TECHNICAL REPORT FOR NFPA 13

Large-Scale Validation of: (1) In-Rack Automatic Sprinkler Designs for Open-Frame Rack Storage Using Quick-Response, Pendent K200 lpm/bar$^{1/2}$ (K14.0 gpm/psi$^{1/2}$) and Larger Sprinklers, and (2) Protection of Uncartoned Unexpanded Plastics in Open-Frame Double-Row Racks Using Two Different In-Rack Sprinkler Protection Arrangements

FM Global

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For

NFPA 13 Standard for the Installation of Sprinkler Systems
Technical Committee on Sprinkler System Discharge Criteria

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1. Introduction

This report details large-scale fire test validation of (1) in-rack automatic sprinkler (IRAS) designs for open-frame rack storage using quick-response, pendent K200 lpm/bar$^{1/2}$ (K14.0 gpm/psi$^{1/2}$) [i.e., K200 (K14.0)] and larger sprinklers, and (2) protection of uncartoned unexpanded plastic in open-frame double-row racks using two different in-rack sprinkler protection arrangements. The purpose of this report is to provide support for proposed changes to the current guidelines of NFPA 13, Standard for the Installation of Sprinkler Systems, Edition 2016 (i.e., NFPA 13, Edition 2016).

NFPA 13, Edition 2016, recommends numerous IRAS configurations for the protection of rack storage. Questions have been raised concerning the guidance provided in this standard regarding in-rack sprinkler protection. Summarized, they are: (a) Can IRAS protection guidelines be updated to reduce both the number of required IRAS in a system and the total cost of that system, and (b) can the storage of uncartoned unexpanded plastics (UUP) in open-frame double-row racks be adequately protected by an IRAS arrangement that is void of face in-rack sprinklers as recommended in Figure 17.3.1.7 of NFPA 13, Edition 2016?

To answer part (a), a research project was created at FM Global to address this question. This project consisted of numerous intermediate-scale fire and water distribution tests coupled with CFD modeling of cold flow water transport over varying standard commodities, to establish the parameters for six large-scale fire tests that were conducted to validate the protection designs. The results of this research project have shown that quick-response, 70°C (160°F) nominally rated, pendent K200 (K14.0) and larger sprinklers can be used in IRAS designs to protect Class 1, 2, 3, 4 and plastic commodities in open-frame rack storage when the sprinklers are installed at maximum 9.1 m (30 ft) vertical increments. In addition, the results of this research project have shown that quick-response, 70°C (160°F) nominally rated, pendent K320 (K22.4) and larger sprinklers can be used in IRAS designs to protect Class 1, 2, 3, 4 and cartoned unexpanded plastic commodities in open-frame rack storage when the sprinklers are installed at maximum 12.2 m (40 ft) vertical increments. The guidelines offered in the Recommendations section of this report are intended to supplement the current guidelines in Chapter 21, Alternative Sprinkler System Designs for Chapters 12 Through 20, of NFPA 13, Edition 2016.

To answer part (b), another research project was created at FM Global. This project initially consisted of a full-scale fire test to determine if the in-rack sprinkler arrangement recommended in Figure 17.3.1.7 could provide an acceptable level of protection for the open-frame double-row rack storage of UUP. The results of Test 7 have shown that it could not. As a result, guidelines offered in the Recommendations section of this report indicate the scope of Section 17.3.1.7 and Figure 17.3.1.7 of NFPA 13, Edition 2016, should be modified to apply to only cartoned plastics and not to exposed, non-expanded Group A plastics.

Based on the unsuccessful results of Test 7, numerous intermediate-scale fire and water distribution tests coupled with CFD modeling were conducted to establish the parameters for Tests 8 and 9. The intent of Test 8 was to determine if the use of horizontal barriers in combination with the IRAS arrangement recommended in Figure 17.3.1.7 could provide acceptable fire control for the protection of UUP. The results of Test 8 were not favorable and thus are not addressed in this report. The intent of Test 9 was to determine whether an IRAS retrofit protection solution consisting of supplemental quick-response, 70°C (160°F) nominally rated, pendent K320 (K22.4) and larger face sprinklers installed at the 9.1 m (30 ft) tier level, on 2.4 m [8 ft] maximum horizontal spacing, a maximum 0.46 m (18 in.) from the face of the array and arranged to provide a minimum flow of 330 lpm (88 gpm) in combination with the in-rack arrangement indicated in Figure 17.3.1.7 could provide an acceptable level of protection for open-frame single- and double-row rack storage of UUP over 7.6 m (25 ft) high. The results of Test 9 are reflected in the Recommendations section of this report.

2. FM Global Test Facilities Information

2.1 Description of Research Campus/Laboratories

The tests for this program were conducted under the North movable ceiling in the Large Burn Laboratory (LBL) located in the Fire Technology Laboratory at the FM Global Research Campus in West Glocester, Rhode Island, USA. Figure 2.1-1 is a plan view of the large burn lab (LBL) showing the North movable ceiling, the South movable ceiling, and the 20-MW Calorimeter. The air emission control system (AECS) exhaust ducting for each movable ceiling consists of four extraction points, located at the lab ceiling, that merge into a single duct with a cross sectional area of 6.1 m2 (66 ft2). Gas concentration, velocity, temperature and moisture measurements are made downstream of the manifold. Beyond the measurement location, the exhaust duct connects to a wet electrostatic precipitator (WESP) prior to the gases venting to the atmosphere. The movable ceilings measure 24.4 m x 24.4 m (80 ft x 80 ft) and are adjustable for heights above the floor ranging from 3.1 m to 18.3 m (10 ft to 60 ft). All large scale tests are conducted at an exhaust rate of 94 m3/s (200,000 ft3/min). The lab is provided with an advanced humidity control system to ensure testing consistency. The system circulates up to 104,000 ft3/min (49 m3/s) of air and removes up to on ton (900 kg) of water per hour.

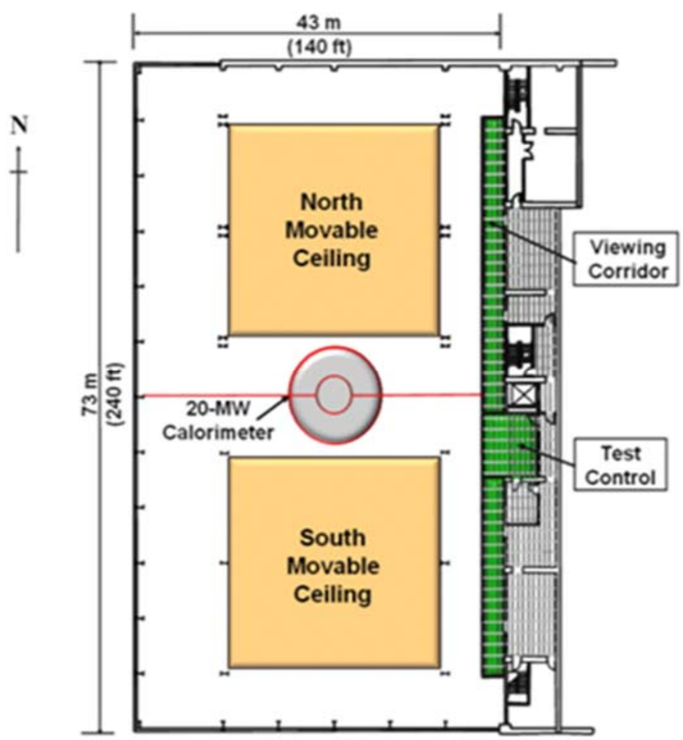


Figure 2.1-1: Illustration of FM Global Large Burn Laboratory test locations.

2.2 IRAS Sprinkler Designs Using Quick-Response, Pendent, K200 (K14.0) and Larger Sprinklers

2.2.1 Instrumentation

The following instrumentation was installed for each test:

- Each IRAS was monitored with a timing wire that signaled the activation of that specific sprinkler.
- Bare-bead, 0.8 mm (20 gage), Chromel-Alumel (Type-K) thermocouples, placed 165 mm (6.5 in.) below the ceiling. Thermocouples were located at the ceiling center as well as at numerous locations that radiated outward from the ceiling center to the perimeter of the 24.4 m x 24.4 m (80 ft x 80 ft) movable ceiling. The ceiling level thermocouples had RTI values controlled to 8.0±1.5 $(m\text{-}s)^{1/2}$ (14.5±2.7 $(ft\text{-}s)^{1/2}$).
- Thermocouples embedded in a steel angle at the ceiling center measured steel temperatures. The steel angle forms a cross with 90° angles; each leg of the cross is 0.6 m (2 ft) in length and 6.4 mm (0.25 in.) thick. There is one thermocouple at the center of the cross and eight more thermocouples located at 0.15 m (6 in.) intervals along the length of each leg.
- Bi-directional velocity probes at eight locations measured the near-ceiling gas velocity. These probes were located approximately 2.1 m (7 ft) and 4.0 m (13 ft) north, south, east, and west from the ceiling center.
- Gas analyzers that measured the carbon dioxide and carbon monoxide generation, oxygen depletion, and total hydrocarbon[1] emissions of the fire.
- A pressure transducer was installed at the downstream end of each of the either six (Tests 3, 4, and 5) or nine (Test 1, 2, and 6) independent branch lines that supplied the IRAS system.

Data collected from those instruments was recorded at a 10 Hz frequency. Data presented in the subsequent section is averaged to result in 1 Hz frequency.

2.2.2 Test Evaluation Criteria

Determination of a successful test was based on fire spread, the total number of IRAS activations and ceiling level gas temperature.

The extent of fire travel in a large-scale test can be used to assess the adequacy of sprinkler protection. Fire spread to the north or south end of the main array, or the back side of either target array, indicates an uncontrolled fire. Additionally, a new flame spread metric was used in this test series. Ignition of the commodity above the IRAS would signal failure of the IRAS protection scheme to operate in a modular fashion. Protection was deemed inadequate if any of these results occurred.

[1] The total hydrocarbon flame ionization detector (FID) analyzer was calibrated with methane gas.

The total number of sprinklers required to control a fire is an indication of the effectiveness of the protection scheme. An unreasonably high water demand for the IRAS system is indicative of an inadequate or inefficient system and is considered a failure.

In order to make a determination that the ceiling level sprinkler system can act independently from the IRAS system, the ceiling level gas temperatures must remain below the level that would cause sprinkler activation. Therefore, the protection is deemed inadequate if ceiling level gas temperatures reach a sufficient magnitude to cause ceiling level sprinkler activation.

2.2.3 Ignition

Ignition was achieved by means of one FM Global standard full ignitor. It was located at the base of the central 1st tier pallet load on the east face of the main array. When ceiling level sprinklers were present (i.e., Tests 1 and 2), ignition was offset 0.6 m (2 ft) between two ceiling sprinklers (i.e., 0.9 m [3 ft] west of the nearest ceiling sprinkler) and was equidistant from the two nearest IRAS. The ignition location is illustrated in Figure 3.1.2.1-1, Figure 3.1.2.1-3, Figure 3.1.2.1-5, and Figure 3.1.2.1-7 as the yellow/red colored starburst. A representative image of the ignitor placement is shown in Figure 2.2.3-1.

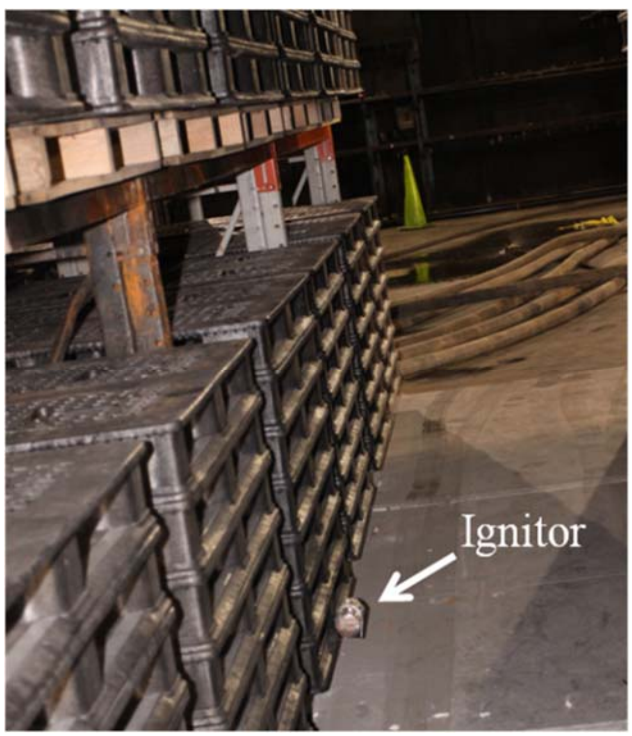


Figure 2.2.3-1: Ignition Location (Example of UUP Commodity).

2.3 Protection of Uncartoned Unexpanded Plastics in Open-Frame Double-Row Racks Using Two Different In-Rack Sprinkler Protection Arrangements

2.3.1 Instrumentation

For Test 7, the following instrumentation was installed:

- Ceiling level sprinklers at 56 locations on a 3.0 m x 3.0 m (10 ft x 10 ft) spacing, which resulted in sprinklers located 1.5 m (5 ft) east and west of ceiling center. Each sprinkler was monitored with a timing wire that signaled the activation of that specific sprinkler.
- Each IRAS was monitored with a timing wire that signaled the activation of that specific sprinkler.
- Bare-bead, 0.8 mm (20 gage), Chromel-Alumel (Type-K) thermocouples, placed 165 mm (6.5 in.) below the ceiling. Thermocouples were located at the ceiling center as well as at numerous locations that radiated outward from the ceiling center to the perimeter of the 24.4 m x 24.4 m (80 ft x 80 ft) movable ceiling. The ceiling level thermocouples had RTI values controlled to 8.0 ± 1.5 $(m\text{-}s)^{1/2}$ (14.5 ± 2.7 $(ft\text{-}s)^{1/2}$).
- Thermocouples embedded in a steel angle at the ceiling center measured steel temperatures. The steel angle forms a cross with 90° angles; each leg of the cross is 0.6 m (2 ft) in length and 6.4 mm (0.25 in.) thick. There is one thermocouple at the center of the cross and eight more thermocouples located at 0.15 m (6 in.) intervals along the length of each leg.
- Bi-directional velocity probes at eight locations measured the near-ceiling gas velocity. These probes were located approximately 2.1 m (7 ft) and 4.0 m (13 ft) north, south, east, and west from the ceiling center.
- A pressure transducer installed at the midpoint of the central branch line to monitor the required ceiling level sprinkler system pressure.
- Gas analyzers that measured the carbon dioxide and carbon monoxide generation, oxygen depletion, and total hydrocarbon emissions[2] of the fire.
- Pressure transducer installed at the downstream end of each independent branch line that supplied the in-rack system (twelve in Test 7 and ten in Test 9).

Data collected from those instruments was recorded at a 10 Hz frequency. Data presented herein is averaged to create a 1 Hz frequency.

Test 9 used the same instrumentation indicated for Test 7, however ceiling sprinklers were not provided.

[2] The total hydrocarbon flame ionization detector (FID) analyzer was calibrated with methane gas.

2.3.2 Test Evaluation Criteria

Determination of a successful test was based on fire spread, the total number and location of IRAS and ceiling level sprinklers, and near ceiling gas and steel temperatures.

The extent of fire travel in a large-scale test can be used to assess the adequacy of sprinkler protection. Fire spread to the north or south end of the main array, or the back side of either target array indicates an uncontrolled fire. Protection is deemed inadequate if this result occurs.

Ceiling level gas and steel temperatures, which are monitored throughout the test, help assess the effectiveness of the sprinkler system to 1) provide cooling to the ceiling layer and 2) reduce the possibility of thermally induced degradation of structural steel roof supports. Persistent elevated ceiling level temperatures are indicative of lack of fire control. Actual or calculated steel temperatures near ceiling level that reach 538℃ (1000℉) indicate that structural steel would have lost approximately 50% of its load bearing capacity and a possibility of roof collapse. Protection is deemed inadequate if this temperature threshold is exceeded.

The total number of sprinklers required to control a fire is also an indication of the effectiveness of the protection scheme. An unreasonably high water demand for the in-rack sprinkler system, ceiling level sprinkler system or the combination thereof is indicative of an inadequate or inefficient system. Additionally, ceiling level sprinklers that activate along the perimeter of the ceiling make it difficult to assess the total number of sprinklers activations that may have occurred had additional sprinklers been installed. Therefore, perimeter activations are unacceptable and their occurrence indicates an inadequate protection scheme.

2.3.3 Ignition

Ignition was achieved by means of one FM Global standard full ignitor. It was located at the base of the central 1st tier pallet load on the east face of the main array. For Test 7, when ceiling level sprinklers were present, ignition was offset 0.6 m (2 ft) between two ceiling sprinklers (i.e., 0.9 m [3 ft] west of the nearest ceiling sprinkler) and was equidistant from the two nearest IRAS. The ignition location relative to the IRAS and ceiling level sprinklers for Test 7 is illustrated as a yellow/red colored starburst in Figure 2.3.3-1. A representative picture of the ignitor prior to ignition is shown in Figure 2.2.3-1.

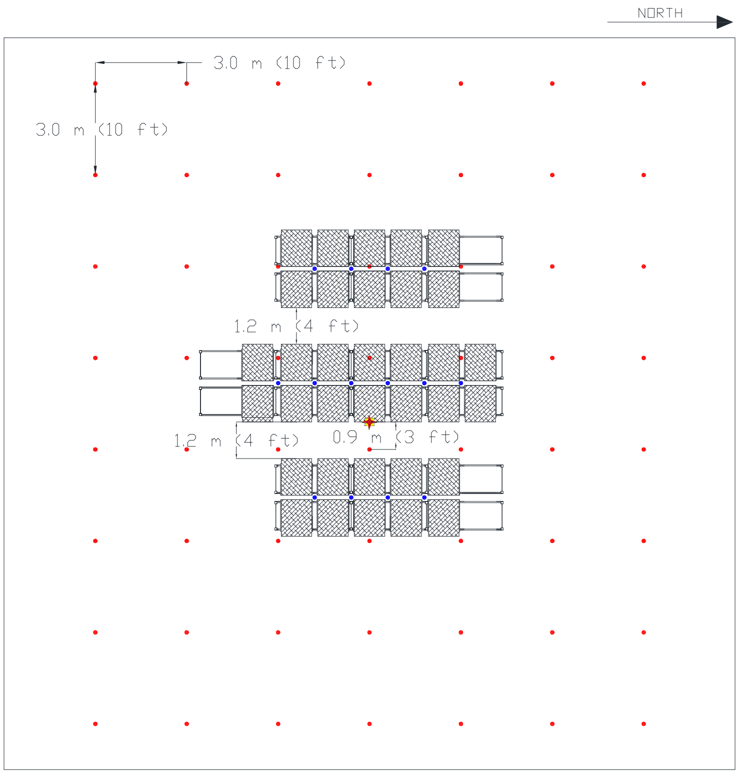


Figure 2.3.3-1: Test 7 ignition location relative to ceiling level sprinklers.

3. Test Summaries

3.1 IRAS Sprinkler Designs Using Quick-Response, Pendent, K200 (K14.0) and Larger Sprinklers

3.1.1 Test Overview

The following section details the results of the six full-scale fire tests whose parameters have been documented previously. Table 3.1.1-1 summarizes test parameters and results.

Table 3.1.1-1: Summary of Parameters and Results for Tests 1 through 6.

Test Number	1	2	3	4	5	6
Test Date	5-Dec-2013	23-Jan-2014	12-Feb-2014	3-Mar-2014	14-Mar-2014	8-Apr-2014
Ceiling Height (m) [ft]	(18.3) [60]					
Test Commodity/Fuel	UEP	CUP	UUP	UUP	UUP	CUP
Array Size	Large-Scale					
Storage Arrangement	2x7x11	2x7x11	2x7x8	2x7x8	2x7x8	2x7x10
Nominal Storage Height (m) [ft]	(16.8) [55]	(16.8) [55]	(12.2) [40]	(12.2) [40]	(12.2) [40]	(15.2) [50]
Pre-test Lab Temperature (˚C) [˚F]	(15) [59]	(0) [32]	(4) [39]	(3) [37]	(6) [43]	(17) [63]
Pre-test Lab Relative Humidity (%)	58	23	17	24	23	69
Pre-test Sample Moisture Content – Dry Basis (%)	N/A	5.8	N/A	N/A	N/A	6.5
Lab Ventilation Rate (m^3/s) [scfm]	(94.4) [200,000]					
In-Rack Sprinkler Protection Details						
Number of In-Rack Levels	1					
Elevation of In-Rack Level (m) [ft]	(9.1) [30]					(12.2) [40]
In-Rack Sprinkler Temperature Rating (˚C) [˚F]	(74) [165]					
In-Rack Sprinkler Type	Pendent, QR Fusible Element					
In-Rack Sprinkler Orifice Diameter (mm) [in.]	(19) [0.75]	(19) [0.75]	(19) [0.75]	(25) [1.0]	(19) [0.75]	(25) [1.0]
In-Rack Sprinkler K-factor (lpm/(bar)^{½}) [gpm/(psi)^{½}]	(200) [14.0]	(200) [14.0]	(200) [14.0]	(360) [25.2]	(200) [14.0]	(360) [25.2]
In-Rack Location	Every Face and Every Transverse/Longitudinal Flue Intersection					
In-Rack Horizontal Spacing (m) [ft]	(1.2) [4 ft] On-Line					
In-Rack Sprinkler Discharge Pressure (bar) [psig]	(3.9) [57]	(1.2) [17]	(2.2) [32]	(0.8) [12]	(5.0) [72]	(1.2) [18]
Nominal Discharge per In-Rack Sprinkler (lpm) [gpm]	(400) [105]	(220) [58]	(300) [79]	(330) [87]	(450) [120]	(410) [110]
FIRE TEST RESULTS						
Total In-Rack Sprinkler Activations	6	2	5	2	2	2
First/Last In-Rack Sprinkler Activation Times (mm:ss)	01:00/ 03:26	03:32/ 03:37	06:36/ 26:27	07:22/ 07:25	08:29/ 13:39	03:40/ 03:42
Maximum Ceiling Level Gas Temperature (˚C) [˚F]	(64) [148]	(61) [142]	(196) [384]	(72) [162]	(193) [379]	(61) [142]
Target Ignition	YES	NO	YES	NO	NO	NO
Target Ignition Time (mm:ss)	00:55	N/A	10:33	N/A	N/A	N/A
Ignition of Commodity Above IRAS	NO	NO	NO	NO	YES	NO
Test Termination Time (min)	30	30	30	13	16	30
Test Pass or Fail	PASS	PASS	FAIL	PASS	FAIL	PASS

Note that all times stated in this report are from the start of the fire test (i.e., ignition) and are expressed as min:sec unless otherwise noted.

3.1.2 Test Setup

3.1.2.1 Array Description

All six full-scale fire tests were conducted under the North Movable Ceiling in the Large Burn Laboratory at the FM Global Research Campus within the Fire Technology Building. The test ceiling was set to a height of 18.3 m (60 ft) for all six tests. Each test contained a double row, open-frame, main array which was seven pallet loads long. Tests 1, 2, and 6 contained two double row, open-frame, target arrays which were each five pallet loads long and located to the east and west of the main array across 1.2 m (4 ft) aisles. Tests 3, 4 and 5 contained one double row, open-frame, target array located 1.2 m (4 ft) east of the main array and one single row, open-frame, target array located 1.2 m (4 ft) west of the main array; each were five pallet loads long. All arrays had 0.15 m (6 in.) wide transverse and longitudinal flue spaces throughout. The main and target arrays were configured such that the east face of the main array was offset 0.9 m (3 ft) east of the center of the ceiling.

The detailed drawings of the array configuration and pre-test images of the array setup for each test are shown in Figure 3.1.2.1-1–Figure 3.1.2.1-8.

Front and side elevation views of Tests 1 and 2 are shown in Figure 3.1.2.1-1 and Figure 3.1.3.1-3, respectively. The test setup consisted of 11-tier high (16.8 m [55 ft]) storage. A single level of IRAS, detailed in Section 3.1.2.3.1, was located above the 6th tier commodity and five tiers of commodity were present above the IRAS. Pre-test images of each test are shown in Figure 3.1.2.1-2 and Figure 3.1.2.1-4.

Front and side elevation views of Tests 3, 4 and 5 are shown in Figure 3.1.2.1-5. The test setup consisted of eight-tier high (12.2 m [40 ft]) storage. A single level of IRAS, detailed in Section 3.1.2.3.1, was located above the 6th tier commodity and two tiers of commodity were present above the IRAS. An image of the pre-test configuration is shown in Figures 3 6.

Front and side elevation views of Test 6 are shown in Figure 3.1.2.1-7. The test setup consisted of 10-tier high 15.2 m [50 ft]) storage. A single level of IRAS, detailed in Section 3.1.2.3.1, was located above the 8th tier commodity and two tiers of commodity were present above the IRAS. An image of the pre-test configuration is shown in Figure 3.1.2.1-8.

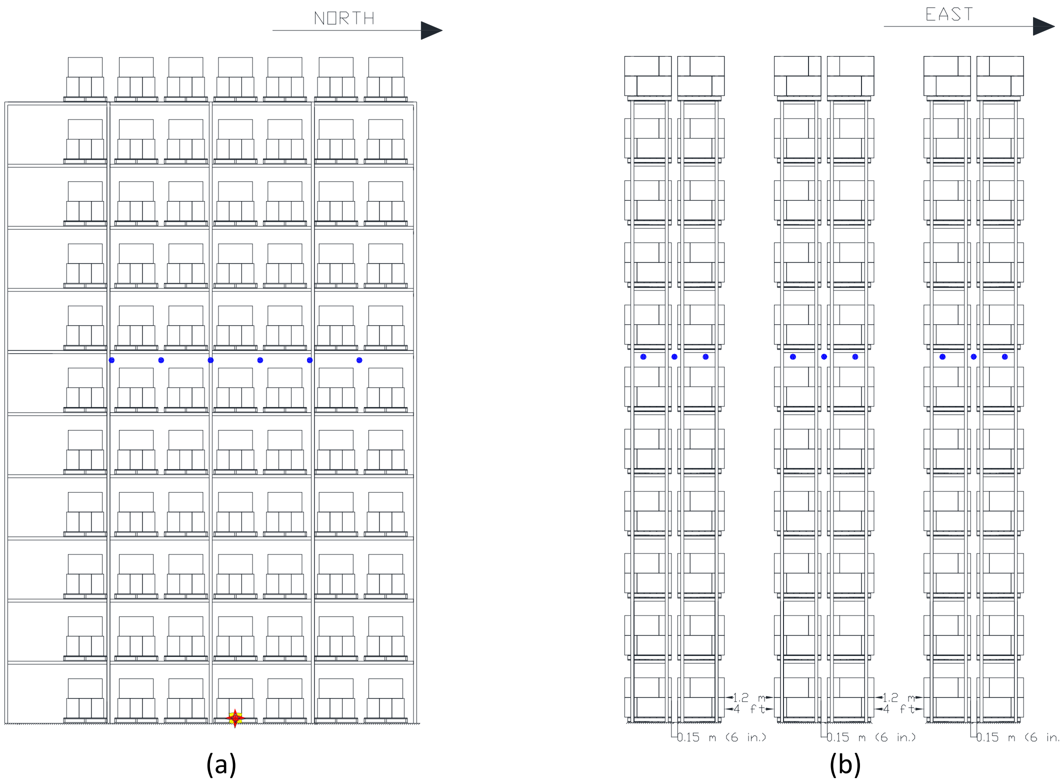


Figure 3.1.2.1-1: Test 1 Rack Storage Configuration, (a) Front Elevation View of East Side of Main Array, (b) Side Elevation View of Main and Two Target Arrays.

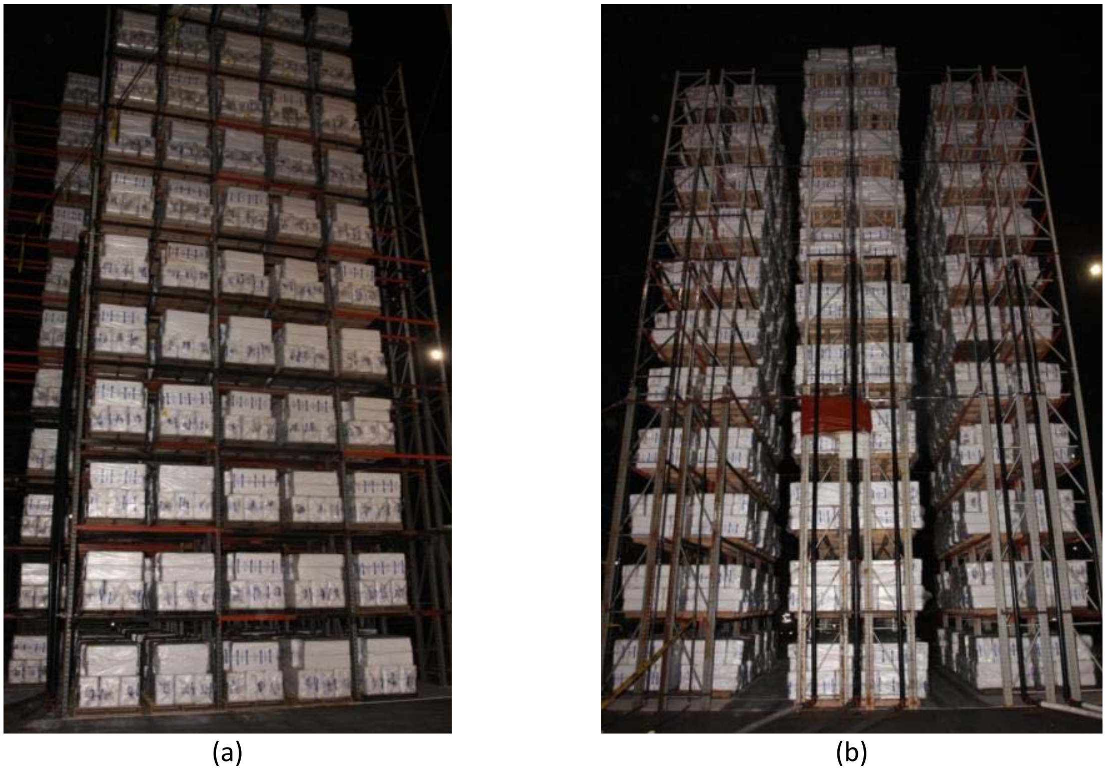


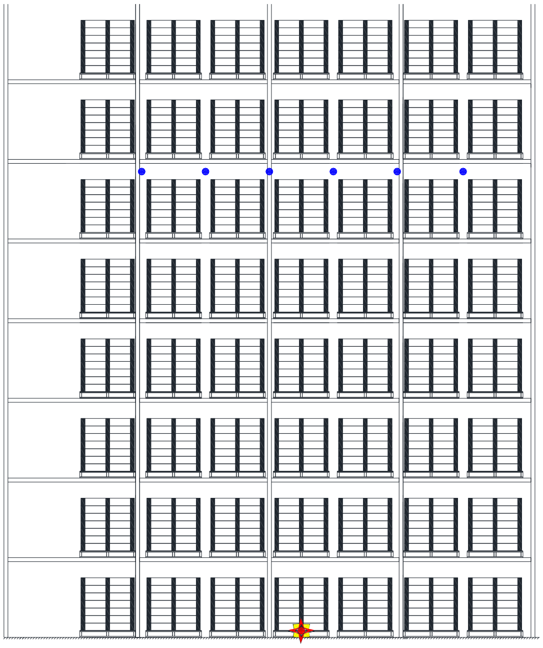
Figure 3.1.2.1-2: Test 1 Pre-Test Images of Arrays, (a) Front Elevation View of East Target Array, (b) Side Elevation View of Main and Two Target Arrays.

(a) (b)

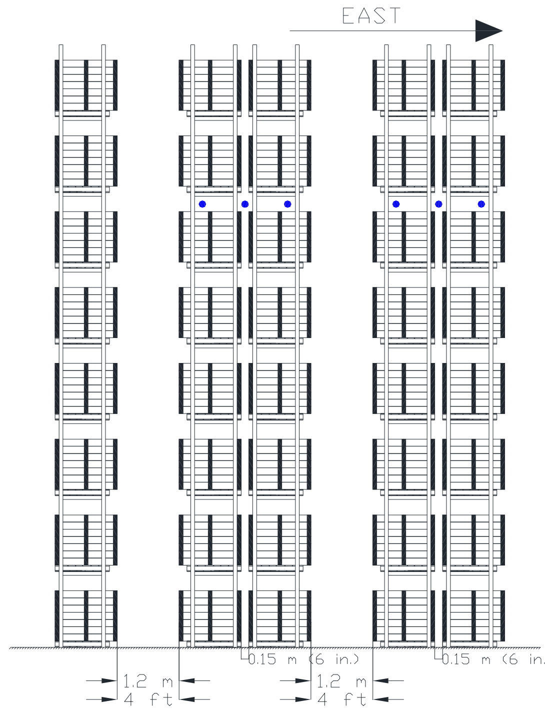
Figure 3.1.2.1-3: Test 2 Rack Storage Configuration, (a) Front Elevation View of East Side of Main Array, (b) Side Elevation View of Main and Two Target Arrays.

(a) (b)

Figure 3.1.2.1-4: Test 2 Pre-Test Images of Arrays, (a) Front Elevation View of East Target Array, (b) Side Elevation View of Main and Two Target Arrays.



(a)



(b)

Figure 3.1.2.1-5: Test 3, 4 and 5 Rack Storage Configuration, (a) Front Elevation View of East Side of Main Array, (b) Side Elevation View of Main and Two Target Arrays.

(a)

(b)

Figure 3.1.2.1-6: Test 3, 4 and 5 Pre-Test Images of Arrays, (a) Front Elevation View of East Target Array, (b) Side Elevation View of Main and Two Target Arrays.

(a) (b)

Figure 3.1.2.1-7: Test 6 Rack Storage Configuration, (a) Front Elevation View of East Side of Main Array, (b) Side Elevation View of Main and Two Target Arrays.

(a) (b)

Figure 3.1.2.1-8: Test 6 Pre-Test Images of Arrays, (a) Front Elevation View of East Target Array, (b) Side Elevation View of Main and Two Target Arrays.

3.1.2.2 Test Commodities

Three different commodities were used in the test series. Test 1 utilized the FM Global Standard Uncartoned Expanded Plastic (UEP) commodity. The specifics of this commodity type are given below in Section 3.1.2.2.1. Tests 2 and 6 utilized the FM Global Standard Cartoned Unexpanded Plastic (CUP) commodity which is detailed in Section 3.1.2.2.2. Tests 3, 4 and 5 utilized the FM Global Standard Uncartoned Unexpanded Plastic (UUP) commodity, details of which are given in Section 3.1.2.2.3.

3.1.2.2.1 Uncartoned Expanded Plastic (UEP)

The FM Global Standard UEP test commodity, consists of expanded polystyrene meat trays packed in a plastic bag. Eight bags are then stacked onto an ordinary, two-way, slatted deck, hardwood pallet. The overall dimension of the commodity is 1.07 m x 1.18 m x 1.09 m (42 in. x 46 in. x 43 in.). The total combustible weight of one pallet load is approximately 52.3 kg (115.3 lb); the expanded plastic weighs approximately 29.9 kg (65.9 lb), and the hardwood pallet that supports the commodity weighs approximately 22.4 kg (49.4 lb). A photo of a representative pallet load of UEP commodity (note that this is not the actual pallet arrangement for the UEP test commodity) is provided in Figure 3.1.2.2.1-1.

Figure 3.1.2.2.1-1: FM Global Standard Uncartoned Expanded Plastic (UEP) Commodity.

3.1.2.2.2 Cartoned Unexpanded Plastic (CUP)

The FM Global Standard CUP commodity consists of rigid crystalline polystyrene cups (empty, 0.46 L [16 oz.]) packaged, facing down, in a single-wall corrugated containerboard box. The cups are individually compartmentalized with single-layer corrugated board partitions, arranged in five layers of 25 cups per layer, yielding a total of 125 cups per box. Each cup is separated by corrugated containerboard partitions, and each layer separated by a corrugated containerboard pad. Eight 53 cm (21 in.) cubic cartons are arranged in a 2 x 2 x 2 arrangement on an ordinary, two-way, slatted deck, hardwood pallet resulting in a total dimension of 1.07 m x 1.07 m x 1.19 m (42 in. x 42 in. x 47 in.). Total combustible weight of one pallet load is approximately 73.8 kg (162.8 lb); the corrugated containerboard weighs approximately 19.8 kg (43.7 lb), the plastic cups weigh approximately 31.6 kg (69.7 lb), and the hardwood pallet that supports the commodity weighs approximately 22.4 kg (49.4 lb). A photo of the CUP commodity is provided in Figure 3.1.2.2.2-1.

Figure 3.1.2.2.2-9: FM Global Standard Cartoned Unexpanded Plastic (CUP) Commodity.

3.1.2.2.3 Uncartoned Unexpanded Plastic (UUP)

The rack storage UUP test commodity consists of seven plastic pallets stacked on top of an ordinary, two-way, slatted deck, hardwood pallet resulting in an overall dimension of 1.07 m x 1.22 m x 1.11 m (42 in. x 48 in. x 44 in.). The standard plastic pallets used by FM Global are high-density polyethylene plastic pallets. The four-way entry plastic pallets are not FM Approved and do not contain fire retardant materials. The pallets have dimensions of 1.02 m (40 in.) long by 1.22 m (48 in.) wide by 14 cm (5.6 in.) high and weigh about 25.4 kg [56 lb] each. The total combustible weight of one standard rack storage UUP pallet load is 200.3 kg (441.6 lb); the plastic pallets weigh approximately 177.9 kg (392.2 lb), and the hardwood pallet that supports the commodity weighs approximately 22.4 kg (49.4 lb). A photo of the standard rack storage UUP commodity is provided in Figure 3.1.2.2.3-1.

Figure 3.1.2.2.3-1: FM Global Standard Uncartoned Unexpanded Plastic (UUP) Commodity.

3.1.2.3 Protection Description

3.1.2.3.1 In-Rack Sprinkler Protection

A single level of IRAS protection was installed for each test. In Tests 1 through 5 the IRAS were located at the 9.1 m (30 ft) elevation (i.e., above the 6th tier commodity). In Test 6 the IRAS were located at the 12.2 m (40 ft) elevation (i.e., above the 8th tier commodity).

The IRAS layout was practically identical for all six tests. The layout is shown in Figure 3.1.2.3.1-1. IRAS were installed within the longitudinal flue at the intersection of every transverse flue, which resulted in a sprinkler located every 1.2 m (4 ft) horizontally. IRAS were also installed within every transverse flue, 0.46 m (18 in.) horizontally from the face. Due to the differing dimensions of the various commodity types, the distance between the longitudinal and the face IRAS (designated at “D” in Figure 3.1.2.3.1-1) varied from 0.69 m (27 in.) for CUP, 0.76 m (30 in.) for UEP, and 0.84 m (33 in.) for UUP. All IRAS were installed with their deflector located 0.15 m (6 in.) above the top of the commodity.

Each of the three branch lines within each array (i.e., longitudinal, and two face lines) were supplied with an independent water feed. The water flow and pressure to each line was independently controlled by a valve system and pressure was held constant throughout the test regardless of the number of IRAS activations.

The sprinkler K-factor and water flow rate selection was chosen via a coupled strategy using intermediate-scale suppression tests and CFD modeling and are summarized in Table 3.1.2.3.1-1 2. Tests 1, 2, 3 and 5 utilized quick-response, 74°C (165°F) rated K200 (K14.0) pendent sprinklers, whereas Tests 4 and 6 utilized quick-response, 74°C (165°F) rated K360 (K25.2) pendent sprinklers. Flows for Tests 1 through 6 ranged from 220 lpm (57 gpm) to 450 lpm (119 gpm) as outlined in Table 3.1.1-1.

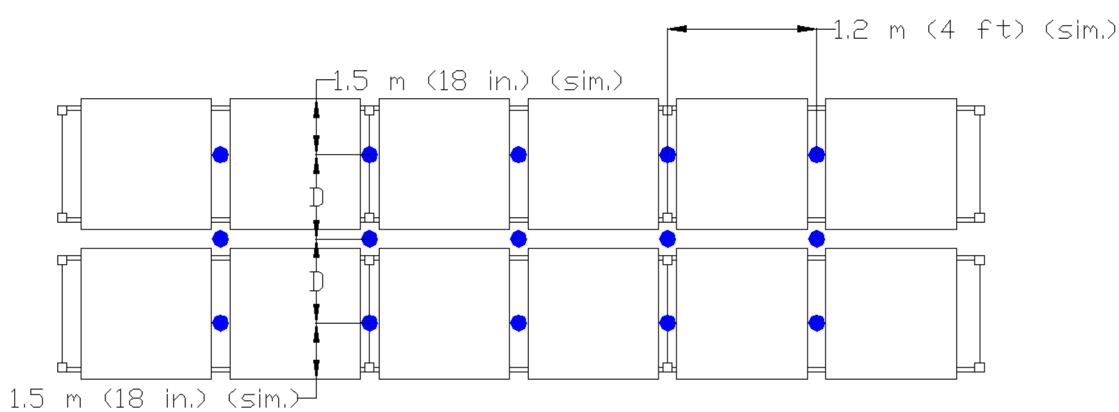


Figure 3.1.2.3.1-10: Plan View of IRAS Layout.

Table 3.1.2.3.1-1: In-Rack Sprinkler K-factor, Vertical Elevation and Supplied Water Flow Rate.

Test #	In-Rack Sprinkler Parameters		
	K-Factor (lpm/bar$^{1/2}$) [gpm/psi$^{1/2}$]	Vertical Elevation (m) [ft]	Supplied Water Flow (lpm) [gpm]
1	200 [14.0]	9.1 (30)	400 [106]
2	200 [14.0]	9.1 (30)	220 [57]
3	200 [14.0]	9.1 (30)	300 [79]
4	360 [25.2]	9.1 (30)	330 [88]
5	200 [14.0]	9.1 (30)	450 [119]
6	360 [25.2]	12.2 (40)	410 [107]

3.1.2.3.2 Ceiling Sprinkler Protection (Tests 1 and 2 Only)

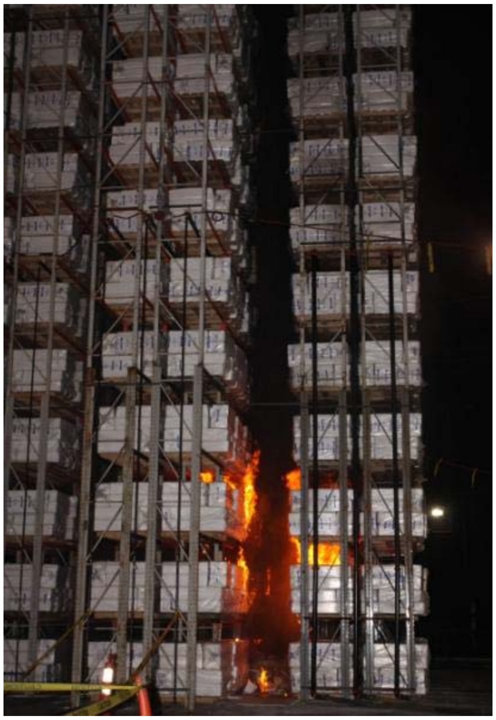
Ceiling level sprinkler protection was provided in Tests 1 and 2; however, no ceiling level sprinkler activations occurred and the use of ceiling level protection was discontinued for the remainder of the series in an effort to prove the modularity of the IRAS system. The ceiling level protection provided in Tests 1 and 2 consisted of quick-response, 74°C (165°F) rated K200 (K14.0) pendent sprinklers. The distance from the ceiling to the sprinkler thermal element was nominally 330 mm (13 in.). Fifty-six (56) ceiling level sprinklers were installed on a 3.0 m x 3.0 m (10 ft x 10 ft) spacing. The target water pressure in both Tests 1 and 2 was 6.9 bar (100 psig) resulting in a density of 57 mm/min (1.4 gpm/ft^2).

3.1.3 Results

3.1.3.1 Test 1

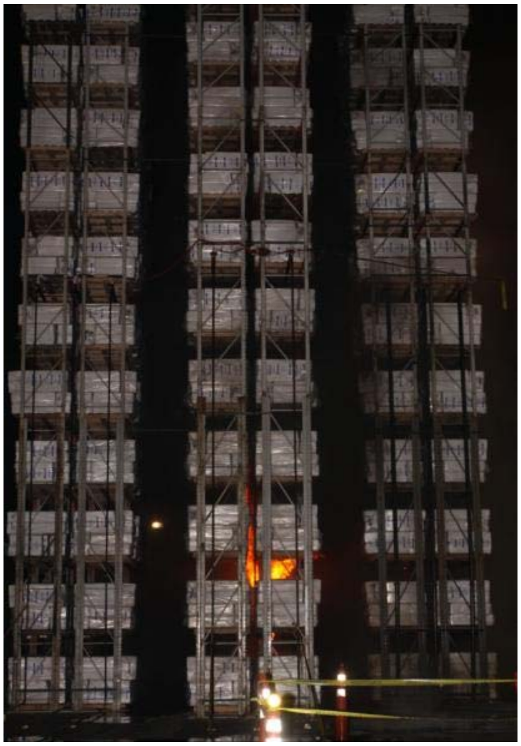
3.1.3.1.1 Test Overview, Sprinkler Activation Times and Patterns

Ignition occurred at 00:00. Flame tips reached the top of the 1st tier commodity at 00:16, the top of the 2nd tier commodity at 00:38, and the top of the 4th tier commodity at 00:48. A burning piece of commodity became airborne by the fire plume and caused ignition of the east target at 00:55. As flames reached the top of the 5th tier commodity in the main array at 01:00 the 1st IRAS activation occurred in the transverse flue north of ignition. Following the IRAS activation, the vertical fire growth in the main array ceased; however, the fire remained in tiers 1-5 and the fire in the east target array was intensifying (Figure 3.1.3.1.1-1a). At 01:34 the 2nd IRAS activation occurred in the longitudinal flue of the main array south of ignition. The fire began to subside in the main array and intensify in the east target array to involve tiers 1-4. At 02:18 the 3rd IRAS activated in the southern most transverse flue in the east target array; Figure 3.1.3.1.1-1b shows the state of the fire 4 seconds prior to this IRAS activation. The 4th IRAS activation occurred seconds later at 02:21 in the longitudinal flue of the east target array. By 02:40 the fire in the east target array was confined to the west face and appeared to be stable and was of greater intensity than the fire in the main array, which remained confined to the east face. However, at 03:13 (Figure 3.1.3.1.1-2a shows the fire at 03:16) flames became visible in the longitudinal flue of the main array and two subsequent IRAS activated at 03:21 and 03:26 bringing the final IRAS count to six. By 03:55 the fire intensity had greatly diminished; Figure 3.1.3.1.1-2b shows the state of the fire at 04:12. At 06:30 small localized fires were observed in the 2nd and 4th tiers of the main array and the 3rd tier of the east target array. At no point during the test did fire ignite the commodity above the IRAS. The fire remained small in size until the test was terminated at 30:00.



(a) (b)

Figure 3.1.3.1.1-11: Test 1 (a) at 01:04, (b) at 02:14.



(a) (b)

Figure 3.1.3.1.1-2: Test 1 (a) at 03:16, (b) at 04:12.

In Test 1, six IRAS activated within the time frame of 01:00 to 03:26 and suppressed the fire. Activation times and location are shown in Figure 3.1.3.1.1-3. Considering the IRAS activation pattern resulting from this test, where skipping was prevalent, it is apparent that the supplied flow rate is capable of protecting this commodity, in this configuration, with face sprinklers located on up to 2.4 m (8 ft) horizontal spacing.

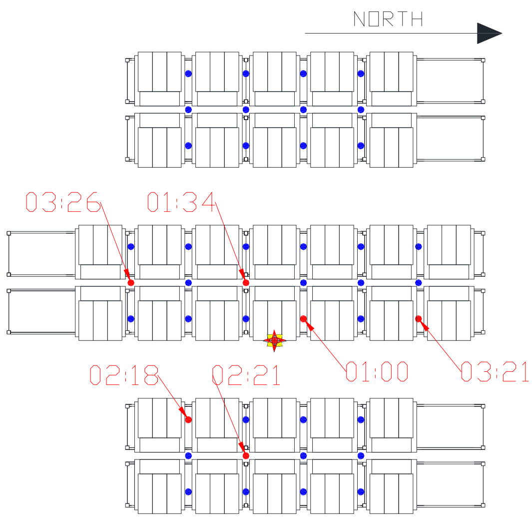


Figure 3.1.3.1.1-3: Test 1 IRAS Activations (UEP Commodity).

3.1.3.1.2 Gas Temperatures

Ceiling level gas temperatures reached a maximum of 64˚C (148˚F) in Test 1, which was insufficient to cause ceiling level sprinkler activation. The IRAS protection system was successful at providing modular fire control.

3.1.3.1.3 Extent of Damage

Test 1 post-test damage is shown in Figure 3.1.3.1.3-1 and Figure 3.1.3.1.3-2. The fire remained primarily on the east side (ignition side) of the main array; however, it did find its way to the west side of the main array where minor damage was sustained. The fire ignited the east target at 00:55 when airborne flaming commodity impacted it and resulted in fire damage to tiers 1-3. The fire and all fire damage remained below the IRAS.

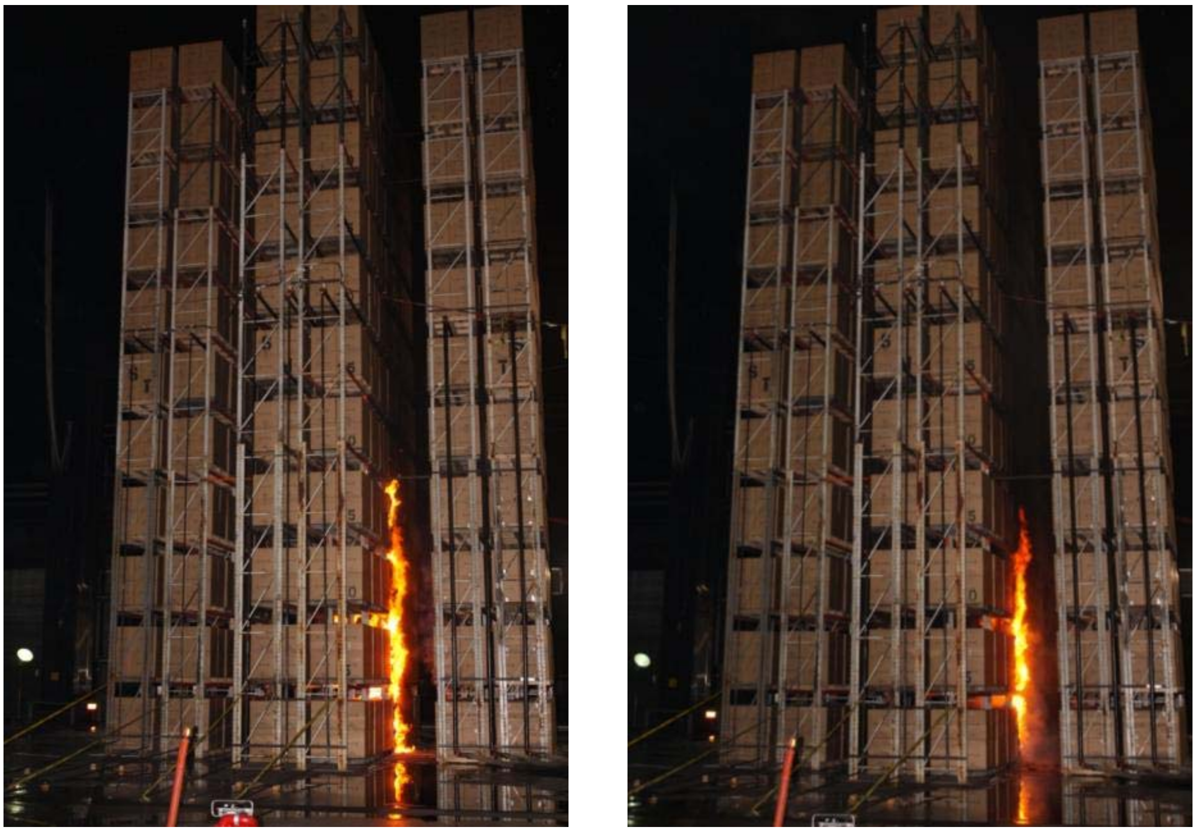
Figure 3.1.3.1.3-1: Test 1 Post Test Damage: (Left) West Face of Main Array, (Center) Ignition Face of Main Array, (Right) Target Facing Ignition.

Figure 3.1.3.1.3-2: Test 1 Post Test Damage: (Left) Side Elevation View of Main and Two Target Arrays, (Right) Plan View of Maximum Extent of Damage.

3.1.3.2 Test 2

3.1.3.2.1 Test Overview, Sprinkler Activation Times and Patterns

Ignition occurred at 00:00. Flame tips reached the top of the 1st tier commodity at 00:30. Flames periodically flashed above the top of the 2nd tier commodity at 02:20 and involved commodity in tiers 1 3 at 02:55. Flames were at the top of the 4th tier commodity at 03:18 and the 1st IRAS activation occurred at 03:32 (Figure 3.1.3.2.1-1a) in the main array within the transverse flue north of ignition. The 2nd and final IRAS activation occurred at 03:37 within the longitudinal flue of the main array south of ignition. Following sprinkler activation the vertical fire growth ceased and the fire remained contained to tiers 1-4 on the east side of the main array. The fire intensity remained fairly constant for the next couple of minutes (Figure 3.1.3.2.1-1b) but began to show a noticeable decrease in severity by 06:15. Figure 3.1.3.2.1-2a shows the state of the fire at 06:32. The fire severity continued to decrease and at 09:00 flames were only visible in tiers 2 and 3 on the east side of the main array. For the remainder of the test the fire remained very small in size with localized burning in tiers 1-3 on the east side of the main array (Figure 3.1.3.2.1-2b). The test was terminated at 30:00.



(a) (b)

Figure 3.1.3.2.1-1: Test 2 (a) at 03:32, (b) at 4:46.

(a) (b)

Figure 3.1.3.2.1-2: Test 2 (a) at 06:32, (b) at 24:24.

The fire in Test 2 was suppressed by two IRAS activations; the 1st at 03:32 and the 2nd and final at 03:37. Their locations are shown in Figure 3.1.3.2.1-3. Additionally, one will note that the fire was suppressed with the combined water flow of a single face IRAS and a single longitudinal flue IRAS. This provides evidence that the outcome of the test should be the same if only every other face IRAS had been installed in the main and target arrays. This conclusion is supported by the modeling results where artificial sprinkler skipping was applied to calculate the recommended IRAS water flow rate for this large-scale validation test. This result allows recommending that face sprinklers can be installed with up to 2.4 m (8 ft) horizontal spacing.

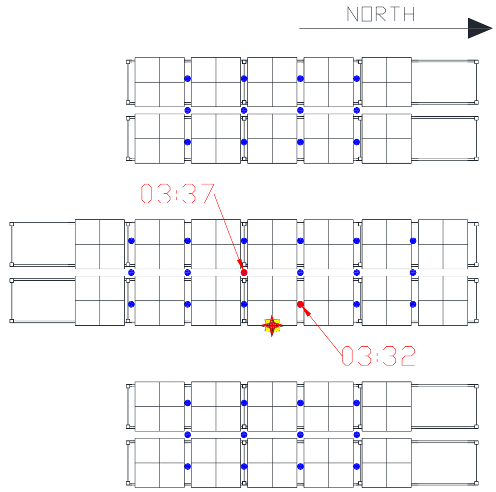


Figure 3.1.3.2.1-3: Test 2 IRAS Activations (CUP Commodity).

3.1.3.2.2 Gas Temperatures

Ceiling level gas temperatures reached a maximum of 61˚C (142˚F) in Test 2, which was insufficient to cause ceiling level sprinkler activation. The IRAS protection system was successful at providing modular fire control.

3.1.3.2.3 Extent of Damage

Test 2 post-test damage is shown in Figure 3.1.3.2.3-1 and Figure 3.1.3.2.3-2. The fire remained exclusively on the east side (ignition side) of the main array. Heat from the ignition region cause discoloration of the commodity directly across the aisle in the east target; however, that commodity did not ignite. The fire and all fire damage remained below the IRAS.

Figure 3.1.3.2.3-1: Test 2 Post Test Damage: (Left) Ignition Face of Main Array, (Right) Target Facing Ignition.

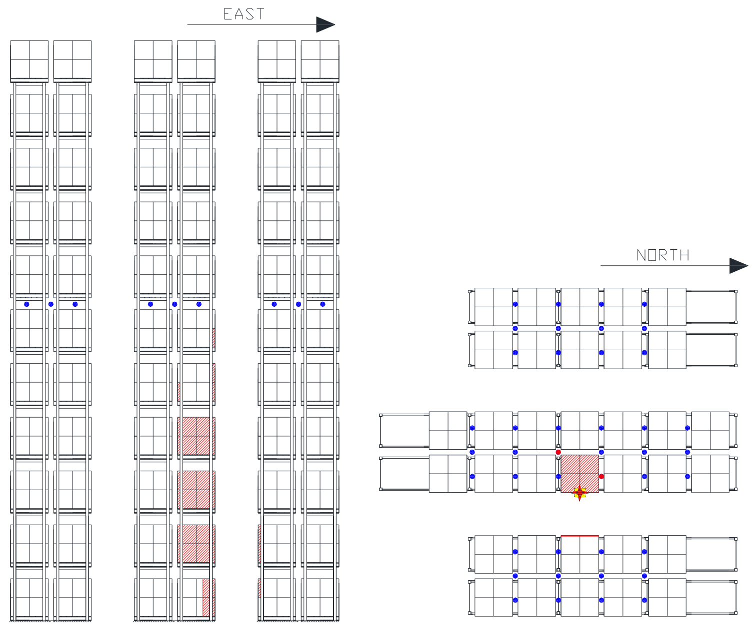


Figure 3.1.3.2.3-2: Test 2 Post Test Damage: (Left) Side Elevation View of Main and Two Target Arrays, (Right) Plan View of Maximum Extent of Damage.

3.1.3.3 Test 3

3.1.3.3.1 Test Overview, Sprinkler Activation Times and Patterns

Ignition occurred at 00:00. At 04:15 flame tips reached the top of the 1st tier commodity and at 05:45 flame tips were at the top of the 2nd tier commodity and periodically impinged on the 3rd tier commodity. Flames periodically flashed to the top of the 4th tier commodity at 06:15 and the 1st IRAS activation occurred at 06:36 in the main array in the transverse flue north of ignition. Figure 3.1.3.3.1-1a shows the state of the fire 4 seconds prior to 1st IRAS activation. That activation hindered vertical flame propagation but the fire continued to involve commodity in tiers 1-4.

By 07:55 the fire severity was noticeably increasing and flame tips extended to the top of the 5th tier commodity and periodically flashed to the top of the 7th tier commodity by 08:30. By 09:10 flames periodically flashed above the top of the 12.2 m (40 ft) high array. The fire severity continued to increase and at 09:55 the 2nd IRAS activated (Figure 3.1.3.3.1-1b) in the main array within the 2nd transverse flue south of ignition (note: the IRAS in the transverse flue south of ignition was skipped). The 3rd IRAS activated in the longitudinal flue of the main array at 10:29. Radiant ignition of the west face of the east target occurred at 10:33.

Subsequently the fire in the main array subsided while the fire in the target array intensified (Figure 3.1.3.3.1-2a). At 16:20 there were no visible flames within the main array; however, the fire in the target array involved tiers 1-6. At 16:32 the 4th IRAS activation occurred in the east target array within the transverse flue south of ignition. This activation greatly reduced the fire severity in the target array, confining the fire to tiers 1 and 2. However, at 17:40 the fire shifted into the longitudinal flue of the east target array at the 2nd tier level where it began to intensify.

During the 23rd minute the fire in the east target array involved tiers 1-6 within the longitudinal flue and flames began to impinge on the east row commodity of the east target array in tiers 2-4. At 25:15 flame tips were extending out the east side of the east target at the 3rd tier elevation. The state of the fire at 26:16 is shown in Figure 3.1.3.3.1-2b. The 5th and final IRAS activated at 26:27 at the southern most location within the longitudinal flue of the east target array. Following that activation, smoke temporarily obscured the east target array. However, at 29:25 the fire was intensifying and was actively involving commodity on the east face of the east target at the 2nd and 3rd tier levels. The test was terminated at 30:00 and water from firefighter hose streams was used to extinguish the fire.


(a)


(b)

Figure 3.1.3.3.1-1: Test 3 (a) at 06:32, (b) at 09:55.

(a)

(b)

Figure 3.1.3.3.1-2: Test 3 (a) at 15:34, (b) at 26:16.

Five IRAS activated in Test 3; however, the fire was intensifying when the test was terminated. The 1st activation occurred at 06:36 and the final at 26:27. It is noted that the IRAS located within the transverse flue south of ignition did not activate even with the fire located directly below it. This sprinkler was likely being cooled from water discharging from the adjacent IRAS activation. Activated IRAS locations and activation time are shown in Figure 3.1.3.3.1-3.

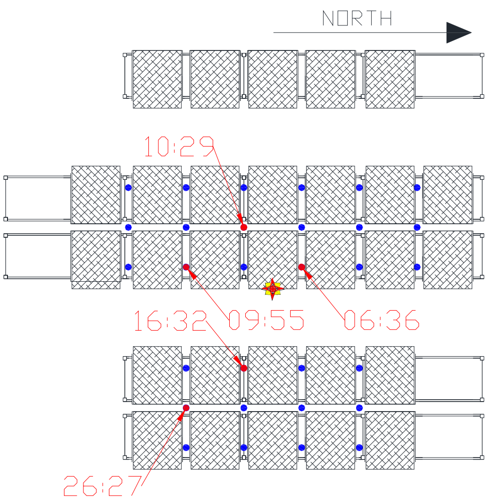


Figure 3.1.3.3.1-3: Test 3 IRAS Activations (UUP Commodity).

3.1.3.3.2 3.1.3.3.2 Gas Temperatures

Ceiling level gas temperatures reached a maximum of 196˚C (384˚F) in Test 3, which would have been sufficient to cause activation of low temperature ceiling level sprinklers had they been installed. Further sprinkler activation analysis is not conducted because this protection scheme exceeded failure criteria for flame spread. The IRAS protection system was unsuccessful at providing modular fire control.

3.1.3.3.3 Extent of Damage

Test 3 post test damage is shown in Figure 3.1.3.3.3-1 and Figure 3.1.3.3.3-2. Within the main array, the fire remained on the east row of commodity and did not involve commodity on the opposite side of the longitudinal flue. Flames within the main array periodically extended above the IRAS and commodity in the 7th and 8th tiers exhibited signs of melting but where not observed to ignite. The fire in the main array caused radiant ignition of the east target array at 10:33. The fire in that target array ultimately propagated to the back side as shown in Figure 3.1.3.3.3-2.

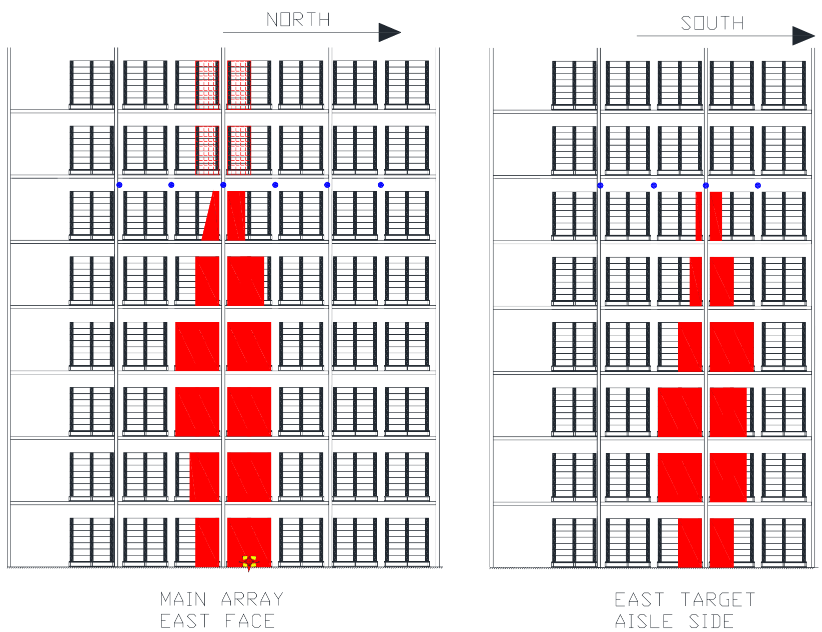


Figure 3.1.3.3.3-1: Test3 Post Test Damage: (Left) Ignition Face of Main Array, (Right) Target Facing Ignition.

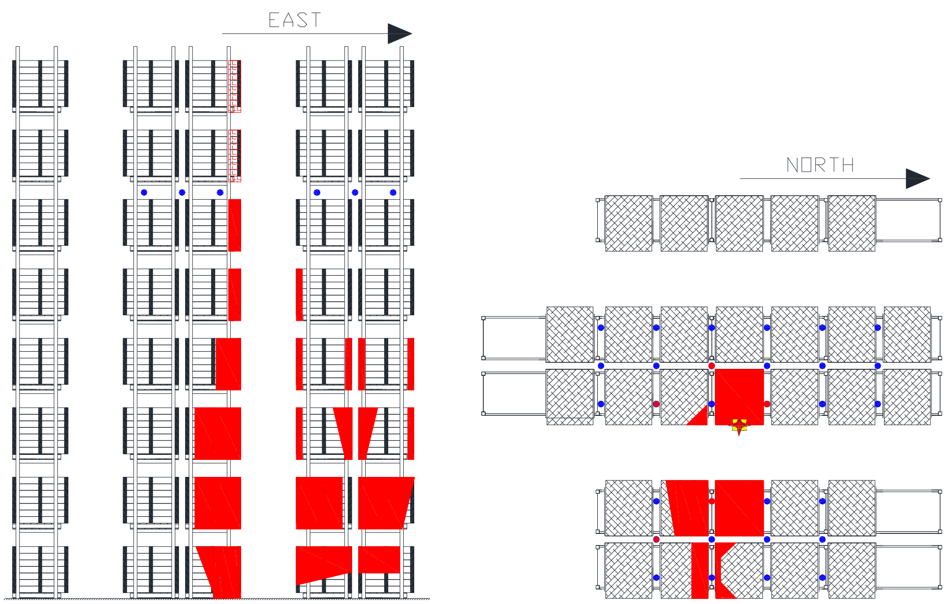


Figure 3.1.3.3.3-2: Test 3 Post Test Damage: (Left) Side Elevation View of Main and Two Target Arrays, (Right) Plan View of Maximum Extent of Damage.

3.1.3.4 Test 4

3.1.3.4.1 Test Overview, Sprinkler Activation Times and Patterns

Ignition occurred at 00:00. At 03:05 flame tips reached the top of the 1st tier commodity and periodically extended to the bottom of the 3rd tier commodity at 06:00. At 07:14 flame tips were periodically extending to the top of the 5th tier commodity (Figure 3.1.3.4.1-1a). The 1st IRAS activation occurred at 07:22 immediately followed by the 2nd and final IRAS activation at 07:25. The activations occurred within the transverse flue spaces directly north and south of ignition. At 07:47 flames had been driven down to below the 5th tier level. At 07:52 the fire was confined to tiers 1-3 (Figure 3.1.3.4.1-1b). By 08:01 flames were below the 3rd tier level and by 08:14 the fire was confined to the 1st tier commodity. No flames were visible in the main array at 08:52 (Figure 3.1.3.4.1-2). At 12:47 firefighters confirmed that the fire was extinguished and the test was terminated at 13:00.

(a) (b)

Figure 3.1.3.4.1-1: Test 4 (a) at 07:14, (b) at 07:52.

Figure 3.1.3.4.1-2: Test 4 at 08:52.

In Test 4, two IRAS activated and suppressed the fire; the 1st at 07:22 and the 2nd at 07:25. Their locations are shown in Figure 3.1.3.4.1-3. Note that in this test two face IRAS activated nearly simultaneously; consequently it is not possible to conclude that the face IRAS horizontal spacing can be extended to 2.4 m (8 ft). However, the practically simultaneous face IRAS activations show that the activation time of the face IRAS located behind a rack upright is very similar to that of the face IRAS at the mid-bay location. This is a desirable outcome indicating that activation time is not hindered when the IRAS is located behind a rack upright.

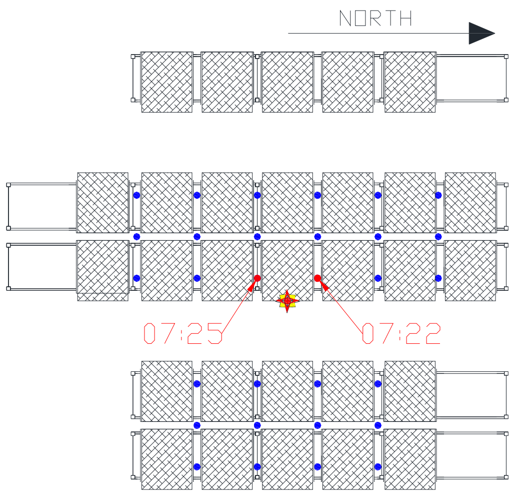


Figure 3.1.3.4.1-3: Test 4 IRAS Activations (UUP Commodity).

3.1.3.4.2 Gas Temperatures

Ceiling level gas temperatures reached a maximum of 72˚C (162˚F) in Test 4, which would have been insufficient to cause ceiling level sprinkler activation had sprinklers been installed. The IRAS protection system was successful at providing modular fire control.

3.1.3.4.3 Extent of Damage

Test 4 post test damage is shown in Figure 3.1.3.4.3-1 and Figure 3.1.3.4.3-2. The fire remained exclusively on the east side (ignition side) of the main array. Fire damage was evident in tiers 1-4 and the 5th tier commodity exhibited signs of melting. The fire and all fire damage remained below the IRAS.

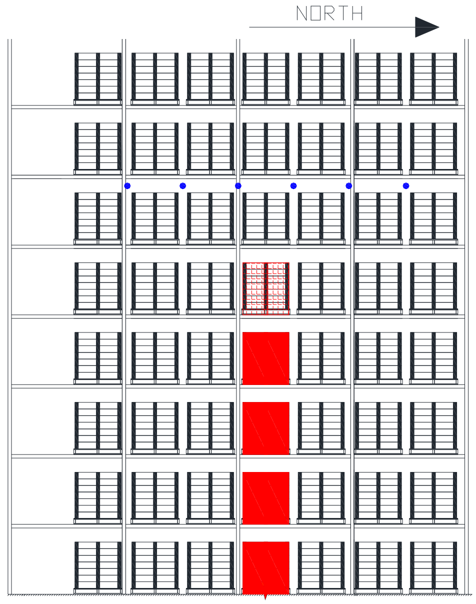


Figure 3.1.3.4.3-1: Test 4 Post Test Damage: Ignition Face of Main Array.

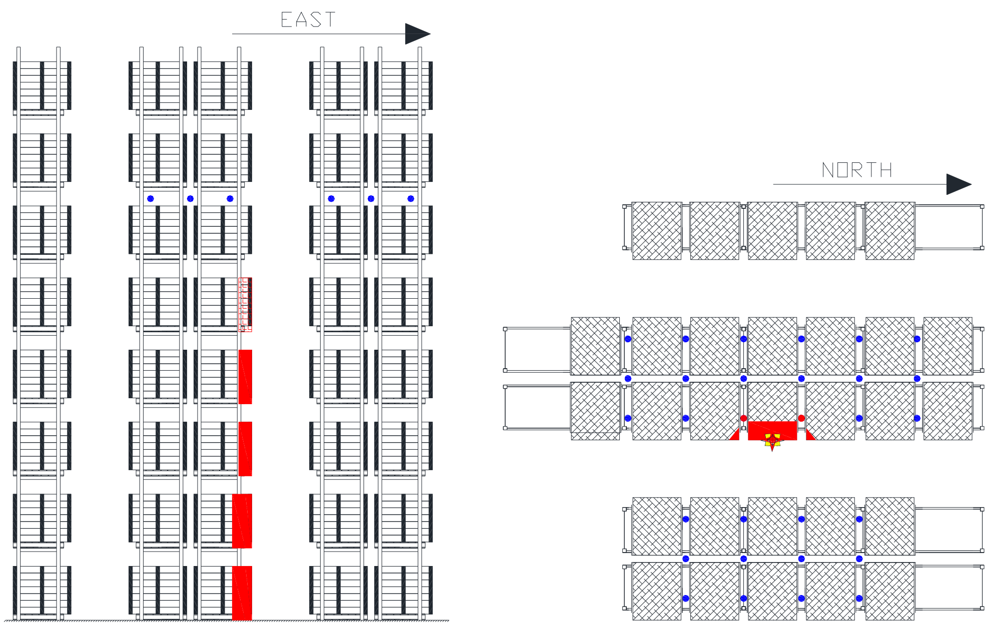


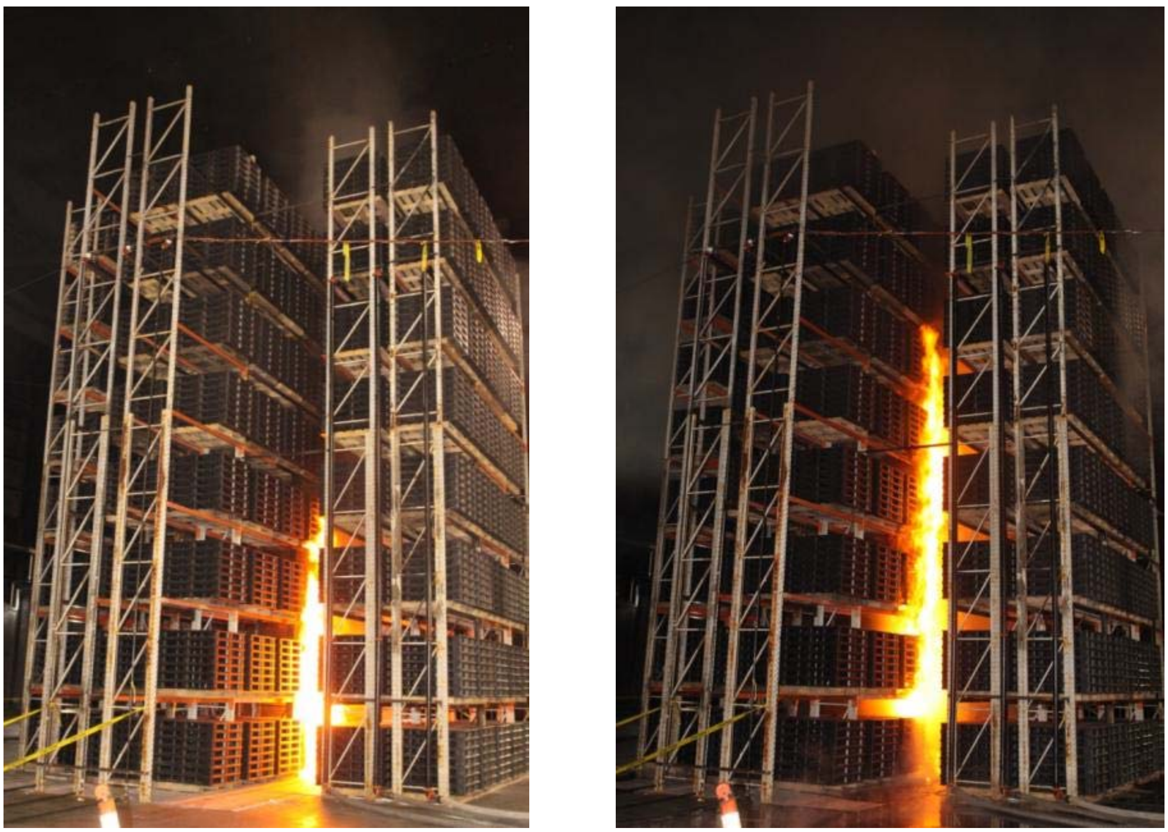
Figure 3.1.3.4.3-2: Test 4 Post Test Damage: (Left) Side Elevation View of Main and Two Target Arrays, (Right) Plan View of Maximum Extent of Damage.

3.1.3.5 <u>Test 5</u>

3.1.3.5.1 Test Overview, Sprinkler Activation Times and Patterns

Ignition occurred at 00:00. At 05:00 flame tips periodically extended to the top of the 1st tier commodity. At 07:55 flame tips reached the top of the 3rd tier commodity and periodically flashed toward the 4th tier commodity. Flames were steadily above the 4th tier commodity and flashed to the 5th tier commodity at 08:22. The 1st IRAS activation occurred at 08:29 in the main array within the transverse flue north of ignition; Figure 3.1.3.5.1-1a shows the state of the fire 5 seconds after IRAS activation. Water from that activation reduced the fire size to the bottom three tiers; however, the fire shifted into the south transverse flue and was intensifying at 10:15. At 11:55 the fire was spanning tiers 1-6 in the south transverse flue and was also present in the longitudinal flue. It is noted that there was an inactivated IRAS directly above this fire that was likely being cooled by the adjacent active IRAS.

The fire continued to intensify and at 13:07 flames were steadily impinging on the 7th tier commodity and occasionally flashed above the top of the array (Figure 3.1.3.5.1-1b shows the fire at 13:16). At 13:39 the 2nd and final IRAS activated in the main array within the second transverse flue south of ignition (note: the IRAS in the transverse flue south of ignition was skipped). That activation had no noticeable effect on reducing fire severity, in fact the fire intensified and flames reached 1.5-3.0 m (5-10 ft) above the top of the array at 14:20. At 15:18 the commodity above the IRAS had ignited and the fire continued to intensify. Figure 3.1.3.5.1-2 shows the state of the fire at 15:42. The test was terminated at 16:00 and water from firefighter hose streams was used to extinguish the fire.



(a) (b)

Figure 3.1.3.5.1-1: Test 5 (a) at 08:34, (b) at 13:16.

Figure 3.1.3.5.1-2: Test 5 at 15:42.

Test 5 resulted in two IRAS activations; however, the fire was intensifying when the test was terminated due to reaching the failure criteria of commodity ignition above the IRAS. The 1st activation occurred at 08:29 and the 2nd at 13:39; their locations are shown in Figure 3.1.3.5.1-3. It is noted that the IRAS located within the transverse flue south of ignition failed to activate even in the presence of fire directly below it. As with Test 3, it is likely that water discharging from the adjacent IRAS acted to cool this sprinkler preventing its activation. This sprinkler skipping was only observed when K200 (K14.0) IRAS were employed.

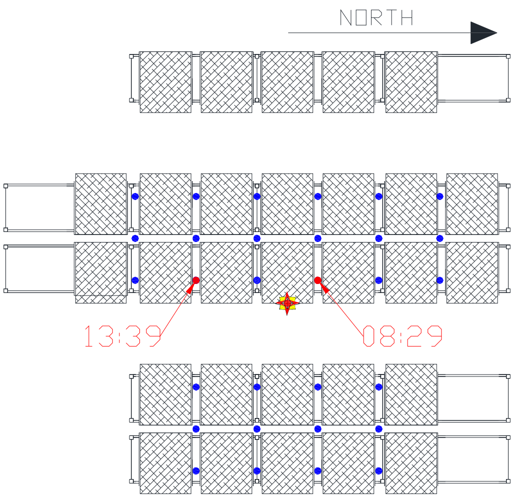


Figure 3.1.3.5.1-3: Test 5 IRAS Activations (UUP Commodity).

3.1.3.5.2 Gas Temperatures

Ceiling level gas temperatures reached a maximum of 193˚C (379˚F) in Test 5, which would have been sufficient to cause activation of low temperature ceiling level sprinklers had they been installed. Further sprinkler activation analysis is not conducted because this protection scheme exceeded failure criteria for flame spread. The IRAS protection system was unsuccessful at providing modular fire control.

3.1.3.5.3 Extent of Damage

Test 5 post-test damage is shown in Figure 3.1.3.5.3-1 and Figure 3.1.3.5.3-2. Within the main array, the fire remained on the east row of commodity and did not involve commodity on the opposite side of the longitudinal flue. Flames within the main array continuously extended above the IRAS and commodity in the 7th and 8th tiers ignited at approximately 15:00. The test was terminated at 16:00, at which time radiant target ignition appeared to be imminent but was not observed due to test termination.

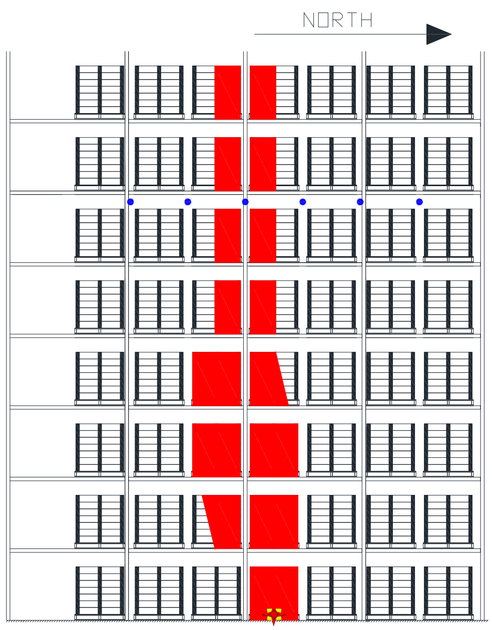


Figure 3.1.3.5.3-1: Test 5 Post Test Damage: Ignition Face of Main Array.

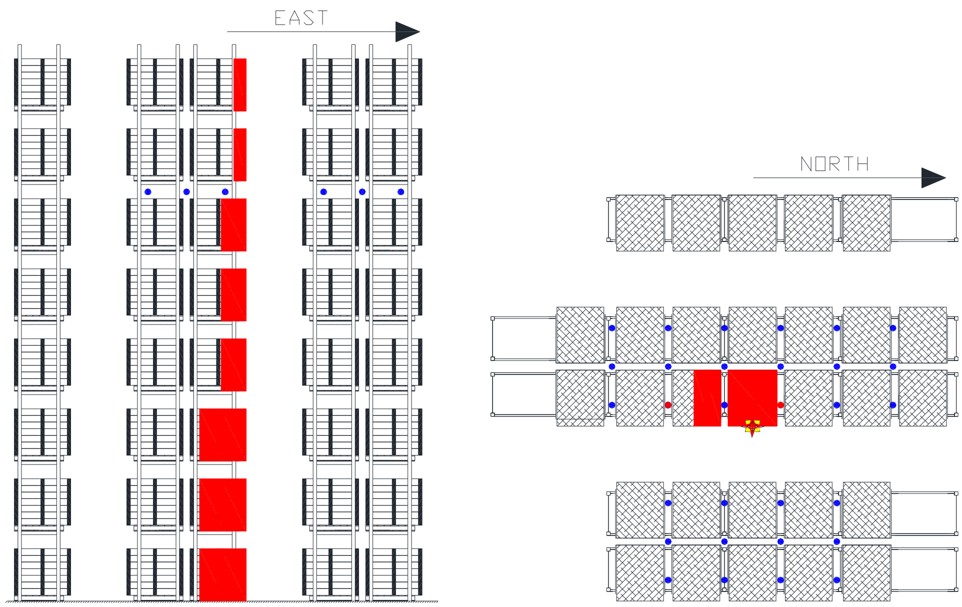


Figure 3.1.3.5.3-2: Test 5 Post Test Damage: (Left) Side Elevation View of Main and Two Target Arrays, (Right) Plan View of Maximum Extent of Damage.

3.1.3.6 Test 6

3.1.3.6.1 Test Overview, Sprinkler Activation Times and Patterns

Ignition occurred at 00:00. At 00:20 flame tips periodically extended to the top of the 1st tier commodity. At 02:45 flames were impinging on the 3rd tier commodity and at 03:20 flames periodically flashed to the top of the 4th tier commodity. At 03:35 flames were observed within the longitudinal flue and at 03:39 the fire was impinging on the 5th tier commodity. The 1st IRAS activated in the transverse flue at 03:40, followed immediately by the 2nd and final IRAS activation at 03:42 within the longitudinal flue. Figure 3.1.3.6.1-1a shows the state of the fire 2 seconds after the 2nd IRAS activation. By 04:00 the fire was confined to tiers 1-3; Figure 3.1.3.6.1-1b shows the fire at 04:10. The fire exhibited a continuous decrease in severity until the test was terminated at 30:00 and water from firefighter hose streams was used to extinguish the small residual fire.

(a) (b)

Figure 3.1.3.6.1-1: Test 6 (a) at 03:34, (b) at 04:10.

The fire in Test 6 was suppressed by two IRAS activations. They occurred at 03:40 and 03:42 and their locations are shown in Figure 3.1.3.6.1-2. Similar to Tests 1 and 2, the IRAS activation pattern resulting from this test provides evidence that the protection would be adequate if only every other face IRAS had been installed in the main and target arrays. This conclusion is supported by the modeling results where artificial sprinkler skipping was applied to calculate the recommended IRAS water flow rate for this large-scale validation test. This result allows recommending that face sprinklers can be installed with up to 2.4 m (8 ft) horizontal spacing.

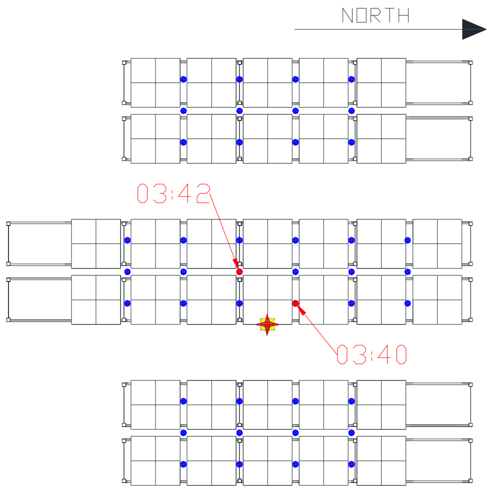


Figure 3.1.3.6.1-2: Test 6 IRAS Activations (CUP Commodity).

3.1.3.6.2 Gas Temperatures

Ceiling level gas temperature reached a maximum of 61˚C (142˚F) in Test 6, which would have been insufficient to cause ceiling level sprinkler activation had sprinklers been installed. The IRAS protection system was successful at providing modular fire control.

3.1.3.6.3 Extent of Damage

Test 6 post-test damage is shown in Figure 3.1.3.6.3-1 and Figure 3.1.3.6.3-2. The fire remained primarily on the east side (ignition side) of the main array; however, flames entered the longitudinal flue at the 2nd tier level and surface charring was observed on the commodity within the longitudinal flue in tiers 2-5. The target did not ignite and the fire and all fire damage remained below the IRAS.

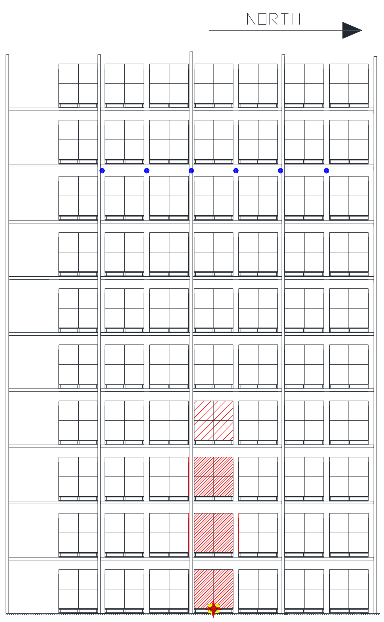


Figure 3.1.3.6.3-1: Test 6 Post Test Damage: Ignition Face of Main Array.

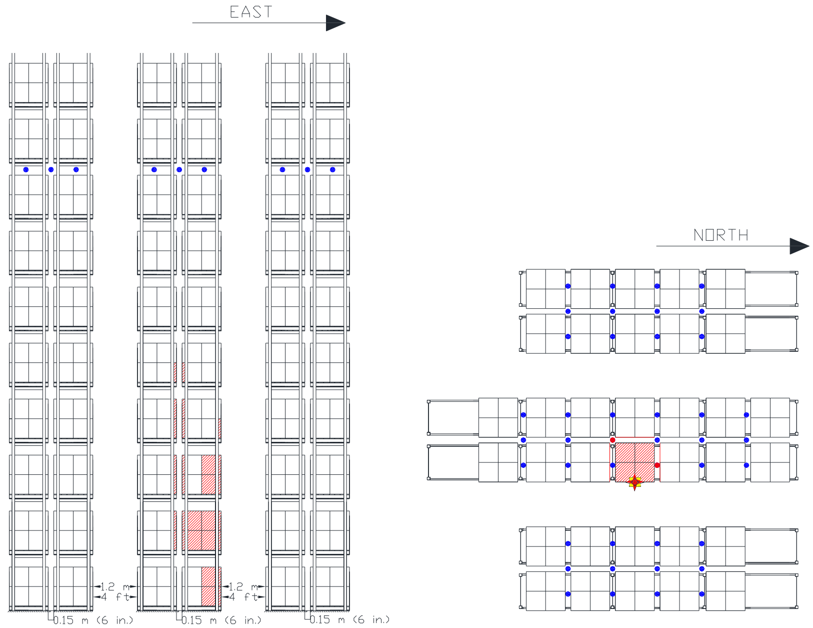


Figure 3.1.3.6.3-2: Test 6 Post Test Damage: (Left) Side Elevation View of Main and Two Target Arrays, (Right) Plan View of Maximum Extent of Damage.

3.2 Protection of Uncartoned Unexpanded Plastics in Open-Frame Double-Row Racks Using Two Different In-Rack Sprinkler Protection Arrangements

3.2.1 Test Overview

A full-scale fire test was conducted to determine if the in-rack sprinkler arrangement recommended in Figure 17.3.1.7 could provide an acceptable level of protection for the open-frame double-row rack storage of UUP. The results of Test 7 have shown that it could not.

Based on the unsuccessful results of Test 7, numerous intermediate-scale fire and water distribution tests coupled with CFD modeling were conducted to establish the parameters for Tests 8 and 9. The intent of Test 8 was to determine if the use of horizontal barriers in combination with the IRAS arrangement recommended in Figure 17.3.1.7 could provide acceptable fire control for the protection of UUP. The results of Test 8 were not favorable and thus are not addressed in this report. The intent of Test 9 was to determine whether an IRAS retrofit protection solution consisting of supplemental quick-response, 70°C (160°F) nominally rated, pendent K320 (K22.4) and larger face sprinklers installed at the 9.1 m (30 ft) tier level, on 2.4 m [8 ft] maximum horizontal spacing, a maximum 0.46 m (18 in.) from the face of the array and arranged to provide a minimum flow of 330 lpm (88 gpm) in combination with the in-rack arrangement indicated in Figure 17.3.1.7 could provide an acceptable level of protection for open-frame single- and double-row rack storage of UUP over 7.6 m (25 ft) high.

The following section details the results of the two tests whose parameters have been documented previously. Table 3.2.1-1 summarizes test parameters and results.

Table 3.2.1-1: Summary of Parameters and Results for Tests 7 and 9.

Test Number	7	9
Test Date	12-May-2014	25-Nov-2014
Ceiling Height (m) [ft]	15.2 (50)	12.2 (40)
Test Commodity/Fuel	FM Global Standard Uncartoned Unexpanded Plastic (UUP)	
Array Size	Large-Scale	
Storage Arrangement – Main Array	2x7x9	2x7x7
Storage Arrangement – Target Array	2x5x9 (x2)	2x5x7 (East), 1x5x7 (West)
Nominal Storage Height (m) [ft]	13.7 (45)	10.7 (35)
Aisle Width (m) [ft]	1.2 (4)	
Pre-test Lab Temperature (˚C) [˚F]	23 (73)	16 (60)
Pre-test Lab Relative Humidity (%)	28	24
Lab Ventilation Rate (m³/sec) [scfm]	94.4 (200,000)	
Ceiling Level Sprinkler Protection Details		
Ignition Location with Respect to Ceiling Sprinklers	Offset Between 2	DNA
Distance from Ceiling to Sprinkler Deflector (mm) [in.]	305 (12)	DNA
Ceiling Sprinkler Temperature Rating (˚C) [˚F]	68 (155)	DNA
Ceiling Sprinkler Orientation	Upright	DNA
Ceiling Sprinkler RTI Rating	Standard-Response	DNA
Ceiling Sprinkler K-factor (lpm/(bar)½) [gpm/(psi)½]	80 (5.6)	DNA
Ceiling Sprinkler Spacing (m x m) [ft x ft]	3.0 x 3.0 (10 x 10)	DNA
Ceiling Sprinkler Discharge Pressure (bar) [psi]	0.8 (11)	DNA
Nominal Discharge per Ceiling Sprinkler (l/min) [gpm]	68 (18)	DNA
In-Rack Sprinkler Protection Details		
Number of In-Rack Levels	4	3
Elevation of Longitudinal In-Rack Level (m) [ft]	3.0, 6.1, 9.1, 12.2 (10, 20, 30, 40)	3.0, 6.1, 9.1, 12.2 (10, 20, 30)
Elevation of Face In-Rack Level (m) [ft]	DNA	9.1 (30)
In-Rack Sprinkler Temperature Rating (˚C) [˚F]	74 (165)	
In-Rack Sprinkler Type	Pendent	
In-Rack RTI Rating	Quick-Response	
Longitudinal In-Rack Sprinkler K-factor (lpm/(bar)½) [gpm/(psi)½]	115 (8.0)	
Face In-Rack Sprinkler K-factor (lpm/(bar)½) [gpm/(psi)½]	DNA	360 (25.2)
Longitudinal In-Rack Sprinkler Location	Intersection of Every Transverse/Longitudinal Flue	
Face In-Rack Sprinkler Location	DNA	At Every Transverse Flue Space at Rack Upright
Longitudinal In-Rack Horizontal Spacing (m) [ft]	1.2 (4)	
Face In-Rack Horizontal Spacing (m) [ft]	DNA	2.4 (8)
Distance from Commodity to Sprinkler Deflector (mm) [in.]	102 (4)	
Nominal Discharge per Longitudinal In-Rack Sprinkler (lpm) [gpm]	114 (30)	
Nominal Discharge per Face In-Rack Sprinkler (lpm) [gpm]	DNA	330 (88)
FIRE TEST RESULTS		
Total Ceiling Sprinkler Activations	56	DNA
Total Longitudinal In-Rack Sprinkler Activations	8 (7 in Main Array and 1 in Target Array)	2
Total Face In-Rack Sprinkler Activations	DNA	2
First/Last Ceiling Sprinkler Activation Times (min:s)	7:13/12:59	DNA
First/Last In-Rack Sprinkler Activation Times (min:s)	7:10/14:56	6:42/15:22
Maximum Ceiling Level Gas Temperature (˚C) [˚F]	1,060 (1,940) @ 14:25	290 (554] @ 7:14
Target Ignition	Yes	No
Target Ignition Time (min:s)	12:10	DNA
Ignition of Commodity Above IRAS	Yes	No
Test Termination Time (min)	15:00	30:00
Test Pass or Fail	Fail	Pass

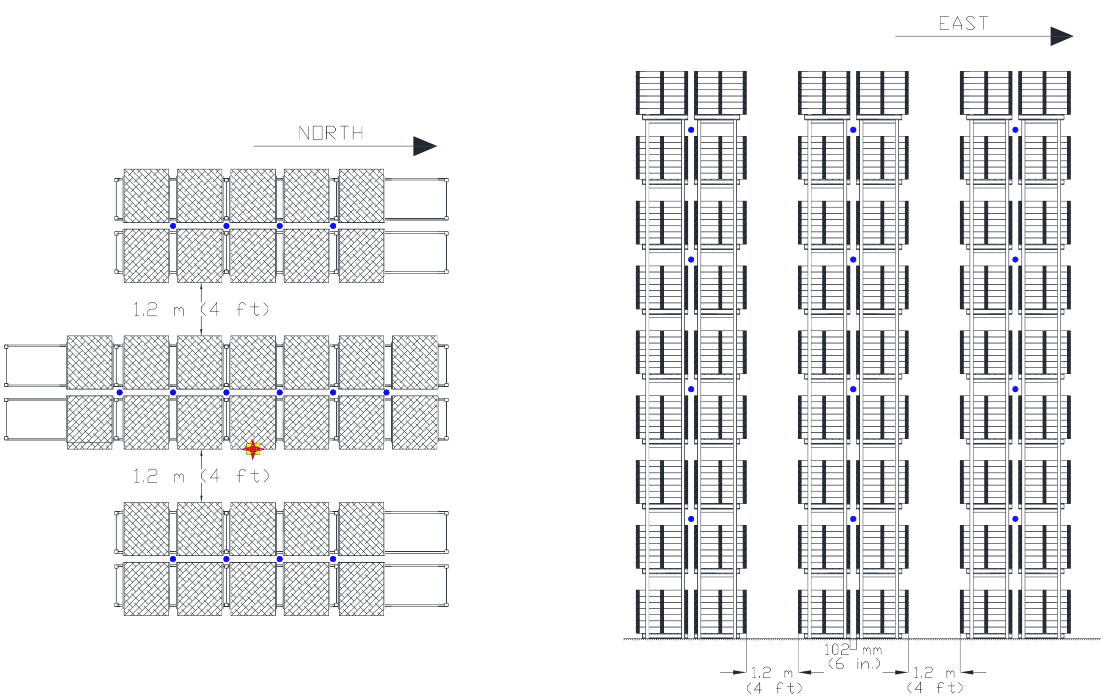
Note that all times stated in this report are from the start of the fire test (i.e., ignition) and are expressed as min:sec unless otherwise noted.

3.2.2 Test Setup

3.2.2.1 <u>Array Description</u>

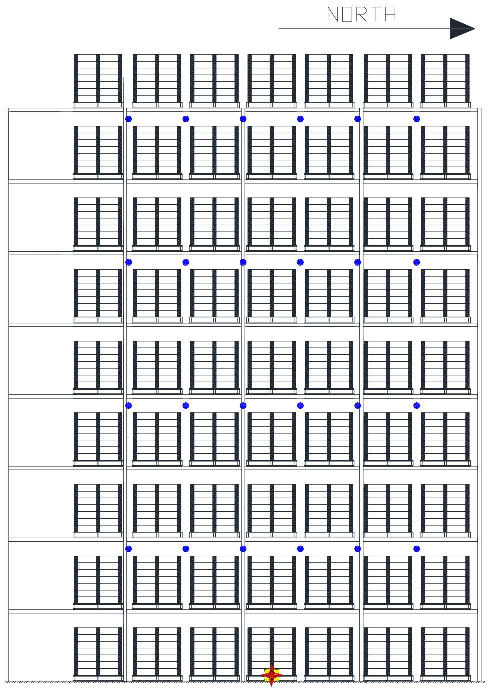
Test 7 was conducted under the north movable ceiling within the Large Burn Laboratory at the FM Global Research Campus within the Fire Technology Building. The test ceiling was set to a height of 15.2 m (50 ft). The test setup consisted of nine-tier high, open-frame rack storage arrangements of FM Global Standard Uncartoned Unexpanded Plastic (UUP). The total storage height was approximately 13.7 m (45 ft). The main array was a double-row rack which was seven pallet loads long and had 0.15 m (6 in.) transverse and longitudinal flue spaces. The center of the main array was positioned 0.69 m (27 in.) west of the ceiling center. The target arrays, which were identical to the main array with the exception that they were five pallet loads long, were located to the east and west of the main array across from a 1.2 m (4 ft) aisle.

The plan view and side elevation view of the array setup are shown in Figure 3.2.2.1-1. The front elevation view of the main array is given in Figure 3.2.2.1-2a, while Figure 3.2.2.1-2b shows a pre-test picture of the test setup looking north.

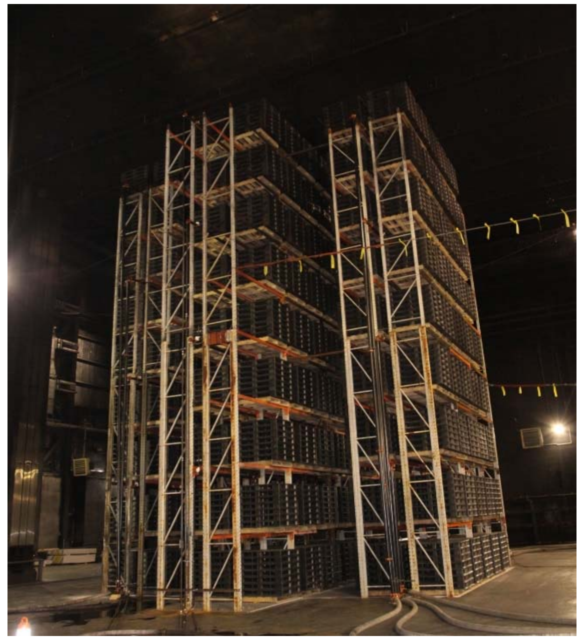


(a) (b)

Figure 3.2.2.1-1: Test 7 (a) plan view of main and target arrays IRAS, (1.2 m [4 ft] horizontal spacing) shown within longitudinal flue, (b) side elevation view of main and target arrays separated by 1.2 m (4 ft) aisles. IRAS, (3.0 m [10 ft] vertical spacing), shown within longitudinal flue.



(a)



(b)

Figure 3.2.2.1-2: Test 7 (a) front elevation view of main array, (b) pre-test image of setup looking northwest.

Test 9 was conducted under the North movable ceiling and the ceiling was set to a height of 12.2 m (40 ft). The test setup consisted of seven tier high, open-frame rack storage arrangement of FM Global Standard Uncartoned Unexpanded Plastic (UUP). The total storage height was approximately 10.7 m (35 ft). The main array was a double-row rack which was seven pallet loads long and had 0.15 m (6 in.) transverse and longitudinal flue spaces. The center of the main array was positioned 0.69 m (27 in.) west of the ceiling center. The target arrays were located to the east and west of the main array across from a 1.2 m (4 ft) aisle. Both east and west targets were five pallet loads long; the west target was a single row rack (i.e., 1x5x7), whereas the east target array was a double-row rack (i.e., 2x5x7).

The plan view, side elevation view and pretest picture of the array setup are shown in Figure 3.2.2.1-3 and Figure 3.2.2.1-4. The front elevation view of the main array is shown in Figure 3.2.2.1-5.

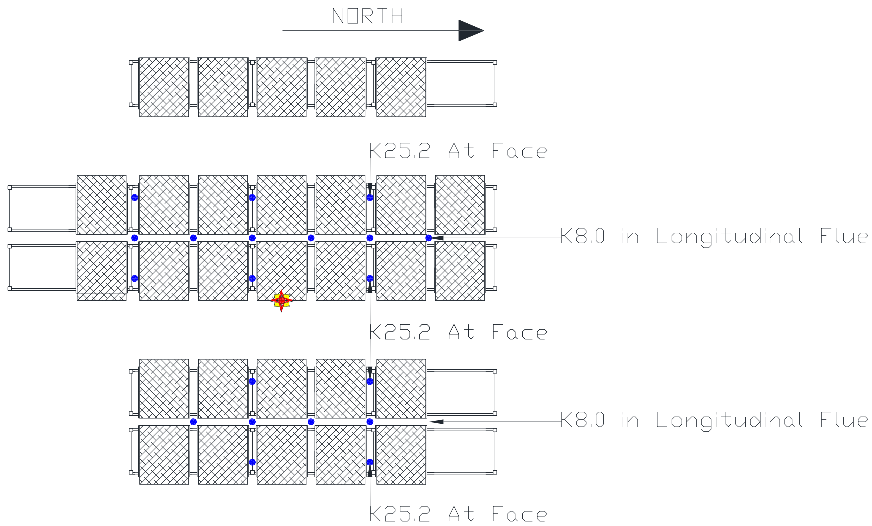
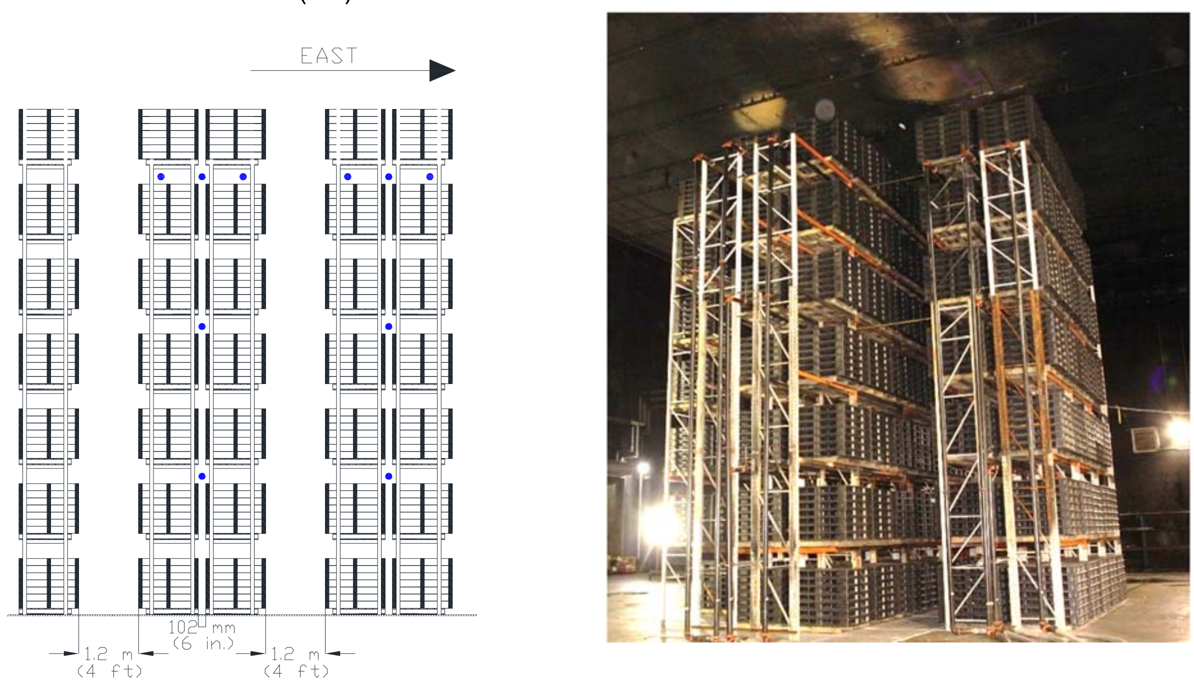


Figure 3.2.2.1-3: Test 9 plan view of main and target arrays separated by 1.2 m (4 ft) aisles.



(a) (b)

Figure 3.2.2.1-4: Test 9 (a) side elevation view, (b) pre-test image of setup looking northwest

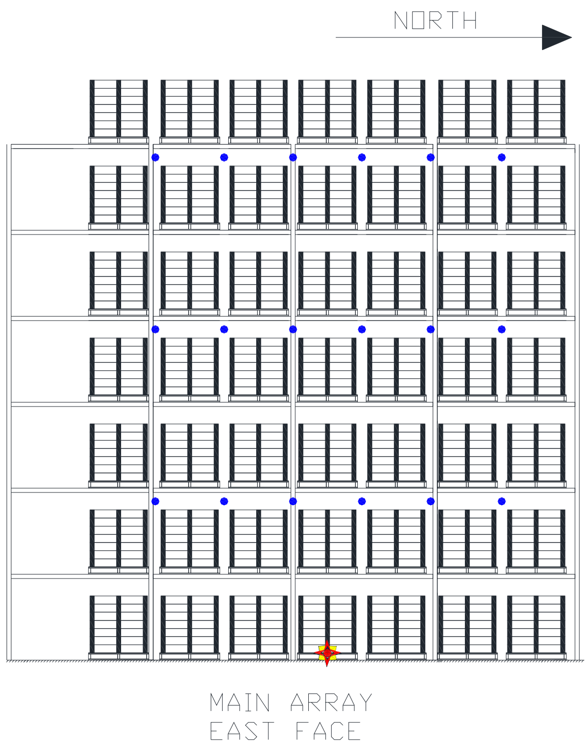


Figure 3.2.2.1-5: Test 9 front elevation view of main array

3.2.2.2 Test Commodity

The rack storage UUP test commodity consists of seven plastic pallets stacked on top of an ordinary, two-way, slatted deck, hardwood pallet resulting in an overall dimension of 1.07 m x 1.22 m x 1.11 m (42 in. x 48 in. x 44 in.). The standard plastic pallets used by FM Global are high-density polyethylene plastic pallets. The four-way entry plastic pallets are not FM Approved and do not contain fire retardant materials. The pallets have dimensions of 1.02 m (40 in.) long by 1.22 m (48 in.) wide by 14 cm (5.6 in.) high and weigh about 25.4 kg [56 lb] each. The total combustible weight of one standard rack storage UUP pallet load is 200.3 kg (441.6 lb); the plastic pallets weigh approximately 177.9 kg (392.2 lb), and the hardwood pallet that supports the commodity weighs approximately 22.4 kg (49.4 lb). A photo of the standard rack storage UUP commodity is provided in Figure 3.2.2.2-1.

Figure 3.2.2.2-1: FM Global Standard Uncartoned Unexpanded Plastic (UUP) Commodity.

3.2.2.3 Protection Description

3.2.2.3.1 In-Rack Sprinkler Protection

In-rack sprinkler protection for Test 7 was provided in the longitudinal flue space only. In-rack sprinkler protection for the longitudinal flue space in Test 9 was the same as provided for Test 7, however it was supplemented with face sprinklers as outlined below.

In-rack automatic sprinkler protection in the longitudinal flue space for Tests 7 and 9 was provided by quick-response, 74°C (165°F) rated, K115 (K8.0) pendent sprinklers. Each sprinkler was outfitted with a water shield. The distance from the sprinkler deflector to the top of the commodity was 102 mm (4 in.). The IRAS were installed on 1.2 m [4 ft] horizontal spacing and located at the intersection of every transverse flue. The vertical separation was approximately 3.0 m (10 ft) resulting in IRAS located above the 2nd, 4th, 6th, and 8th tier commodity. Figure 3.2.2.1-1 shows a plan and elevation view of the IRAS placement (blue colored solid circles within longitudinal flue), respectively.

For Test 7 the longitudinal in-rack sprinkler system was designed to flow a constant 114 lpm (30 gpm) per sprinkler. A constant pressure of 1.0 bar (15 psig) was supplied to the in-rack system regardless of vertical elevation.

For Test 9 the longitudinal in-rack sprinkler system was designed to flow a constant 114 lpm (30 gpm) per sprinkler. A constant pressure of 1.0 bar (15 psig) was supplied to the in-rack system regardless of vertical elevation.

For Test 9 in-rack automatic sprinkler protection was provided at the face of the rack using quick-response, 74°C (165°F) rated, K360 (K25.2) pendent sprinklers. They were not equipped with water shields. These sprinklers were installed at the 9.1 m (30 ft) elevation on 2.4 m (8 ft) horizontal spacing in every other transverse flue space at the rack uprights, 0.46 m (18 in.) from the face of the array and 102 mm (4 in.) above the top of the commodity. The face sprinklers were provided with constant water flow of 330 lpm (88 gpm) per sprinkler.

Figure 3.2.2.1-3 and Figure 3.2.2.1-4a show a plan and elevation view of the IRAS placement (blue colored solid circles), respectively.

3.2.2.3.2 Ceiling Sprinkler Protection

Ceiling sprinkler protection for Test 7 was provided by standard-response, 68°C (155°F) rated, K80 (K5.6) upright sprinklers. The distance from the ceiling to the sprinkler thermal element was nominally 0.3 m (12 in.). Fifty-six (56) ceiling level sprinklers were installed. They were installed on a 3.0 m x 3.0 m (10 ft x 10 ft) spacing and supplied with a constant 0.8 bar (11 psig) resulting in a water density of 7.3 mm/min (0.18 gpm/ft^2).

Ceiling sprinkler protection was not provided for Test 8. Ceiling level gas temperatures were used to calculate the maximum potential sprinkler activation area.

3.2.3 Results

3.2.3.1 Test 7

3.2.3.1.1 Sprinkler Activation Times and Patterns

Ignition occurred at time 00:00. At 01:45 flame tips had extended to the top of the 1st tier commodity. At 04:45 active flaming was confined to the eastern half of the 1st tier ignition pallet load and flame tips extended to the base of the 2nd tier commodity. At 05:34 flames extended to the top of the 2nd tier commodity, and were flashing to the top of the 4th tier commodity at 06:10. At 06:59 flames were observed extending into the longitudinal flue at the 2nd and 3rd tier; at 07:10 the first IRAS activated above the 4th tier commodity (6.1 m [20 ft]). Three seconds later (07:13) the first ceiling level sprinkler activated followed immediately by the 2nd IRAS activation at 07:14 above the 2nd tier commodity (3.0 m [10 ft]). An image of the state of the fire at this time is shown in Figure 3.2.3.1.1-1a.

At 07:55 no flames were present in the longitudinal flue; however, the fire on the east face of the main array appeared unabated by application of sprinkler water. The fire intensity increased and at 09:12 flames were flashing to the top of the nine-tier high array (13.7 m [45 ft]) (Figure 3.2.3.1.1-1b). At 09:50 the 3rd IRAS activated above the 4th tier commodity. The fire continued to intensify and at 10:13 flames had reached ceiling level, at which time ten ceiling level sprinklers had activated (Figure 3.2.3.1.1-1c). At 11:20 the fire continued to intensify, with 36 ceiling level sprinklers activated. Flames continued to involve tiers 1-9 of the main array and impinged on the ceiling spreading radially to a distance of 6.1 m (20 ft). Figure 3.2.3.1.1-1d shows an image of the fire at approximately this time. Forty-six (46) ceiling level sprinklers had activated by 11:50 and the 4th IRAS activated at 11:56 above the 8th tier commodity (12.2 m [40 ft]).

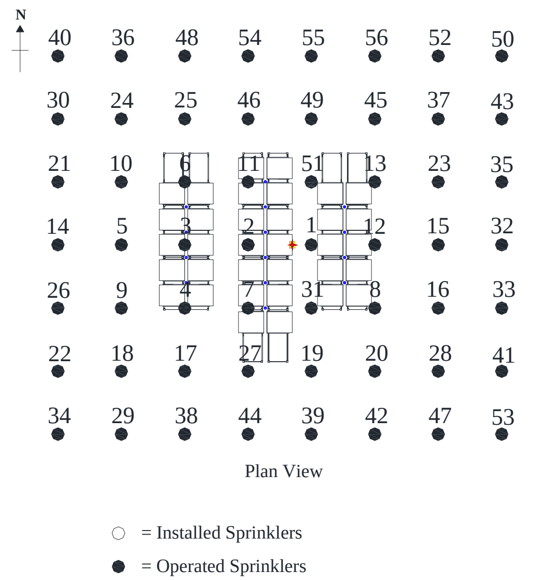
At 12:09 two IRAS activated above the 6th tier commodity bringing the total IRAS count to six. Radiant ignition of the east target occurred at approximately 12:10 (Figure 3.2.3.1.1-1e). The fire continued to intensify and at 12:59 all of the fifty-six (56) ceiling level sprinklers installed for the test had activated. The fire continued to intensify. Fire involved tiers 1-9 in the east side of the main array and tiers 3-9 in the west side of the east target. Flames impinged on the ceiling and spread radially to a distance of up to 12.2 m (40 ft). The state of the fire at 14:18 is shown in Figure 3.2.3.1.1-1f. At 14:56 an IRAS in the east target activated above the 8th tier commodity. The fire continued to intensify. At 15:00 the test was terminated by application of firefighter hose streams.

(a) (b) (c)

(d) (e) (f)

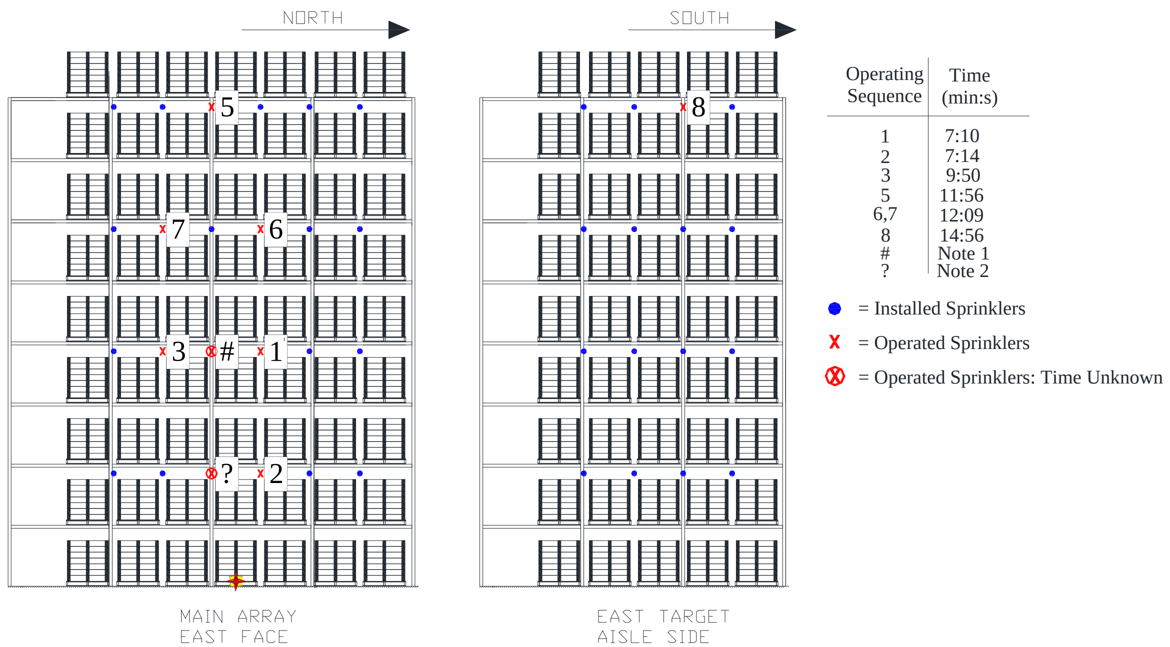
Figure 3.2.3.1.1-1: Test 7 images of fire test: (a) 07:18, eight and five seconds after the 1st IRAS and 1st ceiling level sprinkler activation, respectively, (b) 09:18, flames reach top of main array, (c) 10:13, 10 ceiling sprinklers active, (d) 11:32, 41 ceiling sprinklers active, (e) 12:10, east target ignites, (f) 14:18, state of fire prior to test termination. [Note: different view angles and scale]

Sprinkler activation times and locations are given separately for the ceiling and the in-rack system in Figure 3.2.3.1.1-1 and Figure 3.2.3.1.1-3, respectively. Seven IRAS are known to have activated during the 15 minute test. During a post-test inspection, nine IRAS were found active; it is unknown whether the two additional activations occurred during the fire test or post-test firefighter intervention. Every ceiling level sprinkler activated during the test (i.e., 56 total) and ceiling level gas temperatures at the perimeter of the ceiling indicate that the activation area would have been greater.



Operating Sequence	Time (min:s)	Operating Sequence	Time (min:s)
1	7:13	31	11:00
2	7:26	32	11:04
3	9:21	33	11:05
4	9:46	34	11:07
5	9:52	35,36	11:10
6	9:56	37	11:13
7,8	9:57	38	11:17
9	10:08	39	11:18
10	10:13	40	11:19
11	10:15	41	11:26
12	10:21	42	11:36
13,14,15	10:25	43	11:38
16	10:26	44	11:40
17,18	10:30	45	11:45
19	10:36	46	11:47
20	10:37	47	11:58
21	10:38	48	12:02
22	10:39	49	12:09
23	10:40	50,51	12:10
24	10:41	52	12:18
25,26	10:44	53	12:19
27	10:46	54	12:29
28	10:55	55	12:52
29	10:58	56	12:59
30	10:59		

Figure 3.2.3.1.1-2: Test 7 ceiling level sprinkler activation location and sequence of operation.



Note 1: Post test inspection revealed that this sprinkler had activated; however, its activation did not report to the data acquisition system. Based on the pressure in the pipe, it is believed that this sprinkler activated simultaneously with either the first (07:10) or third (09:50) IRAS activation bringing the total number of in-rack activations to four.
Note 2: Post test inspection revealed that this sprinkler had activated; however, its activation did not report to the data acquisition system and activation time is unknown.

Figure 3.2.3.1.1-3: Test 7 in-rack sprinkler activation location and sequence of operation.

3.2.3.1.2 Gas Temperatures

Temperature contour plots in Figure 3.2.3.1.2-1 and Figure 3.2.3.1.2-2 show the ceiling level gas temperatures in one minute increments starting at 07:00 and ending at 15:00. The temperature scale has a range of 38˚C-538˚C (100˚F 1000˚F); the green squares represent inactivate ceiling level sprinklers. The red squares represent active ceiling level sprinklers. These contour plots show the increasing trend of ceiling level gas temperatures resulting from the uncontrolled fire. Note that temperatures reported herein have been rounded to three significant digits.

The maximum ceiling level gas temperature was 1060˚C (1940˚F) at 14:25. The maximum one-minute average gas temperature was 1040˚C (1900˚F). The gas temperature at the center of the ceiling achieved 538˚C (1000˚F) at 10:17 and remained above that value until the end of the 15-minute test with an average value of 932˚C (1710˚F) during that time frame. Figure 3.2.3.1.2-3 shows a representative ceiling level gas temperature trend.

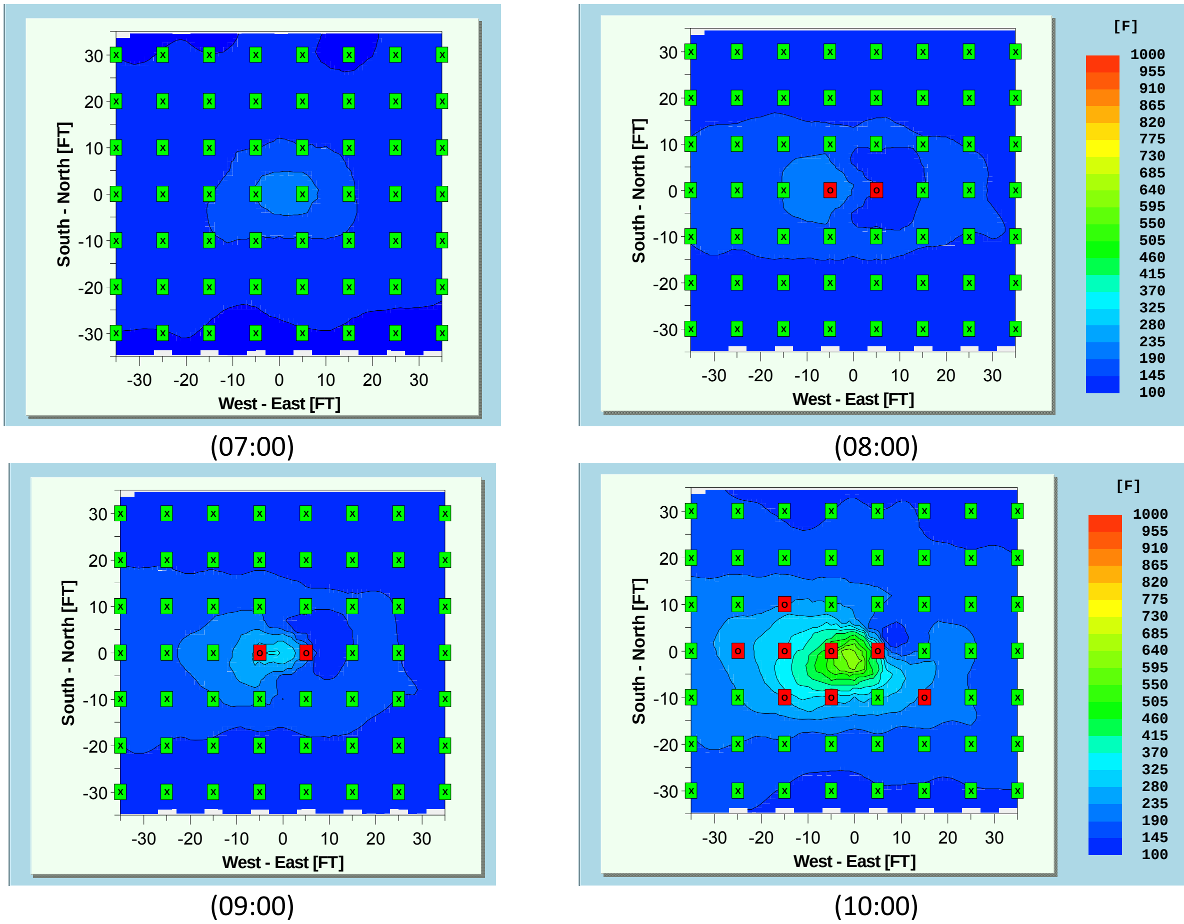


Figure 3.2.3.1.2-1: Test 7 ceiling level gas temperature contours: 07:00 through 10:00.

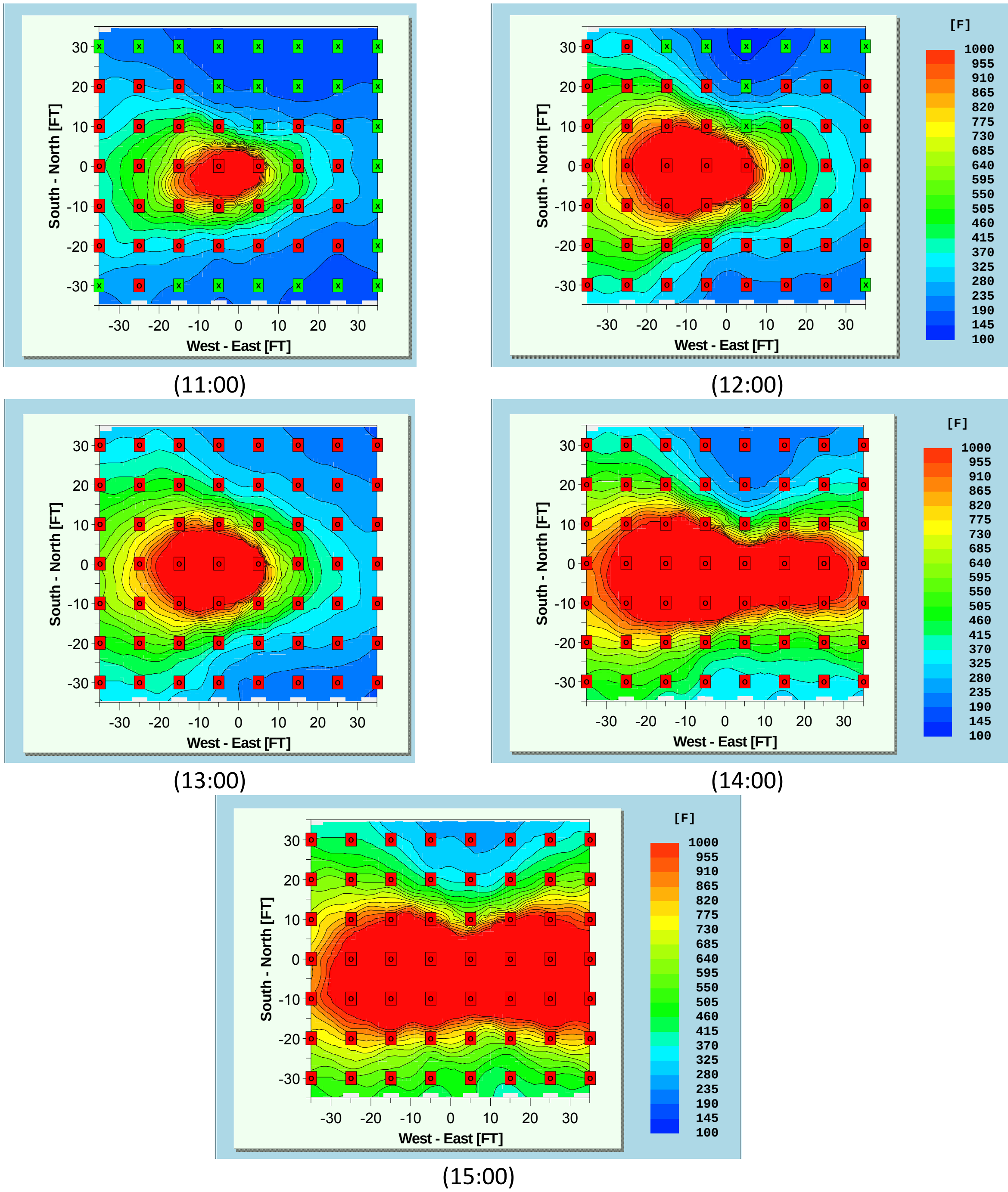


Figure 3.2.3.1.2-2: Test 7 ceiling level gas temperature contours: 11:00 through 15:00 test termination.

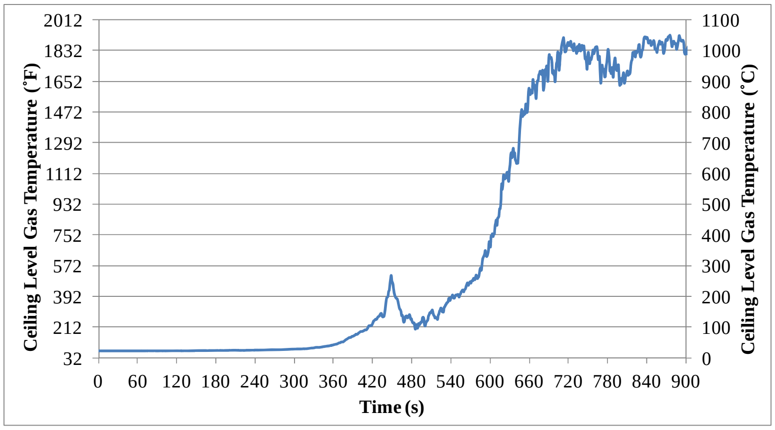


Figure 3.2.3.1.2-3: Test 7 ceiling level gas temperature.

3.2.3.1.3 Extent of Damage

Diagrams depicting the extent of damage are shown in Figure 3.2.3.1.3-1. The fire remained on the east side of the main array, never traversing the longitudinal flue to the west side of the array. Its north-south propagation was limited to the pallets of commodity directly above, north, and south of ignition. Although fire progression was limited to the west, north, and south, the damage resulting from the face fire on the east side of the main array was severe. Damage resulted to the west face of the east target array due to radiant ignition from the main array fire. East target array damage was confined to the west side of the array within the column of commodity directly across from ignition as well as those directly north and south of that column. The fire was intensifying at the time of test termination and the extent of damage would likely have been greater had the test been allowed to continue.

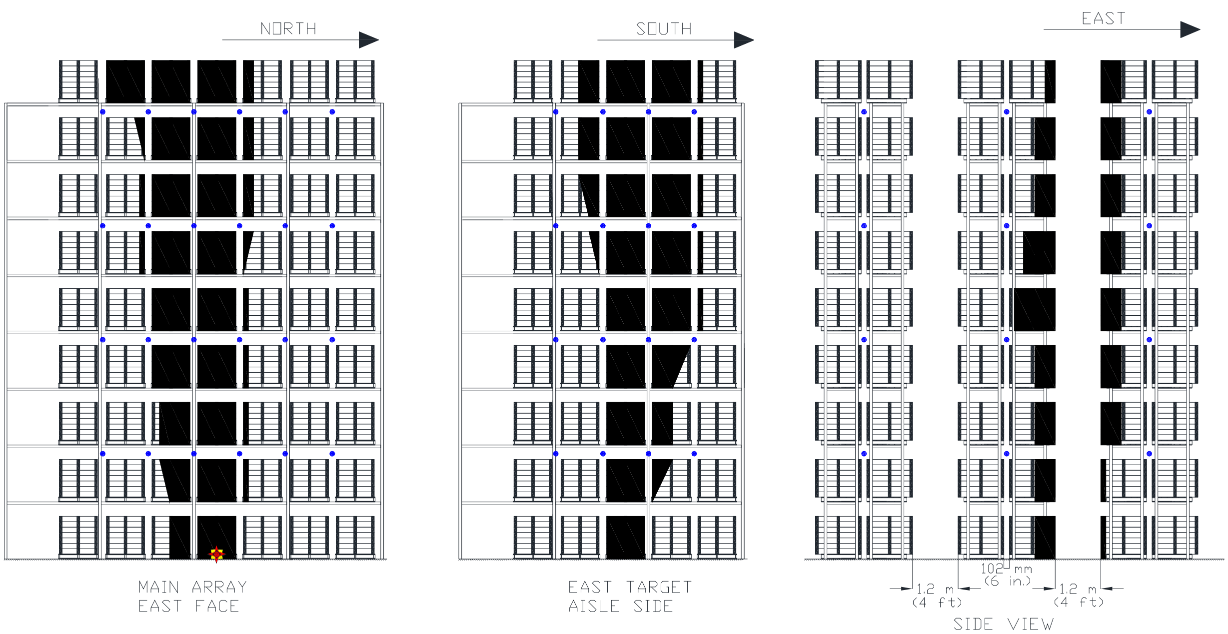


Figure 3.2.3.1.3-1: Test 7 fire damage to main and east target array.

3.2.3.2 Test 9

3.2.3.2.1 Sprinkler Activation Times and Patterns

Ignition occurred at time 00:00. The flames steadily extended to the top of the ignition pallet at 02:00 and were still confined to the ignition pallet at 04:00. At 04:30 flames were steadily impinging on the 2nd tier commodity; flames extended above the top of the 3rd tier commodity at 05:45. Flame tips periodically extended above the top of the 5th tier commodity at 06:25. The 1st IRAS activation occurred at 06:42 (Figure 3.2.3.2.1-1a); it was a K360 (K25.2) face sprinkler installed at the 9.1 m (30 ft) elevation and located within the transverse flue south of ignition. The application of that sprinkler water stopped fire propagation in the southern direction.

At 07:01 the 2nd IRAS activation occurred at the 6.1 m (20 ft) elevation at the intersection of the transverse/longitudinal flue north of ignition. The 3rd IRAS activation occurred 4 seconds later (07:05) directly below the previous at the 3.0 m (10 ft) elevation; the state of the fire at this time is shown in Figure 3.2.3.2.1-1b. At 07:10 the application of water appeared to have reduced the overall flame height; commodity in tiers 1-3 was burning and flames periodically extended to the top of the 5th tier commodity. By 07:20 flame tips had been reduced and extended to the top of the 4th tier commodity. The fire was confined in tiers one and two at 07:50 (Figure 3.2.3.2.1-1c) and remained relatively stable until 09:15 when the fire intensity exhibited a marginal increase.

At 09:33 the fire was observed to have shifted northward and was now involving the column of commodity north of ignition. The fire intensified and at 10:50 flames extended above the 3rd tier commodity and would occasionally flash to the 4th tier commodity by 11:30. At 15:00 the fire involved tiers 1-4 and flames periodically extended to the top of the 5th tier commodity. At 15:20 the fire was observed propagating into the northern transverse flue containing a face sprinkler. That K360 (K25.2) face sprinkler, 9.1 m (30 ft) elevation north of ignition, activated at 15:22; it was the 4th and final IRAS activation; Figure 3.2.3.2.1-1d shows the state of the fire at this time. The fire severity had decreased significantly by 15:40 (Figure 3.2.3.2.1-1e) and by 15:50 flames were barely visible within the test array. At 17:25 it was noted that the ceiling level gas temperatures had returned to ambient and minor flames (less than 0.15 m [6 in.]) could be seen in the 1st and 2nd tiers of the ignition column. Figure 3.2.3.2.1-1f shows the state of the fire at 20:00. The fire remained fully suppressed until the test was terminated at 30:00.

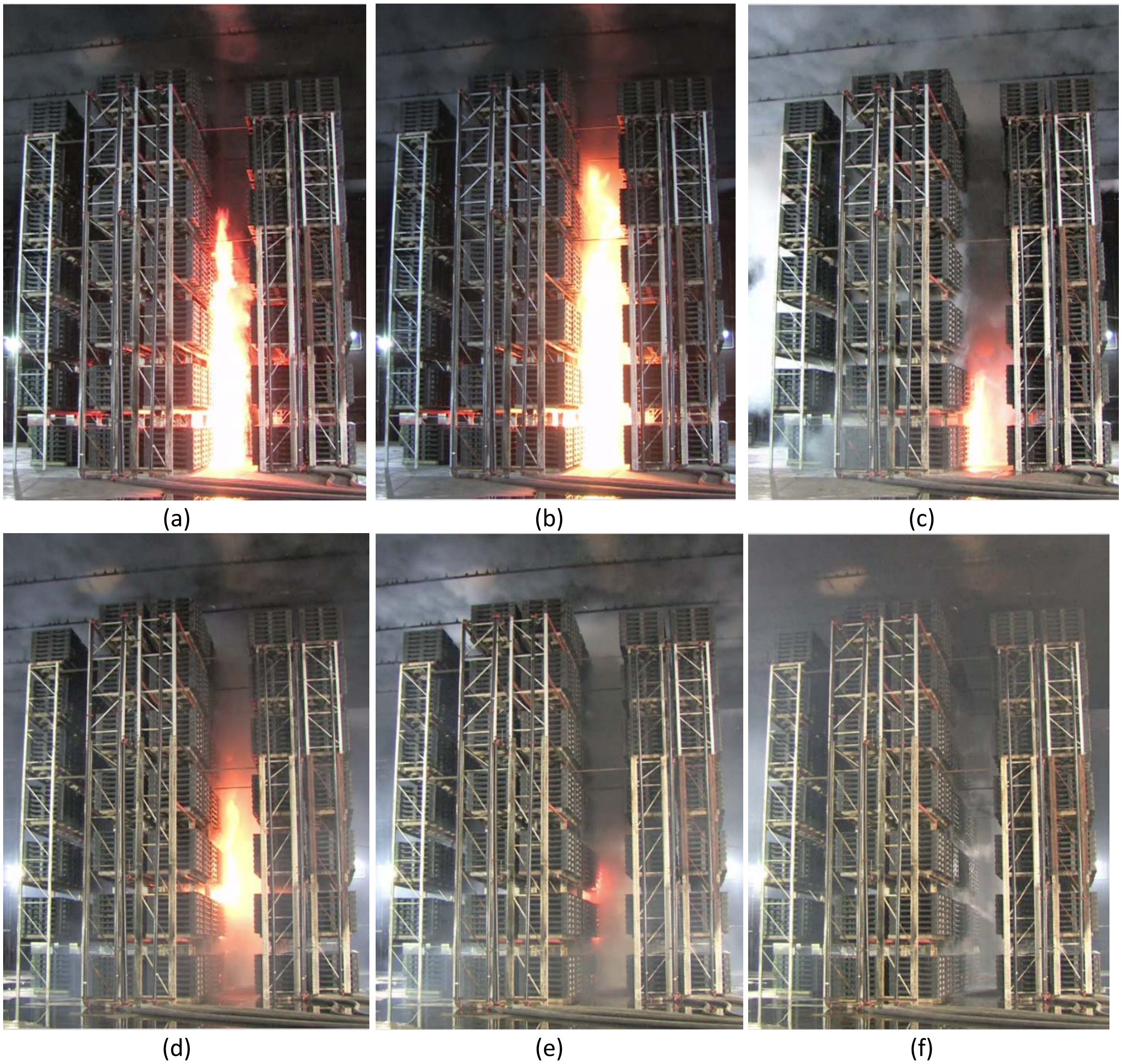


Figure 3.2.3.2.1-1: Test 9 images: (a) 06:42, time of 1st IRAS activation, (b) 07:05, time of 3rd IRAS activation, (c) 07:50, reduced fire severity, 45 seconds after 3rd IRAS activation (d) 15:22, time of 4th and final IRAS activation, (e) 15:40, fire severity decreased, (f) 20:00, fire is suppressed.

There were no ceiling level sprinklers installed during Test 9; four IRAS activated and suppressed the fire. These activations are shown in Figure 3.2.3.2.1-2. The first IRAS activation occurred at 06:42 and was a K360 (K25.2) sprinkler located at the face of the array in the transverse flue south of ignition. The sprinkler was located behind a rack upright and provided a water flow rate of 330 lpm (88 gpm). The fire severity did not immediately decrease following this activation. The 2nd and 3rd IRAS activations occurred at 07:01 and 07:05. They were K115 (K8.0) sprinklers each providing a water flow rate of 114 lpm (30 gpm). Both were located at the intersection of the transverse/longitudinal flue north of ignition at the 6.1 m (20 ft) and 3.0 m (10 ft) elevation. These three IRAS activations reduced the fire size and prevented southern and western flame propagation. However, the fire was able to propagate north where it activated the 4th and final IRAS at 15:22. That IRAS, a K360 (K25.2) sprinkler providing 330 lpm (88 gpm) of water, was located at the 9.1 m (30 ft) elevation two transverse flues north of ignition. The fire was rapidly suppressed following this final IRAS activation.

Additionally, the fire was suppressed with the combined water flow of two face sprinklers that had 2.4 m (8 ft) horizontal spacing and two longitudinal flue sprinklers. This outcome, when used in conjunction with the data from Test 4 and modeling results, provides evidence that, for UUP, face sprinklers can be installed behind rack uprights with up to 2.4 m (8 ft) horizontal spacing when designed in accordance with the recommendations given in Section 5.

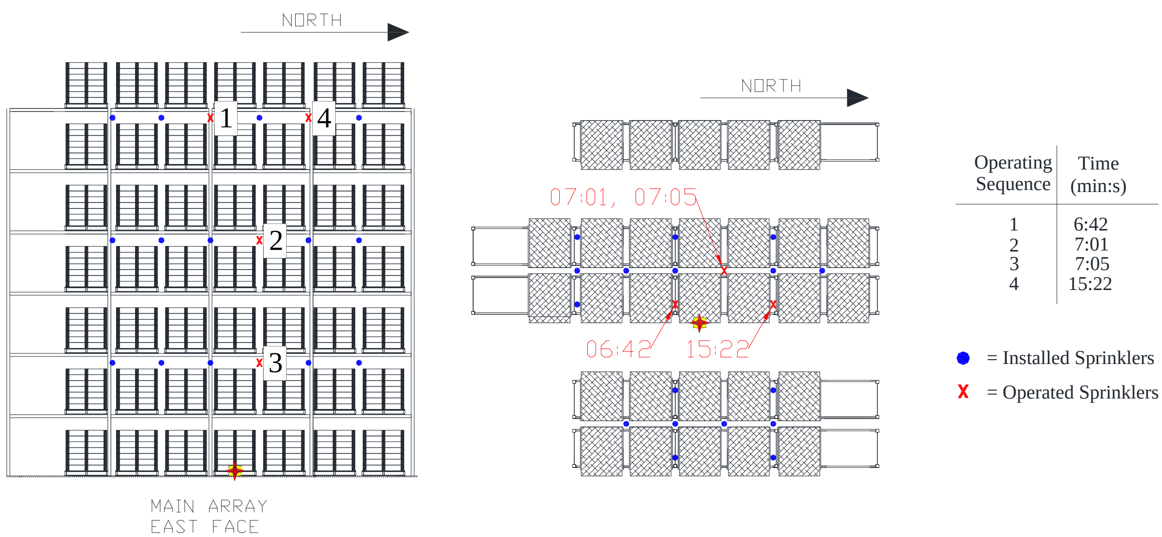


Figure 3.2.3.2.1-2: Test 9 in-rack sprinkler activation location and sequence of operation.

3.2.3.2.2 Gas Temperatures

The maximum ceiling level gas temperature was 290˚C (554˚F) at 07:14. The maximum one-minute average gas temperature was 206˚C (403˚F). Figure 3.2.3.2.2-1 shows a representative ceiling level gas temperature trend.

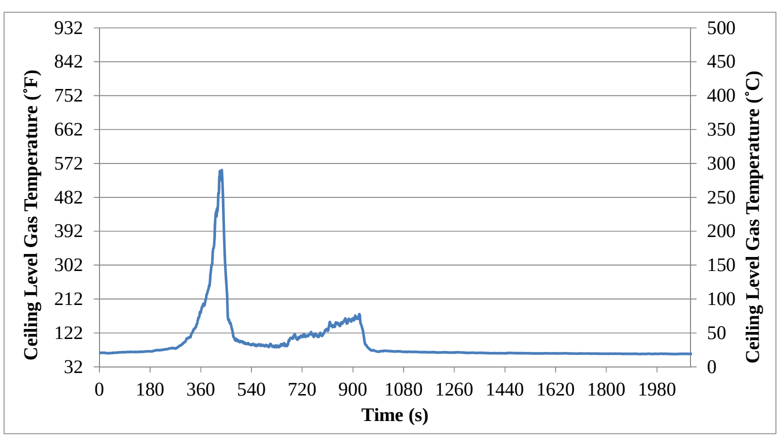
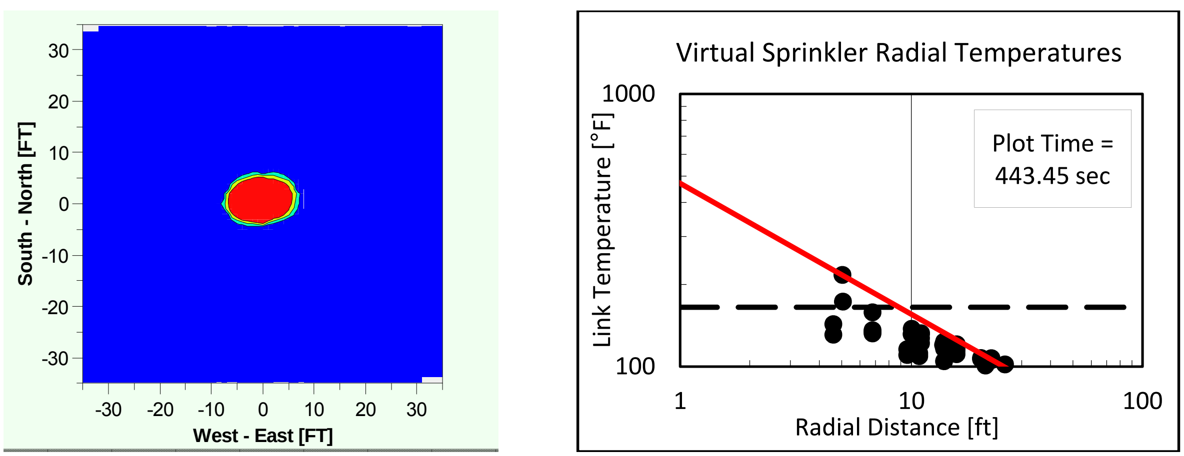


Figure 3.2.3.2.2-1: Test 9 ceiling level gas temperature.

An analysis was conducted using ceiling level gas temperature data to determine if ceiling sprinklers would have activated had they been present, and if so, to what extent. This approach was taken in lieu of providing ceiling level protection so the results could be extrapolated to storage heights greater than that tested. The analysis assumed a ceiling level sprinkler with a standard-response thermal element with a response time index (RTI) of 100 (m-s)$^{1/2}$ (181 (ft-s)$^{1/2}$). Calculated sprinkler thermal element temperatures (STET) are shown in a temperature contour plot in Figure 3.2.3.2.2-2a. The contour plot spans the extent of the 24.4 m by 24.4 m (80 ft by 80 ft) movable ceiling and the temperature range has been selected to highlight the activation area of a ceiling level sprinkler with a 74°C (165°F) temperature rating. The moment in time, 07:23, is selected because it is representative of the largest calculated activation area during the fire test. The red colored temperature region in the center of the contour plot indicates the maximum area where ceiling level sprinkler activations would have been expected to occur.

Additionally, the STET are plotted versus their radial distance from the ceiling center in Figure 3.2.3.2.2-2b for the time step which yielded the maximum radius (i.e., 07:23). A fit is applied to the points defining the outer envelope of the calculated data to identify the maximum radial distance at which the calculated STET drops below the activation temperature of 74°C (165°F). In these figures, the radial distance from the ceiling center is on the abscissa, and calculated STET on the ordinate. During Test 9, 74°C (165°F) rated sprinklers with an RTI of 100 (m s)$^{1/2}$ (181 (ft-s)$^{1/2}$) would be expected to activate within a 2.7 m (9 ft) radius of the ceiling center. Sprinklers with the same RTI and a temperature rating of 141°C (286°F) would not be expected to activate.



(a) (b)

Figure 3.2.3.2.2-2: Estimation of extent of ceiling level sprinkler activations for 74°C (165°F) standard-response sprinklers for the time step which yielded the maximum radius (a) Temperature contour plot showing region of potential activations (red region), (b) Log-log plot of sprinkler link temperature as a function of radial distance from ceiling center.

3.2.3.2.3 Extent of Damage

Diagrams depicting the extent of damage are shown in Figure 3.2.3.2.3-1. The fire remained on the east side of the main array. It never traversed the longitudinal flue to the west side of the array nor did it cause radiant ignition of the east target. The north-south propagation was limited to the pallets of commodity directly above and north of ignition. Damage to the 1st tier commodity in the main array was approximately one half pallet deep, while that to the 2nd and 3rd tier commodity was a quarter pallet deep. Minor damage, apparently due to melting, occurred to the face of the 4th and 5th tier commodity.

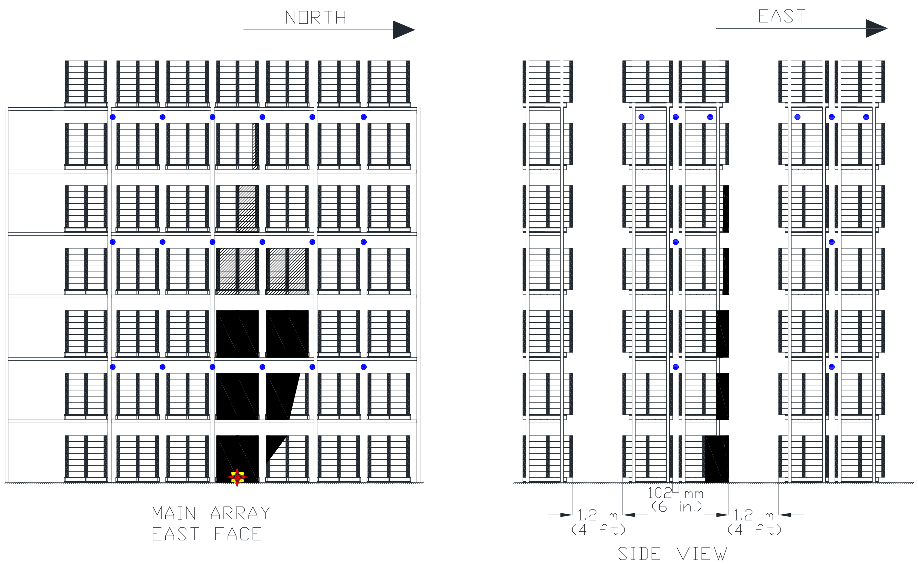


Figure 3.2.3.2.3-1: Test 9 fire damage to main array.

4. Conclusions

4.1 IRAS Sprinkler Designs Using Quick-Response, Pendent, K200 (K14.0) and Larger Sprinklers

The research described in this report indicates that IRAS can be installed at vertical increments up to 9.1 m (30 ft) for Class 1, 2, 3, 4 and plastic commodities, and up to 12.2 m (40 ft) for Class 1, 2, 3, 4 and cartoned unexpanded plastic commodities when IRAS are located at the intersection of every transverse and longitudinal flue (approximately 1.2 m [4 ft] horizontal spacing) as well as within every other transverse flue at the face of the storage up to a maximum horizontal spacing of 2.4 m (8 ft). At this spacing, face IRAS may be placed behind rack uprights to give added protection against accidental activation.

The results of the work described in this technical report led to the following conclusions:

- The K200 (K14.0) sprinkler is adequate to protect CUP at 9.1 m (30 ft) vertical increments at sufficient flow rates, however it is not adequate to protect UUP at this same vertical increment.
- The K360 (K25.2) sprinkler is adequate to protect UUP at 9.1 m (30 ft) vertical increments and CUP at 12.2 m (40 ft) vertical increments at sufficient flow rates.
- For all commodities, protection of commodity at less than 9.1 m (30 ft) vertical increments at equal flow rates is allowed.
- Successful protection schemes were capable of preventing fire spread above the level of IRAS. Therefore, IRAS can be installed in a modular fashion to protect arbitrarily high storage heights.
- In instances where a K200 (K14.0) sprinkler has proven successful, protection designs could allow larger orifice sprinklers at an equivalent flow rate.
- For designs where only the K360 (K25.2) sprinkler was successful, e.g., UUP, use of sprinklers smaller than K360 (K25.2) would not be allowed with the exception of K320 (K22.4) sprinklers.
- Ceiling level sprinklers in the tested designs are only responsible for suppressing the commodity above the topmost IRAS level. Since the IRAS can suppress the fire below their level, the topmost IRAS level can be considered a “floor” for the purpose of selecting the appropriate ceiling level design.

A note of caution regarding sprinkler skipping: IRAS protection systems in the field will likely provide water pressure to the first active sprinkler that is in excess of the design pressure and up to 8.3 bar (120 psig). This high-pressure system pre-charge could result in finer droplets at higher speeds during the initial IRAS activation, thus increasing the risk of skipping. This effect was not quantified in this study but is listed here as a potential concern.

A significant increase in water flow rate is required when the vertical spacing is increased from 9.1 m (30 ft) to 12.2 m (40 ft). At vertical spacing greater than 9.1 m (30 ft), the water demand becomes impractical for commodity hazards greater than CUP. Testing has shown that, when face sprinklers are installed, the fire size at the time of 1st sprinkler activation is practically the same whether the sprinkler is located at the 9.1 m (30 ft) or 12.2 m (40 ft) vertical elevation. However, by increasing the vertical spacing of the IRAS, the sprinkler water requires additional time to reach the base of the protected module. This delay results in a larger fire size when the water eventually provides complete coverage. Based on this reasoning, it is possible to apply the successful protection schemes detailed herein to vertical increments equal to, or less than, those tested.

This test program has also validated a new innovative coupled experimental and computational fluid dynamics (CFD) modeling strategy. Intermediate-scale cold flow water distribution tests were used to validate a newly developed CFD model. Additionally, intermediate-scale IRAS suppression tests were conducted in order to determine the amount of water flux needed to suppress a specific fire size. The validated CFD model was then used to calculate the required sprinkler flow rate necessary to provide that required water flux. The large-scale fire tests detailed herein utilized the calculated optimized IRAS flow rate and successful test results were achieved for CUP, UUP and UEP commodities. This coupled experimental and modeling strategy has proven to provide efficiency and cost savings in large-scale testing. Utilization of this new coupled strategy allows for the number of large-scale fire tests to be minimized and successful protection to be often validated with a single test.

4.2 Protection of Uncartoned Unexpanded Plastics in Open-Frame Double-Row Racks Using Two Different In-Rack Sprinkler Protection Arrangements

The research detailed in this report based on the results of Test 7 shows that open-frame rack storage of UUP cannot be adequately protected by in-rack sprinklers supplied with 114 lpm (30 gpm) located within the longitudinal flue at 1.2 m (4 ft) horizontal and 3.0 m (10 ft) vertical spacing (Figure 17.3.1.7 of NFPA 13, Edition 2016). This IRAS scheme is incapable of providing adequate water to the face of the array thus allowing an uncontrolled fire that will overtax the ceiling-level protection system and result in excessive ceiling-level steel temperatures, threatening building structural integrity.

The research detailed in this report based on the results of Test 9 shows that enhancing the IRAS protection recommended in Figure 17.3.1.7 of NFPA 13, Edition 2016, with the addition of 74°C (165°F) rated, quick-response, pendent K320 (K22.4) or larger face sprinklers at maximum 9.1 m (30 ft) vertical increments on maximum horizontal spacing of 2.4 m (8 ft) and arranged to discharge a minimum flow of 330 lpm (88 gpm) can provide adequate protection for UUP commodity stored in open-frame single- and double-row racks.

5. Recommendations

5.1 IRAS Sprinkler Designs Using Quick-Response, Pendent, K200 (K14.0) and Larger Sprinklers

The IRAS protection options recommended in this section are intended to supplement existing IRAS designs recommended in current standards to protect Class 1, 2, 3, 4 and plastic commodities maintained in open-frame single-, double- and multiple-row racks.

Sprinkler systems acceptable for the IRAS protection options recommended in this section are wet-type only.

Sprinklers acceptable for the IRAS protection options recommended in this section are FM Approved standard-coverage, quick-response, 70˚C (160˚F) nominally rated, K200 (K14.0) and higher pendent Storage sprinklers. Use minimum K320 (K22.4) sprinklers for design flows greater than 380 lpm (100 gpm).

Install sprinklers horizontally within open-frame storage racks as follows:

- Single-row racks up to 0.9 m (3 ft) deep: Maximum 1.2 m (4 ft) horizontal spacing and within 457 mm (18 in.) of either face of the rack face, as shown in Figure 5.1-1.
- Single-row racks over 0.9 m (3 ft) deep and up to 1.8 m (6 ft): Maximum 2.4 m (8 ft) horizontal spacing, staggered with adjacent face sprinklers and within 457 mm (18 in.) of the rack face, as shown in Figure 5.1-2.
- Double-row racks up to 2.7 m (9 ft) deep:
  - Longitudinal IRAS: Maximum 1.2 m (4 ft) horizontal spacing as shown in Figure 5.1-4.
  - Face IRAS: Maximum 2.4 m (8 ft) horizontal spacing and within 457 mm (18 in.) of the rack face as shown in Figure 5.1-4.
- Double-row racks over 2.7 m (9 ft) deep and up to 3.7 m (12 ft): Maximum 1.2 m (4 ft) horizontal spacing with the face sprinklers within 457 mm (18 in.) of the rack face, as shown in Figure 5.1-5.
- Multiple-row racks:
  - Longitudinal IRAS: Maximum 1.2 m (4 ft) horizontal spacing as shown in Figure 5.1-6.
  - Face IRAS: Maximum 2.4 m (8 ft) horizontal spacing and within 457 mm (18 in.) of the rack face as shown in Figure 5.1-6.

Open-frame single-row racks over 0.9 m (3 ft) deep and up to 1.8 m (6 ft) located no more than 0.3 m (1 ft) horizontally from a wall can have a horizontal IRAS arrangement as shown in Figure 5.1-3.

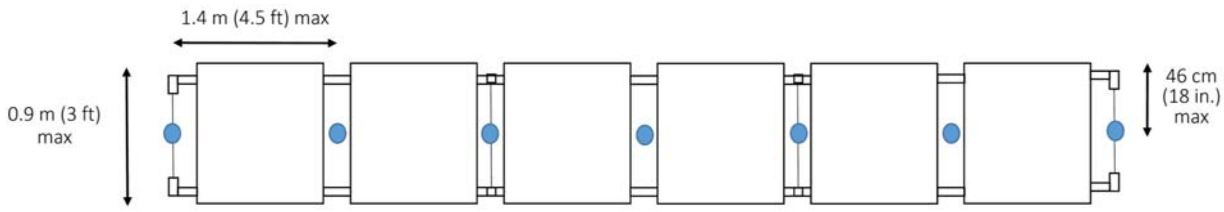


Figure 5.1-1: IRAS arrangement for open-frame, single-row racks up to 0.9 m (3 ft) deep.

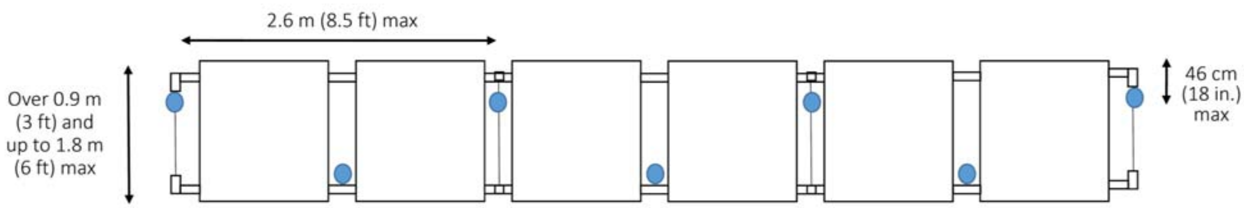


Figure 5.1-2: IRAS arrangement for open-frame, single-row racks over 0.9 m (3 ft) and up to 1.8 m (6 ft) deep.

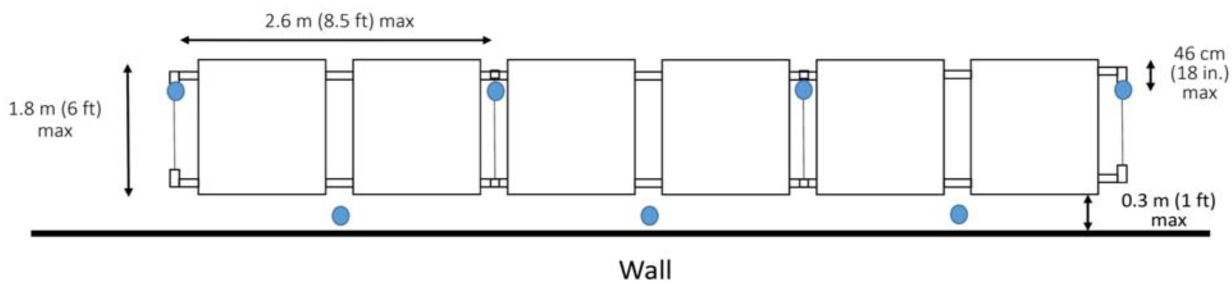


Figure 5.1-3: IRAS arrangement for open-frame, single-row racks over 0.9 m (3 ft) and up to 1.8 m (6 ft) deep located within 0.3 m (1 ft) of a wall.

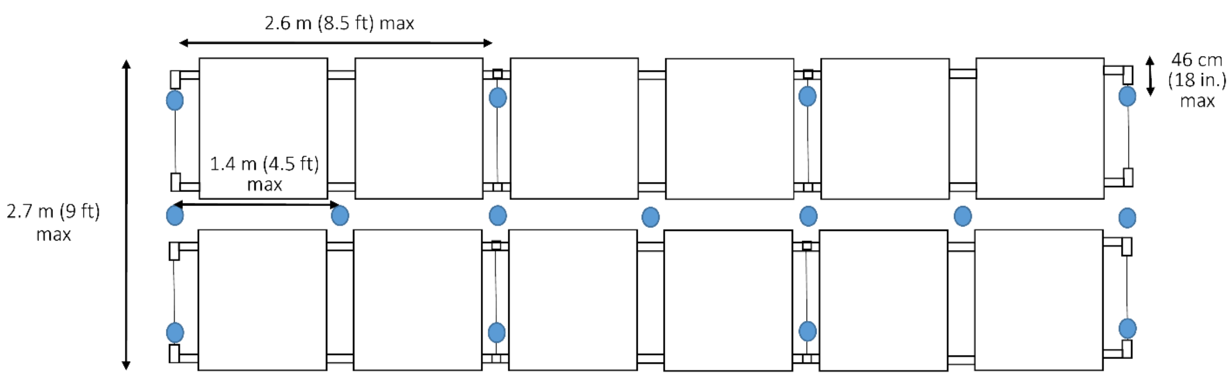


Figure 5.1-4: IRAS arrangement for open-frame, double-row racks up to 2.7 m (9 ft) deep.

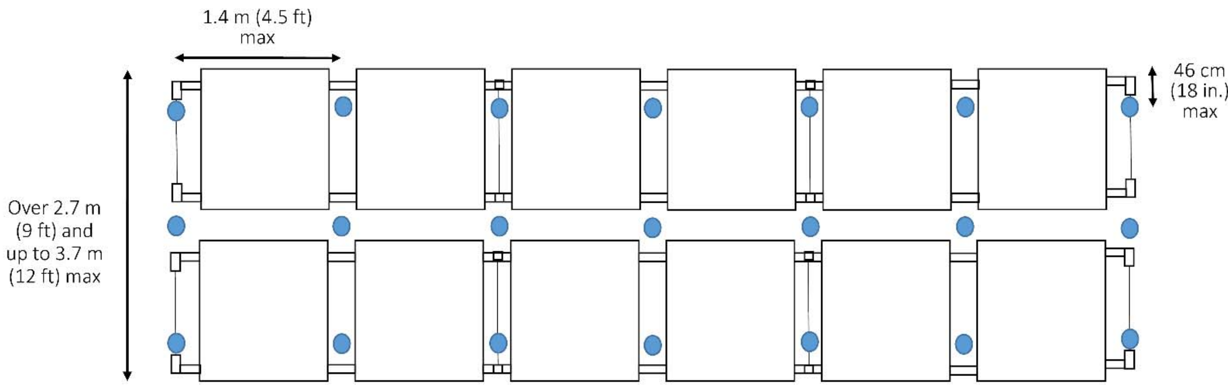


Figure 5.1-5: IRAS arrangement for open-frame, double-row racks over 2.7 m (9 ft) and up to 3.7 m (12 ft) deep.

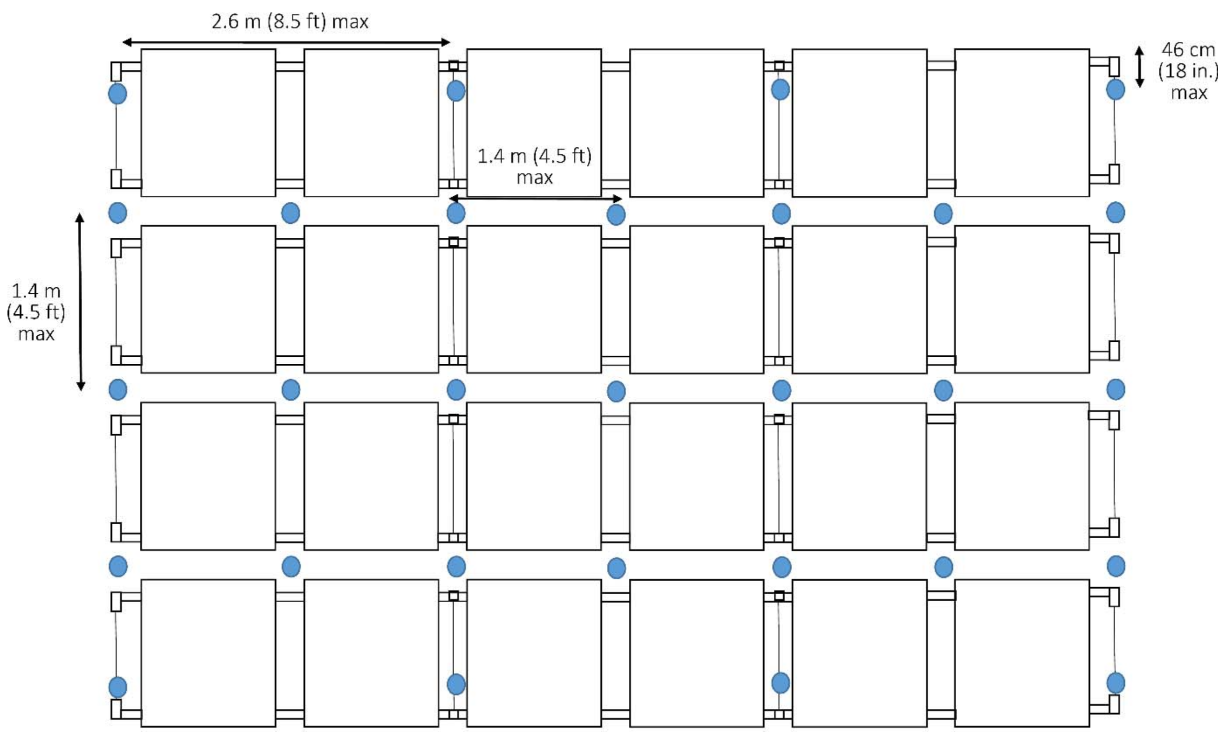


Figure 5.1-6: IRAS arrangement for open-frame, multiple-row racks.

IRAS may be located behind rack uprights.

Provide a minimum vertical clearance of 180 mm (6 in.) between the top of storage and the in-rack sprinkler deflector.

Limit the vertical separation between IRAS levels to 9.1 m (30 ft) for cartoned expanded plastics as well as uncartoned plastics, however the vertical separation between IRAS levels can be increased to 12.2 m (40 ft) for Class 1, 2, 3, 4 and cartoned unexpanded plastics.

Base the number of in-rack sprinklers in the IRAS design per Table 5.1-1.

Table 5.1-1: Number of Sprinklers in the IRAS Design.

Rack Storage Arrangement	Number of Sprinklers in IRAS Design	
	Class 1 through 4 and Cartoned Plastics	Uncartoned Plastics
Single-row rack up to 0.9 m (3 ft) deep	4	4
Single-row rack over 0.9 m (3 ft) and up to 1.8 m (6 ft) deep	5	5
Double-row and multiple-row racks	6	5 & 5*

*5 in-rack sprinklers in two adjacent racks

Base the minimum flow from the most remote in-rack sprinkler in the IRAS design per Table 5.1-2.

Table 5.1-2: Minimum flow from most remote in-rack sprinkler in the IRAS Design.

Max. Vertical IRAS Spacing (m) [ft]	Commodity Hazard	Min. Flow From Most Remote In-Rack Sprinkler (lpm) [gpm]
9.1 (30)	Class 1, 2, 3, 4 and cartoned unexpanded plastics	250 (65)
	Cartoned expanded plastics	380 (100)
	Uncartoned plastics	455 (120)
12.2 (40)	Class 1, 2, 3, 4 and cartoned unexpanded plastics	455 (120)

The following comments apply when an IRAS system has been designed per the recommendations outlined above in this section:

- IRAS systems can be treated as modular such that each level of IRAS is independent from the other and the ceiling level sprinkler protection is independent from the IRAS system. This eliminates the need for hydraulic balancing within the IRAS system and simultaneous flow between the IRAS and ceiling level systems.
- This modular approach allows these protection schemes to be applied to storage arrays of arbitrary height.
- Protect the storage height above the topmost IRAS level according to the ceiling-only protection guidelines provided in DS 8-9. Assume that the topmost level of IRAS is a virtual floor and design for the height of commodity stored above that level.

5.2 Protection of Uncartoned Unexpanded Plastics in Open-Frame Double-Row Racks Using Two Different In-Rack Sprinkler Protection Arrangements

Except for open-frame single-row racks up to 0.9 m (3 ft) deep where the in-rack sprinklers are located no more than 450 mm (18 in.) horizontally from either rack face, do not protect open-frame single-row racks storing uncartoned unexpanded plastics (UUP) over 7.6 m (25 ft) high using an in-rack sprinkler arrangement that consists of a single line of in-rack sprinklers spaced a maximum of every 1.5 m (5 ft) horizontally and 3.0 m (10 ft) vertically. In addition, do not protect open-frame double-row racks of any depth using the same in-rack sprinkler arrangement previously indicated for open-frame single-row racks.

For open-frame single-row racks over 0.9 m (3 ft) and up to 1.8 m (6 ft) deep, or open-frame single-row racks up to 0.9 m (3 ft) deep where the in-rack sprinklers cannot be located within 450 mm (18 in.) horizontally from each rack face, design and install in-rack sprinkler protection as follows:

- At vertical tier level intervals closest to multiples of 9.1 m (30 ft), install quick-response, nominal 70ºC (160ºF) rated, minimum K320 (K22.4) sprinklers as shown in Figure 5.1-2. Design the in-rack sprinklers based on the guidelines provided in Section 5.1.
- For the other vertical tier levels closest to multiples of 3.0 m (10 ft) not already protected with minimum K320 (K22.4) in-rack sprinklers, install quick-response, nominal 70ºC (160ºF) rated, minimum K80 (K5.6) in-rack sprinklers on maximum 1.5 m (5 ft) horizontal and 3.0 m (10 ft) vertical spacing. Design the in-rack sprinkler system to provide a minimum flow of 115 lpm (30 gpm) from the most remote 14 sprinklers (7 sprinklers on top two levels).
- Arrange the in-rack sprinklers so that there is no more than 1.5 m (5 ft) of storage above the top level of in-rack sprinklers.
- Hydraulically balance the minimum K80 (K5.6) in-rack sprinkler system with the ceiling sprinkler system at their point of connection.

For open-frame double-row racks up to 2.7 m (9 ft) deep, design and install in-rack sprinkler protection as follows:

- At vertical tier level intervals closest to multiples of 9.1 m (30 ft), install quick-response, nominal 70ºC (160ºF) rated, minimum K320 (K22.4) sprinklers as shown in Figure 5.1-4. Design the in-rack sprinklers based on the guidelines provided in Section 5.1.
- For the other vertical tier levels closest to multiples of 3.0 m (10 ft) not already protected with minimum K320 (K22.4) in-rack sprinklers, install quick-response, nominal 70ºC (160ºF) rated, minimum K80 (K5.6) in-rack sprinklers on maximum 1.5 m (5 ft) horizontal and 3.0 m (10 ft) vertical spacing within the longitudinal flue space. Locate the in-rack sprinklers horizontally so they are at the intersection of the transverse flue spaces. Design the in-rack sprinkler system to provide a minimum flow of 115 lpm (30 gpm) from the most remote 14 sprinklers (7 sprinklers on top two levels).
- Arrange the in-rack sprinklers so that there is no more than 1.5 m (5 ft) of storage above the top level of in-rack sprinklers.

- Hydraulically balance the minimum K80 (K5.6) in-rack sprinkler system with the ceiling sprinkler system at their point of connection.

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