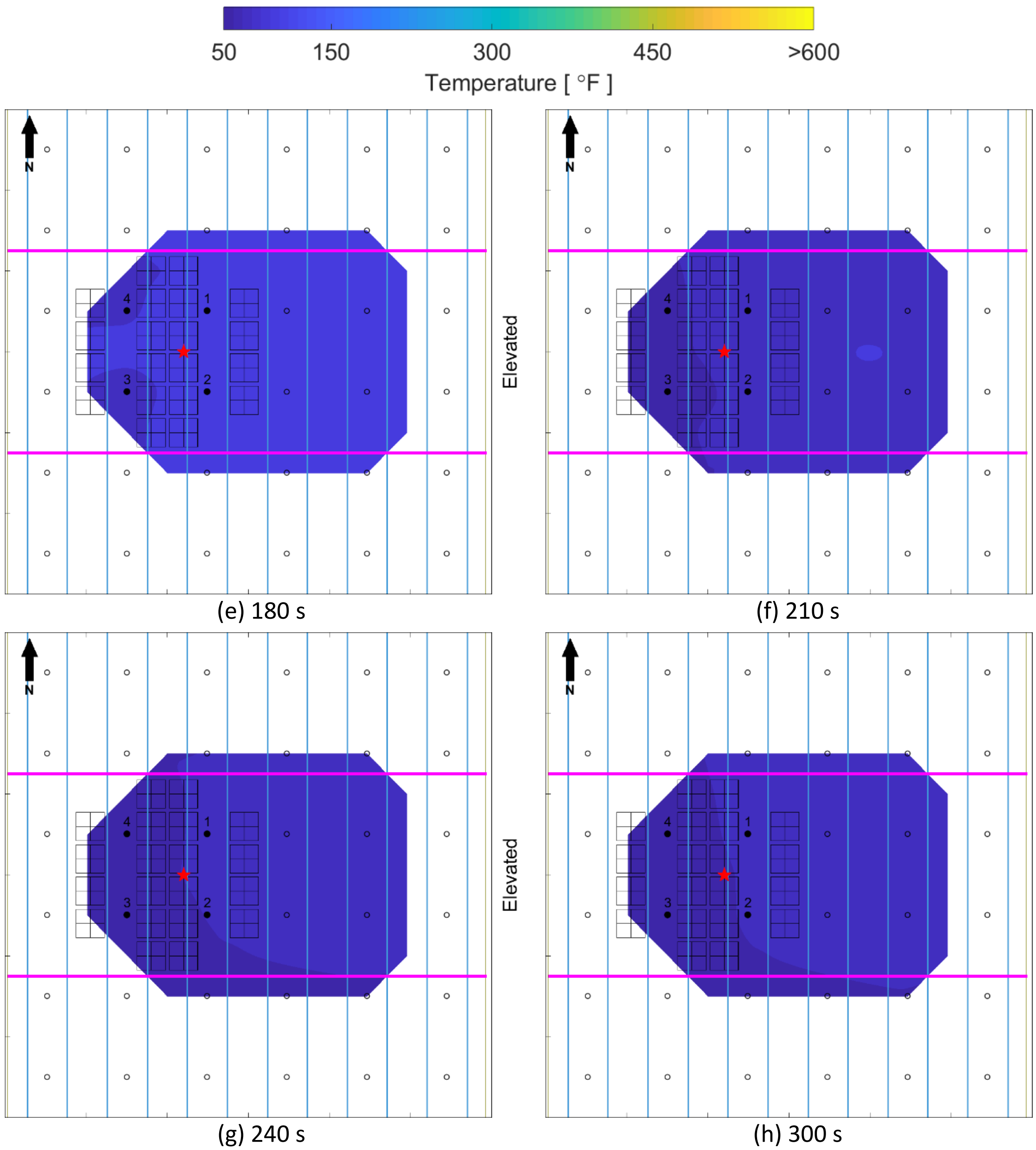
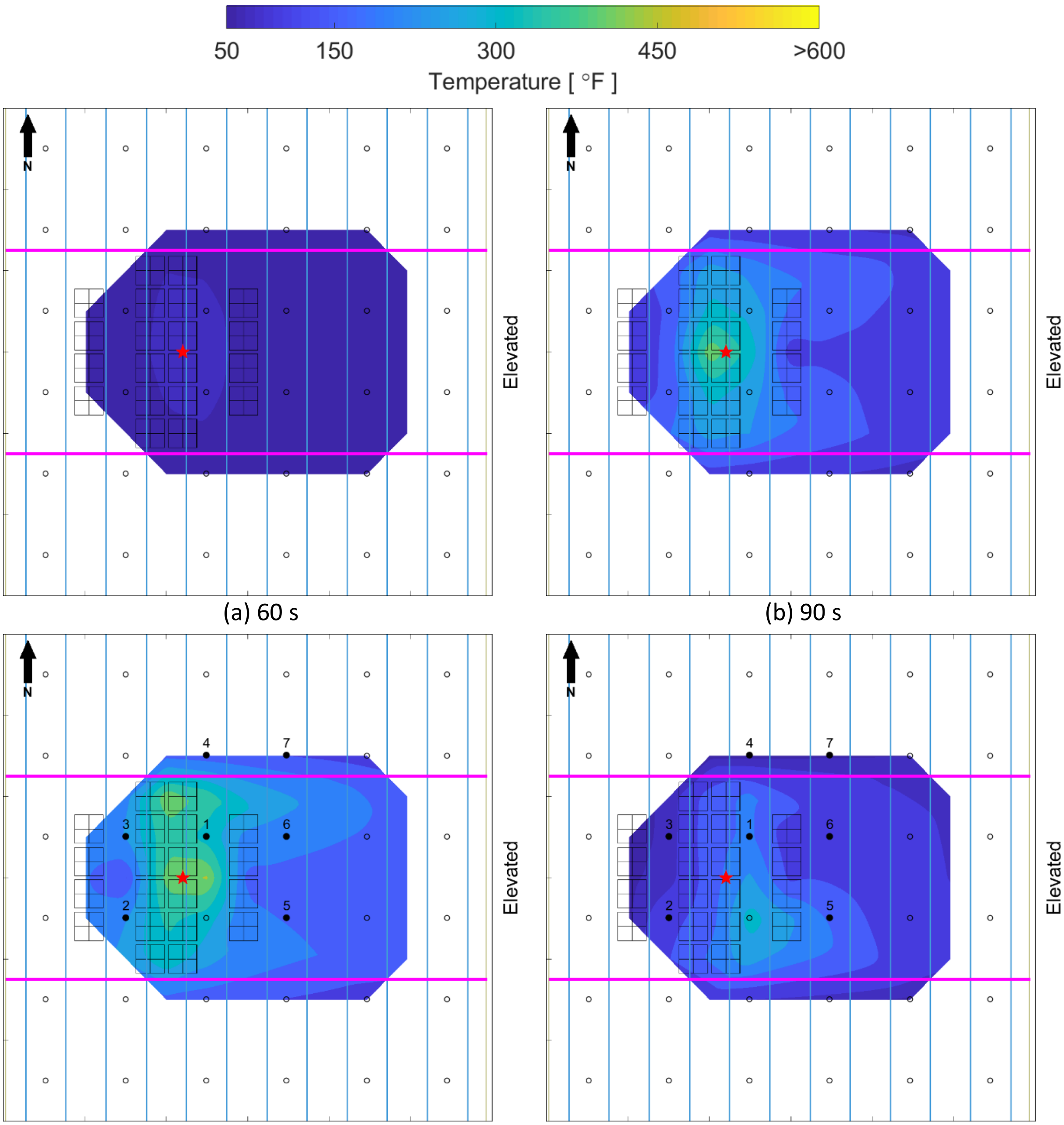


Figure C-4: Test #4 ceiling temperature contours shown from 60 s to 300 s.

C.5 Test #5



(a) 60 s (b) 90 s (c) 120 s (d) 180 s

Figure continues on following page

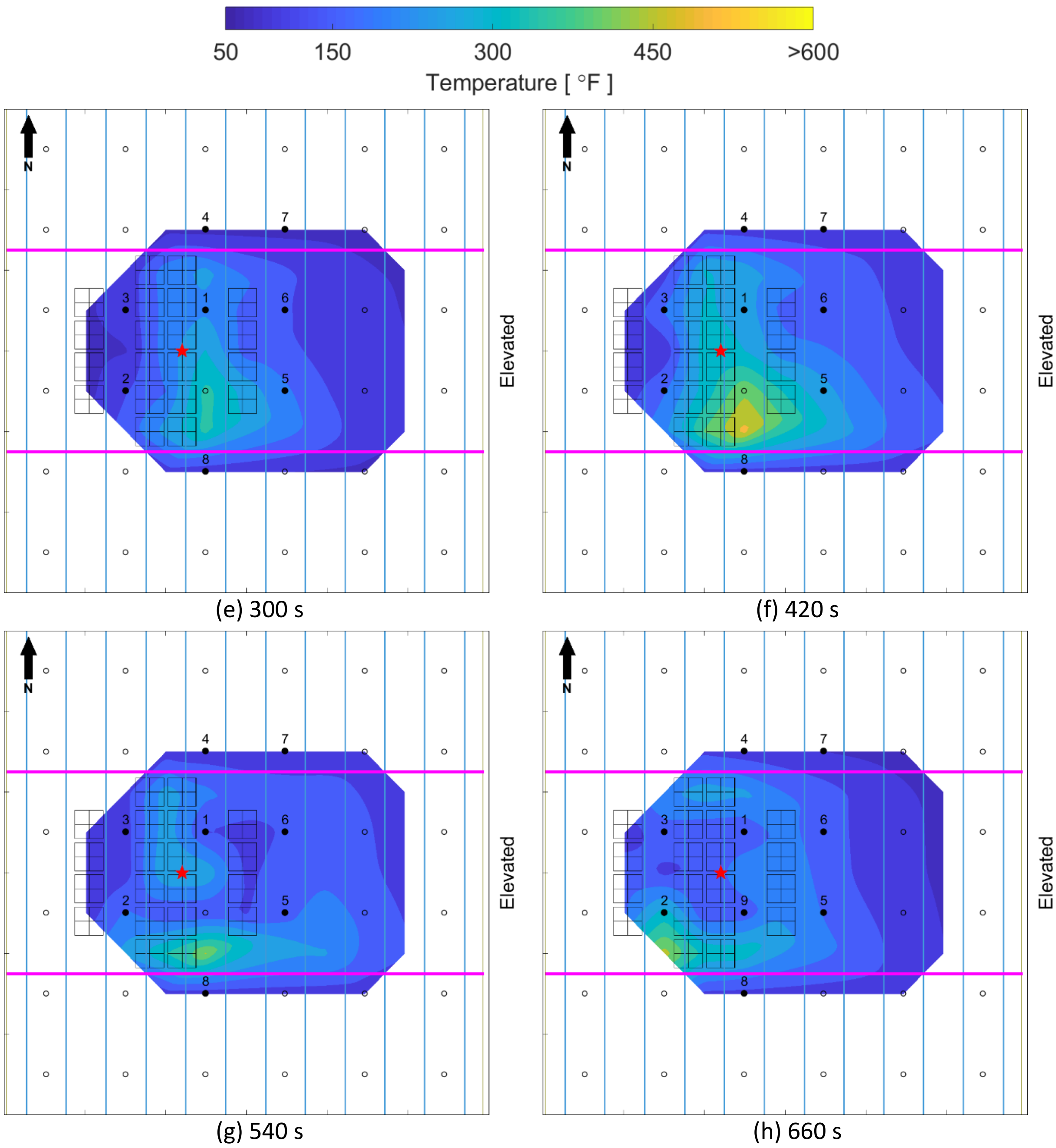
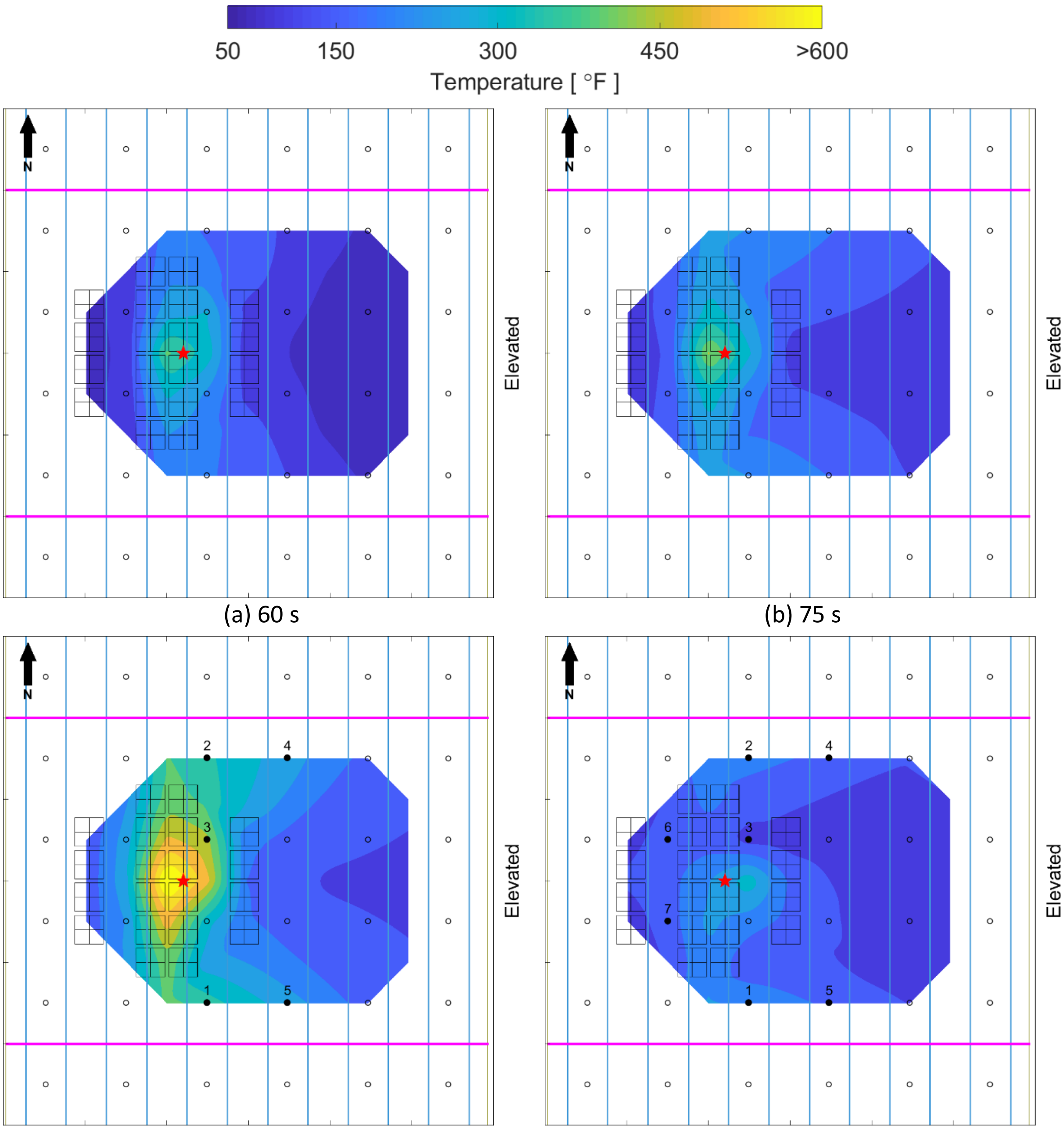


Figure C-5: Test #5 ceiling temperature contours shown from 60 s to 660 s.

C.6 Test #6



(a) 60 s (b) 75 s (c) 90 s (d) 105 s

Figure continues on following page

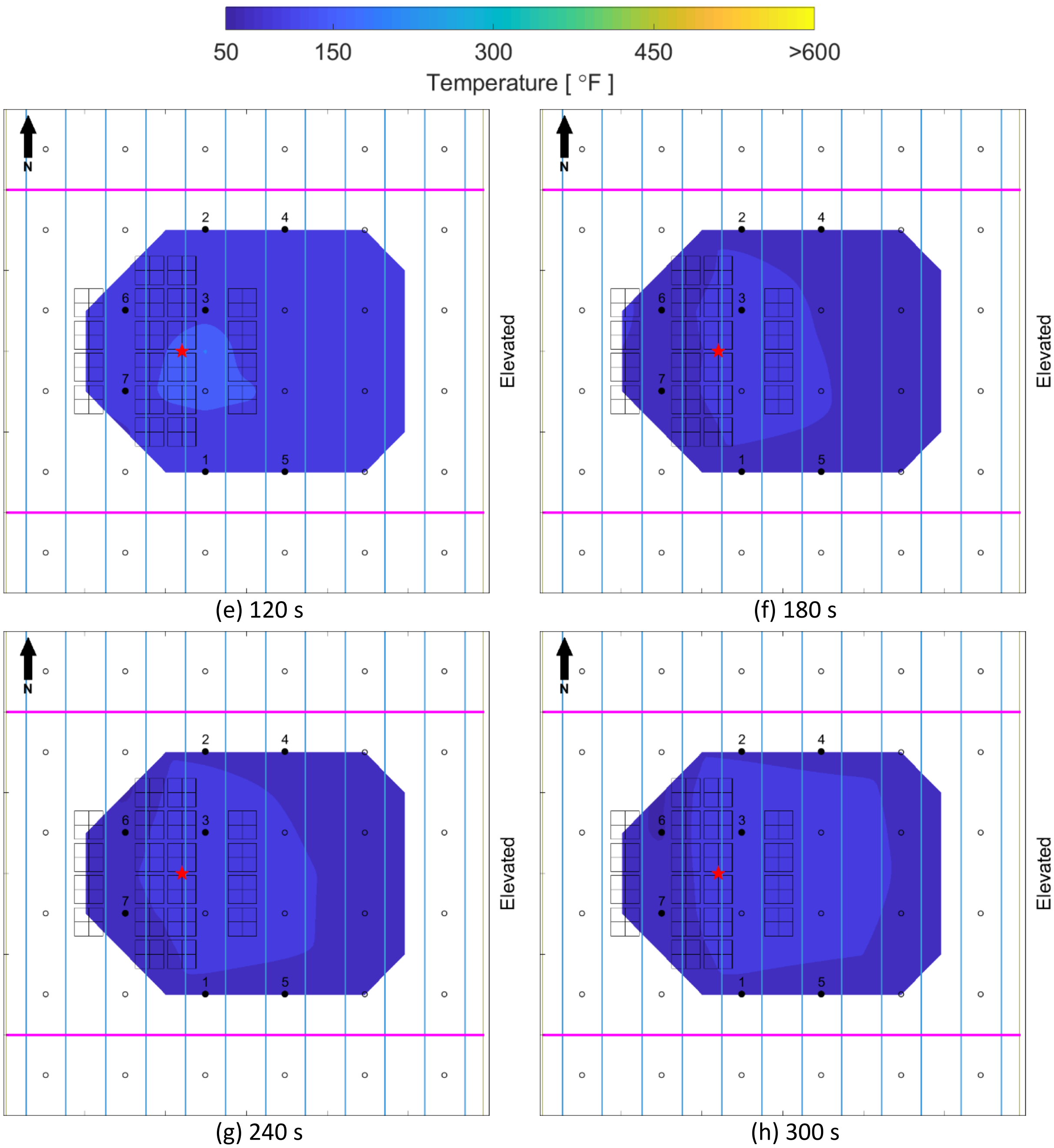
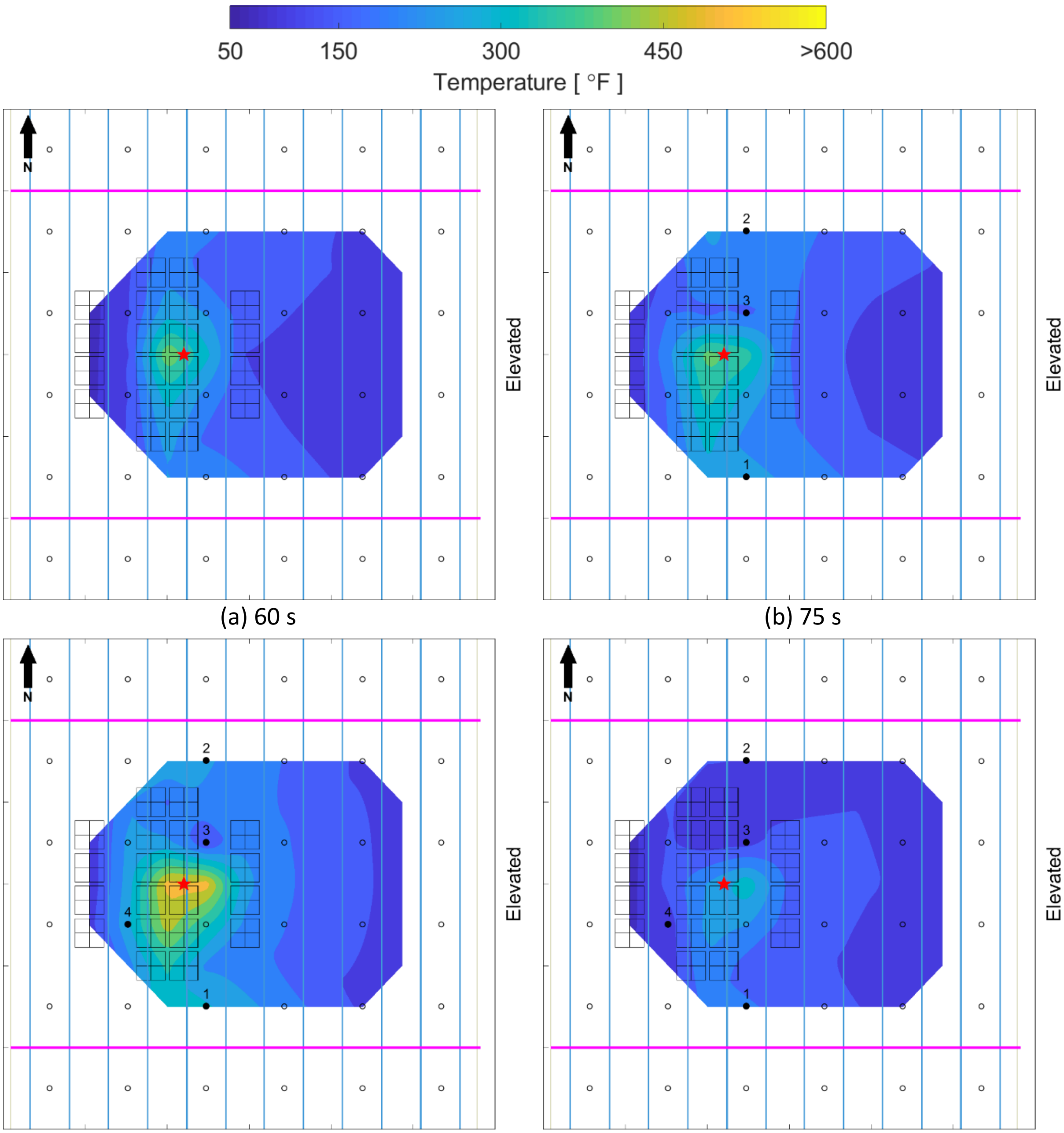


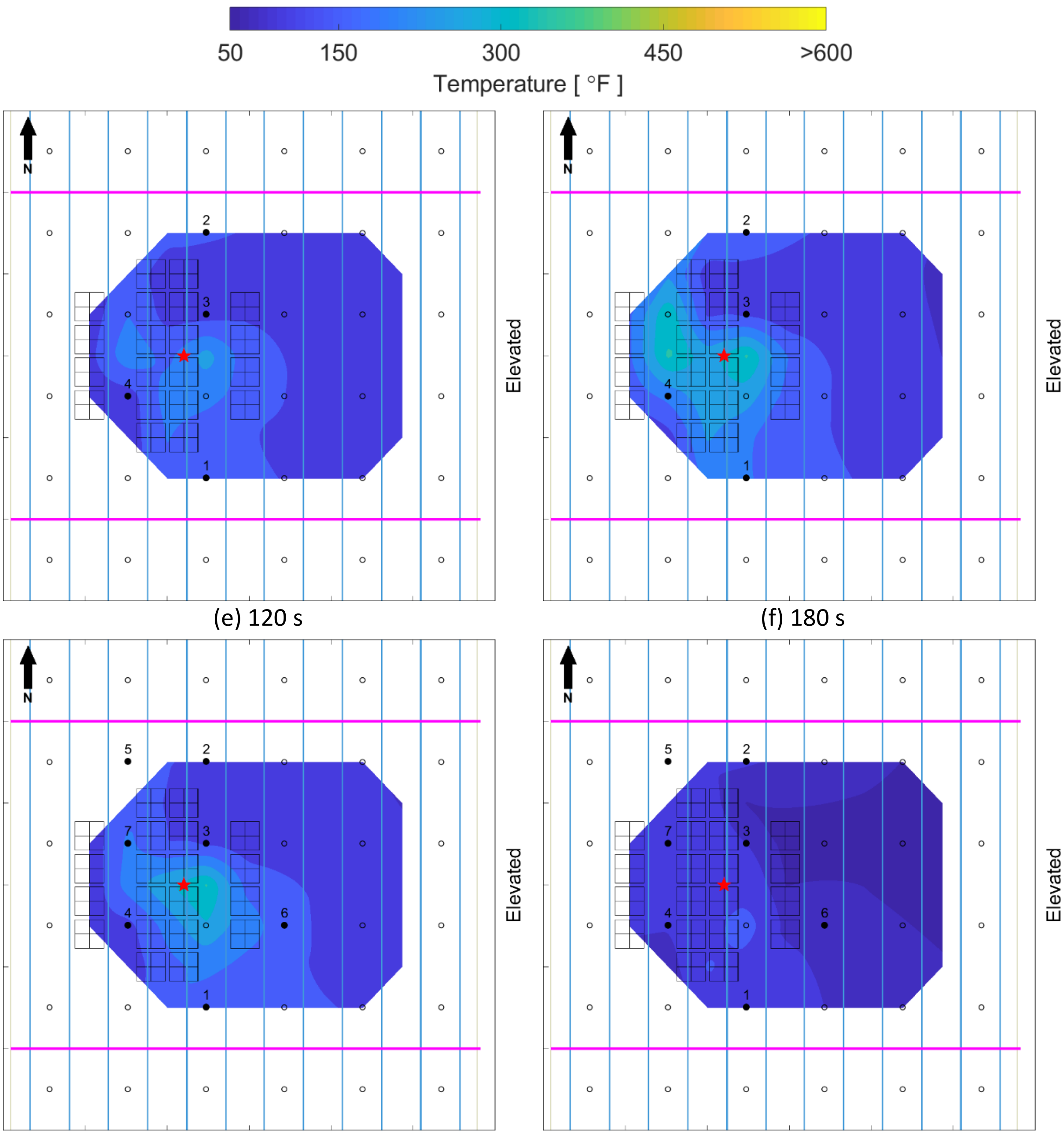
Figure C-6: Test #6 ceiling temperature contours shown from 60 s to 300 s.

C.7 Test #7



(a) 60 s (b) 75 s (c) 90 s (d) 105 s

Figure continues on following page



(e) 120 s

(f) 180 s

(g) 240 s

(h) 300 s

Figure C-7: Test #7 ceiling temperature contours shown from 60 s to 300 s.

Appendix D. Ceiling Level Velocities

Ceiling level gas velocities were measured using bi-directional probes placed parallel to the ceiling slope for Tests #2-7 to compare the ceiling jet flow in the central purlin channel with the upslope and downslope velocities. The locations and orientations of the probes are shown in Figure D-1. In the subsequent figures, positive velocities correspond to flow going outward from the plume impingement region (which is above the ignition location), i.e., 1) for the downslope probe, positive velocity means the flow is moving toward the downslope (westbound), 2) for the purlin channel probe located on the north side, flow is moving from south to north, and 3) for the upslope probe, positive velocity means the flow is in the upslope direction (eastbound).

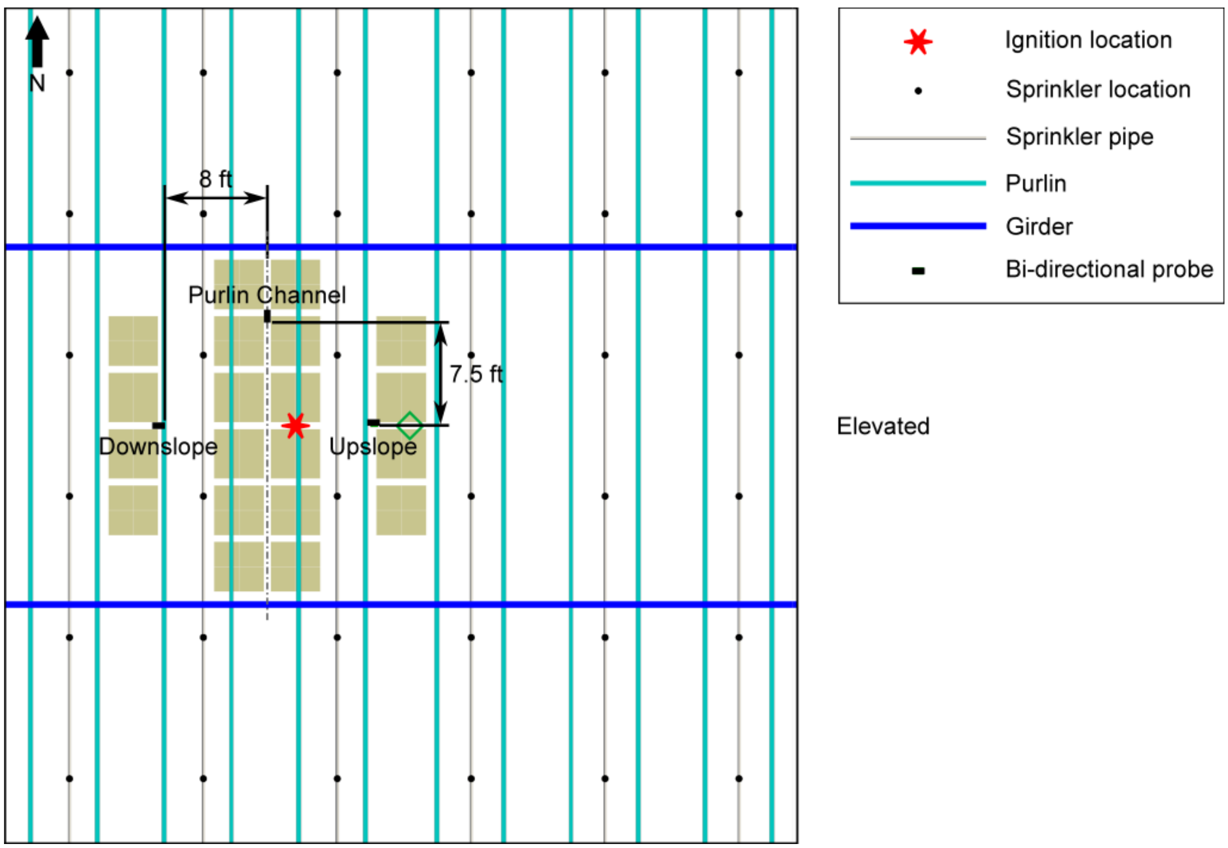


Figure D-1: Locations of three bi-directional probes under the ceiling. The green diamond is the mid-point of the ceiling.

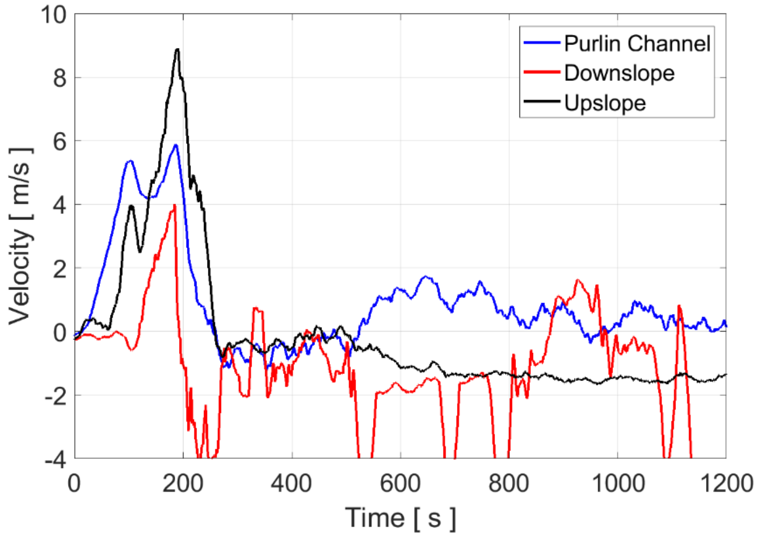


Figure D-2: Velocity measurements for Test #2.

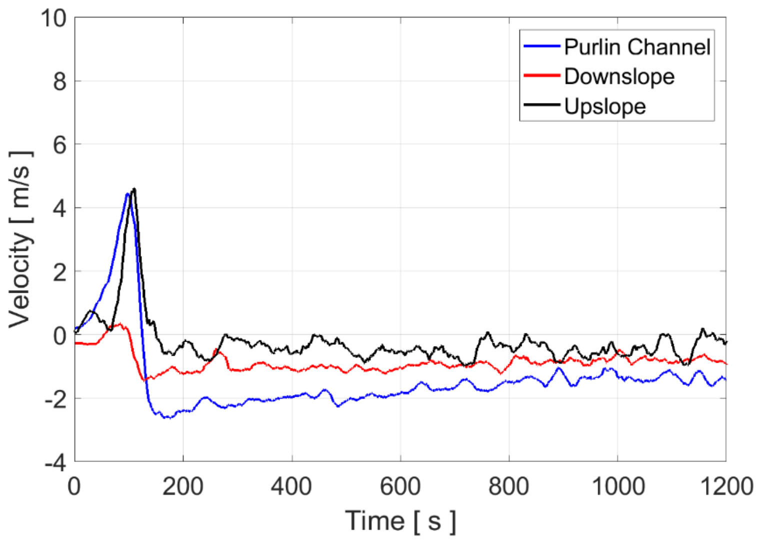


Figure D-3: Velocity measurements for Test #3.

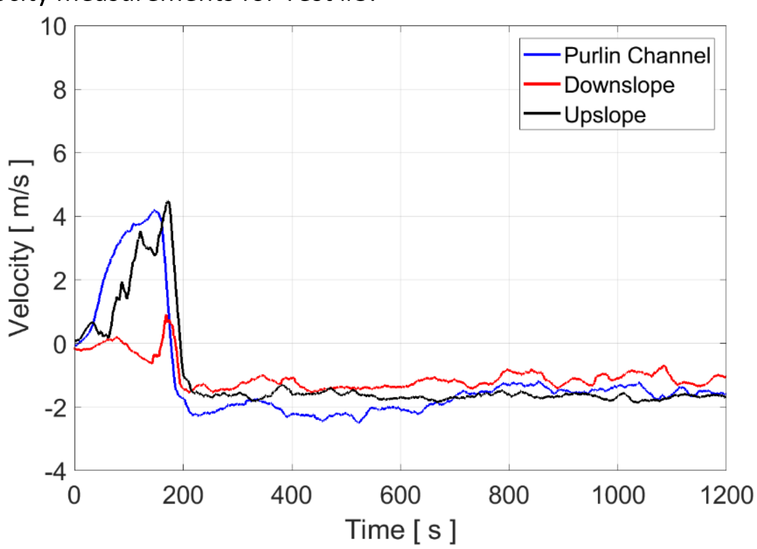


Figure D-4: Velocity measurements for Test #4.

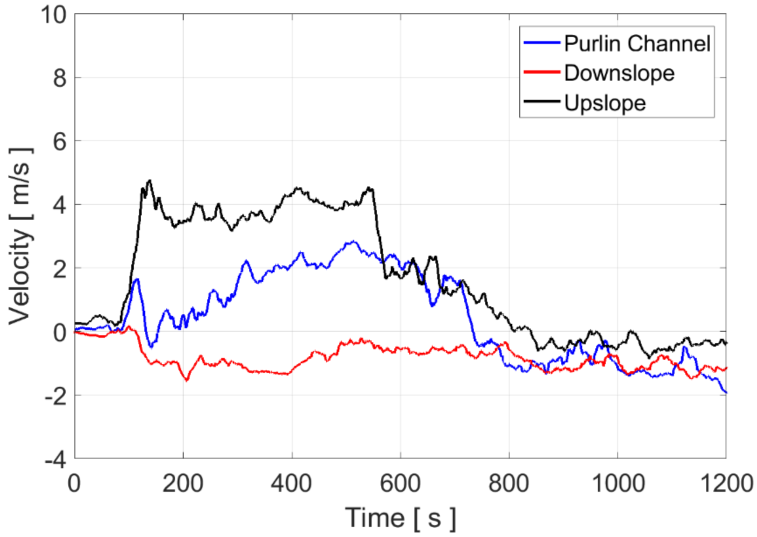


Figure D-5: Velocity measurements for Test #5.

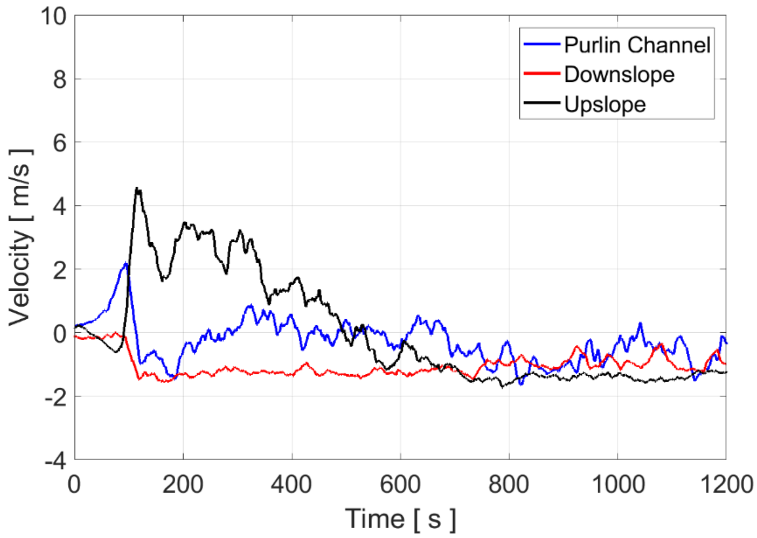


Figure D-6: Velocity measurements for Test #6.

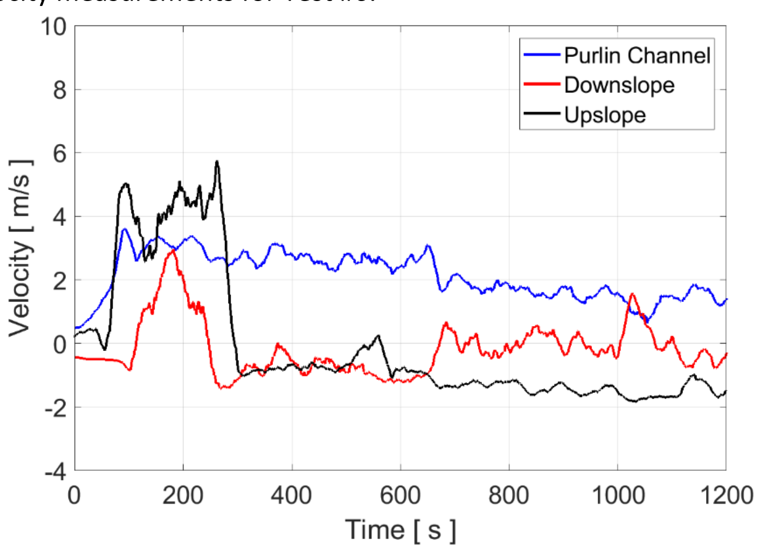


Figure D-7: Velocity measurements for Test #7.

Appendix E. Selected Test Photographs

E.1 Baseline Test

Figure E-1: Baseline test array at 1 min after ignition.

Figure E-2: Baseline test array at 1 min 20 s after ignition.

Figure E-3: Baseline test array at 1 min 30 s after ignition.

Figure E-4: Baseline test array at 1 min 40 s after ignition.

Figure E-5: Baseline post-test photograph of the east face of the main array showing fire damage.

E.2 Test #1

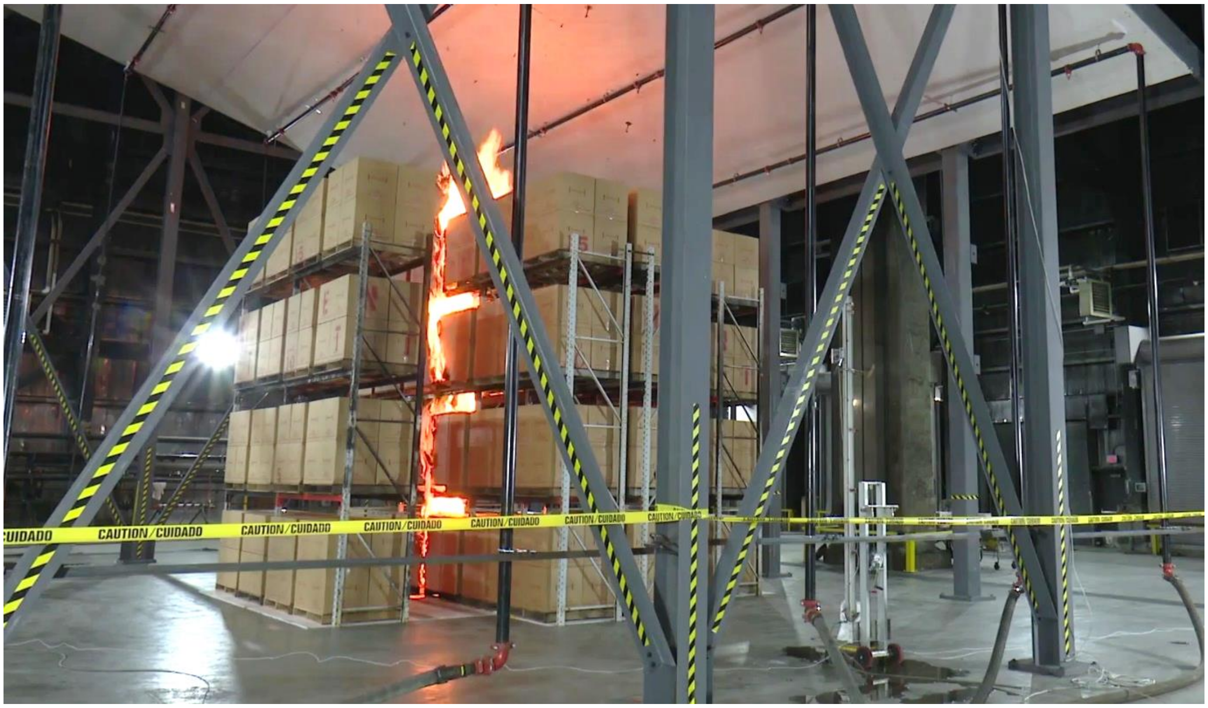


Figure E-6: Test #1 array at 1 min after ignition.

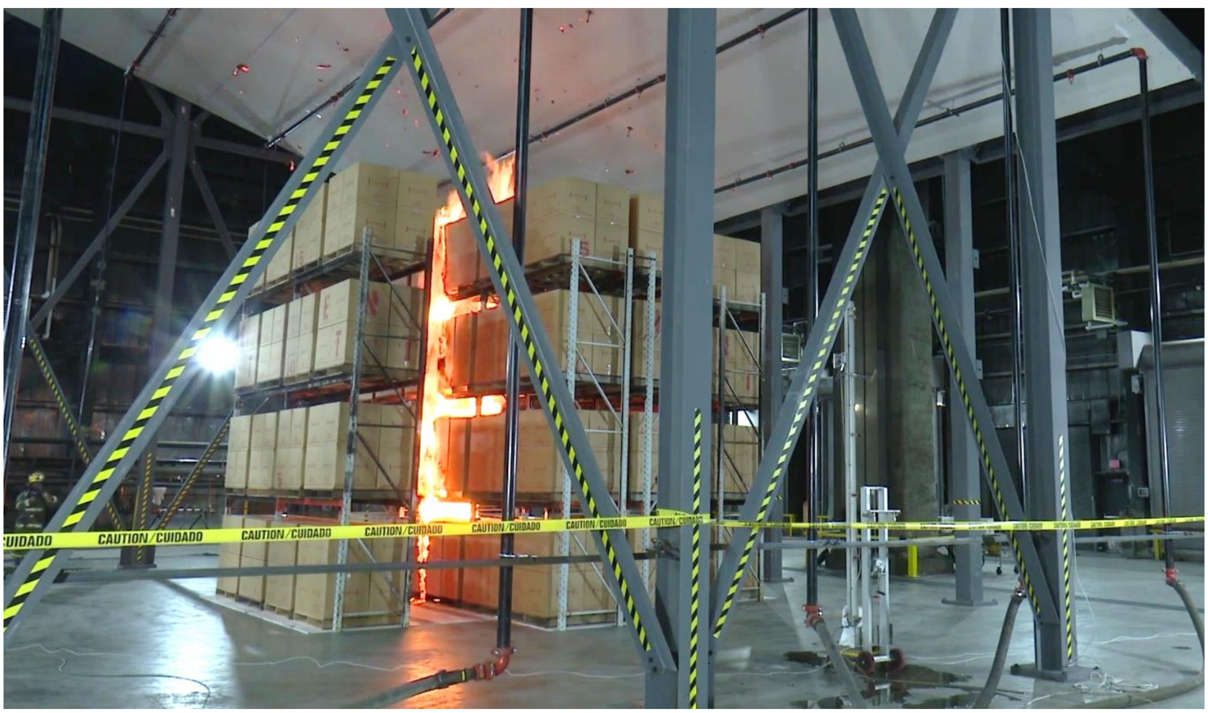


Figure E-7: Test #1 array at 1 min 15 s after ignition.

Figure E-8: Test #1 array at 1 min 30 s after ignition.

Figure E-9: Test #1 array at 1 min 45 s after ignition.

Figure E-10: Test #1 array at 2 min after ignition.

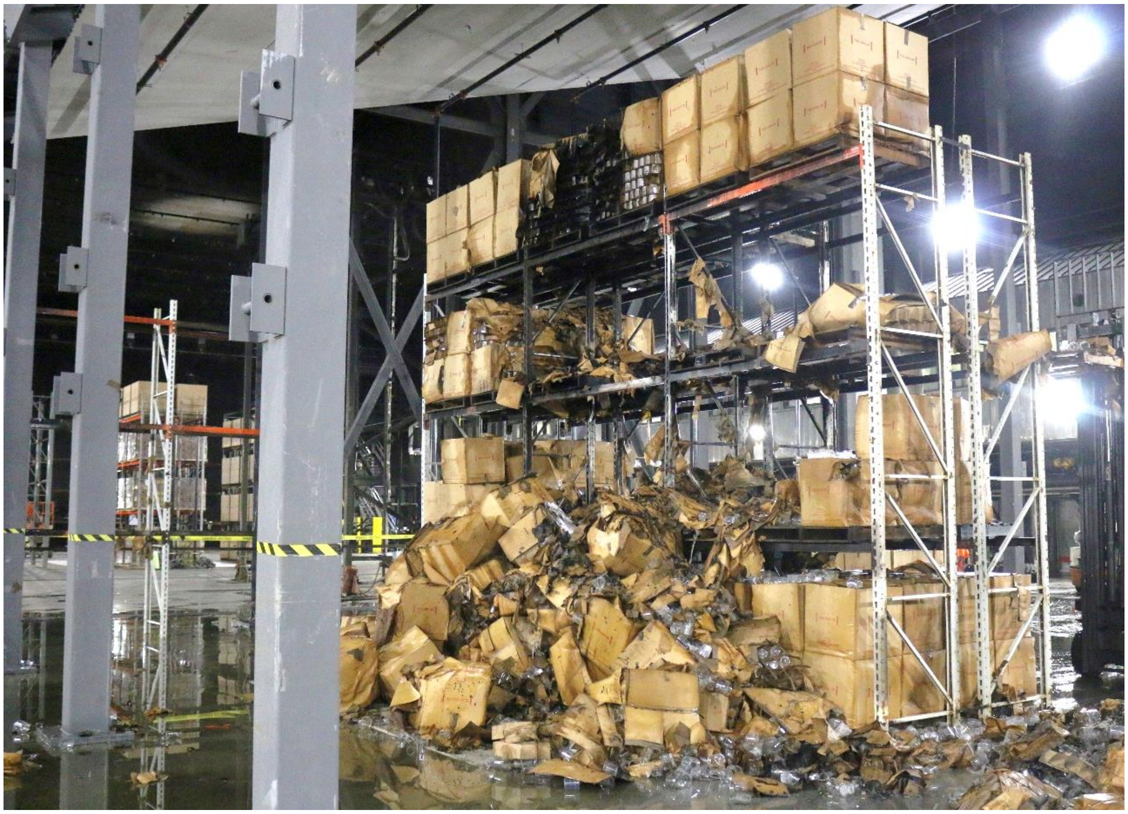


Figure E-11: Test #1 post-test photograph of the west face of the main array showing fire damage. Most of the boxes (incl. undamaged ones) were removed for firefighting convenience.

E.3 Test #2

Figure E-12: Test #2 array at 1 min after ignition.

Figure E-13: Test #2 array at 1 min 15 s after ignition.

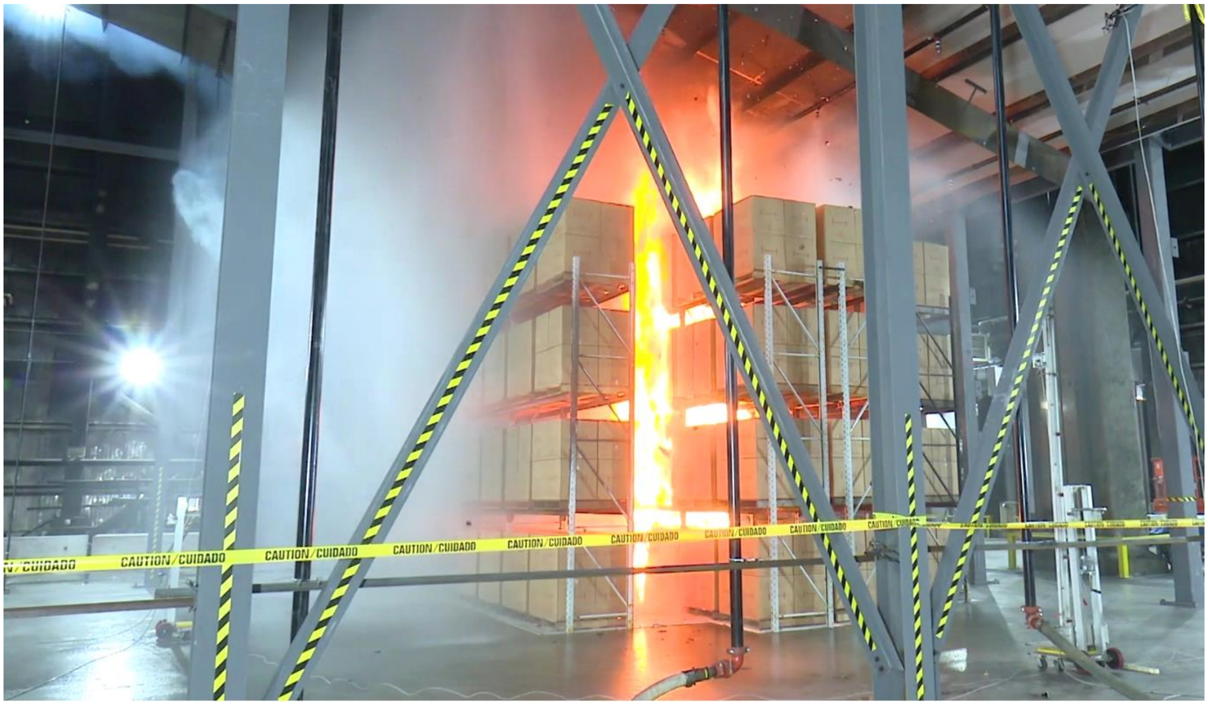


Figure E-14: Test #2 array at 1 min 30 s after ignition.

Figure E-15: Test #2 array at 1 min 45 s after ignition.

Figure E-16: Test #2 post-test photograph of the east face of the main array showing fire damage.

E.4 Test #3

Figure E-17: Test #3 array at 1 min after ignition.

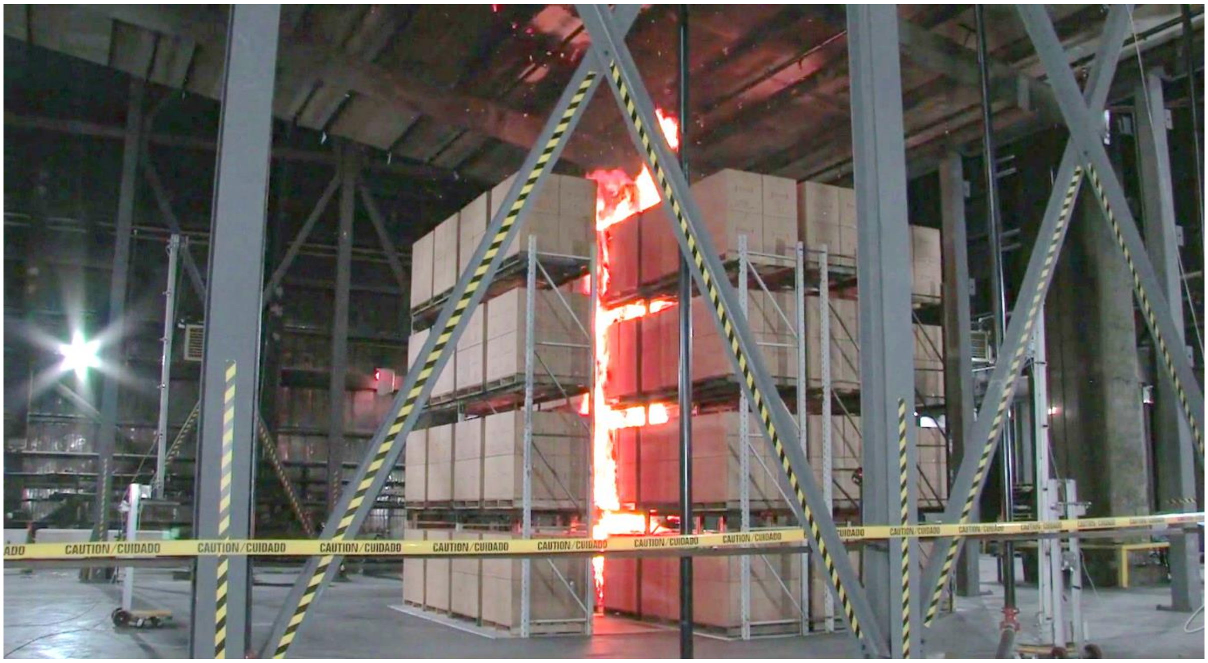


Figure E-18: Test #3 array at 1 min 15 s after ignition.

Figure E-19: Test #3 array at 1 min 30 s after ignition.

Figure E-20: Test #3 array at 1 min 45 s after ignition.

Figure E-21: Test #3 post-test close-up photograph of the east face of the main array showing fire damage.

E.5 Test #4

Figure E-22: Test #4 array at 1 min after ignition.

Figure E-23: Test #4 array at 1 min 15 s after ignition.

Figure E-24: Test #4 array at 1 min 30 s after ignition.

Figure E-25: Test #4 array at 1 min 45 s after ignition.

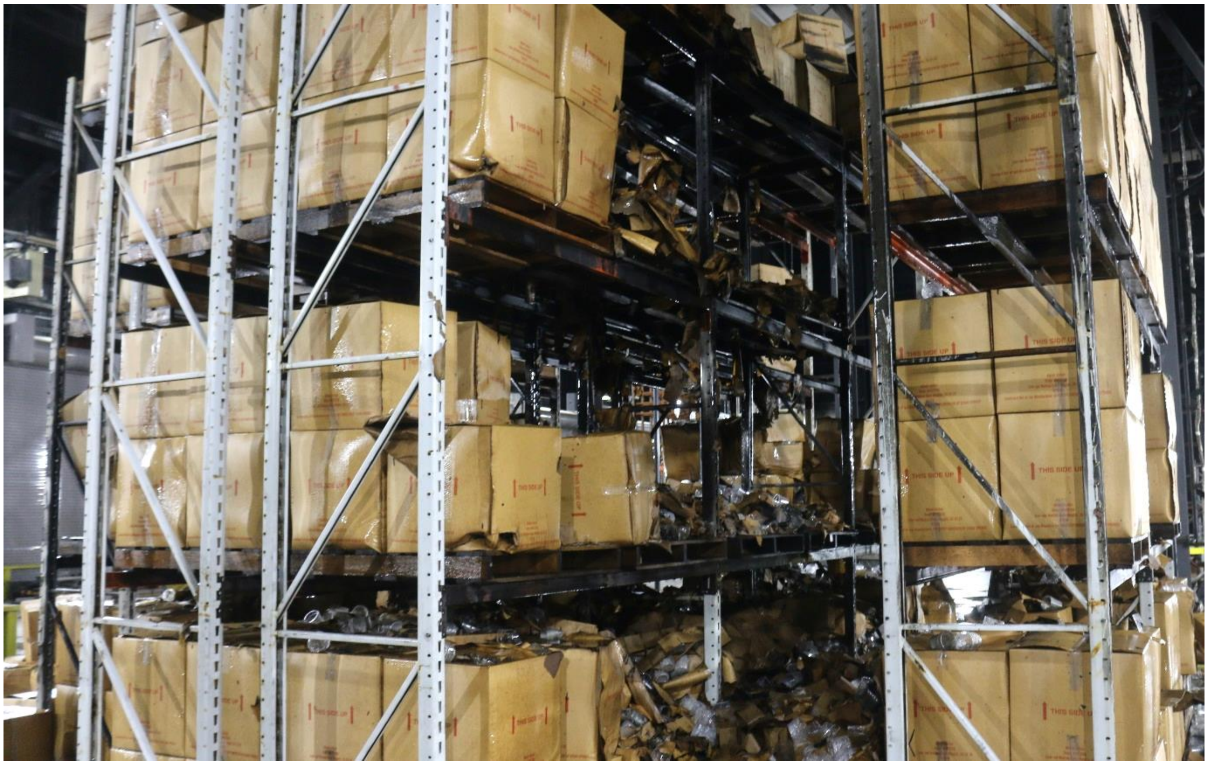


Figure E-26: Test #4 post-test close-up photograph of the east face of the main array showing fire damage.

E.6 Test #5

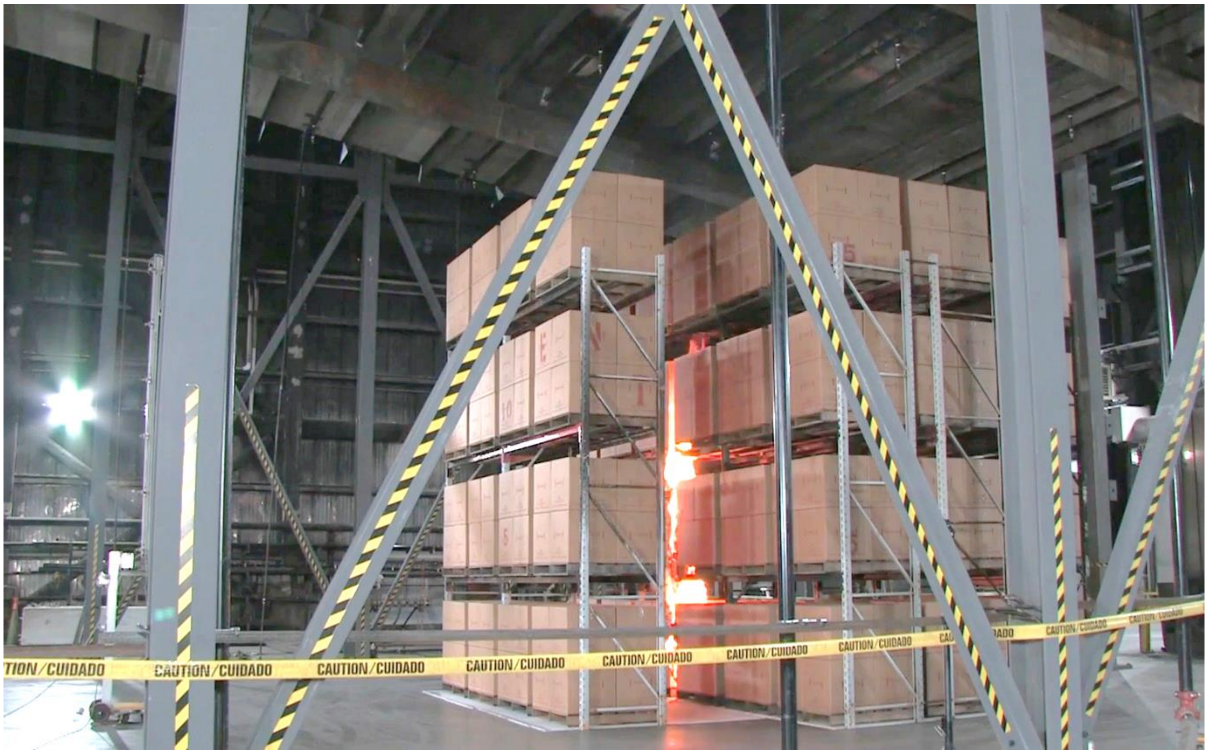


Figure E-27: Test #5 array at 1 min after ignition.

Figure E-28: Test #5 array at 1 min 15 s after ignition.

Figure E-29: Test #5 array at 1 min 30 s after ignition.

Figure E-30: Test #5 array at 1 min 45 s after ignition.

Figure E-31: Test #5 post-test photograph of the east face of the main array showing fire damage.

E.7 Test #6

Figure E-32: Test #6 array at 1 min after ignition.

Figure E-33: Test #6 array at 1 min 15 s after ignition.

Figure E-34: Test #6 array at 1 min 30 s after ignition.

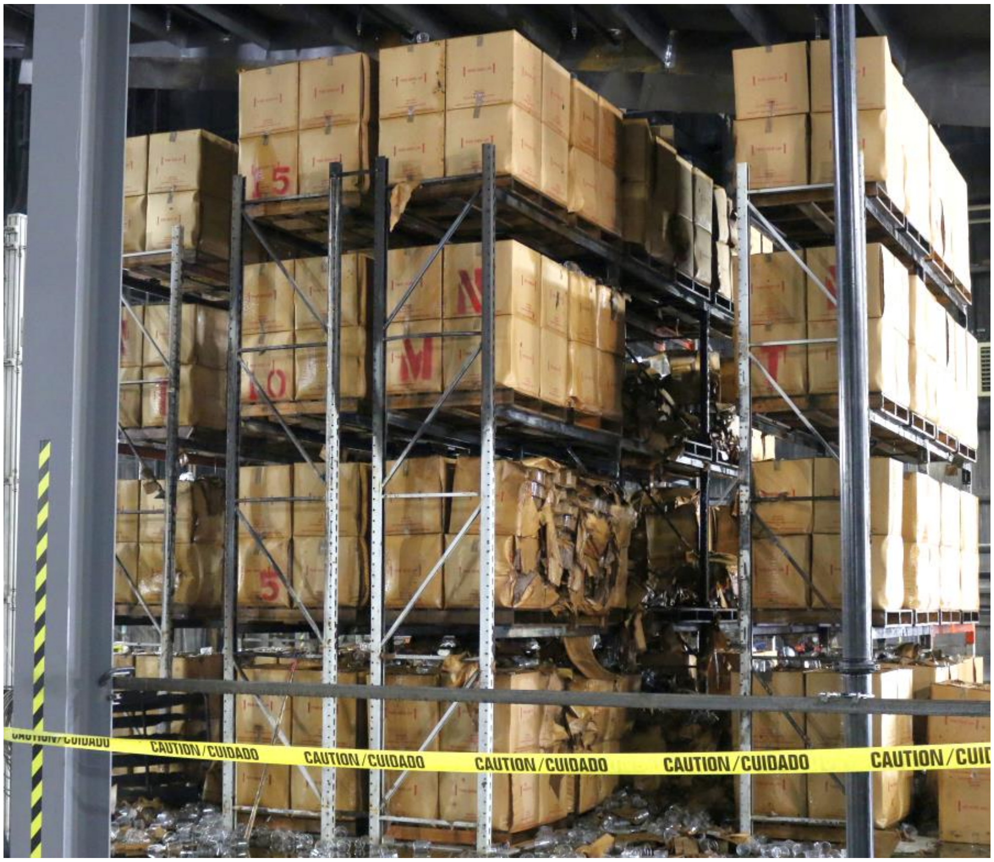


Figure E-35: Test #6 post-test photograph of the east face of the main array showing fire damage.

E.8 Test #7

Figure E-36: Test #7 array at 1 min after ignition.

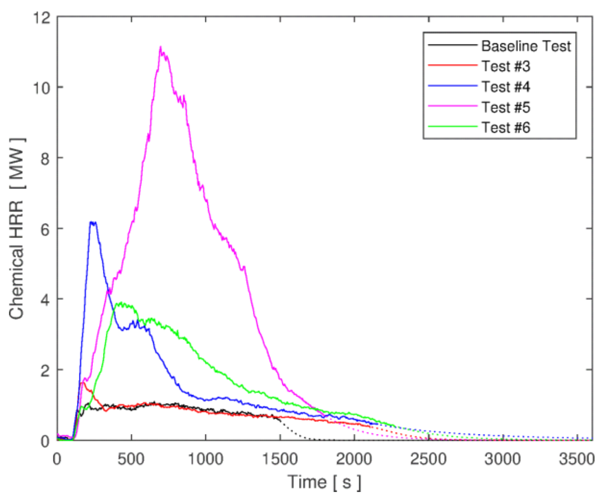
Figure E-37: Test #7 array at 1 min 15 s after ignition.

Figure E-38: Test #7 array at 1 min 30 s after ignition.

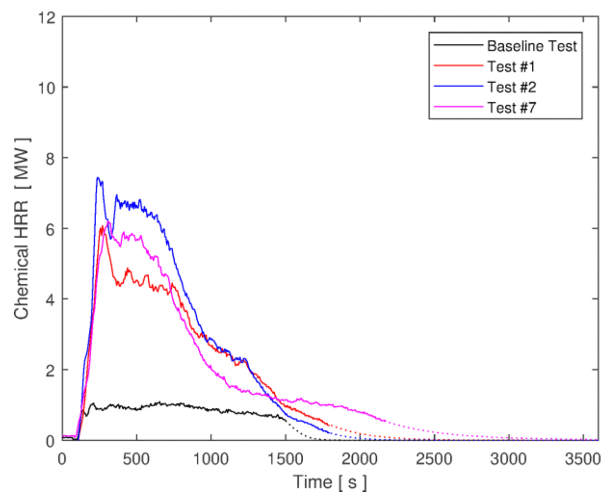
Figure E-39: Test #7 post-test close-up photograph of the east face of the main array showing fire damage.

Appendix F. Total Energy and Combustible Consumption

Fuel consumption in the eight tests conducted, the baseline and seven sloped ceiling tests, is estimated from the total energy released. The total energy released is calculated by integrating the chemical heat release rate (HRR) curve recorded during the tests. The mass flow rate and gas analysis of CO and CO_2 along with their heats of formation recorded by calorimetry instrumentation are used to estimate the chemical HRR. It should be noted that the recordings are made at a faraway location from the ceiling and therefore include the effect of smear and delay in the HRR estimations. Accurate HRR estimation as a function of time is, therefore, not possible. However, integration of the chemical HRR curves provides good estimates of the overall chemical energy released. At the end of the data recording period, if the chemical HRR had not decayed to zero, the curves were extrapolated using a logistic power function fit (HRR_{extrap} = a/[1+(time/b)^c], where a, b and c are constants) to provide data for the decay period. The uncertainty of the total energy released has been estimated to be 10% of the recorded data plus 50% of that contributed by the extrapolated decay period. Figure F-1 shows the recorded (solid curves) and extrapolated (dotted curves) chemical HRR for the eight tests. As can be seen, the extrapolated portion of the curves contributed little to the total energy calculated during the time covered by the recorded data.



(a) 10° tests



(b) 18° tests

Figure F-1: Chemical HRR measurements and extrapolations for (a) 10° inclination, and (b) 18° inclination tests.

Appendix G. Structural Steel Temperatures

In the sloped ceiling tests, structural steel temperatures were not measured using the steel angle which is fixed to the moveable ceilings in the Large Burn Laboratory (LBL) at the FM Global Research Campus. The steel temperatures were only measured for the baseline test, since it was carried out under that ceiling. For the sloped ceiling tests, steel temperatures are estimated using a lumped capacity heat transfer model. The steel cross-section depth (δ = 3.2 mm) was taken as the half-width of the steel angle used in the baseline test. One face of the steel was assumed to be exposed to fire conditions (i.e., the fire plume and ceiling jet), whereas the half-width location was assumed to have an adiabatic condition, thereby simulating the thermal response of a plate twice as thick and exposed to the same heat flux on both faces. A transient heat transfer equation was solved using the recorded gas-temperatures (T_g) under the ceiling:

$$\rho\, C_p \delta \frac{dT_s}{dt} = (h_c + h_r)\left(T_g - T_s\right). \quad (1)$$

Here, T_s is the steel temperature, ρ is the steel density (= 7850 kg/m^3), C_p is the steel specific heat capacity, h_c the convective heat transfer coefficient (= 25 kW/m^2), h_r is a radiative heat transfer coefficient estimated using the relation

$$h_r = \varepsilon\, \sigma \left(T_g^2 + T_s^2\right)\left(T_g + T_s\right), \quad (2)$$

where, ε is emissivity (= 1) and $\sigma = 5.67\times 10^{-8}$ W/m^2-K^4 is the Stefan-Boltzmann constant. The specific heat, C_p, is computed from temperature-dependent functions:

C_p (J/kg-K)	Temperature Range
$425 + 0.773T - 1.69\times10^{-3}T^2 + 2.22\times10^{-6}T^3$	$20^\circ C \le T < 600^\circ C$
$666 + 13002/(738 - T)$	$600^\circ C \le T < 735^\circ C$
$545 + 17820/(T - 731)$	$735^\circ C \le T < 900^\circ C$
650	$900^\circ C \le T < 1200^\circ C$

The baseline test steel temperatures were predicted and compared against the measured steel angle temperatures. The comparison is shown in Figure G-1 which shows the steel temperatures predicted using the gas temperatures measured at selected ceiling thermocouple locations (colored curves) with the measured temperatures at the steel angle, all within a 0.3 m (1 ft) radius from the center of the ceiling (dashed black curves). The peak measured steel angle temperature was approximately 118°F, whereas the model predicted a peak value of 117°F. The model was then applied to compute steel temperatures for the seven sloped ceiling tests.

Temperatures measured at several locations along the sloped ceiling structure are also reported below. Thermocouples were attached to the corrugated structure and flanges as shown in Figure G-2 to ensure that the integrity of the ceiling structure is maintained during the test. Figures G-3 to G-9 show the variation of the thermocouple temperatures for the seven sloped ceiling tests. These temperatures are not representative of steel structures that are attached to the bottom of warehouse ceilings but provide an estimation of temperatures encountered above the flat part of the ceiling.

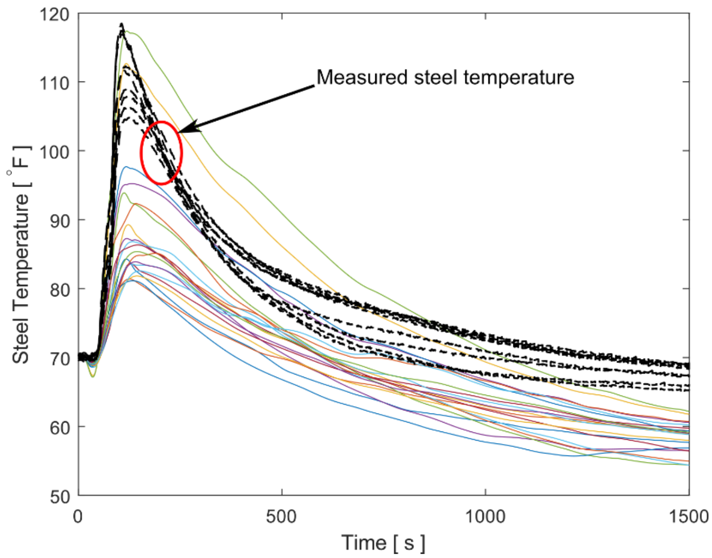


Figure G-1: Predicted steel temperatures (solid curves) compared with measured steel angle temperatures (dashed curves) for the baseline test.

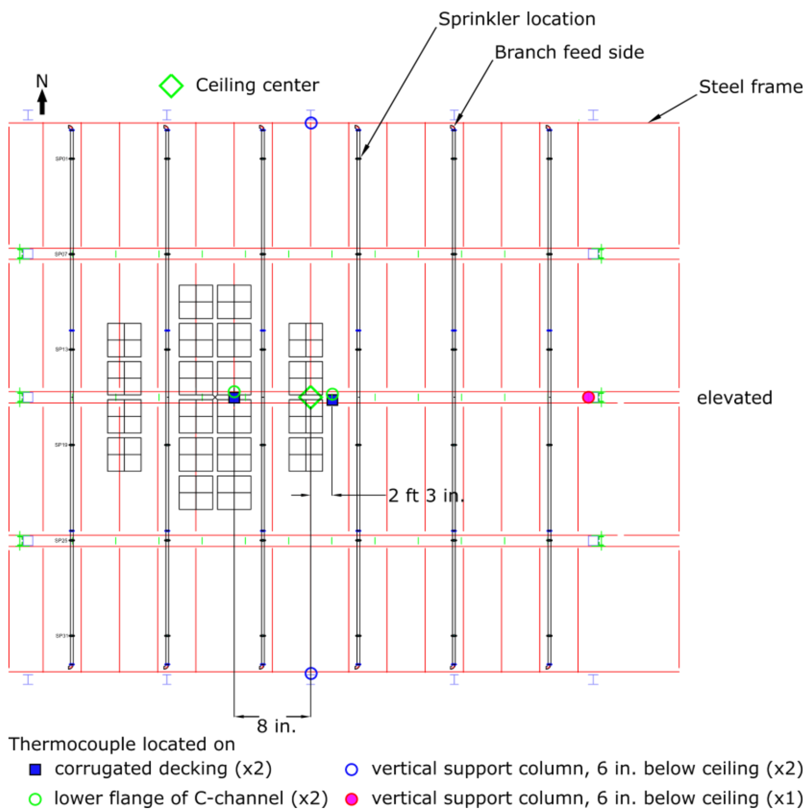


Figure G-2: Thermocouple locations above the flat part of the sloped ceiling. Temperatures were recorded during the sloped ceiling tests to ensure structural integrity was maintained.

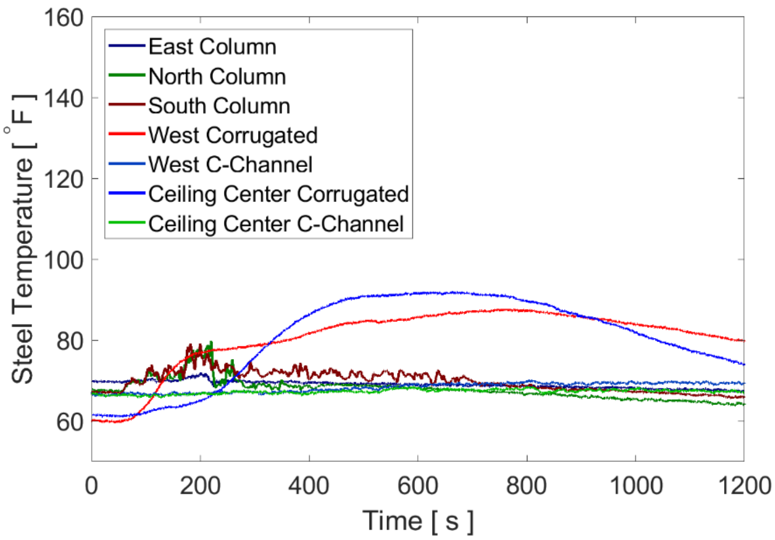


Figure G-3: Measured ceiling temperatures for Test #1.

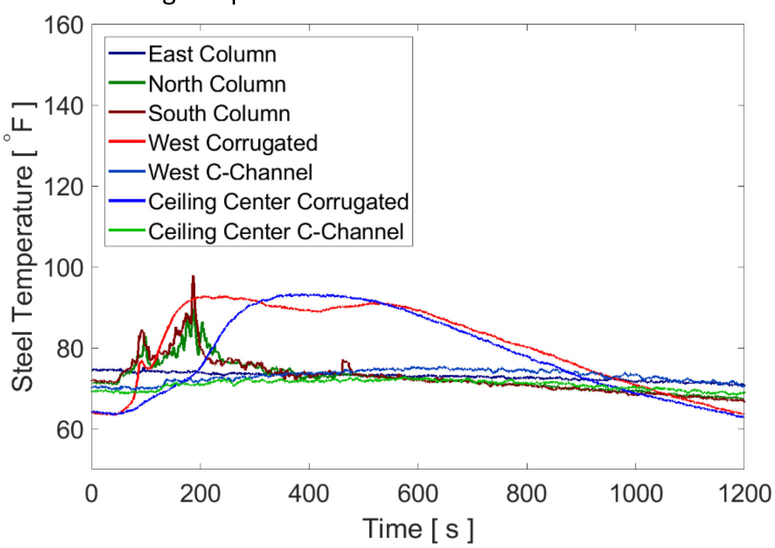


Figure G-4: Measured ceiling temperatures for Test #2.

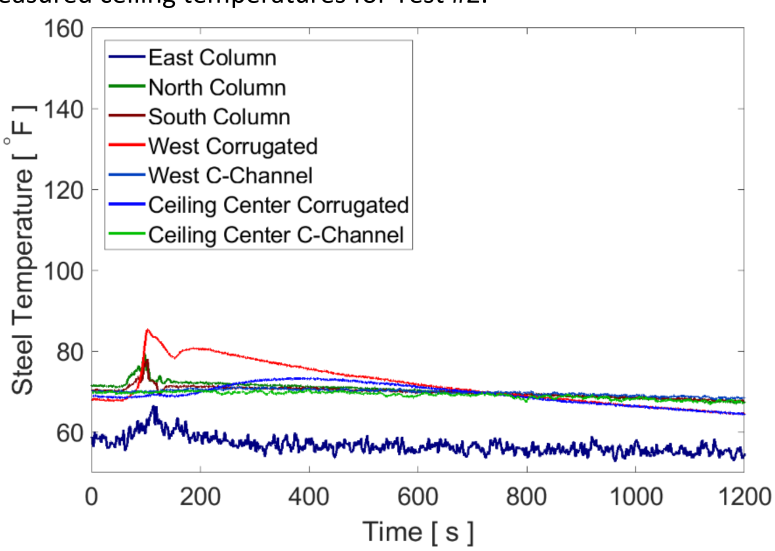


Figure G-5: Measured ceiling temperatures for Test #3.

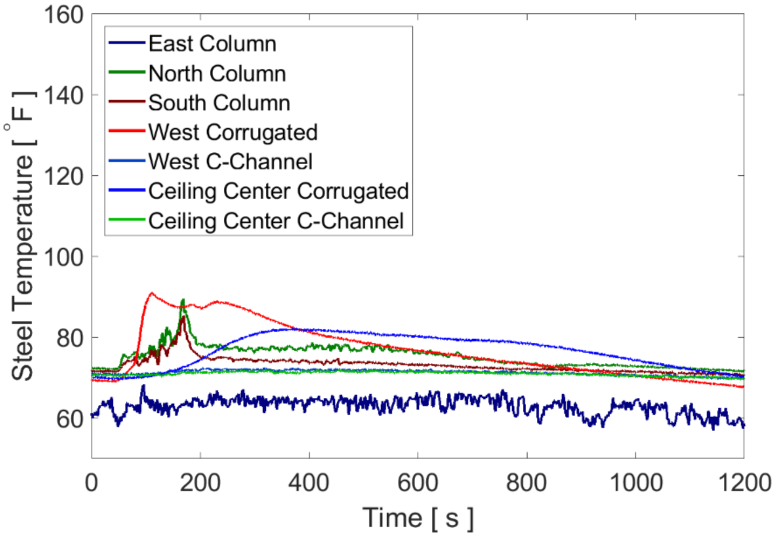


Figure G-6: Measured ceiling temperatures for Test #4.

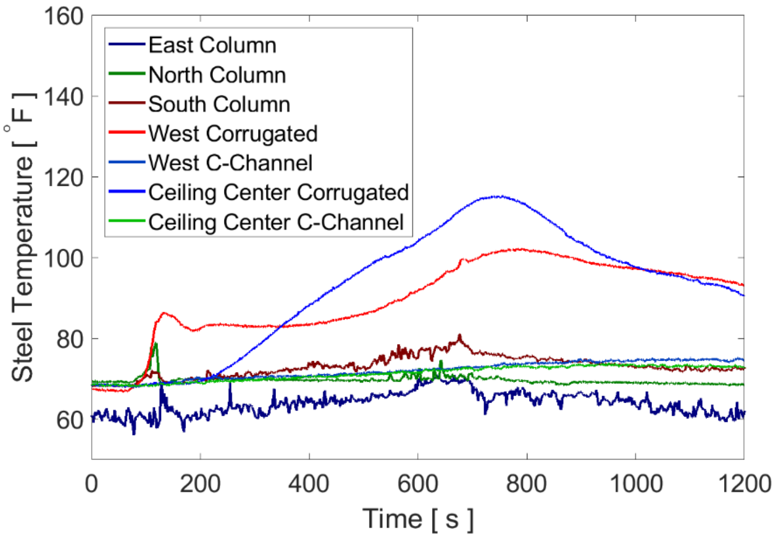


Figure G-7: Measured ceiling temperatures for Test #5.

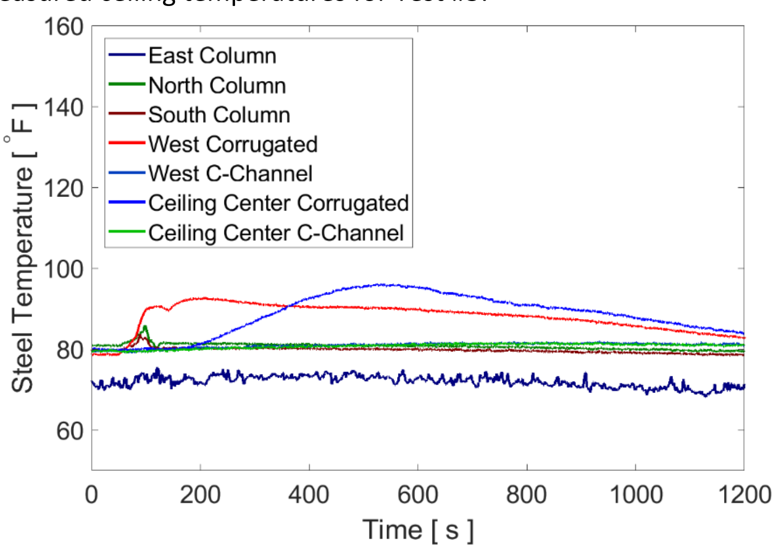


Figure G-8: Measured ceiling temperatures for Test #6.

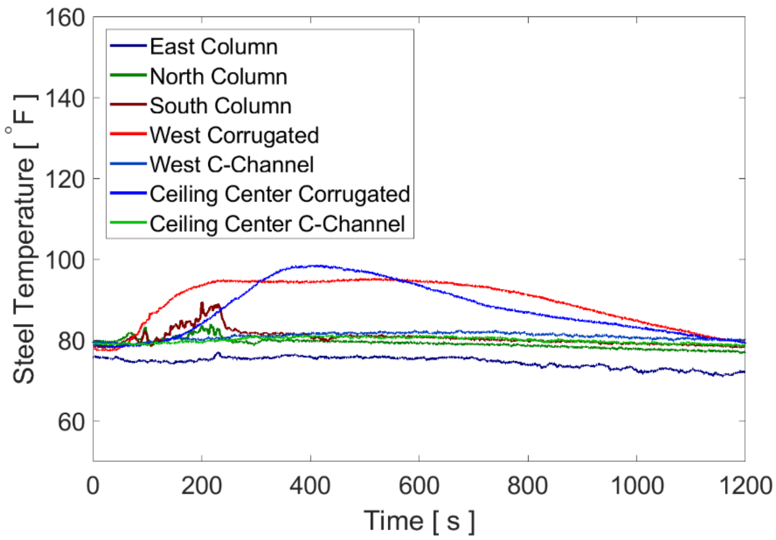


Figure G-9: Measured ceiling temperatures for Test #7.

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