TECHNICAL REPORT FOR NFPA 13

ESFR Sprinkler Protection of Exposed Nonexpanded Group A Plastics for Ceilings over 30 ft (9.1 m) and up to 40 ft (12.2 m) High

FM Global

ESFR Sprinkler Protection of Exposed Nonexpanded Group A Plastics for Ceilings over 30 ft (9.1 m) and up to 40 ft (12.2 m) High

Prepared by

Weston C. Baker Jr

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FM Global
1151 Boston-Providence Turnpike
Norwood, MA 02062

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Executive Summary

This report details large-scale fire testing that was conducted for the purpose of validating the protection of exposed, nonexpanded Group A plastics using ceiling-level Early Suppression Fast Response (ESFR) sprinklers.

The purpose of this report is to demonstrate that many of the protection options currently offered in the 2019 Edition of NFPA 13 for the protection of exposed, nonexpanded Group A plastics, and subsequently as well for rubber tires, is insufficient for ceiling heights in excess of 30 ft (9.1 m).

It is recommended that Tables 23.4.2, 23.6.1, and 23.8 be modified as outlined in this report due to the test results presented in this document.

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1. Introduction

This report details large-scale fire testing that was conducted for the purpose of validating the protection of exposed, nonexpanded Group A plastics using ceiling-level Early Suppression Fast Response (ESFR) sprinklers.

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*, (i.e. NFPA 13) pertaining to the protection of exposed, nonexpanded Group A plastics, and subsequently as well for rubber tires, by ESFR sprinklers for ceiling heights in excess of 30 ft (9.1 m).

The 2019 Edition of NFPA 13 has three tables – Table 23.4.2, Table 23.6.1, and Table 23.8 – that contain protection options for either exposed, nonexpanded Group A plastic commodities, or rubber tires. Table 23.4.2 provides the ESFR sprinkler protection options for exposed, nonexpanded Group A plastic commodities maintained in a palletized or solid-piled arrangement whereas Table 23.6.1 provides the ESFR sprinkler protection options for this commodity hazard when maintained in an open-frame rack storage arrangement. Table 23.8 provides the ESFR sprinkler protection options for rubber tires.

This report will detail five full-scale fire tests conducted at the FM Global Research Campus that demonstrate the need for modifications to current NFPA 13 protection guidelines. These five tests are: (1) Test 13 of FM Global Research Project 3021170, (2) Tests 8 and 9 of FM Global Research Project 3038062, and (3) Tests 5 and 6 of FM Global Research Project 3056422. A summary of these five tests is provided in Table 1-1.

Based on the successful results of Test 13 conducted on October 31, 2005, a design of 12 quick-response, 165^{o}F (74^{o}C) rated, K25.2 (K360) pendent ESFR sprinklers at a minimum operating pressure of 60 psi (4.1 bar) is acceptable for a ceiling height of 40 ft (12.2 m). It should be noted, however, that the number of sprinklers that operated during this test is at the maximum allowable (8) for a design that is based on 12 sprinklers in NFPA 13 (50% safety factor). This would place in doubt any ESFR sprinkler design using a K22.4 (K320) or lower sprinkler where the design flow is less than 195 gpm (738 L/min) per operating sprinkler.

This doubt was further reinforced based on the unsuccessful results of Test 8 conducted on March 17, 2010. In this test a flow of roughly 195 gpm (738 L/min) per operating K22.4 (K320) ESFR sprinkler was not able to provide an acceptable level of protection with the storage height at 35 ft (10.7 m) and the ceiling height at 40 ft (12.2 m). As a result, the only acceptable ESFR sprinkler design for open-frame rack storage of exposed, nonexpanded Group A plastics with ceilings up to 40 ft (12.2 m) high would be a K25.2 (K360) pendent ESFR sprinkler using a design of 12 AS @ 60 psi (4.1 bar).

Based on the unsuccessful results of Test 9 conducted on May 13, 2010, this would place in doubt any ESFR sprinkler design for open-frame rack storage with ceilings over 30 ft (9.1 m) and up to 40 ft (12.2 m) high that are not based on a minimum flow of 195 gpm (738 L/min).

Table 1-1: Summary of test data for exposed, nonexpanded Group A plastics

	Test No.	13	8	9	5	6
Test Parameters	Date	31-Oct-2005	17-Mar-2010	13-May-2010	19-Feb-2016	23-Feb-2016
	Commodity	Exposed, Nonexpanded Group A Plastic				
	Storage Arrangement	Open-Frame Rack	Open-Frame Rack	Open-Frame Rack	Solid-Piled	Solid-Piled
	Ceiling Height, ft (m)	40 (12.2)	40 (12.2)	35 (10.7)	35 (10.7)	35 (10.7)
	Storage Height, ft (m)	35 (10.7)	35 (10.7)	30 (9.1)	16 (4.9)	16 (4.9)
	Aisle Width, ft (m)	4 (1.2)	4 (1.2)	4 (1.2)	DNA	DNA
	Ignition Location Scenario	Between 2 Sprinklers	Between 2 Sprinklers	Between 2 Sprinklers	Under 1 Sprinkler	Under 1 Sprinkler
	Ceiling Sprinkler K-Factor	25.2 (360)	22.4 (320)	25.2 (360)	16.8 (240)	25.2 (360)
	Ceiling Sprinkler Orientation	Pendent	Pendent	Pendent	Pendent	Pendent
	Ceiling Sprinkler RTI Rating	Quick-Response	Quick-Response	Quick-Response	Quick-Response	Quick-Response
	Ceiling Sprinkler Temperature Rating, °F (°C)	165 (74)	165 (74)	165 (74)	165 (74)	165 (74)
	Ceiling Sprinkler Spacing, ft x ft (m x m)	10 x 10 (3 x 3)	10 x 10 (3 x 3)	10 x 10 (3 x 3)	10 x 10 (3 x 3)	10 x 10 (3 x 3)
	Ceiling Sprinkler Discharge Pressure, psi (bar)	60 (4.1)	75 (5.2)	50 (3.4)	50 (3.4)	60 (4.1)
Test Results	First Sprinkler Activation, min:sec	4:38	4:54	4:59	3:25	4:10
	Last Sprinkler Activation, min:sec	9:00	23:32	23:19	16:56	5:25
	Total Number of Sprinkler Activations	8	7	7	12	2
	Peak Ceiling Gas Temperature, °F (°C)	512 (267)	1,312 (711)	1,563 (850)	1,115 (602)	324 (162)
	Maximum 60 s Average Ceiling Gas Temperature, °F (°C)	327 (164)	904 (484)	1,160 (627)	617 (325)	170 (77)
	Maximum 60 s Average Ceiling Steel Temperature, °F (°C)	129 (54)	146 (63)	136 (56)	162 (72)	84 (29)
	Unacceptable Horizontal Fire Spread in Main or Target Array?	No	Yes	Yes	Yes	No
	Fire Jump to Target Array?	No	Yes	Yes	DNA	DNA
	Test Duration, min:sec	25:00	33:00	30:00	41:00	30:00
	Acceptable Test Result?	Yes	No	No	No	Yes

Based on the unsuccessful results of Test 5 conducted on February 19, 2016, this would place in doubt any K14.0 (K200) or K16.8 (K240) ESFR design for ceilings over 30 ft (9.1 m) high.

Based on the successful results of Test 6 conducted on February 23, 2016, it confirms that a minimum design flow of 195 gpm (738 L/min) per operating pendent ESFR sprinkler is acceptable for the protection of on-floor exposed, nonexpanded Group A plastics up to 16 ft (4.9 m) high under a 35 ft (10.7 m) high ceiling.

Due to the results of these five tests, the following is being recommended:

- In Table 23.4.2 where the ceiling height exceeds 30 ft (9.1 m), remove all existing K14.0 (K200) and K16.8 (K240) sprinkler designs for exposed nonexpanded Group A plastics.

- In Table 23.4.2 where the maximum ceiling height exceeds 30 ft (9.1 m), revise all existing K22.4 (K320) sprinkler designs for exposed, nonexpanded Group A plastics by changing the indicated design pressure of “50 psi (3.4 bar)” to “75 psi (5.2 bar)”.
- In Table 23.4.2 where the maximum ceiling height exceeds 30 ft (9.1 m), revise all existing K25.2 (K360) sprinkler designs for exposed, nonexpanded Group A plastics by changing the indicated design pressure of “50 psi (3.4 bar)” to “60 psi (4.1 bar)”.
- In Table 23.4.2 add two new rows for exposed, nonexpanded Group A plastics where the maximum storage height is 20 ft (6.1 m) and the maximum ceiling height is 40 ft (12.2 m). The first row would be for the K22.4 (K320) pendent sprinkler with a minimum operating pressure of 75 psi (5.2 bar). The second row would be for the K25.2 (K360) pendent sprinkler with a minimum operating pressure of 60 psi (4.1 bar).
- In Table 23.6.1 where the maximum ceiling height exceeds 30 ft (9.1 m), remove all existing K14.0 (K200) and K16.8 (K240) sprinkler designs for exposed nonexpanded Group A plastics.
- In Table 23.6.1 where the maximum ceiling height is 35 ft (10.7 m) for exposed, nonexpanded Group A plastics, add a new sprinkler design for the K22.4 (K320) sprinkler based on a design pressure of “75 psi (5.2 bar)”. This would apply to maximum storage heights of 20 ft (6.1 m), 25 ft (7.6 m) and 30 ft (9.1 m).
- In Table 23.6.1 where the maximum ceiling height exceeds 35 ft (10.7 m), remove all existing K22.4 (K320) sprinkler designs for exposed nonexpanded Group A plastics.
- In Table 23.6.1 where the maximum ceiling height is 35 ft (10.7 m) for exposed, nonexpanded Group A plastics, add a new sprinkler design for the K25.2 (K360) sprinkler based on a design pressure of “60 psi (4.1 bar)”. This would apply to maximum storage heights of 20 ft (6.1 m), 25 ft (7.6 m) and 30 ft (9.1 m).
- In Table 23.6.1 where the maximum ceiling height is 40 ft (12.2 m) for exposed, nonexpanded Group A plastics, revise all existing K25.2 (K360) sprinkler designs by changing the indicated design pressure of “50 psi (3.4 bar)” to “60 psi (4.1 bar)”.
- In Table 23.6.1 where the maximum ceiling height is 40 ft (12.2 m) for exposed, nonexpanded Group A plastics and the maximum storage height is 20 ft (6.1 m), add a new sprinkler design for the K25.2 (K360) pendent sprinkler based on a design pressure of “60 psi (4.1 bar)”.
- In Table 23.8 where the maximum ceiling height exceeds 30 ft (9.1 m), remove all existing K14.0 (K200) and K16.8 (K240) sprinkler designs.
- In Table 23.8 where the maximum ceiling height is 35 ft (10.7 m), revise the existing K22.4 (K320) pendent sprinkler design by changing the indicated design pressure of “35 psi (2.4 bar)” to “75 psi (5.2 bar)”.
- In Table 23.8 where the maximum ceiling height is 35 ft (10.7 m), revise the existing K25.2 (K360) pendent sprinkler design by changing the indicated design pressure of “25 psi (1.7 bar)” to “60 psi (4.1 bar)”.
- In Table 23.8 where the maximum ceiling height is 40 ft (12.2 m), revise the existing K25.2 (K360) pendent sprinkler design by changing the indicated design pressure of “40 psi (2.8 bar)” to “60 psi (4.1 bar)”.

2. FM Global Test Information

2.1 Description of Research Campus/Laboratories

All tests in this report were conducted in the Large Burn Laboratory (LBL) at the FM Global Research Campus located in West Glocester, RI. Figure 2-1 is a plan view of the LBL that shows the North Movable Ceiling, the South Movable Ceiling, and the 20-MW Calorimeter. The movable ceilings measure 80 ft x 80 ft (24.4 m × 24.4 m) and are adjustable for heights above the floor ranging from 10 ft (3.0 m) to 60 ft (18.3 m). 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 66 ft^2 (6.1 m^2). Gas concentrations, gas velocity, gas temperature, and moisture content are measured 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 tests were conducted at an exhaust rate of 200,000 ft^3/min (5,700 m^3/min).

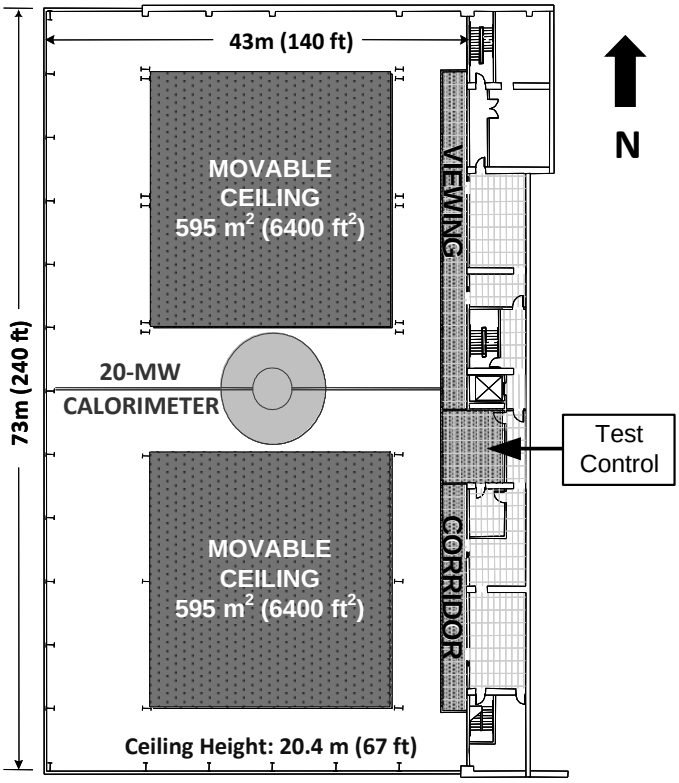


Figure 2-1: Illustration of the FM Global Large Burn Laboratory Test Sites.

2.2 Instrumentation

The instrumentation used in these tests was selected to monitor the effects of the fires and allow assessment to be made regarding sprinkler system performance. Instrumentation for these tests included the following: (1) thermocouples to monitor and record near ceiling gas temperatures at

various locations over the test area; (2) thermocouples to monitor and record ceiling steel temperatures over the ignition zone; and (3) electrical circuits wired through the sprinkler actuation mechanisms to allow determination of sprinkler actuation times.

The thermocouples used to monitor near-ceiling gas temperatures were fabricated from 20-gauge chromel-alumel wires. The beads of the thermocouples were positioned 7 in. (178 mm) down from the ceiling surface. A faster responding thermocouple made from 28 gauge chromel-alumel wire was paired with the standard 20 gauge thermocouple installed at the center of the ceiling directly over the center of the main array.

The ceiling steel temperatures over the ignition zone were monitored by thermocouples peened to a steel angle. The recorded temperatures are used to determine the potential for thermal damage to structural roof supports. The steel angle is constructed of 4 ft (1.2 m) sections of 2 in. x 2 in. (51 mm x 51 mm) steel angle attached with one side flush against the ceiling directly over the center of the main fuel array.

2.3 Test Evaluation Criteria

Instrumentation, visual documentation, and observations from trained observers were used to assess the effectiveness of the tested sprinklers for the five different fire scenarios described in this report. Of interest for determination of sprinkler system effectiveness were the following: (1) the total number of sprinkler operations occurring during the test, (2) near-ceiling gas and ceiling steel temperatures, and (3) the extent of fire damage to the fuel arrays.

The total number of sprinkler operations is one criterion used to evaluate the effectiveness of a sprinkler system. The quick-response, ESFR pendent sprinklers are designed to suppress fires quickly with relatively few sprinkler operations. The water supplies for ESFR sprinkler systems are typically designed to accommodate twelve (12) operating sprinklers. Because of the necessity to maintain a safety factor, this criterion is satisfied when the number of sprinkler actuations occurring during standard tests does not exceed eight.

Near-ceiling gas and steel temperatures are monitored to evaluate the ability of sprinklers to successfully cool the fire zone and to assess the potential for collapse of structural steel roof support members. Continued elevated ceiling gas temperatures after actuation of sprinklers indicate that the fire is not being suppressed. Ceiling steel temperatures in excess of 1,000^{o}F (538^{o}C) indicate the potential for collapse of structural steel support members. The ceiling steel criterion is considered satisfied when the ceiling steel temperature remains below 1,000^{o}F (538^{o}C) for the duration of the test.

The third major test evaluation criterion is the extent of fire damage to the fuel arrays. The fuel arrays used in large-scale storage fire tests are designed to replicate a representative section of warehouse storage. This usually consists of a main array, in which ignition is placed, and one or two target arrays separated by an aisle space. If fire damage is not confined to main and target arrays, the assumption is that the fire is not controlled and in a real-world event the entire warehouse would have been involved

in the fire. For these tests, successful fire suppression requires that fire damage not extend to either longitudinal end of the main array or to the opposite faces (away from the main array) of target arrays.

2.4 Ignition

Ignition for the rack storage tests was provided by two FM Global standard full igniters. The FM Global standard full igniter is a 6 in. long x 3 in. diameter (152 mm x 76 mm) cellu-cotton roll soaked with 8 fluid ounces (236 ml) of gasoline. The igniters are each individually sealed in a clear polystyrene plastic bag. Igniters are prepared just prior to ignition and placed at the base of the bottom pallet-loads within the central transverse flue of the main array 2 ft (0.61 m) from the centerline of the longitudinal flue for rack storage scenarios. This transverse flue space also contained a rack upright. For solid-pile storage arrangements the ignitors were placed at the base of the bottom pallet-loads, one ignitor on each side of the flue, 4.0 ft (1.2 m) down the central flue space. The igniters were lighted using a propane torch to begin each test. Verbal confirmation of the lighting of the igniters was recorded as an event on the data record which served as the official start of each fire test.

2.5 Test Commodity

The exposed, nonexpanded Group A plastic test commodity (referred to as uncartoned, unexpanded plastic [UUP] by FM Global) consists of high-density polyethylene RACK'R plastic pallets from ORBIS Corporation®. The four-way entry plastic pallets are not FM Approved and do not contain fire retardant materials. The pallets have dimensions of 40 in. (1.02 m) long by 48 in. (1.22 m) wide by 5.6 in. (14 cm) high and weigh about 56 lb (25.4 kg) each.

For rack storage tests, an individual pallet load consists of seven plastic pallets stacked on top of an ordinary, two-way, slatted deck, hardwood pallet resulting in an overall dimension of 42 in. x 48 in. x 44 in. (1.07 m x 1.22 m x 1.11 m). The total combustible weight of this pallet load is 441.6 lb (200.3 kg); the plastic pallets weigh approximately 392.2 lb (177.9 kg), and the hardwood pallet that supports the commodity weighs approximately 49.4 lb (22.4 kg). A photo of this test commodity is provided in Figure 2-2.

Figure 2-2: FM Global Standard Uncartoned Unexpanded Plastic (UUP) Test Commodity for Rack Storage Tests (Considered Exposed, Nonexpanded Group A Plastic per NFPA 13).

3. Test Summaries, Setups and Results

3.1 Rack Storage of Exposed, Nonexpanded Group A Plastics to 35 ft (10.7 m) High Under a 40 ft (12.2 m) Ceiling Protected with K25.2 (K360) ESFR Pendent Sprinklers (Test 13 of Research Project 3021170)

3.1.1 Test Overview

The purpose of Test 13 was to determine if quick-response K25.2 (K360) pendent ESFR sprinklers operating at a minimum pressure of 60 psi (4.1 bar) would be able to provide an acceptable level of protection for open-frame rack storage of exposed, nonexpanded Group A plastics under a maximum 40 ft (12.2 m) high ceiling.

3.1.2 Test Setup

In this test, the main array consisted of an open-frame double row rack that was separated from two open-frame single-row rack target arrays by a 4 ft (1.2 m) aisle space. Storage within the main array consisted of 2 pallets load deep, 6 pallet loads in length and 7 pallet loads high. Storage within the two target arrays consisted of 4 pallet loads in length; 2 pallet loads directly across from ignition were exposed, nonexpanded Group A plastic and the pallet loads at each end of the target arrays were Class II test commodity. The main array was centered between two ceiling level sprinklers.

Ceiling sprinkler protection was provided by a FM Approved quick-response, 165^{o}F (74^{o}C) temperature rated K25.2 gpm/psi$^{1/2}$ (K360 lpm/bar$^{1/2}$) pendent ESFR sprinkler. The sprinklers were installed under the North Ceiling of the Large Burn Lab with the sprinkler deflector located 18 in. (457 mm) down from the ceiling surface. The exposed sprinkler branchlines were nominal 2-1/2 in. (63 mm) diameter steel pipe with the sprinklers evenly distributed over the entire ceiling on 10 ft x 10 ft (3 m x 3 m) spacing. The water supply system was set to provide a constant discharge pressure independent of the number of operating sprinklers. Prior to test, the system pressure was set to 60 psi (4.1 bar), which resulted in a sprinkler discharge rate of about 195 gpm (738 L/min).

3.1.3 Results

3.1.3.1 Sprinkler Activation Times and Patterns

The fire reached the top of the fifth tier (approximately 25 ft [7.6 m]) and flames were up to the third tier on the east face of the ignition array when the first sprinkler actuated at 4 min 38 s after ignition. The first sprinkler was 2 ft (0.6 m) east from directly over the array center. The sprinkler actuation sequence for this test is presented in Figure 3-1.

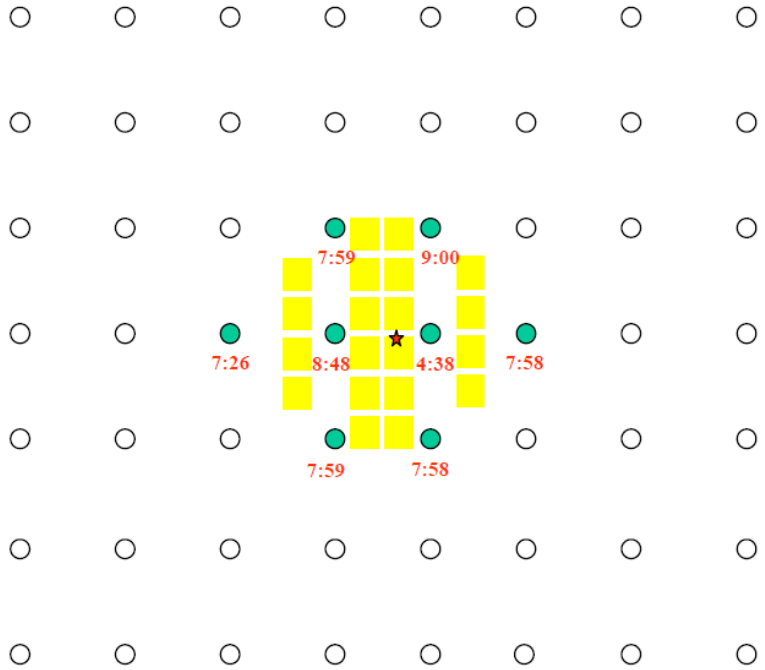


Figure 3-1: Sprinkler Actuation Sequence for Test 13.

The flames were pushed down to the level of the third tier (approximately 15 ft [4.6 m] high) and at 4 min 45 s flames began to extend from the bottom of the first tier onto the west face of the ignition array. At approximately 5 min after ignition the fire began to intensify in the first and second tiers. By 5 min 45 s, flames on the west face extended up to the third tier.

By 7 min after ignition, flames on the west face of the ignition array extended up to the top of the fifth tier and near-ceiling gas temperatures over the center of the array were increasing (Figure 3-2).

The second sprinkler actuated at 7 min 26 s after ignition and was 15 ft (4.6 m) west of the array center. This sprinkler had minimal effect upon the fire. The fire continued to increase in intensity. At 7 min 58 s two sprinklers actuated and at 7 min 59 s two additional sprinklers actuated. The two sprinkler actuations at 7 min 59 s included the second closest over the array (the sprinkler protecting the west face of the ignition array and the west side aisle space). Operation of these sprinklers caused immediate generation of smoke and steam that significantly reduced visibility of the test site.

By 8 min 25 s the test site was totally obscured by smoke and steam. The seventh and eighth sprinkler actuations occurred at 8 min 49 s and 9 min, respectively. There was significant reduction of near-ceiling gas temperatures after operations of these two sprinklers.

The fire was eventually controlled and suppressed by eight sprinklers.

3.1.3.2 Gas and Steel Temperatures

The near-ceiling temperature over the array center was 320°F (160°C) at the time of first sprinkler actuation and in the range of 171°F to 203°F (77°C to 95°C) at locations 5 ft (1.5 m) from directly over the array center. The maximum steel temperature was 133°F (56°C).

3.1.3.3 Extent of Damage

An intense fire developed in the first and second tiers before it was controlled by the sprinkler system. The result was the warping of the rack uprights in the central transverse flue space of the main array. There was also distortion of shelf beams at the second tier of the ignition array. Fire damage was confined to the main array and the ceiling steel temperature began decreasing at around 9 min after ignition indicating that the fire was being controlled and suppressed. See Figure 3-2 for the extent of fire damage within the array of fire ignition.

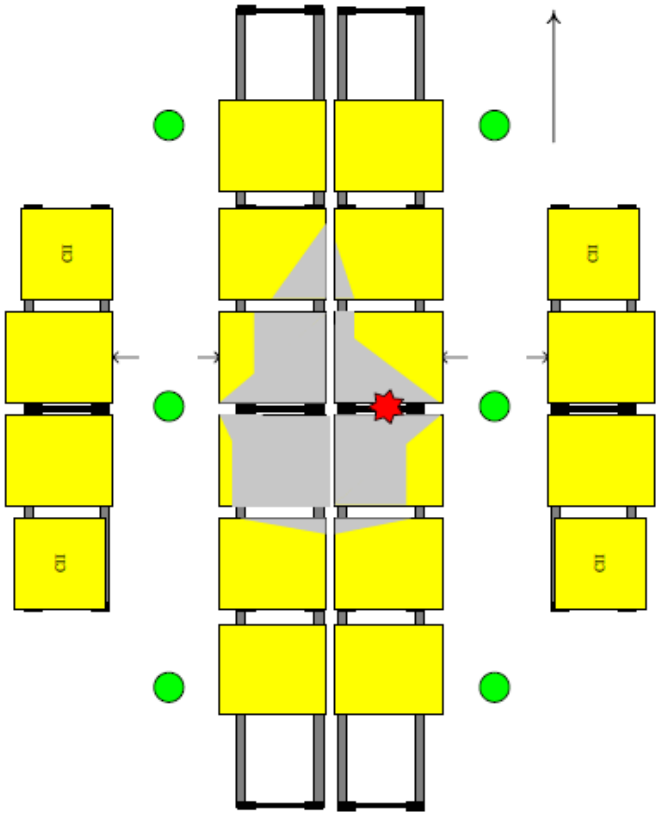


Figure 3-2: Extent of Fire Damage for Test 13.

3.2 Rack Storage of Exposed, Nonexpanded Group A Plastics to 35 ft (10.7 m) High Under a 40 ft (12.2 m) Ceiling Protected with K22.4 (K320) ESFR Pendent Sprinklers (Test 8 of Research Project 3038062)

3.2.1 Test Overview

The purpose of Test 8 was to determine if quick-response K22.4 (K320) pendent ESFR sprinklers operating at a minimum pressure of 75 psi (5.2 bar) would be able to provide an acceptable level of protection for open-frame rack storage of exposed, nonexpanded Group A plastics under a maximum 40 ft (12.2 m) high ceiling.

3.2.2 Test Setup

In this test, the main array consisted of an open-frame double row rack that was separated from two open-frame single-row rack target arrays by a 4 ft (1.2 m) aisle space. Storage within the main array consisted of 2 pallets load deep, 8 pallet loads in length and 7 pallet loads high. Storage within the two single-row target arrays consisted of 6 pallet loads in length. The main array was centered between two ceiling level sprinklers.

Ceiling sprinkler protection was provided by a FM Approved quick-response, 165°F (74°C) temperature rated K22.4 gpm/psi$^{1/2}$ (K320 lpm/bar$^{1/2}$) pendent ESFR sprinkler. The sprinkler deflectors were installed 18 in. (457 mm) down from the ceiling surface. The exposed sprinkler branchlines were nominal 2-1/2 in. (63 mm) diameter steel pipe with the sprinklers evenly distributed over the entire ceiling on 10 ft x 10 ft (3 m x 3 m) spacing. The water supply system was set to provide a constant discharge pressure independent of the number of operating sprinklers. Prior to test, the system pressure was set to 75 psi (5.2 bar), which resulted in a sprinkler discharge rate of about 195 gpm (738 L/min).

3.2.3 Results

3.2.3.1 Sprinkler Activation Times and Patterns

Flames reaches the top of the third tier at 3 min 11 s after ignition and by 3 min 15 s were extending onto the east face of the ignition array from the base of second-tier pallet loads. At 4 min 15 sec the flames on the east face of the ignition array extended up to the fourth tier.

Flames reached the top of the fifth tier at 4 min 47 s and first sprinkler actuation occurred at 4 min 54 s after ignition. The near-ceiling gas temperature over ignition was approximately 257°F (125°C) at this time. The operating sprinkler was one of the two sprinklers over ignition and was the one actually closest over the ignition source (Figure 3-3). Following the sprinkler operation there was immediate reduction in near-ceiling gas temperatures and the flames were reduced to the level of the third tier.

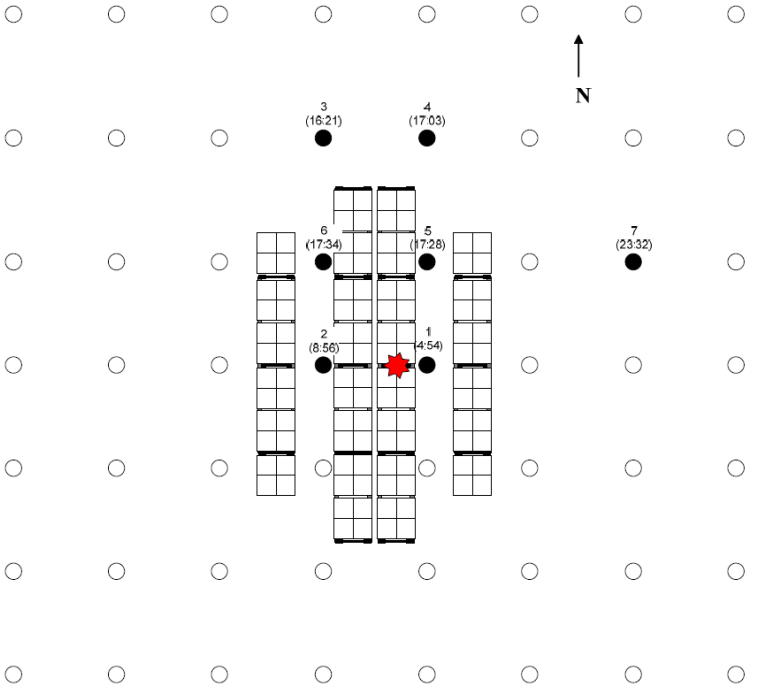


Figure 3-3: Sprinkler Actuation Sequence for Test 8.

By 5 min 55 s after ignition the fire had begun to intensify, and flames now extended onto the west face of the ignition array at the second tier. At 6 min 40 s the flames on the east face if the ignition array extended up to the sixth tier. With just one sprinkler operating, the fire continued to increase.

Ceiling thermocouple measurements over the ignition zone indicated a rise in near-ceiling gas temperature beginning at approximately 8 minutes after ignition. By 8 min 40 s after ignition the flames on the east face of the ignition array extended up to the seventh tier and the flames on the west face were up to the level of the fifth tier.

The near-ceiling gas temperature at the ceiling center reached 347^{o}F (175^{o}C) just prior to the second sprinkler actuation at 8 min 56 s. This sprinkler was the second closest over ignition. Ceiling gas temperatures declined immediately. The flames on the east face of the ignition array were also reduced to the top of the second tier and dense smoke was generated which began to obscure the view of the test arrangement. By 10 minutes after ignition view of the test arrangement was almost totally obscured by smoke.

At 12 minutes after ignition the view of the test arrangement was mostly obscured by the smoke; however, the fire remained concentrated in the lower three tiers. By 15 minutes after ignition, infrared (IR) video monitoring indicated increased involvement of the upper tiers of the test arrangement. By 15 min 30 s IR video indicated that the fire had again reached ceiling level.

The third sprinkler actuation occurred at 16 min 21 s after ignition. The sprinkler was located 20 ft (6.1 m) northeast of ignition and had little effect upon the fire. The near-ceiling gas temperatures at this time

indicated high temperatures in the vicinity of the two sprinklers immediately north (10 ft [3.0 m]) of ignition. However, these two sprinklers "skipped" i.e., they had not actuated. The near-ceiling gas temperatures over ignition indicated the beginning of a significant increase in temperatures at this time. The near-ceiling gas temperature 10 ft (3.0 m) north of ignition reached 1,312°F (711°C). The temporary skipping of the sprinklers at 10 ft (3.0 m) north ended as three additional sprinkler actuations occurred at 17 min 3 sec, 17 min 28 s, and 17 min 34 s after ignition and included those sprinklers.

The seventh and final sprinkler actuation occurred at 23 min 32 s after ignition and the test was terminated at 33 minutes after ignition.

3.2.3.2 Gas and Steel Temperatures

The maximum near-ceiling gas temperature was 1,312°F (711°C) for the test period with a maximum 60-second ceiling steel temperature of just 146°F (63°C).

3.2.3.3 Extent of Damage

Fire damage did not extend to the end of the main array; however, the fire damage to the east target array did include damage to the rear (east) face.

3.3 Rack Storage of Exposed, Nonexpanded Group A Plastics to 30 ft (9.1 m) High Under a 35 ft (10.7 m) Ceiling Protected with K25.2 (K360) ESFR Pendent Sprinklers (Test 9 of Research Project 3038062)

3.3.1 Test Overview

The purpose of Test 9 was to determine if quick-response K25.2 (K360) pendent ESFR sprinklers operating at a minimum pressure of 50 psi (3.4 bar) would be able to provide an acceptable level of protection for open-frame rack storage of exposed, nonexpanded Group A plastics under a maximum 35 ft (10.7 m) high ceiling.

3.3.2 Test Setup

In this test, the main array consisted of an open-frame double row rack that was separated from two open-frame single-row rack target arrays by a 4 ft (1.2 m) aisle space. Storage within the main array consisted of 2 pallets load deep, 8 pallet loads in length and 6 pallet loads high. Storage within the two single-row target arrays consisted of 6 pallet loads in length. The main array was centered between two ceiling level sprinklers.

Ceiling sprinkler protection was provided by a FM Approved quick-response, 165°F (74°C) temperature rated K25.2 gpm/psi$^{1/2}$ (K360 lpm/bar$^{1/2}$) pendent ESFR sprinkler. The sprinkler deflectors were installed 18 in. (457 mm) down from the ceiling surface. The exposed sprinkler branchlines were nominal 2-1/2 in. (63 mm) diameter steel pipe with the sprinklers evenly distributed over the entire ceiling on 10 ft x 10 ft (3 m x 3 m) spacing. The water supply system was set to provide a constant discharge pressure

independent of the number of operating sprinklers. Prior to test, the system pressure was set to 50 psi (3.4 bar), which resulted in a sprinkler discharge rate of about 178 gpm (674 L/min).

3.3.3 Results

3.3.3.1 Sprinkler Activation Times and Patterns

By 4 min 45 s after ignition, flames within the longitudinal flue had reached the top of the fourth tier and were extending into the fifth tier. The first sprinkler actuated at 4 min 49 s and was the closer of the two sprinklers over ignition (Figure 3-4). The temperatures over ignition were 320°F (160°C) and peaked at a maximum of approximately 392°F (200°C) just after the first sprinkler operation.

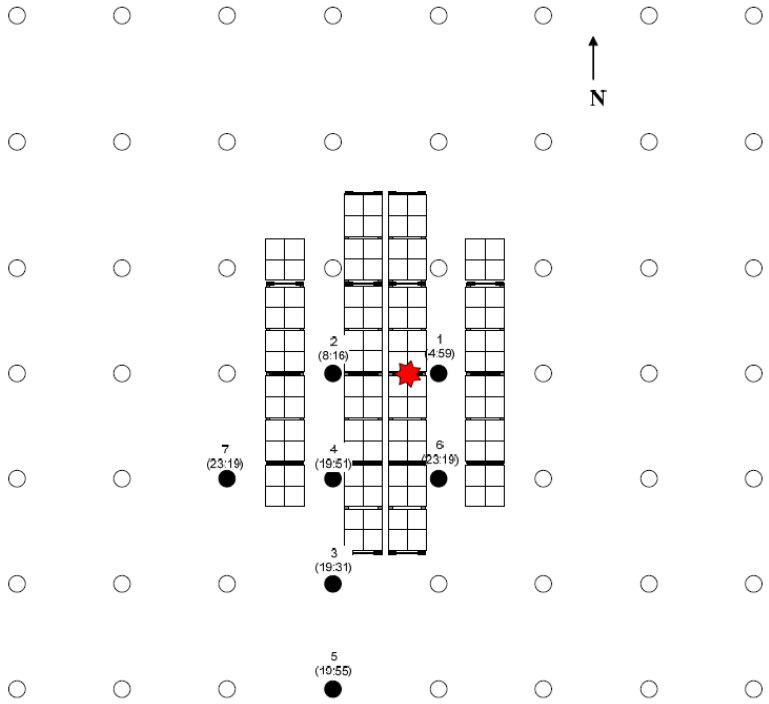


Figure 3-4: Sprinkler Actuation Sequence for Test 9.

The operation of the single sprinkler did not provide control and the fire began to increase in intensity. By 5 min 30 s flames had returned to the level of the fourth tier and extended from the base of the first tier onto the west face of the ignition array. Smoke began to accumulate and by 6 minutes after ignition view of the test arrangement was mostly obscured by smoke. The fire continued moderate growth until 8 minutes after ignition.

At 8 min 10 s flames on the west face of the ignition array increased up to the level of the fourth tier. The second sprinkler closest over ignition actuated at 8 min 16 s and reduced the upward fire spread on the west face of the ignition array. By 8 min 40 s view of the test arrangement was obscured by smoke.

Infrared (IR) imagery indicated that the fire continued in the lower tiers of the storage array up to the level of the third tier. The fire remained steady until 18 min 30 s after ignition. Additional sprinkler actuations occurred at 19 min 31 s, 19 min 51 s, and 19 min 55 s. These sprinklers were to the southeast of ignition. Five sprinklers were now operating and included three of the six sprinklers closest over the ignition array. The maximum near-ceiling gas temperatures for the test were recorded during the period 19 to 20 minutes after ignition.

Infrared imagery indicated that the fire continued to progress to the south end of the main array and had ignited the east target array. An additional two sprinklers actuated at 23 min 19 s after ignition resulting in a total of seven sprinkler actuations. The fire remained concentrated in the lower tiers until the test was terminated at 33 minutes after ignition.

3.3.3.2 Gas and Steel Temperatures

The maximum near-ceiling gas temperature of 1,563°F (850°C) was measured 10 ft (3.0 m) south of ignition. The 60-second average maximum ceiling steel temperature was 136°F (58°C).

3.3.3.3 Extent of Damage

Although fire damage did not extend to the end of the main array, the east target array did become involved with fire damage extending to the south end of the east target array.

3.4 Solid-Piled Storage of Exposed, Nonexpanded Group A Plastics to 16 ft (4.9 m) High Under a 35 ft (10.7 m) Ceiling Protected with K16.8 (K240) ESFR Pendent Sprinklers (Test 5 of Research Project 3056422)

3.4.1 Test Overview

The purpose of Test 5 was to determine if quick-response K16.8 (K240) pendent ESFR sprinklers operating at a minimum pressure of 50 psi (3.4 bar) would be able to provide an acceptable level of protection for solid-piled storage of exposed, nonexpanded Group A plastics under a maximum 35 ft (10.7 m) high ceiling.

3.4.2 Test Setup

Test 5 was conducted under the South Movable Ceiling. Figure 3-5 shows the test setup in plan and elevation views. Figure 3-6 shows a photograph of the test array prior to ignition. A total of 700 plastic pallets was used as fuel. As shown in Figure 3-5, the main fuel array was double-row solid pile, 6 pallets long, 35 pallets high with a 1 ft (0.3 m) flue space in the longitudinal direction (N-S) and with the pallets butted together in the other direction. The storage height was 16 ft (4.9 m). In addition, two rows that were 4 pallets long and 16 ft (4.9 m) high were placed both east and west of the main array with a 1 ft (0.3 m) flue space.

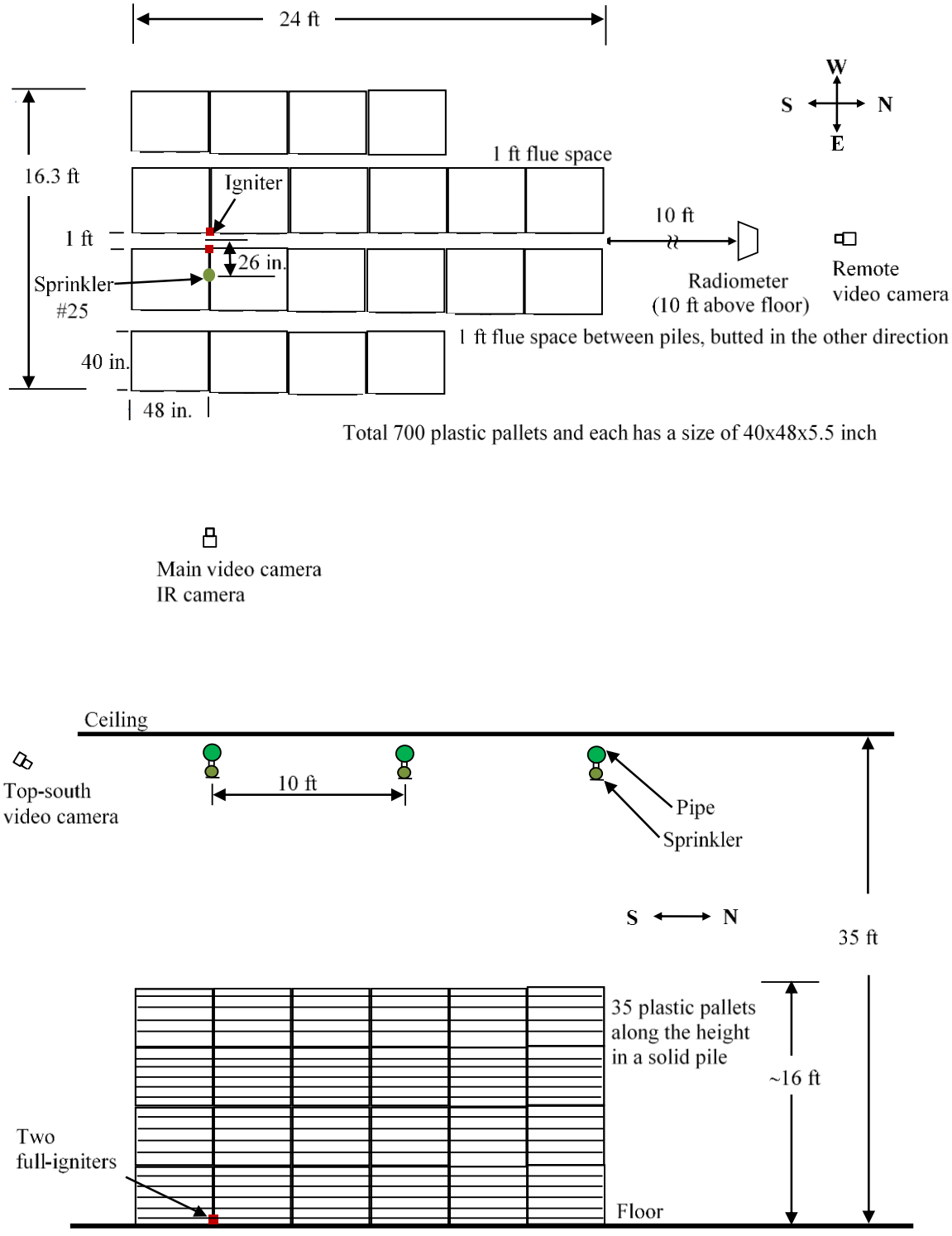


Figure 3-5: Plan and Elevation View of Test 5.

Figure 3-6: Photo of Test 5 Captured from the East Side of the Test Arrangement.

Ceiling sprinkler protection was provided by FM Approved quick-response, 165°F (74°C) temperature rated K16.8 gpm/psi$^{1/2}$ (K240 lpm/bar$^{1/2}$) pendent ESFR sprinklers. The sprinkler deflectors were installed under the South Ceiling of the Large Burn Lab 14 in. (356 mm) down from the ceiling surface. The exposed sprinkler branchlines were nominal 2-1/2 in. (63 mm) diameter steel pipe with the sprinklers evenly distributed over the entire ceiling on 10 ft x 10 ft (3 m x 3 m) spacing. The water supply system was set to provide a constant discharge pressure independent of the number of operating sprinklers. Prior to test, the system pressure was set to 50 psi (3.4 bar), which resulted in a sprinkler discharge rate of about 119 gpm (450 L/min).

3.4.3 Results

3.4.3.1 Sprinkler Activation Times and Patterns

Figure 3-7, which indicates the sprinklers that actuated (in red), the time at which they actuated and the near-ceiling gas temperatures at the time of sprinkler actuation, shows that first sprinkler actuation (No. 25) occurred at 205 s after ignition. At the time of first sprinkler actuation, Figure 3-8 shows that the flames reached a height of about 7 ft (2.1 m) above the top of the fuel array.

Figure 3-7: Sprinkler Actuation Sequence of 12 Sprinklers (Red Colors) and the Associated Gas Temperature (°F) at Activation and the Activation Time (s) After Ignition for Test 5.

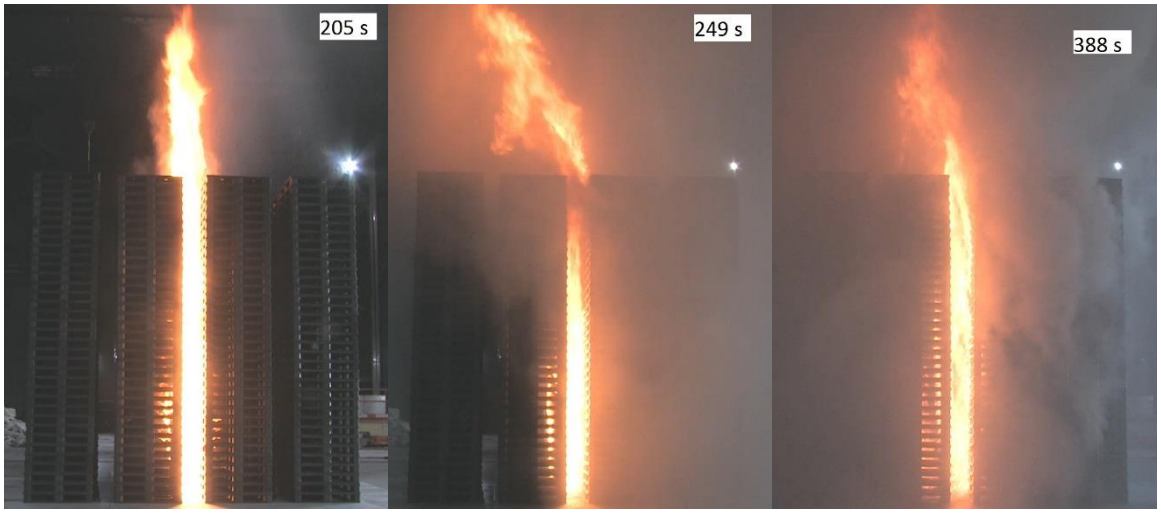


Figure 3-8: Photos of Test 5 from South Side at 205 s, 249 s and 388 s After Ignition.

After first sprinkler actuation, the fire size decreased for a short time period and then continued to increase. At 249 s after ignition, just before second sprinkler (No. 24 in Figure 3-7) actuation, a strong flame appeared at the top of the fuel array. Because the ignition was offset west from the first sprinkler actuation, the center image of Figure 3-8 also shows that the flame was pushed to the west side by the downward spray.

At the time of eighth sprinkler actuation (No. 20 at 388 s), the fire was still very strong. From this time, the whole burning area was filled with smoke and water vapor and the fire could not be observed. Only the infrared imagery showed that the fire continued in the fuel array. Several seconds later, two additional sprinklers – Nos. 18 and 33 in Figure 3-7 – actuated at 6 min 32 s and 6 min 46 s after ignition, respectively. The fire appeared to be controlled; however, the fire size started to increase again at 20

minutes after ignition. The final two sprinklers – Nos. 19 and 26 in Figure 3-7 – actuated at 23 min 41 s and 26 min 56 s after ignition, respectively. The test was terminated at 41 minutes after ignition.

3.4.3.2 Gas and Steel Temperatures

At the time of first sprinkler actuation (205 s after ignition), the near-ceiling gas temperature was 252°F (122°C)and increased over time after first sprinkler actuation to a peak value of 1,116°F (612°C) and then declined after the 10th sprinkler actuation. A second temperature rise occurred with a peak value of 693°F (367°C) east of the fuel array measured at 1616 s. The 60-second average maximum ceiling steel temperature was 162°F (72°C).

3.4.3.3 Extent of Damage

The infrared imagery showed that the east target array was ignited after 1200 s. Fire fighters also confirmed this observation.

3.5 Solid-Piled Storage of Exposed, Nonexpanded Group A Plastics to 16 ft (4.9 m) High Under a 35 ft (10.7 m) Ceiling Protected with K25.2 (K360) ESFR Pendent Sprinklers (Test 6 of Research Project 3056422)

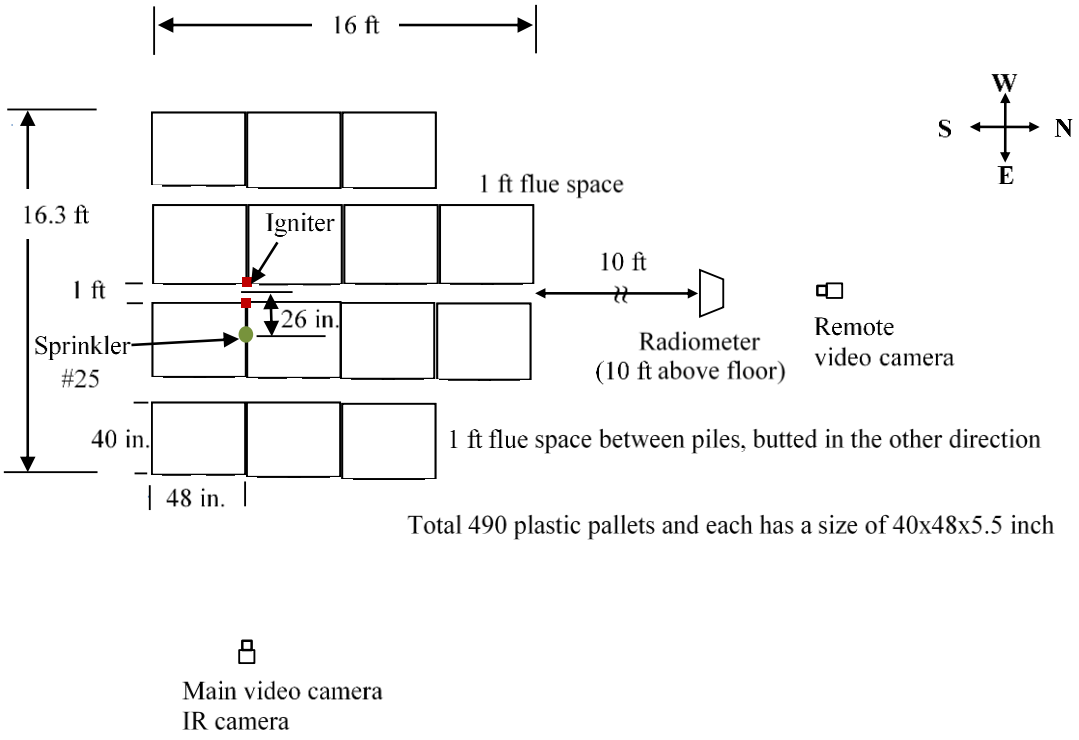
3.5.1 Test Overview

Due to the results of Test 5, the purpose of Test 6 was to determine if quick-response K25.2 (K360) pendent ESFR sprinklers operating at a minimum pressure of 60 psi (4.1 bar) would be able to provide an acceptable level of protection for solid-piled storage of exposed, nonexpanded Group A plastics under a maximum 35 ft (10.7 m) high ceiling.

3.5.2 Test Setup

Test 6 was conducted under the North Movable Ceiling. Figure 3-9 shows the test setup in plan and elevation views. A total of 490 plastic pallets was used as fuel. As shown in Figure 3-9, the main fuel array was double-row solid pile, 4 pallets long, 35 pallets high with a 1 ft (0.3 m) flue space in the longitudinal direction (N-S) and with the pallets butted together in the other direction. The storage height was 16 ft (4.9 m). In addition, two rows that were 3 pallets long and 16 ft (4.9 m) high were placed both east and west of the main array with a 1 ft (0.3 m) flue space.

Ceiling sprinkler protection was provided by FM Approved quick-response, 165°F (74°C) temperature rated K25.2 gpm/psi$^{1/2}$ (K360 lpm/bar$^{1/2}$) pendent ESFR sprinklers. The sprinkler deflectors were installed under the North Ceiling of the Large Burn Lab 18 in. (457 mm) down from the ceiling surface. The exposed sprinkler branchlines were nominal 2-1/2 in. (63 mm) diameter steel pipe with the sprinklers evenly distributed over the entire ceiling on 10 ft x 10 ft (3 m x 3 m) spacing. The water supply system was set to provide a constant discharge pressure independent of the number of operating sprinklers. Prior to test, the system pressure was set to 60 psi (4.1 bar), which resulted in a sprinkler discharge rate of about 195 gpm (738 L/min).



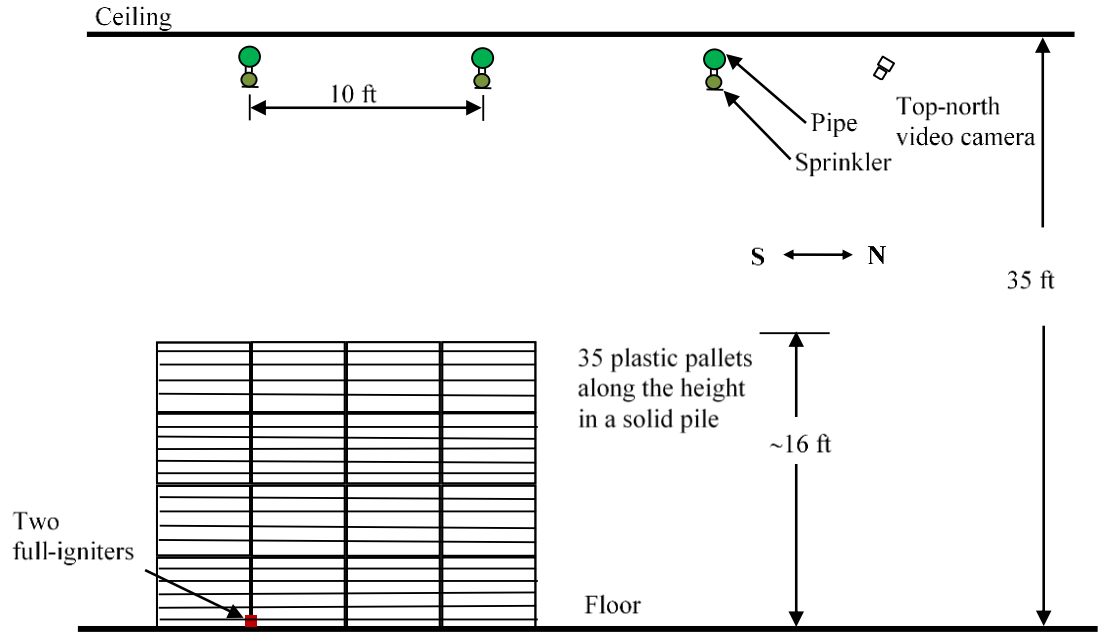


Figure 3-9: Plan and Elevation View of Test 6.

3.5.3 Results

3.5.3.1 Sprinkler Activation Times and Patterns

From the south side of the fuel array, Figure 3-10 shows a sequence of fire images that were captured at three instances (250 s, 325 s and 1,800 s) after ignition. The right side of the images denotes east.

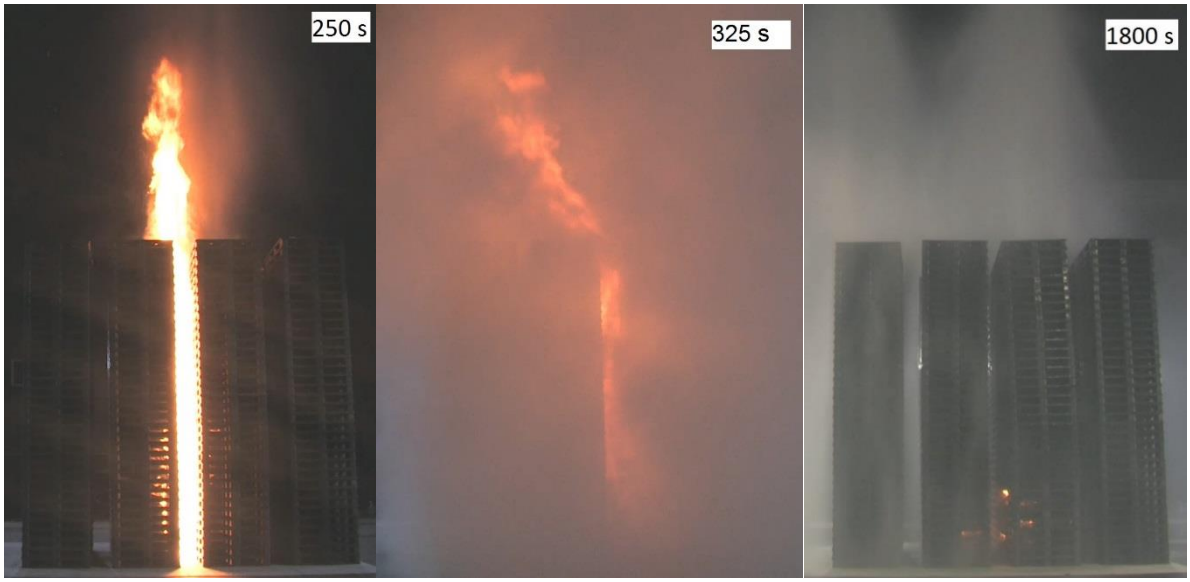


Figure 3-10: Photos of Test 6 from South Side at 250 s, 325 s and 1,800 s After Ignition.

The first sprinkler actuated at 250 s and was the sprinkler closest to the ignition location (approximately 2 ft [0.6 m] east of ignition). Figure 3-10 shows that the flames at 250 s reached a height of about 8 ft (2.4 m) above the top of the fuel array. After first sprinkler actuation, the fire size was reduced slightly and the fire continued in the fuel array. Because the ignition was offset west from the first sprinkler actuation, the center image of Figure 3-10 also shows that the flame was pushed to the west side by the downward spray. Upon second sprinkler actuation at 325 s, which was the sprinkler approximately 8 ft (2.4 m) to the west of ignition, the fire size was significantly reduced. The test was terminated at 1,800 s after ignition with only two sprinkler actuations.

3.5.3.2 Gas and Steel Temperatures

The maximum near-ceiling gas temperature was 324ºF (162ºC) and the 60-second average maximum ceiling steel temperature was 84ºF (29ºC).

3.5.3.3 Extent of Damage

The fire of Test 6 was deemed to be suppressed based on the actuation of two ceiling sprinklers, the near-ceiling gas temperatures and the test observations.

4. Conclusions

This report highlights the results of five full-scale fire tests conducted with the test commodity for exposed, nonexpanded Group A plastics.

4.1 Test No. 13

In Test 13, quick-response, K25.2 (K360) pendent sprinklers operating at a minimum discharge pressure of 60 psi (4.1 bar) were able to provide an acceptable level of protection for the storage of exposed, nonexpanded Group A plastics when maintained in open-frame single-row and double-row racks under a ceiling height of 40 ft (12.2 m). This is based on a total of 8 sprinklers activating during this test and keeping near-gas ceiling and steel temperatures at an acceptable level while also preventing excessive horizontal fire spread. The successful results of testing conducted with open-frame storage racks are also typically applicable to solid-piled and palletized storage arrangements.

4.2 Test No. 8

In Test 8, quick-response, K22.4 (K320) pendent sprinklers operating at a minimum discharge pressure of 75 psi (5.2 bar) were not able to provide an acceptable level of protection for the storage of exposed, nonexpanded Group A plastics when maintained in open-frame single-row and double-row racks under a ceiling height of 40 ft (12.2 m). Even though the number of sprinkler actuations was limited to 7, near-gas ceiling temperatures peaked at 1,312°F (711°C) well after the first two sprinkler actuations, sprinkler skipping was observed and fire jumped the aisle and progressed to the backside of the east target array.

4.3 Test No. 9

In Test 9, quick-response, K25.2 (K360) pendent sprinklers operating at a minimum discharge pressure of 50 psi (3.4 bar) were not able to provide an acceptable level of protection for the storage of exposed, nonexpanded Group A plastics when maintained in open-frame single-row and double-row racks under a ceiling height of 35 ft (10.7 m). Even though the number of sprinkler actuations was limited to 7, near-gas ceiling temperatures peaked at 1,563°F (850°C) well after the first two sprinkler actuations, sprinkler skipping was observed and fire jumped the aisle and progressed to the end of the east target array.

4.4 Test No. 5

In Test 5, quick-response, K16.8 (K240) pendent sprinklers operating at a minimum discharge pressure of 50 psi (3.4 bar) were not able to provide an acceptable level of protection for the storage of exposed, nonexpanded Group A plastics when maintained in a solid-piled arrangement up to 16 ft (4.9 m) high under a ceiling height of 35 ft (10.7 m). Even though the number of sprinkler actuations was limited to 12, near-gas ceiling temperatures peaked at 1,115°F (602°C) well after the first two sprinkler actuations and the fire progressed through the storage array and involved the east target array. The unsuccessful results of testing conducted with solid-piled storage are typically applicable to palletized storage as well as and open-frame rack storage arrangements.

4.5 Test No. 6

In Test 6, quick-response, K25.2 (K360) pendent sprinklers operating at a minimum discharge pressure of 60 psi (4.1 bar) were able to provide an acceptable level of protection for the storage of exposed, nonexpanded Group A plastics when maintained in a solid-piled storage arrangement up to 16 ft (4.9 m) high under a ceiling height of 35 ft (10.7 m). This is based on a total of 2 sprinklers activating during this test and keeping near-gas ceiling and steel temperatures at an acceptable level while also preventing excessive horizontal fire spread.

5. Recommendations

Due to the results of the five tests outlined in this report, the following sections contain recommendations that pertain to both Tables 23.4.2 and 23.6.1 for the protection of exposed, nonexpanded Group A plastics. In addition, due to the similarities in the protection requirements for rubber tires, which are a form of exposed, nonexpanded Group A plastics, recommendations are also provided that pertain to Table 23.8

5.1 Table 23.4.2

It is recommended that Table 23.4.2 of the 2019 Edition of NFPA 13 be modified as follows:

1) Where the maximum ceiling height exceeds 30 ft (9.1 m), remove all existing K14.0 (K200) and K16.8 (K240) sprinkler designs for exposed nonexpanded Group A plastics.
2) Where the maximum ceiling height exceeds 30 ft (9.1 m), revise all existing K22.4 (K320) sprinkler designs for exposed, nonexpanded Group A plastics by changing the indicated design pressure of “50 psi (3.4 bar)” to “75 psi (5.2 bar)”.
3) Where the maximum ceiling height exceeds 30 ft (9.1 m), revise all existing K25.2 (K360) sprinkler designs for exposed, nonexpanded Group A plastics by changing the indicated design pressure of “50 psi (3.4 bar)” to “60 psi (4.1 bar)”.
4) Add two new rows for exposed, nonexpanded Group A plastics where the maximum storage height is 20 ft (6.1 m) and the maximum ceiling height is 40 ft (12.2 m). The first row would be for the K22.4 (K320) pendent sprinkler with a minimum operating pressure of 75 psi (5.2 bar). The second row would be for the K25.2 (K360) pendent sprinkler with a minimum operating pressure of 60 psi (4.1 bar).

5.2 Table 23.6.1

It is recommended that Table 23.6.1 of the 2019 Edition of NFPA 13 be modified as follows:

1) Where the maximum ceiling height exceeds 30 ft (9.1 m), remove all existing K14.0 (K200) and K16.8 (K240) sprinkler designs for exposed nonexpanded Group A plastics.
2) Where the maximum ceiling height is 35 ft (10.7 m) for exposed, nonexpanded Group A plastics, add a new sprinkler design for the K22.4 (K320) sprinkler based on a design pressure of “75 psi (5.2 bar)”. This would apply to maximum storage heights of 20 ft (6.1 m), 25 ft (7.6 m) and 30 ft (9.1 m).
3) Where the maximum ceiling height exceeds 35 ft (10.7 m), remove all existing K22.4 (K320) sprinkler designs for exposed nonexpanded Group A plastics.
4) Where the maximum ceiling height is 35 ft (10.7 m) for exposed, nonexpanded Group A plastics, add a new sprinkler design for the K25.2 (K360) sprinkler based on a design pressure of “60 psi (4.1 bar)”. This would apply to maximum storage heights of 20 ft (6.1 m), 25 ft (7.6 m) and 30 ft (9.1 m).

5) Where the maximum ceiling height is 40 ft (12.2 m) for exposed, nonexpanded Group A plastics, revise all existing K25.2 (K360) sprinkler designs by changing the indicated design pressure of “50 psi (3.4 bar)” to “60 psi (4.1 bar)”.
6) Where the maximum ceiling height is 40 ft (12.2 m) for exposed, nonexpanded Group A plastics and the maximum storage height is 20 ft (6.1 m), add a new sprinkler design for the K25.2 (K360) pendent sprinkler based on a design pressure of “60 psi (4.1 bar)”.

5.3 Table 23.8

It is recommended that Table 23.8 of the 2019 Edition of NFPA 13 be modified as follows:

1) Where the maximum ceiling height exceeds 30 ft (9.1 m), remove all existing K14.0 (K200) and K16.8 (K240) sprinkler designs.
2) Where the maximum ceiling height is 35 ft (10.7 m), revise the existing K22.4 (K320) pendent sprinkler design by changing the indicated design pressure of “35 psi (2.4 bar)” to “75 psi (5.2 bar)”.
3) Where the maximum ceiling height is 35 ft (10.7 m), revise the existing K25.2 (K360) pendent sprinkler design by changing the indicated design pressure of “25 psi (1.7 bar)” to “60 psi (54.1 bar)”.
4) Where the maximum ceiling height is 40 ft (12.2 m), revise the existing K25.2 (K360) pendent sprinkler design by changing the indicated design pressure of “40 psi (2.8 bar)” to “60 psi (54.1 bar)”.

References

1. X. Zhou, S. P. D'Aniello, and H. Z. Yu, "Spray characterization measurements of a pendent fire sprinkler," *Fire Safety Journal*, vol. 54, pp. 36-48, 2012.

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