RESEARCH TECHNICAL REPORT

Summary Report of Fire Testing Involving Ignitable Liquids – for NFPA 30

FM Global®

Summary Report of Fire Testing Involving Ignitable Liquids

(document prepared in support of code changes)

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NFPA 30 Flammable and Combustible Liquid Code

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1. **Introduction**

The term ignitable liquid as used in this report and by FM Global is defined as any liquid that can burn. Ignitable liquids include all flammable and combustible liquids as defined by NFPA 30.

1.1 Background

The contents of this report are being submitted to support the following Public Comments made to NFPA 30-2018:

Table 1-1: Summary of Code Changes

Public Input No.	NFPA 30 Section	Subject	Public Report Section(s) Supporting Changes
109	9.1.4	Elimination of consumer product and distilled spirit exemption	3.6, 3.7, 3.8
111	Table 12.8.1	Modification to allowable liquid-container combination in general purpose warehouses	3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8
113	Figure 16.4.1(b)	Add 2 oz plastic containers and liquids with a flash point greater than or equal to 450°F (230°C)	3.4
114	Figure 16.4.1(c)	Eliminate incorrect commodity protection reference for 50-50 alcohol-water mixtures and add new tables with protection for these liquids and a pointer to the table for 6 oz bottles.	3.5, 3.6, 3.7, 3.8
116	16.5.2	Protection criteria for FP $\geq$ 450°F (230°C) in plastic containers. New Table 16.5.2.14 and Fire Protection Scheme D.	3.1, 3.2, 3.3
118	16.5.2	Protection criteria for 2oz (60 ml) and smaller plastic containers. New Table 16.5.2.13.	3.4
119	16.5.2	Protection criteria for rack storage of alcohol in plastic or glass bottles < 6 oz (180 ml). New Table 16.5.2.15.	3.5
120	16.5.2	Protection criteria for rack storage of 50-50 alcohol water mixtures in plastic or glass bottles. New Table 16.5.2.16 and Fire Protection Scheme E.	3.6, 3.7, 3.8
121	16.5.2	Protection criteria for palletized storage of 50-50 alcohol water mixtures in plastic or glass bottles. New Table 16.5.2.17.	3.7, 3.8

This report was compiled from eight (8) full scale fire test programs conducted by FM Global. The test work spans from 1994 through 2014. The test work was aimed at defining adequate fire protection for the storage of ignitable liquids (i.e., liquids that burn). This testing covered the following liquid types:

a. Vegetable oil in 48 oz (1.4 L) plastic bottles in cartons and uncartoned.
b. Low flash point hydrocarbon liquids in 2 oz (59 ml) plastic bottles in cartons.

c. 99% ethyl alcohol in 6 oz (180 ml) plastic bottles in cartons.
d. 50-50 isopropyl alcohol-water mixture in 1 gal (3.8 L) plastic bottles in cartons.
e. 50-50 ethyl alcohol-water mixture in 1.75 L (59 oz) glass bottles in cartons.

The storage arrays were rack and palletized arrangements. Ceiling heights were either 30 ft (9 m) or 40 ft (12 m). Protection included both ceiling sprinkler only designs and ceiling + in-rack sprinkler designs.

1.2 Organization of this Report

As noted above, this document contains documentation from eight (8) full scale fire test programs. Each program is presented in Section 3.0. Each section is fully self contained. Not all of the tests that may have been done in a particular research program are included. Only tests that are related to the public comments were included. This has created gaps in test numbering. This was intentional to ensure the original content was maintained as written by the original author.

The content of this report correlates with the various Public inputs as shown in Table 1-1.

2. **FM Global Test Facilities Information**

This report documents testing that spans from 1994 to 2014. Between 2002 and 2003 FM Global transitioned from the original test facility in West Gloucester, RI called the Factory Mutual Test Center to the current testing facility called the FM Global Fire Technology Laboratory located on the same property. Section 2.1 provides an overview of the current facility. Section 2.2 provides a historical description of the original test building.

2.1 Description of Research Campus / Laboratories

The Fire Technology Laboratory is located at the FM Global Research Campus in West Glocester, Rhode Island, USA. Figure 2-1 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 m^2 (66 ft^2). 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 m^3/s (200,000 ft^3/min). The lab is provided with an advanced humidity control system to ensure testing consistency. The system circulates up to 104,000 m^2/min (49 m^3/s) of air and removes up to on ton (900 kg) of water per hour.

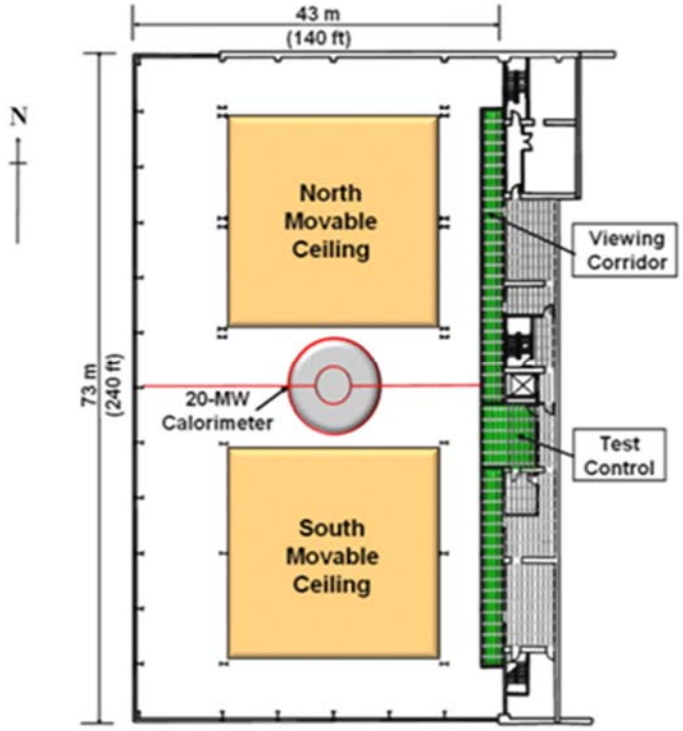


Figure 2-1: Illustration of FM Global Large Burn Laboratory test locations

2.2 Description of the Factory Mutual Test Center

This information is historical only. This facility was decommissioned at the end of 2002.

The Factory Mutual Test Center was located in West Glocester, Rhode Island. A pictorial sketch of the Test Center is shown in Figure 2-2 and a floor plan in Figure 2-3.

The sprinkler systems at the Test Center were specially designed to limit friction loss and maintain a relatively uniform discharge from the operating sprinklers. The branch lines were 2-in.nominal diameter; they were connected to 8-in.cross mains to form a gridded system. The 8-in.cross mains were connected at both ends to 10-in.fed mains, and each feed main was connected to a separate 10-in. riser. A sufficient number of fittings and branch lines were installed to permit several sprinkler arrangements. Both pendent and upright sprinklers could have been installed. A plan view of the sprinkler system is shown in Figure 2-4.

Water pressure was held constant by an automatic controller which may be set at any pressure up to 150 psig. The water pressure could also have been controlled by the Test Center computer to simulate decaying pressure curves. The facility was equipped with a pollution control system which collected smoke and other products of combustion. In normal operation, the 100,000 cfm exhaust system was balanced by fully opening three 12-ft x 12-ft doors on the lee side of the building. In this operating mode, the system had negligible effect on fire development and the final results of a test.

Installed instrumentation was able monitor gas temperatures near the ceiling, water pressure and flow, sprinkler operating times and sequence, and such other varieties as may be appropriate to a particular test.

All data was recorded on tape in a computerized data acquisition system. The computer had been programmed to process and reduce certain data in a standardized manner and to provide output in tabular and/or graphic form.

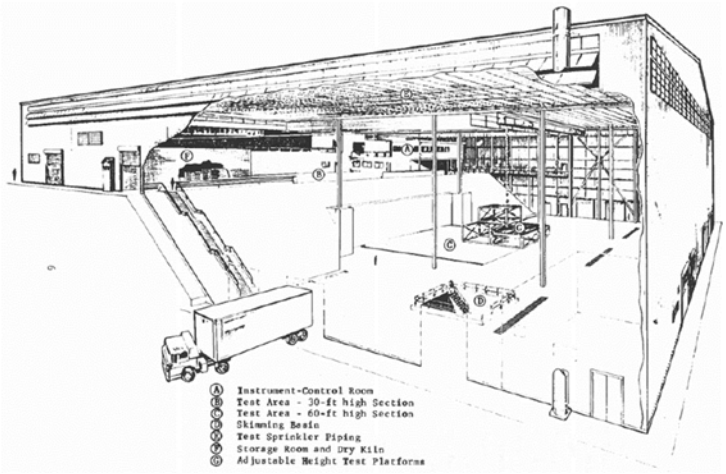


Figure 2-2: Factory Mutual Test Center (historical image)

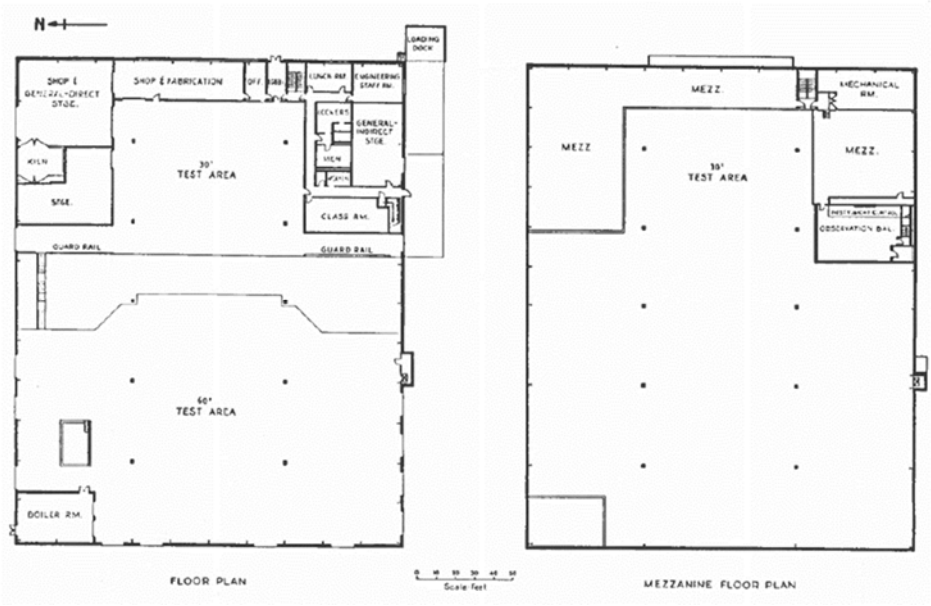


Figure 2-3: Factory Mutual Test Center – Plan View (historical image)

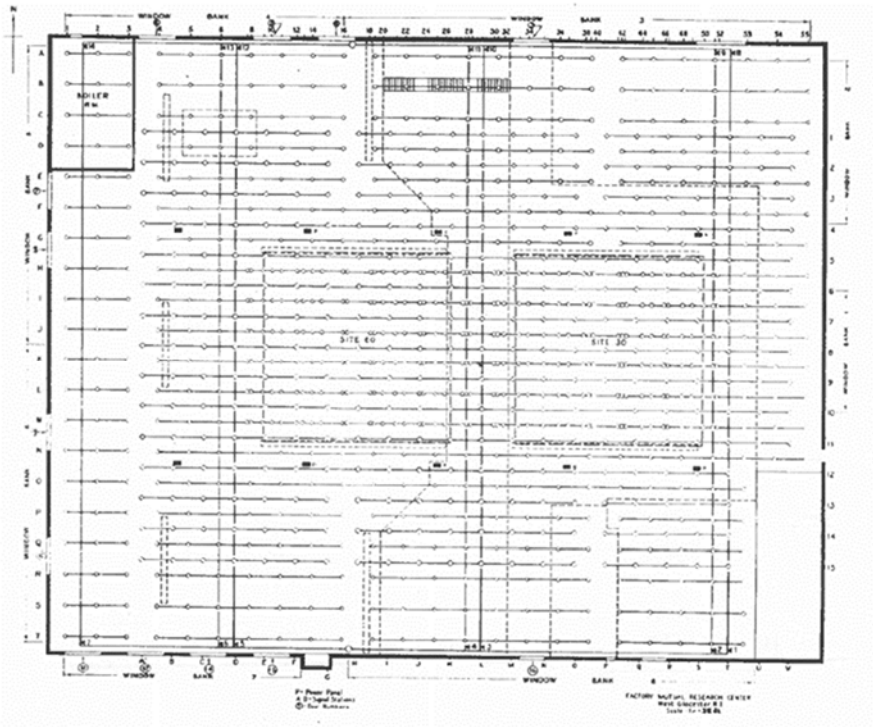


Figure 2-4: Test Center Sprinkler System (historical image)

3. **Test Summaries**

3.1 Protection of Rack Stored Vegetable Oil in Small Plastic Containers / Ronald Dean / August 1995

3.1.1 Test Overview

The test facility used for this program is described in Section 2.2.

3.1.2 Test Setup (Figures 3-1 – 3-6)

3.1.2.1 Commodity

In two tests, the commodity consisted of 48 oz polyethylene terephthalate (PET) bottles filled with soybean oil. Eight bottles were stored in a corrugated carton. In two tests the commodity consisted of 48 oz PET bottles filled with a mixture of corn and canola oils. Twelve bottles were sealed in a corrugated tray with plastic sheet encapsulation (identified as tray packs). Figure 3-1 show a typical pallet load of each type of commodity.

3.1.2.2 Storage Arrangement

3.1.2.2.1 General

In all tests, commodity was stored five tiers high (about 24 ft). The main array consisted of a double row rack. Tests 1-3 had a single rack row target to the east and west of the main array, across an 8 ft aisle. In Test 4, there was only a single row target array to the east.

3.1.2.2.2 Storage Arrangement - Test 1 (cartoned commodity)

Fifty pallet loads of vegetable oil were located in the central portion of the main and east target arrays. The remaining loads which filled out the array were the standard Class II commodity, consisting of double triwall cartons with sheet metal liners. Each oil load contained 320 bottles of soybean oil (120 gal.). Figure 3-1 shows a typical commodity pallet load. Overall array dimensions were about 35 ft long, 30 ft wide and 24 ft high. Combustibles in the oil loads consisted of about 85% oil, 7% wood, 4% plastic and 4% corrugated paper. The main array contained 40 pallet loads of oil, representing about 45,000 lb of combustible material. Including the triwall cartons, 140 loads comprised the entire array. Total fuel weight was about 69,000 lb. The array rested on the floor of the 30 ft high test site so that a 6 ft clearance existed between the ceiling and array top.

3.1.2.2.3 Storage Arrangement - Test 2 (cartoned commodity)

The number of oil commodity pallet loads was increased to 80, filling the main array and representing about 90,000 lb of combustibles. The percent of combustibles in the oil loads was the same as in Test 1. The 140-load total in the entire array contained about 108,000 lb of combustibles. Other than the in-rack sprinkler system, all other setup parameters remained the same as in Test 1 (Figure 3-3).

Table 3-1: Fire Test Summary

PROJECT: RACKED VEGETABLE OIL		FIRE TEST SUMMARIES			
Test Parameters	Test No.	1	2	3	4
	Test Date	7-28-93	8-04-93	9-15-93	11-15-93
	Commodity	Soybean Oil in PET Bottles in Cartons	Soybean Oil in PET Bottles in Cartons	Corn/Canola Oil in PET Bottles in Tray Packs	Corn/Canola Oil in PET Bottles in Tray Packs
	Storage Arrangement	Rack	Rack	Rack	Rack
	Array Size (ft x ft x ft)	35X30X24	35X30X24	35X26X23	18x19x23
	Stack Height (ft-in)	24-0	24-0	23-3	23-3
	No. of Tiers	5	5	5	5
	Clearance to Celling (ft-in)	6-0	6-0	6-9	6-9
	Clearance to Sprinklers (ft-in)	5-5	5-5	6-2	6-2
	Aisle Width (ft)	8	8	8	8
	Ignition Centered Below (No. Sprinklers)	4	4	4	4
	Sprinkler K-Factor	5.6	5.6	5.6	5.6
	Sprinkler Temperature Rating (°F)	165	165	165	165
	Sprinkler RTI - English Units (ft-s)$^{1/2}$	50 / 300[1]	50 / 300[1]	50 / 300[1]	50 / 300[1]
	Sprinkler Spacing (ft x ft)	10 x 10[2]	10 x 10[3]	10 x 10[3]	10 x 10[2]
	Constant Water Pressure (psi)	29.0 / 29.8[1]	29.0 / 29.9[1]	29.0 / NA[1]	29.0 / 28.1[1]
Test Results	First Sprinkler Operation (min:sec)	3:40 / 3:36[1]	4:22 / 4:02[1]	8:09 / 8:52[4]	5:51 / 17:00[1]
	Last Sprinkler Operation (min:sec)	4:39 / 9:36[1]	16:47 / 8:12[1]	8:52 / 9:17[4]	17:04 / 18:03[1]
	Total Sprinklers Opened	4 / 9	4 / 32[1]	4 / 52[4]	4 / 7[1]
	Total Sprinklers Discharge (gpm)	123 / 269[1]	123 / 1007[1]	125 / NA[4]	125 / 211[1]
	Avg. Discharge per Sprinkler (gpm)	30.7 / 30.0[1]	30.7 /31.5[1]	31.2 / NA[4]	31.2 / 30.1[1]
	Peak Gas Temperature (°F)	803[5]	1646[6]	1715[5]	579[7]
	Max. One Min. Avg. Gas Temperature (°F)	698[5]	1592[6]	1540[5]	470[7]
	Peak Celling Steel Temperature (°F)	172	117	202	147
	Max. One Min. Avg. Steel Temp. (°F)	170	1091	137	143
	Time of Aisle Jump (min:sec)	none	none	9:07	none
	Equiv. No. Pallet Loads Consumed	<0.5[8]	1.5[8]	2.0[9]	0.5[9]
	Test Concluded (min:sec)	20:02	25:02	9:17	30:00

Table 1 - Fire Test Summary Notes

1. In-rack (fast response)/ceiling (ordinary response) sprinkler
2. Ceiling spacing; in-rack pendent sprinklers located at every transverse/longitudinal intersection (4-ft 7-in. along pipe). Lines were installed above 2nd and 4th tiers.
3. Ceiling spacing; in-rack pendent sprinklers located 8-ft 3-in. on centers above 2nd and 4th tiers, staggered vertically.
4. Test 3 was terminated at 9:17 (52 sprinklers operating) and sprinkler discharge pressure was maximized. Data presented for this test occurred at or prior to termination time. NA = Not Available.
5. Location: 10-ft south of ignition.
6. Location: over ignition.
7. Location: 10-ft west of ignition.
8. Based on 40 carton (320 bottle or 120 gal. oil) pallet loads.
9. Based on 33 plastic sheet encapsulated tray packs (396 bottles or 148.5 gal. oil) pallet loads.

3.1.2.2.4 Storage Arrangement - Test 3 (tray pack commodity)

Based on Test 1 and 2 results, the length of the array was reduced for Test 3 and the main array again filled with oil commodity (60 loads) equaling about 65,300 lb of combustible materials. The 120-load total in the entire array contained about 83,300 lb of combustibles. Each oil load contained 396 - 48 oz bottles of corn/canola oil (148 gal.), the composition of which was 89% oil, 5% plastic, 4% wood and 2%

corrugated paper and fiberboard by weight. Overall array dimensions were about 26 ft long, 30 ft wide and 23 ft high. Otherwise, the setup was the same as in Test 2 (Figure 3-4).

3.1.2.2.5 Storage Arrangement - Test 4 (tray pack commodity)

Following a review of the three previous tests, the array size was again changed. The length was shortened and the west target omitted. The main array contained 28 pallet loads of oil (30,500 lb) and 12 of triwall cartons. The east target contained only triwalls. The entire 60 load array contained about 35,000 lb of combustibles. The percent of combustibles in the oil loads was the same as in Test 3. Overall array dimensions were about 18 ft long, 19 ft wide and 23 ft high. Otherwise, the setup was the same as that of Test 3 (Figure 3-5).

3.1.2.3 Ignition Method

Ignition was accomplished by means of two 3-in. diameter by 6-in. long cellucotton rolls each soaked in 8 oz of gasoline and enclosed in a polyethylene plastic bag. In Tests 1 and 2 they were located on the east face of the main array bordering the center transverse flue space (Figure 3-2 and 3-3). In the other tests they were located in the central transverse flue space, close to the east face of the main array (Figure 3-4 and 3-5).

3.1.2.4 Instrumentation

Numerous ceiling thermocouples were located at the ceiling. A steel angle (2-in. x 2-in. x 1-in. x 4-ft long) with imbedded thermocouples was located at the ceiling over ignition. A second steel angle was located at the ceiling 10-ft north of ignition. Ceiling and in-rack sprinklers were timed to obtain an opening sequence (Figure 3-6).

3.1.3 Protection

In all tests, ceiling sprinkler protection was provided by ordinary response, 165°F rated, ½-in. orifice sprinklers on a 10-ft x 10-ft spacing discharging at a constant density of 0.30 gpm/ft^2. The east end of the central transverse flue space of the array (ignition area) was located beneath and centered among four ceiling sprinklers. Additionally, in Tests 1 and 4, fast response, ½-in orifice, in-rack sprinklers rated at 165°F were located at every transverse/longitudinal flue space above the second and fourth storage levels (Figure 3-2 and 3-5). Discharge from the most remote sprinkler was 30 gpm. In-rack sprinkler conditions were the same in Tests 2 and 3 except that sprinklers were located on about eight foot intervals and staggered vertically (Figure 3-3 and 3-4).

3.1.4 Test Results (3.1.8)

3.1.4.1 General

In both tests of cartoned oil (Tests 1 and 2), fire incubated for about 3 minutes before beginning rapid initial fire development. Fire progress of the two tests then became quite different. In the tray pack tests (Tests 3 and 4), an extended incubation period established a deep-seated fire in the ignition loads ultimately resulting in an eruption of vertical fire spread. Fire chronologies for each test are presented in 3.1.9.

3.1.4.2 Test 1 (cartoned commodity)

Following the initial four sprinkler operations between 3:36 and 3:41 (2 each, ceiling and in-rack), fire shifted from the ignition flue to the adjacent southern flue causing a maximum near-ceiling gas temperature of 803°F 10-ft south of ignition. Between about 8½ and 11½ minutes, the fire burned at a steady rate before declining significantly over the next two minutes. Ceiling temperatures during the final six minutes of the 20 min test remained at about 75°F. A total of four in-rack and nine ceiling sprinklers were opened. Greatest fire damage resulted in the pallet loads about 5-ft south of the ignition flue.

3.1.4.3 Test 2 (cartoned commodity)

The operation of the ceiling and two in-rack sprinklers caused a temporary retardation in fire growth. Following recovery, the fire continued to grow, causing the near-ceiling gas temperature over ignition to reach 1646°F at 5:45 with a total of 23 operating sprinklers (including 2 in- racks). Steady burning continued for about 3½ minutes before temperatures declined significantly. Ceiling temperatures during the final 11 minutes of the 25 minute test remained at about 75°F. At test conclusion a total of four in-rack and 32 ceiling sprinklers were operating and the fire was essentially confined to the ignition bay.

3.1.4.4 Test 3 (tray packs)

During the long incubation time, the fire burrowed into the ignition pallet loads, spreading laterally rather than vertically. Within 20 sec bottles were melting and releasing oil. By 2:15 a non-burning oil pool was forming in the ignition area. By 7:50, the unignited oil pool extended almost across the 8-ft aisle to the target array. Shortly thereafter, vertical fire development began, opening the first in-rack sprinkler at 8:09 which resulted in an increased level of fire activity. At 8:44 oil streams from breached bottles were spanning the aisle space and impinging on the target. Following the first ceiling sprinkler operation at 8:52, events occurred rapidly. Licking flames from the main array caused pilot ignition of the target array at the fourth level of storage. This event was repeated a couple seconds later at the second level. Steady flames from the main array extended about 4-ft into the aisle and occasionally flared to 6-ft. The oil pool was flaming for about half its length across the aisle. At about 9:10 a ball of flame rolled across the uninvolved portion of the aisle pool and ignited the bottom pallet load of the target. Flames immediately ascended and connected with the fire in the upper tiers. Once joined, the radiant feedback between target and main arrays caused the remaining non-burning part of the oil pool to ignite, subsequently causing a wall of flame across the 8-ft aisle which extended from the floor to the ceiling. These events occurred within a span of about 20 seconds. The test was terminated at 9:17 with a total of 52 timed sprinklers operating.

3.1.4.5 Test 4 (tray packs)

Fire development was very similar to that of Test 3 for close to six minutes. However, due to increased protection, with sprinklers in every transverse/longitudinal flue intersection above the second and fourth tiers, the first in-rack sprinkler operated at 5:51 while the fire was still in the ignition loads. This effectively restrained vertical development until about 15 minutes when it became evident that the fire severity was building. Between 16:30 and 17:00, fire spread rapidly from the 10-ft to the ceiling level (30-ft). The intensity continued to grow for another minute with the peak near-ceiling gas temperature reaching 579°F at 17:12. Beginning about 17:30, sprinkler water gained control, resulting in a quick

decline in ceiling temperatures together with a rapid buildup of white smoke and steam which obscured the fire view by 18:35. Near-ceiling gas temperatures reached 125°F at about 18:30 then slowly declined to 75°F by test conclusion at 30:00.

3.1.5 Discussion

3.1.5.1 Test 1 (longitudinal in-rack sprinklers in every transverse flue)

With in-rack sprinklers positioned at every transverse/longitudinal flue intersection, igniters were located on the east face of the main array adjacent to the central transverse flue (ignition flue). This provided a very hazardous condition since the fire was allowed to develop for a long period of time before actuating sprinklers. As a result, two ceiling sprinklers opened followed shortly thereafter by two in-rack sprinklers. In-rack sprinkler operations were such that the seat of the fire shifted to the south of ignition. Fire damage was essentially confined to the pallet loads on either side of the upright in the adjacent flue south of the ignition flue. Although fire burned the north faces of the upper three tiers of triwall cartons bordering the oil commodity, reaching the sheet metal inserts in some places, it was judged that, had actual oil commodity been present instead of the triwall cartons, the fire would not have gone much beyond the observed limit. Except in the immediate area of the transverse flue spaces, the sides of all pallet loads facing the longitudinal flue space (west face of east rack row) were not burned. Even in the most severely damaged area, a significant part of each pallet load remained intact. There was no fire damage in the west rack row across the longitudinal flue (Figure 3-16). Measured near-ceiling gas temperatures were below 1000°F and posed no threat to ceiling steel. Four in-rack and nine ceiling sprinklers opened. The protection was considered acceptable.

3.1.5.2 Test 2 (longitudinal in-rack sprinklers located 8-ft 3-in. on centers)

Lesser protection was used than in Test 1. The result was a more severe fire. Peak near-ceiling gas temperature over ignition exceeded 1600°F. Measured ceiling steel temperature was close to, but below the critical value for unsafe deflections. Fire damage was essentially confined to the pallet loads on either side of the ignition flue. There was penetration of the first row of bottles in the 3-5 tier pallet loads across the adjacent flue space to the north. Essentially only face charring was experienced by the pallet loads in the 2-5 tiers across the south adjacent flue space. Except in the immediate area of the transverse flue spaces, the sides of all pallet loads facing the longitudinal flue space (west face of east rack row) were not burned. Even in the most severely damaged area, much of each pallet load remained intact. With the exception of minor charring of a corner of a northerly pallet load in each of tiers 4 and 5, together with some melted plastic sheet coverings, there was no fire damage in the west rack row across the longitudinal flue. Again, with the exception of melted plastic sheets on the target across the 8-ft aisle to the east, there was no fire damage (Figure 3-17). Four in-rack and 32 ceiling sprinklers opened. The protection was considered unacceptable due to the large number of ceiling sprinklers that would be needed for an effective protection design.

3.1.5.3 Test 3 (longitudinal in-rack sprinklers located 8-ft 3-in. on centers)

The fire behavior exhibited by the tray packs was considerably different than that of the cartoned product using the same protection as in Test 2. This behavior was exhibited in Test 3. Upon initial sprinkler operations, the fire developed more rapidly. It changed from growing flames at the top of the

second tier storage to significant involvement of the main and target arrays with a flaming pool between them and ultimately test was terminated. At 9:17 (official test conclusion time - data collection was continued until 15:00) the ceiling sprinkler pressure was increased to the maximum obtainable. It is estimated that by about 10:00 the final total of 11 in-rack and 91 ceiling sprinklers (both timed and untimed) were open. Ceiling sprinkler discharge density was 0.47 gpm/ft^2 and in-rack sprinklers were discharging 21-gpm per sprinkler. The damage assessment revealed extensive damage in the main array east row with the fire reaching the south end in all tiers. However, with the exception of some minor plastic sheet melting, fire damage fell short of the north end. The adjacent western row of the main array suffered relatively little damage affecting only the first, second, and fourth storage tiers. The target, though, experienced considerable damage (Figure 3-18). Igniters in all tray pack tests were located inside the central transverse flue space within two inches of the east face of the main array. The protection was considered unacceptable.

3.1.5.4 Test 4 (longitudinal in-rack sprinklers in every transverse flue)

A single in-rack sprinkler held the fire in check for about 10 minutes. Eventually, however, the burrowing fire moved into the adjacent transverse flue, south of ignition and there developed rapidly, but not to the same degree, as in Test 3. Three additional in-rack and seven ceiling sprinklers opened between 17:00 and 19:03, gained control and then quickly reduced the fire's severity. Some charring was experienced on two faces each of three triwall cartons used in the three upper tiers of the array. The effect of this commodity on the resulting fire was judged to be negligible. Except in a small area of the bottom tier, no damage occurred to the commodity loads in the west row across the 6-in, longitudinal flue (Figure 3-19). The protection was considered acceptable.

3.1.5.5 Closing Remarks

As in the palletized test program enough oil was released from the bottles to allow a pool to develop on the floor in each test. Only in the inadequately protected tray packs (Test 3) was this pool observed to burn. Even then, following test termination, after the ceiling density was increased to 0.47 gpm/ft^2 the pool was rapidly cooled, and the fire brought under control. Table II lists some of the combustible properties of the vegetable oils used in this program.

3.1.6 Conclusions

1. Vegetable oil in PET bottles, in either corrugated cartons or tray packs, was adequately protected with in-rack sprinklers located above the second and fourth storage tiers along the longitudinal flue at each transverse flue intersection.

2. When lesser protection, consisting of in-rack sprinklers along the longitudinal flue on 8-ft 3-in. centers above the second and fourth storage tiers was applied, the provided protection was determined to be unacceptable for the cartoned vegetable oil and for the tray packs.

3.1.7 Figures

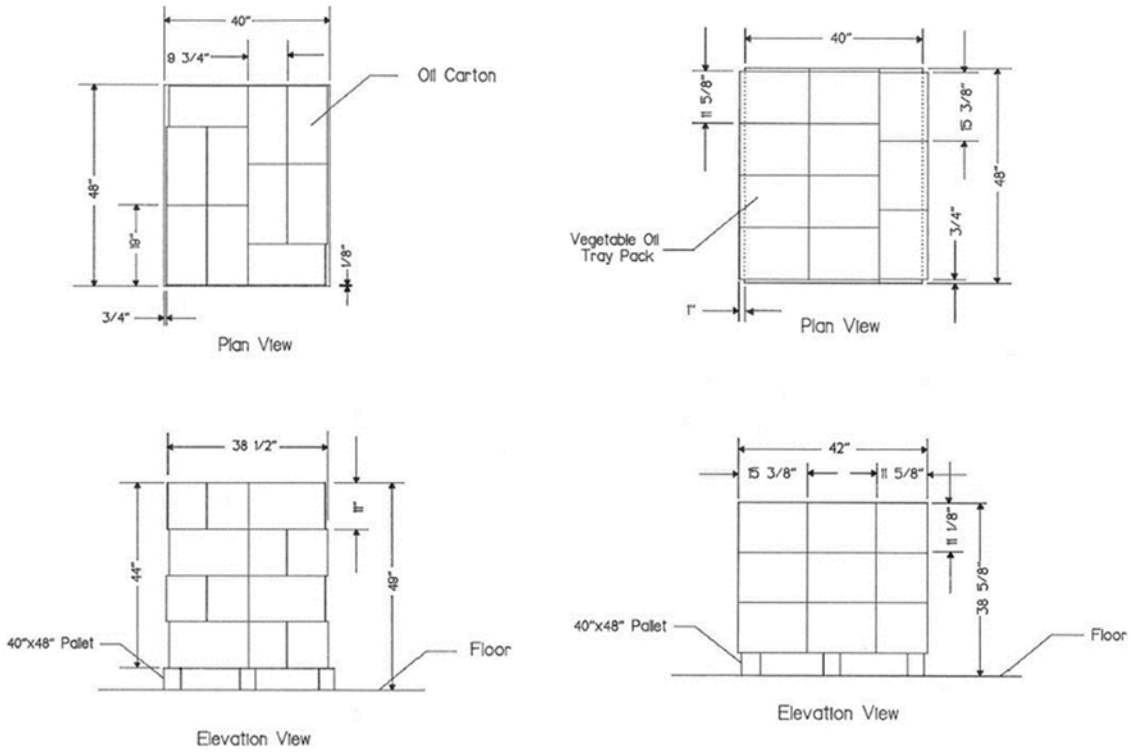


Figure 3-1: Cartoned Vegetable Oil Commodity / Sheet Encapsulated Vegetable Oil Commodity

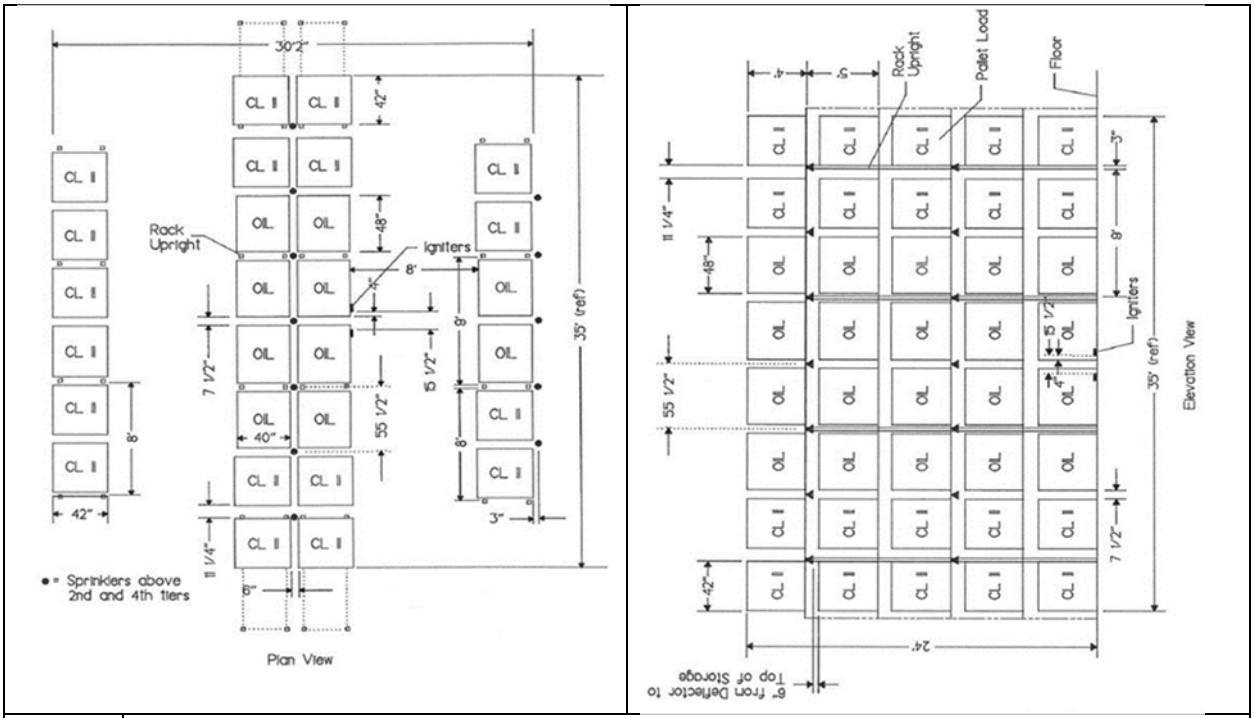


Figure 3-2: Array Setup – Test 1

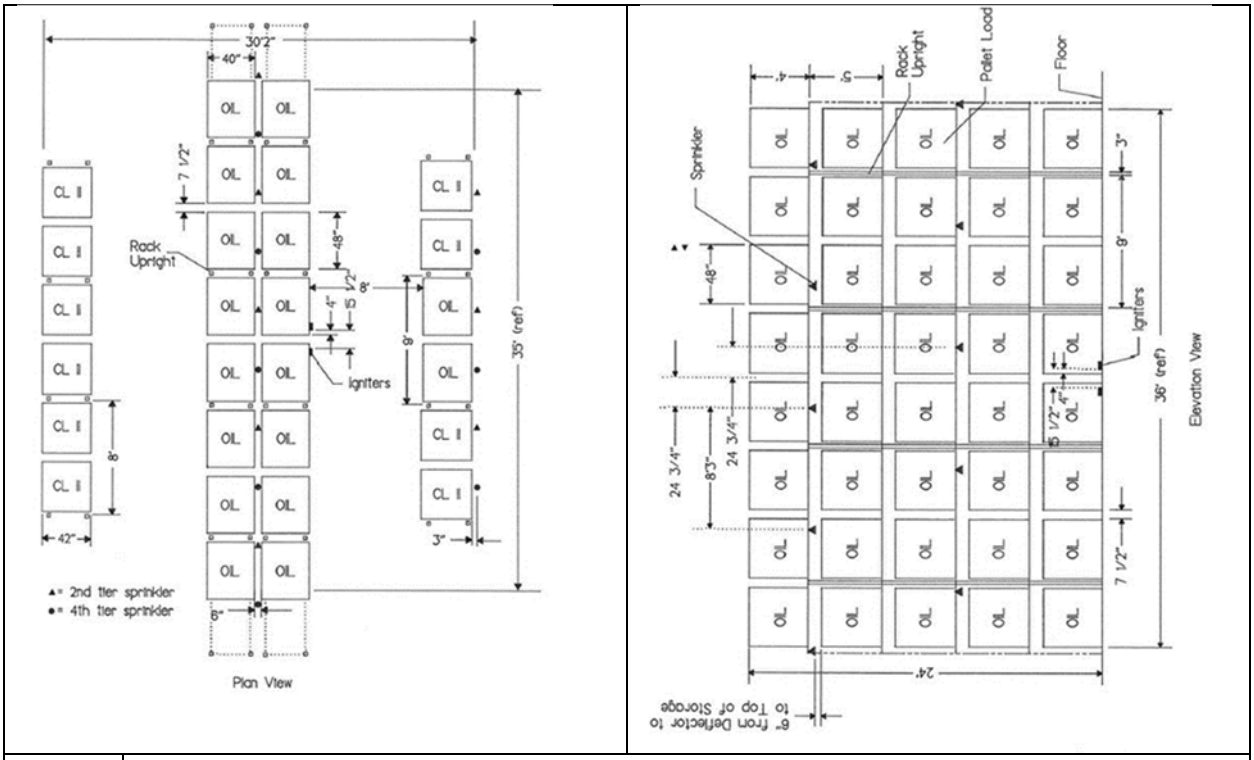


Figure 3-3: Array Setup – Test 2

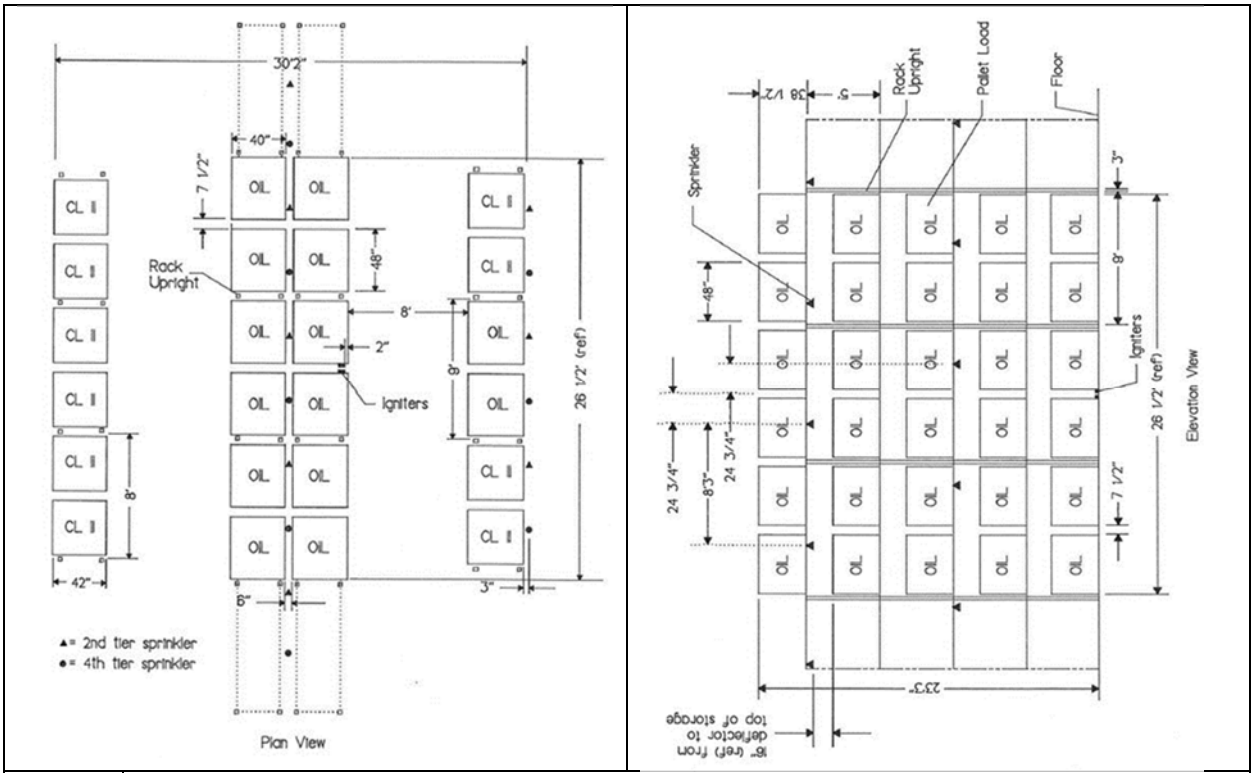


Figure 3-4: Array Setup – Test 3

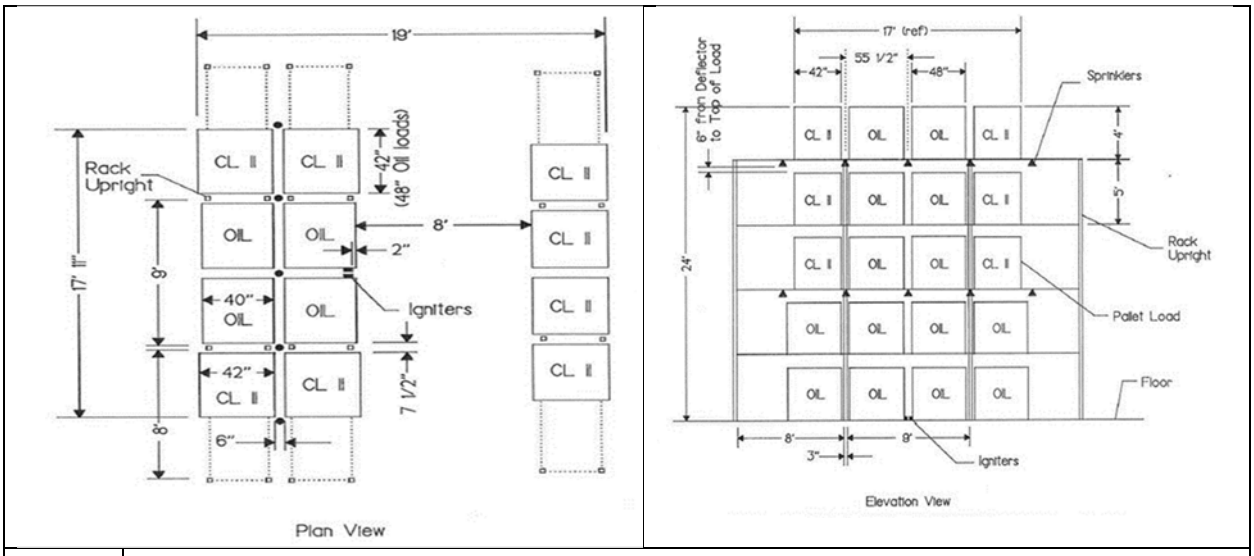
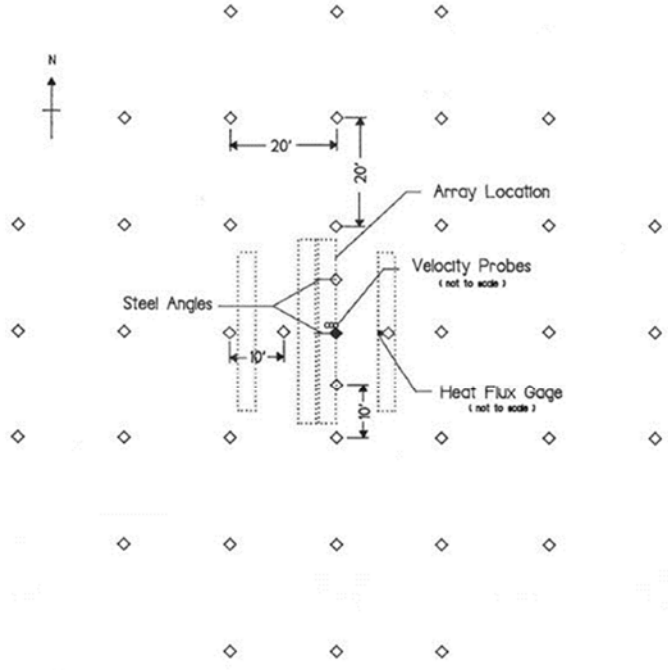


Figure 3-5: Array Setup – Test 4



NOTES:
1. ◇ - Installed Thermocouples (size not to scale).
2. ◆ - Thermocouple over Ignition (size not to scale).
3. Thermocouple Location 6 1/2 Inches below Ceiling.

Figure 3-6: Instrumentation Layout

3.1.8 Test Data

Oil Type	SOYBEAN	CORN-CANOLA	CORN*
Autoignition Temp (°F)	750	780	765
Boiling Temp - initial (°F)	520	675	690
- steady rapid boil (°F)	660	710	740
Closed Cup Flash Point (PM) (°F)	450	500	510
Open Cup Flash Point (Cleve) (°F)	590	620	610
Open Cup Fire Point (Cleve) (°F)	630	650	675
Heat of Combustion (BTU/lb)	16,990	17,195	16,650
Specific Gravity	0.930	0.920	0.925

Figure 3-7: Vegetable Oil Characteristics

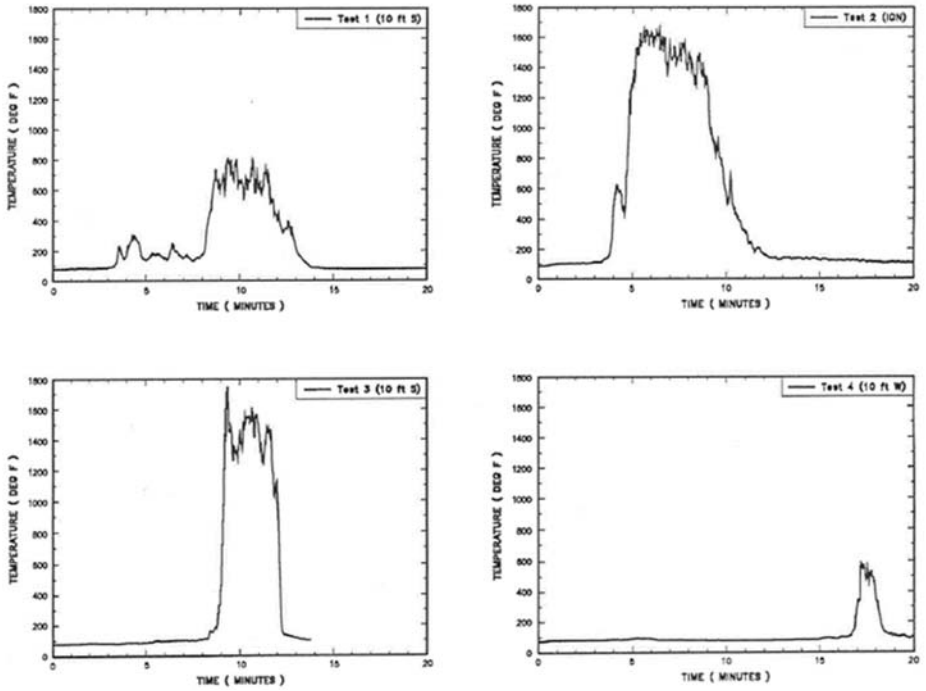


Figure 3-8: Near Ceiling Gas Temperatures

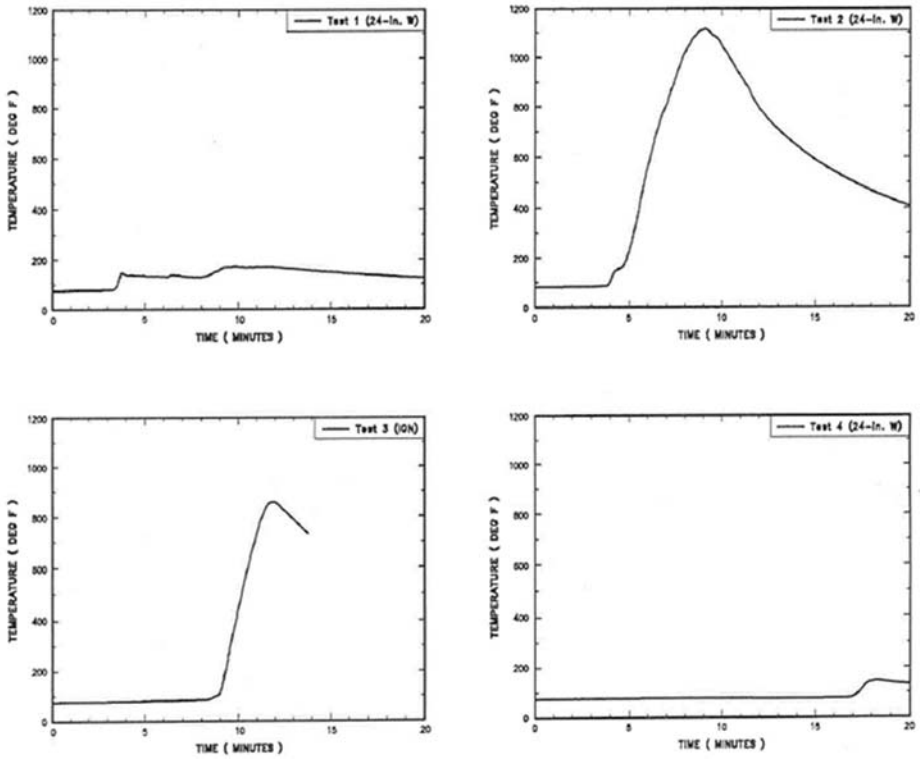


Figure 3-9: Ceiling Steel Temperatures

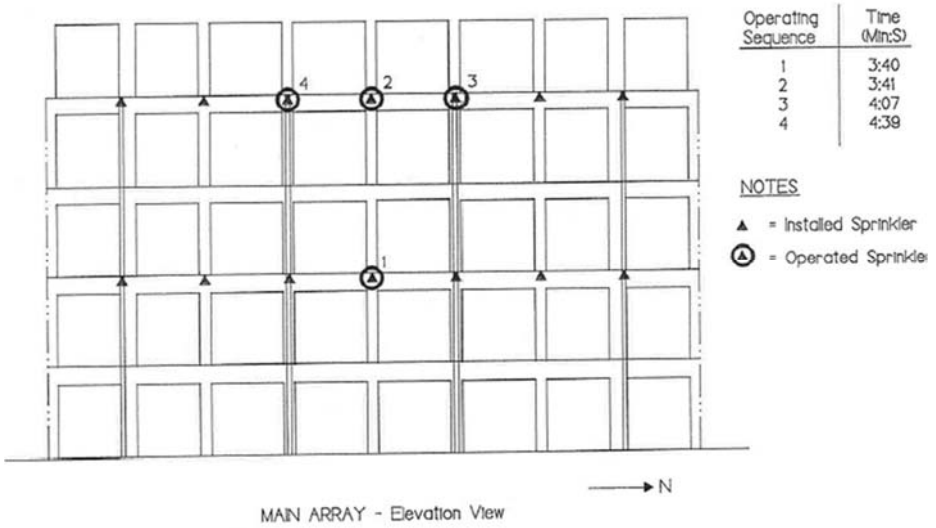


Figure 3-10: In-Rack Sprinkler Operations – Test 1

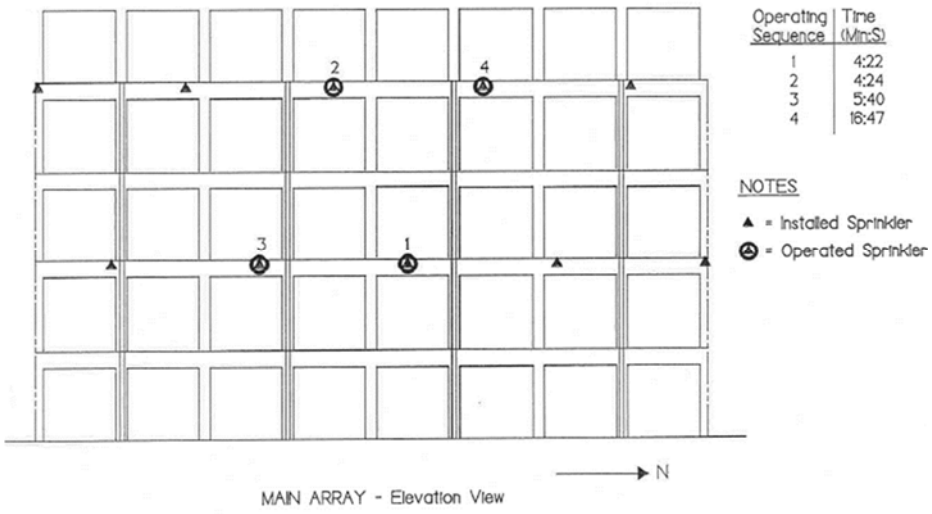


Figure 3-11: In-Rack Sprinkler Operations – Test 2

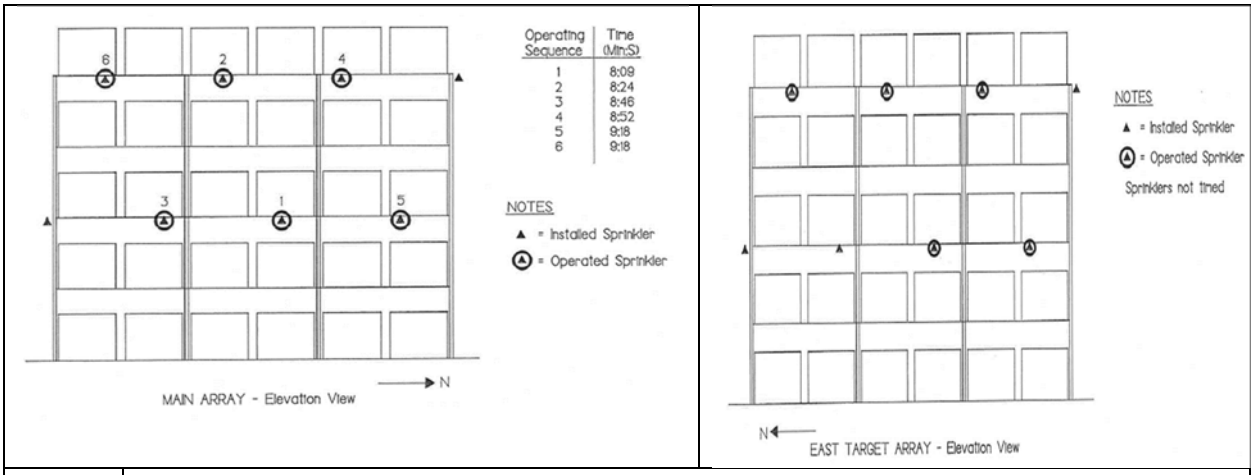


Figure 3-12: In-Rack Sprinkler Operations – Test 3

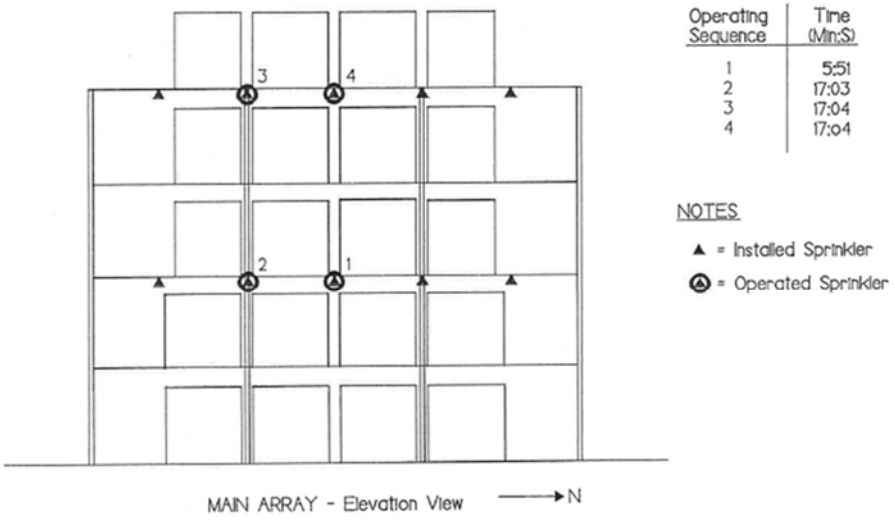


FIGURE 22. IN-RACK SPRINKLER OPERATIONS - TEST 4

Figure 3-13: In-Rack Sprinkler Operations – Test 4

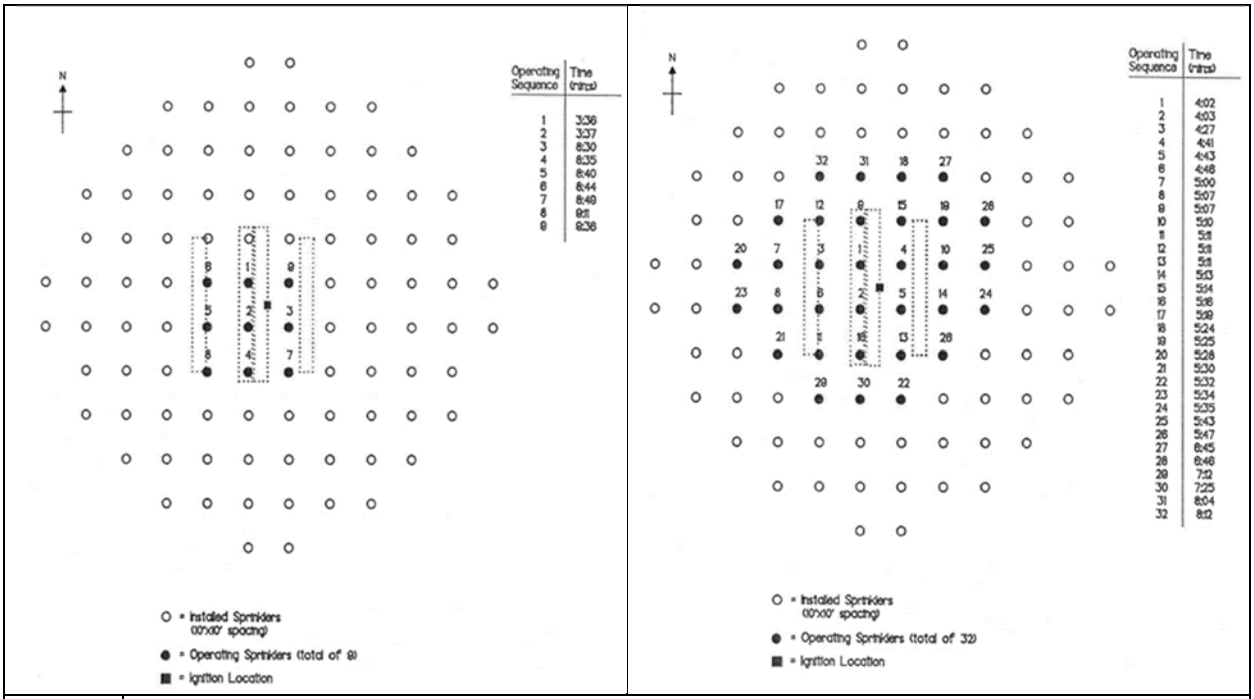


Figure 3-14: Ceiling Sprinkler Operations – Test 1 (left) / Test 2 (right)

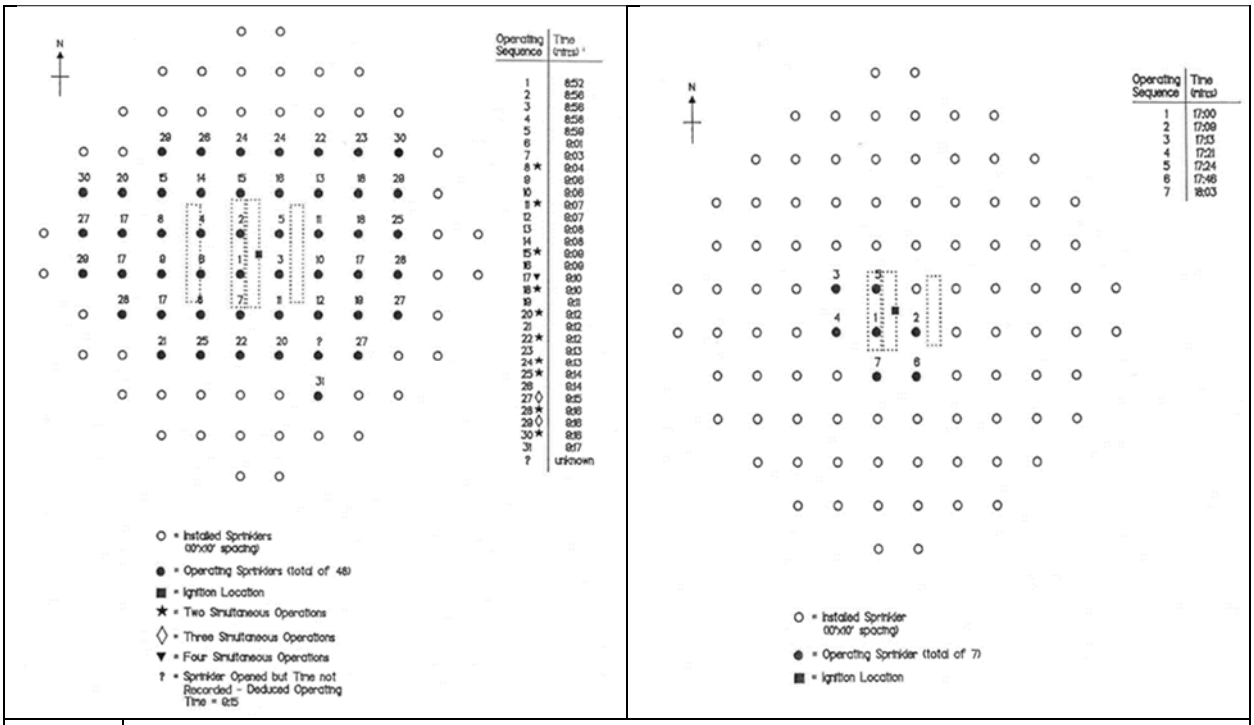


Figure 3-15: Ceiling Sprinkler Operations – Test 3 (left) / Test 4 (right)

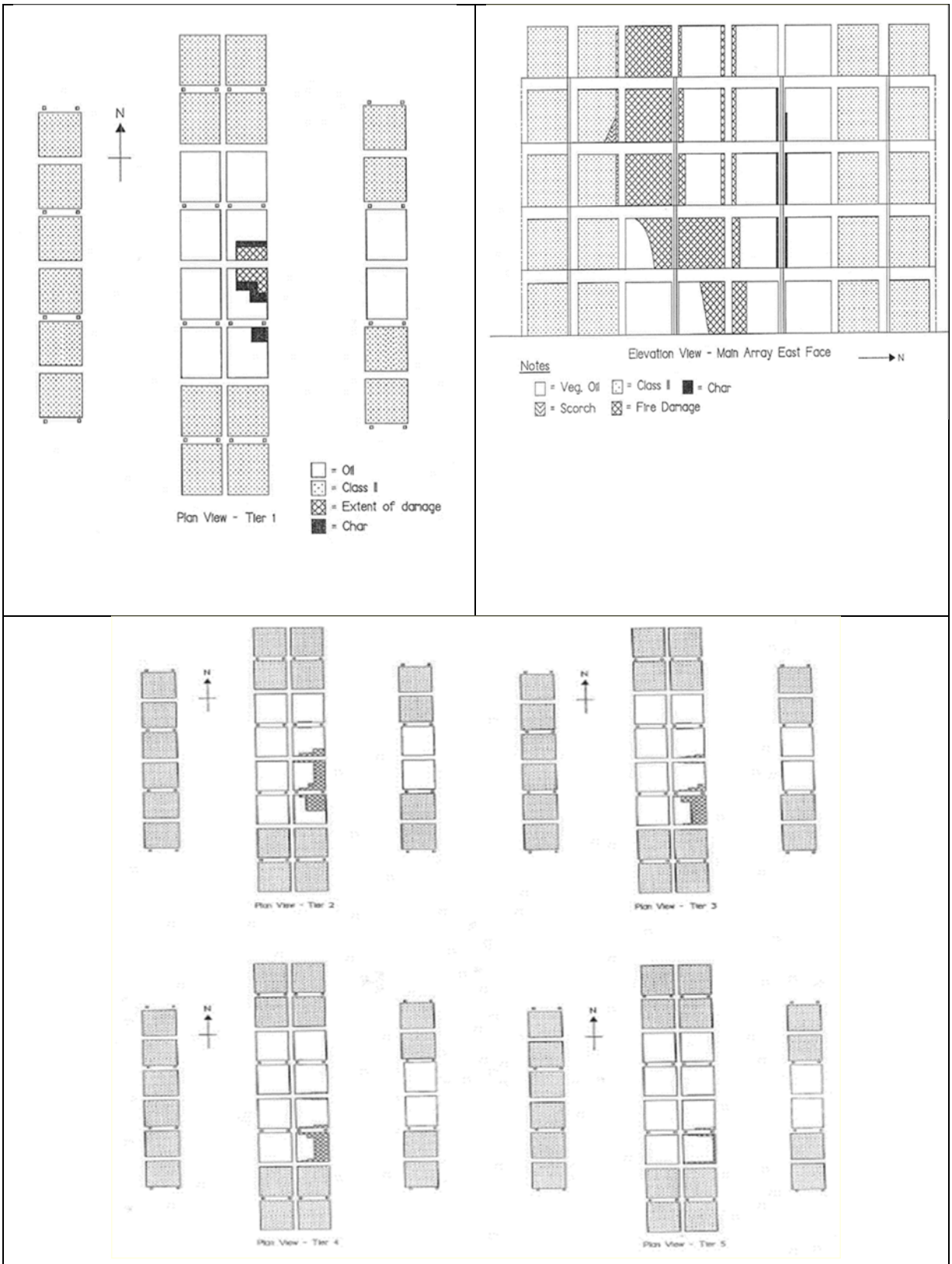


Figure 3-16: Extent of Fire Damage – Test 1

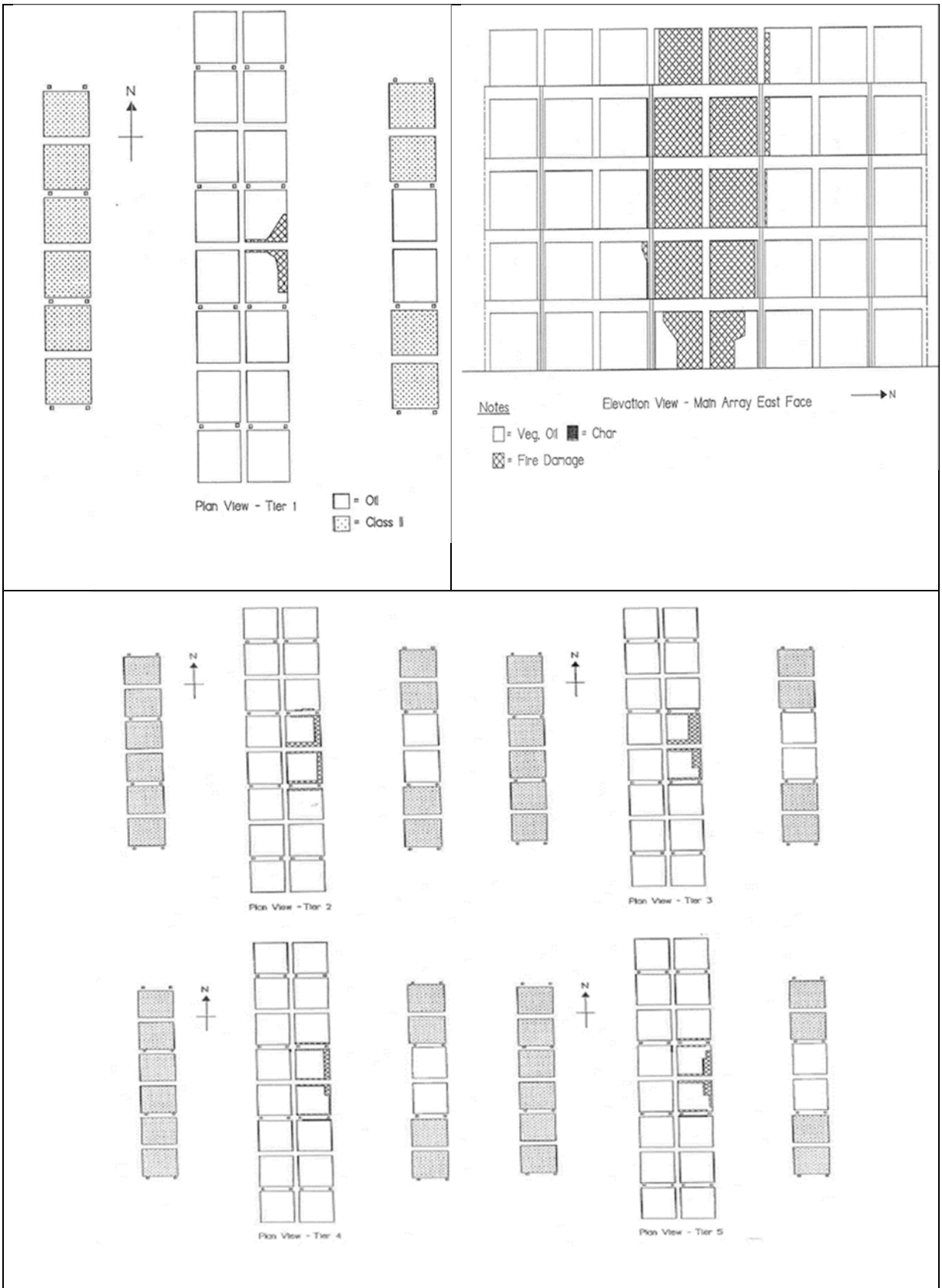


Figure	3-17: Extent of Fire Damage – Test 2

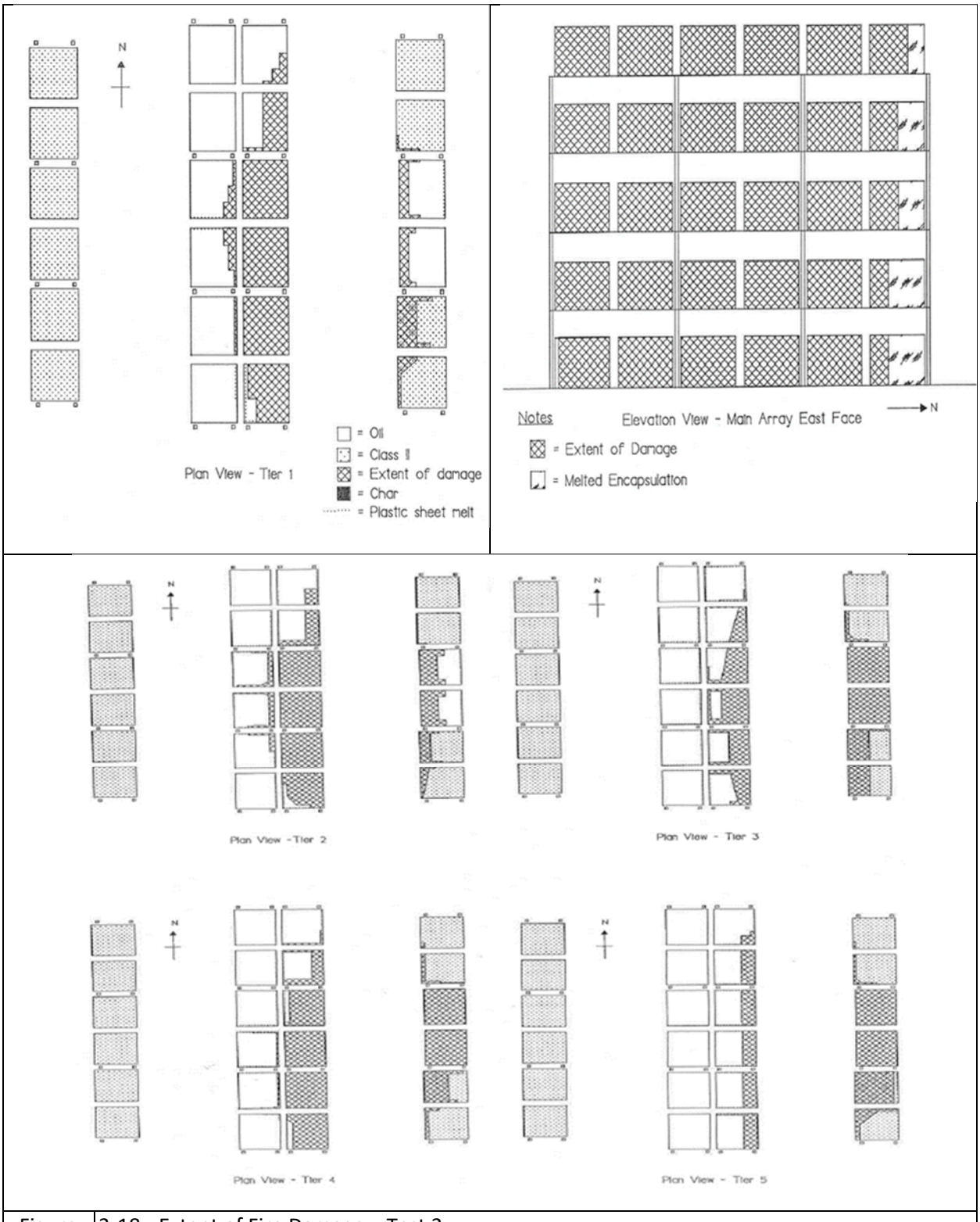


Figure	3-18: Extent of Fire Damage – Test 3

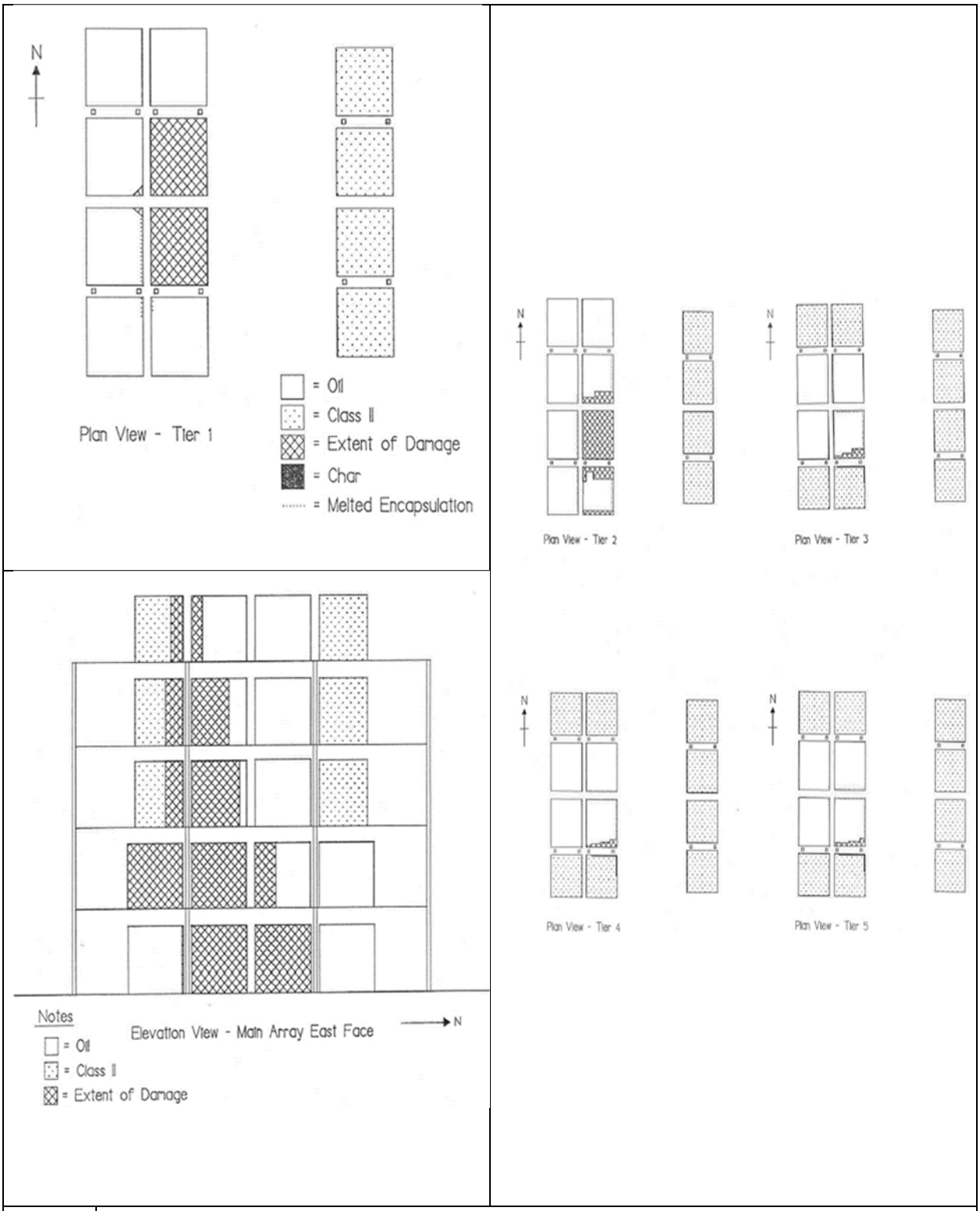


Figure 3-19: Extent of Fire Damage – Test 4

3.1.9 Fire Chronologies

Time (min:sec)	Observation
0:00	Ignition.
0:14	Plastic sheet beginning to melt.
0:15	Flames 2 ft high.
0:20	Plastic sheet peels back away from igniters.
0:27	Flames 4 ft high.
0:31	Flames 5 ft high on east face, main array.
0:40	Popping sound heard and small flare-ups extend out from bottom two layers of cartons in area behind igniter fire.
0:55	Flames have not spread into transverse flue yet; they still lick 5 to 6 ft high on east face.
1:15	Stream of vegetable oil spurts from a breached bottle into east aisle.
1:35	Flames well into cartons of southern ignition load.
1:37	Flames about 3½ ft high.
2:15	Flames again about 5 ft high.
2:30	Flames 5 to 6 ft high and spreading into transverse flue adjacent to igniters.
2:40	Bottle balls into flue space.
2:52	More bottle spillage.
3:03	More spillage - more or less on a continuing basis.
3:10	Flames 10 ft high.
3:13	Flames 15 ft high.
3:15	Oil pool has been forming.
3:27	Flames lock at ceiling (30 ft high).
3:30	Flames steady on ceiling. Flames also spreading horizontally, especially below second tier pallet.
3:36	First ceiling sprinkler operates.
3:40	First in-rack sprinkler operates.
3:43	Flames reduced to 15 ft high.
4:15	Increased involvement of oil loads at second and third tiers.
4:20	Flames again lick at ceiling.
4:29	Flames reach Class II commodity at south end of array at top of third tier.
4:32	Fire still appears confined to east side of main array; no flames in longitudinal flue.
4:50	Flames 20 ft high.
5:00	No flames visible above array top; smoke obscures view somewhat.
5:11	Flames appear concentrated in second tier, some fire in third and fourth tiers.
5:15	More spillage of bottles from array. Intense fire on face of array at bottom two tiers in ignition area and one pallet load to south at third tier.
5:40	No flaming into west aisle space - much whitish smoke being generated, filling western aisle space.
6:00	Fire on east face persisting at bottom through fourth tiers.
6:04	More spillage into east aisle; fire appears concentrated in flue space just south of ignition.
6:10	Spillage of several cartons into aisle; sounds of oil spilling.
6:25	More spillage into east aisle.
6:36	Flames lick at ceiling.
6:45	Flames reduced to top of array (24 ft high).
6:55	No steaming or smoking of east target.
7:00	Flames 18 ft high.
7:10	Smoke extends at least 15 ft below ceiling over most of test site and to floor level in west aisle and beyond.
7:25	Most intense fire at second through fourth tiers in flue south of ignition.
8:24	Flames again steady on ceiling about 5 ft south of ignition flue.
8:43	Fire now involves Class II commodity.
8:45	Smoke filling east aisle down to floor level and some of the area east of array.
9:05	Smoke beginning to obscure fire view; entire test site has a veil of smoke throughout.
9:45	Almost continuous sounds of bottle spillage. Fire seems to have increased; still concentrated from top of second tier to top of array.
10:15	Sounds of cartons falling. Only faint fire glow visible down east aisle.
11:00	Only faint fire flow visible down east aisle.
11:15	More spillage into east aisle; fire concentrated from bottom of third tier to top of array.
12:00	Fire seems concentrated in east portion of main array with no fire in west part.
12:30	Fire seems to have diminished considerably. Some independent fires seen at bottom of third and fourth tiers.
12:58	Smoke totally obscures fire view.
13:08	Copious quantities of thick white smoke being generated.
13:26	End of racks can be seen, but no commodity.
20:02	Test concluded.

Figure 3-20: Fire Chronology – Test 1

Time (min:sec)	Observation
0:00	Ignition.
0:10	Flames about 2 ft high; plastic wrapping peeling away.
0:20	Flames about 3 ft high; cardboard discoloring and charring.
0:26	Flames 4 ft high.
0:30	Flames 5 ft high.
1:06	Oil squirts from south ignition load, carton at second layer.
1:25	Flames died down to about 4 ft high.
1:36	Flames on face moving into pallet load.
2:00	Fire still appears confined to east carton faces - has not yet entered central flue.
2:03	Flames 3½ ft high.
2:15	Flames intensifying, licking 4 ft high from both ignition loads. More oil squirting into aisle.
2:30	Flames becoming established on flue side of cartons on both ignition loads.
2:56	Flames 5 ft high.
3:00	Non-burning oil puddle forming in aisle space.
3:05	Two bottles fell into aisle. Small flames on carton scraps on aisle floor.
3:15	Flames extending about 1 ft into flue, licking 6 to 7 ft high.
3:30	Flames in the flue increasing - 10 ft high.
3:39	Flames 15 ft high, additional bottle spillage.
3:47	Flames 20 ft high.
3:50	Flames 24 ft high (at top of array).
3:54	Flames lick at ceiling (30 ft high)
3:59	Flames steady on ceiling.
4:02	First ceiling sprinkler opens.
4:15	Fire still confined to east side of rack; spillage of bottles.
4:19	Flames drop back from ceiling somewhat.
4:22	In-rack sprinkler opens, followed by another.
4:25	Flames driven back to about 24 ft high (array top) in ignition flue.
4:30	Flames on east face extend to ceiling.
4:45	No fire visible in longitudinal flue. Some flames in spillage on floor.
4:53	No fire into west aisle yet.
5:00	Flames on ceiling extent at least 10 ft in diameter. Smoke being driven down into west aisle.
5:10	Flames occasionally visible in longitudinal flue of main array at top two tiers.
5:11	Fire increasing in severity; flames reach about 3 ft into east aisle.
5:26	Much grayish smoke being driven down. Smoking or steaming of east target.
5:31	Flames about 15 ft in diameter across ceiling.
5:49	West aisle smoky but no flames seen.
5:55	Smoke and steam being driven down obscures clear view.
6:00	Whitish smoke obscures fire view above 10 ft.
6:10	Fire still appears concentrated in center (ignition) bay of main array.
6:15	Additional bottle spillage.
6:19	Cartons of oil falls into east aisle.
6:23	Fire glow at ceiling extends over main array and over both aisles; smoke obscures clear view.
6:41	Flames seen from base to about 20 ft high on east face main array.
7:01	Bottle spillage fairly continuous.
7:14	Flames not yet into west aisle.
7:23	Some discoloration on third tier loads of east target.
7:24	No indication that flames will jump to east target. However, plastic sheet encapsulation appears to be melting
7:35	Flames in longitudinal flue at third and fourth tiers.
7:47	Sounds of bottle spillage.
7:53	Flames at ceiling still span 20 ft diameter.
8:05	Third pallet load from north end at third tier becoming involved.
8:20	Fire glow still visible over ceiling. Fire persisting over entire center bay at east face.
8:28	Whitish smoke rises and falls, pretty much confined to ignition area.
8:30	Much smoke being driven down to floor. No ignition of east target.
8:52	Dense smoke layer extends 20 ft below ceiling, obscuring view down both aisles.
9:00	Sounds of continual bottle spillage are heard.
9:09	Thick whitish smoke descends to floor obscuring view of east aisle.
9:15	Only northeast corner of test site partially clear.
9:55	Smoke has descended to floor, obscuring view of array.
10:03	Copious quantities of smoke being generated.
25:02	Test concluded.

Figure 3-21: Fire Chronology – Test 2

Time (min:sec)	Observation
0:00	Ignition.
0:10	Flames 3 ft high.
0:18	Oil streaming from bottles in bottom layer of ignition pallet loads.
0:30	Flames reach top of bottom loads; more streams of oil.
0:40	Fire still concentrated over igniters; some ruptured bottles distorting. Oil almost continuously streaming from bottles in bottom two layers of trays in both ignition pallet loads.
0:54	Flames about 2½ ft high.
1:00	Flames almost surround trays at corner of each ignition pallet load.
1:08	Bottle fell from load; other bottles leaning.
1:13	Considerable number of vegetable oil streams spurting from bottles.
1:15	Flames extend about 2 ft into transverse ignition flue from east face of array.
1:30	Flames at top of bottom tier; about 5 ft high.
1:38	A flash of fire occurs as a squirt of vegetable oil ignites momentarily.
1:45	Flames still confined to ignition pallet loads.
1:57	Bottle falls into east aisle.
2:00	Oil stream hits observer about 10 ft away.
2:10	Flames reduced slightly to about 4 ft high.
2:15	Liquid pool has been forming in ignition area; it has not ignited.
2:24	Flames penetrating ignition loads at least one tray deep and 1½ trays long, along the flue side.
2:33	More bottle spillage.
2:44	Flames about 3½ ft high on east face.
2:57	Small flames on puddle of oil in longitudinal flue.
3:20	Flames rebuilt to about 5 ft high.
3:22	Partial tray of bottles fall into east aisle.
4:05	Increased flaming under top cap; flames penetrating deeper into ignition loads.
4:20	Flames in transverse flue almost reach longitudinal flue.
4:25	Flames on floor spill in longitudinal flue extinguished.
4:34	Fire appears to have moved into transverse flue space about ⅔ of a pallet load.
4:35	About 25% of each ignition load appears involved. Flames intensifying on top cap.
5:05	Smoke is whitish. Flames still confined to east side of main array and extend slightly into second tier.
5:06	Flames lick into longitudinal flue space at top of bottom tier.
5:25	Flames increasingly spreading up into second tier.
5:45	Flames about 6 ft high.
6:00	Fire still primarily concentrated in ignition area of both pallet loads.
6:07	Fire confined to bottom tier.
6:20	Flames spreading under top caps reach longitudinal flue.
6:45	Fire appears to be burning at a steady rate. Whitish, hazy smoke rising to ceiling, extends over test site below sprinkler piping.
6:48	Fire occasionally licks into adjacent southern transverse flue toward east face under cardboard cover, topping pallet load (top cap).
7:15	Flames still reach 5 to 6 ft high, appear to be intensifying.
7:28	Fire building in severity; heat is releasing sheet plastic banding in second pallet load level.
7:50	No ignition of oil spill on floor, which almost spans aisle and extends about 12 ft long. Flames persist on some of the fallen bottles in aisle.
7:57	Fire in longitudinal flue about halfway up second tier.
8:09	First in-rack sprinkler opens. Flames rapidly increasing following opening sprinkler.
8:15	Flames in flue at top of second tier (8 ft high).
8:20	Flames quickly extend to top of array (23 ft high). Much smoke being generated.
8:38	No fire on west face of main array.
8:44	Vegetable oil streams going across east aisle, impinging on target.
8:50	Dense dark gray smoke starting to obscure view. Flames on east face reach the ceiling.
8:52	First ceiling sprinkler opens.
8:58	Flames steady on ceiling. Lots of hissing noise.
9:07	East target pilot ignited at fourth tier.
9:11	Radiant heat becoming intense.
9:15	Fire on east face approaching north end loads of oil at second tier.
9:19	Very intense fire, continuing to spread over more of array.
9:24	Flames 60 ft dia. across ceiling; there is a pool fire.
9:30	Only north end pallet loads on east face of main array not yet fully involved.
9:34	East target is being totally involved; main array also appears to be coming totally involved.
9:46	Flaming pool in east aisle is main cause of fire.
10:09	Smoke closing down, rapidly obscuring view.
10:18	View above 10 ft level pretty well obscured.
10:22	Dense blackish smoke almost fills test site; faint fire glow still visible.
10:27	No indication of fire control; very, very vigorous fire in progress.
10:51	Smoke down to floor; except for a glow, view is totally obscured.
11:16	Fire view totally obscured.
15:00	Test concluded.

Figure 3-22: Fire Chronology – Test 3

Time (min:sec)	Observation
0:00	Ignition.
0:09	Flames lick about 3 ft high in ignition flue.
0:21	Flames about 5 ft high.
0:23	Sounds of bottles rupturing; oil streaming.
0:31	Multiple oil streams into east aisle.
0:36	Flames drop back to about 3 ft.
0:57	Bottle falls into flue space.
1:11	Another bottle falls; popping sounds; oil streams squirt into east aisle.
1:20	Flames still about 3 ft high.
1:25	Almost continuous streams of oil, some reach 4 ft across aisle from fire.
1:39	Fire moved down ignition flue about ⅓ pallet length.
2:12	Stream of oil almost spanned 8 ft aisle.
2:14	Fire below top of bottom pallet load burrowing into ignition loads.
2:30	Flames established on cardboard trays, more so on south than north load at east end of ignition flue.
2:56	No flames in longitudinal flue yet.
3:21	Flames lick about 5 ft high, primarily due to flaming cardboard.
3:40	Sounds of more bottles rupturing. Flames have penetrated at least 25% (from NE corner) into south ignition load under cardboard capping.
3:45	Fire moved down ignition flue a little over ½ pallet length.
4:11	Flame into longitudinal flue at top of ignition loads.
4:34	Ignition flue appears to be totally involved its full length.
4:49	Smoke generation increasing - light grey smoke.
5:03	Flames appear fairly steady at 5 ft level.
5:28	More bottle spillage into east aisle; non-ignited oil pool in east aisle.
5:51	First in-rack sprinkler opens in 2nd tier over ignition flue.
6:06	Fire height reduced to about 4 ft.
6:47	Fire confined to ignition loads.
6:57	Fire appears to be increasing in severity, impinging on bottom of 2nd tier loads.
7:26	Fire appears to be somewhat sheltered from sprinkler water.
7:45	Flames occasionally lick at bottom of 2nd tier.
8:48	Fire appears concentrated in upper ⅓ of ignition loads; flames occasionally lick to 5 ft, more generally they are 3½ ft high
10:00	Increased smoke generation. Smoke still appears like a haze.
11:00	Smoke haze reaching floor level throughout most of test site (except NE corner). Fire persisting primarily in product bordering ignition flue. Smoke becoming denser.
11:03	Flames about 3 ft high (at top of ignition loads).
12:03	Evidence of flaming under most of cardboard cap in north ignition pallet load.
12:39	No fire seen in longitudinal flue.
12:51	Flames lick up and occasionally strike bottom of 2nd tier load.
13:36	Flames fairly continuous on bottom of 2nd tier pallet load.
15:00	Fire building. Bottom of load at second tier above south ignition load becoming involved.
15:20	Fire is in longitudinal flue space curling up to 12 in. above bottom of 2nd tier.
15:55	Flames 10 ft high in southern flue adjacent to ignition flue.
16:10	Increased sizzling - fire severity increasing.
16:31	Fire is in flue just south of ignition.
16:39	Flames 15 ft high.
16:43	Flames 20 ft high.
16:45	Flames above top of array, more than 25 ft high. East faces of loads south of ignition flue at 3rd and 4th tiers becoming involved.
16:56	Fire licks at ceiling (30 ft high).
17:05	Oil streams squirt across aisle.
17:12	Flames across ceiling about 10 ft in diam.
17:22	2nd - 4th tiers all involved in east row of main array.
17:42	Appears to be no fire in west row of main array.
17:50	Increasing fire severity.
17:57	No pool or target ignition yet.
18:07	Fire seems to be diminishing in intensity.
18:14	Much whitish smoke building up, beginning to obscure fire view.
18:20	Flames no longer visible above array top.
18:35	View is totally obscured.
18:42	Fairly severe fire in ignition loads (smoke lifts occasionally allowing views).
19:36	Vigorous fire persists in bottom loads.
20:46	Smoke lifts more, showing vigorous fire in bottom and 2nd tiers.
21:06	Bottle spillage from 2nd tier into east aisle.
21:53	Vigorous fire still in progress although reduced in severity.
23:15	Fire appears confined to east row of main array.
24:02	2nd tier pallet load leaning toward aisle.
24:14	Load spills partly into east aisle.
24:20	Fire flares up; flames reach about 10 ft high.
24:29	Flames reduced to about 8 ft high.
25:11	Fire burning at steady rate; flames about 6 ft high, with smoke obscuration above that level.
26:17	Smoke haze increasing; fire visibility reduced.
26:45	Fire severity appears reduced.
30:00	Test concluded.

Figure 3-23: Firer Chronology – Test 4

3.2 ESFR Sprinkler Protection for Rack Storage of Vegetable Oil / B. G. Vincent / May 1994

3.2.1 Testing Overview

Data for Tests 1 and 3 were not included since they are not associated with the proposed code modification. They both involve a lower storage or roof height. The test facility used for this program is described in Section 2.2.

Table 3-2: Fire Test Summary – ESFR Protection for Vegetable Oils

	Test No.	2	4	5
	Test Date	10-26-93	3-15-94	3-21-94
Test Parameters	Commodity	Cartoned Vegetable Oil	Cartoned Vegetable Oil	Uncartoned Vegetable Oil
	Storage Arrangement	Rack	Rack	Rack
	Array Size (ft x ft x ft)	2 x 6 x 5	2x6x5	2x6x5
	Stack Height (ft-in)	24-6	24 – 0	23 – 9
	No. of Tiers	5	5	5
	Clearance to Celling (ft-in)	5-6	6 – 0	6 – 3
	Clearance to Sprinklers (ft-in)	4-5	4 – 11	5 – 2
	Aisle Width (ft)	4	4	4
	Ignition Centered Below (No. Sprinklers)	2	2	2
	Sprinkler Orifice Size (in)	0.7	0.7	0.7
	Sprinkler Temperature Rating (°F)	155	155	155
	Sprinkler RTI (ft-s)$^{1/2}$	50	50	50
	Sprinkler Spacing (ft x ft)	10x10	10 x 10	10 x 10
	Constant Water Pressure (psi)	50	75	75
Test Results	First Sprinkler Operation (min:sec)	2:01	1:14	9:34
	Last Sprinkler Operation (min:sec)	4:36	2:35	11:31
	Total Sprinklers Opened	23	3	33
	Total Sprinklers Discharge (gpm)	2450	385	3500 *
	Avg. Discharge per Sprinkler (gpm)	106	128	104
	Peak Gas Temperature (°F)	1237	578	1376
	Max. One Min. Avg. Gas Temperature (°F)	1032	252	1123
	Peak Celling Steel Temperature (°F)	321	131	265
	Max. One Min. Avg. Steel Temp. (°F)	307	129	261
	Time of Aisle Jump (min:sec)	2:45	DNJ	10:03
	Equiv. No. Pallet Loads Consumed	11	3/4	25
	Test Concluded (min:sec)	16:15	15:00	26:00

3.2.2 Introduction

3.2.2.1 Background and Objective

Vegetable oils, which are classified as combustible liquids, are excluded by the FM Global Property Loss Prevention Data Sheets from protection by Early Suppression Fast Response (ESFR) sprinklers. As a result, ESFR sprinklers are not recommended for fire protection of certain occupancies such as grocery warehouses where significant quantities of vegetable oil are stored along with other commodities that are candidates for ESFR sprinkler protection.

The prohibition of ESFR sprinkler protection for occupancies containing significant quantities of vegetable oil may be an overly conservative approach, given the relatively high flash point of vegetable oils and therefore may not present the same degree of fire challenge that more volatile liquids would.

Under the existing conditions, vegetable oils must be protected differently from the other commodities. This requires separation and use of special fire protection guidelines in warehouses where these oils were stored along with other commodities. These special considerations provided the impetus for examining warehouse sprinkler protection for vegetable oils.

The intent of this project was to examine the accepted warehouse protection scheme for high hazard commodities, that is, ceiling sprinklers used in conjunction with in-rack sprinklers, as well as to investigate the feasibility of using Early Suppression Fast Response (ESFR) sprinklers (ceiling only) for protection of vegetable oils.

The results of tests conducted during a previous project demonstrated that consumer retail-size plastic bottles of vegetable oil in cartons or plastic-encapsulated tray packs could be adequately protected when stored in rack storage arrangements by a combination of standard ceiling and quick response in-rack sprinklers.

The specific objective of the tests described herein was to determine if ceiling-mounted ESFR sprinklers can be used to protect rack storages of cartoned and uncartoned, i.e., plastic- encapsulated tray packs of vegetable oil, and thereby eliminate the need for the in-rack sprinkler protection.

To make this determination, a series of large-scale fire tests was conducted under a 30-ft (9.1m) ceiling.

The fire tests were conducted using an ESFR sprinkler having a 155°F (68°C) temperature-rated glass bulb actuation mechanism. The sprinkler system pressure was set at either 50 psig (3.4 bar) or 75 psig (5.2 bar).

3.2.3 Test Description

The tests were performed below the 30-ft (9.1-m) ceiling site and involved rack storage arrangements of consumer retail-sized containers of vegetable oil in cardboard cartons or plastic shrink-wrapped tray packs.

3.2.3.1 Commodity Description

The test commodity consisted of vegetable oil in plastic bottles. The bottles were stored either in cartons or partially exposed in tray packs arranged on hardwood pallets. The oils used were soybean for the cartoned oil evaluation and a blend of corn and canola oils for a single test of uncartoned vegetable oil. Selected fire characteristics of the two products are presented in Table 3-3. The flash point of the soybean oil was 590°F (310°C) with a heat of combustion of 16,990 Btu/lb (39.5 m/Kg). The corn/canola oil blend had a 620°F (327°F) flash point and heat of combustion of 17,195 Btu/lb (40 m/Kg).

Table 3-3: Measured Vegetable Oil Properties

	SOYBEAN OIL	CORN/CANOLA OIL
Autoignition Temperature	750°F	780°F
Flash Point*	590°F	620°F
Fire Point	630°F	650°F
Heat of Combustion	16,990 BTU/lb	17,195 BTU/lb
Specific Gravity	0.93	0.92
*Flash point and fire point determined using the Cleveland Open Cup Apparatus, ASTM D92.		

Soybean oil was used for the cartoned oil tests. The soybean oil was contained in 48 fluid- ounce-capacity (1.4 L) polyethylene terephthalate (PET) plastic bottles with polypropylene plastic caps. Pallet-loads of the commodity were received from the distributor in the pallet configuration normally shipped to grocery warehouses and retail outlets. Each pallet-load consisted of forty (40) single-wall corrugated cardboard cartons arranged in a four-carton high stack upon a 40 in. x 48 in. x 5 in. high (102 cm x 122 cm x 13 cm) slatted deck hardwood pallet. Eight bottles of oil were placed in each of the cardboard cartons which had dimensions of 18.75 in. x 9.75 in. x 11 in. high (48 cm x 25 cm x 28 cm). The empty carton weighed 16.5 ounces (465 g). Several layers of polyethylene plastic shrink-wrap were wound circumferentially about each pallet-load to hold the cartons in place. Each forty-carton pallet-load of cartoned oil weighed an average of 1055 lbs (479 kg). Eighty-five (85) percent of this weight or 897 lbs (407 kg) was the soybean oil; 74 lbs (34 kg) or 7 percent was the hardwood pallet; 42 lbs (19 kg) or 4 percent was the PET plastic bottles and the remaining 42 lbs (19 kg) or 4 percent was the weight of the corrugated cardboard cartons.

The uncartoned test commodity utilized the corn/canola oil blend. This oil was also stored in 48 fluid-ounce (1.4 L) capacity PET plastic bottles with polypropylene plastic caps. Twelve bottles were placed in a 15.38 in. x 11.68 in. x 3.0 in. (39 cm x 30 cm x 7.6 cm) single-wall corrugated cardboard tray and shrink-wrapped in 2.5 mil (0.06 mm) polyethylene plastic film. Each cardboard tray weighed 5.5 ounces (156 g) and the shrink-wrap weighed 1.6 ounces (46 g). Thirty-three (33) of these tray packs were placed upon a 48 in. x 48 in. x 5 in. high (122 cm x 122 cm x 13 cm) slatted deck hardwood pallet in a three-tier arrangement. Corrugated paper sheets were placed between each tier and on the upper deck of the hardwood pallet. A 48 in. x 48 in. (122 cm x 122 cm) sheet of fiberboard was placed on top of the pallet-load. This fiberboard cap weighed 9.1 lbs (4.1 kg). The tray packs were held on the pallet using a wrapping of three layers of 0.8 mil (0.02 mm) polyethylene plastic film. Pallet-loads of the uncartoned oil commodity weighed an average of 1285 lbs (583 kg). Eighty-nine (89) percent or 1145 lbs (519 kg)

was vegetable oil; plastics represented 5 percent or 63 lbs (29 kg) of the weight; less than 2 percent were the corrugated cardboard trays (13 lbs[6 kg]) and the fiberboard cap (9 lbs [4 kg]).

3.2.3.2 Test Arrangement

A plan view schematic of the rack arrangement is presented in Figure 3-24.

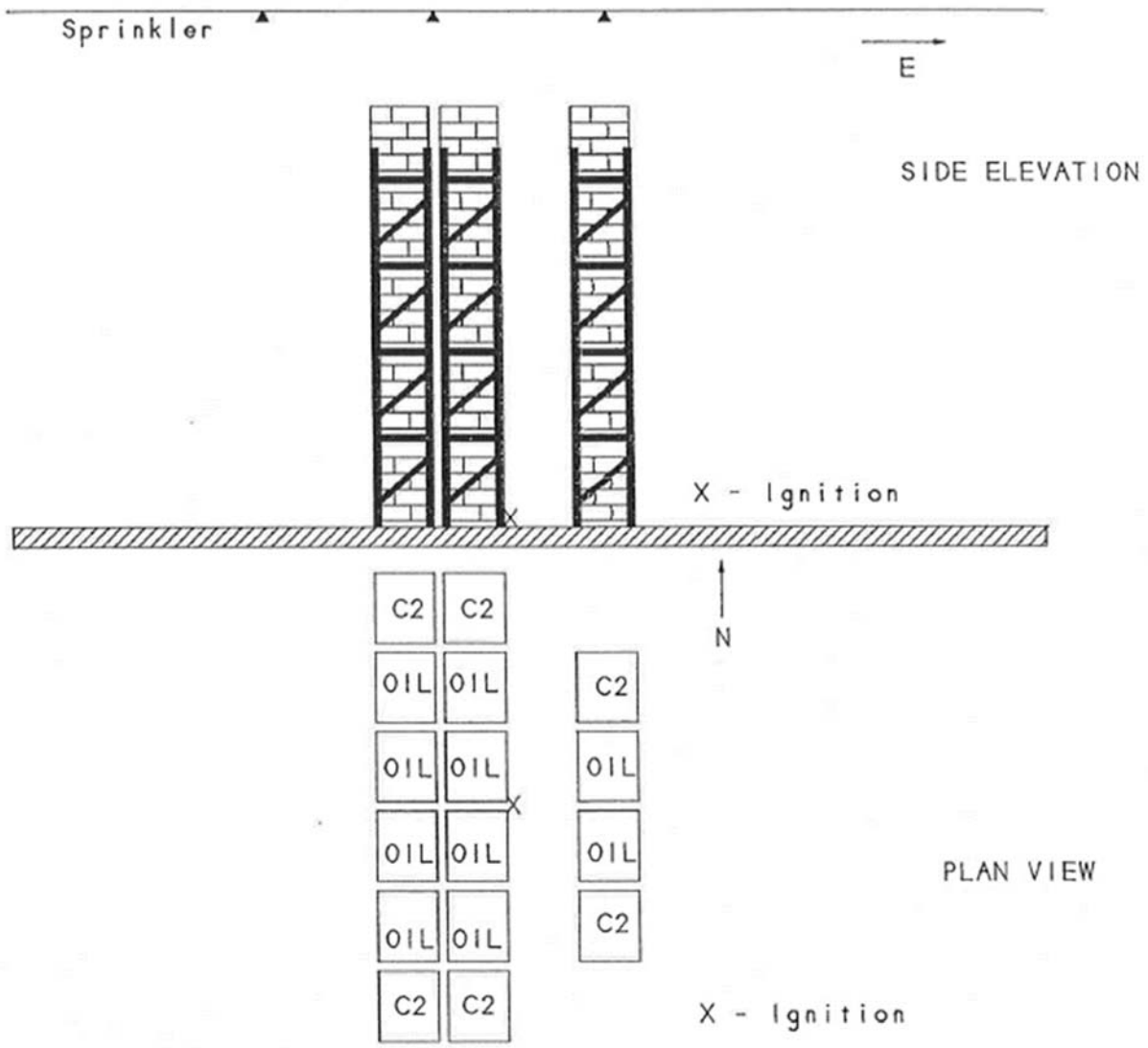


Figure 3-24: Rack Storage Arrangement of Vegetable Oil (Five Tiers)

The main array, i.e., the array in which the ignition source was placed, consisted of a double-row steel rack having 9 ft (2.7 m) wide bays. When loaded, the main array was two pallet loads deep and six pallet loads long. Linear measurements for the main array were 28 ft (8.5 m) long by 7.25 ft (2.2 m) deep. The long dimension of the array was oriented north-to-south, perpendicular to the direction of the overhead sprinkler piping.

In all tests, the bottom pallet-load of commodity rested on the floor, with additional levels of storage in racks at 5 ft (1.5 m) vertical spacings. The 25 ft (7.6 m) high arrays (Tests 2, 4 and 5) were five tiers high.

To provide indication of fire spread potential in a large warehouse, a target array was positioned east of the main array across a 4 ft (1.2 m) aisle. The target array was one pallet load deep by four pallet loads long and was the same height of the main array in all fire tests. This target array was 17.2 ft (5.2 m) long and 3.5 ft (1.1 m) deep. The end pallet loads of the main and target arrays were the standard Class II Commodity which are 42 in. (107 cm)-cube double triwall corrugated cardboard cartons with a metal liner.

3.2.3.3 Sprinkler Protection

Automatic sprinkler protection was provided by an ESFR pendent sprinkler and had a nominal 0.7 in. diameter orifice with a K-factor of 14.0 gpm/psig^{½} (202 L/min/bar^{½}). The actuation mechanism for the model tested was a frangible glass bulb with a 155°F (68°C) temperature rating and Response Time Index (RTI) rating of 50 (ft-s).

Sprinklers were installed on 10 ft x 10 ft (3 m x 3 m) spacing over the test area using nominal 2 in. diameter piping. The sprinklers were in pendent position with actuation links 13 in. (330 mm) down from the ceiling. A total of 49 sprinklers were installed over the test area in a 7 x 7 grid arrangement.

The water pumping system was set to provide either a 50 psig (3.4 bar) or 75 psig (5.2 bar) constant discharge pressure. At these pressures, each operating sprinkler would discharge 100 gpm (379 L/min) and 120 gpm (454 L/min), respectively.

3.2.3.4 Instrumentation

The instrumentation used in these tests was designed to assist in making the determination of sprinkler effectiveness in fire suppression or control. Instrument locations used in these tests are shown in Figures 3-25 and 3-26.

Test instrumentation included: 1) thermocouples for making ceiling gas temperature measurements at 6.5 in. (165 mm) down from the ceiling over ignition and other selected locations over the test area; 2) 4 ft-long (1.2 m) sections of steel angle, nominally 2 in. x 2 in. x 1/4 in. thick, instrumented with thermocouples and installed at the ceiling over the center of the main array to assess potential damage to ceiling structural steel members; and 3) electrical circuits wired to the sprinklers and monitored by the data acquisition computer system to record sprinkler actuation times.

Two sections of steel angle were used in each test. The steel was oriented in the north- south direction, aligned with the longitudinal flue of the main array. When the array was centered directly below a sprinkler, one section of steel was 5 ft (1.5 m) east from directly over the main array. The second steel section was an additional 10 ft (3 m) east. When the main array was centered below two sprinklers, one steel section was directly over the longitudinal flue of the main array with the second section 10 ft (3 m) east.

The thermocouples used for near-ceiling gas and steel temperature measurements were 20-gauge ceramic-insulated chromel-alumel (Type K) types.

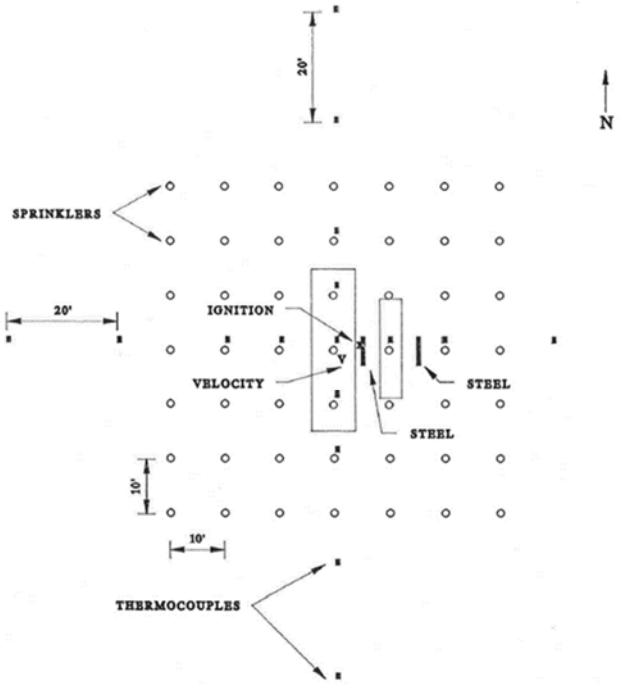


Figure 4. Plan View of Test Instrumentation - Main Array Centered Under One Sprinkler.

Figure 3-25: Plan View of Test Instrumentation – Main Array Centered Under One Sprinkler

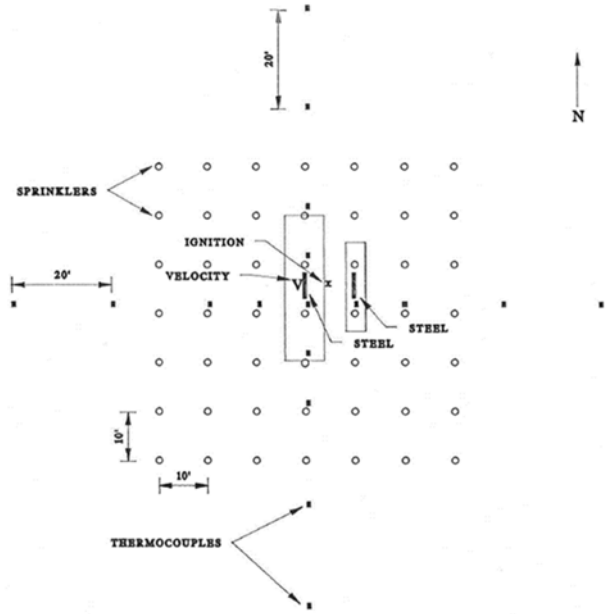


Figure 3-26: Plan View of Test Instrumentation – Main Array Centered Below Two Sprinklers

3.2.3.5 Ignition

The ignition was centered at the east face of the main fuel array instead of at the intersection of the central transverse flue and the longitudinal flue. This location was chosen to represent a worst-case scenario and would allow a longer incipient time for the fire prior to first sprinkler actuation. The longer incipient time would increase the possibility of getting vegetable oil involved in the fire prior to first sprinkler actuation.

The ignition source was two 6 in. (152 mm) long by 3 in. (76 mm) diameter cellucotton roll soaked with 8 fluid ounces (237 ml) of gasoline and wrapped in a polyethylene plastic bag. Two standard full ignitors were placed against the bottom edge of cartons at the base of the first tier, one on either side of the central transverse flue space. These were ignited with a propane torch to begin each test.

3.2.3.6 Test Results

Ambient air temperature and the relative humidity inside the Test Center near the fuel arrays for each of the five tests in this series are presented in Table 3-4.

Table 3-4: Initial Test Conditions

Test No.	Type Fuel	Height /Clearance ft	Array Location	Sprinkler Pressure psig	Initial Temperature °F	Initial Humidity	Carton Moisture Content
2	Carton	25/5	Below 2	50	69	30%	6.0%
4	Carton	25/5	Below 2	75	72	27%	8.6%
5	Tray Packs	25/5	Below 2	75	68	24%	7.1%

In these tests, the intersection of the central longitudinal and central transverse flue spaces of the main fuel array was centered either directly below a sprinkler or between two sprinklers. Ignition was centered at the east face along the bottom edge of the first tier.

During the tests, no forced ventilation was provided to the test area and all windows and doors communicating to the outside were closed.

3.2.3.7 Test 2

In Test 2, the fuel arrays were five tiers (nominally 25 ft [7.6 m]) high and the intersection of the central longitudinal and transverse flue spaces of the main array was centered between two overhead sprinklers. Ignition was centered along the east face of the main array at the bottom tier of pallets.

3.2.3.7.1 Test Highlights

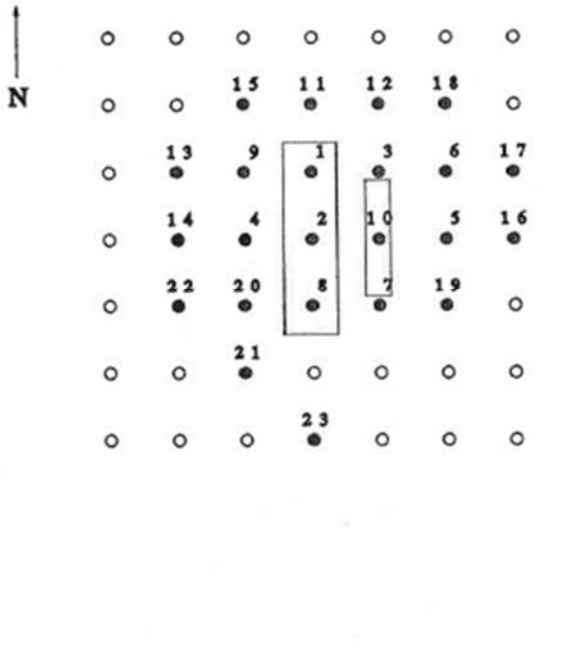
The sequence for sprinkler actuations for Test 2 is presented in Figure 3-27. Selected test data are presented in Figures 3-28 and 3-29.

Flames had reached the top of the first tier by 25 s after ignition. The plastic shrink wrap had begun to loosen and burn on the bottom tier. By 1 min, flames were 7 ft (2.1 m) high on the east face at the ignition point and were being drawn into the central transverse flue space. At 1 min 30 s, flames were at the top of the fourth tier, and bottles in cartons on the east face at the lower tiers were squirting oil

from pinhole-sized openings into the aisle space between the main and target arrays. The flames reached the ceiling at 1 min 55 s. By this time, flames in the central transverse flue were extending to the center of the main array.

The first sprinkler to actuate was 5 ft (1.5 m) north over the center of the main array and this sprinkler actuated at 2 min 1 s after ignition. The flames remained at the ceiling and at 2 min 12 s the second sprinkler closest over ignition actuated. The fire was not immediately suppressed and flames remained at the ceiling.

At 2 min 30 s flames on the east face of the main array were almost spanning the 4 ft (1.2 m) aisle to the target array. Four additional sprinklers actuated at 2 min 41 s; one of these sprinklers was over the target array. The target array ignited at 2 min 44 s.



SEQUENCE	TIME (MIN:S)
1	2:01
2	2:12
3	2:41
4	2:41
5	2:41
6	2:41
7	2:42
8	2:44
9	2:50
10	2:50
11	2:53
12	2:55
13	2:56
14	2:56
15	2:56
16	2:58
17	3:01
18	3:05
19	3:08
20	4:20
21	4:23
22	4:24
23	4:38

Figure 3-27: Sprinkler Actuation Sequence – Test 2

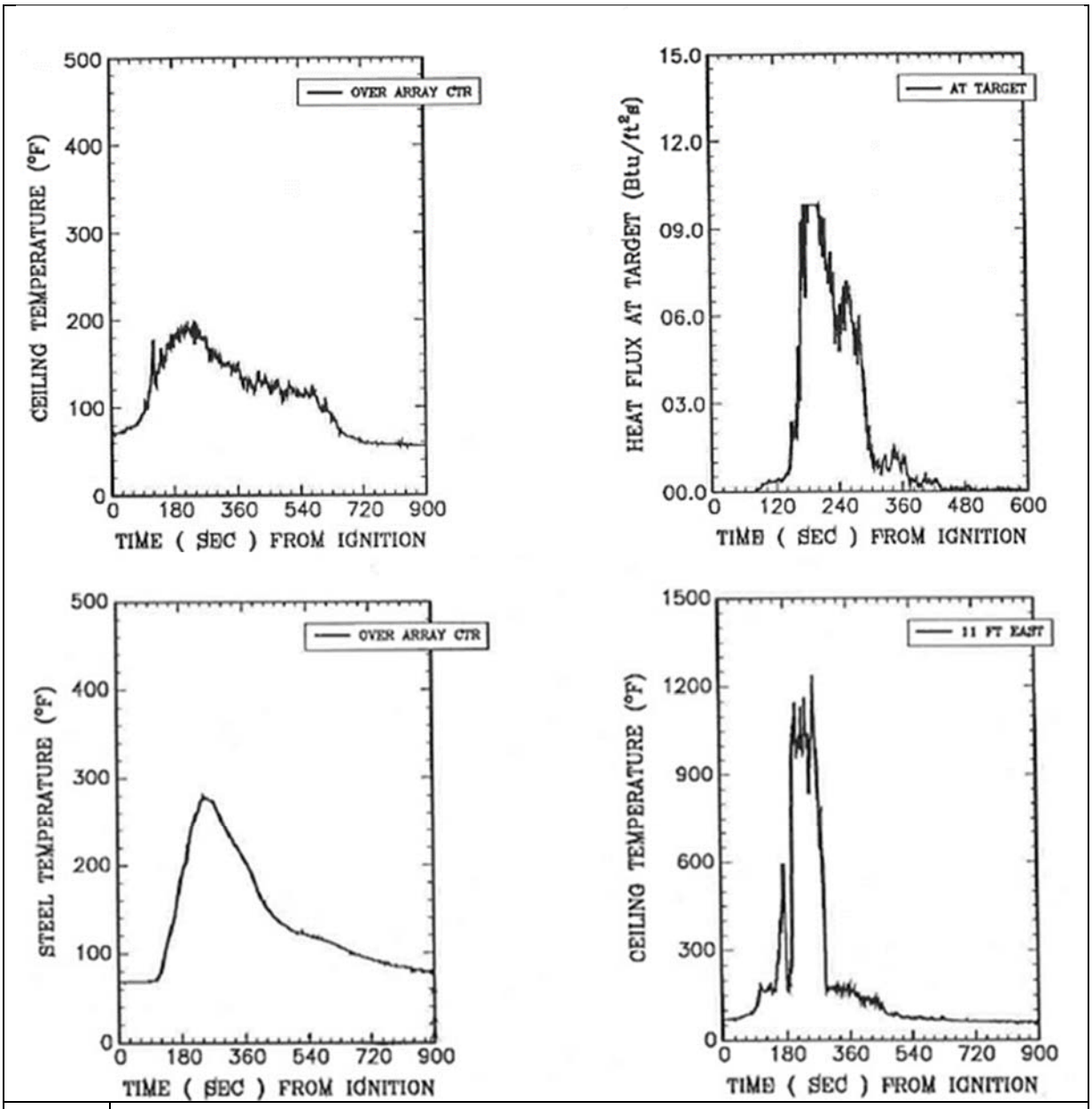


Figure 3-28: Selected Test Data – Test 2

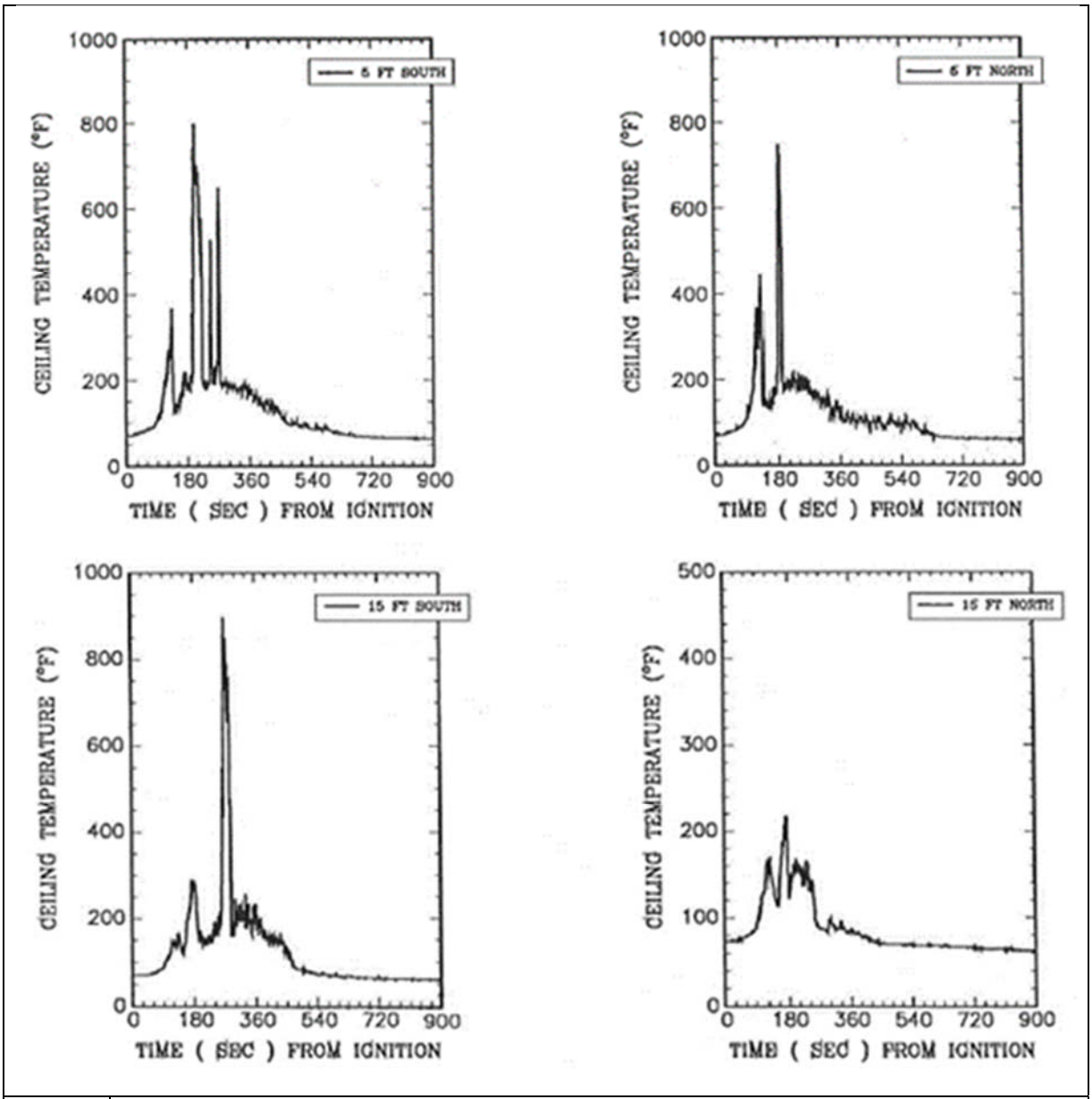


Figure 3-29: Selected Test Data – Test 2

Smoke and steam descended from the ceiling layer at 2 min 55 s, obscuring most of the test arrays. Between the period 2 min 42 s to 2 min 58 s after ignition, a total of ten sprinklers operated. At 3 min 10 s, there was intense burning of the target array. The test site was totally obscured by smoke by 4 min and additional sprinkler actuations continued until 4 min 38 s after ignition. A total of 23 sprinklers were needed to suppress the fire during this test.

Recorded test data indicate that fire intensity peaked at about 5 min after ignition. No spill fire was observed during this test. Data collection continued until 16 min.

3.2.3.7.2 Damage Assessment

The schematic of fire damage for Test 2 is presented in Figure 3-30.

Eleven (11) pallet loads of the vegetable oil commodity were consumed by the fire. This damage included pallets in the target array across the 4 ft (1.2 m) aisle space. Of the eleven pallet loads damaged by the fire, 6 3/4 were in the two-pallet by two-pallet by five tier high ignition array within the main fuel array. This represented 34 percent of the ignition array.

The fire did not travel to the end of the arrays; however, the last pallet in the second, third, fourth and fifth tiers at the south end of both main and target arrays sustained some fire damage.

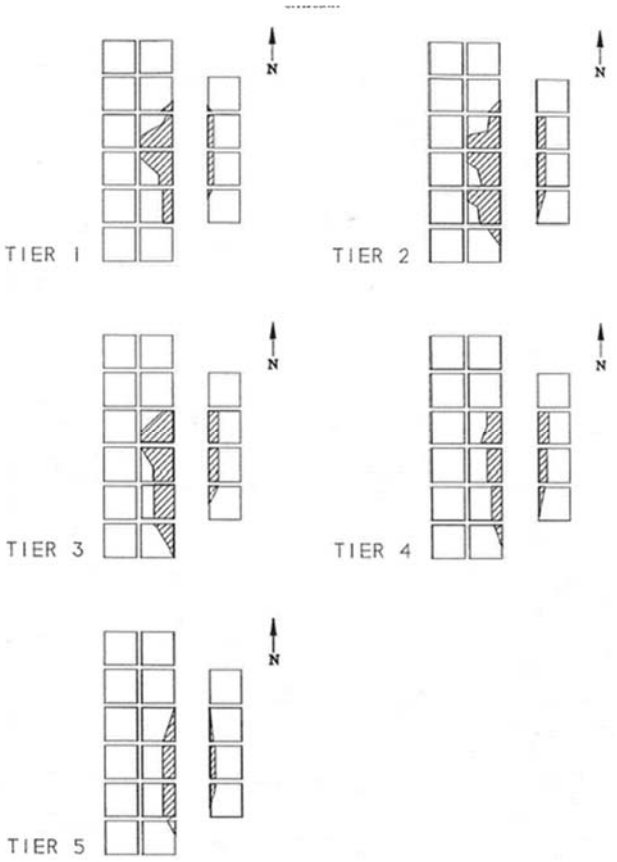


Figure 3-30: Fire Damage Assessment – Test 2

3.2.3.7.3 Water Demand

The total water demand for the system is shown in Figure 3-31. This figure shows that, initially, the two sprinklers over ignition were discharging 227 gpm (859 L/min), for a discharge rate of 114 gpm (431 L/min) per sprinkler. After the last sprinkler actuation and through to the end of the test, twenty-three sprinklers were discharging 2450 gpm (9273 l/min) for a 106 gpm (401 L/min) per sprinkler rate.

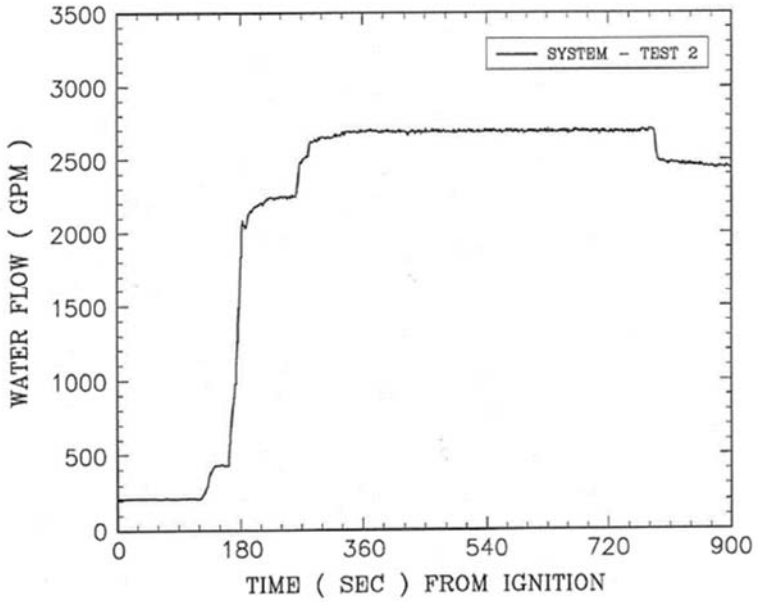


Figure 3-31: Total Water Demand – Test 2

3.2.3.7.4 Fire Signature Data

The fire test chronology is provided in Figure 3-41.

The near-ceiling gas temperature over the main array reached 192°F (89°C) just prior to first sprinkler actuation. After the two sprinklers over the ignition zone actuated, the fire continued to grow, reaching a maximum intensity at about three minutes after ignition. At this point ceiling gas temperatures began to decrease, indicating suppression by the sprinkler system.

Maximum near-ceiling gas temperatures of 600°F (316°C) to 800°F (427°C) were measured at locations close over ignition, i.e., 5 ft (1.5 m) north and south, over the array center and 11 ft (3.4 m) west. The temperature data taken at these locations also indicate resurgences in the intensity of the fire up until 5 min after ignition.

The fire in this test was biased toward the south ends of the arrays and did involve the target array which was located east of ignition. Consequently, the highest recorded near-ceiling gas temperatures were at locations 11 ft (3.4 m) east and 15 ft (4.6 m) south of ignition. The temperature at the 11 ft (3.4 m) east location, over the target array, reached a maximum of 1237°F (669°C) and was in excess of 1000°F (538°C) for approximately 1min 30 s. At the 15 ft (4.6 m) south location the near-ceiling gas temperature reached 896°F (480°C) at 4 min 30 s after ignition

The target array did ignite and sustain significant fire damage.

The highest one-minute average maximum temperature was 1032°F (556°C), which was recorded by the thermocouple located 11 ft (3.4 m) east of ignition over the target array.

Although the fire was not suppressed immediately, the steel temperature measurement over the array center was less than 350°F (177°C), which is less than the 1000°F (538°C) maximum temperature that is considered unsafe for structural steel support members.

At 6 minutes after ignition, near-ceiling gas and steel temperatures at all monitored locations had begun to decline, indicating that the fire was under control at this time.

3.2.3.8 Test 4

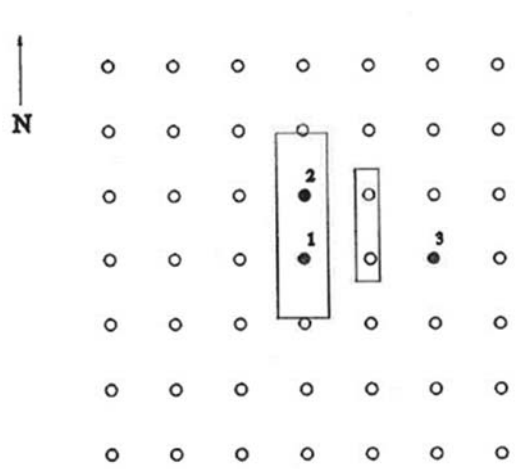
Five-tier high arrays were used in this test. The main array was centered between two sprinklers. The ignition was at the bottom tier, centered along the east face of the main array. The sprinkler system was set to discharge at 75 psig (5.2 bar).

3.2.3.8.1 Test Highlights

Flames had reached the top of the bottom pallet loads by 20 s after ignition and the plastic shrink-wrap was peeling away from the pallets. At 25 s the flames were extending into the second tier. At 1 min 3 s the flames were above the top of the array and were being drawn into the central transverse flue. Flames contacted the ceiling at 1 min 12 s. The first sprinkler, 5 ft (1.5 m) south of the main array center actuated at 1 min 14 s (see Figure 3-32). Flames remained at the ceiling until 1 min 32 s when they started to recede. At this time the flames had been drawn nearly 4 ft (1.2 m) into the central transverse flue. The fire began to become established on the east faces of the first four tiers.

By the time the second sprinkler 5 ft (1.5 m) north of the array center actuated at 2 min, flames were once again contacting the ceiling. Smoke and steam from the ceiling began to descend, obscuring the upper tiers of the fuel arrays. At 2 min 25 s flames were still well above the top of the array and were also extending 1-2 ft (0.3-0.6 m) into the aisle space between main and target arrays. The third and final sprinkler actuation occurred at 2 min 35 s after ignition and involved a sprinkler in the third ring, over 20 ft (6.1 m) away. Flames were concentrated on the east face of the ignition array and remained at least as high as the top of the array at 3 min 25 s after ignition. Much of the upper portion of the test arrays was becoming increasingly obscured by the smoke, but steady fire was still observed in the bottom two tiers after 5 min 45 s.

Smoke had almost totally obscured the test site at 9 min; however, the sound of oil bottles striking the floor could still be heard. At 10 min after ignition, the test site was vacated since smoke had mostly obscured all vision of the test site. At 11 min the smoke began to thin out and only small flames were visible. All burning took place within the racks with no ignition of spilled oil. The test was terminated at 15 min after ignition.



SEQUENCE	TIME (MIN:S)
1	1:14
2	2:00
3	2:35

Figure 3-32: Sprinkler Actuation Sequence – Test 4

3.2.3.8.2 Damage Assessment

A fire damage schematic for Test 4 is presented as Figure 3-33.

The fire in Test 4 was suppressed by three sprinklers. The equivalent of just 3/4 of one pallet-load was damaged by the fire. This represented just 4 percent of the ignition array. The target array did not become involved and all fire damages were confined to the ignition stack of the main array.

3.2.3.8.3 Water Demand

Three sprinklers actuated during this test, discharging a total of 385 gpm (1,457 L/min) for an average discharge rate of 128 gpm (484 L/min). Two of these were those closest over the main array. The remaining sprinkler represented a skip to the third ring, more than 20 ft (6.1 m) from over the main array. System flows for the sprinkler system are presented in the graph shown as Figure 3-34.

3.2.3.8.4 Fire Signature Data

Selected test data and the fire test chronology are presented in Figures 3-35, 3-36, and 3-42.

The ceiling gas temperature directly over ignition reached a maximum of 578°F (303°C) three seconds after the first sprinkler actuated. Temperature maxima over the main array were 396°F (202°C) over the center; 319°F (160°C) and 350°F (178°C) at the sprinkler locations 5 ft (1.5 m) north and 5 ft (1.5 m) south from center, respectively. Maximum ceiling gas temperatures recorded at other ceiling locations were less than 250°F (121°C) and were generally in the range of 100°F - 150°F (38°C - 66°C).

Ceiling gas temperatures over the main array exhibited a rapid decline at first sprinkler actuation at 1 min 14 s, then an increase in temperature until 2 minutes after ignition when the second sprinkler over the main array actuated. Temperatures again declined rapidly but remained elevated for a period of 2 minutes before approaching ambient.

The return of ceiling gas temperatures to nearly ambient at locations 40 ft (12.2 m), 55 ft (16.8 m) and 65 ft (19.8 m) away at 6 minutes after ignition indicated that the fire was suppressed.

The highest one-minute average maximum temperature was 252°F (122°C), which occurred over ignition.

Maximum ceiling steel temperatures were less than 140°F (60°C).

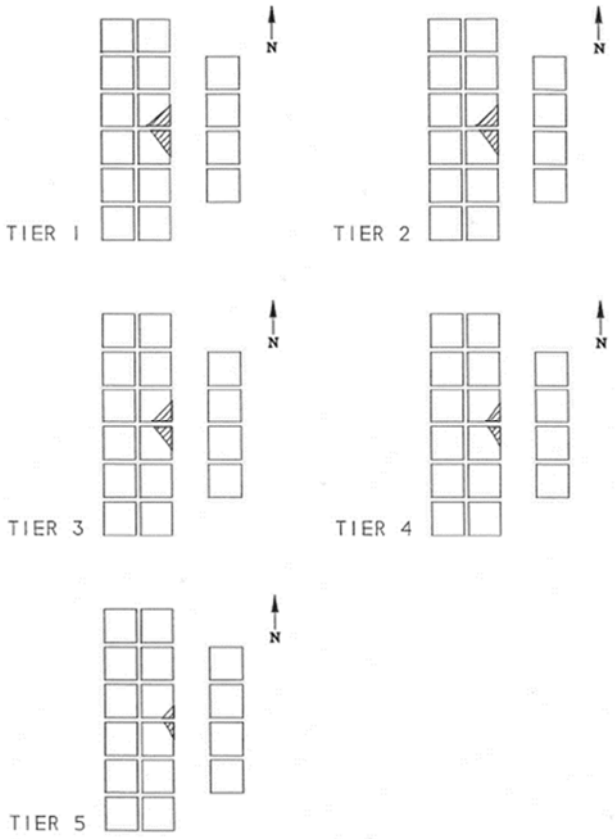


Figure 3-33: Fire Damage Assessment – Test 4

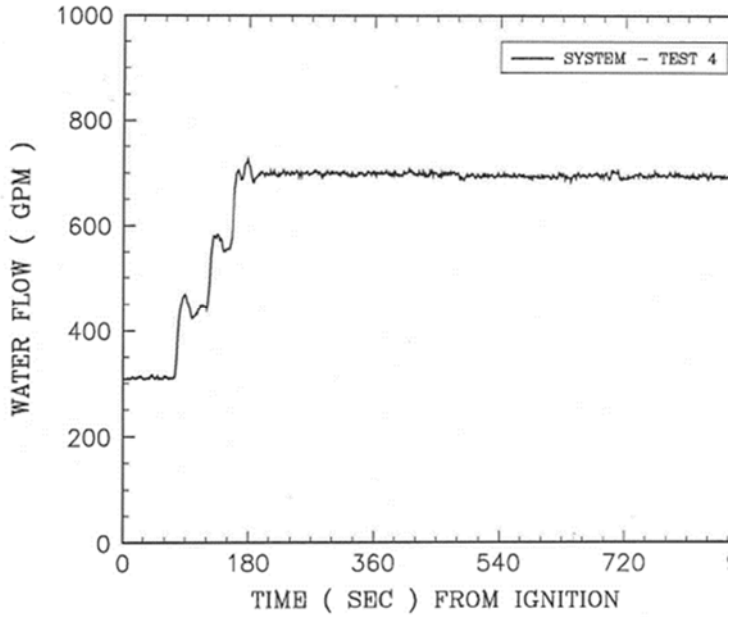


Figure 3-34: Total Water Demand – Test 4

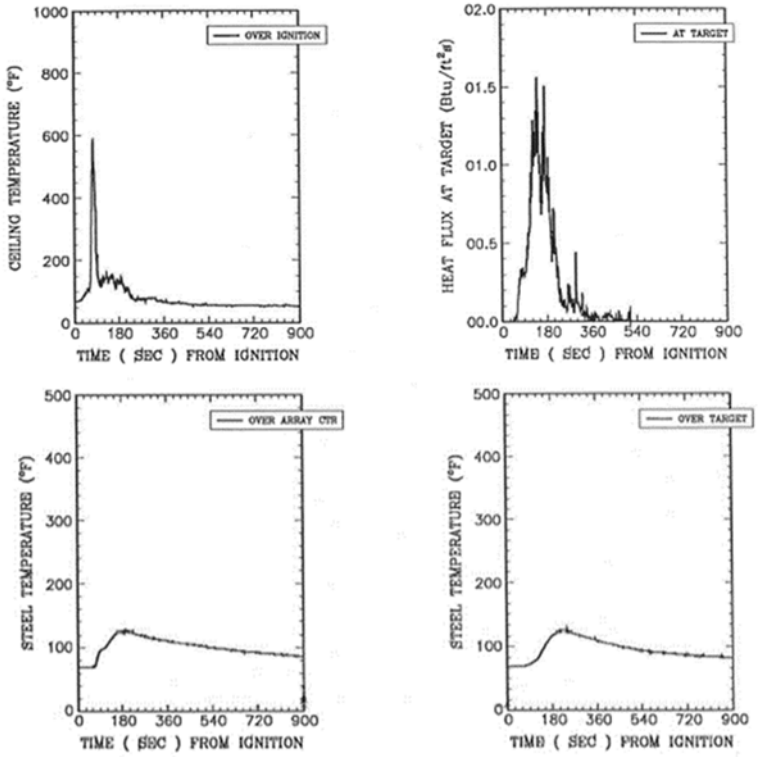


Figure 3-35: Selected Test Data – Test 4

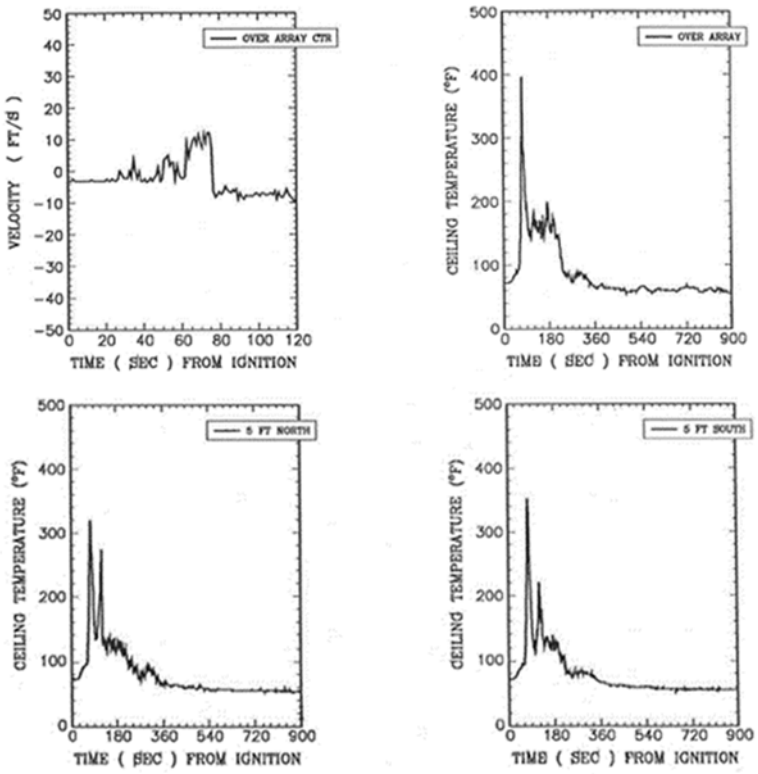


Figure 3-36: Selected Test Data – Test 4

3.2.3.9 Test 5

Test 5 was a large-scale fire test evaluation of ESFR sprinkler protection for uncartoned vegetable oil. The test commodity was the 48 fluid-ounce bottles of a corn/canola oil blend shrink-wrapped on corrugated cardboard trays. This commodity was stored five tiers high on wood pallets.

The sprinkler system was set to discharge at 75 psig (5.2 bar) and the main array was centered between two sprinklers.

3.2.3.9.1 Test Highlights

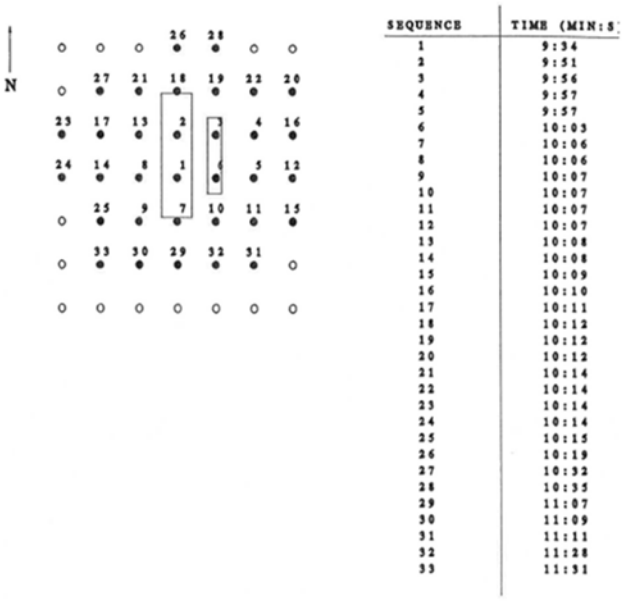
At 10 s after ignition flames were 1 - 2 ft (0.3- 0.6 m) high on the east face. By 26 s flames were approximately 3 ft (0.9 m) high and oil was spurting from ruptured bottles into the aisle space between main and target arrays. At 1 min 15 s bottles of oil were still falling into the aisle as the fire melted the plastic shrink-wrap. The fire was still confined to the two east side pallet-loads of the ignition array but had also began to spread into the central transverse flue. At 3 min 20 s, flames were steady over top of the first pallet-load and occasionally reaching the underside of the second tier.

The fire was still confined to the bottom pallet-loads at 7 minutes after ignition. A puddle of oil had formed on the floor that spanned the 4 ft (1.2 m) aisle space and covered a 12 ft (3.7 m) long section of aisle space. The fire became established in second-tier pallets at 8 min 35 s. At 9 min 30 s oil was streaming from the second-tier pallet-loads onto the top of the bottom tier. The fire began rapid increase as the flames traveled up the east face and reached over the top of the array. The first sprinkler

actuation occurred at 9 min 34 s. This was the sprinkler 5 ft (1.5 m) south of the center of the main array. Upper tiers of the test array were obscured as the ceiling smoke layer descended. The fire began to spread south to north along the east face of the main array.

The second sprinkler, located 5 ft (1.5 m) north of the array center, actuated at 9 min 51 s and was followed by 25 sprinkler actuations within the next 30 seconds. The target array was ignited at 10 min 2 s and aisle space between the main and target arrays was filled with flame. At 10 min 15 s the test site was evacuated of personnel. The test site was totally obscured by smoke and steam at 10 min 32 s after ignition. Although this was a very severe fire, ignition of the oil spilled in the aisle space did not occur. At 26 min the building was vented; data collection continued until 33 min after ignition.

A total of 33 sprinklers actuated during the first 11 min 31 s of this test. The sprinkler actuation sequence is shown in Figure 3-37.



SEQUENCE	TIME (MIN:S
1	9:34
2	9:51
3	9:56
4	9:57
5	9:57
6	10:03
7	10:06
8	10:06
9	10:07
10	10:07
11	10:07
12	10:07
13	10:08
14	10:08
15	10:09
16	10:10
17	10:11
18	10:12
19	10:12
20	10:12
21	10:14
22	10:14
23	10:14
24	10:14
25	10:15
26	10:19
27	10:32
28	10:35
29	11:07
30	11:09
31	11:11
32	11:28
33	11:31

Figure 3-37: Sprinkler Actuation Sequences – Test 5

3.2.3.9.2 Damage Assessment

There was significant involvement of both main and target arrays during this test. Fire damage extended nearly to the ends of the main array and all the way to the ends of the target array. The equivalent of 25 pallet-loads of commodity were damaged by the fire. The equivalent of 10-¾ pallet-loads or 54 percent of the 2 pallet-load x 2 pallet-load x 5 tier high ignition array of the main array was damaged by the fire.

3.2.3.9.3 Water Demand

The sprinkler system was set to maintain a constant discharge pressure of 75 psig (5.2 bar). System pressure is presented in Figures 3-38, respectively. The accurate determination of water demand by the sprinkler system could not be made because of the high number of sprinkler actuations during a relatively short period of time, i.e., 34 sprinklers within two minutes. The maximum water flow for the range selected, i.e., 2700 gpm (10,220 L/min) was exceeded at ten minutes into the test. Once sprinklers

started to actuate, the system could not maintain the required 75 psig (5.2 bar) pressure and decreased to a low of 41 psig (2.8 bar) after twelve sprinkler actuations (10 min 8 s).

The branch line pressure stabilized at 55 psig (3.8 bar) at 13 min 30 after ignition with 34 sprinklers operating. The total water demand at this time was estimated to be 3500 gpm (13,248 L/min).

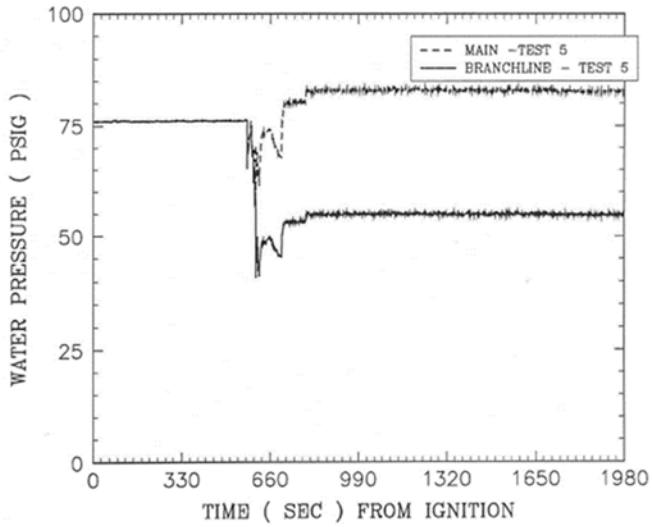


Figure 3-38: Sprinkler System Water Pressure – Test 5

3.2.3.9.4 Fire Signature Data

Selected test data and the fire test chronology are presented in Figures 3-39, 3-40, and 3-43.

This was a slowly developing fire with little increase in ceiling gas temperatures during the first 9 minutes after ignition. The ceiling gas temperature directly over ignition reached 900°F (482°C) just prior to first sprinkler actuation at 9 min 34 s after ignition. There was a brief decrease in this temperature as the sprinkler operated but it began to increase reaching 1376°F (747°C) at 12 min 6 s. There was another decline in temperature at 13 min 30s that lasted until 20 minutes after ignition. The temperature increased to 1000°F (538°C) before declining again. The fire intensity increased once more when the building was vented at 26 minutes after ignition as additional air was introduced to the test facility. The temperature over ignition reached 1619°F (882°C) at this time.

Elevated ceiling gas temperatures 40 ft (12.2 m), 55 ft (16.8 m) and 65 ft (19.8 m) away show resurgences in the fire during the 600 s to 1200 s period and also indicate the increase in fire intensity when the building was vented at 26 minutes after ignition.

The target array was ignited at 10 min 3 s.

There were three ceiling locations where the one-minute average maximum temperature exceeded 1100°F (593°C); over ignition (1123°F [606°C]), 5 ft (1.5 m) south of the center of the main array (1119°F [604°C]), and 15 ft (4.6 m) south of the center of the main array (1189°F [643°C]).

The maximum ceiling steel temperatures at the two overhead locations were less than 270°F (132°C) prior to venting of the test facility.

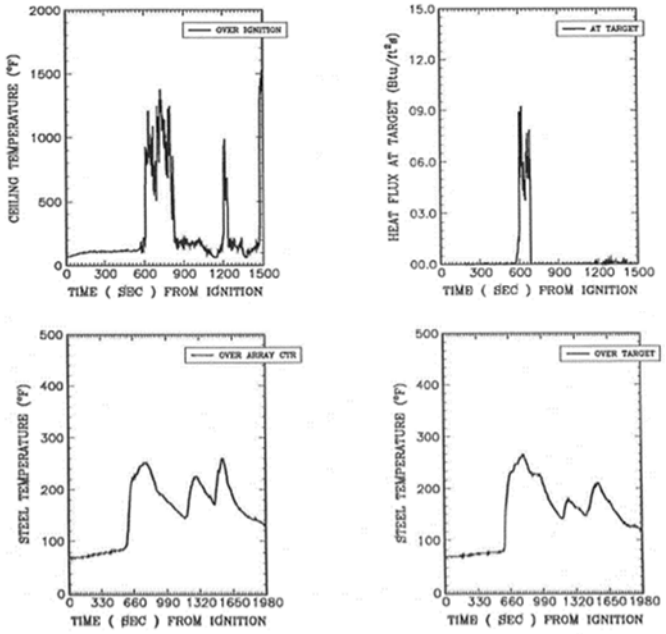


Figure 3-39: Selected Test Data – Test 5

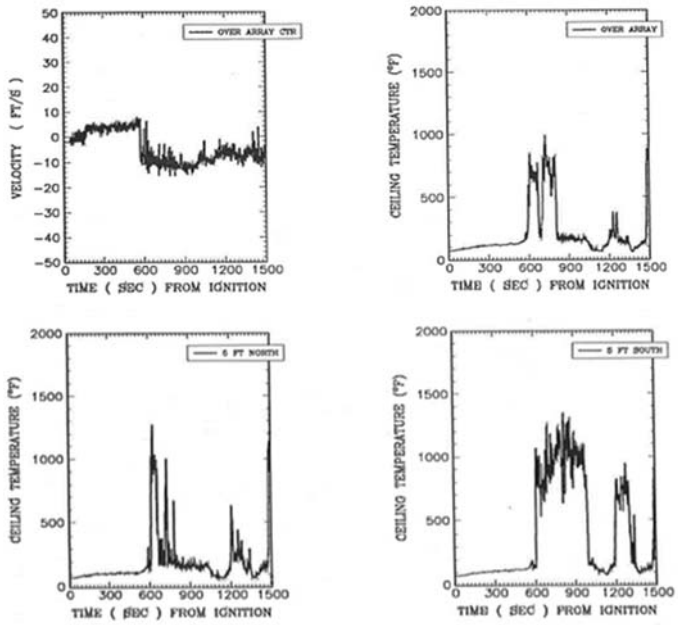


Figure 3-40: Selected Test Data – Test 5

3.2.4 Discussion

As the result of extensive large-scale fire testing of Early Suppression Fast Response (ESFR) sprinklers, two large-scale fire test scenarios are now used to assess the feasibility of using an ESFR sprinkler system for certain rack storage fire protection applications. This approach was used in this program to evaluate ESFR sprinkler protection for rack storage arrangements of cartoned vegetable oil stored to 25 ft (7.6 m) high in 30 ft (9.1 m) high buildings or to 20 ft (6.1 m) high in 25 ft (7.6 m) high buildings.

The two fire test scenarios are: 1) low storage, large ceiling clearance rack storage arrangement with the fuel centered directly below a sprinkler, and 2) high storage, small ceiling clearance rack storage arrangement with the ignition array centered below two sprinklers. The first scenario was Test 1 in which a 15 ft (4.6 m) high array was centered directly below a sprinkler. The second involved either a 20 ft (6.1 m) high rack storage arrangement in a 25 ft (7.6 m) high building or a 25 ft (7.6 m) high rack storage arrangement in a 30 ft (9.1 m) high building with the main array centered below two sprinklers.

Success in the large-scale ESFR sprinkler fire tests was determined by evaluating the total number of operating sprinklers, maximum ceiling steel temperature over the array, and the quantity of test commodity consumed and extent of fire damage to the available fuel.

Under the first criterion, success with an ESFR sprinkler system requires that fires be suppressed by operation of less than twelve sprinklers. Ideally, when the main array is centered below a sprinkler, as in Test 1, the fire should be suppressed by one sprinkler; when the main array is centered below two sprinklers (Test 2), the fire is expected to be suppressed by two operating sprinklers but no more than six sprinklers.

The second evaluation criterion requires that the sprinkler system suppress the fire before the temperature of ceiling structural steel reaches 1000°F (538°C), which is generally considered the maximum safe temperature for load-bearing structural steel members.

Acceptable sprinkler performance under the third criterion requires that the maximum amount of fuel consumed in the ignition array, i.e., the center two pallet load wide by two pallet deep portion of the main fuel array, be in the range of 25 to 30 percent and that fire damage not extend to the end of the fuel arrays. Test results are summarized in Table 3-5.

Table 3-5: Sprinkler Performance Summary

Test No.	Flame Top Array	Flame To Ceiling	1st Sprinkler	Last Sprinkler	Fuel Consumption
2	1:40	1:55	2:01	4:38	11
4	1:03	1:12	1:14	2:35	3/4
5	9:30	9:30	9:34	11:31	25

In Test 2, in which the main array was centered below two sprinklers, the commodity proved to be more of a fire challenge than the ESFR sprinkler system could successfully protect against. Immediate fire suppression was not achieved and this resulted in a high water demand and fire damage to the ignition

array in excess of the accepted limit. In this test a total of 23 sprinklers actuated. The failure of the ESFR sprinklers to provide immediate fire suppression in this test indicates that they could not be recommended for this application under the conditions tested.

The results from Test 2 indicated that cartoned vegetable oil stored to 25 ft high under a 30 ft high ceiling cannot be protected adequately using a 50 psig (3.4 bar) ESFR sprinkler system. The options were to either decrease the hazard level or increase sprinkler system capability.

Test 4 was used to examine increased system capability for an ESFR sprinkler system resulting from increasing the system pressure from 50 psig (3.4 bar) to 75 psig (5.2 bar). The test scenario was the same as used in Test 2, i.e., cartoned vegetable oil stored 25 ft high under a 30 ft (9.1 m) high ceiling. At the higher water discharge pressure, the system suppressed the fire with three operating sprinklers. Further, one of the sprinklers that operated was in the third ring and did not contribute significant water to the fire source as it was installed more than 20 ft (6.1 m) away from over the center of the main array. This result indicates that an ESFR sprinkler system operating at 75 psig (5.2 bar) is capable of protecting rack storages of cartoned vegetable oil to 25 ft (7.6 m) high under 30 ft (9.1 m) ceilings.

The final test, Test 5, was performed to examine ESFR sprinkler protection for the higher challenge of uncartoned vegetable oil stored to 25 ft (7.6 m) high under a 30 ft (9.1 m) ceiling. In this test, the reduction in the amount of corrugated cardboard from 4 percent to 1 percent per pallet-load for the uncartoned product resulted in a longer time for the fire to reach ceiling level. The relatively easily-ignited cardboard cartons used in Tests 2 and 4 offered an easy vertical path for the fire plume. Without this avenue in Test 5, the fire incubated in the lower tier of the main array for over eight minutes. During this period, oil released from ruptured bottles, as well as bottled oil, was being heated by the fire ever closer to its flash point.

At 9 min 10 s there was a rapid escalation in fire intensity as the oil ignited and the fire spread up the entire east face of the main array extending well over the top of the array and was intermittently contacting the ceiling. The two sprinklers closest over ignition actuated at 9 min 34 s and 9 min 51 s after ignition but had no immediate effect in decreasing the fire plume. In fact, operation of these two sprinklers appeared to increase fire intensity.

The prolonged incubation period for the fire resulted in the involvement of more oil than was the case with the cartoned oil fire tests. By the time the sprinklers operated, the fire was too large to be suppressed immediately. The result of this test indicated that uncartoned vegetable cannot be adequately protected by ESFR sprinklers when stored to 25 ft (7.6 m) high under 30 ft (9.1 m) high ceilings.

Finally, the objective of employing ignition at the face of the rack storage arrangement instead of within the center of the array was to insure a longer incipient time that would allow the oil to become involved. Even in Test 4 where the ESFR sprinklers successfully suppressed the fires the large fire plume and relatively small carton damage indicated significant involvement of the oil commodity and not just combustion of cardboard cartons. The release of oil from ruptured bottles onto cardboard surfaces apparently created a "wicking" effect that allowed burning of oil with only small contribution from the

cardboard cartons. However, once the oil was spilled onto the floor, the sprinkler water provided cooling sufficient to prohibit ignition of the high flash point oils (590°F [310°C] and 620°F [327°C]) and prevent pool fires.

3.2.5 Conclusions

The high volumes of water discharged by the ESFR sprinkler systems were sufficient to keep the oil spilled on the floor below its flash point and prevent the formation of pool fires for all large-scale fire tests conducted during this program.

The results of the five large-scale fire tests conducted for this program indicate that Early Suppression Fast Response (ESFR) sprinklers, operating at a 75 psig (5.2 bar) discharge pressure, will provide adequate fire protection for rack storages of cartoned vegetable oil stored to 25 ft (7.6 m) high in 30 ft (9.1 m) high buildings.

The results of the large-scale fire test of uncartoned vegetable oil, i.e., consumer retail-size plastic bottles of vegetable oil in shrink-wrapped tray packs, illustrated the increased fire hazard for this commodity when compared with cartoned vegetable oil. The test indicated that ESFR sprinklers could not provide adequate fire protection for uncartoned vegetable oil stored to 25 ft (7.6 m) high in 30 ft (9.1 m) high buildings.

3.2.6 Fire Chronologies

Time (min:s)	Observation
0:00	Ignition.
0:10	Flames mid-way up bottom of 1st tier.
0:25	Flames at top of 1st tier. Plastic shrink-wrap peeling away from pallets.
0:50	Flames extend into bottom tier.
1:14	Flames reach top of 2nd tier. Streams of oil from rupturing bottles.
1:20	Flames reach top of 3rd tier.
1:30	Flames reach top of 4th tier.
1:40	Flames over top of array (5th tier). Fire is concentrated on east face of main array.
1:55	Flames contact the ceiling.
2:01	First sprinkler actuates (one of two over ignition).
2:06	Flames remain at ceiling level.
2:12	Second ignition zone sprinkler actuates.
2:25	Flames on east face remain at ceiling. Flames almost fill 4 ft aisle space.
2:44	Target array ignites.
2:50	Target array is burning at all five tiers. Ten sprinklers are operating.
2:55	Ceiling smoke layer descends, obscuring the test arrays from view.
3:45	Cameras and observers are removed from the test site.
4:00	Test site totally obscured by smoke.
4:38	Last of 23 sprinklers actuates.
16:00	Test terminated.

Figure 3-41: Fire Chronology – Test 2

Time (min:s)	Observation
0:00	Ignition.
0:05	Flames mid-way 1st tier.
0:15	Plastic shrink-wrap peeling away from ignition pallet-loads.
0:20	Flames reach top of 1st pallet-load.
0:25	Flames 5 ft high.
0:35	Flames 6 ft high.
0:53	Flames reach top of 2nd tier and are extending into the 3rd tier.
0:57	Flames are beyond the level of the 3rd tier.
1:03	Flames are above top of array; being drawn into the central transverse flue.
1:12	Flames reach ceiling level.
1:14	First sprinkler (one of the two closest over ignition) actuates.
1:20	Flames remain at ceiling level.
1:30	Flames extend 4 ft into the central transverse flue.
1:32	Flames being driven down from the ceiling.
2:00	Second sprinkler over ignition actuates. Flames over top of array.
2:10	Ceiling-level steam and smoke being driven down to floor level.
2:25	Flames on east face extend over top of array.
2:35	Third and last sprinkler (located 20 ft east) actuates.
3:15	Flames on east face extend 20 ft high.
3:45	Light hazy smoke begins to obscure the test site.
4:10	Visibility decreasing.
4:20	Fire persisting in bottom two tiers; flames extend over top of 3rd tier on east face.
5:00	Fire continues in bottom two tiers.
6:00	Fire continues; smoke becoming more dense.
8:00	Fire continues.
9:00	Smoke almost totally obscures view of fire.
10:00	Smoke heavier; camera removed from test site.
11:00	Smoke begins to thin.
12:00	No visible flame.
15:00	Test terminated.

Figure 3-42: Fire Chronology – Test 4

Time (min:s)	Observation
0:00	Ignition.
0:10	Flames mid-way 1st tier.
0:26	Bottles in 1st tier pallets ruptured by heat, stream oil into the aisle space.
0:45	Flames top of 1st tier on east face. Two bottles of oil fallen into aisle.
1:00	Bottles have fallen into the aisle; more oil from ruptured bottles in 1st tier.
1:20	Approximately 12 bottles have fallen into the aisle space.
2:00	Flames reach top of 1st tier. Some flaming at bottom edge of 1st tier.
2:50	Steady burning in 1st tier ignition pallets.
4:00	Oil streams extinguishing recently fallen bottles in aisle; no pool fire. Fire remains in 1st tier. Plastic shrink-wrap intact on 2nd through 5th tiers.
6:15	Steady but low level burning in ignition pallets continues.
7:00	Fire continues in 1st tier; oil pool fill aisle, 8 ft length. No pool fire.
8:00	Burning begins at bottom of 2nd tier; oil begins to stream down onto top of 1st tier.
8:30	Fire intensity increases; becomes established in the 2nd tier.
9:10	Flames in central longitudinal flue at 2nd tier.
9:30	Flames spread up east face. Fire rapidly intensifies.
9:34	First sprinkler (one of the two over array center) actuates.
9:43	East face of pallets of oil in the main array covered with flame. Flames extend to ceiling level.
9:51	Second sprinkler (over array center) actuates.
10:03	Target array ignited; six sprinklers now operating.
10:15	Large number of sprinkler actuations within past 12 s. Twenty-five (25) sprinklers now operating. Flames remain at ceiling .
10:32	Smoke and steam obscure view of test site.
11:00	Test site is filled with dense light grey smoke.
11:31	Last of 34 sprinklers actuates. Test site totally obscured by smoke.
26:00	Test terminated.

Figure 3-43: Fire Chronology – Test 5

3.3 Protection of Rack Stored Vegetable Oil in 48 oz (1.4 L) Plastic Containers in a 40 ft (12 m) Ceiling/ Seth Sienkiewicz / October 2011

3.3.1 Testing Overview

This test was part of a 4-test program. The first 3 tests looked at ceiling only protection options that did not provide acceptable fire protection. The forth test is described here and summarized in Table 3-6. The test facility used for this program is described in Section 2.1.

Table 3-6: Tabulated Results Test 4

PARAMETERS	
Test No	4
Test Date	03-25-2011
Commodity	Soybean Oil Class 2 Commodity
Main Array Size [Pallets]	2 x 8 x 7 DRR
Target Array Size [Pallets]	(2) 1 x 4 x 7 SRR
Ceiling Height [ft (m)]	40 (12.2)
Storage Height [ft (m)]	35 (10.7)
Aisle Width [ft (m)]	4 (1.2)
Ceiling Sprinkler Protection	
Sprinkler K-Factor [gpm/psi$^{1/2}$ (Lpm/bar$^{1/2}$)]	25.2 (363)
Sprinkler Temp Rating [°F (°C)]	165 (74)
Sprinkler Response	QR
Sprinkler Spacing [ft x ft (m x m)]	10 x 10 (3.0 x 3.0)
Sprinkler Discharge Pressure [psi (bar)]	40 [2.8]
Sprinkler Discharge Density [gpm/ft^2 (mm/min)]	1.6 [65.2]
In-Rack Sprinkler Protection	
Sprinkler K-Factor [gpm/psi$^{1/2}$ (Lpm/bar$^{1/2}$)]	8 (115)
Sprinkler Temp Rating [°F (°C)]	155 (68)
Sprinkler Response	QR
Sprinkler Spacing [ft (m)]	4 (1.2)
Sprinkler Discharge Pressure [psi (bar)]	15 (1)
Sprinkler Flowrate [gpm (L/min)]	30 (110)
Vertical Location Of In-Rack [ft (m)]	15 (4.7)
Results	
Total Ceiling Sprinklers Opened	4
Total In-Rack Sprinklers Opened	2
TEST DURATION [min:sec]	20:00
Peak 10-Sec Gas Temperature [°F (°C)]	800 (427)
Peak 1-Min Avg Steel Temperature [°F (°C)]	135 (57)
Damage To Test Array	Acceptable

3.3.2 Introduction

This project was initiated to establish additional protection options for the rack storage of consumer size bottles of high flash point cooking oils in corrugated cartons. FM Global Property Loss Prevention Data Sheet 7-29 has existing protection for this hazard for ceiling heights up to 30 ft (9.1 m). The goal of the project was to expand the protection options to higher ceiling heights and larger K-factor sprinklers.

3.3.3 Test Details

3.3.3.1 Commodity

The commodity was cartoned, soybean oil, with a closed cup flashpoint of 505°F (263°C). The soybean oil was supplied in 48 oz. (1.4 L) plastic bottles, stored in corrugated cartons. Nine bottles were stored per carton and there were 52 cartons per pallet. A layer of stretch wrap held the commodity on the pallet. A photo of the commodity is provided in Figure 3-44 (extra pallets are not part of the commodity).

Figure 3-44: Photo of Cartoned Soybean Oil on Pallet

To reduce the quantity of soybean oil required for each test, the test array also contained Standard Class 2 commodity. This allowed for a larger test array without filling the entire array with cartoned soybean oil.

3.3.3.2 Storage Method

The commodity was stored in warehouse-style double-row racks. The main array consisted of commodity stored in an open frame rack that was eight pallet loads wide. The storage bays were each 8 ft (2.4 m) wide, with a rack upright provided in the center transverse flue. Commodity was placed on the floor in the 1st tier, and additional tiers were located every 5 ft (1.5 m) from the floor. The array was 7 tiers high, providing a storage height of nominally 35 ft (10.7 m).

For the test, the number of pallets in the array containing oil was reduced per tier up the array. The pallets of oil were 6-wide in Tier 1, 8-wide in Tiers 2+3, 4-wide in Tier 4, and 2-wide in Tiers 5 7. FM Global Standard Class 2 commodity was used throughout the rest of the array. This arrangement provided pallets of oil where the fire was expected to propagate, while reducing the total quantity of oil used in the test.

Single-row, open frame rack target arrays were provided on either side of the main array to assess fire propagation. The target arrays consisted entirely of FM Global Standard Class 2 commodity. The target arrays were four pallet loads wide and were placed across a 4 ft (1.2 m) aisle. The target arrays were also 35 ft (10.7 m) high.

Nominal 6 in. (12.7 cm) flues were provided throughout the main and target arrays.

A photo of the test array is provided in Figure 3-45.

Figure 3-45: Photo of the Test Array 30 s After Ignition)

3.3.3.3 Sprinkler Protection

Ceiling only protection was provided by K factor 25.2 gpm/psi$^{1/2}$ (363 L/min/bar$^{1/2}$), quick response, pendent sprinklers, with a 165°F (74°C) link. The sprinklers were installed on 10 ft x 10 ft (3.0 m x 3.0 m) spacing and the system discharge pressure was set to 40 psi (2.8 bar). This resulted in a flow of 160 gpm (606 L/min) per sprinkler, and a 1.60 gpm/ft^2 (65.2 mm/min) density at the floor.

A single level of in-rack sprinklers was also installed for the test. The in-rack sprinklers were K factor 8.0 gpm/psi$^{1/2}$ (115 L/min/bar$^{1/2}$), quick response, pendent sprinklers, with a 155°F (68°C) link. The sprinklers were installed above the 3rd tier, roughly 15 ft (4.6 m) from the floor. The sprinklers were installed in the longitudinal flue at 4 ft (1.2 m) increments and operated at a pressure of 15 psi (1.0 bar), or 30 gpm (114 L/min) per sprinkler.

3.3.4 Test 4 – 35 ft Storage, 40 ft Ceiling, K-25.2 Ceiling Sprinklers and K-8.0 In-Rack Sprinklers

3.3.4.1 Test 4 Observations

Ignition was between 2 sprinklers in the center transverse flue of the main array, offset from the eastern face of the array. Flames reached the top of the array at 51 s and had reached ceiling level at 53 s. The 1st in-rack sprinkler operated at 1 min 1 s. At 1 min 12 s, a break was observed in the flames on the face of the array, located at the level of the operated in-rack sprinkler.

The 1st ceiling sprinkler operated at 1 min 15 s. The peak ceiling thermocouple temperature observed during the test was 800°F (427°C) at 1 min 17 s. Two additional ceiling sprinklers operated at 1 min 19 s and 1 min 22 s. All three sprinkler operations were over the eastern aisle. At 1 min 33 s, flames were observed on the western face of the array below the 2nd tier. A second in rack sprinkler operated at 1 min 33 s.

At 1 min 45 s, majority of fire was observed below the 2nd tier. At 1 min 57 s, flames on the western face of the array had travelled up into the 2nd and 3rd tiers. At 2 min 48 s, flames were still present below the 2nd tier and observed in the western row of the array. The peak 1-min average ceiling steel thermocouple measurement was 135°F (57°C) at 3 min 34 s.

At 4 min, fire was still observed at the bottom of the array but had been restricted to the ignition flue. At 7 min, there was limited involvement within the array, but a fire persisted in the western aisle. Over the next several minutes, the fire intensity slowly grew, and flames travelled up the west face of the array. At 9 min 39 s, a sprinkler operated over the western aisle and the fire was quickly knocked down.

At 10 min, four ceiling sprinklers and two in-rack sprinklers were operating. At 15 minutes no flames could be seen from visual observation and the infra-red cameras revealed small hot spots in the lower sections of the array. The test was terminated at 20 minutes.

3.3.4.2 3.3.4.2 Test 4 Results

Post test observations showed that the fire spread through the main array had been contained by the combination of ceiling and in-rack sprinklers. The fire did jump to the west target array during the test, but prior to a sprinkler operation over the west aisle. Upon operations of a sprinkler over that aisle, the fire was quickly suppressed on the face of both the main array and the target array. Photos of the post-test damage to the main array are provided in Figure 3-46.

A total of four ceiling sprinklers and two in-rack sprinklers operated during the test. The peak 1 min average ceiling steel temperature of 135°F (57°C) was below the evaluation threshold of 1000°F (538°C).

Figure 3-46: Post-test Photos of Test Array (West face on Left)

3.4 Protection of Small Plastic Bottles Containing Low Flash Point Flammable (Ignitable) Liquids / Ronald Dean / September 2003

3.4.1 Test Overview

This test program consisted of five full scale fire tests. Tests 1-3 involved defining a baseline test for cartoned unexpanded plastic to compare the small bottle commodity to. Unfortunately Test 4 demonstrated that the small bottle containing low flash point liquids represents a fire hazard well beyond plastic commodities rendering the first 3 tests meaningless to this program. The test facility used for this program is described in Section 2.2.

Table 3-7: Fire Test Summary

Test No.	4	5
Test Date	01-14-03	03-12-03
PARAMETERS		
Commodity	**Sm. Bottle (4)**	**Sm. Bottle (4)**
Storage Arrangement	Rack	Rack
Array Nominal Size - LxWxH (mxmxm [*ftxftxft*])	7.5x2.3x4.7 [*24¾x7½x15½*]	4.9x2.3x7.1 [*16x7½x23*]
Stack Height (m [*ft-in*])	4.7 [*15-5*]	6.7 [*21-10*]
Nominal Pallet Load Height (m [*ft-in*])	1.3 [*4-5*]	1.3 [*4-5*]
No. of Storage Levels	3	4
Ceiling Height (m [*ft*])	9.1 [*30*]	9.1 [*30*] (5)
Clearance to Ceiling (m [*ft-in*])	4.4 [*14-4*]	2.1 [*7-0*]
Clearance to Ceiling Sprinklers (m [*ft-in*])	4.7 [*13-9*]	4.7 [*6-5*]
Aisle width (m [*ft*])	2.4 [*8*]	2.4 [*8*]
Ignition Centered Below (No. Ceiling Sprinklers)	4	4
Ceiling {In-rack} Sprinkler Orifice Size (mm [*in.*])	16 (2) (ELO) [*0.64*]	13 {14} [*½ {17/32}*]
Ceiling {In-rack} Sprinkler Temperature Rating (°C [*°F*])	68.3 (2) [*155*]	141.1 {73.9} (6) [*286 {165}*]
Ceiling {In-rack} Sprinkler RTI ((m-sec)^{½} [(ft-sec)^{½}])	125.9 (2) [*228*]	125.9 {29.3} [*228 {53}*]
Ceiling {In-rack} Sprinkler Spacing (mxm [*ftxft*])	3.0x3.0 (2) [*10x10*]	3.0x3.0 (7) [*10x10*]
Ceiling {In-rack} Sprinkler Discharge Pressure (bar [psi])	2.0 (2) [*29*]	0.8 {3.4} (8) [*13 {50}*]
Ceiling {In-rack} Sprinkler Discharge Density (mm/min [gpm/ft^2])	24.4 (2) [*0.60*]	8.1 (9) [0.*20*]
RESULTS		
First Ceiling {In-rack} Sprinkler Operation (min:sec)	1:01 (2)	none {1:59}
Last Ceiling {In-rack} Sprinkler Operation (min:sec)	1:54 (2)	none {2:05}
Total Ceiling {In-rack} Sprinklers Opened	33 (10) {NA}	none {3}
Peak Gas Temperature (°C [*°F*])	648.9 [*1200*]	84.4[*184*]
Peak Ceiling Steel Temperature (°C [*°F*])	82.8 [*181*]	42.8 [*109*]
Equivalent No. Pallet Loads Consumed	(11)	negligible
Test Concluded (min:sec)	1:54 (3)	16:00

NOTES:
1. Not Applicable
2. In-rack sprinklers not installed in Test 4.
3. Test terminated.
4. Small bottle commodity consisted of 59 mℓ [2 fl oz] polyethylene containers with heptane in individual cardboard compartments within corrugated cartons on wood pallets.
5. Clearance to ceiling measured from top horizontal barrier.
6. Fast response in-rack sprinklers used.
7. Three lines of in-rack sprinklers were located above the 2nd and 4th array levels under horizontal barriers. Sprinkler spacing in the longitudinal flue was 1.2 m [4 ft] on centers whereas the two lines of face sprinklers were spaced 2.4 [8 ft] on centers.
8. At the most remote in-rack sprinkler.
9. In-rack sprinkler density not applicable.
10. Six seconds after test termination 54 sprinklers had operated. Ultimately, all installed sprinklers (64) were opened.
11. Not determined.

3.4.2 Test Setup

3.4.2.1 Small Bottle Commodity

A small bottle commodity was created for test purposes. The product consisted of 59 mℓ [2 fl oz] polyethylene bottles filled with heptane. The bottle shape and consequently the corrugated carton size were chosen to provide a good fit on a 1.1 m x 1.1 m [42-in. x 42-in.] pallet. The carton was designed to supply the required bottle wrapping by using thin cardboard vertical partitions and horizontal dividers. Figure 3-47 details the construction of a single carton of commodity.

Each pallet load of test commodity was constructed by using a central core of FM Global standard unexpanded plastic commodity surrounded by 24 cartons of the small bottle commodity as shown in Figure 3-48. This allowed an additional reduction in amount of small bottle commodity yet should have no effect on the fire hazard.

3.4.2.2 Storage Arrangement

3.4.2.2.1 Tests 4

The main array consisted of double row rack storage, three pallet loads high. Dimensions were about 7.5 m long by 2.3 m wide by 4.3 m high [24¾ ft x 7½ ft x 14 ft]. The array rested on the floor of the 9.1 m [30 ft] high test site so that a clearance of about 4.7 m [15 ft 5-in.] existed between the ceiling sprinklers and the top of the array. A single row target array, three bays long and three levels high, was located across a 2.4 m [8 ft] aisle to the east. See the array setup diagram for more details (Figure 3-49).

3.4.2.2.2 Test 5

The four level high main array consisted of double row rack storage with in-rack sprinklers at two levels. Dimensions were about 4.9 m long by 2.3 m wide by 6.7 m high [16 ft x 7½ ft x 22 ft]. The array rested on the floor of the 9.1 m [30 ft] high test site so that a clearance of about 2.5 m [8 ft 2-in.] existed between the ceiling sprinklers and the top of the array. A single row target array, one bay long and four levels high, was located across a 2.4 m [8 ft] aisle to the east. See the array setup diagram for more details (Figure 3-50).

3.4.2.3 Ignition Method

For Test 4, two 76-mm diam. by 76-mm long [3-in. x 3-in.] cellucotton rolls each soaked in 0.12 ℓ [4 oz] of gasoline served as igniters. They were located at the base of the array on either side of the central transverse flue, 533 mm [21-in.] in from the east face of the main array (Figure 3-49) and lit with a propane torch. In Test 5, ignition was by means of a single 76-mm diam. by 152-mm long [3-in. x 6-in.] cellucotton roll soaked in 0.24 ℓ[8 oz] of gasoline. It was located in the third level pallet, north of and adjacent to the central transverse flue, 152 mm [6-in.] in from the east face of the main array (Figure 3-50)

3.4.2.4 Instrumentation

Numerous thermocouples monitored near-ceiling gas temperatures. Additionally, imbedded thermocouples in an angle at the ceiling, measured steel temperatures. All sprinklers were timed so that a sequence of operation was obtained. (Figure 3-51)

3.4.3 Protection

Different protections were used in each test as listed in Table 3-8. The ceiling sprinkler layout for both tests is shown in Figure 3-52.

Table 3-8: Fire Test Summary

Test No.	4	5
Ceiling Sprinklers		
Type	ELO	STANDARD
Orifice Size (mm [*in.*])	16 [*0.64*]	13 [*½*]
Rating (°C [°*F*])	68.3 [*155*]	141.1 [*286*]
Discharge Pressure (bar [*psi*])	2.0 [*29*]	0.8 [*13*]
Density (mm/min [*gpm/ft²*])	24.4 [*0.60*]	8.1 [0.*20*]
Spacing (mxm [*ftxft*])	3.0x3.0 [*10x10*]	3.0x3.0 [*10x10*]
In-rack Sprinklers		
Type	Type	Type
Orifice Size (mm [*in.*])	Orifice Size (mm [*in.*])	Orifice Size (mm [*in.*])
Rating (°C [°*F*])	Rating (°C [°*F*])	Rating (°C [°*F*])
Discharge Pressure (bar [*psi*])		3.4 [*50*]
Discharge/sprinkler (mℓ/min [*gpm*])		212 [*56*]
Spacing along pipe (m [*ft*])		Face: 2.4 [*8*] Longitudinal: 1.2 [*4*]
Discharge Pressure (bar [*psi*])		3.4 [*50*]

Notes:
1. Sprinkler types – ELO = Extra Large Orifice / LO = Large Orifice
2. No in-rack sprinklers used in Tests 4

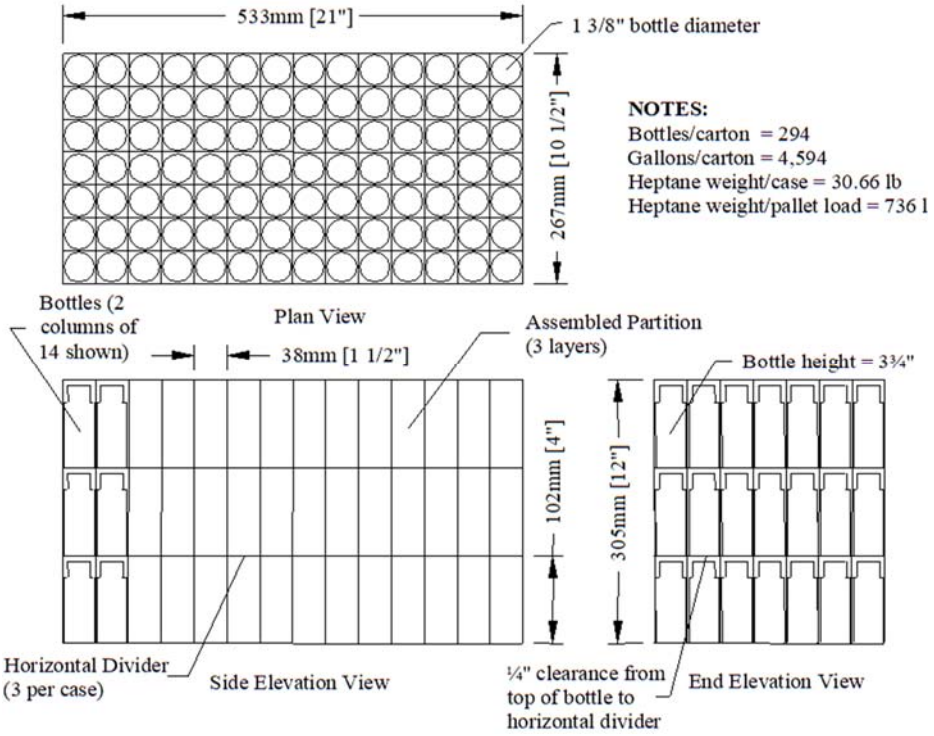


Figure 3-47: Single Carton of Commodity

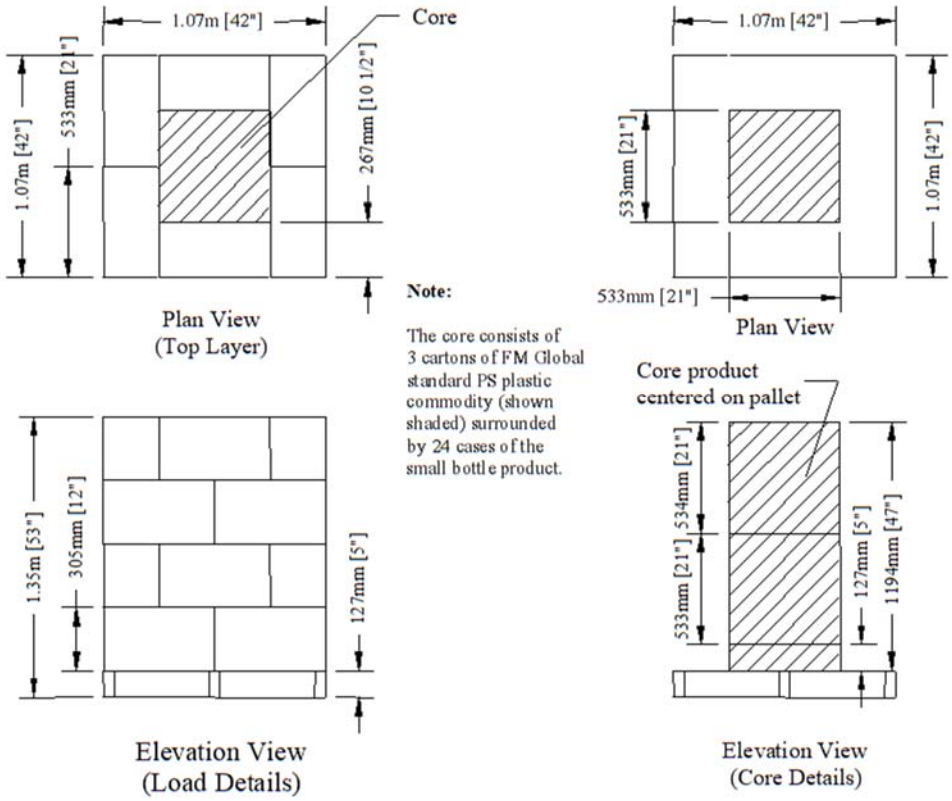


Figure 3-48: Typical Pallet Load

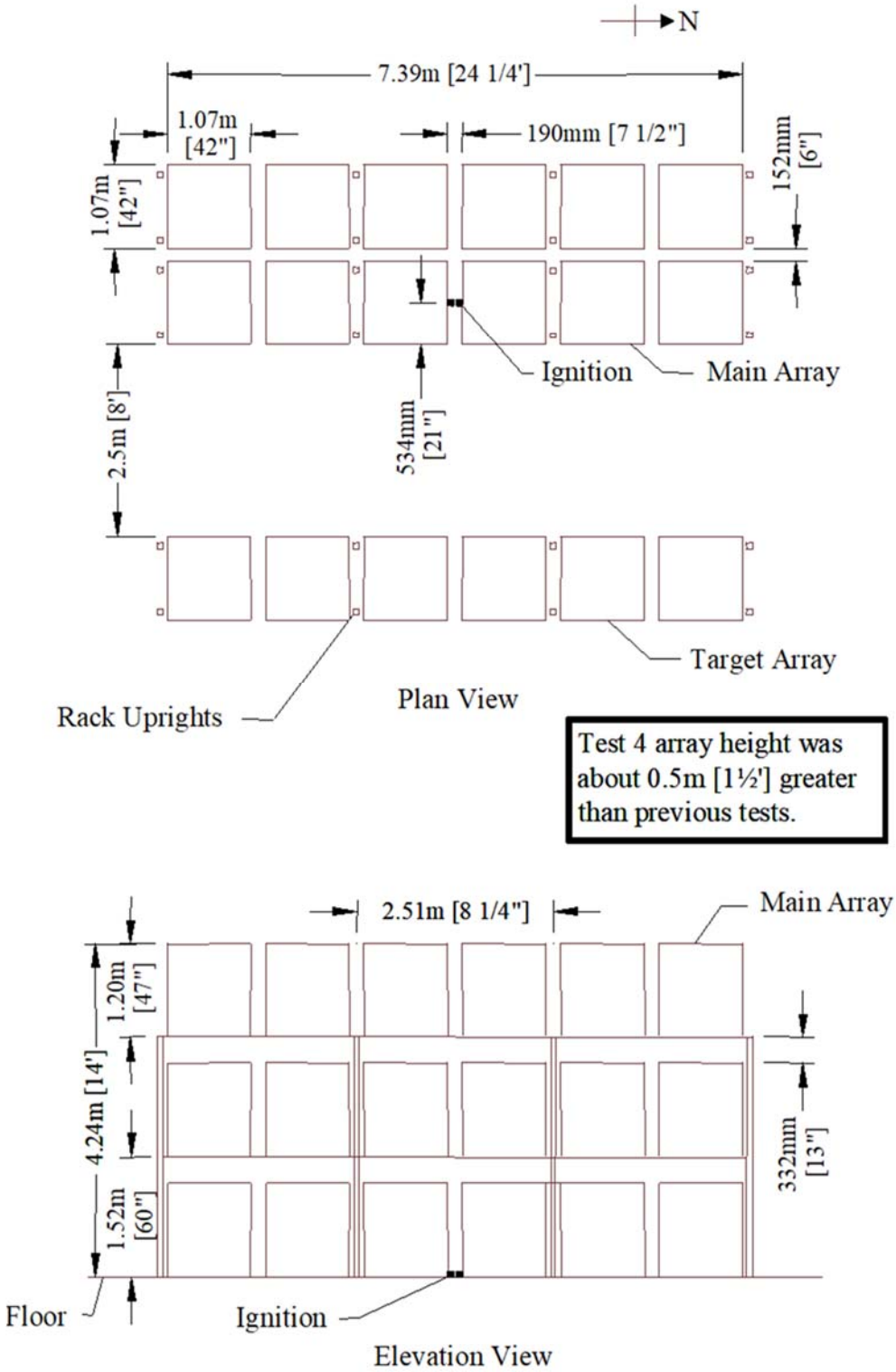


Figure 3-49: Array Set-Up – Test No. 4

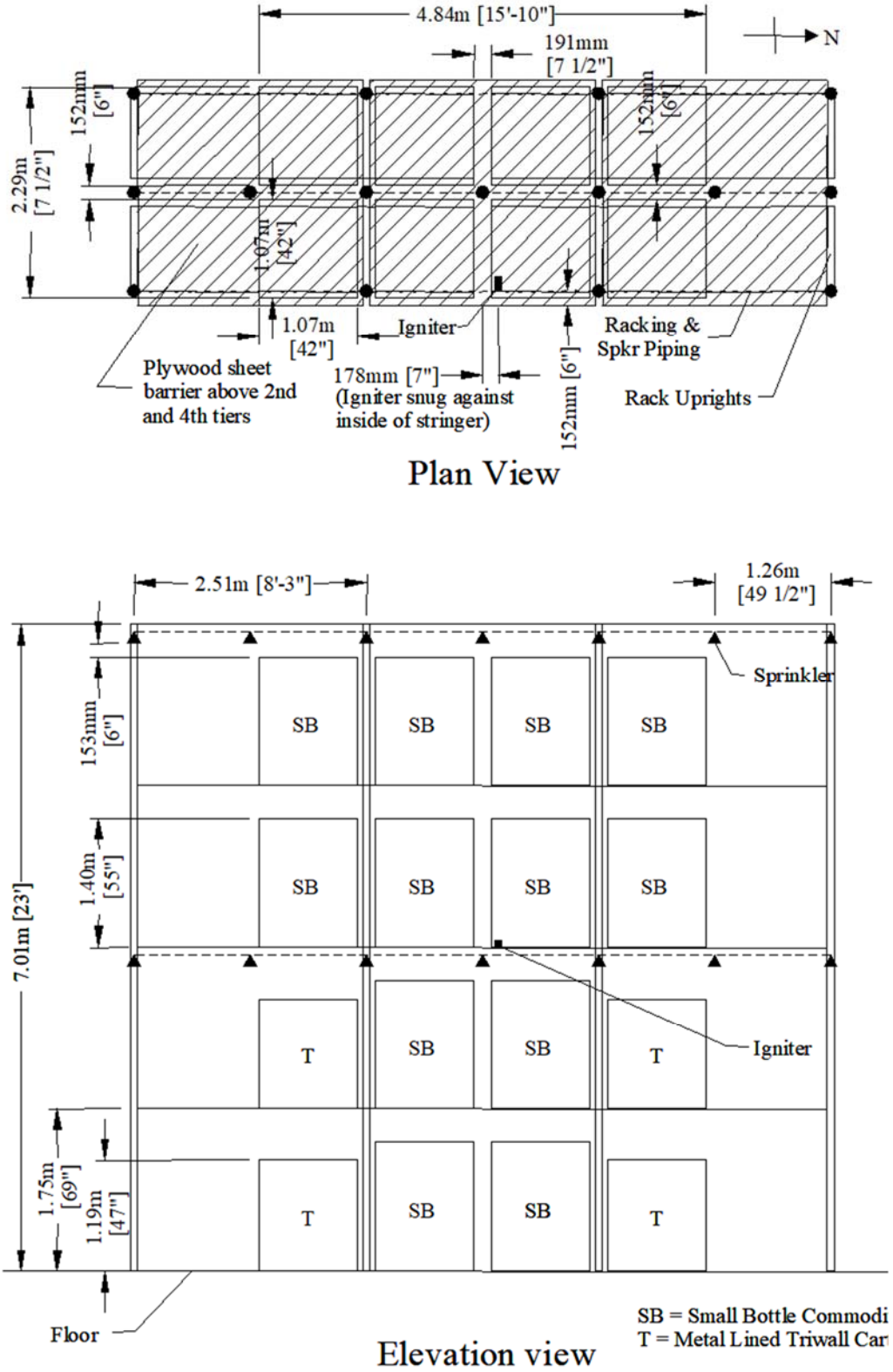


Figure 3-50: Array Set-Up – Test No. 5

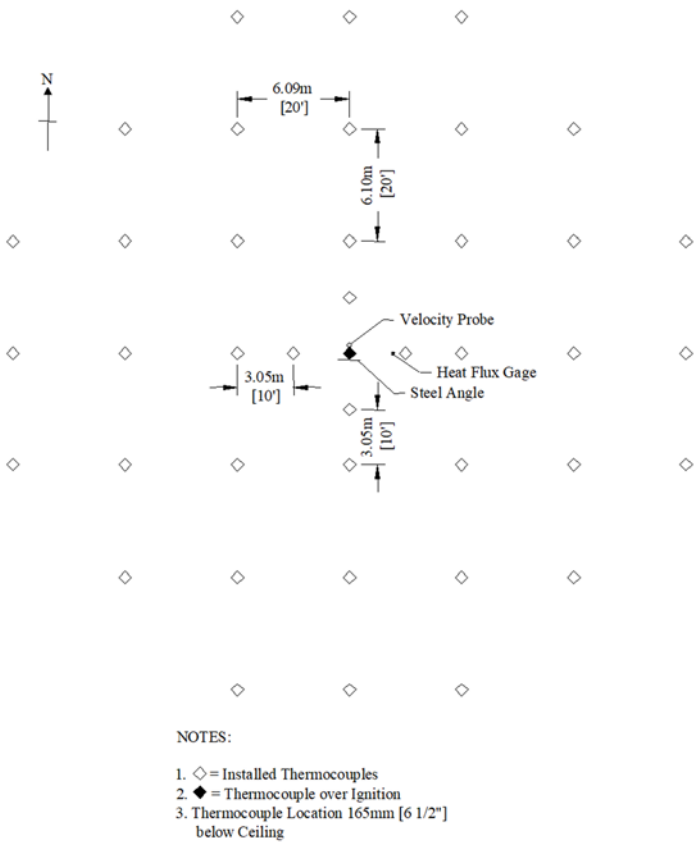


FIGURE 4. INSTRUMENTATION LAYOUT

Figure 3-51: Instrumentation Layout

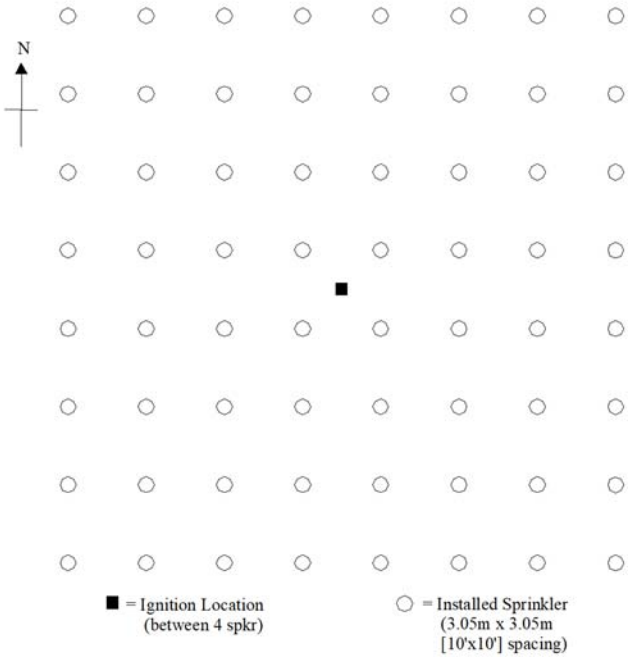


Figure 3-52: Ceiling Sprinkler Layout

3.4.4 Test Results

3.4.4.1 General

Table 3-7 summarizes test conditions and results.

3.4.4.2 Test 4 Summary {nominal 4.7 m [15½ ft] high array; ELO @ 2.0 bar [29 psi]; small bottle commodity}

(Note: all times in this section are from test start – some expressed as min:sec)

Incubation time was about 15 seconds less in Test 4 than in the benchmark Test 3. A parallel fire development existed between the two tests for about 1½ minutes. At about this time, serious involvement of the flammable liquid occurred, causing exponential fire growth. The result was test terminated at 1:54. An aggressive mop-up attack required more than one hour to control and eventually extinguish the fire. At the time of test termination there was no pool fire on either side of the main array and just a little flaming in the residual material on the floor which had fallen from the rack. Selected ceiling temperature data is provided in Figures 3-53 and 3-54. The fire chronology is provided in Section 3.4.6. Ceiling sprinkler operation times are shown in Figure 3-56. The extend of fire damage is shown in Figure 3-58. Figure 3-60 provides some select photographs from the test.

3.4.4.3 Test 5 Summary {nominal 6.7 m [23 ft] high array; fire protection, Scheme A; small bottle commodity}

(Note: all times in this section are from test start – some expressed as min:sec)

Commodity salvaged from the previous test was used to create a higher storage array for this test. A combination of in-rack and ceiling sprinklers was used in order to determine an adequate protection for the small bottle commodity. Ignition was at the base of the third level close to the array east face. Fire development was such that flames were licking at sprinklers under the horizontal barrier over ignition at 1:57. Two seconds later the two adjacent face sprinklers opened and flames were reduced from about 3.4 to 1.5 m [11 to 5 ft] high. By about 6 minutes the fire appeared to be burning at a steady rate. Flames occasionally licked above the top barrier but fire was contained to the two ignition loads and the two immediately above them. A total of 3 in-rack and no ceiling sprinklers had operated by test conclusion at 16:00. Selected ceiling temperature data is provided in Figures 3-53 and 3-55. The fire chronology is provided in Section 3.4.7. In-rack sprinkler operations are shown in Figure 3-57. The extent of fire damage is shown in Figure 3-59. Figure 3-61 provides some select photographs from the test.

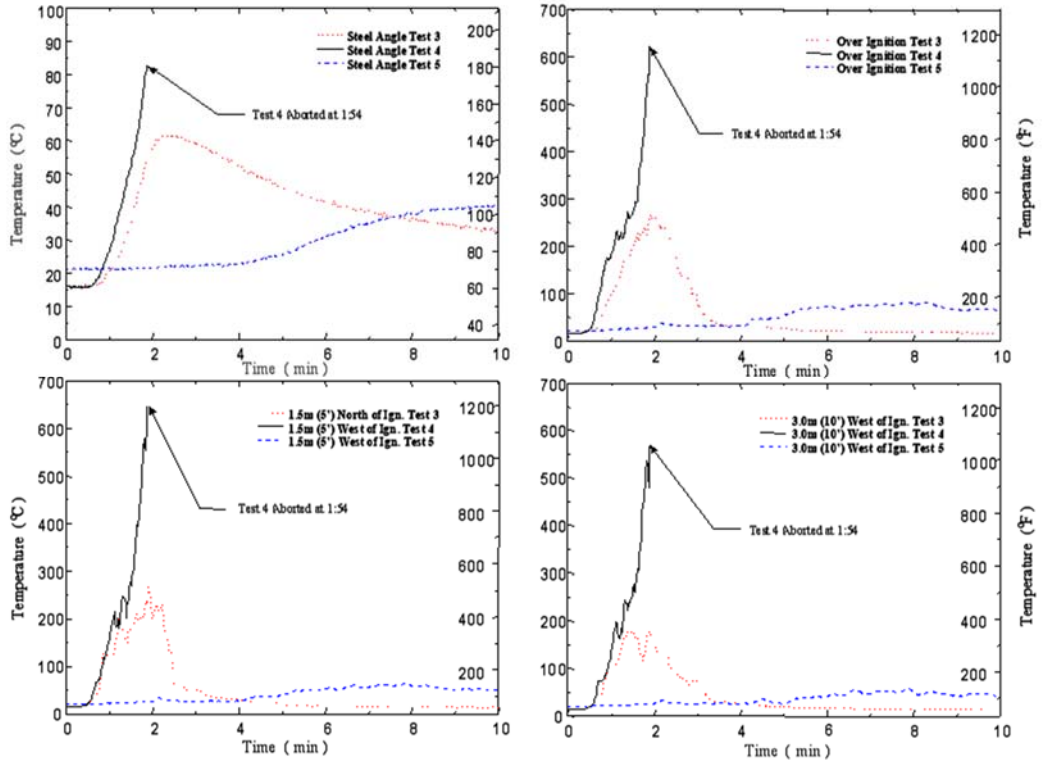


Figure 3-53: Various Ceiling Temperature Comparisons – Tests 4 and 5

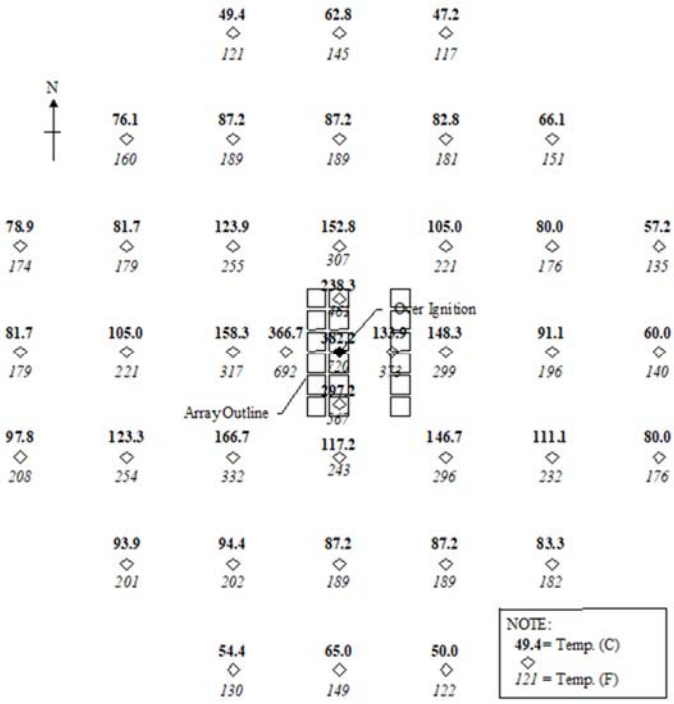


Figure 3-54: Near Ceiling Maximum One Minute Average Gas Temperatures – Test 4

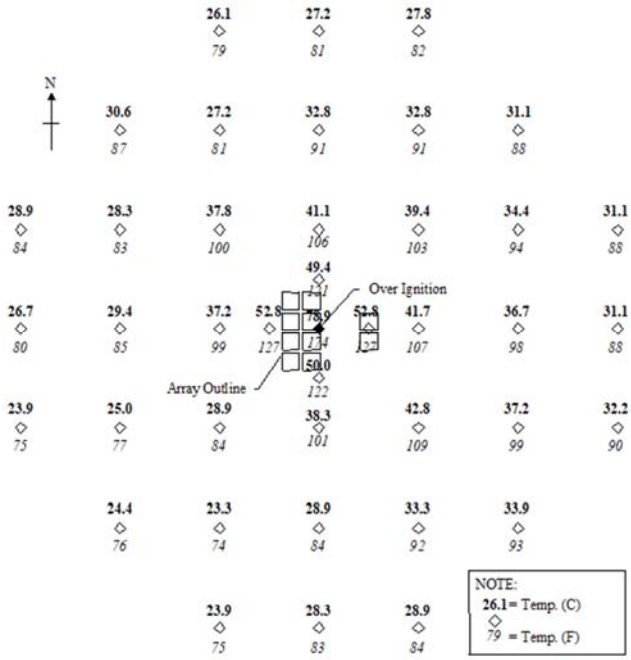


Figure 3-55: Near Ceiling Maximum One Minute Average Gas Temperatures – Test 5

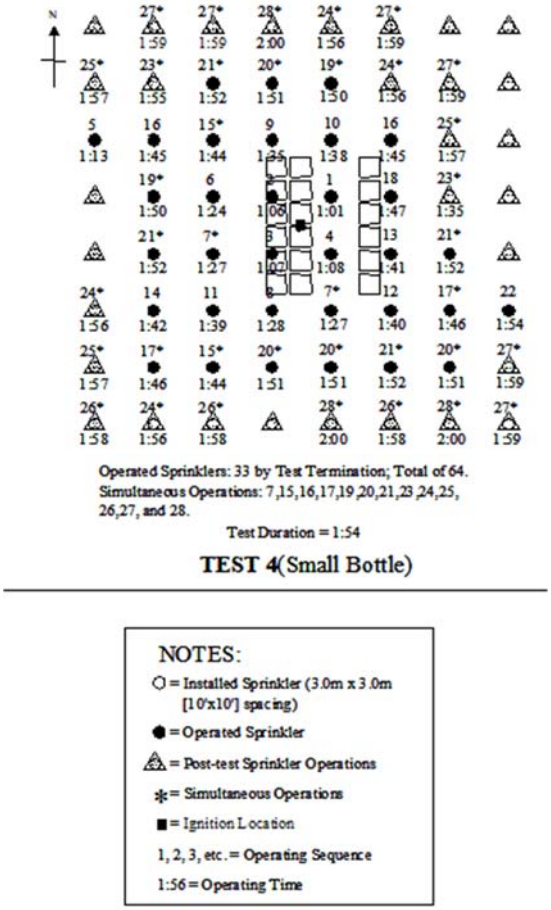


Figure 3-56: Ceiling Sprinkler Operations – Test 4

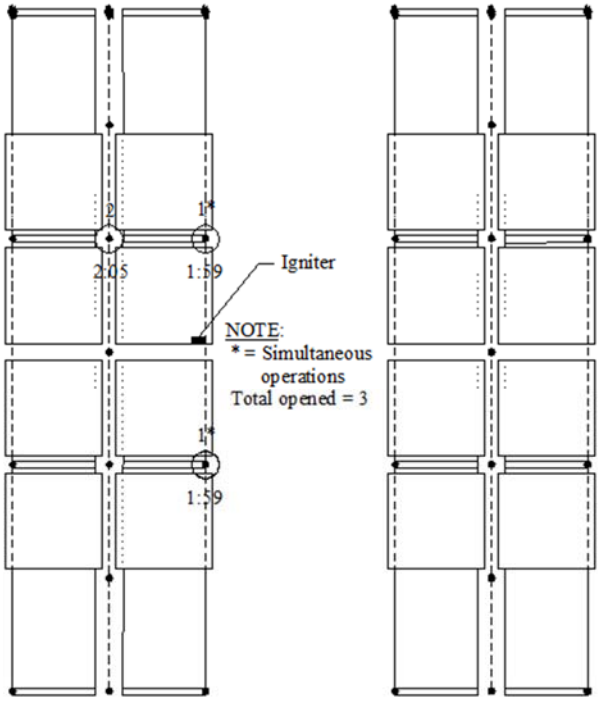


Figure 3-57: In-Rack Sprinkler Operations – Test 5

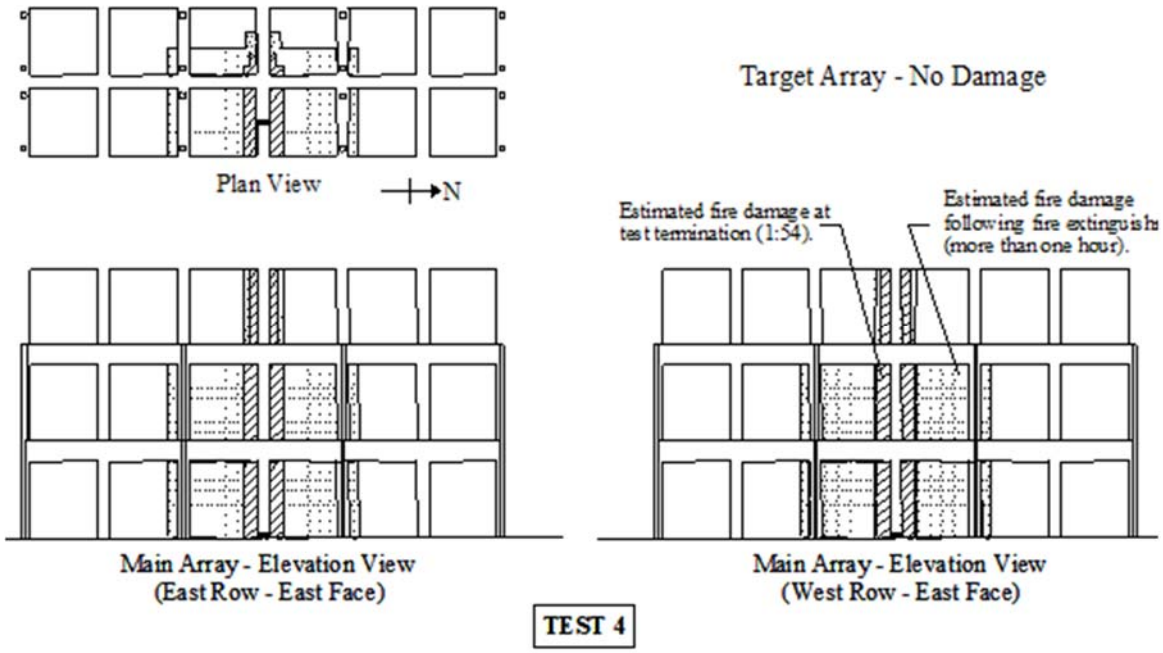


Figure 3-58: Damage Extent – Test 4

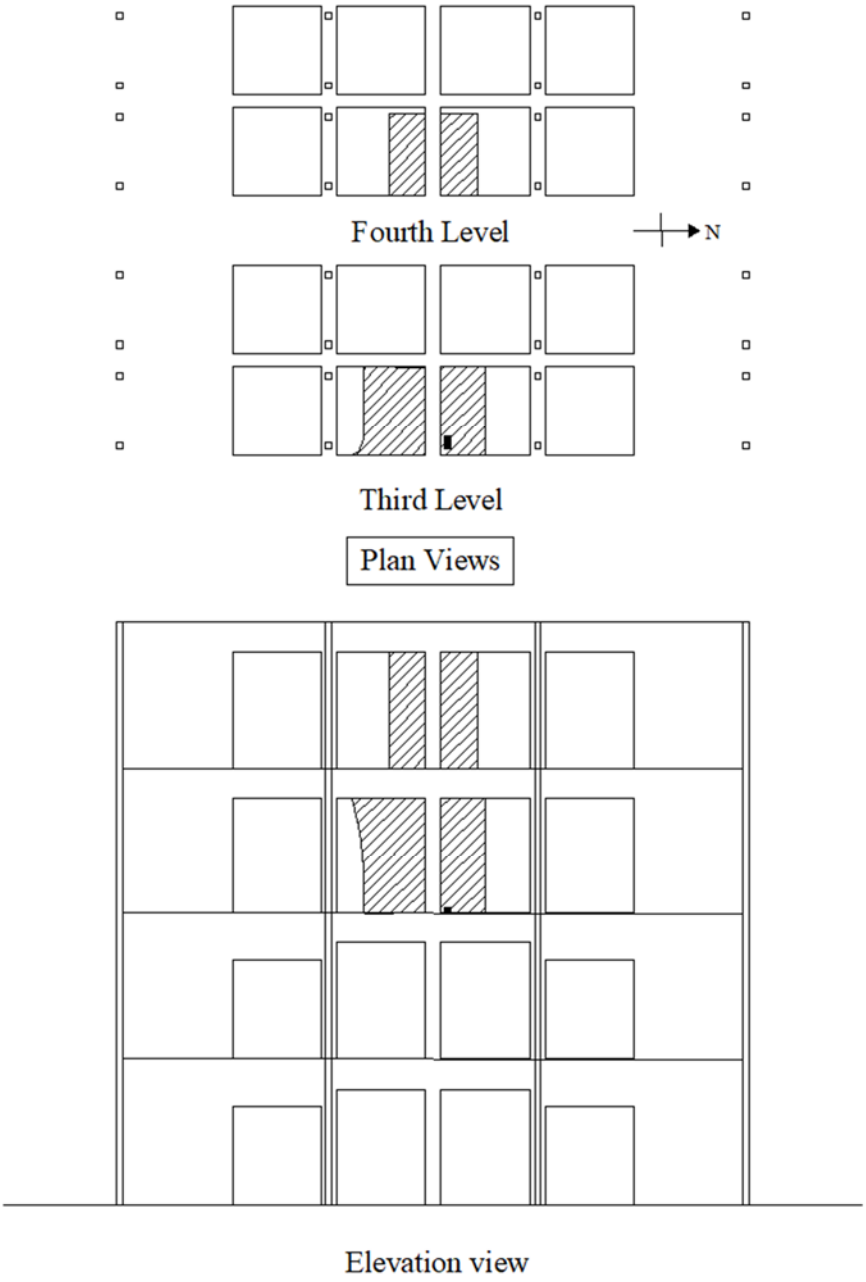


Figure 3-59: Damage Extent – Test 5

3.4.4.4 Test 4 (ref: FM Global Properly Loss Prevention Data Sheet 8-9: unexpanded plastics protection)

The protection level for Test 4 was shown to provide control for cartoned unexpanded plastic commodity. The intent of the test was to show this level of protection could control a fire in the ignitable liquid filled small bottles.

As the initial fire developed, a muffled “pop” was heard prior to 30 sec when the ignition flue space flames had reach about 3.0 m [10 ft] high. Another “pop” occurred shortly after a half minute with flames about 4.9 m [16 ft] high. As the heat built up and flames reached the ceiling, an explosion

occurred followed shortly by operation of the first four sprinklers. Frequent explosions occurred between one minute and 1:54 when the test was terminated and flames were across the ceiling in about a 6.1 m [20 ft] diameter. The severity of the fire was well beyond expectations. However, there was no contribution by a pool fire since none was formed. Although the explosions were surprising, and many cartons and bottles were blown out of the racks as a result, it was determined that they had no significant effect on the fire's severity. Cartoned unexpanded plastics protection was inadequate to control a fire in the small bottle commodity.

3.4.4.5 Test 5 (ref: FM Global Properly Loss Prevention Data Sheet 7-29: fire protection Scheme A)
Using the salvaged commodity from Test 4, a final test was run using a 6.1 m [20 ft] high array with a combination of barriers and in-rack and ceiling sprinklers. A total of 3 in-rack sprinklers opened and contained the fire to the ignition pallet loads and the two loads directly above them. Protection was adequate.

3.4.5 Discussion and Analysis

3.4.5.1 Small Bottle Test Commodity
In order to keep commodity costs as low as possible, the amount of small bottle product used per pallet load was minimized. Each pallet load was comprised of a central core of standard plastic commodity, surrounded by one layer of cartons containing the flammable liquid in small bottles. This particular design was predicated on the belief that the small bottle commodity posed a fire hazard no worse than that of plastics and could be protected as such. Even if the hazard assumption was incorrect, there would still be sufficient bottle product to allow a valid test with meaningful results. This technique allowed a 25% reduction in the amount of small bottle commodity purchased. The rationale was that adequate protection would keep the test duration short and fire weak enough so that the seven rows of bottles within the cartons which provided an insulating barrier would be sufficient to prevent the fire from penetrating to the core. If for some reason, such as copious bottle spillage, the fire did reach and involve the core, there would be no appreciable change in fire intensity since the core was believed to be of equal hazard. Conversely, if the presumption was incorrect and the small bottle commodity was of a greater fire hazard than expected, the provided protection would be insufficient and the fire severity would be such that the test would be terminated and the core material would be irrelevant.

3.4.5.2 Test 4 Carton Explosions
A case of product contained 294 standard HDPE plastic bottles each filled with 59 mℓ [2 fl oz] heptane. A small vapor space existed above the liquid in each bottle. The cartons (cases) were compartmented containers with 98 bottles to a layer (7x14 bottles/layer), in three layers within the case. A pallet load was composed of 24 cases, pin wheeled around a 5.3 m x 5.3 m x 1.2 m [21-in. x 21-in. x 47-in.] central core of the FM Global standard plastic commodity which fit snugly in the chimney which was created by pin wheeling. The entire load was wrapped with stretch wrap.

At 0:25 and 0:36 "pops" (muffled explosions) were heard. At 0:55 a significant explosion blew cartons and bottles from the array. From that time on, until the test termination at 1:54, numerous explosions occurred which blew cartons and bottles out either side of the array. Neither fireballs nor burning bottles were observed accompanying the explosions. Flames reached the array top (4.9 m [16 ft] high) at

0:32 and the 9.1 m [30 ft] high ceiling at 0:49. The initial sprinkler opened at 1:01. A total of 33 sprinklers were open and flames were 6.1 m [20 ft] in diameter across the ceiling by test termination. By 2:00 (6 seconds following test termination) an additional 21 sprinklers had opened.

Apparently, many if not all, the product cases contained heptane vapors at the lower explosive limit (LEL). When the fire burned through the carton a violent rupture occurred.

Fireballs and/or trailing streams of fire from ruptured bottles were not observed to accompany the explosions. Only carton parts and unbreached bottles were scattered about. Other than disrupting the array integrity, the explosions appeared not to contribute to the fire's spread or severity. If anything, they may have contributed somewhat to reducing the fire severity by removing product from the fire area and opening up the array for easier access to discharged sprinkler water. The test outcome was not significantly influenced by the explosions.

3.4.6 Fire Chronology – Test 4

Time (min:s)	**Observations**
0:00	Ignition
0:10	Flames half-way up 1st pallet load (about 0.8 m [2½ ft] high).
0:15	Flames at top of 1st pallet load (about 1.4 m [4¾ ft] high).
0:18	Flames 1.5 m [5 ft] high.
0:25	"Pop" heard.
0:26	Flames about 3.0 m [10 ft] high.
0:32	Flames at top of array (about 4.9 m [16 ft] high)
0:36	Another "pop" heard.
0:49	Flames lick at ceiling (9.1 m [30 ft] high)
0:55	Major explosion.
1:01	First sprinkler operates.
1:02	Cartons blown into aisle.
1:06	Cartons blown out west side of array.
1:10	More cartons blown into aisle.
1:11	Flames reach west side of array at bottom of 3rd tier.
1:14	More cartons blown into aisle.
1:19	More explosions.
1:25	Flames steady on ceiling.
1:44	Another "pop" heard.
1:54	More explosions; flames across ceiling about 6.1 m [20 ft] diameter; test terminated, hose streams applied.
Post-Test	
2:14	Flames are off ceiling and hose streams seem to be effectively driving flames down
2:29	Flames about 1.5 m [5 ft] above array (6.4 m [21 ft] high).
2:47	Flames occasionally lick at ceiling (9.1 m [30 ft] high).
2:49	Explosions continue.
3:06	Whitish smoke beginning to buildup and obscure array view.
3:22	Fire view temporarily obscured by smoke.
Time (min:s)	**Observations**
3:45	Fire view appears totally obscured.

13:55	Seems to be no fire control yet. Entire array except for south end appears to be involved.
14:45	Foam is going to be applied from in-rack sprinklers at top of array.
15:50	Fire reduced considerably. Foam also being applied via hose streams.
16:18	Residual flaming (0.3 or 0.6 m [1 or 2 ft] high) by target across from ignition.
16:37	Fire appears confined to ignition area, burning from base to top of array. Burning confined primarily from top of bottom, to top of 2nd pallet loads.
17:00	Flames occasionally lick 0.9 to 1.5 m [3 to 5 ft] above top of array.
18:03	Fire has been reduced pretty much to bottom level.
18:21	Some flaming out of ignition flue at to top of array to east.
20:50	Flare-up in eastern part of array; flames burning in 2nd and top tiers.
21:02	Burning in bottom level in west part of array seems to be a vigorous fire.
23:30	A hand pallet truck is being put into array at west side in order to remove a flaming pallet load of material and open up access.
23:50	Pallet load removed and foam being applied to it.
25:09	Another flaming pallet load is removed from array.
27:39	Another flaming pallet load is removed from array.
28:45	Flames about 1.5 m [5 ft] above top of array in east part.
30:00	Fire burning steadily.
30:12	Flames licking at ceiling.
30:17	Flames off ceiling; licking to 3.0 m [10 ft] above array (7.9 m [26 ft] high).
30:29	Foam stopped and water streams applied.
30:41	Additional foam being applied. Plan is to reduce or stop foam and apply monitor guns and blast it with water to blow array apart.
31:50	Monitor guns applied to array.
32:14	Fire appears to be increasing somewhat in severity.
34:48	Fire seems to be reduced somewhat. Core fire remains in ignition area, longitudinal flue.
36:30	Fork truck brought in to remove some upper pallet loads.
37:52	The western, southernmost pallet load has been removed. Does not appear to be on fire, but two sides seen were not directed toward the fire area.
38:56	Foam is being applied around and under the lift truck due to some spreading fire from the load that was removed.
41:50	Fire seems confined to upper part of 2nd tier and top pallet loads. There has been a severity reduction.
42:45	Additional material spills out of racks from top tier into aisle space and immediately extinguished.
43:10	Monitor gun has blown off another pallet load at southeast, end, top into east aisle.
45:20	Fire considerably reduced, located primarily in bottom tier and somewhat into 2nd tier.
45:30	Third tier has effectively been removed from array due to monitor gun.
47:20	Monitor guns are off; 2nd tier pallet loads pretty well removed from array.
47:35	Fire confined to bottom level and in some 2nd tier rubble.
51:25	Foam applied close up and personal to residual fire in lower part of array in ignition area.
51:45	Still some flickering flames seen. Also still some fire in 2nd tier rubble.
58:11	Still some residual fire in array.

Time (min:s)	**Observations**

58:28	Fire has moved through target rack to east side. Hose streams have been directed onto that fire.
59:12	Fire seems to residue and be confined to in aisle space. Fire appears out in main array – no fire seen.
66:07	No fire is seen at moment. – Correction there is some fire at north end within main array – small residual fires.
66:30	Hose streams applied to north end residual fires – seem to be out.
67:02	Still some residual fire at north end of main array at west part.
67:38	Pallet pulled from aisle rubble disturbing more combustible material which springs back to fire.

******

At test conclusion there was no pool fire on either side of the main array and just a little flaming in the residual material on the floor. The bottles that were blown out of the array onto the floor were not burning. The target was not ignited.

3.4.7 Fire Chronology – Test 5

Time (min:s)	**Observations**
0:00	Ignition
0:15	Flames just beginning to get established at ignition pallet load corner (0.3 m [1 ft] high).
0:39	Flames half-way up 1st pallet load (about 0.8 m [2½ ft] high).
1:10	Flames at top of 1st pallet load (about 1.4 m [4¾ ft] high).
1:31	Flames licking 1.5 m [5 ft] high.
1:57	Flames licking at sprinklers just under barrier.
1:59	First two sprinklers operate.
2:15	Fire reduced to 1.5 m [5 ft] high.
2:20	Flaming embers fall to floor.
2:33	Streaming liquid to floor in aisle.
2:42	Plastic wrapping being burned off face of 2nd pallet load.
2:50	Fire in wrap now extinguished.
2:55	Flames lick 2.4 m [8 ft] high.
3:14	Residual fire falls from rack into aisle and pool burns.
3:24	Pool fire goes out.
3:38	Fire appears to be confined pretty much to ignition area. It has not yet moved into longitudinal flue.
4:01	Flames lick rack barrier at 3.0 m [10 ft] level.
4:19	More spillage of liquid into aisle forming a small pool fire.
4:27	Pool fire goes out.
4:46	Fire impinges fairly steadily on barrier.
4:59	Flames lick about 0.4 m [3 ft] above barrier at east face.
5:15	Fire has spread about a half pallet length to north and south of ignition in pallet.
5:54	Fire appears to burning at steady rate.
5:59	More spillage of liquid into aisle.
6:06	Pool fire in aisle is extinguished.
6:14	Flames no longer beat on barrier; they go above rack by about 0.6 m [2 ft].
6:25	Flames still go above rack by about 0.6 m [2 ft].
Time (min:s)	**Observations**

6:45	Dripping liquid persists. Periodically this action occurs and the pool fire burns up released fluid and is extinguished.
8:12	Occasionally flames lick into longitudinal flue at about 1.5 m [5 ft] level. Generally, there are no flames into flue.
9:00	Fire burns at a steady rate as last reported. Occasionally they lick above top of array then sometimes they will be reduced to bottom of top pallet level.
10:12	Fire has, some time ago, exposed bottles in south portion of ignition flue. Bottles primarily are in place and have not spilled out of rack.
12:00	Fire burns at steady rate – not increasing or decreasing; primarily confined to ignition area.
15:40	Fire continues to burn steadily as last reported. Sprinklers will not put it out, but fire is being contained.
16:00	Test concluded; hose streams applied and mop-up operations are underway.
Post Test	
16:42	Flames driven out bottom of pallet at 3rd level at west face by hose streams. Other hose streams being applied to this fire.
23:12	Hose streams stopped, fire appears to be out.

3.4.8 Selected Photographs

Major Explosion at 0:55; Flames on Ceiling (9.1 m [*30 ft*] High).

Fire Progress at 1:27, Eight Sprinklers Operating; Flames Steady on ceiling.

Fire Progress at 1:54 When Test Was Terminated. 33 Operating Sprinklers; Six Seconds Later 54 Sprinklers Were Open.

Extinguishment Efforts at About 45 minutes. Note Residual Flaming and Many Bottles in Debris.

Figure 3-60: Test 4

Fire Development at 1:57 Two Seconds Prior to Initial In-rack Sprinkler Operation.

Fire Progress at 4:19, Final Total of Three In-rack Sprinklers Operating.

Fire Confinement at about Test Conclusion (16:00)

Damage

Figure 3-61: Test 5

3.5 Determination of Sprinkler Protection for Rack Storage of Flammable Liquids in Small Plastic or Glass Containers / Kristin L.T. Jamison / December 2007

3.5.1 Testing Overview

This fire test program consisted of 3 full scale tests. The first test looked at a specific commodity that is not needed to support the results of the two provided tests. The test facility used for this program is described in Section 2.1.

Table 3-9: Fire Test Summaries

Test No.	2	3
Test Date	07-21-05	12-01-06
PARAMETERS		
Commodity	PS Plastic[2]	99% IPA[3]
Storage Arrangement	Rack	Rack
Array Nominal Size – LxWxH (mxmxm [*ftxftxft*])	7.3x2.3x4.2 [*24x7½x14*]	7.4x2.4x4.4 [*24.3 x7.75x14.4*]
Stack Height (m [*ft-in*])	4.2 [*13-11*]	4.4 [*14-5*]
Nominal Pallet Load Height (m [*ft-in*])	1.2 [*3-11*]	1.3 [*4-4*]
No. of Storage Levels	3	3
Ceiling Height (m[*ft*])	9.1 [*30*]	9.1 [*30*]
Clearance to Ceiling (m [*ft-in*])	4.9 [*16-1*]	4.8 [*15-7*]
Clearance to Ceiling Sprinklers (m [*ft-in*])	4.7 [*15-6*]	4.6 [*15-1*]
Aisle width (m [*ft*])	2.4 [*8*]	2.4 [*8*]
Ignition Centered Below (No. Ceiling Sprinklers)	1	1
Ceiling Sprinkler Orifice Size (mm [*in.*])	16 (ELO) [*0.64*]	16 (ELO) [*0.64*]
Ceiling Sprinkler Temperature Rating (°C [°*F*])	68.3 [*155*]	68.3 [*155*]
Ceiling Sprinkler RTI ((m-s)$^{1/2}$ [(ft-s)$^{1/2}$])	125.9 [*228*]	125.9 [*228*]
Ceiling Sprinkler Spacing (mxm [*ftxft*])	3.0x3.0 [*10x10*]	3.0x3.0 [*10x10*]
Ceiling Sprinkler Discharge Pressure (bar [psi])	2.0 [*29*]	2.0 [*29*]
Ceiling Sprinkler Discharge Density (mm/min [gpm/ft^2])	24.4 [*0.60*]	24.4 [*0.60*]
RESULTS		
Test Site Relative Humidity (%)	65	83
Carton Moisture Content (%)	7.9	9.0
First Ceiling Sprinkler Operation (min:sec)	0:57	1:08
Last Ceiling Sprinkler Operation (min:sec)	10:54	5.59
Total Ceiling Sprinklers Opened	26	19
Peak Gas Temperature (°C [°*F*])	357.8 [*676*]	346.7 [*656*]
Peak Ceiling Steel Temperature (°C [°*F*])	83.3 [*182*]	100.6 [213]
Equivalent No. Pallet Loads Consumed	2½	1/3
Test Concluded (min:sec)	20:00	30:00

NOTES:
2. The FM Global standard cartoned unexpanded plastic commodity consisted of crystalline polystyrene plastic jars in compartmented corrugated cartons.
3. The commodity consisted of packages of 6 fl. oz. High Density Polyethylene (HDPE) bottles of 99% IPA in compartmented corrugated cartons.

3.5.2 Introduction

3.5.2.1 Background

The project detailed in the following report was intended to develop information on which to base reliable sprinkler protection for small plastic and glass containers in rack storage.

An initial report on the subject of protection of small containers containing low flash point liquids was issued in September of 2003. In that report, it was concluded that 59 cc (2 oz) containers of non- water miscible low flash point liquid could not be considered as “small” and that they should be protected in accordance with FM Global Property Loss Prevention Data Sheet 7-29. This report is a continuation of the previous project. The fire testing summary is outlined in Table 3-9.

3.5.2.2 Objective

The primary objective of the previous report, and the current report, was to generate sufficient information on which to base a modified automatic sprinkler protection scheme for “small” containers of water miscible and non-water miscible flammable liquids. An inherent accompanying objective was to determine what size constitutes a “small” container; the term “small” is relative to the specific liquid-container configuration.

3.5.2.3 Small Container Defined

A small container is defined as being small enough that there is a significant reduction in fire severity when compared to that created from a larger container filled with the same flammable liquid.

Note: The size of the container that constitutes “small” may be different for the two types of flammable liquid (i.e. water miscible and non-water miscible). From past testing it was established that neither 59 cc [2 oz] containers of hydrocarbon, nor 473 cc [16 oz] of alcohol liquids belong in the “small” container category.

3.5.3 Test Setup

3.5.3.1 Commodity

3.5.3.1.1 Test #2: FM Global Standard Cartoned Unexpanded Plastic Commodity

Test 2 was conducted using the FM Global Standard Cartoned Unexpanded Plastic Commodity. Each pallet load consists of eight compartmented corrugated cartons. Each carton is packaged with 125 polystyrene cups that are positioned in rows and columns of five cups and five layers deep; the cups are positioned with open end down.

3.5.3.1.2 Test #3: 99% IPA

Test 3 was conducted using a commodity of 99% IPA in 177 cc [6 fl oz] High Density Polyethylene (HDPE) containers. Containers were packaged into corrugated cartons and stacked onto pallets as illustrated in and Figures 3-62 and 3-63.

3.5.3.2 Storage Arrangement

Both tests had a main array consisting of a double row rack, three pallet loads high as well as a target array consisting of a single row rack, three pallet loads high and comprised of the FM Global Class II commodity. The target array was located across a 2.4 m [8 ft] aisle to the east of the main array.

3.5.3.2.1 Test #2

Main array dimensions were about 7.3 m long by 2.3 m wide by 4.7 m high [24-ft x 7½-ft x 15½- ft]. The array rested on the floor under the moveable ceiling which was adjusted to a 9.1 m [30 ft] floor to ceiling height so that a clearance of about 4.3 m [14 ft] existed between the ceiling sprinklers and the top of the array. The main array consisted of FM Global standard cartoned unexpanded plastic commodity throughout. The setup is illustrated in Figure 3-64.

3.5.3.2.2 Test #3

Main array dimensions were about 7.4 m long by 2.4 m wide by 4.4 m high [24.3-ft x 7.75-ft x 14.4-ft]. The array rested on the floor under the moveable ceiling which was adjusted to a 9.1 m [30 ft] floor to ceiling height so that a clearance of about 4.6 m [15.1 ft] existed between the ceiling sprinklers and the top of the array. A total of 36 pallet loads of 99% IPA were located in the main array. The setup is illustrated in Figures 3-65.

3.5.3.3 Ignition Method

Ignition was by means of two 76 mm diameter by 76 mm long [3-in. x 3-in.] cellucotton rolls each soaked in 48 cc [4 fl oz] of gasoline; this ignition source is commonly known as two FM Global Standard Half Ignitors. They were located on either side of the central transverse flue, 533 mm [21-in.] in from the east face of the main array. Figures 3-64 through 3-65 show the ignition location within the arrays.

3.5.3.4 Instrumentation

More than eighty-one (81+) thermocouples monitored near-ceiling gas temperatures. Additionally, nine imbedded thermocouples in a steel angle at the ceiling above ignition measured steel temperatures. The steel angle forms a cross with 90° angles; each leg of the cross is 0.3 m [1 ft] in length and 6.4 mm [0.25 in] thick. There is one thermocouple at the center of the cross and 4 more thermocouples located at 0.15 m [6 in] intervals along the length of each leg. Sprinkler operations were timed so that a sequence of operation was obtained.

3.5.3.5 Protection

Ceiling-only protection was provided by standard response, K 11.2 sprinklers. They were rated at 68.3oC [155oF], arranged on a 3.0 m x 3.0 m [10-ft x 10-ft] spacing and discharged at a pressure of 2 bar [29 psi] thus providing a density of 24.4 mm/min [0.60 gpm/ft^2]. Ignition was centered under one sprinkler.

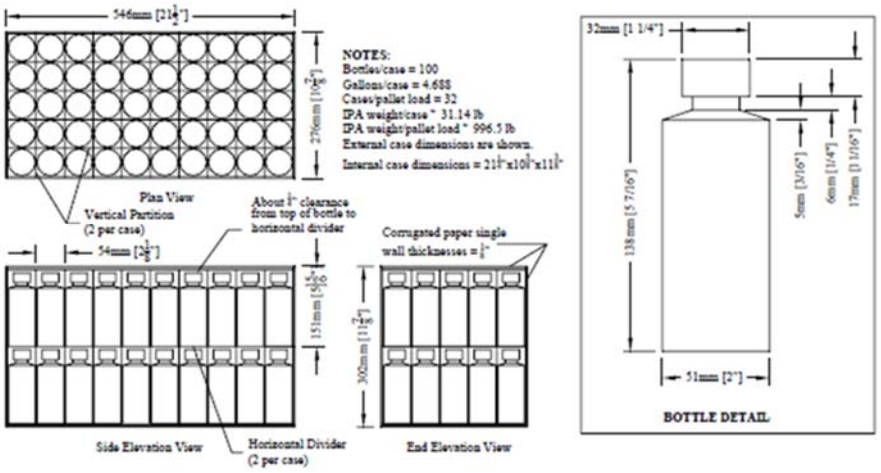


Figure 3-62: Detail of Commodity Packaging of 99% IPA in HDPE containers used in Test #3

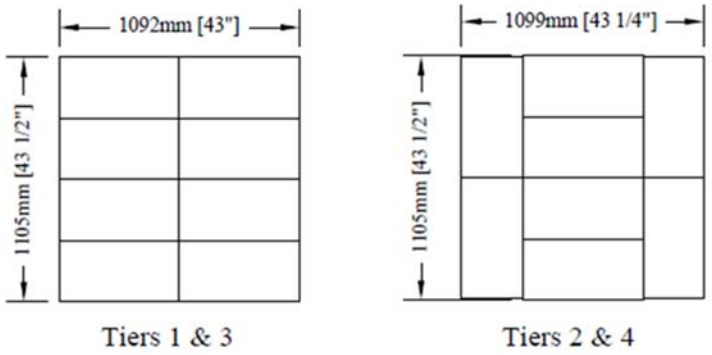


Figure 3-63: Pallet Load Details for the Cartoned IPA used in Test #3

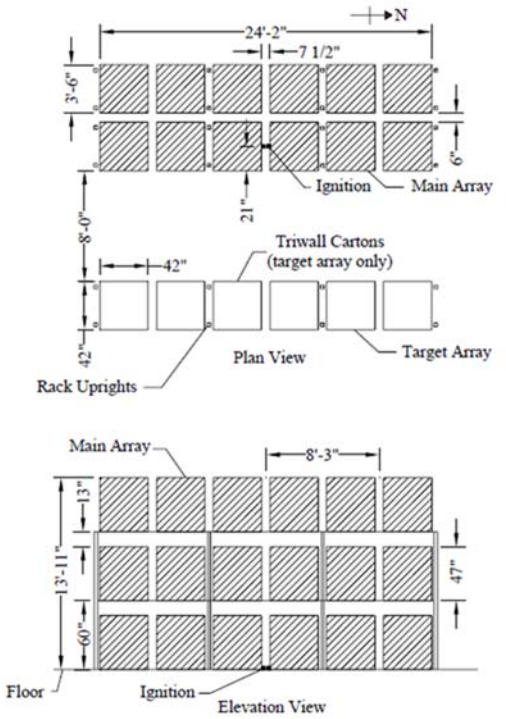


Figure 3-64: Plan and Elevation View of Test #2 Array Setup

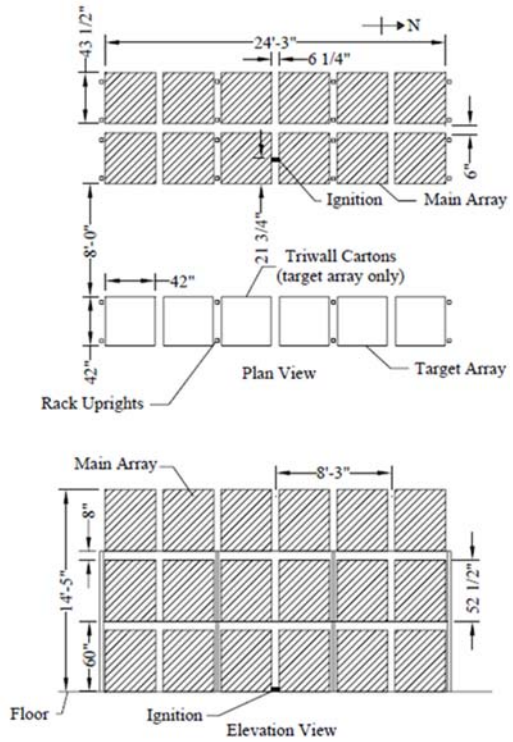


Figure 3-65: Plan and Elevation View of Test #3 Array Setup

3.5.4 Test Results

3.5.4.1 General

The following section details the results for the two large scale fire tests. Additionally, Table 1.1 summarizes test conditions and results. Fire chronologies of the test events are found in Appendix A and selected photographs are in Appendix B.

3.5.4.2 Test #2 Summary

{Nominal 4.3 m [14 ft] high array; ELO @ 2.0 bar [29 psi]; uncartoned unexpanded plastic commodity}

(Note: all times in this section are from test start – expressed as min:sec)

Following ignition the vertical fire spread was rapid with flames reaching about 7.6 m [25 ft] high at 40 seconds before dropping back to 5.5 m [18 ft] as the corrugated cartons experienced extensive surface charring. Then at 0:58 the first sprinkler operated. By about 2:15, flames were licking on the ceiling and the upper two levels of the target array were steaming. Smoke color remained a dark gray throughout the test and at 3:20 reached the floor, completely obscuring the array view. The fire view displayed by the infrared camera indicated the presence of a considerable amount of flaming and/or hot gases in the core of the array at about 9 minutes. By 10:54 twenty-six sprinklers were open, the final total. The test was concluded at 20:00. The target array did not become involved in the fire.

3.5.4.3 Test #3 Summary

{nominal 4.4 m [14.4 ft] high array; ELO @ 2.0 bar [29 psi]; 99% IPA commodity}

(Note: all times in this section are from test start – some expressed as min:sec)

Similar to Test 2, the vertical fire spread following ignition was fairly rapid with flames impinging on the ceiling within 43 seconds and the first sprinkler opening at 1:08. The activated sprinkler drove the flames down to approximately 3.7 m [12 ft] high. By 3 minutes, the flames were impinging on the ceiling again. Between 3 and 6 minutes additional sprinklers opened, the fire maintained a height in the approximate range of 6.1 to 9.1 meters [20-30 ft]; the fire was well contained to the central bay of the main test array and an opaque whitish smoke was generated and gradually dropped to the floor. By 7 minutes the white smoke had almost completely cleared, the fire continued to burn at nearly steady state and was almost completely confined to the central bay. Throughout the test there was frequent spillage of flaming containers from the array, but the spillage fires were extinguished as soon as they reached the aisle floor. After 7 minutes and until test termination at 30 minutes, the fire maintained a nearly steady state; flames with heights ranging from approximately 10 to 20 feet, were predominately confined to the north end of the central bay. The last sprinkler operated at 5:59 minutes yielding a total of 19 activated sprinklers. The target array never ignited. The test was concluded at 30:00 minutes.

3.5.4.4 Environmental Conditions

The environmental conditions associated with each test are presented in the following table.

Table 3-10: Environmental Conditions

ITEM	TEST 2	TEST 3
Carton Moisture Content (%)*	7.9	9.0
Outside Conditions		
Weather	mostly sunny	light rain
Wet Bulb Temp. (°C [°F])	19.4 [67]	N/A
Dry Bulb Temp. (°C [°F])	25.0 [77]	16.7 [62]
Relative Humidity (%)	59	85
Inside Conditions		
Wet Bulb Temp. (°C [°F])	18.9 [66]	N/A
Dry Bulb Temp. (°C [°F])	23.3 [74]	17.2 [63]
Relative Humidity (%)	65	83

3.5.4.5 Ceiling Temperatures

Figures 3-66 and 3-67 show temperature contours for Tests #2 and #3, respectively; at the point of the 1st sprinkler activation, the ceiling level gas temperatures generated by each type of commodity were very similar. Figures 3-68 and 3-69 show that 10 seconds after the first sprinkler activation in Tests #2, and #3, respectively, the ceiling level gas temperatures were reduced.

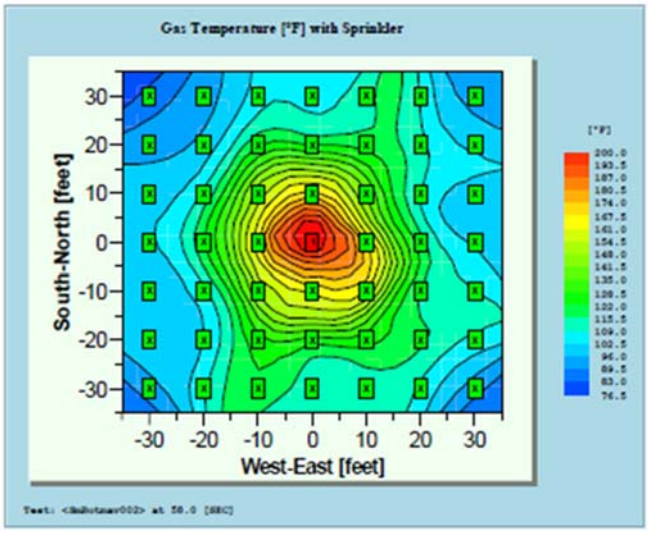


Figure 3-66: Test #2 Ceiling Gas Temperature Contour at the Time of 1st Sprinkler Operation

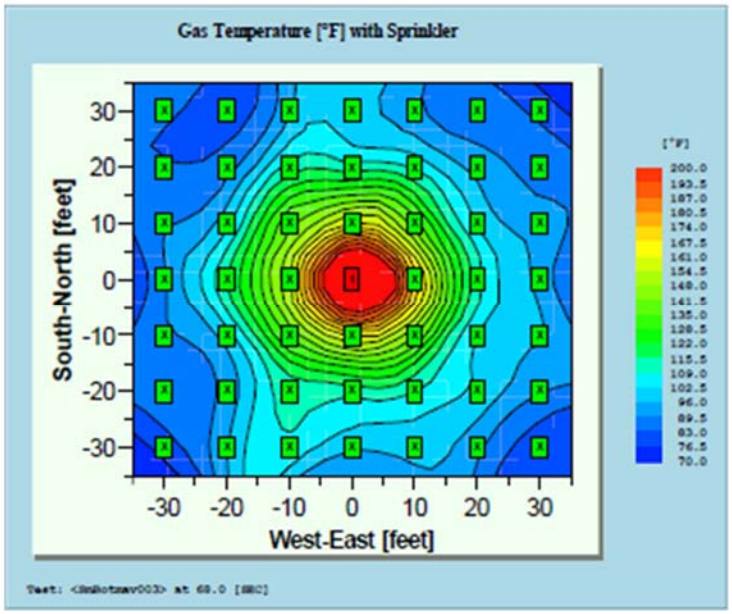


Figure 3-67: Test #3 Ceiling Gas Temperature Contour at the Time of 1st Sprinkler Operation

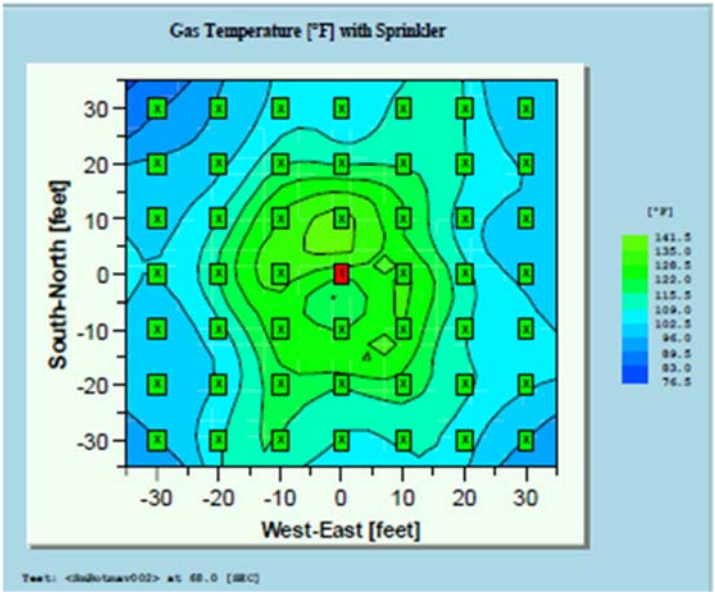


Figure 3-68: Test #2 Ceiling Gas Temperature Contour 10 sec after 1st Sprinkler Operation

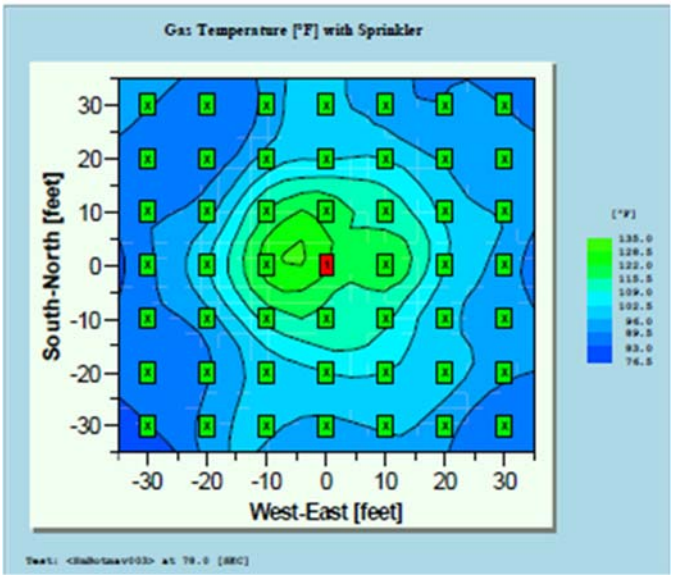


Figure 3-69: Test #3 Ceiling Gas Temperature Contour 10 Sec after 1st Sprinkler Operation

Figures 3-70 and 3-71 show the ceiling level gas temperatures 30 seconds after the first sprinkler activation in Tests #2, and #3, respectively. Ceiling level gas temperatures remained low at this point in time following the 1st sprinkler activation; this is indicative of the effectiveness of the sprinkler to not only drive the flames downward, but also to reduce the fire size and hinder the thermal thrust.

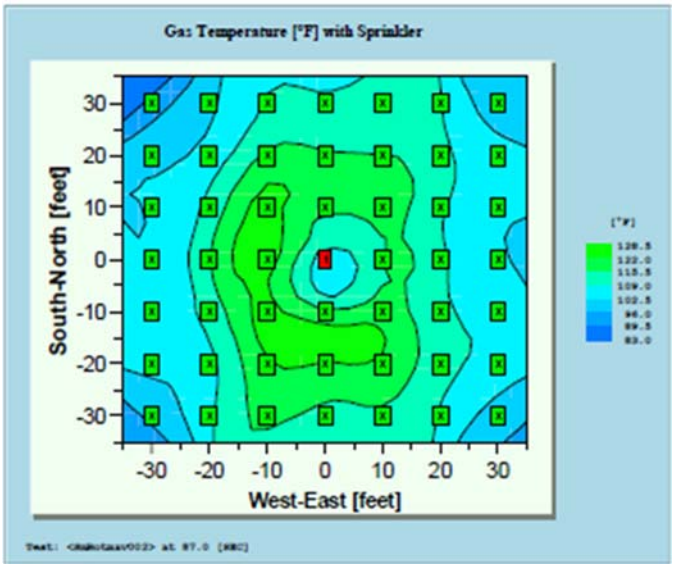


Figure 3-70: Test #2 Ceiling Gas Temperature Contour 30 sec after 1st Sprinkler Operation

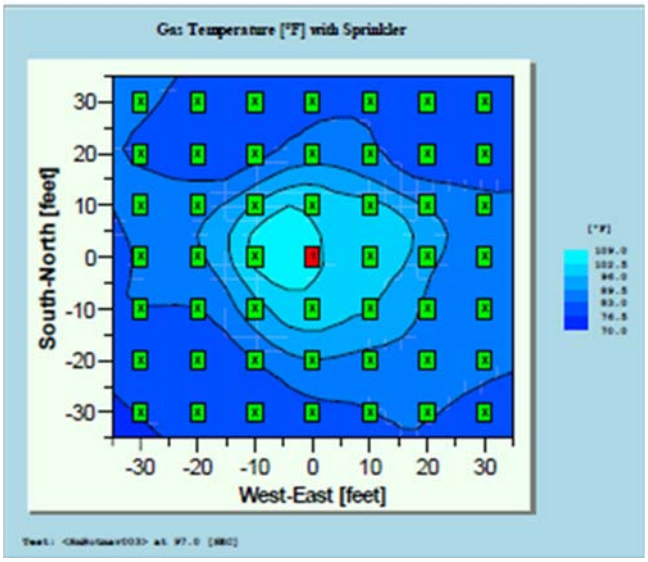


Figure 3-71: Test #3 Ceiling Gas Temperature Contour 30 sec after 1st Sprinkler Operation

Figures 3-72 and 3-73 show ceiling level gas temperature contours 60 seconds (1 minute) after the 1st sprinkler activation for Tests #2, and #3, respectively.

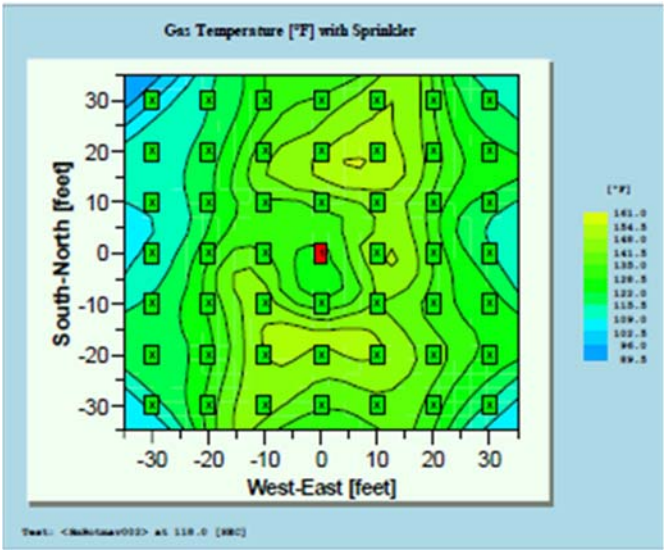


Figure 3-72: Test #2 Ceiling Gas Temperature Contour 60 sec after 1st Sprinkler Operation

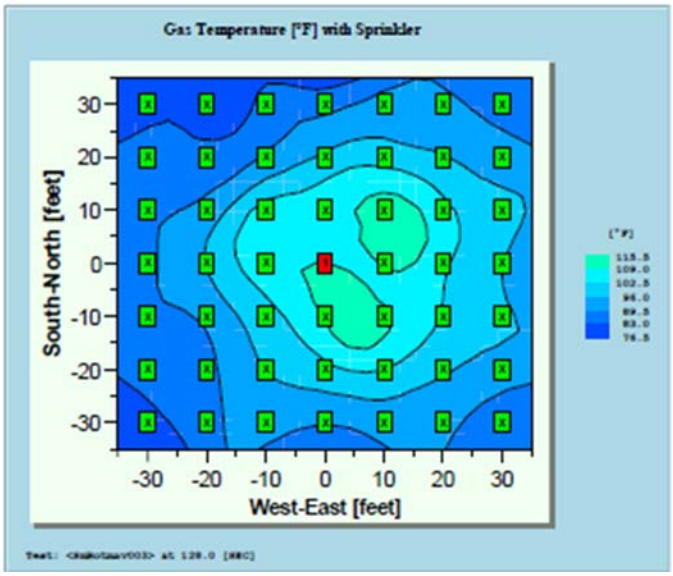


Figure 3-73: Test #3 Ceiling Gas Temperature Contour 60 sec after 1st Sprinkler Operation

It should be noted that, although ceiling level gas temperatures remained cooler in Tests #2, and #3, during the first minute following the 1st sprinkler activation, the fires in both tests were gaining in severity. There was a rapid sequence of sprinkler activations in both fire tests which occurred at 2:18, and 4:11 for Test #2, and #3, respectively. Figures 3-74 and 3-75 show contour plots of ceiling level gas temperatures for Tests #2, and #3, respectively, for time equal to 300 seconds (5 minutes) after the 1st sprinkler activation; these figures also depict the ceiling level gas temperatures after the rapid sequence of sprinkler activations.

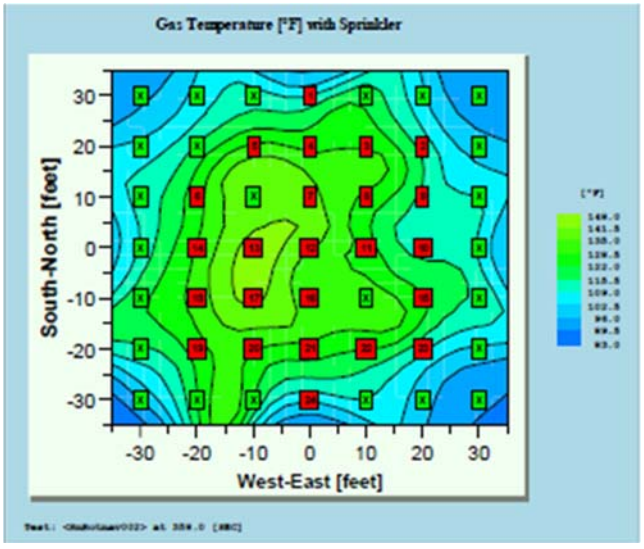


Figure 3-74: Test #2 Ceiling Gas Temperature Contour 300 sec after 1st Sprinkler Operation

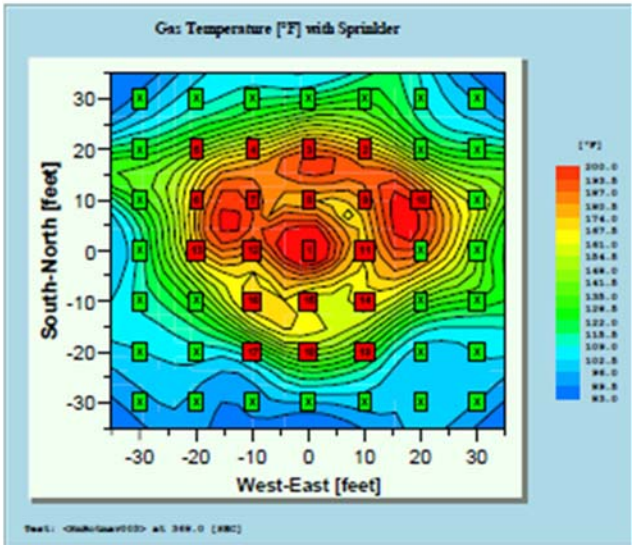


Figure 3-75: Test #3 Ceiling Gas Temperature Contour 300 sec after 1st Sprinkler Operation

Ceiling level gas temperature contours for time equal to 600 seconds (10 minutes) after the 1st sprinkler activation are shown in Figures 3-76 and 3-77 for Test #2, and #3, respectively. At this point in time there were a total of 26 activated sprinklers in Test #2, and 19 activated sprinklers in Test #3. From this point until the termination of each test, no additional sprinklers operated in Tests #2, and #3. As can be seen in Figure 3-76, the ceiling gas temperatures along the western edge of the ceiling have the potential activate additional sprinklers beyond that edge. At this point in the fire test (10 minutes after the 1st sprinkler activation), the fire created by the consumption of the FM Global Standard Cartoned Unexpanded Plastic Commodity had subsided into the lower tiers of the main array. In comparison, at this point in time, 600 seconds after the 1st sprinkler activation, the fire that remained within the 99% IPA commodity used in test #3 had been reduced to a single small swirling flame.

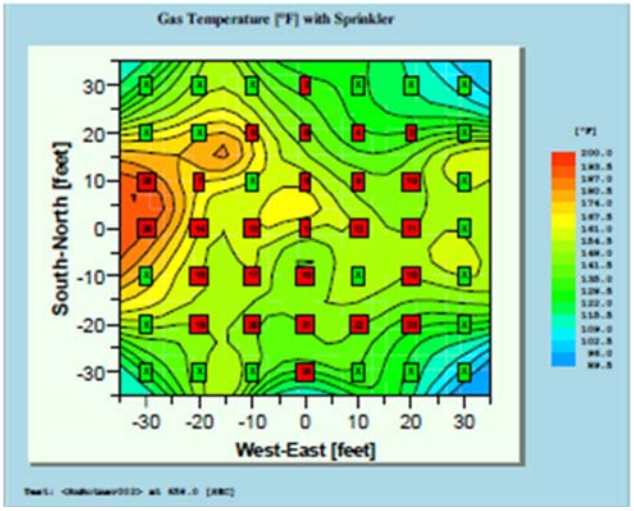


Figure 3-76: Test #2 Ceiling Gas Temperature Contour 600 sec after 1st Sprinkler Operation

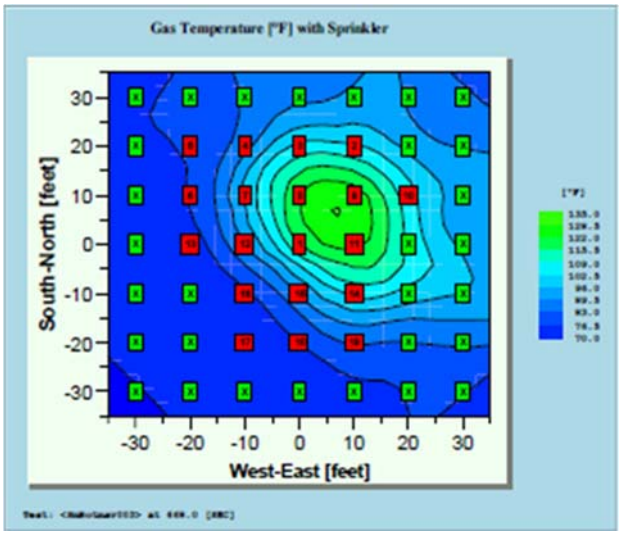


Figure 3-77: Test #3 Ceiling Gas Temperature Contour 600 sec after 1st Sprinkler Operation

Figures 3-78 through 3-79 show the maximum one-minute average gas temperatures. These values are useful in assessing whether or not structural damage may have occurred as a result of the fire. One-minute average gas temperatures for Test #3 were slightly higher in some locations than those measured in Test #2.

It needs to be noted that when ignition is located under one sprinkler there are many ceiling thermocouples in close proximity to the installed sprinklers. When a sprinkler operates it could potentially wet the adjacent thermocouple causing the temperature of the water to be measured as opposed to the gas temperature. The wetting of thermocouple beads can prevent realization of the true peak gas temperatures. Although the maximum one-minute average gas temperatures for Test #3 were approximately equal to those seen in Test #2, sprinkler activation data as well as video footage of Tests #2 and #3 show that Test #2 was a more severe test than that created by the 99% IPA in Test #3.

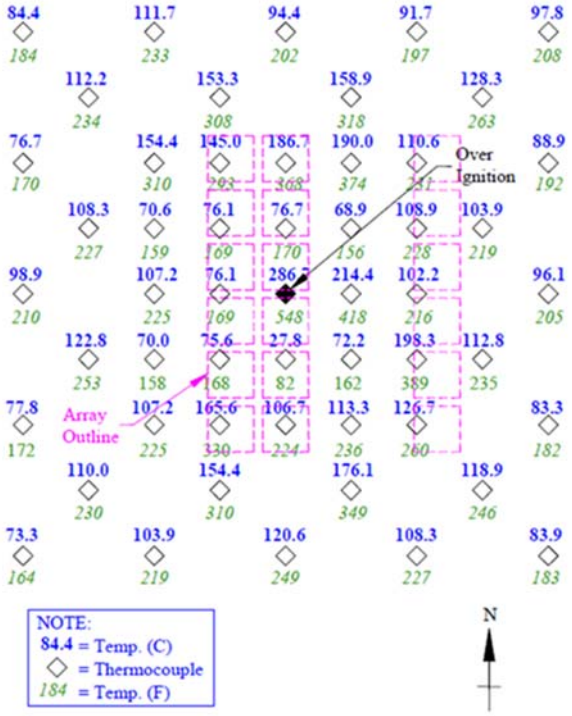


Figure 3-78: Test #2 Near Ceiling Maximum One-Minute Average Gas Temperature

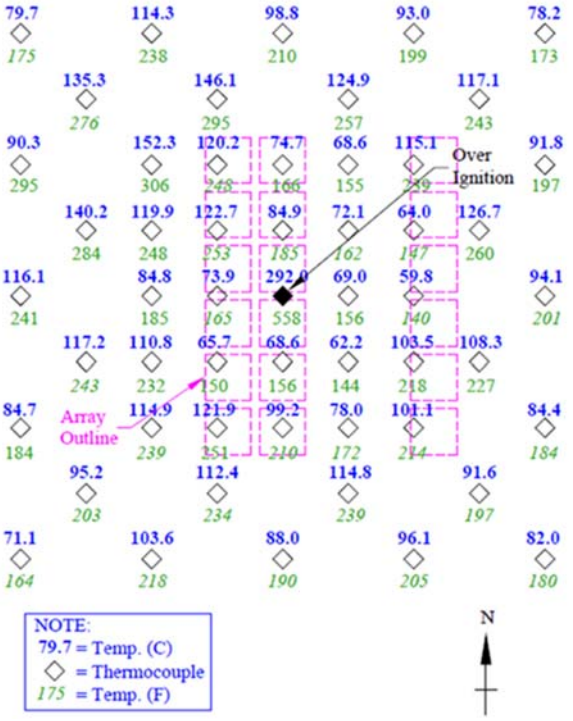


Figure 3-79: Test #3 Near Ceiling Maximum One-Minute Average Gas Temperature

3.5.4.6 Sprinkler Operations

Test #2 caused the activation of 26 sprinklers and Test #3 (99% IPA) operated a total of 19 sprinklers. The total amount of sprinkler water used in the 1st 20 minutes of the test for each test is as follows: 27,210 gallons, and 19,410 gallons for Test #2, and #3, respectively. The sprinkler operating times, sequence and location are illustrated in Figure 3-80 for Tests #2, and #3. Fire chronologies from both tests are shown in Tables 3-11 and 3-12. Selected photographs from each test are shown in Figures 3-82 and 3-83.

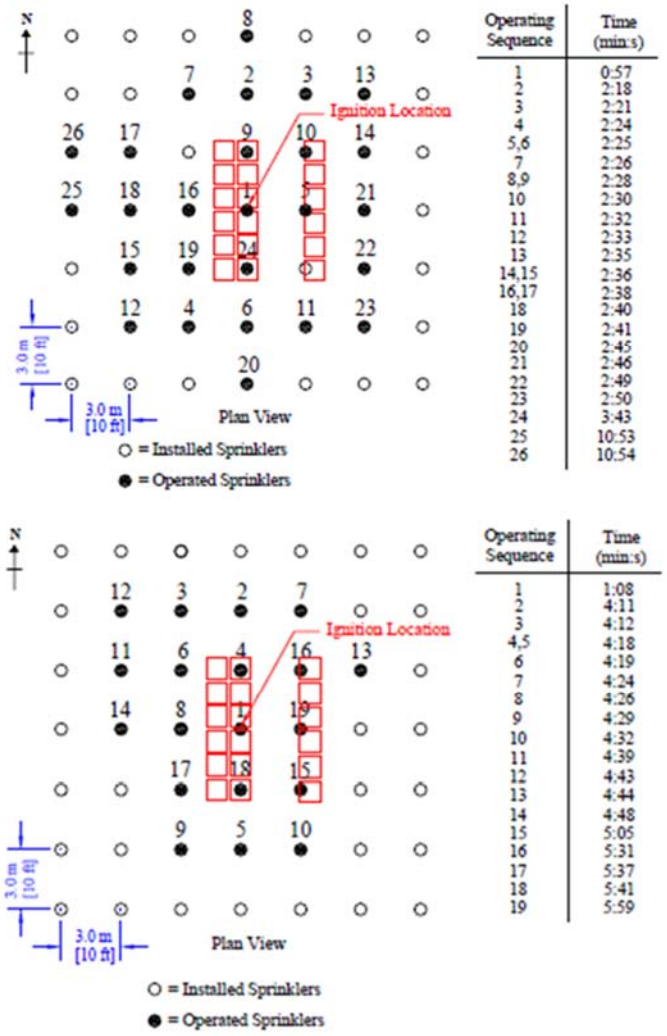


Figure 3-80: Sprinkler Operations – Test 2 (top) / Test 3 (bottom)

3.5.4.7 Extent of Damage

The extent of fire damage and amount of commodity consumed are important indicators of fire severity and protection effectiveness. Comparing the two tests on this basis, it was found that the number of pallet loads involved in the fire was greater in Test 2 (Standard Cartoned Unexpanded Plastic Commodity) than in Test 3 (99% IPA). In none of the tests did the fire damage reach the ends of the array nor did the fire jump to the target array. These are both positive factors relating to the applied

protection. The total commodity consumption in Test 3 was approximately 5 times less than that consumed in Test 2. Figure 3-81 illustrates the extent of damage for both tests.

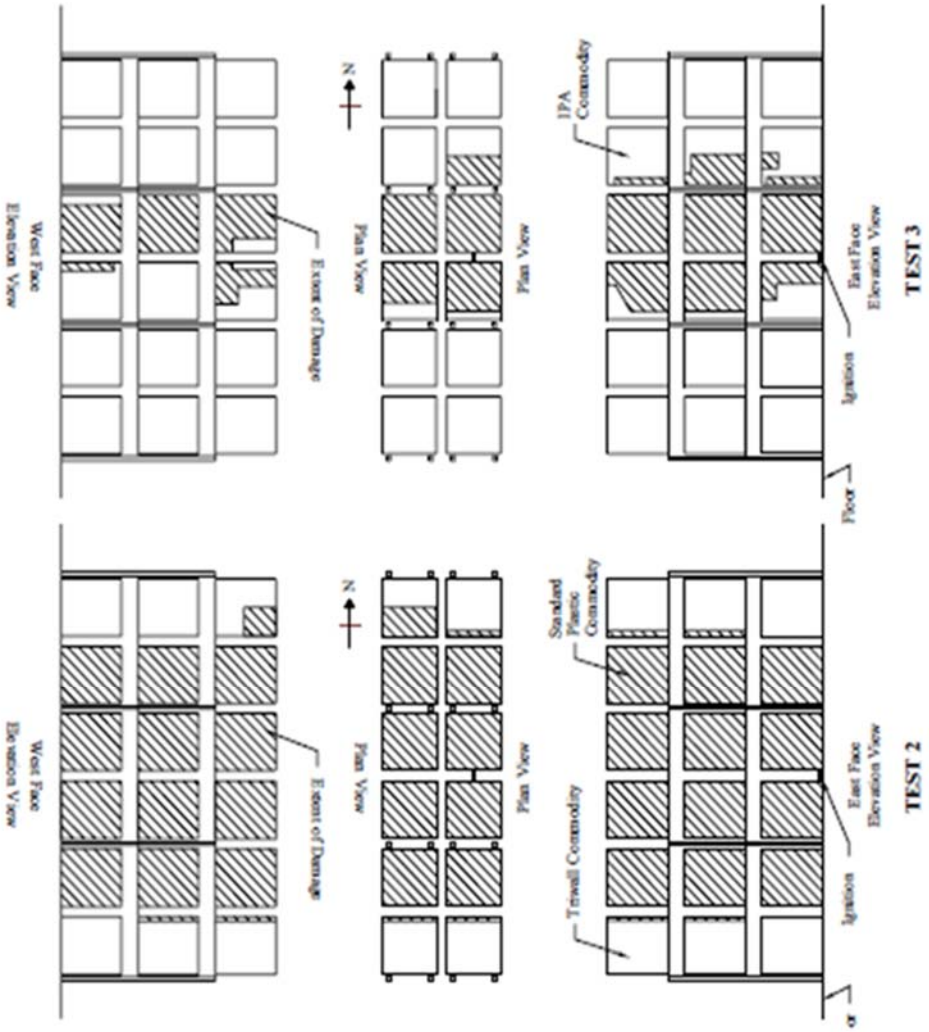


Figure 3-81: Extent of Damage for Test 2 and 3

3.5.5 Discussions and Conclusions

3.5.5.1 Summary of Findings

1. Sprinkler Operations:
   a) Test #3 sprinkler operations were significantly less than in comparison to Test #2.
2. Near Ceiling Gas and Steel Angle Temperatures
   a) Near ceiling gas and steel angle temperatures measured in Test #3 were slightly higher in some locations than those measured in Test #2. However, over the duration of the tests, temperatures in Test #3 were predominantly lower than those measured in Test #2.
3. Fire spread remained within the limits of the Main Array in both tests.
4. Fuel Consumption:
   a) Fuel consumption was approximately five times less in Test #3 than in Test #2.

5. With all parameters in both tests remaining the same except for the commodity:
   a) Test #3 (99% IPA) produced a less severe fire than Test #2 (Standard Plastic Commodity).
6. The fire in both tests appeared to be under control prior to test conclusion. In Test #3, spillage did not seem to have a significant effect on the condition of the fire; it appeared that the fire was predominately controlled by the discharging water.

3.5.6 Conclusions

1. The results of this test series indicate that the 177cc [6 fl oz] containers of 99% IPA produce a lesser fire exposure than the FM Global Standard Cartoned Unexpanded Plastic Commodity.
2. 177cc [6 fl oz] containers of water miscible liquids exhibit a fire hazard that is significantly less than that posed by the same liquid in larger containers.
3. The ceiling-only protection was very successful in mitigating the hazard posed by the liquid-container combination.

3.5.7 Fire Chronologies

Table 3-11: Test #2 Fire Chronology

Time (min:s)	Observation
00:00	Ignition
00:16	Flames at bottom of 2nd pallet load (1.5 m [5 ft] high).
00:23	Flames at top of 2nd pallet load (2.7 m [9 ft] high).
00:29	Flames halfway up top pallet load (3.7 m [12 ft] high).
00:34	Flames at top of array (4.3 m [14 ft] high).
00:40	Flames about 7.6 m [25 ft] high.
00:49	Flames drop back to about 1.2 m [4 ft] above array top (5.5 m [18 ft] high).
00:57	First sprinkler operates.
01:08	East face of main array fire has licked out into aisle about 0.3 m [1 ft] at 2nd level.
01:39	Smoke is coming out from under ceiling and continuing upward toward the roof.
01:50	Flames about 7.6 m [25 ft] high.
01:59	Flames licking out bottom of 3rd level to west.
02:12	Flames licking at ceiling (9.1 m [30 ft] high)
02:18	2nd and 3rd target levels are steaming
02:45	20 sprinklers are operating
02:49	Smoke driven down to floor in vicinity of main array
02:58	Fire glow seen through smoke.
03:01	All fire obscured from view.
03:07	Smoke rises and moves around allowing occasional glimpses of fire
03:20	Entire array totally obscured from view.
04:52	Copious quantities of thick dark smoke continue to be generated; array view still obscured.
05:07	Smoke color is slightly lighter.
06:10	View on infrared camera shows flaming or hot gases at all levels extending perhaps about 1.5 m [5 ft] above array top.
07:32	Smoke coloration continues about as last reported, dark gray.
09:00	Infrared camera indicates that a considerable amount of flaming and/or hot gases in main array which appears more severe than last reported.
09:25	Hot gases and flames extend out west face at bottom of 3rd level.
20:00	Test concluded

Table 3-12: Test #3 Fire Chronology

Time (min:s)	Observation
00:00	Ignition
00:20	Flames 5 ft high
00:28	Flames 10 ft high
00:35	Flames at top of array (14 ft high).
00:43	Flames about 5 ft above array top (19 ft high).
00:53	Flames lick at ceiling (30 ft high).
01:08	1st sprinkler opens. Flames at bottom of 3rd level have gone one pallet load width to south.
01:22	Flames driven back to about 12 ft high.
01:30	Flames lick about halfway to ceiling (15 ft high).
01:43	Flames within 5 ft of ceiling (25 ft high).
01:54	Flames reach transverse flue south of ignition at 3rd level
02:09	Flames in 3rd level about a half pallet load width to north
02:19	Flames again to within about 5 ft from ceiling (25 ft high); flames seem fairly steady
03:00	Flames are again licking at ceiling (30 ft high).
03:09	Fire in array seem pretty well confined to central bay.
03:23	Fire reaches transverse flue in 2nd and 3rd levels
03:39	Flames do not seem to be into south transverse flue very well at 3rd level.
04:11	Another sprinkler opens.
04:18	Two more sprinklers open
04:24	Another sprinkler opens
04:32	Another sprinkler opens.
04:40	Flames are on ceiling steadily (30 ft high).
04:43	Another sprinkler opens
04:54	Target array is steaming.
05:19	Flame out west side of array at 3rd level in ignition flue.
05:34	Whitish smoke has reached floor and is thickening up; so far no fire jump to target.
06:00	View of array is pretty well obscured by whitish smoke.
06:16	Flames are close if not actually on ceiling (30 ft).
06:37	Smoke essentially obscures the view and is filling up the site completely from floor to ceiling
07:03	Smoke thins out and view improves; fire is pretty much contained in ignition flue; flames about 20 ft high.
07:45	Originally observed target steaming is no longer seen. It may be masked by steam and smoke being generated in aisle.
08:10	There is no indication of a fire jump to target or that there will be.
08:17	Fire seems to be burning at steady rate; flames about 20 ft high licking perhaps a little higher.
08:36	Fire still seems pretty well confined to ignition area
08:47	There is not quite continuous, but frequent, spillage of bottles from array, but fire is extinguished as they reach aisle floor.
09:03	A small liquid pool is being formed but it is non-flaming.
09:26	Fire which was previously reported on west side of array is no longer present.
09:41	Diminished flames are perhaps 15 ft high.

09:54	There seem to be some fire in west row about halfway to west face at top of bottom level.
11:17	Once again fire seems to be burning at a steady rate flames from 10 ft level up seem to be tending eastward. From top of array they extend from array face perhaps 4-5 ft toward east; lower part hugs face.
12:14	Bottles continue to fall occasionally into aisle but their fire is extinguished and they ignite no pool.
13:10	Fire seems to have taken an almost triangular position from floor, where it is at face, to 6ft above top of array where flames (20 ft vertically) lean away from face about 5 ft toward east.
15:13	Fire appears to be pretty much still confined to ignition bay.
16:15	Fire burning at a steady rate but subdued from what it was about 5 minutes ago. It is concentrated in top of bottom load and into the 2nd level.
18:15	There is a face fire on bottom level, halfway up, and pretty much the entire 2nd level (at least in the transverse ignition flue).
18:35	There does not appear to be any face spreading fire on the 3rd level although fire is under 3rd level in east row.
19:00	Flames still have that steady east leaning bias, same angle as last reported, etc.
19:25	Flame height appears reduced; flames at array top (14 ft high) occasionally licking a little higher.
20:47	Fire in west part of array limited to ignition area on top part of bottom pallet; flames do not come out west face. No flaming at top of 2nd pallet load.
21:10	Fire in eastern row about same – concentrated in bottom and into 2nd level.
21:28	Flames are detached from 3rd level.
21:38	Occasionally flames lick out east face from fire that is in 3rd level.
22:20	A case or two of bottles fall into aisle and their fire is immediately extinguished.
23:39	Major amount of material falls into aisle and becomes extinguished.
27:25	Burning continues as last reported fire remains in bottom two levels; flames lick at top of array; fire retains its easterly bias.
29:00	Fire is reduced a little since last reported still tenacious, but going nowhere.
30:00	Test concluded.
30:04	Hose streams applied to residual fires

3.5.8 Selected Photographs

Array Setup

Fire Development at 2 min 40 sec

Fire Development at 44 sec

Post Test Damage

Figure 3-82: Test #2 Photographs

Array Setup

Fire Development at 2 min 40 sec

Fire Development at 44 sec

Post Test Damage

Figure 3-83: Test #3 Photographs

3.6 Protection of 50/50 Mix of Water Miscible Flammable Liquids in Small Plastic Containers / Ron Dean, John LeBlanc / July 2000

3.6.1 Testing Overview

This test program contained 4 large scale fire tests. Test No. 3 was excluded because it consistent of a very conservative protection approach that was not submitted to NFPA 30. The test facility used for this program is described in Section 2.2.

Table 3-13: Test Summaries

Test No.	1	2	4
Test Date	12-14-1990	01-06-2000	02-22-2000
PARAMETERS			
Commodity	50% IPA (1)	50% IPA (1)	50% IPA (1)
Storage Arrangement	Rack	Rack	Rack
Array Nominal Size - LxWxH (ft x ft x ft)	24¾x7½x22½	24¾x7½x22½	24¾x7½x22½
Stack Height (ft-in.)	22-6	22-6	22-6
Nominal Pallet Load Height (ft-in)	3-6	3-6	3-6
No. of Rack Levels	5	5	5
Clearance to Ceiling (ft-in.)	7–6	7–6	7–6
Clearance to Ceiling Sprinklers (ft-in.)	6-4	6-4	6-4
Aisle Width (ft)	8	8	8
Ignition Centered Below (No. Spkrs)	2	2	4
In-rack Sprinkler Orifice Size (in.)	Note 2	Note 2	17/32
In-rack Sprinkler Temperature Rating (°F)	Note 2	Note 2	165
In-rack Sprinkler RTI (ft-sec)½	Note 2	Note 2	53
In-rack Sprinkler Discharge Pressure (psi)	Note 2	Note 2	30
Ceiling Sprinkler Orifice Size (in)	0.70	0.70	.064
Ceiling Sprinkler Temperature Rating (°F)	165	165	155
Ceiling Sprinkler RTI (ft-sec)1/2	53	53	229
Ceiling Sprinkler Spacing (ftxft)	10x10	10x10	10x10
RESULTS			
Ceiling Sprinkler Discharge Pressure (psi)	75.0	50.0	30.1
First Sprinkler Operation (min:sec)	1:06	1:03	3:21/1:59 (4)
Last Sprinkler Operation (min:sec)	2:59	2:52	7:06/6:42 (4)
Total Ceiling Sprinklers Opened	6	11	4
Total Ceiling Sprinklers Discharge (gpm)	712	1059	241
Total In-rack Sprinklers Opened	Note 2	Note 2	5
Total In-rack Sprinklers Discharged (gpm)	Note 2	Note 2	219
Avg. Discharge per Sprinkler (gpm(	119	96	43.8
Peak Gas Temperature (F)	470	545	282
Peak Ceiling Steel Temperature	129	158	118
Pilot Ignition of Target Array (min:sec)	2:27	1:46	3:19
Eqiv. No. Pallet Loads Consumed (main array)	1/8	¼	1/8
Test Concluded (min:sec)	15:00	15:00	15:00

Fire Test Summary Notes

1) Gallon plastic bottles of 50% isopropyl alcohol packaged 4 per corrugated carton.
2) Item does not apply.
3) In-rack sprinkler operation time.
4) Ceiling/In-rack sprinklers.

Table 3-14: Protection Outcome Summary

TEST	MIX	PROVIDED PROTECTION	OUTCOME
1	50/50	*Ceiling*: K-14 ESFR, 165°F rated, 10'x10' spacing 75 psi discharge pressure	Acceptable
2	50/50	*Ceiling*: K-14 ESFR, 165°F rated, 10'x10' spacing 50 psi discharge pressure	Unacceptable
4	50/50	*Ceiling*: ELO, 155°F rated, 10'x10' spacing, 0.60 gpm/ft^2 density *In-Rack*: 17/32" orifice, fast response 165°F rated, single line of sprinklers at one levels, 4' sprinkler spacing, 30 psi discharge pressure yielding 43 gpm discharge per sprinkler	Acceptable

3.6.2 Introduction

3.6.2.1 Background

Investigation of the fire behavior of water miscible flammable liquids began with fire testing in December of 1994. Phase I focused on the pure liquid concentrate. The commodity was 99% Isopropyl Alcohol (IPA). Phase II consisted of a series of five large-scale fire tests begun in April 1998 and concluded in January 1999. The flammable liquid used throughout the Phase II program was water diluted IPA. Various alcohol-water mixtures ranging from 20/80 to 70/30 mixes were studied. Fires in diluted alcohol yielded severities greater than anticipated. At program conclusion, no appropriate protection of 50/50 alcohol/water mixtures was available. This program (Phase III) was undertaken to resolve the problem.

3.6.2.2 Purpose

Using IPA as the test commodity, adequate protection was established in Phase I for pure miscible flammable liquids contained in 16 oz. plastic bottles and for 70/30 mix in gallon plastic bottles. Phase II established protection only for 20/80 mixtures. A protection gap remained for mixtures above 20/80 through 50/50. The purpose of Phase III was to address this issue and determine appropriate protection for mixtures above 20/80 through 50/50.

3.6.3 Test Conditions

3.6.3.1 Commodity

The commodity consisted of 50/50 IPA/water mixture (volume basis) in one gallon, polyethylene bottles, packaged four per corrugated carton. Each commodity pallet load consisted of three layers with nine cases per layer. Each pallet load provided 108 gal of flammable liquid (Figure 3-84).

3.6.3.2 Storage Arrangements

3.6.3.2.1 Tests 1 and 2 (Figures 3-85 and 3-86)
The main array consisted of a double row containing five storage levels to about 22 1/2-ft. A replica target array was located across an 8-ft aisle to the east of the main array. Eight feet to the east beyond the double row target array, was another target containing a single row with one load high storage. The racks rested on the floor of the 30-ft high test site, thus providing a clearance of about 7-ft between the sprinklers and array top. The main array contained 60 pallet loads of miscible flammable liquid commodity weighing about 56,000 lb. and consisting of about 88% liquid, 6% wood, 3% plastic and 3% corrugated.

3.6.3.2.2 Tests 4 (Figures 3-87 and 3-88)
The arrangement was the same as the previous two tests but with the added feature of in- rack sprinklers. Details may be found in the referenced figures.

3.6.3.3 Ignition Method
In Tests 1 and 2, two 3-in. diameter x 3-in. long cellucotton rolls served as igniters. Each roll was placed in a polyethylene plastic bag and soaked with four ounces of gasoline. They were located on either side of the central transverse flue space at the base of the array, 21-in. in from the East face. (Figures 3 and 4). Test 4 used two 3-in. diameter x 6-in. long cellucotton rolls each soaked with eight ounces of gasoline. Their location was on the east face of the main array, bordering the center transverse flue (Figures 3-85, 3-86, 3-87, and 3-88).

3.6.3.4 Instrumentation
Ceiling thermocouple locations are shown in Figure 3-89. In the first two tests, 49 ceiling sprinklers were installed and in the latter two tests, 64 sprinklers. In the third test, in-rack sprinklers were installed in the longitudinal flues above the second and fourth storage levels and above the third level in the fourth test. Most in-rack sprinklers were timed to obtain an opening sequence. A 2-in. x 2-in. x 1/4-in thick. steel angle, four feet long was located on the ceiling over ignition. Imbedded thermocouples monitored steel temperatures.

3.6.3.5 Protection

3.6.3.5.1 Tests 1 and 2 (Figure 3-90 top image)
Ceiling only, ESFR sprinklers were provided in these tests. They were pendent; 0.70-in. orifice; 165oF rated; located on 10-ft x 10-ft spacing and designed to provide discharge pressures of 75 and 50 psi, respectively, in Tests l and 2.

3.6.3.5.2 Test 4 (Figures 3-87, 3-88, and 3-90 bottom image)
Protection was provided by a combination of ceiling and one or two levels of in-rack sprinklers. The extra large orifice (ELO) ceiling sprinklers were upright; 0.64-in. orifice; 155^{o}F rated; located on a 10-ft x 10-ft spacing and designed to discharge at a 0.60 gpm/ft^2 density. In Test 4, a single line of in-rack sprinklers was located above the third level. Pendent in-rack sprinklers were 17/32-in. orifice; 165^{o}F rated; fast response and located on about 4-ft centers at every intersection of transverse and

longitudinal flue spaces. The designed discharge pressure was 30 psi to yield about 43 gpm discharge from each operating sprinkler.

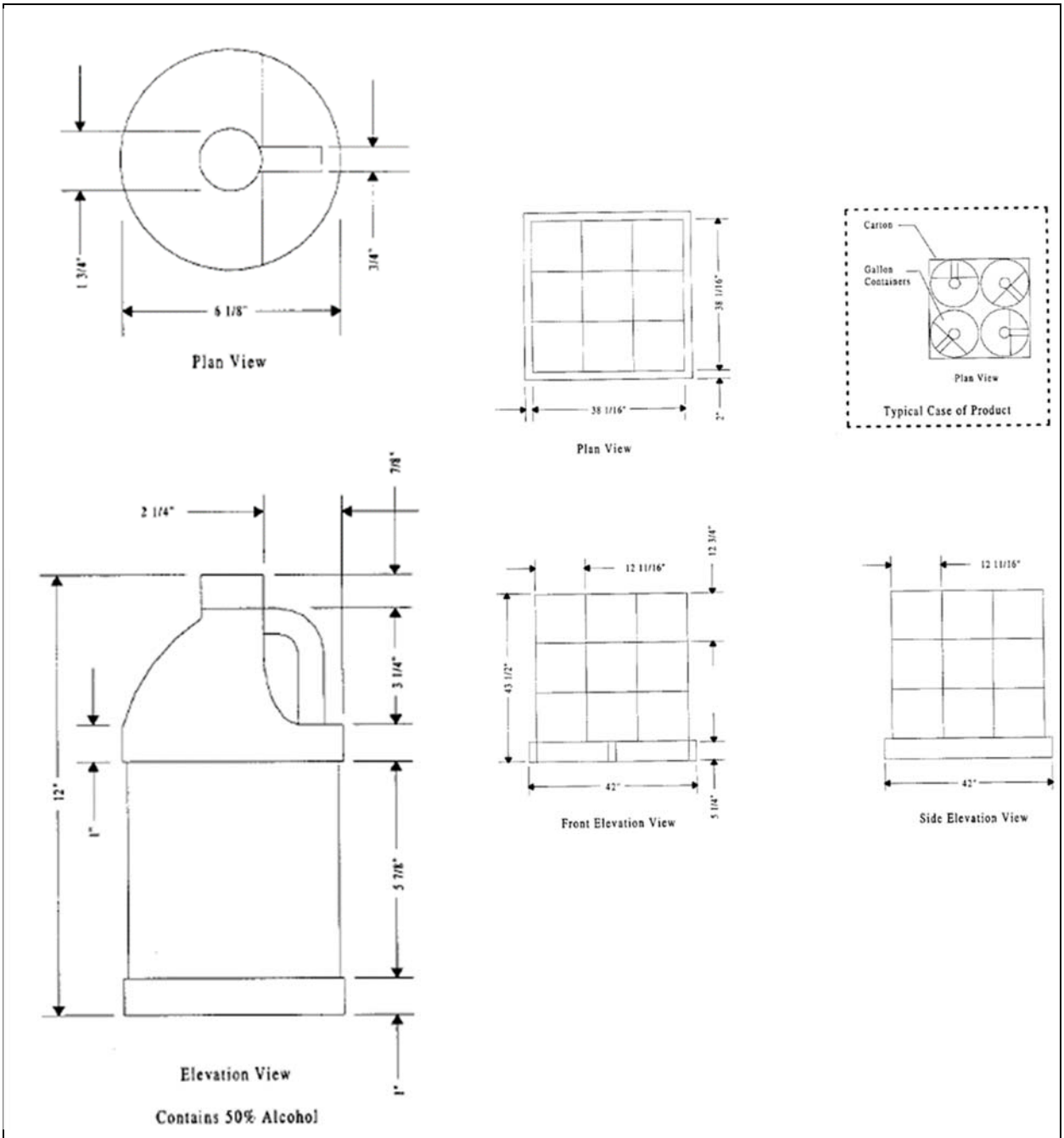


Figure	3-84: Product Container / Typical Pallet Load

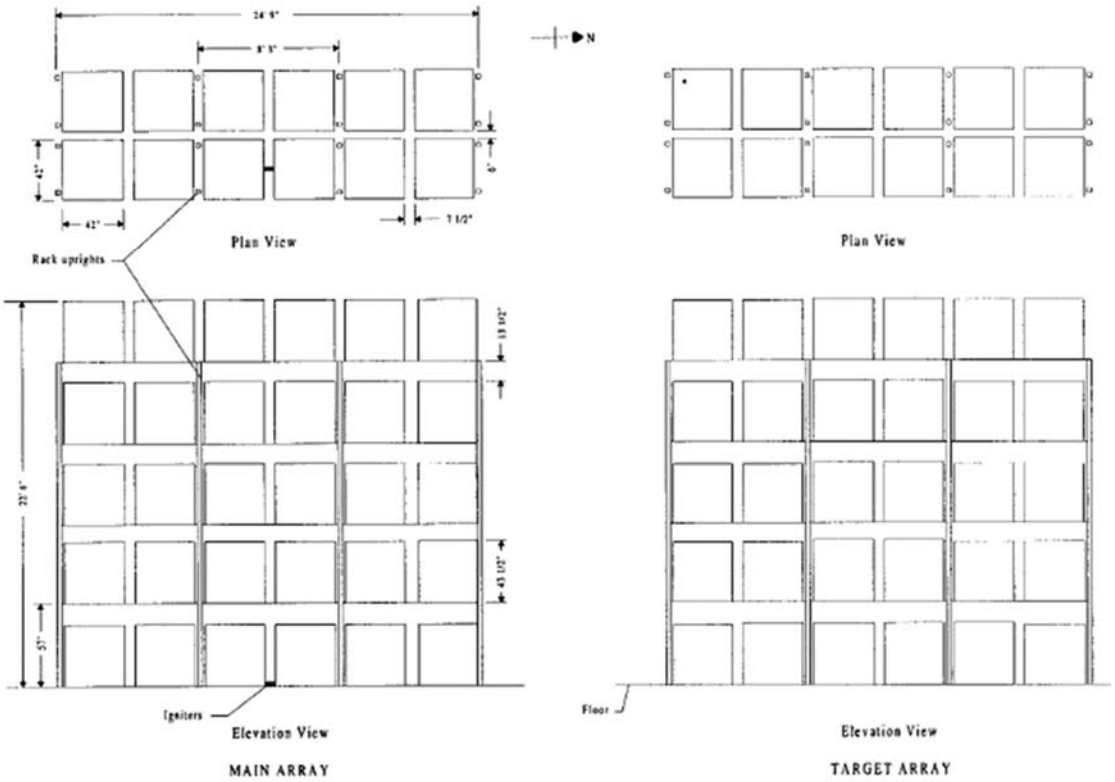


Figure 3-85: Array Setup – Test 1 and 2 Elevation View

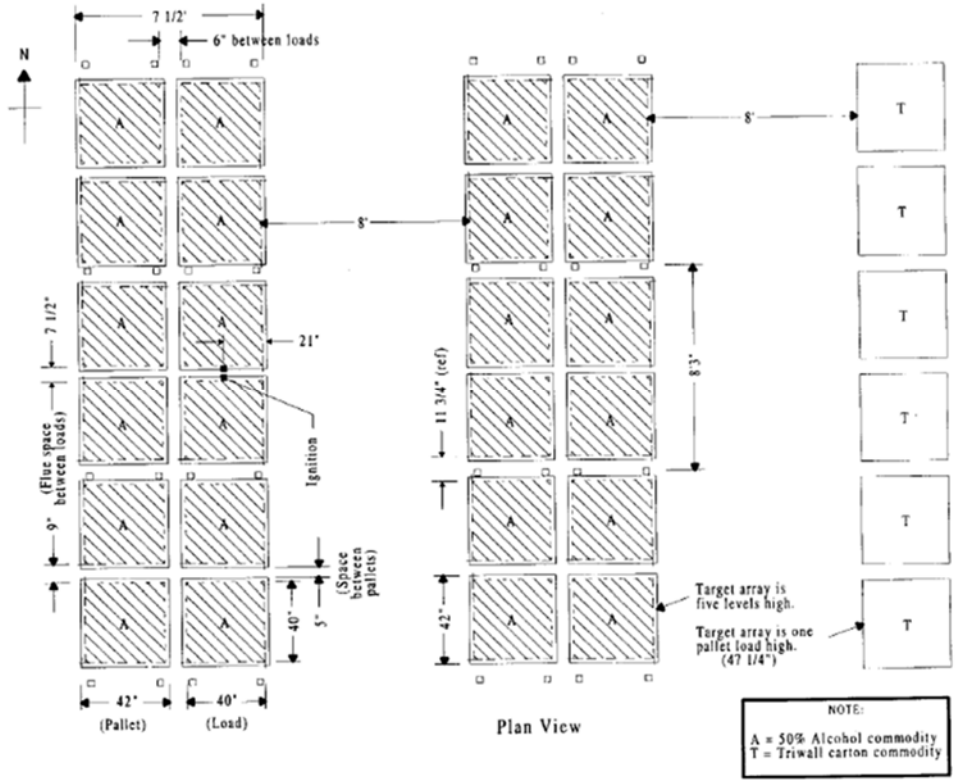


Figure 3-86: Array Setup – Test 1 and 2 Plan View

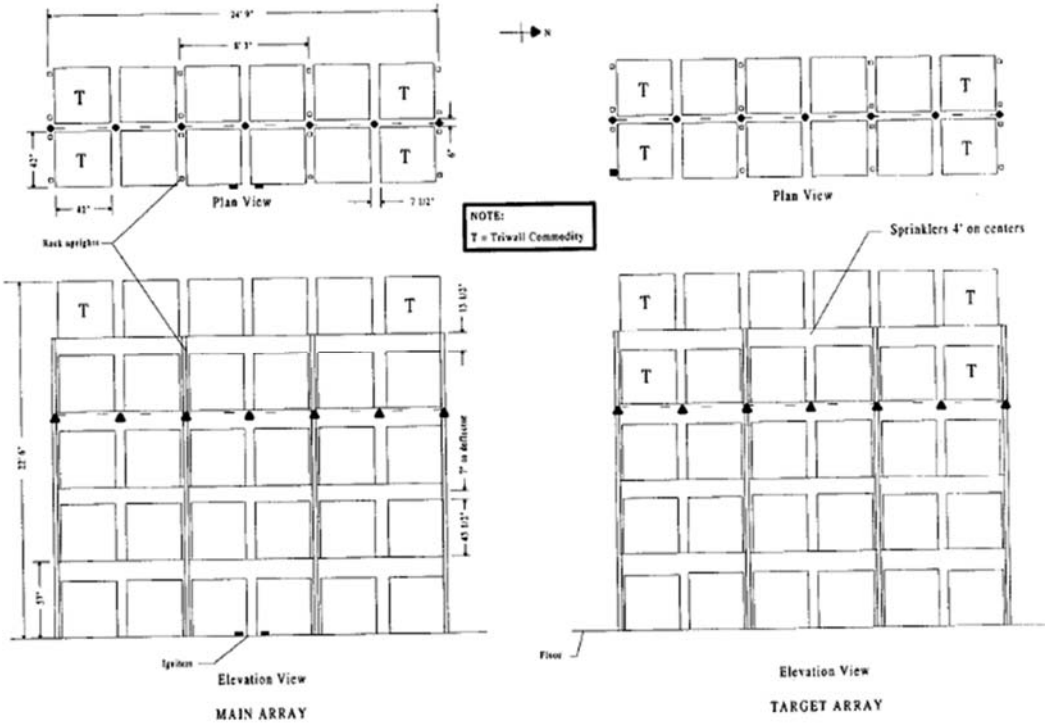


Figure 3-87: Array Setup – Test 4 Elevation View

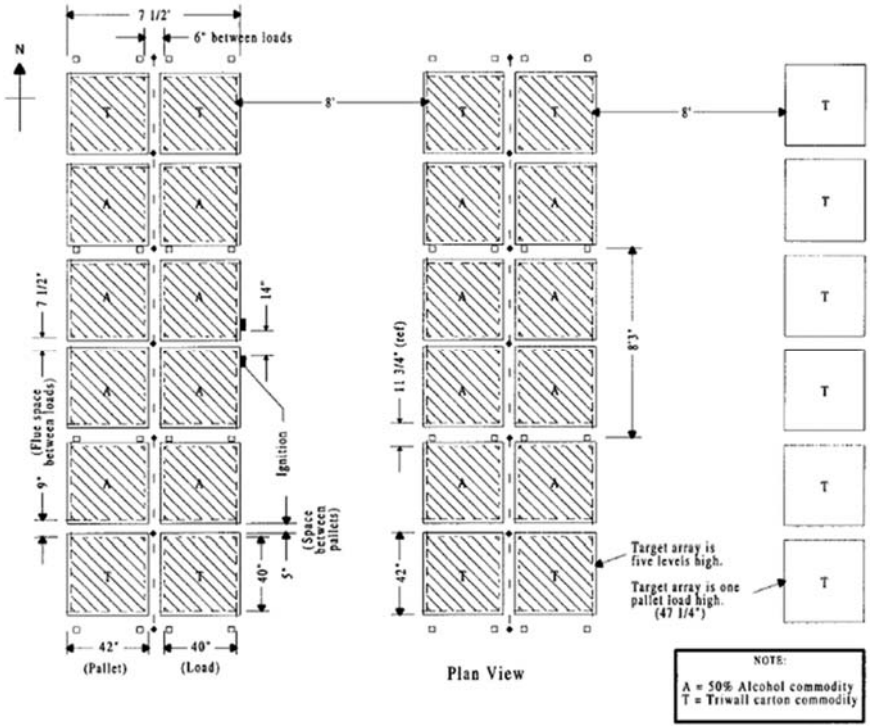


Figure 3-88: Array Setup – Test 4 Plan View

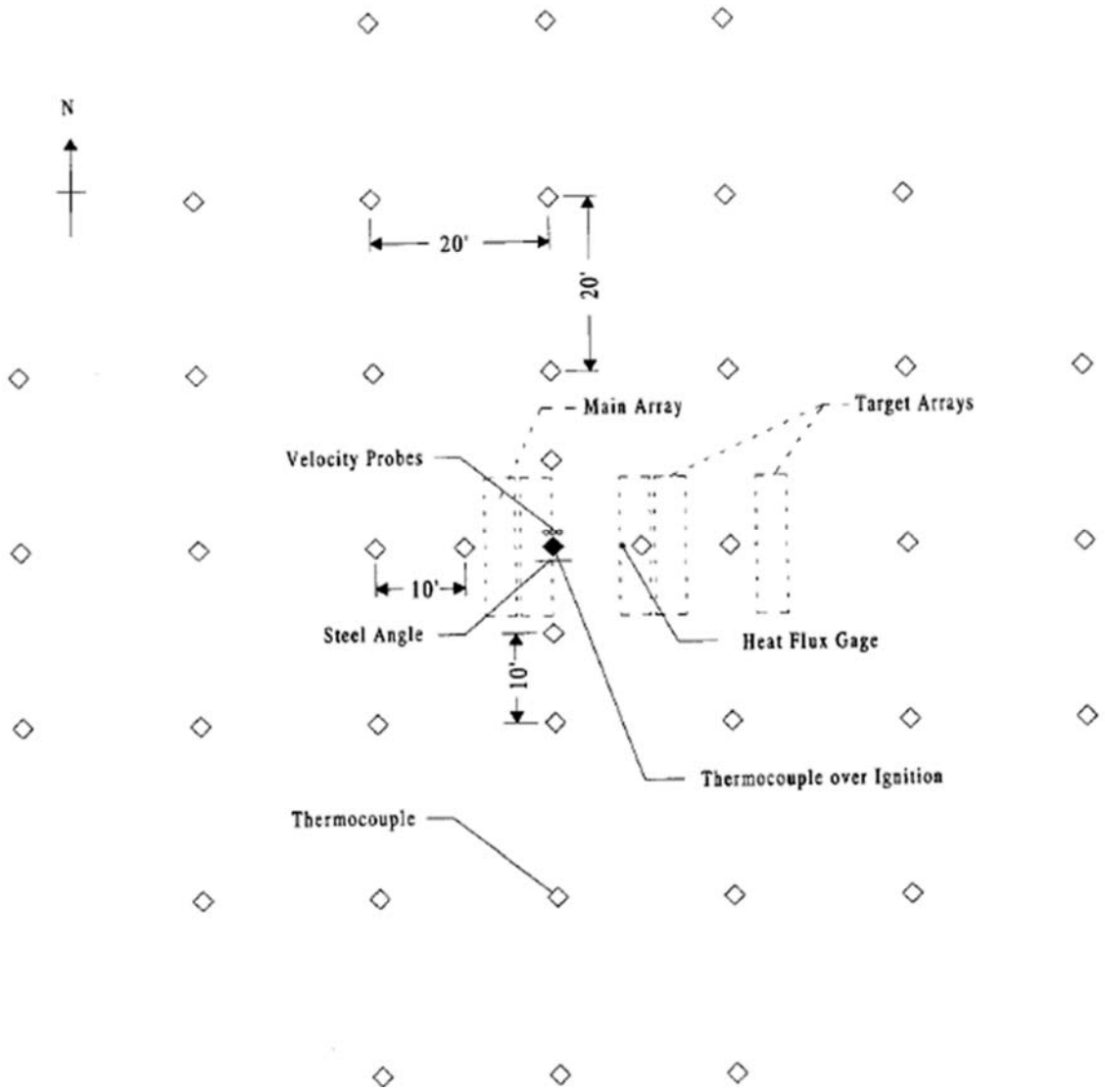


Figure 3-89: Typical Instrumentation Layout

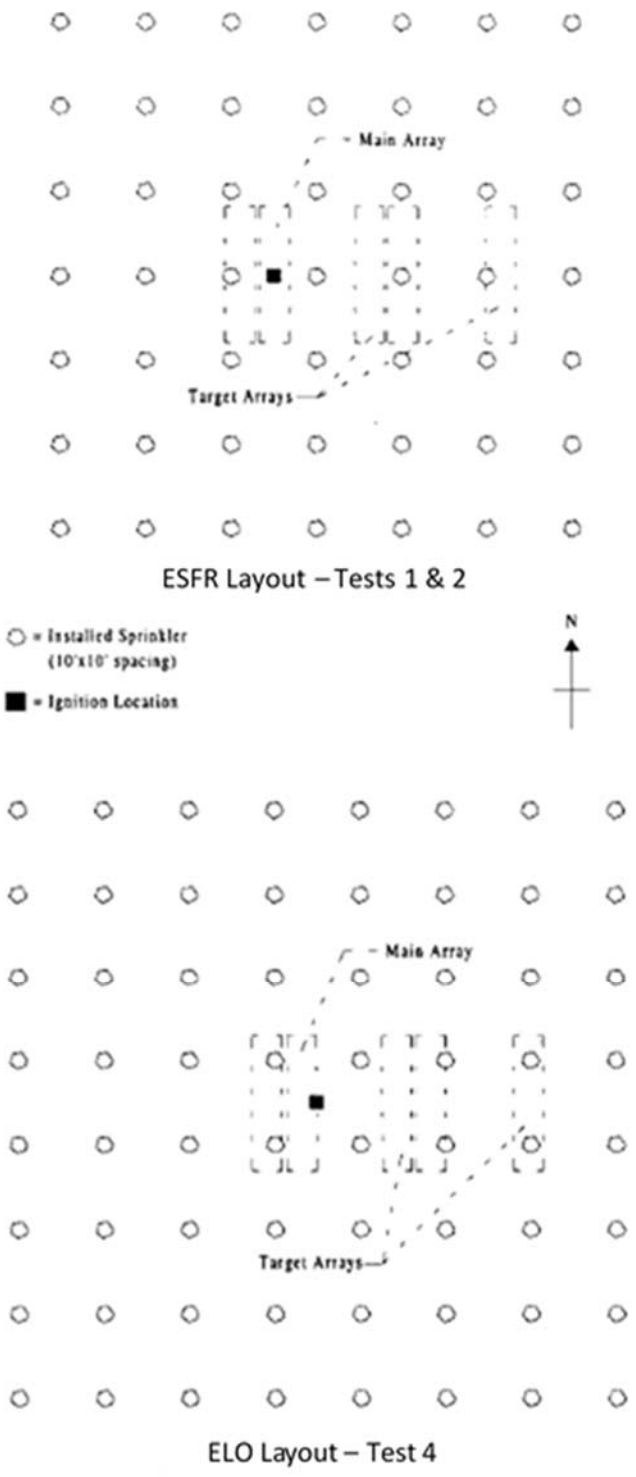


Figure 3-90: Sprinkler Layouts

3.6.4 Test Results

3.6.4.1 General

Sections 3.6.4.5 and 3.6.4.6 provide detailed information on the tests. Complete fire chronologies of test events are provided in Section 3.6.7. Table 3-91 provides test setup and test conditions.

3.6.4.2 Test 1 - ESFR Protection At 75 psi (Figures 3-92, 3-93, 3-94, 3-95, 3-96, and 3-97)

The fire built rapidly and flames were steady on the ceiling at 1:00, followed six seconds later by the first sprinkler operation. Flames were driven off the ceiling and back into the array. By about 2 ¼ minutes, fire in the main array was limited to the bottom three storage levels. Meanwhile, at 1:26, bottles began falling from the array. Those that ruptured created and fed a pool fire which pilot ignited the target storage across the 8-ft aisle at 2:42. Flames in the target array were at the top of the fourth storage level and approached ceiling level by 2:54. Five seconds later, the sixth and final sprinkler opened and flames were quickly reduced to the third storage level. By five minutes, the aisle pool fire was extinguished and the fire was limited to the bottom two levels of the main and target arrays. A persistent fire occasionally reached into upper levels as the test continued. However, they never seriously challenged the provided protection after about 5 minutes from ignition until test conclusion at 15:00.

3.6.4.3 Test 2 - ESFR Protection at 50 psi (Figures 3-98, 3-99, 3-100, 3-101, and 3-103)

This was a repeat of Test 1 with the only change being a reduction in the ceiling protection from a discharge pressure of 75 psi to 50 psi. Initial fire development through the first sprinkler operation at 1:03 was virtually identical to that of Test 1. Flames were driven from the ceiling into the array. Bottles spilled into the aisle resulting in a pool fire with significant flare- ups as bottles ruptured. The target array face was pilot ignited and extinguished a couple times before the flaming pool extended under the target resulting in internal ignition of the array at 2:07. By 2:44, flames built to the top of the target array. By 3:00, the final total of 11 sprinklers were operating and shortly, smoke completely obscured the view of both arrays. As the smoke rose and fell, some fire views were obtained. By about 5 minutes, the aisle pool fire appeared to be out and the main array flames were limited to the bottom of the third storage level about 9 ft high. By six minutes, flame height within the target array was about 5 ft. Fire was persistent, but confined within both arrays until test conclusion at 15:00.

3.6.4.4 Test 4 - In-Rack Protection at 1 Level (Figures 3-104, 3-105, 3-106, 3-107, 3-108, 3-109, and 3-110)

Test 4 consisted of one level of in-rack sprinklers. The first in-rack sprinkler operated at 1:59, two seconds after flames reached the array top. The flames were immediately driven back from the fifth to the third level. The commodity-load plastic wrap in the target array was flash ignited by the aisle pool fire. However, it quickly went out, without causing the cardboard to ignite. At 2:45, the flaming pool was licking at the target base, then flowed under the target igniting it at 3:19 Spillage from both arrays left considerable residue in the aisle by test conclusion. Eventually, a weakened pool fire displaying blue "invisible" flames extended under the second target to the east. The fire went out without causing any damage to the target. A small pool fire also extended about 10 to 15 ft to the south, as well as to the north of the array, but was controlled and eventually extinguished. Fire in the arrays did persist until test

conclusion at 15:00. Yet, it was confined to the bottom storage level, primarily toward the north end of the array.

3.6.4.5 General Test Results

Test Number	1	2		4
Carton Moisture Content (%)	6.2	4.9		5.2
Fuel Array Content - approximate (wt%)				
a. Liquid	88	88		88
b. Wood	6	6		6
c. Plastic	3	3		3
d. Cardboard	3	3		3
Test Site Conditions				
a. Dry Bulb Temp. (°F)	68	65		63
b. Wet Bulb Temp. (°F)	52	46		56
c. Relative Humidity (%)	31	16		21
Outside Conditions				
a. Wind Speed (mph)	10	35		2
b. Wind Direction	S	NNE		N
c. Dry Bulb Temp. (°F)	41	24		32
d. Wet Bulb Temp. (°F)	36	18		28
e. Relative Humidity (%)	61	22		59

Figure 3-91: Setup and Test Conditions

3.6.4.6 Test 1 Test Results

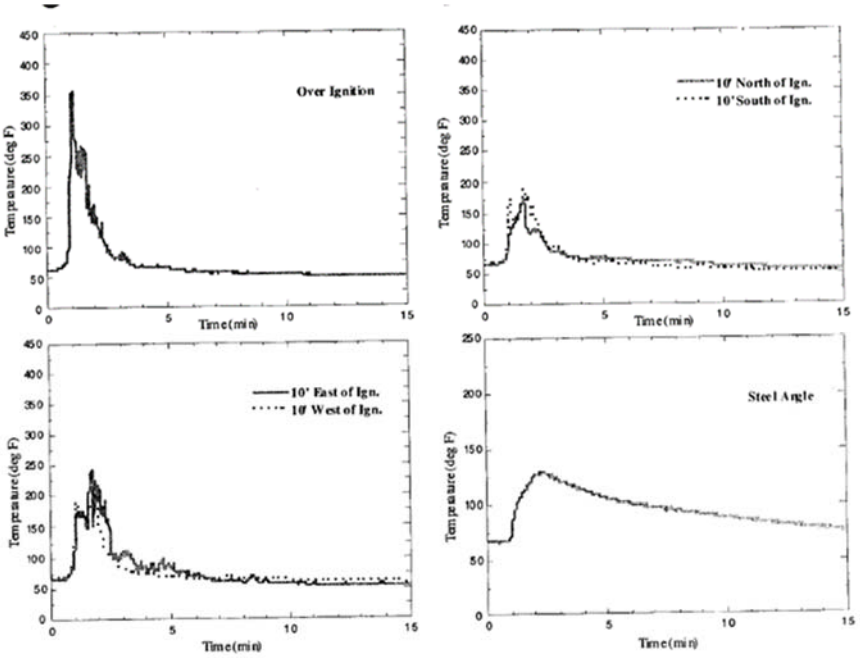


Figure 3-92: Various Temperature Histories – Test 1

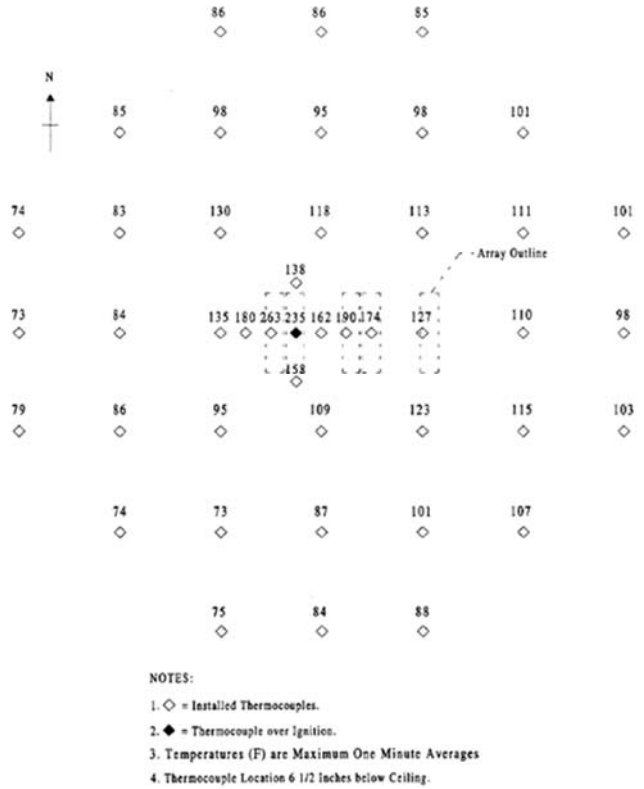


Figure 3-93: Maximum Average Near-Ceiling Gas Temperatures – Test 1

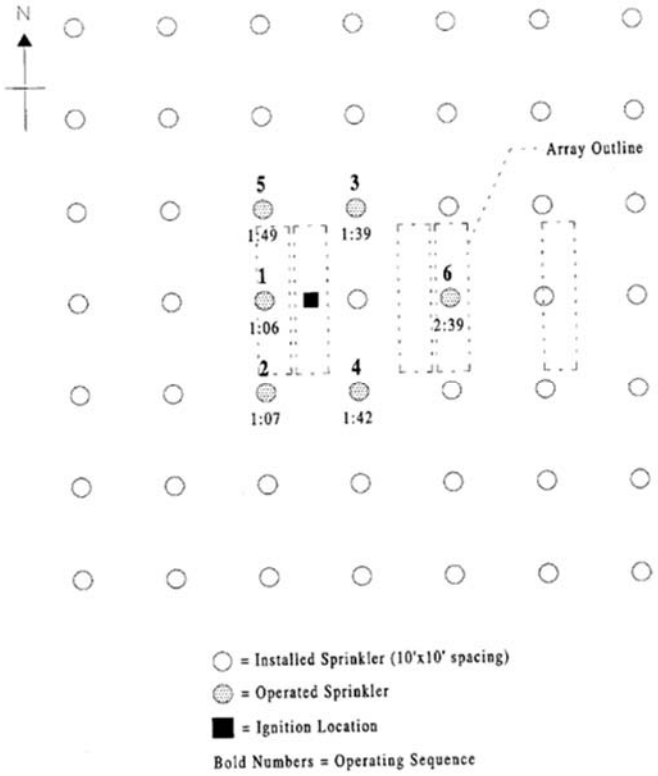


Figure 3-94: Ceiling Sprinkler Operations – Test 1

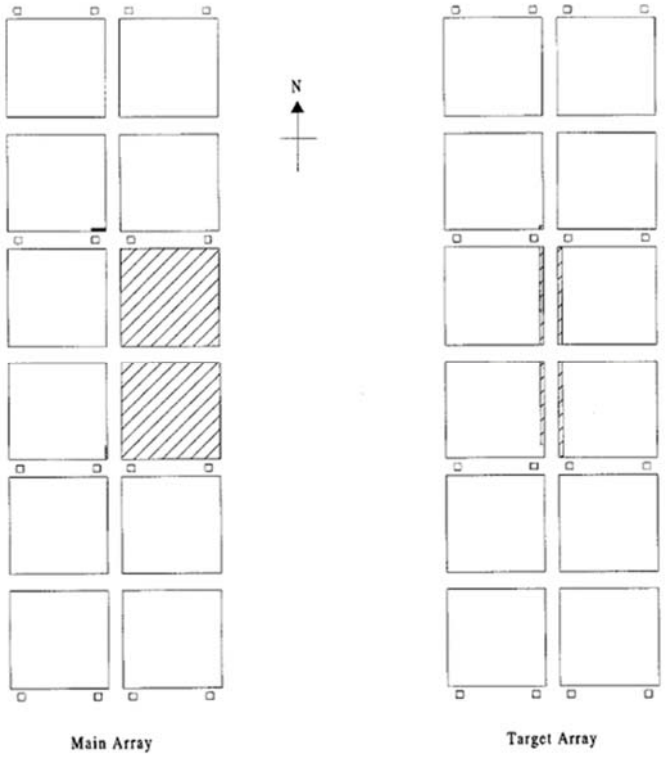


Figure 3-95: Test 1 Extent of Damage – Plan View

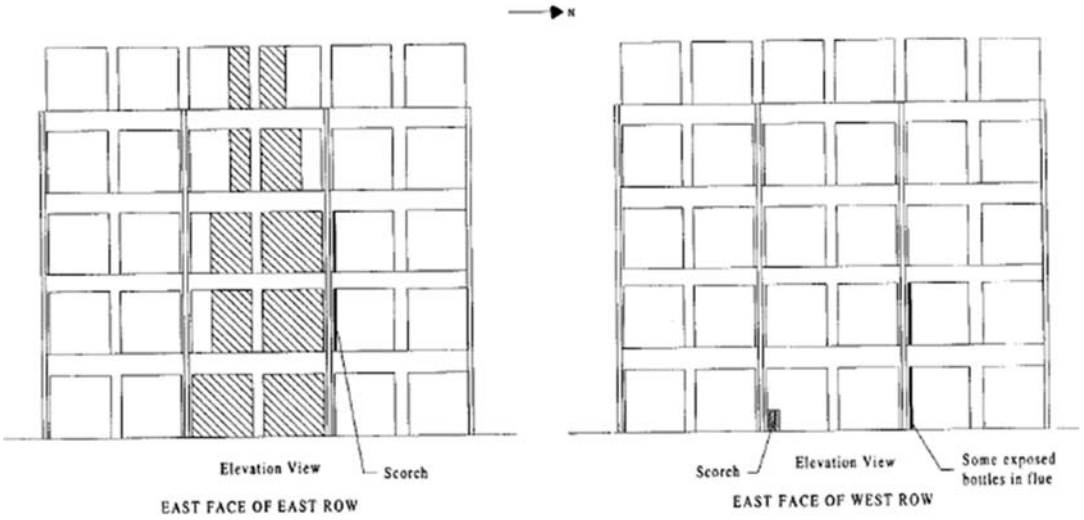


Figure 3-96: Test 1 Extent and Type of Damage – Main Array

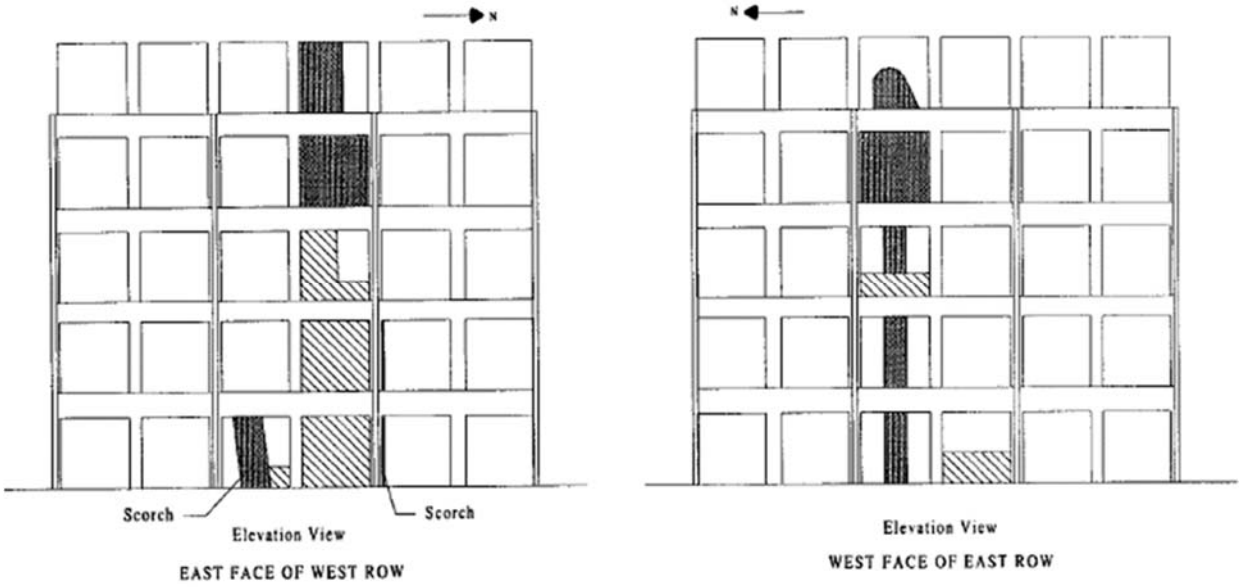


Figure 3-97: Test 1 Extent and Type of Damage – Target Array

3.6.4.7 Test 2 Test Results

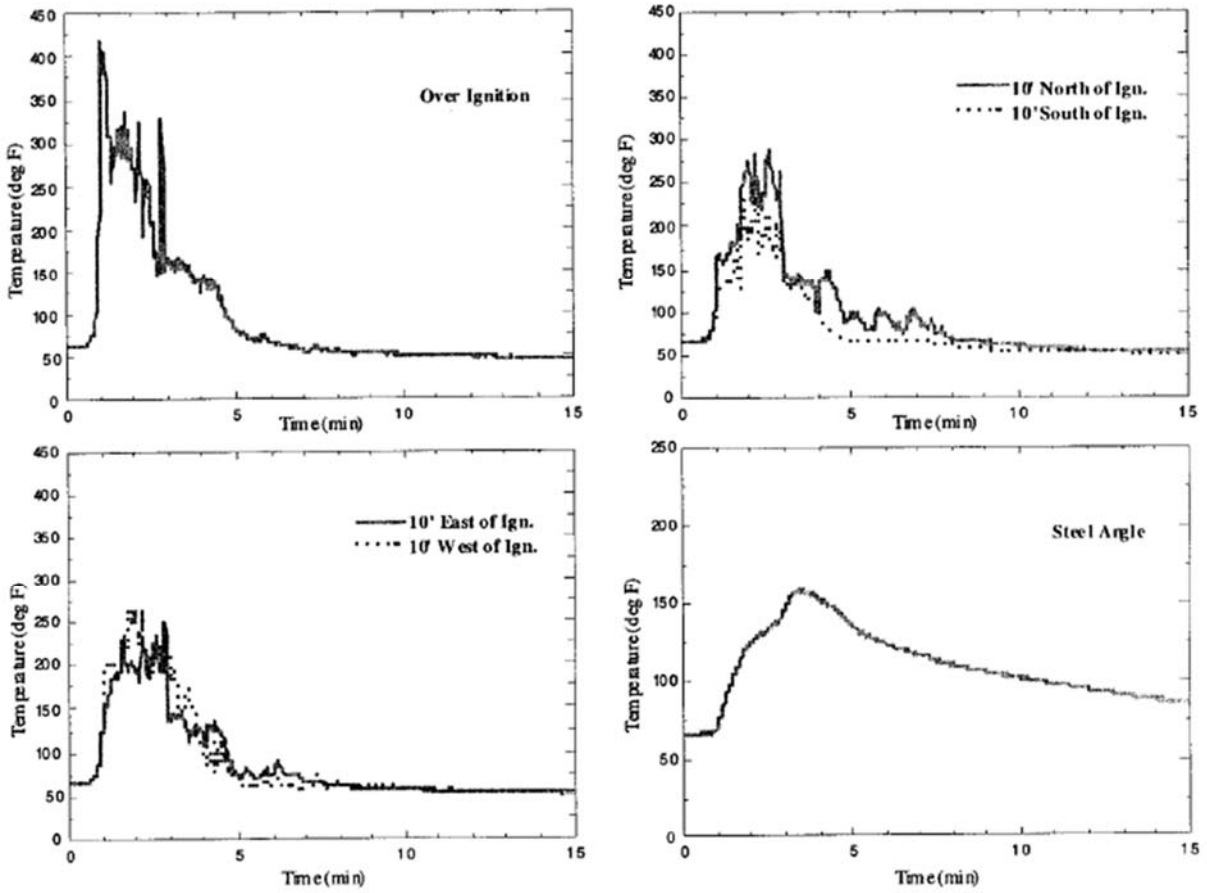
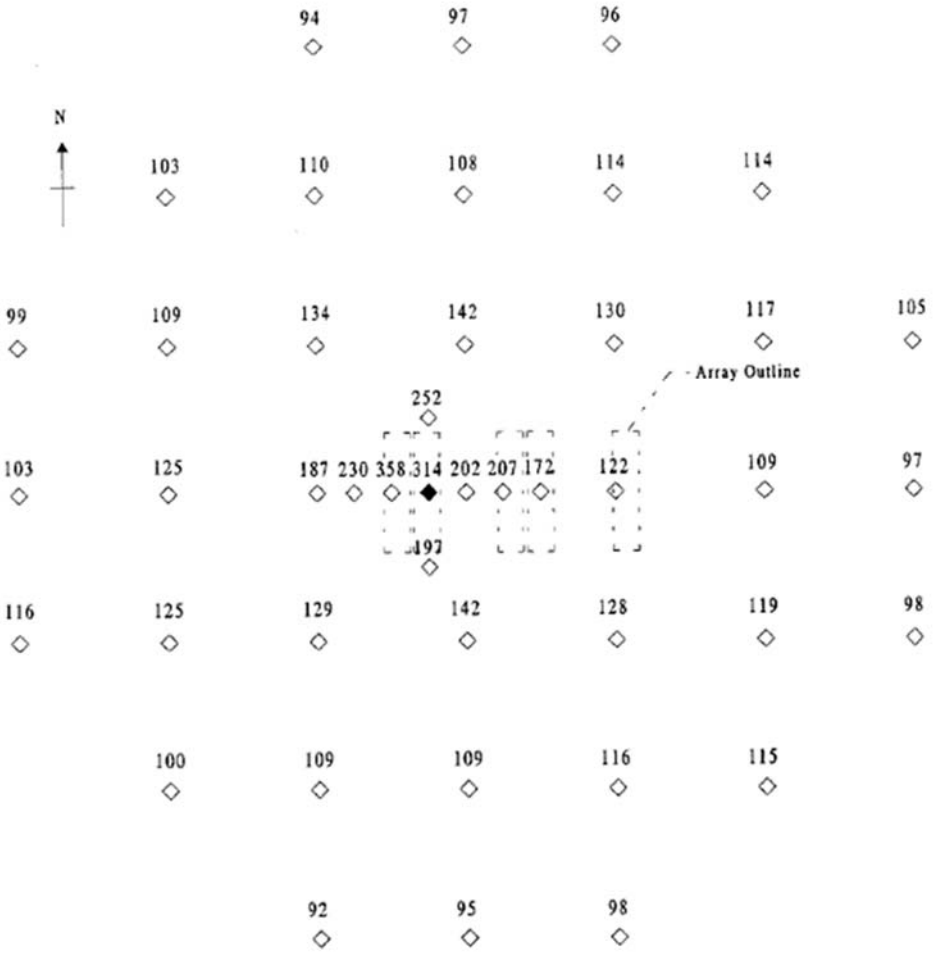


Figure 3-98: Various Ceiling Temperature Histories – Test 2



NOTES:

1. ◇ = Installed Thermocouples.
2. ◆ = Thermocouple over Ignition.
3. Temperatures (F) are Maximum One Minute Averages
4. Thermocouple Location 6 1/2 Inches below Ceiling.

Figure 3-99: Maximum Average Near-Ceiling Gas Temperatures – Test 2

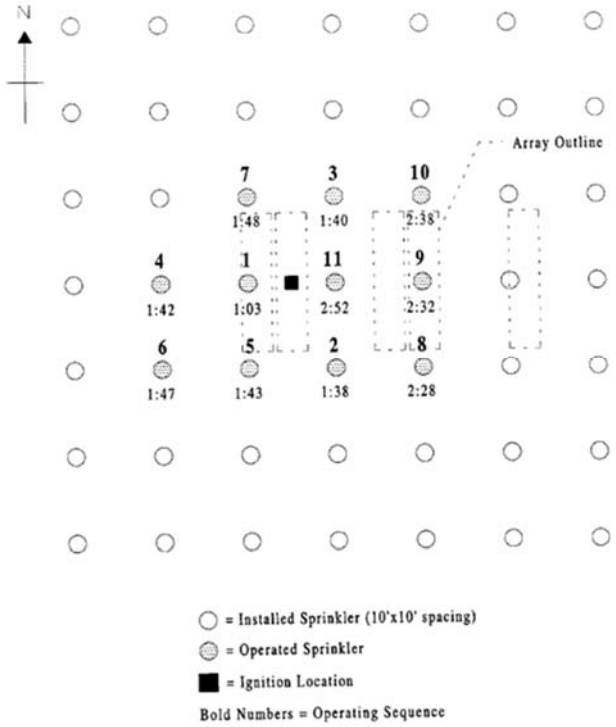


Figure 3-100: Ceiling Sprinkler Operations – Test 2

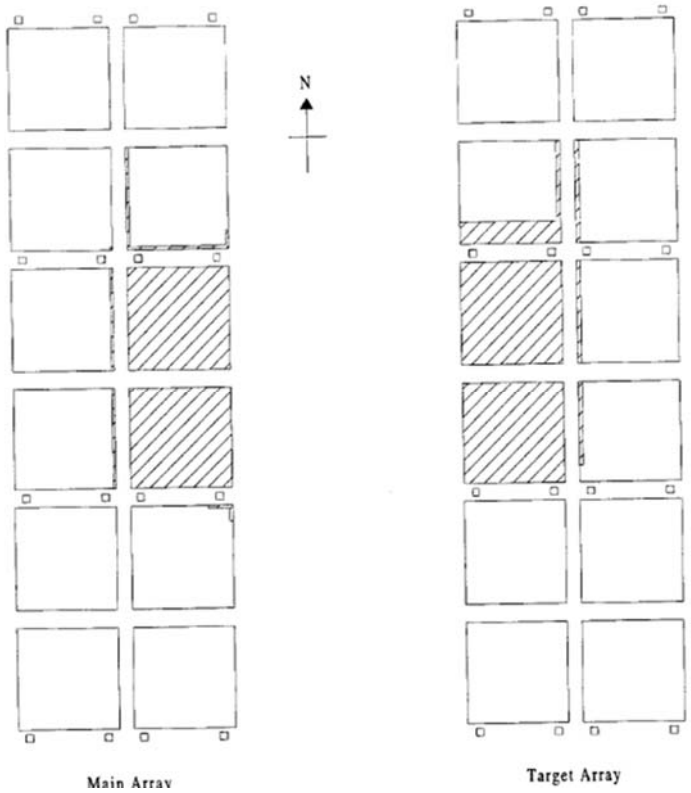


Figure 3-101: Test 2 Extent of Damage – Plan View

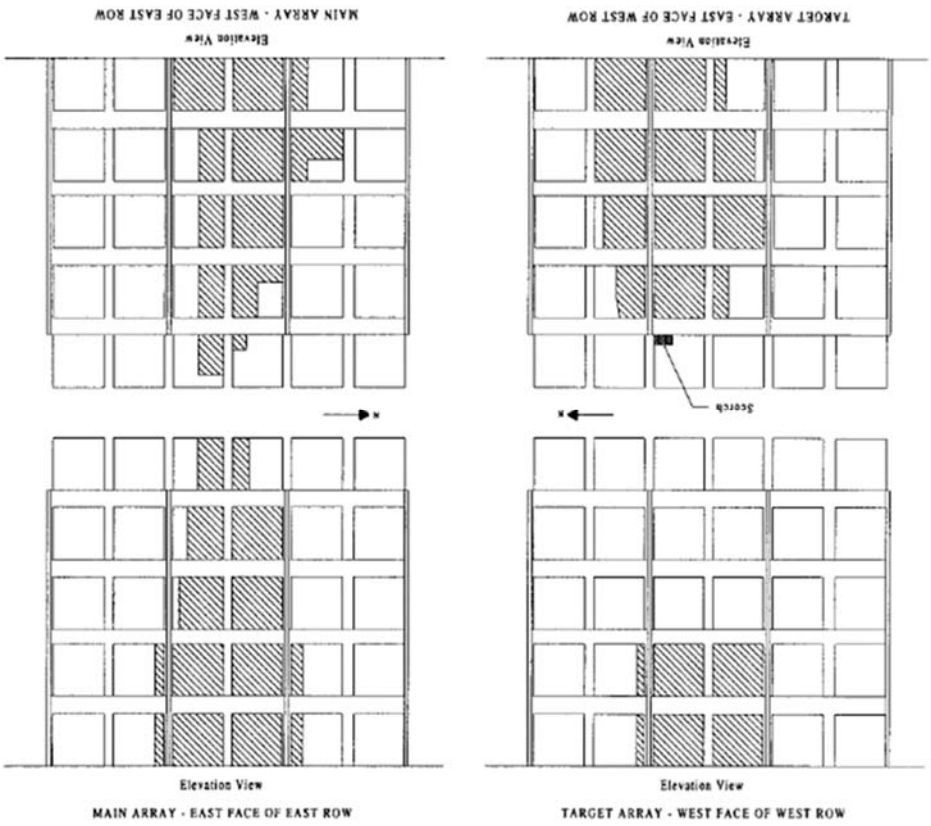


Figure 3-102:Test 2 Extent and Type of Damage

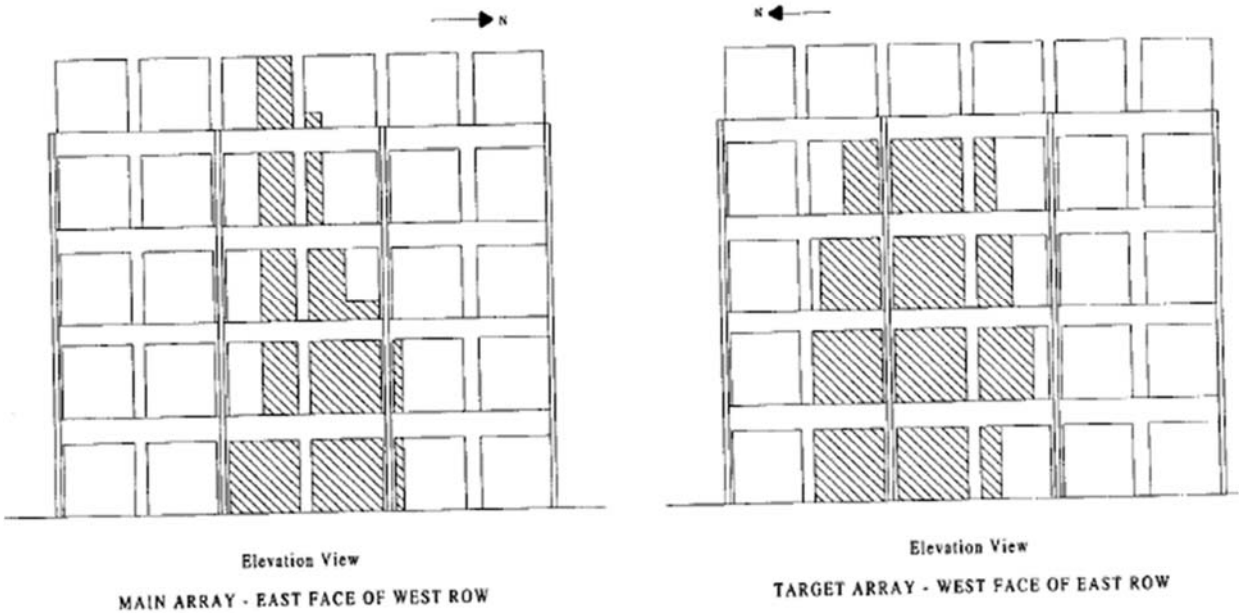


Figure 3-103: Test 2 Additional Damage

3.6.4.8 Test 4 Test Results

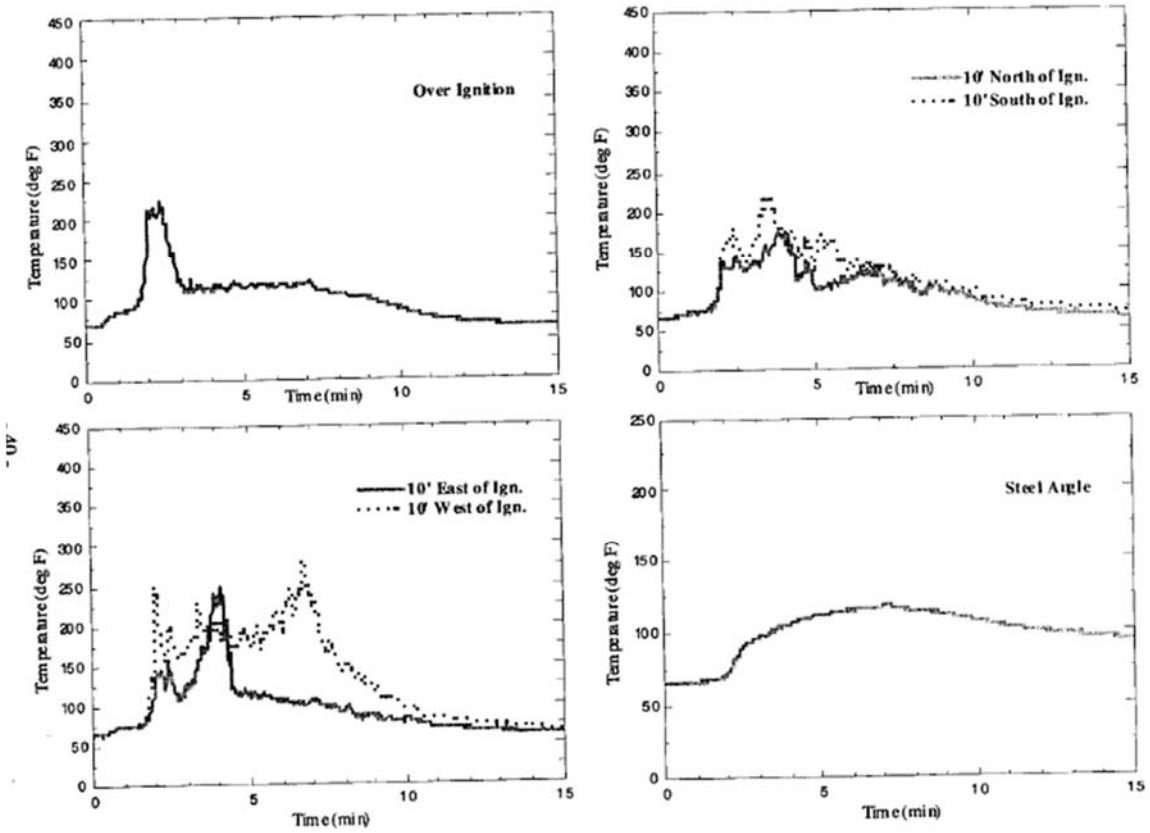
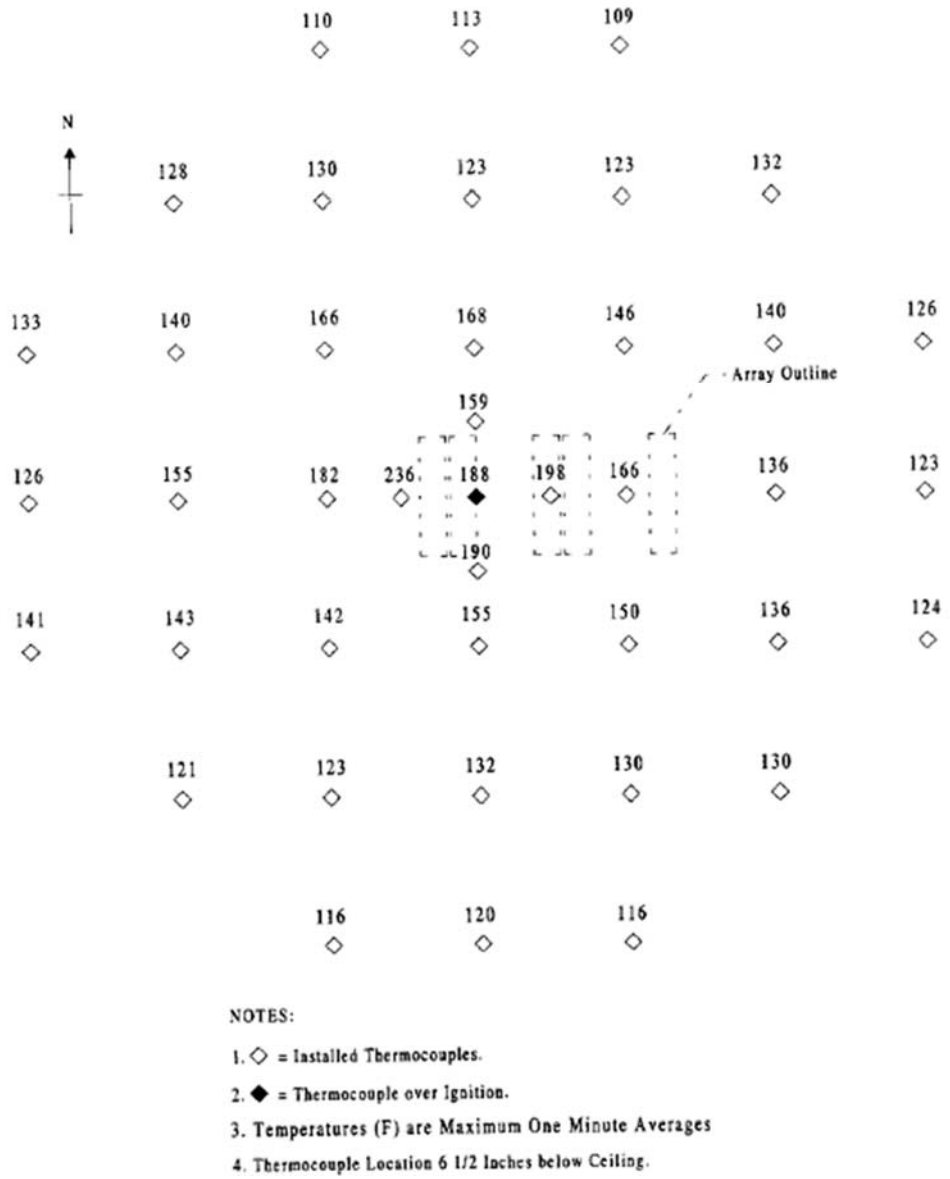


Figure 3-104: Various Ceiling Temperature Histories – Test 4



NOTES:

1. ◇ = Installed Thermocouples.
2. ◆ = Thermocouple over Ignition.
3. Temperatures (F) are Maximum One Minute Averages
4. Thermocouple Location 6 1/2 Inches below Ceiling.

Figure 3-105: Maximum Average Near Ceiling Gas Temperatures – Test 4

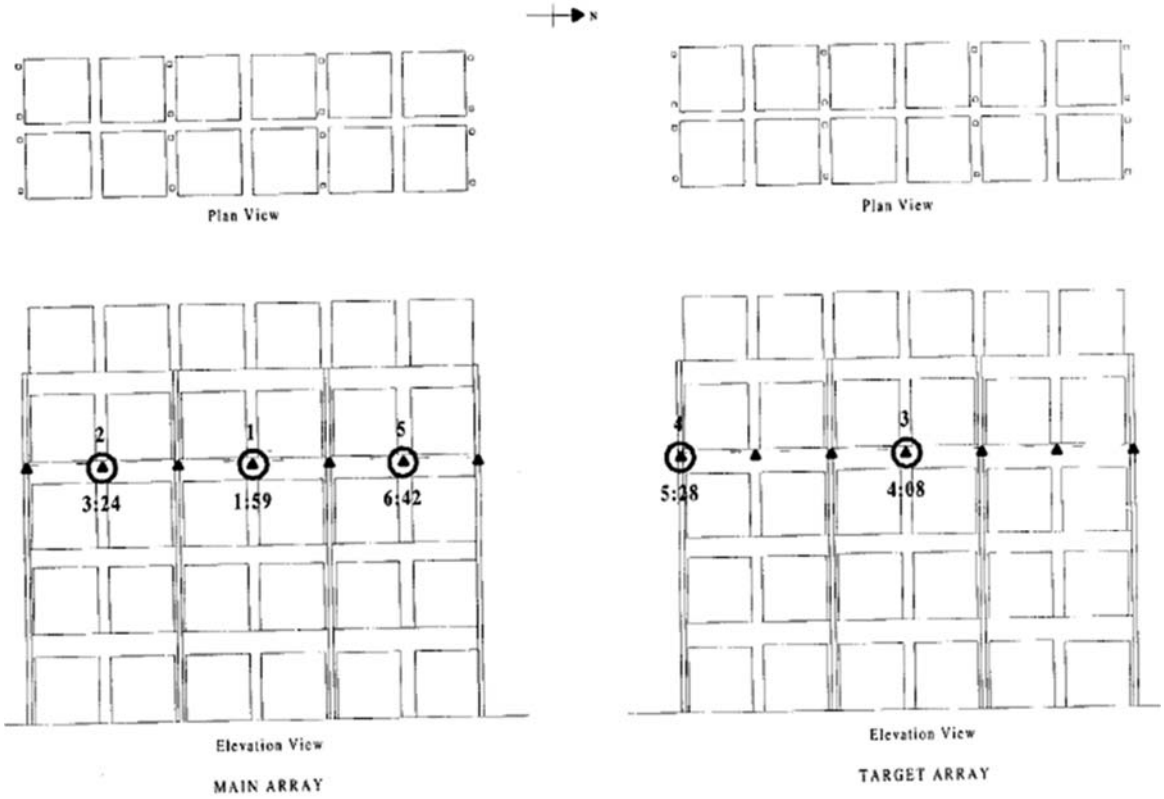


Figure 3-106: In-Rack Sprinkler Operations – Test 4

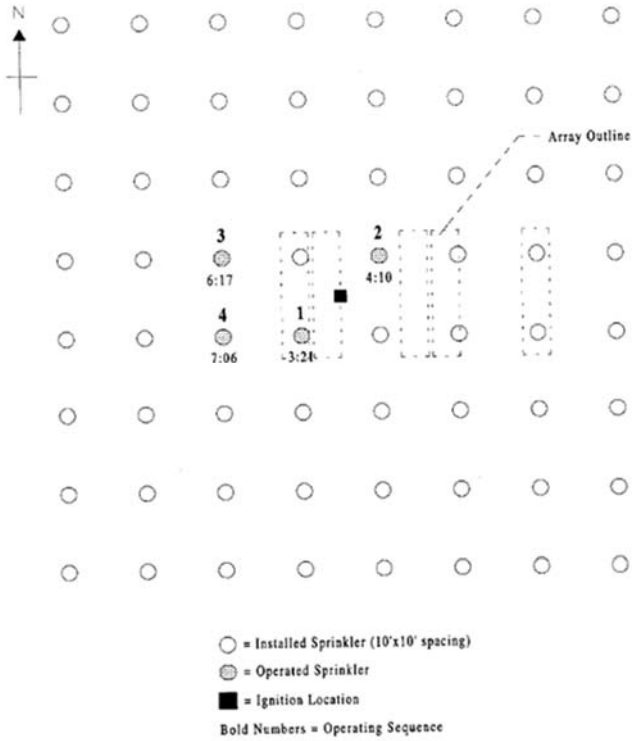


Figure 3-107: Ceiling Sprinkler Operations – Test 4

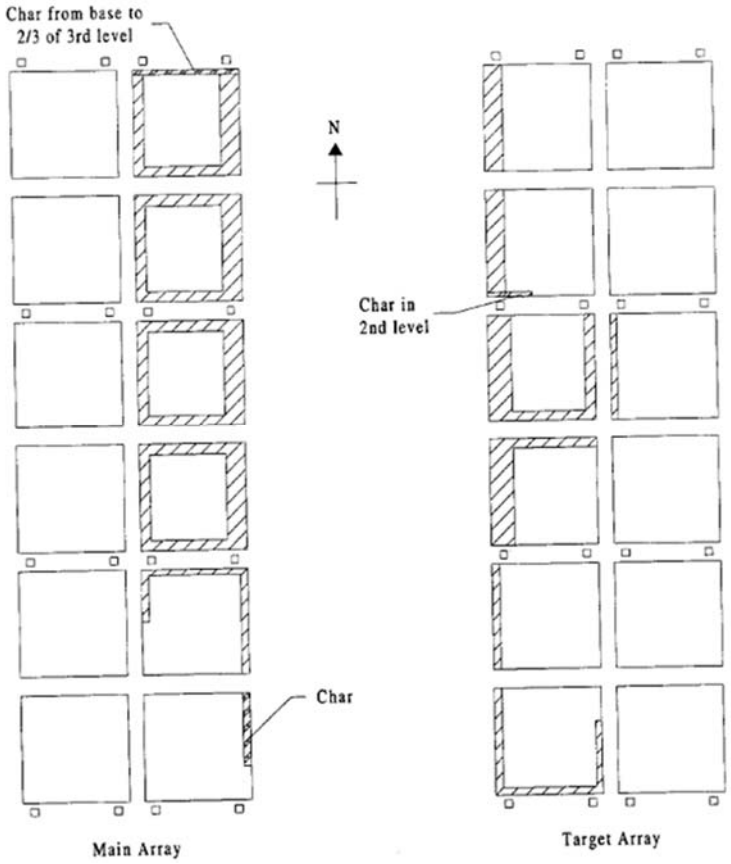


Figure 3-108: Test 4 Extent of Damage – Plan View

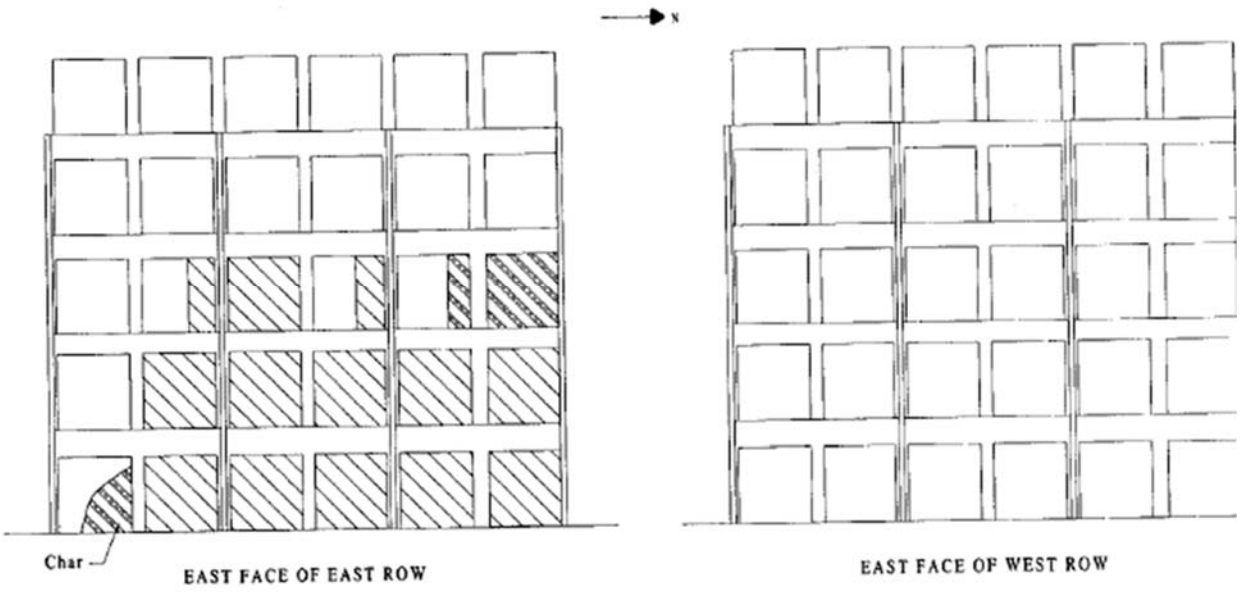


Figure 3-109: Test 4 Extent and Type of Damage – Main Array

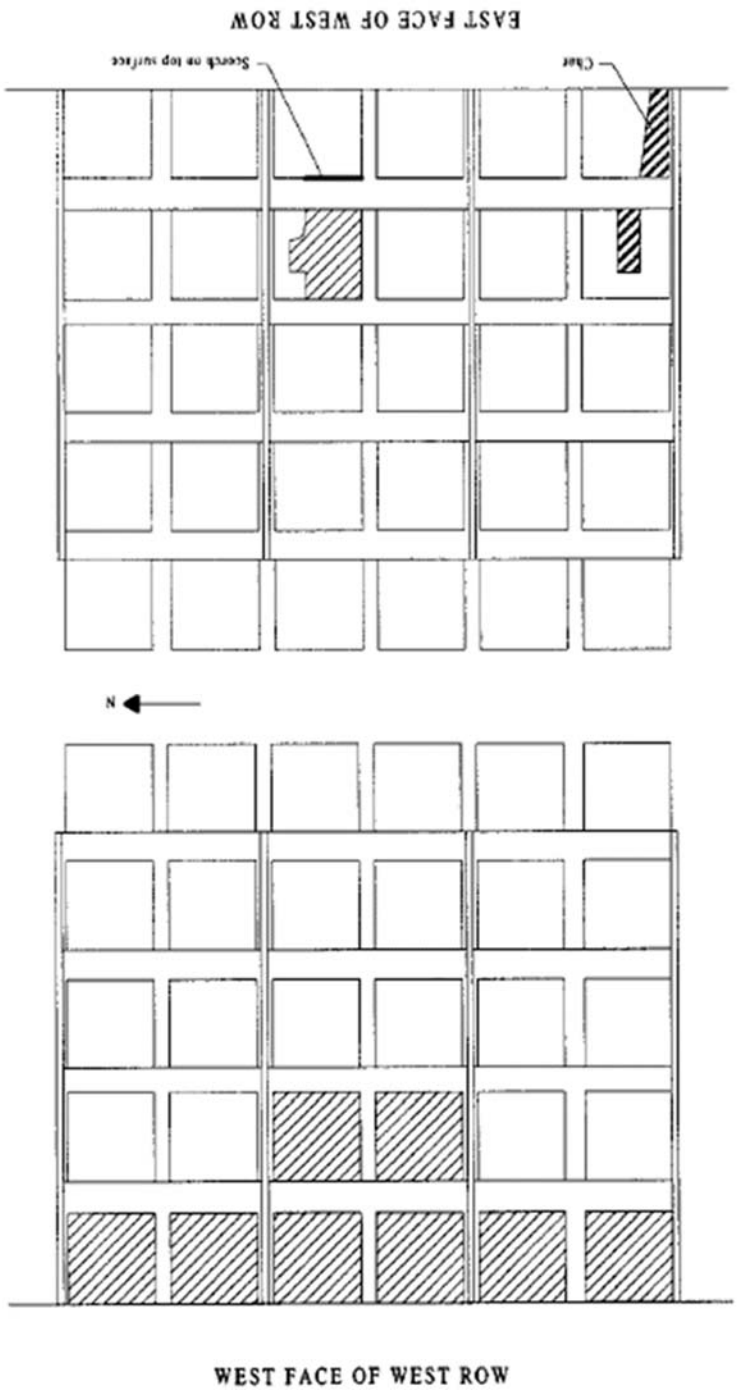


Figure 3-110: Test 4 Extent and Type of Damage – Target Array

3.6.5 Discussion

3.6.5.1 General

The focus of this testing was to develop protection for flammable miscible liquids in the range greater than 20/80 through 5O/5O product/water mixtures. Two methods were investigated:

1) ceiling protection only using ESFR sprinklers and
2) combination of ceiling and in-rack sprinklers.

Table 3-13 provides a summary of the protection used in each test.

3.6.5.2 Test 1 - Ceiling Protection (ESFR at 75 psi)

Each ruptured container released a gallon of mix. This size was a significant factor in rapidly creating a pool fire which quickly bridged the 8 ft aisle space and involved the target storage. However, sprinklers also responded rapidly to the developing rack fire and upon opening, extinguished the pool fire and contained the storage damage within the limits of the main and target arrays. Although the fire was subdued within 5 minutes, the test was continued for 15 minutes to monitor fire behavior. Although it was persistent and was never extinguished, following its initial knockdown in the storage arrays, the fire never posed a serious challenge to the protection. Damage was limited to the central bays of the main and target arrays with the operation of six sprinklers.

3.6.5.3 Test 2 - Ceiling Protection (ESFR at 50 psi)

Test 2 was run with the expectation that a discharge pressure of 50 psi might also result in favorable protection. Initial fire progress, until the first sprinkler operation, was virtually identical in the two tests. The reduced pressure resulted in the operation of 11 sprinklers. Overall, it was more severe than in the previous test. Considerably more smoke was generated. Near-ceiling gas temperatures were a little higher but in the safe range, well below 1000oF. Damage was greater and extended beyond the central bays of the main and target arrays, yet remained comfortably within the storage boundaries. The pool fire which extended briefly into the second aisle space early in the test, was quickly reduced as sprinklers opened. As in Test 1, the fire was subdued within 5 minutes and was contained until test conclusion.

3.6.5.4 Test 4 -In-Rack Protection (one level)

With the fire overwhelmed by the protection provided in Test 3, it was decided to rerun the test with reduced protection consisting of a single line of in-rack sprinklers located above the third storage level. The discharge pressure and sprinkler spacing remained the same as in the previous test. Ceiling protection also remained the same. As expected, the resulting fire was more severe and extensive. Although the fire was persistent, by test conclusion at 15 minutes it was reduced to pockets of flickering flame. A total of five in-rack and four ceiling sprinklers were opened. A considerable amount of commodity spilled into the aisle from both the main and target arrays. The pool fires were extensive, yet mild. Damage extended the length of the main and target arrays in the rows forming the aisle, though generally confined to the pallet load faces. Damage height was limited to three and two storage levels in the main and target arrays, respectively.

3.6.6 Conclusions

Adequate protection was provided by:

1) K-14 ESFR sprinklers discharging at 75 psi (Test 1);
2) A single line of sprinklers above the third level of storage as well as ELO ceiling sprinklers designed for a 0.60 gpm/ft^2 density discharge (Test 4).

3) Although the ESFR sprinklers discharging at 50 psi (Test 2) did control the storage and pool fires, the large number of ESFR sprinklers required to do so, rendered this protection unacceptable.

3.6.7 Fire Chronologies

Time (Min:Sec)	Observation
0:00	Ignition
0:17	Flames 4 ft high.
0:24	Flames 5 ft high.
0:39	Flames 9 ft high.
0:46	Flames 14 ft high.
0:51	Flames 19 ft high.
0:53	Flames 23 ft high (top of array).
0:56	Flames lick at ceiling (30 ft high).
1:00	Flames steady on ceiling.
1:06	First sprinkler operates.
1:16	Flames off ceiling.
1:20	Flames 26 ft high.
1:26	Bottles fall out of array into aisle creating a small pool fire.
1:33	More spillage and contents igniting.
1:42	Continuous spilling - flaming debris close to target (about 1 ft away).
2:11	Flames limited to bottom three tiers of main array.
2:18	Aisle fire minimal; flames continue, limited to bottom three levels of main array.
2:00	Continuous spilling – water seems to be suppressing pool fire in aisle.
2:22	More material falls from rack.
2:25	Water seems to be having an effect.
2:27	Target rack pilot ignited.
2:30	Fire to top of 3rd level in ignition row.
2:42	Flames in target to top of 4th level (19 ft high).
2:44	Fire not yet into west row of main array.
2:46	Flames above target array.
2:53	Vigorous fire in center of target rack (not ignited on face).
2:54	Flames approaching ceiling; pool fire noted into 2nd aisle to east.
2:59	Sixth sprinkler operates, and drives target array flames down from top of array to middle of 3rd level.
3:14	Fire in 2nd aisle continues but is limited; flames in 1st and 2nd levels of target array.
3:30	Flaming at 2nd level at east face of target array trying to lick to top of 3rd level; flames in main array in 1st and 2nd levels.
4:00	Fire in target array seems to be confined to easternmost row. Pool flames extend only a short distance (about 6-in.) into the aisle.
4:19	Flames in main array in 1st and 2nd levels.
4:32	Aisle fire between main array and target array is extinguished.
4:49	No pool fire in aisle; fire limited to 1st and 2nd levels of both arrays.
4:57	Flames still vigorous in 2nd – 4th levels in main array, ignition area.
5:07	Flames in target array limited to 1st level, flames in main array lick at 3rd level.
5:42	Seems to be confined to bottom and 2nd levels of ignition area and easternmost row of target.

Figure 3-111: Fire Chronologies – Test 1

Time (Min:Sec)	Observation
6:20	Flames in main array licking out bottom of 2nd level. Seem to be somewhat reduced. Fire appears to be shielded.
6:37	Fire seems reduced somewhat in target array. Located primarily in center of array and easternmost row. Flames lick at bottom of 2nd level.
7:30	Flames licking at bottom of 3rd level, main array. Flaming appears reduced somewhat, at least in breadth.
7:56	Target array – flames lick to bottom of 2nd level in center of array, biased to east.
8:13	Flames in target to 1st level, flames in main array in 1st and 2nd levels.
9:00	Fire seems to be burning at steady rate, with occasional variation between vigorous and subdued.
9:15	Flames in target only flickering, flames in main array appears limited to 2nd and 3rd levels.
9:33	Flaming can be seen occasionally in main array in bottom level and licking to bottom of 3rd level.
11:00	Some flickering flame can be seen in bottom and 2nd levels of main array and also weak flickering flame in target array.
13:30	Flames persist in 1st level and bottom of 3rd level in main array.
13:45	Seems to be no fire seen in target array – although there may be some hidden from view.
15:00	Test concluded.

Figure 3-112: Fire Chronologies – Test 1 (continued)

Time (Min:Sec)	Observation
0:00	Ignition
0:19	Flames 4 ft high.
0:27	Flames 5 ft high.
0:33	Flames 9 ft high.
0:46	Flames 14 ft high.
0:53	Flames 19 ft high.
0:55	Flames 23 ft high (top of array).
1:02	Flames lick at ceiling (30 ft high).
1:03	First sprinkler operates.
1:16	Flames off ceiling (about 26 ft high).
1:23	Small amount of burning liquid on floor
1:34	Spillage of flaming material into aisle.
1:42	More spillage into aisle.
1:46	Target face pilot ignited.
1:57	Fire in main array pretty well subdued. (*Special Note: target face ignited and extinguished a couple times as flaming material dumped from main array.*)
2:03	Flames under the target array.
2:07	Another dump of flaming material into aisle; target is pilot ignited in its center across from ignition.
2:20	Flames to top of 3rd level of target array
2:25	Some fire in main array at longitudinal flue.
2:33	Flames to bottom of top level in target array, flames to top of 3rd level in main array
2:44	Flaming continues at top of target array
2:50	More material dumping into aisle.
2:53	Small pool fire noted in 2nd aisle to East.
2:58	Fire concentrated in bottom level of target.
3:00	Eleven sprinklers are now operating.
3:06	Smoke obscures fire view in both arrays.
3:40	Smoke obscures array view.
3:45	Both racks completely obscured, no pool fires noted
3:57	Smoke rises and falls; at times array can be seen.
4:01	No fire can be seen in array; aisle is pretty well obscured with smoke.
4:11	Fire seen at face of main array bottom level, ignition area – flames about 6 ft high.
4:35	Smoke clearing – does not appear to be any fire in target.
4:43	Does not appear to be any fire in aisle.
5:01	Flames in main array at bottom of 3rd level (about 9 ft high).
5:20	Smoke pretty well risen; most view obscuration due to sprinkler water.
5:47	Fire about as last reported (flames 9 ft high) in main array.
5:57	Fire seen in target array in center about 5 ft high.

Figure 3-113: Fire Chronologies – Test 2

Time (Min:Sec)	Observation
6:33	Fire in target cannot be seen. It may be present but is either obscured by boxes or mist.
6:52	Fire still present in target; it licks up occasionally to about 5 ft high.
7:34	Fire continues in both racks unchanged.
8:00	Fire in main array still persists with flames to about 9 ft high; primarily concentrated in ignition area in bottom pallet loads.
9:00	Fire burning at a steady rate; no particular change from last report, but it is not building up. It is being contained.
11:20	Fire as last reported. Some flames licking at base of 3rd level in main array.
13:00	Fire persists in bottom and 2nd levels. Perhaps also into 3rd level of main array. No fire is seen in the target currently, although it is probably present.
15:00	Test concluded.

Figure 3-114: Fire Chronologies – Test 2 (continued)

Time (Min:Sec)	Observation
0:00	Ignition
0:22	Flames 4 ft high.
0:28	Flames 5 ft high.
0:35	Flames lick to 6 ft.
0:49	Flames drop back to about 4½ ft high as cardboard chars.
1:07	Bottle spillage into aisle – there are some leaking bottles and flaming cartons.
1:19	Flaming pool has not yet ignited.
1:26	Flames 5 ft high.
1:31	More spillage.
1:35	Flames well into bottom of 2nd storage level.
1:47	Pool is flaming – fire is building up.
1:57	Flames 23 ft high (top of array).
1:59	First sprinkler opens and flames driven back to 14 ft.
2:20	Flash ignition of target array plastic sheet.
2:25	Flaming extinguished.
2:36	Flaming into west row of main array.
2:45	Flames licking at base of target array across from ignition.
2:55	More material spillage.
3:00	Main array lames licking to about 12 ft high.
3:08	Fire is under, but has not yet ignited target array.
3:19	Target array ignited.
3:29	Fire to about 8 ft high on target array face.
3:42	More material spillage.
3:46	Material spilling from target array.
3:52	Flames licking at 3rd level in target array (about 10' high).
4:16	Minor fire appears to be in west row of main array.
4:28	More spillage from target array.
4:35	Flames lick above main array base of 3rd level (about 10 ft high).
4:45	More spillage from target array.
4:50	Fire is at south end of target array and also is involving the middle and south bays.
5:07	More spillage. Lot of material in aisle.
5:15	Flame height in target is about 6 ft high.
5:20	Now it flares to about 10 ft and then drops back.
5:36	Pool fire is about 1½ ft to east of target array.
5:46	"Invisible" pool fire extends across 2nd aisle.
5:50	Pool fire flows under 2nd target but fire is not yet igniting target.
6:19	Fire reduced at south end. It is no longer on south end and has retreated into 1st aisle space between main and target arrays.
6:37	Second aisle space fire now appears to be out.
6:57	Pool fire extends 10 – 15 ft south of array.
7:24	Fire has moved toward north end in target array; seems to be concentrated in this area. No fire in remaining part of array.

Figure 3-115: Fire Chronologies – Test 4

Time (Min:Sec)	Observation
7:47	Main array fire is about 8 ft high.
7:53	More spillage. Also, fire in target array is licking at 7 ft high: Usually, it is about 4 ft high.
8:09	Fire swirl in aisle space.
8:35	Fire about 3 ft beyond north end of target array toward East.
9:05	Fire pretty well reduced in both main and target arrays
9:27	Flickering flame in target array across from ignition and a little toward south end.
9:56	Flame resurges in main array moving toward south end. Flames lick to 8 ft.
10:11	Fire is reduced; flames are not as visible but they do cover quite a bit of face of main array, bottom loads.
10:29	Appears to be no fire in west row of main array.
11:31	Fire persistent, but relatively low key - confined to east row of main array, primarily toward face.
12:00	Still some residual flaming in target array.
13:26	Still a little residual flaming in target, in main array, it has been reduced somewhat.
14:15	Fire not making any progress. Sprinklers have it confined. Some residual flaming, but not increasing.
15:00	Test concluded.

Figure 3-116: Fire Chronologies – Test 4 (continued)

3.7 Fire Testing of Distilled Spirits in 1.75 L Glass Bottles in Cartons - Rack and Palletized Arrays / Ronald Dean / May 2003

3.7.1 Testing Overview

This test program consisted of three full scale tests. Test No. 1 is omitted since it just repeated a ceiling / in-rack protection design that was previously proven to be adequate for 1 gal (3.8 L) plastic bottles of 50-50 IPA-water mixture. That protection was very effective against the smaller glass bottles with a 50-50 ethanol-water mixture. Test No.2 was intended to evaluate the effectiveness of Class 3 commodity protection against this commodity. The test facility used for this program is described in Section 2.2.

Table 3-15: Fire Testing Summary

Test No.	2	3
Test Date	04-09-02	12-09-02
Parameters		
Commodity	50/50 mix,	50/50 mix,
Storage Arrangement	Rack	Palletized
Array Nominal Size - LxWxH (rnxrnxm [ftxftxft])	7.5 x 2.3 x 5.5 [24¾ x 7.5 x 18]	4.7 x 2.1 x 5.0 [15 1/3 x 7 x 16½]
Stack Height (m [ft-in])	5.5 [18-0]	5.0 [16-4]
Nominal Pallet Load Height (m [ft-in])	1.2 [3-10]	1.1 [3-8]
No. of Storage Levels	4	5
Clearance to Ceiling (m [ft-in])	3.7 [12-0]	4.1 [13-6]
Clearance to Ceiling Sprinklers (m [ft-in])	3.5 [11-5]	3.9 [12-11]
Aisle width (m [ft])	2.4 [8]	2.4 [8]
Ignition Centered Below (No. Ceiling Sprinklers)	4	4
Ceiling Sprinkler Orifice Size (mm [in.])	13 [1/2]	13 [1/2]
Ceiling Sprinkler Temperature Rating (°C [°F])	141.1 [286]	773.9 [165]
Ceiling Sprinkler RTI ((m-sec)$^{1/2}$,[(ft-sec)$^{1/2}$])	1125.9 [228]	1125.9 [228]
Ceiling Sprinkler Spacing (m x m [ft x ft])	3.0 x 3.0 [10 x 10]	3.0 x 3.0 [10 x 10]
Results		
Ceiling Sprinkler Discharge Pressure (bar [psi])	2.1 (4) [30]	2.0 (3) [29]
First Ceiling Sprinkler Operation (min:sec)	2:48	1:25
Last Ceiling Sprinkler Operation (min:sec)	4:54	9:59
Total Ceiling Sprinklers Opened	45 (1)	32 (2)
Total Ceiling Sprinklers Discharge (L/min [gpm])	4936 [1304]	3634 [960]
Avg. Ceiling Discharge per Sprinkler (L/min [gpm])	110 [29]	114 [30]
Peak Gas Temperature (°C [°F])	842.2 [1548]	580.6 [1077]
Peak Ceiling Steel Temperature (°C [°F])	135.0 [455]	83.9 [183]
Ignition of Target Array (min:sec)	3:43	no target
Test Concluded (min:sec)	4:54 (3)	10:00(3)

NOTES: Table 1 Fire Test Summary
1) Number at test termination; post-test: 5 more sprinklers opened for a total of 50.
2) Number at test termination; post-test: 1 more sprinkler opened for a total of 32.
3) Test terminated.

3.7.2 Objective

The outcome of testing a 50/50 alcohol/water mixture in plastic bottles resulted in a change to FM Global Property Loss Prevention Data Sheets 7-29. A question arose whether the upgraded protection was needed for both glass and plastic containers of distilled spirits, or could distilled spirits in glass containers be protected using the original recommended Class 3 commodity protection. Thus, the

objective of this program was to determine whether Class 3 commodity protection was adequate for rack storage of 100 Proof distilled spirits in glass bottles.

The scope of the program was expanded to include one additional test. The purpose was to confirm the protection for palletized distilled spirits in glass bottles.

3.7.3 Test Setup

The program consisted of three tests. Although the tested product was the same in each test, array types, heights and protection varied. Testing order was chosen to maximize product salvage. The provided protection was determined from a previous program using a 50/50 isopropyl alcohol/water mixture. Since the ethyl alcohol/water mixture used in this program was considered to be of a similar hazard, it was believed that the provided protection would be satisfactory. The second test was done to observe the effectiveness of Class 3 protection for the 100 Proof distilled spirits product. Test 3 was a palletized array about 5.0 m [16 ft] high. Details are presented in the subsequent sections.

3.7.3.1 Commodity

The commodity used consisted of 1.75 L [0.46 gal.] glass bottles filled with a 50/50 denatured ethanol/water mixture to simulate 100 Proof distilled spirits. Six bottles were packaged in a corrugated paper carton with 24 cartons stored on a pallet. Thus, each pallet load contained 252 L [66.5 gal.] of liquid. Nominal pallet load dimensions were 1067-mm x 1057-mm x 1118-mm [42-in. x 42-in. x 44-in.] high.

3.7.3.2 Storage Arrangement

3.7.3.2.1 Test 2

The main and primary target arrays were four pallet loads high (5.5 m [18 ft]). Thus, a clearance of about 3.5 m [11 ft-5 in.] existed between the ceiling sprinklers and the array top. Again, a second target of tri-wall corrugated cartons one load high was located to the east of the primary target. See Figure 3-117 for more details.

3.7.3.2.2 Test 3

The main array of palletized storage consisted of the simulated distilled spirits product in the middle two rows (expected fire area) with adjacent rows consisting primarily of tri-wall cartons. The height was about 5.2 m [17 ft-2 in]. Thus, a clearance of about 3.9 m [12 ft 10-in.] existed between the ceiling sprinklers and the array top. In lieu of a target array, a heat flux gage was located across a 2.4 m [8 ft] aisle See Figure 3-118 for more details.

3.7.3.2.3 Ignition Method

Two 76-mm diam. by 152-mm long [3-in. x 6-in.] cellucotton rolls each soaked in 0.24 f [8 oz] of gasoline served as igniters. For the rack storage array, igniters were located on the east face on both sides of the central flue space and for the palletized array, one pallet load in from the south face (Figures 3-117 and 3-118). Igniters were lit with a propane torch.

3.7.3.2.4 Instrumentation

Numerous thermocouples monitored near-ceiling gas temperatures. Additionally, imbedded thermocouples in an angle at the ceiling measured steel temperatures. All sprinklers were timed so that a sequence of operation was obtained. In Test 3 a heat flux gage was located across a 2.4 m [8 ft] aisle from the ignition flue, and elevated 2.5 m [8 ft 7-in.] from the floor. The gage's purpose was to monitor the heat exposure across the 2.4 m [8 ft] aisle to determine the possibility of radiantly igniting storage across the aisle [Figure 3-119].

3.7.3.2.5 Protection

Different protections were used in each test. Test 1 protection was that found in FM Global Properly Loss Prevention Data Sheet 7-29 for 50-50 alcohol water mixtures in up to 1 gal plastic bottles. For Test 2, Class 3 protection found in FM Global Properly Loss Prevention Data Sheet 8-9 was provided. Test 3 was protection previously recommended for case goods protection of palletized distilled spirits in glass bottles. Specifics for each test are given in the following three Sections. See ceiling sprinkler layout diagram, Figure 3-120.

3.7.3.2.5.1 Test 2 (Rack Storage)

Protection was provided by 13 mm [1/2-in.] orifice ceiling sprinklers only. They were rated at 141°C [286°F] and arranged on a 3.0-m x 3.0-m [10-ft x 10-ft] spacing. Operated sprinklers discharged at a density of 14.7 mm/min [0.36 gpm/ft^2]. Ignition was centered beneath four sprinklers.

3.7.3.2.5.2 Test 3 (Palletized Storage)

Protection was provided by 13 mm [1/2-in.] orifice ceiling sprinklers only. They were rated at 74°C [165°F] and arranged on a 3.0-m x 3.0-m [10-ft x 10-ft] spacing. Operated sprinklers discharged at a density of 12.2 mm/min [0.30 gpm/ft^2]. Ignition was centered beneath four sprinklers.

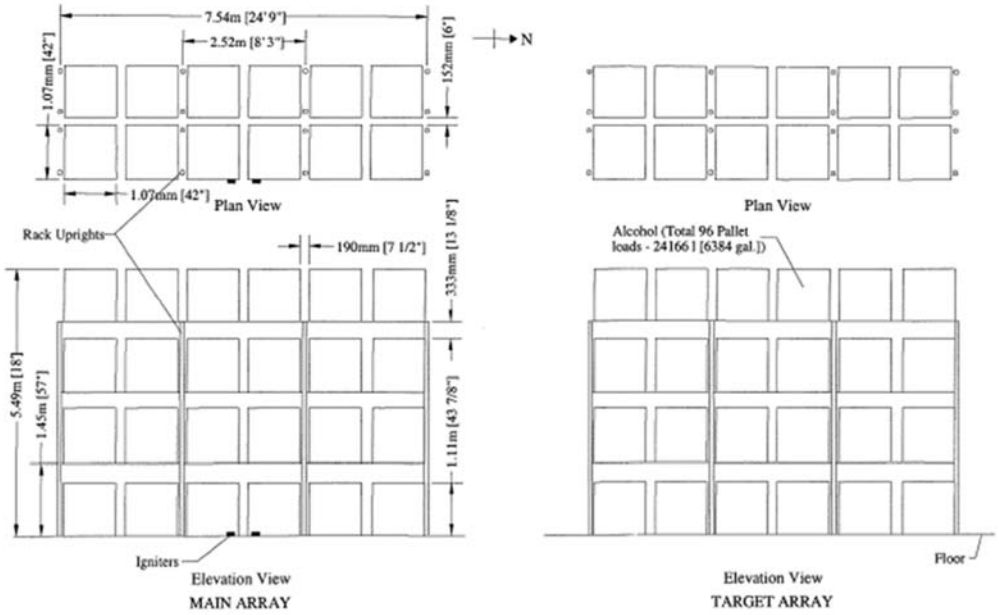


Figure 3-117: Array Setups: Main and Primary Target – Test 2

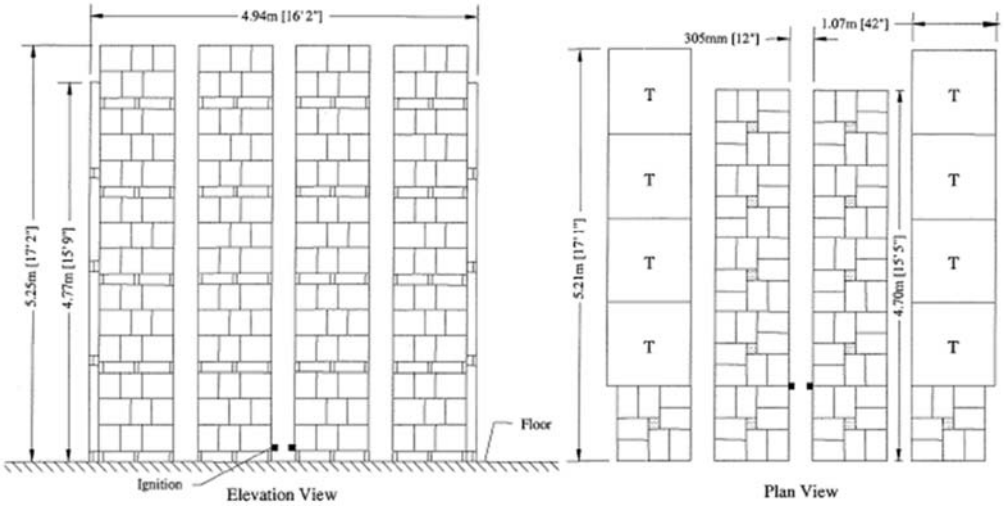


Figure 3-118: Array Setup – Test 3

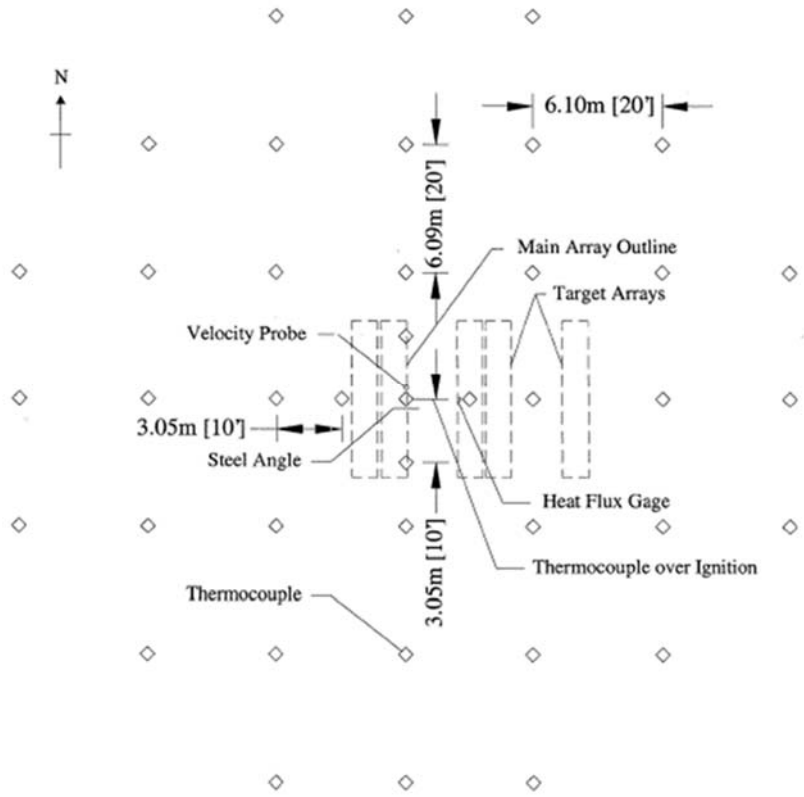


Figure 3-119: Instrumentation and Thermocouple Layout

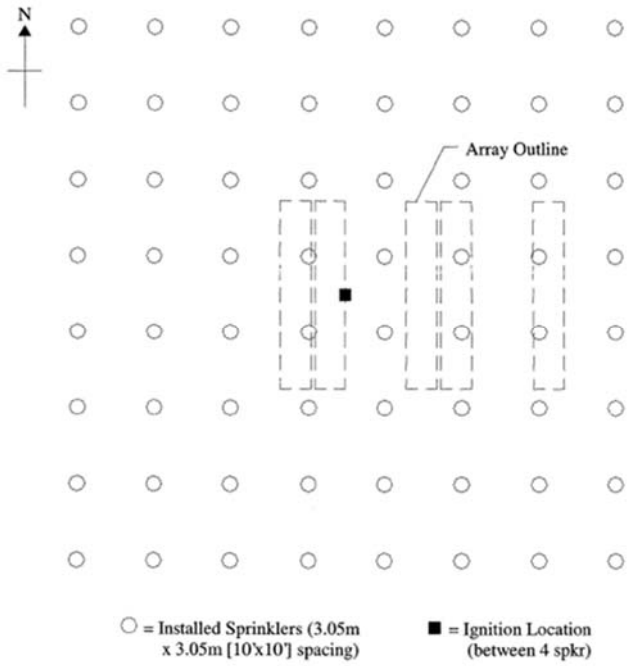


Figure 3-120: Typical Ceiling Sprinkler Layout

3.7.4 Test Results

3.7.4.1 General

Table I summarizes test conditions and results. Figure 3-121 is a summary of pertinent test information. Fire test data for ceiling temperatures, sprinkler operations, and extent of damage are provided in Figures 3-122 through 3-128. Fire chronologies of the test events are found in Section 3.7.6.

3.7.4.2 Test 2 Summary

{nominal 5.5 m [18 ft] high array; Class 3 commodity protection}

(Note: all times in this section are from test start - some expressed as min:sec)

Fire development for the first couple minutes had flames entering the ignition flue; bottle rupturing; pool fire spreading and increasing flame height. The first ceiling sprinkler operated at 2:48 with flames steady on the ceiling. During the subsequent minute, 18 sprinklers opened and the target was pilot ignited. The fire continued developing unabated. At 3:45, the ceiling steel temperature was approximately 104°C [220°F]; about a minute later when the test was terminated at 4:54, the temperature had reached 235°C [455°F] and was steadily increasing. At test termination, the entire main array was involved; fire was in all tiers of the target array and 45 sprinklers were operating. The discharge pressure was expected to be 2.83 bar [41 psi]. However, sprinklers operated so rapidly during the test that the discharge pressure was below 2.41 bar [35 psi] much of the time and at 2.07 bar [30 psi] as the test concluded.

3.7.4.3 Test 3 Summary

{nominal 5.2 m [17 ft] high array; 50-50 alcohol water mixture protection}

(Note: all times in this section are from test start - some expressed as min:sec)

Fire developed rapidly with flames impinging on the ceiling at 1:19. During the next 14 seconds four sprinklers opened bracketing the ignition area. After a brief reduction in flame height, the fire rebuilt with flames again impinging on the ceiling. The peak ceiling temperature of 580°C [1077°F] occurred at 2:31. Temperatures then slowly descended while sprinklers continued to open until about 7 minutes. During the next two minutes, fire severity remained relatively constant. Then at 9 minutes, it began an apparently unrestricted increase resulting in additional sprinkler operations from 20 to a total of 31 when the test was terminated at 10:00. Each of the three major collapses of several stacks which occurred during the test had a minor effect on the fire's severity however the pool fire that was developed covered a large area. Vigorous flaming persisted in the residue as well as the remaining standing product stacks.

TEST NUMBER		2	3
Carton Moisture Content (%)		5.4	5.4
Pallet Load Components (wt%)			
a. Liquid		54	54
b. Glass		37	37
c. Wood		6	6
d. Cardboard		3	3
Pallet Load Combustibles (wt%)			
a. Liquid		85	85
b. Wood		10	10
c. Cardboard		5	5
Laboratory Testing (alcohol/water mix)			
a. Specific Gravity		0.910	0.910
b. Heat of Combustion (kJ/kg [*BTU/lb*])		14,002 [*6020*]	14,002 [*6020*]
c. Closed Cup Flash Point (°C [°*F*])		22.2 [*72*]	22.2 [*72*]
d. Open Cup Flash Point (°C [°*F*])		41.1 [*106*]	41.1 [*106*]
e. Open Cup Fire Point (°C [°*F*])		41.1 [*106*]	41.1 [*106*]
TEST SITE CONDITIONS			
a. Dry Bulb Temp. (°C [°*F*])		21.1 [*70*]	18.3 [*65*]
b. Wet Bulb Temp. (°C [°*F*])		14.4 [*58*]	7.8 [*46*]
c. Relative Humidity (%)		48	16
OUTSIDE CONDITIONS			
a. Wind Speed (m/s [*mph*])		11.2 [*25*]	2.2 [*5*]
b. Wind Direction		SW	N
c. Dry Bulb Temp. (°C [°*F*])		14.4 [*58*]	-5.0 [*23*]
d. Wet Bulb Temp. (°C [°*F*])		11.7 [*53*]	-6.7 [*20*]
e. Relative Humidity (%)		72	59

NOTES:

1. Laboratory Testing
   a. 25 ml pycnometer
   b. Oxygen Bomb Calorimeter
   c. ASTM D-56
   d. ASTM D-92
   e. ASTM D-92
2. The pollution control system was on and all test building windows and doors were closed during the test. System. operation has negligible effect on test fires.

Figure 3-121: Environmental Conditions

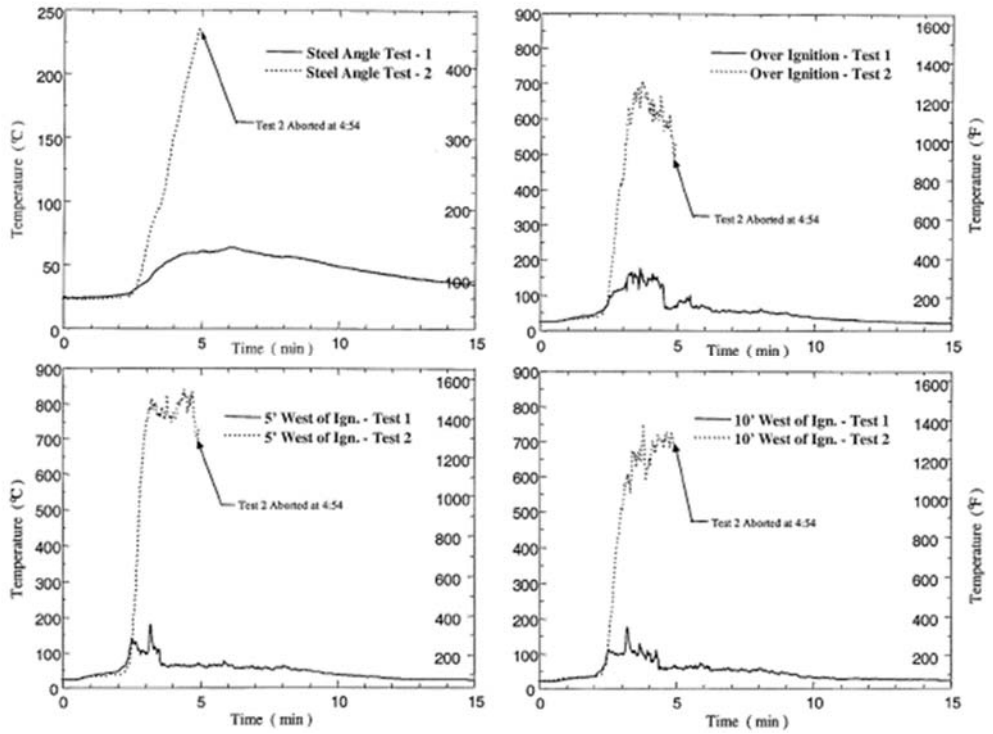


Figure 3-122: Various Ceiling Temperature Comparisons – Tests 2

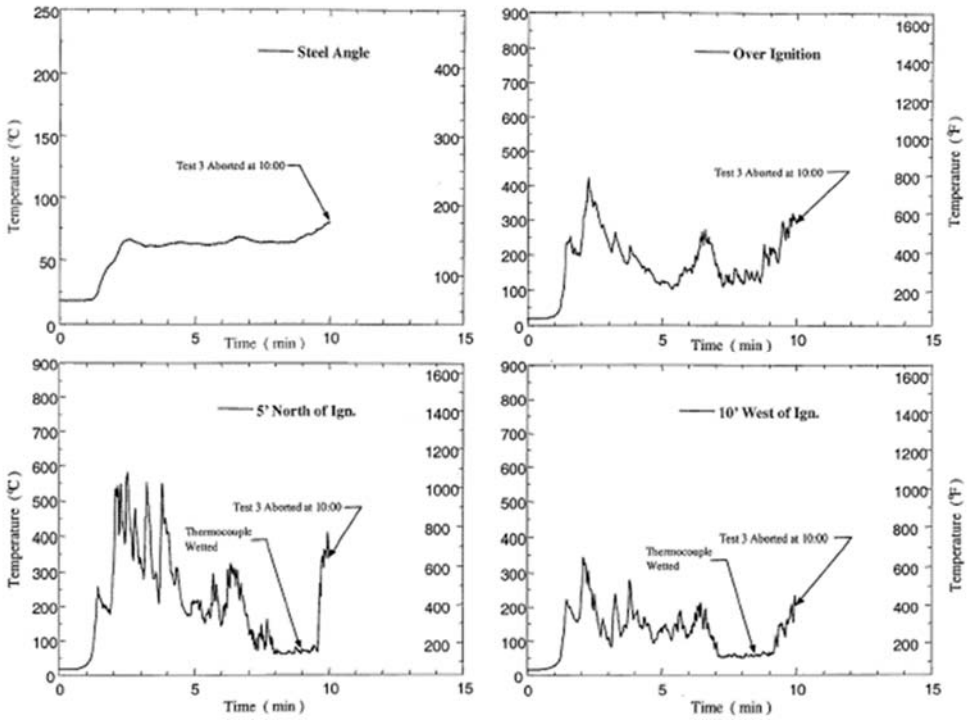


Figure 3-123: Various Ceiling Temperatures – Test 3

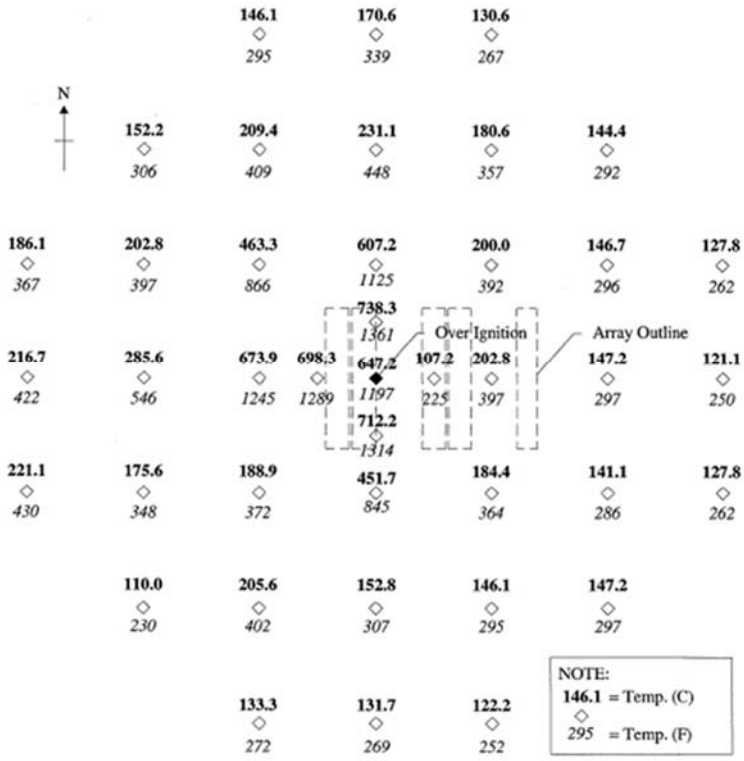


Figure 3-124: Near-Ceiling Maximum One Minute Average Gas Temperatures – Test 2

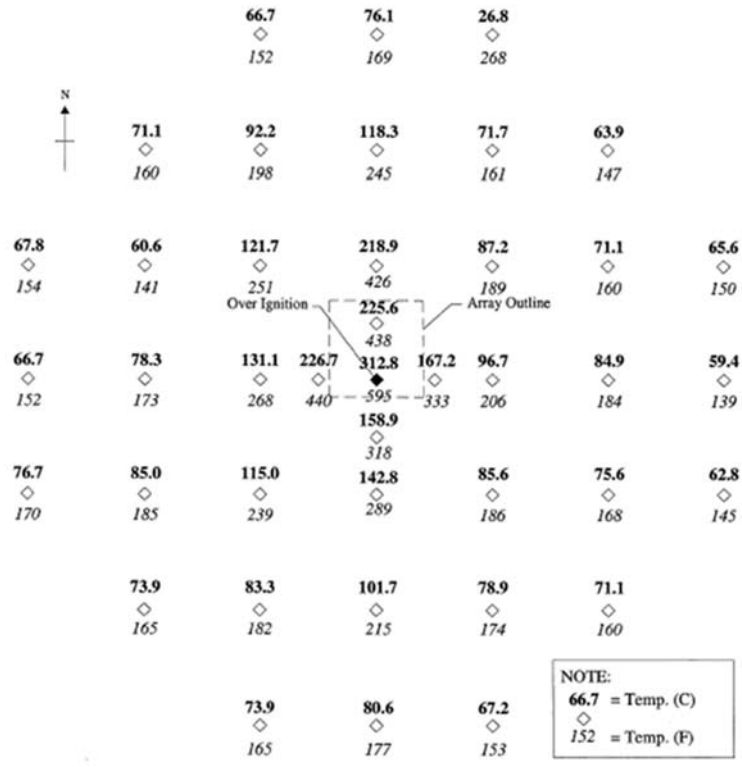
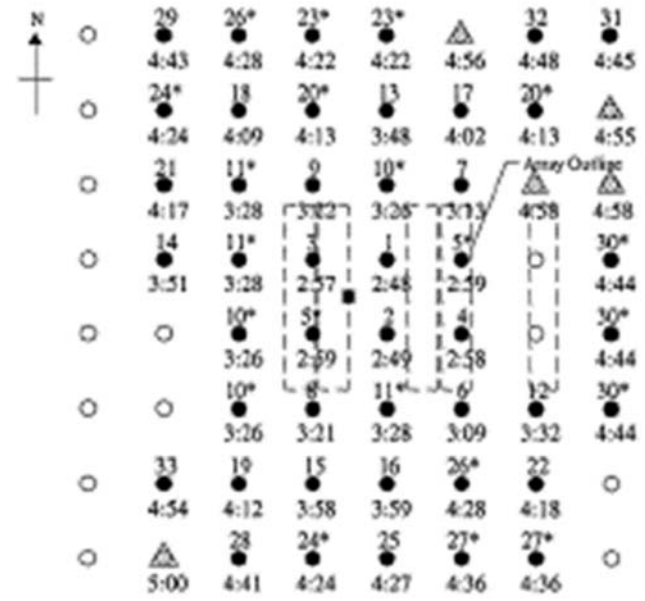


Figure 3-125: Near-Ceiling Maximum One Minute Average Gas Temperature – Test 3



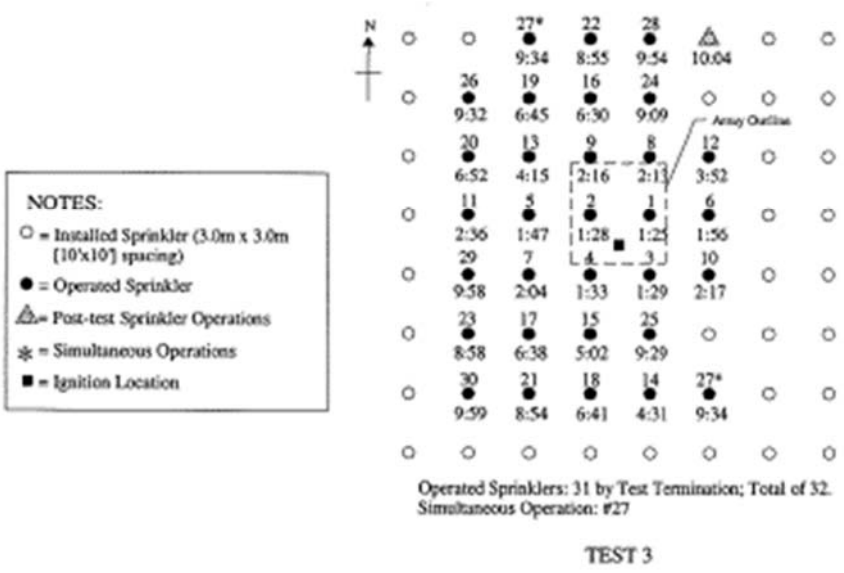


Figure 3-126: Ceiling Sprinkler Operations

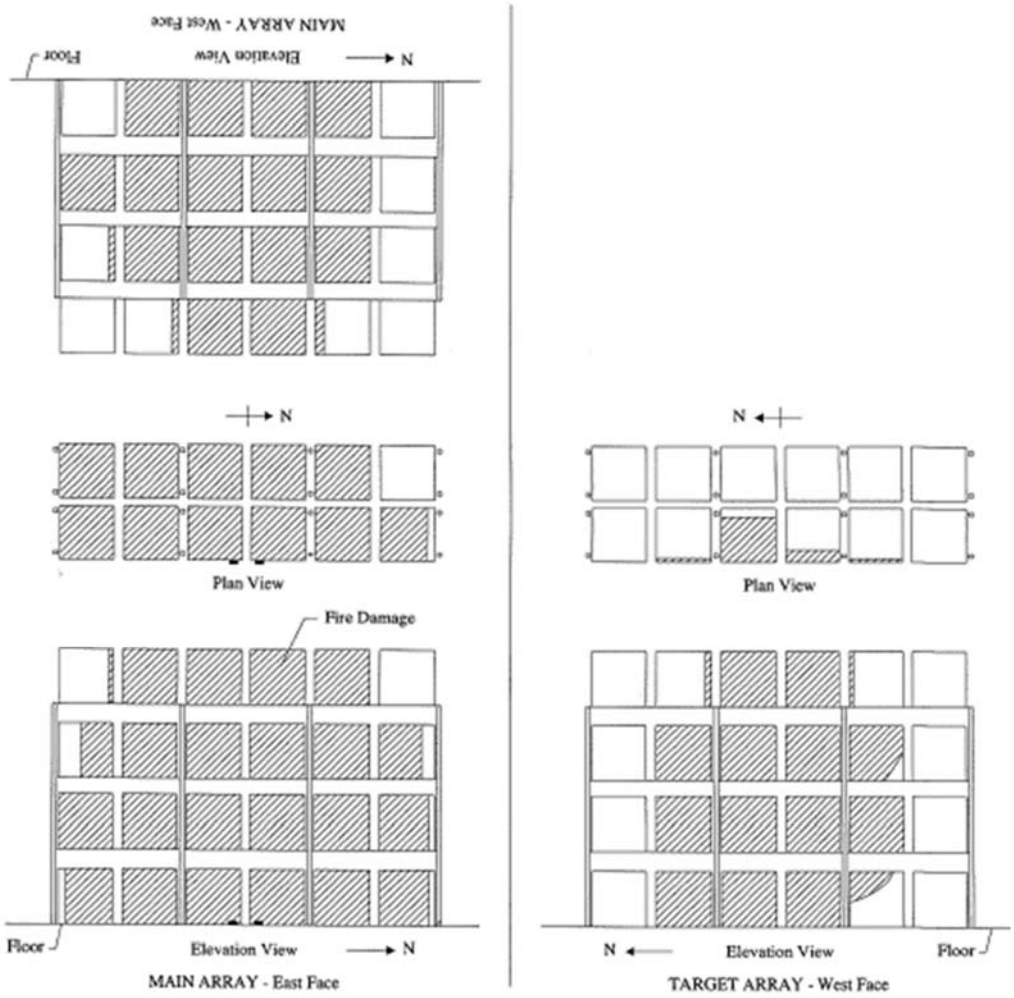


Figure 3-127: Extent of Damage – Test 2

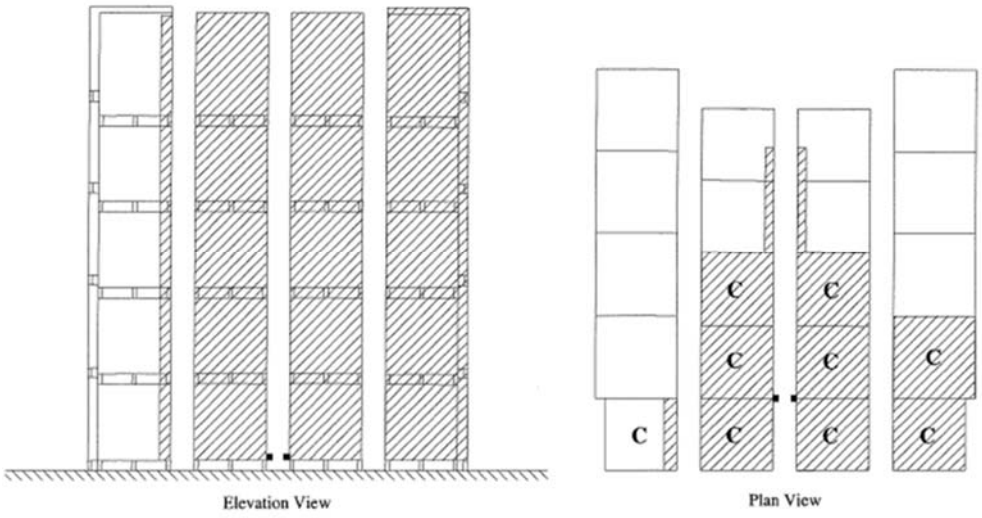


Figure 3-128: Extent of Damage – Test 3

3.7.5 Discussion and Conclusions

3.7.5.1 Test 2

The peak ceiling temperature exceeded 815°C [1500°F]. Fire fully involved the main array and was into all tiers of the target array when the test was terminated at 4:54. It was concluded that Class 3 protection for distilled spirits was inadequate.

3.7.5.2 Test 3

It appeared that collapsing and/or the pool fire which surrounded much of the array, would likely have spread the fire to adjacent storage if such were present. At the 10 minute termination time, flames were on the ceiling where they had been throughout much of the test. Neither the pool nor array fires appeared to be under control at that time. The provided protection was inadequate.

3.7.6 Fire Chronologies

Time (min:sec)	Observations
0:00	Ignition
0:15	Flames half-way up 1st pallet load (about 0.6 m [*2 ft*] high).
0:27	Flames lick to about 1.5 m [*5 ft*] high.
0:34	Flames steady at 1.5 m [*5 ft*].
0:40	Pop and quick horizontal puff of flame.
0:47	Repeat of pop and flame puff.
1:19	Flames into ignition transverse flue space about 0.3 m [*1 ft*] at 1.2 m [*4 ft*] level.
1:48	Flames are about 1.8 m [*6 ft*] high.
2:05	Bottles fall into aisle.
2:09	Flames are into ignition transverse flue space about 0.6 m [*2 ft*].
2:15	Pool fire is about halfway across 2.4 m [*8 ft*] aisle.
2:19	Flames about 3.0 m [*10 ft*] high.
2:25	Flames about 4.6 m [*15 ft*] high.
2:27	Flames are at top of array (about 5.5 m [*18 ft*] high).
2:30	Flames lick at ceiling (9.1 m [*30 ft*] high).
2:40	Flames are into west row of main array.
2:48	First sprinkler opens; flames steady on ceiling.
2:54	Flames out west face at bottom of 3rd & 4th tiers.
3:09	Additional sprinkler opens toward south.
3:10	Weak pool fire reached across aisle to target array.
3:26	Additional sprinklers to west open; flames still on ceiling.
3:28	Report received of 14 open sprinklers.
3:43	Bottle spill onto floor causes liquid release incurring sudden pool fire flame surge, resulting in a pilot ignition of target array's top part of bottom tier.
3:56	Additional sprinklers operate; flames still on ceiling.
4:09	Entire main array involved; fire still building.
4:19	Target array is involved in all tiers across from ignition.
4:54	Hose streams applied - test terminated.

Figure 3-129: Fire Chronology – Test 2

Time (min:s)	Observations
0:00	Ignition
0:18	Flames about 0.9 m [*3 ft*] high.
0:30	Flames about 1.2 m [*4 ft*] high.
0:53	Flames about 2.1 m [*7 ft*] high.
1:02	Flames about 3.7 m [*12 ft*] high.
1:06	Flames about 5.2 m [*17 ft*] high.
1:14	Flames about 7.0 m [*23 ft*] high.
1:19	Flames lick at ceiling (9.1 m [*30 ft*] high).
1:25	1st sprinkler opens.
1:28	2nd sprinkler opens.
1:29	3rd sprinkler opens.
1:33	4th sprinkler opens.
1:40	Flames driven down to about 1.5 m [*5 ft*] above top of array (6.7 m [*22 ft*] high).
1:47	5 sprinklers operating.
1:56	6 sprinklers operating.
2:02	Flames impinging on ceiling (9.1 m [*30 ft*] high).
2:04	Another sprinkler opens.
2:12	Tinkling of glass heard.
2:20	Ignition stacks leaning together at top.
2:29	Flames steady on ceiling.
2:38	Ignition flue is bridged; flames occasionally licking at ceiling.
2:57	Flames are in E & W flues (adjacent to ignition flue).
3:10	Flames steady on ceiling once again.
3:32	Flames are in E adjacent flue to top of array (5.2 m [*17 ft*] high).
3:42	Bottle spillage continues.
3:55	Flames are in W adjacent flue about 1.2 m [*4 ft*] high.
4:05	Additional bottle spillage.
4:13	Area of pool fire surrounding array is increasing. Bluish flames extend out 0.6-0.9 m [*2-3 ft*].
4:30	Another sprinkler opens; additionally, western South ignition stack leans heavily against eastern stacks.
5:02	Another sprinkler opens.
5:26	Fire concentrated in central and eastern flues.
5:33	Major collapse of several stacks (south ignition stacks toward east).
5:47	Flaming pool surrounding residue on floor as well as in residue (fallen material direction is toward SE).
6:00	Fire somewhat reduced over what it was before collapse.
6:16	Several more stacks collapse; major fire flaring up in residue.
6:25	Flames are still on ceiling above standing portion of array.
6:40	Pool fire surrounds residue.
6:48	No fire seen in westernmost row of stacks except pool fire on floor in flue and to west of row.
7:12	Liquid pool fire has moved about 6.1 m [*20 ft*] south from face of original standing array and apparently most of way around array.
7:30	Vigorous fire continues in remaining standing stacks; fire does not appear to be under control.
8:00	Pool fire also does not appear to be under control.
8:55	Flames still appear to be on ceiling. Flare-ups occur as bottles rupture and dump their contents.
9:53	Another stack collapses.
10:00	Test is terminated and hose streams immediately applied to remaining fire.

Post-test Observations

12:10	Some residual fire seen in stacks that remain standing.
15:26	(from IR camera) Indication of a serious shielded fire – hose streams have a tough time getting to it.

Figure 3-130: Fire Chronology – Test 3

3.8 Large-Scale Fire Evaluation: Protection of Cartoned Distilled Liquids in 1.75 Liter Glass Bottles / Seth E. Sienkiewicz / January 2014

3.8.1 Testing Overview

The test facility used for this program is described in Section 2.1.

Table 3-16: Test Summary – Tests 1 - 3

TEST SETUP	TEST NO	01	02	03
	DATE	06/26/2013	07/15/2013	07/29/2013
	Test Commodity	Cartoned Alcohol in Glass Bottles 50% (v/v)		
	Main Array Size [pallets] Target Array Size [pallets]	2 x 6 x 3.5-high (2) 1 x 5, (2) 1 x 2		
	Storage Method	Palletized Standard Array		
	Longitudinal Flue Width [mm (in.)]	305 (12)		
	Ceiling Height [m (ft)]	12.2 (40)	9.1 (30)	
	Storage Height [m (ft)]	5.0 (16.5)		
	Ignition Location	Under 1		
	Carton Moisture Content [% dry (wet)]	7.08 (6.62)	7.17 (6.69)	7.34 (6.84)
	Relative Humidity [%]	33	38	27
	Ambient Temperature [^{o}C (^{o}F)]	23 (74)	23 (73)	32 (89)
PROTECTION	K-Factor [L/min/bar$^{1/2}$ (gpm/psi$^{1/2}$)]	200 (14.0)		
	Sprinkler Temp Rating [^{o}C (^{o}F)]	74 (165)		
	Orientation & Response	Upright QR		
	Spacing [m x m (ft x ft)]	3.0 x 3.0 (10 x 10)		
	Discharge Pressure [bar (psi)]	5.2 (75)	1.2 (18)	3.4 (50)
	Design Density [mm/min (gpm/ft^2)]	49 (1.2)	24 (0.6)	41 (1.0)
TEST RESUTLS	First Ceiling Sprinkler [min:sec]	1:19	1:12	1:04
	Last Sprinkler Operation [min:sec]	22:54	7:50	1:04
	Total Sprinkler Operations	3	13	1
	Peak 10-sec Gas Temp [^{o}C (^{o}F)] @ TIME [min:sec]	88 (191) 20:36	149 (300) 4:52	88 (191) 1:03
	Peak 10-sec Steel Temp [^{o}C (^{o}F)] @ TIME [min:sec]	33 (92) 24:22	49 (121) 6:01	34 (93) 2:23
	Test Duration [min:sec]	30:00	20:00	32:00

Table 3-17: Test Summary – Test 4

TEST SETUP	Test No	04
	Date	08/22/2013
	Test Commodity	Cartoned Alcohol In Glass Bottles - 50% (V/V)
	Storage Method	Rack
	Main Array Size [Pallets] Target Array Size [Pallets]	2 X 6 X 5 (2) 1 X 4 X 5
	Ceiling Height [m (ft)]	10.7 (35)
	Storage Height [m (ft)]	8.8 (29)
	Aisle Width [m (ft)]	1.2 (4)
	Ignition Location	Between 2
	Carton Moisture Content [% Dry (Wet)]	7.22 (6.73)
	Relative Humidity [%]	32
	Ambient Temperature [^{o}C(^{o}F)]	24 (75)
PROTECTION	Ceiling K-Factor [L/min/bar$^{1/2}$ (gpm/psi$^{1/2}$)]	160 (11.2)
	Ceiling Temp Rating [^{o}C (^{o}F)]	68 (155)
	Ceiling Orientation & Response	Upright Sr
	Ceiling Spacing [m x m (ft x ft)]	3.0 X 3.0 (10 X 10)
	Ceiling Discharge Pressure [bar (psi)]	1.9 (28)
	Ceiling Design Density [mm/min (gpm/ft^{2})]	24 (0.6)
	In-Rack K-Factor [L/min/bar$^{1/2}$ (gpm/psi$^{1/2}$)]	115 (8.0)
	In-Rack Temp Rating [^{o}C (^{o}F)]	68 (155)
	In-Rack Orientation & Response	Pendent Qr
	In-Rack Spacing [m (ft)]	1.2 (4)
	In-Rack Pressure [bar (psi)]	1.0 (14)
	In-Rack Flow Rate [L/min (gpm)]	114 (30)
TEST RESUTLS	First Ceiling Sprinkler [min:sec]	N/A
	First In-Rack Sprinkler [min:sec]	0:52
	Total Ceiling Operations /In-Rack Operations	0 2
	Peak 10-Sec Gas Temp [^{o}C (^{o}F)] @ Time [min:sec]	68 (155) 3:19
	Peak 1-Sec Steel Temp [^{o}C (^{o}F)] @ Time [min:sec]	31 (87) 3:48
	Test Duration [min:sec]	15:00

3.8.2 Introduction

3.8.2.1 Background

Testing to date using palletized and solid-pile storage of distilled spirits in glass bottles has used standard and large-orifice sprinklers for ceiling-only fire sprinkler protection. Large-scale fire testing involving ignitable liquids has demonstrated the effectiveness of suppression-mode sprinklers at high water volume discharge rates. However, no current protection options are available for the 1.75 L (59 fl. oz.) glass bottles.

3.8.2.2 Proposed Tests and Objectives

Four large-scale fire tests were planned for this test program. The initial test was designed to investigate the sprinkler fire protection requirements for the maximum anticipated ceiling height for palletized storage. It was anticipated that a successful test at the highest ceiling height would be applicable to lower ceiling heights with the same level of storage beneath it. Two additional fire tests were designed to expand current recommendations contained in in FM Global Property Loss Prevention Data Sheet 7-29 to larger glass bottles and lower sprinkler flow rates than currently available. The fourth test evaluated the protection provided by a combination of ceiling and in-rack sprinklers for a rack storage array, eliminating the need for Scheme A fire protection.

3.8.3 Test Conditions and Procedures

3.8.3.1 Test Commodity

3.8.3.1.1 Distilled Spirits in Glass Bottles

The test commodity used was a 50-percent (by volume) solution of denatured alcohol in 1.75 L (59 fl. oz.) glass bottles. This concentration is representative of 100-proof alcoholic beverages. Per in FM Global Property Loss Prevention Data Sheet 7-29, the commodity would be considered a Group 3 water miscible ignitable liquid. The glass bottles were packaged in corrugated cartons representative of those used in the distilled spirits industry.

Figure 3-131: Photo of 1.75 L (59 fl. oz.) Glass Bottles

The products and materials that made up the test commodity were secured from outside vendors to the distilled spirits industry. The 1.75 L (59 fl. oz.) glass containers were 305 mm (12 in.) high, 125 mm (5 in.) diameter with a formed glass handle (Figure 3-131).

The bottles were packaged in industry-standard 394 mm x 267 mm x 324 mm high (15 ½ in. x 10 ½ in. by 12 ¾ in. high) corrugated paper cartons. Each carton contained six 1.75 L (59 fl. oz.) glass bottles (Figure 3-132).

Figure 3-132: Photo of Bottles Loaded Six per Carton

Thirty-six cartons were arranged in four layers (nine per layer) on the standard FM Global 1.07 m x 1.07 m (42 in. x 42 in.) two-way hardwood pallet. Each pallet-load was approximately 1.41 m (55 ½ in.) high. Due to the box dimensions and positioning on the pallet, the cartons were flush in one direction but did not cover the entire pallet in the other direction. This resulted in a roughly 152 mm (6 in.) difference between the pallet separation and the carton separation (i.e., a 152 mm [6 in.] flue between pallets resulted in a 305 mm [12 in.] flue between cartons). Figure 3-133 presents a photo of the pallet loads from each side. Note the lip created by the pallet on the right-hand photo.

Figure 3-133: Photos of Loading of Cartons on Pallets

3.8.3.1.2 FM Global Standard Class 2 Commodity

FM Global Class 2 commodity was used in the test array to maintain the desired test configurations, but not requiring the main commodity throughout. The Class 2 commodity was used at the periphery of the array, where fire propagation was not expected. However, the corrugated material of the Class 2 commodity does represent an ignitable surface and can be used to assess flame spread.

The FM Global Standard Class 2 commodity consists of three double-wall corrugated paper cartons. The dimensions for the inner, middle, and outer box are 1.02 m x 1.02 m x 0.96 m (40.3 in. x 40.3 in. x 37.8 in.), 1.04 m x 1.04 m x 0.99 m (41.0 in. x 41.0 in. x 39.1 in.), and 1.06 m x 1.06 m x 1.05 m (41.8 in. x 41.8 in. x 41.5 in.), respectively. Inside the cartons is a five-sided sheet metal liner, representing a non-combustible content. The cartoned liner is supported on an ordinary, two-way, slatted deck, hardwood pallet, measuring 1.07 m x 1.07 m x 13 cm (42 in. x 42 in. x 5 in.). A photo of the Class 2 commodity is provided in Figure 3-134.

Figure 3-134: Photo of FM Global Standard Class 2 Commodity

3.8.3.2 Test Arrangement

Two types of tests were conducted as part of this test program. Three palletized tests were conducted to investigate ceiling-only sprinkler protection for the storage method. A single rack storage test was conducted with a combination of ceiling and in-rack sprinklers. The two test setups are described in detail below.

3.8.3.2.1 Palletized Tests

Tests 1-3 were all conducted with a palletized array. All three tests were conducted with an identical storage array setup and the same sprinkler was also used for all tests. The only variables between tests were the ceiling height and the sprinkler design density (water pressure).

The palletized test arrangement consisted of six parallel rows of stacked commodity. Each stack was comprised entirely of cartoned alcohol on pallets or FM Global Class 2 commodity. There were a total of 26 stacks in the test array; 14 stacks of the cartoned alcohol product and 12 stacks of the Class 2

commodity. The center two rows were six pallet-loads long, the two rows on either side of the center were five pallet-loads long, and the outermost rows were two pallet-loads long.

Each row was separated by nominal 305 mm (12 in.) longitudinal flues and the stacks of commodity were butted in the other direction, providing no transverse flues. A plan view schematic of the test array is provided in Figure 3-135 and a pre-test photo of the array is provided in Figure 3-136.

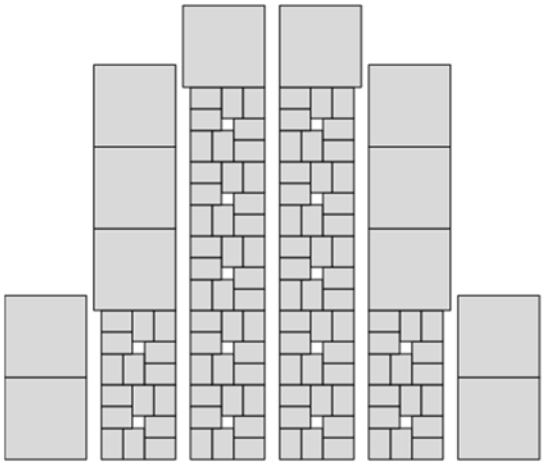


Figure 3-135: Schematic Plan View of Test Array (Tests 1-3)

Figure 3-136: Photo (from Elevation) of the Test Array (Tests 1-3)

The cartoned alcohol commodity was stacked 3.5 pallets high. An attempt was made to stack the commodity higher, but the array lost structural stability as additional weight was added to the array. The 3.5 tiers was the highest that could be stacked stably and safely. The half tier was two cartons high, instead of the four cartons on a full pallet. The overall height of the stacked cartoned alcohol was 5.0 m (16.5 ft). The Class 2 commodity was stacked 4-high for an overall height of 4.8 m (15.7 ft).

Front and side views of the test array are provided in Figure 3-137 and Figure 3-138, respectively.

Figure 3-137: Photo of Front of Test Array (Tests 1-3)

Figure 3-138: Photo of Side of Test Array (Tests 1-3)

The sprinkler used for these tests was a, K200 (K14), quick response, upright-type, 74°C (165°F) temperature-rated sprinkler installed on 3.0 m x 3.0 m (10 ft x 10 ft) spacing at the ceiling only. The sprinkler thermal element was positioned at a nominal distance of 330 mm (13 in.) down from the ceiling.

Forty-nine sprinklers were installed at the ceiling. For these tests, the ignition point within the test array was positioned in the “Under One” ignition configuration (Figure 3-139). Ignition was achieved using two FM Global standard half igniters.

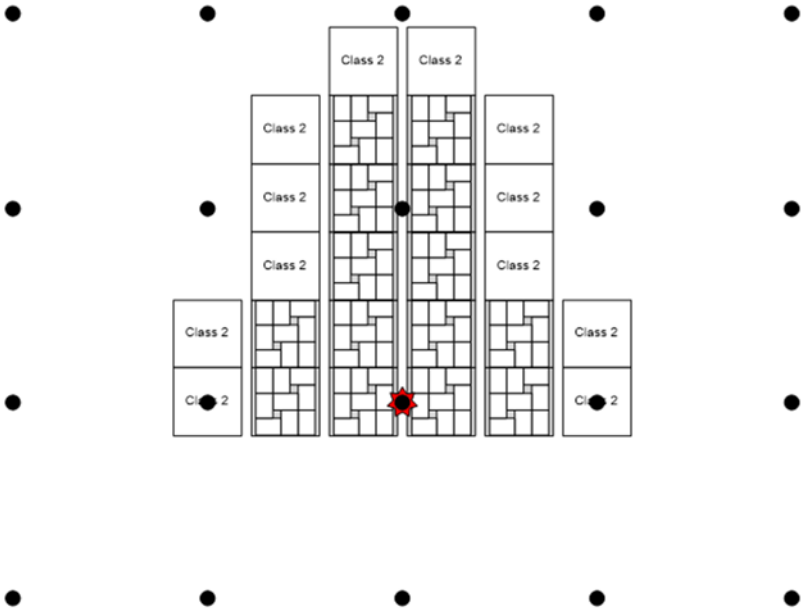


Figure 3-139: Schematic Plan View of Test Array (with Ceiling Sprinklers)

Test 1 was conducted with the ceiling height of 12.2 m (40 ft). The system pressure was set to 5.2 bar (75 psig), which provided a design density of 49 mm/min (1.2 gpm/ft^2).

In Test 2, the ceiling height was reduced to 9.1 m (30 ft) and the system pressure was set to 1.2 bar (18 psig) for a design density of 24 mm/min (0.6 gpm/ft^2).

In Test 3, the final palletized test, the ceiling was kept at 9.1 m (30 ft) but the system pressure was increased to 3.4 bar (50 psig) for a design density of 41 mm/min (1.0 gpm/ft^2).

3.8.3.2.2 Rack Storage Test

Test 4 was the final test of the program and the only test of a rack storage array. The test used a combination of ceiling and in-rack sprinklers to protect the cartoned distilled spirits in glass containers. The test was designed to maximize the distance between the floor and in-rack sprinklers and to provide a ceiling sprinkler design density suitable for protecting the commodity above the in-rack sprinklers.

The double-row rack array was 5 tiers high, with tiers spaced 1.8 m (6 ft) apart, bringing the overall height to nominally 9.1 m (30 ft) high. The ceiling was set to 10.7 m (35 ft), for a clearance of 1.5 m (5 ft). The main array was comprised of the cartoned alcohol commodity in the core of the array and Class 2 commodity at the extent of the array. Two single-row target arrays were placed across 1.2 m (4 ft) aisles and were also made up of cartoned alcohol and Class 2 commodity. The longitudinal flue of the main array and all transverse flues were nominally 150 mm (6 in.). Elevation and plan view schematics of the test array are provided in Figure 3-140 and Figure 3-141, respectively. A photo of the test array is provided in Figure 3-142.

A single-level of in-rack sprinklers were installed 5.5 m (18 ft) above the floor at the 3rd tier level. The in-rack sprinklers were K115 (K8.0), pendent, quick response sprinklers with a 68°C (155°F) link. The sprinklers were spaced every 1.2 m (4 ft) along the pipe, at each flue. Sprinklers were installed in the longitudinal flue, on both faces of the main array, and on the faces of the target arrays facing the main array. The in-rack pressure was set to 1 bar (14 psi) for a flow of 114 lpm (30 gpm) per sprinkler. Schematic drawings of the in-rack sprinkler locations are provided in Figure 3-140 and Figure 3-141. A photo of a face in-rack sprinkler is provided in Figure 3-143.

Ceiling level sprinkler protection was provided by K160 (K11.2), upright, standard response sprinklers with a 68°C (155°F) link. The sprinklers were installed on 3.0 m x 3.0 m (10 ft x 10 ft) spacing and the system pressure was set to 1.9 bar (28 psi). The design density of the ceiling sprinkler system was 24 mm/min (0.6 gpm/ft^2). Ignition was placed between 2 ceiling sprinklers, offset 0.6 m (2 ft) in the transverse flue, and was achieved using two FM Global standard half igniters. Figure 3-141 includes a plan view of the ignition location relative to the in-rack and ceiling sprinklers.

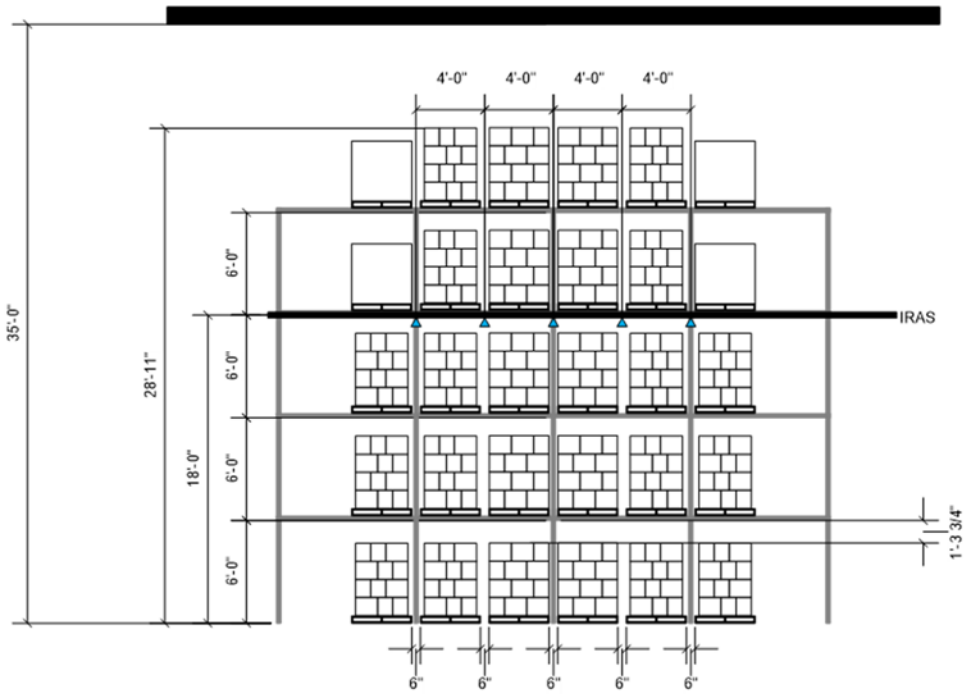


Figure 3-140: Schematic Elevation View of Main Array (Test 4)

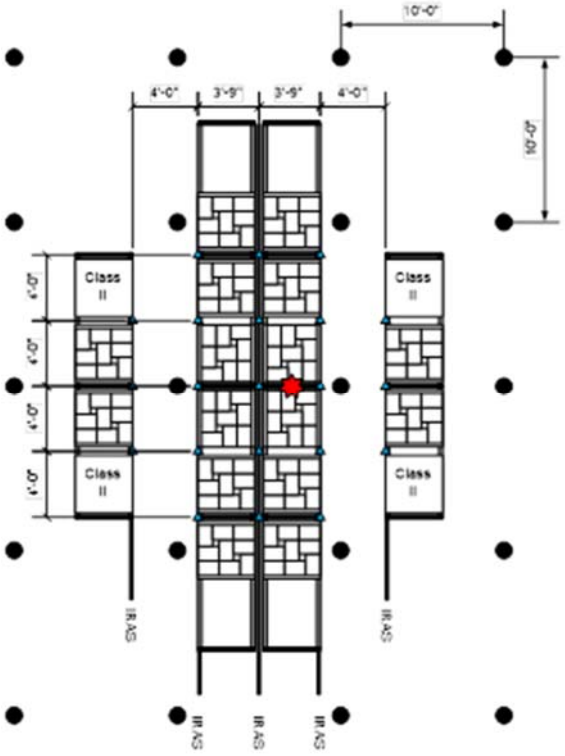


Figure 3-141: Schematic Plan View of Test Array (Test 4)

Figure 3-142: Photo of Test Array (Test 4)

Figure 3-143: Photo of Face In-Rack Sprinkler (Test 4)

3.8.3.2.3 Instrumentation

The following instrumentation was installed for this test program:

- Bare-bead, 0.8 mm (20 gauge), thermocouples installed 165 mm (6.5 in.) below the ceiling at numerous locations. The thermocouples had a response time corresponding to a Response Time Index (RTI) of 8 $(m\text{-}s)^{1/2}$ (14.5 $(ft\text{-}s)^{1/2}$).
- Thermocouples imbedded in a cross-shaped steel angle, made from two 1.2 m (4 ft) long pieces, attached at the ceiling center. Thermocouples are imbedded at the center, at 15 cm (6 in.), and at 30 cm (12 in.) from the ceiling center.

Flow meters and pressure controllers to monitor and control the sprinkler system.

Electrical circuits on each sprinkler to determine individual sprinkler activation times.

3.8.3.3 Test Evaluation Criteria

The following criteria are evaluated and compared for each test. Pass/Fail criteria are indicated with an *, and descriptions indicate pass/fail thresholds. All other criteria described are used for the specific purpose of this project.

3.8.3.3.1 Extent of Fire Damage*

The allowable extent of fire damage was different for the palletized and the rack storage arrays. For the palletized test, the fire damage must not spread beyond the outermost longitudinal flue into the Class 2 commodity. Additionally, the fire must not spread down the longitudinal flue to the face of the array farthest from ignition. Fire spread is allowed to the face closest to ignition. At the time of test termination, the fire must not demonstrate any potential for further propagation.

For the rack storage test, the allowable extent of fire damage below the in-rack sprinklers was limited to the outermost transverse flues. Above the in-rack sprinklers, fire propagation was not allowed into the Class 2 commodity. Fire jump to the target array was permitted, however the fire was not allowed to burn through the back side of the target array. Additionally, the fire must not demonstrate any potential for further propagation at the time of test termination.

3.8.3.3.2 Sprinkler Operations*

For this test program, the total allowable number of sprinkler operations was based on the existing protection points in in FM Global Property Loss Prevention Data Sheet 7-29. All ceiling only protection options are based on a 12-sprinkler design. To verify an existing protection point, or to define new ceiling only protection options, the allowable number of sprinkler operations was based on the 12-sprinkler design, plus a 50 percent safety factor. Therefore, in any test, a maximum of 8 ceiling sprinklers was allowed to operate. For the rack storage test, a limit was not set on the allowable number of in-rack sprinklers and the future design would be based on actual test results.

The operation of a sprinkler is verified four ways. First, a wire was installed onto the sprinkler link/bulb and frame, creating a circuit that is monitored. Upon operation of the sprinkler, the circuit is broken and the event is recorded via electrical signal. Second, select sprinklers at the ceiling core have differential pressure gauges installed in the connecting fitting. Upon operation of a sprinkler, the pressure drop created by the water flow through the open sprinkler orifice is monitored. This method is used to verify the time of operation recorded by the electrical monitoring, or can be used to determine operation time in case of a wire hang-up during the test. Third, for Tests 1-3, a prototype non-contact monitoring method was installed on six sprinklers for feasibility testing. Finally, a post-test ceiling checkout verifies the location of all operated sprinklers and is compared to events registered by the data acquisition system.

3.8.3.3.3 Steel Temperature*

The maximum instantaneous allowable ceiling steel temperature is 538°C (1000°F). This is based on the assessment that structural steel loses 50 percent of its load bearing strength upon reaching the 538°C (1000°F) threshold. The loss of strength could cause failure of the ceiling structure resulting in collapse of the roof. Ceiling steel temperatures in excess of this threshold during a test is taken as an indication of ineffective fire protection.

3.8.3.3.4 Gas Temperatures

Ceiling temperatures are measured at numerous locations on the ceiling, as described in Section 0. Gas temperature trends are analyzed for comparison purposes. Additionally, the peak 10 sec average temperature and the peak 1-min average temperature are recorded for every test.

3.8.4 Test Data, Observations, and Results

3.8.4.1 Palletized Tests

3.8.4.1.1 Test 1

Test 1 was conducted with a ceiling height of 12.2 m (40 ft). The system pressure was set to 5.2 bar (75 psig), which provided a design density of 49 mm/min (1.2 gpm/ft^2).

Upon ignition, flames traveled up the center longitudinal flue and reached the top of the array at 1 min. Flames were 3.0 m (10 ft) above the array, and the first sprinkler operated at 1 min 19 s (Figure 3-144). The sprinkler was very effective at reducing the fire severity and flames were below the top of the array

at 2 min. Alcohol from broken bottles pooled at floor level and flames traveled below the 1st tier pallets into the outermost longitudinal flues.

As the fire continued to burn within the array, glass bottles could be heard breaking as they dropped to the floor causing brief flare-ups in the flue spaces and contributing alcohol to the floor level pool fire. A consistent, small pool fire was present below the pallets of the array, but limited burning was observed in the stacks. As the bottles dropped from the array, the stacks on either side of ignition began to lose stability and were leaning against each other (Figure 3-145).

Figure 3-144: 1st Sprinkler Operation (1 min 19 s)

Figure 3-145: Stack Leaning and Small Pool Fire (5 min 30 s)

Over the next several minutes, glass continued to fall from the array, further reducing the stability of the stacks. At 19 min 54 s, the southernmost stacks collapsed forming large fires at floor level. At 20 min 34 s, additional commodity collapsed towards the west (Figure 3-146). These floor level fires operated two additional ceiling level sprinklers. The operating sprinklers were able to quickly reduce the fire severity in the collapsed commodity and by 25 min, the fires were mostly extinguished. During the remainder of

the test, additional stacks of commodity collapsed, but no additional sprinklers operated and the fire severity never significantly increased. The test was terminated at 30 min.

Figure 3-146: Array Collapse (20 min 36 s)

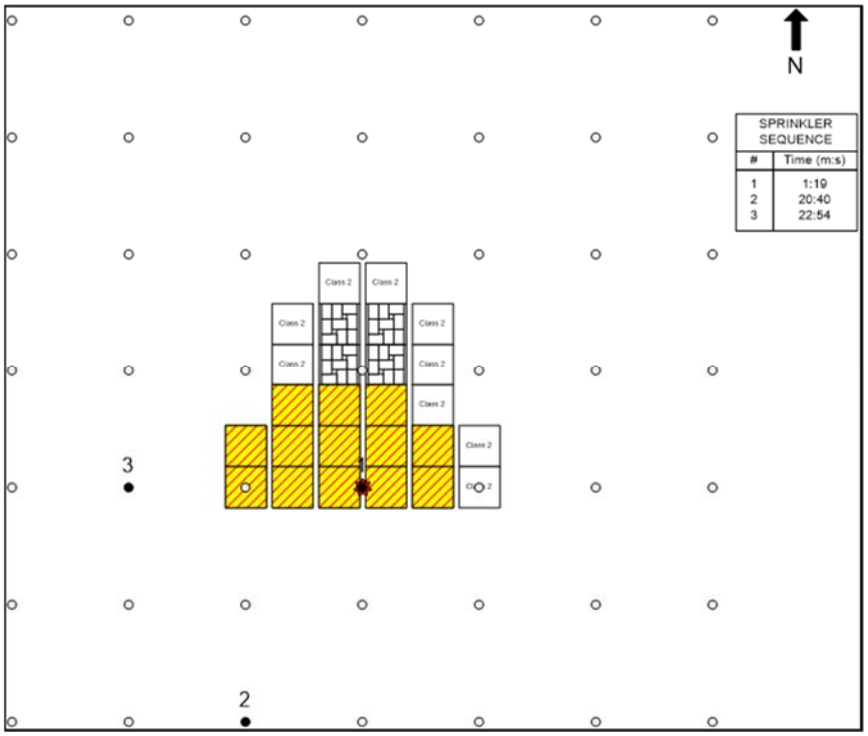


Figure 3-147: Palletized Test - Damage Assessment and Sprinkler Operations

During the test, three sprinklers operated and were able to control the fire present both in the palletized commodity and in collapsed material. In total, 13 of the 26 stacks collapsed during the test. Collapsed material did include Class 2 commodity at the extent of the array, but the fire had not traveled into the commodity at the time of collapse. The pool fire created from the falling bottles did not propagate the

fire beyond the test array prior to collapse. The peak ceiling steel temperature was 33°C (92°F). The damage assessment from the test and the sprinkler operation pattern is provided in Figure 3-147. Data plots from the test can be found in Section 3.8.7 and observations can be found in Section 3.8.8.

3.8.4.1.2 Test 2

In Test 2, the ceiling height was reduced to 9.1 m (30 ft) and the system pressure was set to 1.2 bar (18 psig) for a design density of 24 mm/min (0.6 gpm/ft^2).

The flames traveled up the longitudinal flue and reached the top of the array at 1 min 6 s. The 1st sprinkler operated at 1 min 12 s and flames were 3.0 m (10 ft) above the array at the time the sprinkler operated (Figure 3-148). The sprinkler was able to knock the flames down but the fire persisted within the longitudinal flues and below the pallets of each tier. Glass bottles fell from the stacks as the cartons burned away and the pallet loads began to lean within the array at 2 min 25 s. The top of the stacks leaned in towards each other and completely blocked the longitudinal flue.

Over the next several minutes, glass bottles continued to fall within the test array, causing pooling at floor level, and the fire intensity increased. At 3 min 19 s, four sprinklers were operating but the fire was continuing to spread throughout the array. At 3 min 31 s, fire was present in all four longitudinal flues from pooling liquid that traveled below the floor level pallets. These fires continued to weaken the array and caused the pallet loads to lean. At 5 min, eight sprinklers had operated.

Figure 3-148: Test 2 - 1st Sprinkler Operation (1 min 12 s)

At 5 min 15 s, four stacks of the test array collapsed towards the west (Figure 3-149). Collapsed commodity reached the western extent of the test pad, approximately 6.1 m (20 ft) from the array.

Liquid from the bottles ran into the grates and drains located at the perimeter of the test pad. The collapsed commodity did burn at floor level over the majority of the area and the flames were 1.0-1.2 m (3-4 ft) in height. Flames remained present in the main array (still standing) and were extending beyond the top of the array.

At 7 min 50 s, 13 sprinklers had operated but fires remained in both the remaining stacks of the array and within the collapsed commodity. At 8 min 47 s, the fire had propagated below the remaining stacks and was burning beyond the easternmost stacks of Class 2 commodity, resulting in unacceptable sprinkler performance. Additional stacks did collapse at 15 min 48 s. The test was terminated at 20 min.

Shifting Array (4 min 22s)

Array Collapse (5 min 14 s)

Collapsed Material (5 min 50 s)

Figure 3-149: Test 2 – Array Collapse

During the test, 13 sprinklers operated but did not adequately control the fire. The initial sprinkler operation did reduce the fire intensity, but the fire remained within the pool and test array, and continued to weaken the stability of the stacks. The majority of the array collapsed during the test and commodity was spilled to the western, eastern, and southern extent of the test pad (approximately 6.1 m [20 ft]) in each direction. The peak ceiling steel temperature was 49°C (121°F). The damage assessment from the test and the sprinkler operation pattern is provided in Figure 3-150.

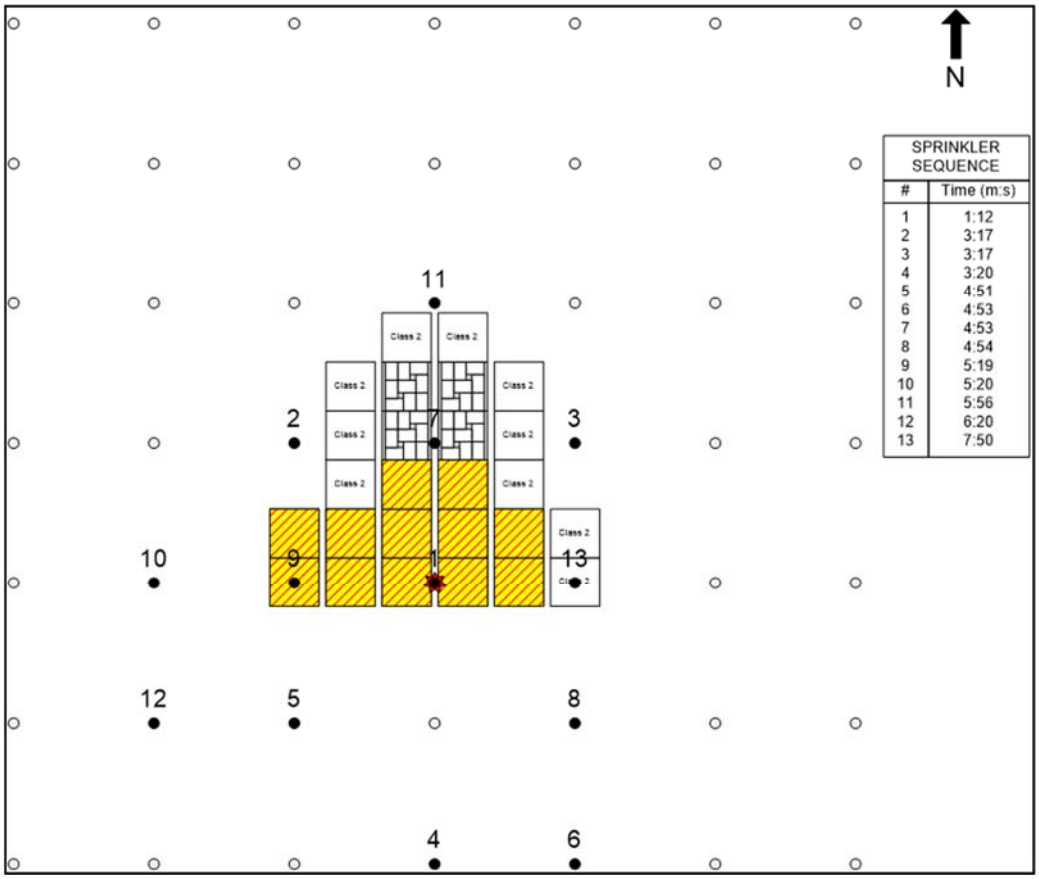


Figure 3-150: Test 2 - Damage Assessment and Sprinkler Operations

3.8.4.1.3 Test 3

In Test 3, the final palletized test, the ceiling was kept at 9.1 m (30 ft) but the system pressure was increased to 3.4 bar (50 psig) for a design density of 41 mm/min (1.0 gpm/ft^2).

Upon ignition, the flames traveled up the longitudinal flue and reached the top of the array at 56 s. The 1st sprinkler operated at 1 min 4 s and flames were 1.8 m (6 ft) above the array at the time the sprinkler operated (Figure 3-151). The fire was knocked down below the top of the array but was still present in the longitudinal flue at 2 min 7 s. Glass bottle breakage was occurring throughout the test. The center stacks around ignition were leaning against each other by 3 min 31 s. Very small fires were present in the longitudinal flue and as glass bottles fell from the array, small flare-ups were caused from the breaking bottles. However, none of these contributed significantly to the fire severity. The breakage continued through to test termination, but no sustained fire was visible within the array. The test was terminated at 32 min.

1st Sprinkler Operation (1 min 4 s)

(7 min 34 s)

(28 min 10 s)

Figure 3-151: Test 3 Fire Progression

During the test, one sprinkler operated and was able to control the fire. During the course of the test, a small fire remained in the longitudinal flue and glass bottles did fall from the array and break. However, none of the falling bottles created a sustained pool fire and the array did not collapse during the test. Stacks were leaning within the array at the time of test termination. Post test, the array did collapse as seen in Figure 3-152. The peak ceiling steel temperature was 34°C (93°F). The damage assessment from the test and the sprinkler operation pattern is provided in Figure 3-153.

Figure 3-152: Test 3 - Array Collapse During Cleanup (Post Test)

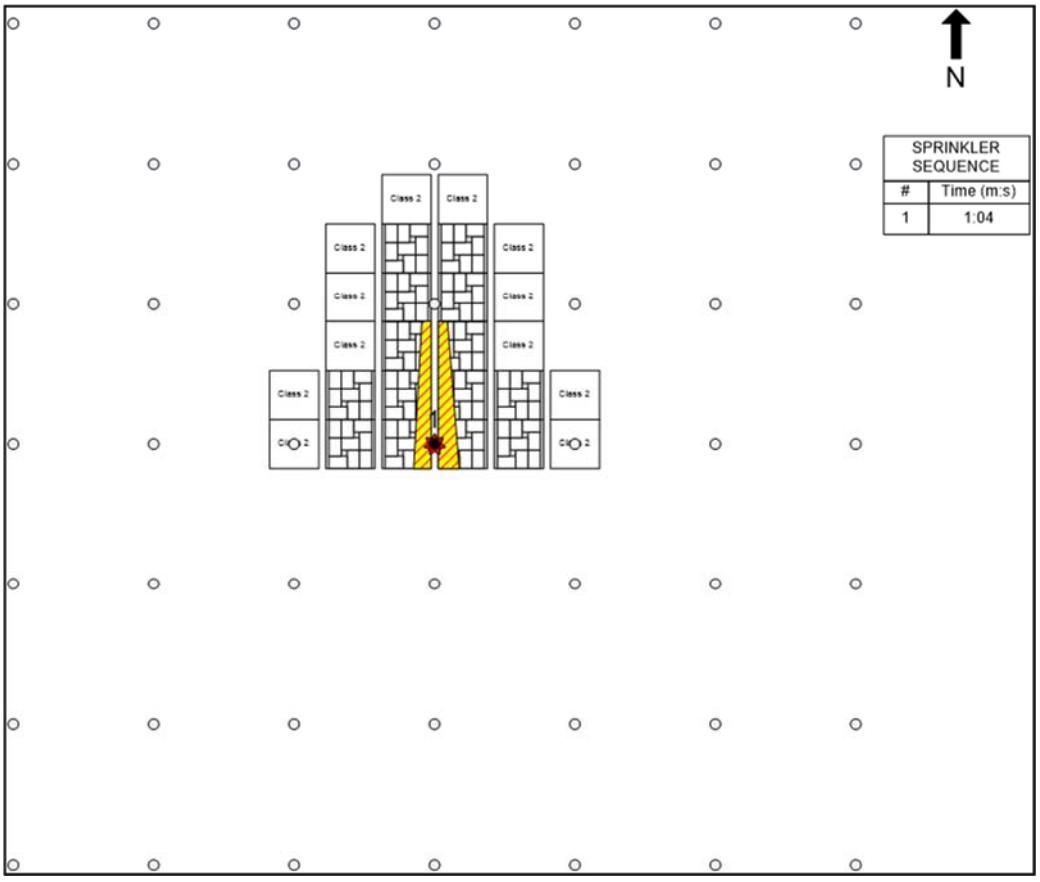


Figure 3-153: Test 3 - Damage Assessment and Sprinkler Operations

3.8.4.1.4 Rack Storage Test

Test 4 was the final test of the program and the only test of a rack storage array. The test used a combination of ceiling and in-rack sprinklers to protect the cartoned distilled spirits in glass containers.

Upon ignition, the fire traveled up the center transverse flue of the array and was above the 1st tier at 24 s. Flames were just reaching the 3rd tier when the 1st in-rack sprinkler operated at 52 s (Figure 3-154). The IRAS reduced the fire intensity and at 1 min 41 s, flames were not observed above the 2nd tier level. During the test bottles fell from the array causing brief flare-ups. Some of these flare-ups sent flames into the second tier. At 3 min 8 s, one of these flare-ups operated a 2nd in-rack sprinkler in the longitudinal flue. At 5 min, no fire could be observed within the array and the test was terminated at 15 min.

Figure 3-154: 52 s - 1st IRAS Operation

During the test, two in-rack sprinklers operated and were able to control the fire. No ceiling level sprinklers operated during the test. Damage within the array was primarily in the 1st and 2nd tier commodity along the face of the ignition flue. A photo of the typical damage observed is provided in Figure 3-155. The peak ceiling steel temperature was 31^{o}C (87^{o}F). The damage assessment from the test and the sprinkler operation pattern are provided in Figure 3-156 and a blown-up view of the damage area with operated in-rack sprinklers is provided in Figure 3-157.

Figure 3-155: Post Test Damage to Commodity near Ignition Flue – Test 4

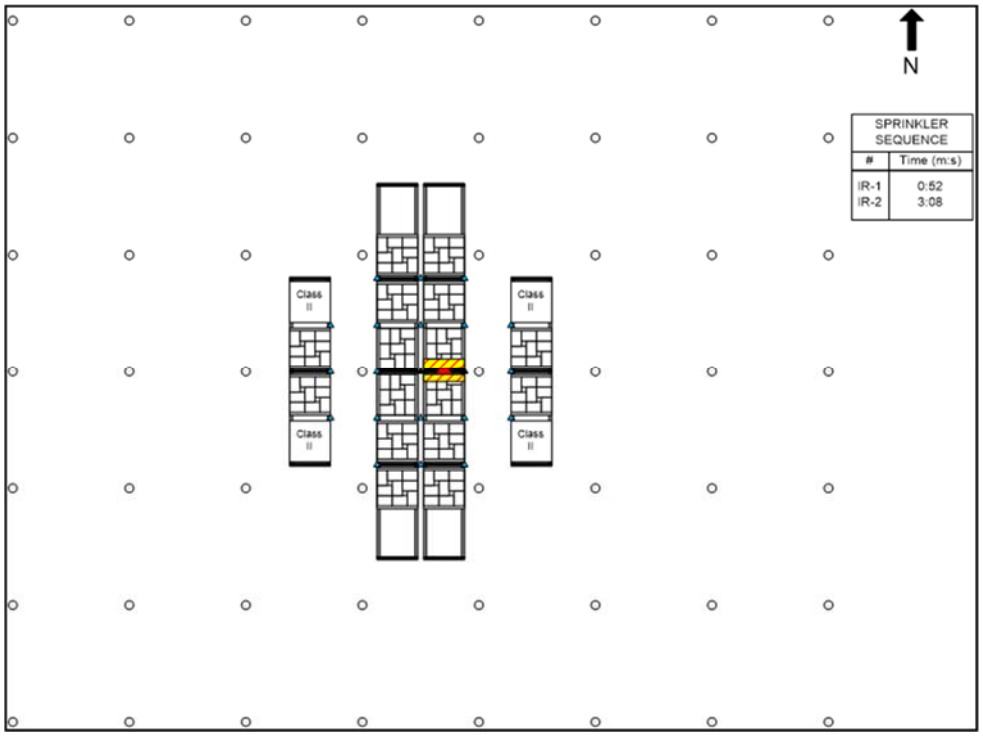


Figure 3-156: Rack Storage Test - Damage Assessment and Sprinkler Operations

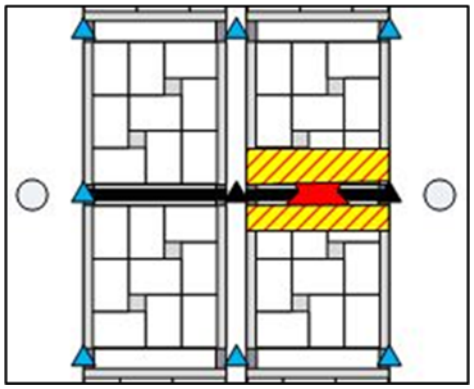


Figure 3-157: Rack Storage Test – Close-up Damage Assessment with IRAS Operations

3.8.5 Analysis and Summary

3.8.5.1 Summary and Analysis of Palletized Tests

During this project, three tests were conducted with palletized arrays of cartoned distilled alcohol (50% v/v) in 1.75 L (59 fl. oz.) glass bottles beneath two different ceiling heights. The commodity was stored to a height of 5.0 m (16.5 ft). Ceiling only protection was provided by upright K200 (K14.0), quick response sprinklers, with a 74°C (165°F) link installed on 3.0 m x 3.0 m (10 ft x 10 ft) spacing. The design density for each test was varied.

For each test, the time of 1st sprinkler activation was comparable. The 12.2 m (40 ft) ceiling height in Test 1 only resulted in a few second delay in the operation of the 1st sprinkler compared to the 9.1 m (30 ft) ceiling in Tests 2 and 3. For Tests 1, 2, and 3, the time to 1st sprinkler operation were 1 min 19 s, 1 min 12 s, and 1 min 4 s.

However, the impact of the water density on the test was significantly different for each of the tests. The lowest design density used in the project was 24 mm/min (0.6 gpm/ft^2) for Test 2. The initial sprinkler operation was able to knock the flames down but the fire persisted within the array. As the fire continued to burn, additional sprinklers operated and the palletized commodity continued to lose structural stability. Alcohol from broken bottles that fell from the array created a floor level pool fire that propagated beneath a significant portion of the array involving additional commodity.

This further weakening of the array caused multiple stacks to collapse over the remainder of the test. During collapse, commodity and liquid reached the extent of the test pad in both the southern and western direction where perimeter grates were present. These perimeter drains were located approximately 6.0 m (20 ft) from the nearest base of the array. As the 5.0 m (16.5 ft) stacks collapsed, the commodity easily reached the drains 6.0 m (20 ft) away. However, if the drains had not been present, the commodity and liquid would have likely spread over a larger area. Ultimately, a combination of the fire spread beyond the array, array collapse, and the overall number of sprinkler operations (13) deemed this test unsuccessful. Regardless of the number of sprinkler operations, the sprinkler design density did provide sufficient protection against the collapsed commodity. Once activated, the sprinklers were able to control and nearly extinguish all floor level pool fires and burning

solid commodity (pallets and corrugated board) present around the array. This result is consistent with the required protection in in FM Global Property Loss Prevention Data Sheet 7 29 for lower storage heights and pool fires.

Directly comparable to Test 2 was Test 3, which was also conducted beneath a 9.1 m (30 ft) ceiling. For this test, the design density was 41 mm/min (1.0 gpm/ft^2). During the 32 min long test, a single sprinkler operated and controlled the fire. The increased design density quickly reduced the fire intensity in the longitudinal flue and prevented a significant portion of the array from becoming involved.

During the test, no collapse was observed. However, the array was unstable and ultimately did collapse during post-test operations. It is likely that had the test been run significantly longer, a portion of the array would have collapsed. This collapse may have operated additional sprinklers, but based on the conclusion that the design density in Test 2 was sufficient for the collapsed commodity, it is implied that the higher density in Test 3 would have also been sufficient.

Finally, Test 1 was conducted at a ceiling height of 12.2 m (40 ft). This test also utilized the highest design density, at 49 mm/min (1.2 gpm/ft^2). During the initial portion of the test, a single sprinkler operated and limited the fire severity in the palletized array. The fire did remain in the array throughout the duration of the test, and the stacks lost structural stability. Eventually several stacks did collapse resulting in two additional sprinkler operations. The three sprinklers were able to control the fire in the palletized array, the pool fire created from spilled liquid, and in the solid commodity near the area of collapse. Similar to the observations from Test 2, collapsed commodity reached the extent of the test floor 6.0 m (20 ft) away.

None of the tests generated unacceptable ceiling steel temperatures. The highest steel temperature measured for any of the palletized tests was 49°C (121°F).

3.8.5.2 Summary and Analysis of Rack Storage Test

A single test was conducted with a rack storage array of cartoned distilled alcohol (50% v/v) in 1.75 L (59 fl. oz.) glass bottles. The commodity was stored to a height of 9.1 m (30 ft) below a 12.2 m (40 ft) ceiling. Protection was provided by a combination of ceiling and in-rack sprinklers. The in-rack sprinklers were installed 5.5 m (18 ft) above the floor at the 3rd tier level.

During the test, two in-rack sprinklers operated and were able to control the fire within the array. The fire never propagated above the level of in-rack sprinklers or beyond the ignition flue. The highest steel temperature measured for the rack test was 31°C (87°F). No ceiling sprinklers operated during the test and the designed ceiling sprinkler density was not evaluated. However, the in-rack sprinkler design was deemed acceptable for protection of 5.5 m (18 ft) vertical increments of cartoned distilled alcohol (50% v/v) in 1.75 L (59 fl. oz.) glass bottles.

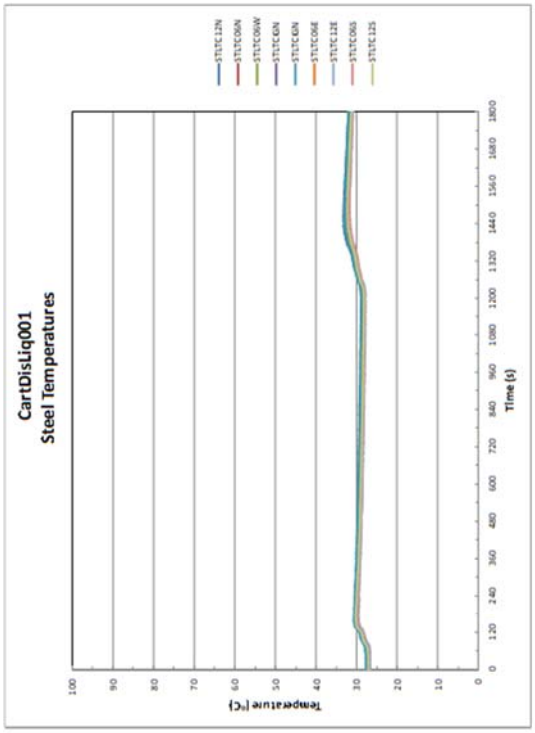
3.8.6 Conclusions and Recommendations

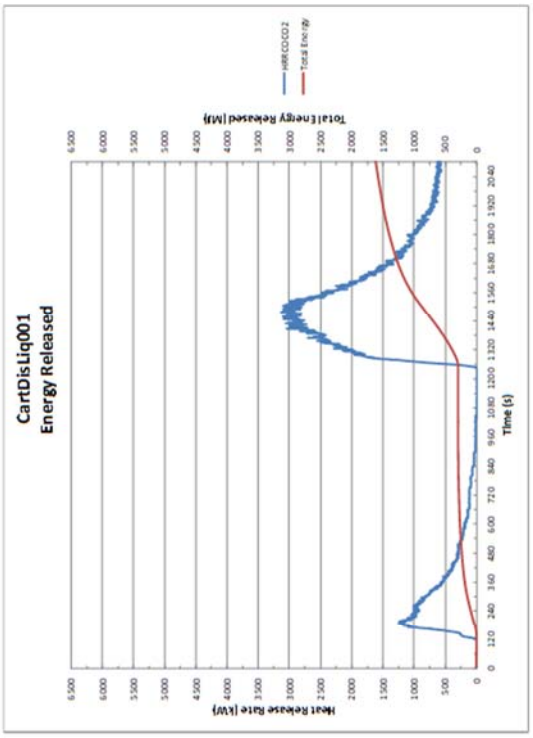
3.8.6.1 Conclusions

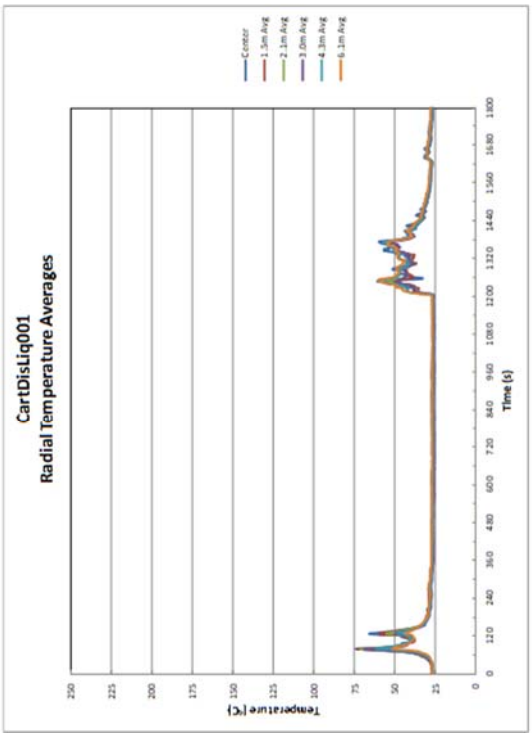
The results of the testing summarized in this report support the following conclusions:

- Palletized cartons of distilled alcohol (50% v/v) in 1.75 L (59 fl. oz.) glass bottles stored 5.0 m (16.5 ft) high below a 9.1 m (30 ft) ceiling cannot be adequately protected with upright K200 (K14.0), quick response, 74°C (165°F) sprinklers operating at 1.2 bar (18 psi). The design does not prevent fire spread through the array and results in an unacceptable number of sprinkler operations.
- Palletized cartons of distilled alcohol (50% v/v) in 1.75 L (59 fl. oz.) glass bottles stored 5.0 m (16.5 ft) high below a 9.1 m (30 ft) ceiling can be adequately protected with upright K200 (K14.0), quick response, 74°C (165°F) sprinklers operating at a pressure of 3.4 bar (50 psi).
- Palletized cartons of distilled alcohol (50% v/v) in 1.75 L (59 fl. oz.) glass bottles stored 5.0 m (16.5 ft) high below a 12.2 m (40 ft) ceiling can be adequately protected with upright K200 (K14.0), quick response, 74°C (165°F) sprinklers operating at a pressure of 5.2 bar (75 psi).
- Even with adequate fire protection, the stability of palletized commodity is impacted and collapse is likely. If collapse does occur, the commodity could spread greater than 6.1 m (20 ft) from the array. Collapse of palletized commodity and resulting ignitable liquid pool should be considered in the design of the fire protection system through operating areas sufficient to accommodate the collapse, drainage, or other viable methods.
- Pool fires from spilled distilled alcohol (50% v/v) and fires involving collapsed solid commodity (nominally 1.5 m [5 ft]) high can be adequately protected with upright K200 (K14.0), quick response, 74°C (165°F) sprinklers operating at 1.2 bar (18 psi) or higher.
- A single level of K115 (K8.0), pendent, quick response in-rack sprinklers, installed on 1.2 m (4 ft) spacing in the flues and along the faces of a rack storage system, discharging at a flow rate of 114 lpm (30 gpm), can adequately protect a 5.5 m (18 ft) vertical section of cartoned distilled alcohol (50% v/v) in 1.75 L (59 fl. oz.) glass bottles.
- No evaluation was made of the ceiling protection provided above the rack storage array since no sprinklers operated during the test.

3.8.7 Data Plots







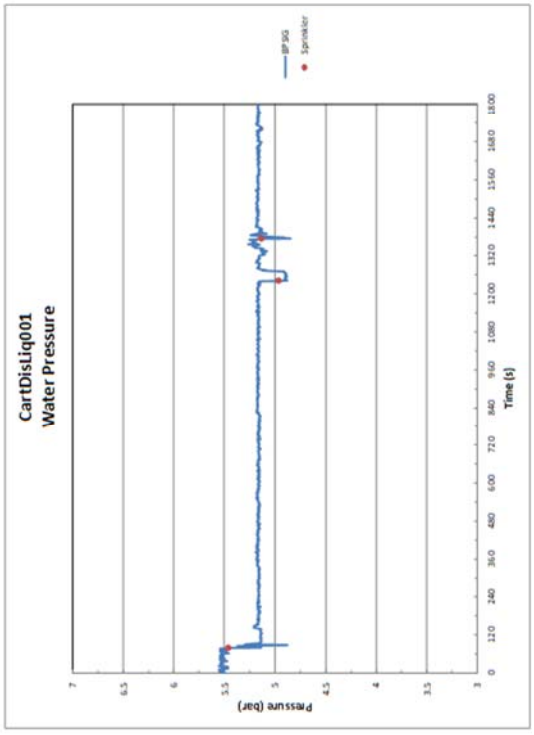
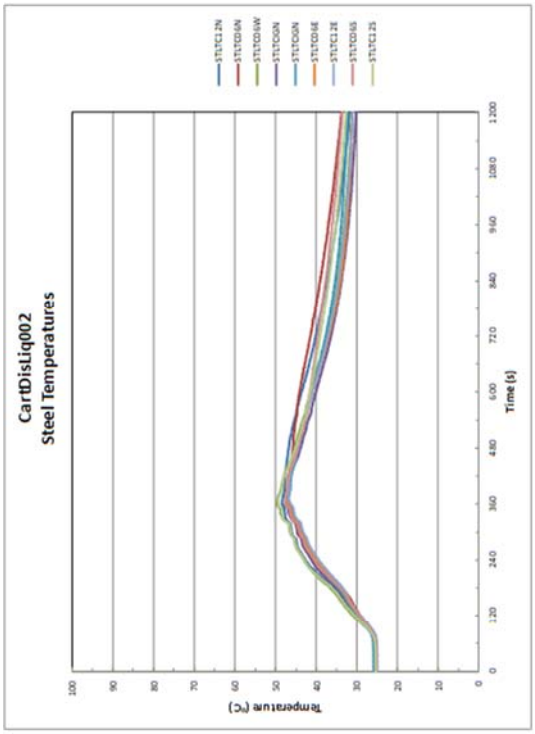
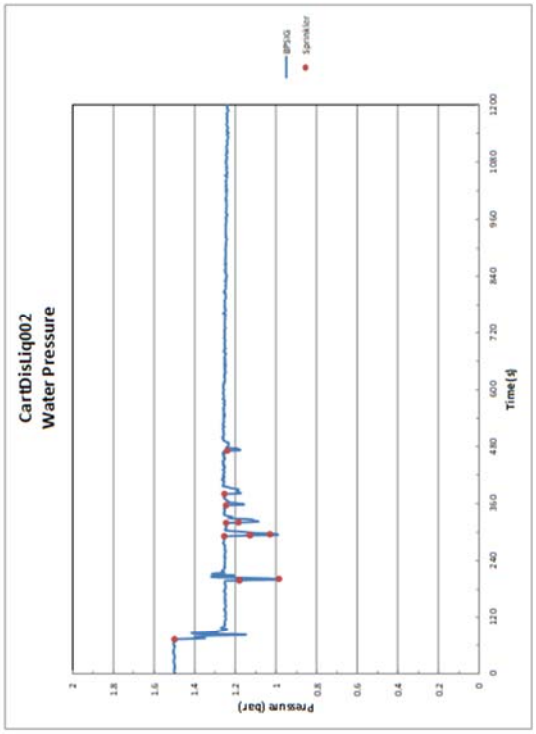
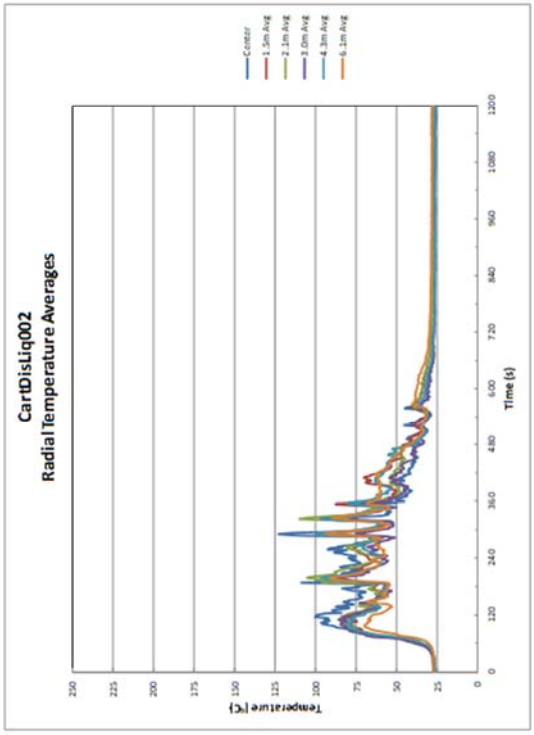


Figure 3-158: Test 1 – Data Plots







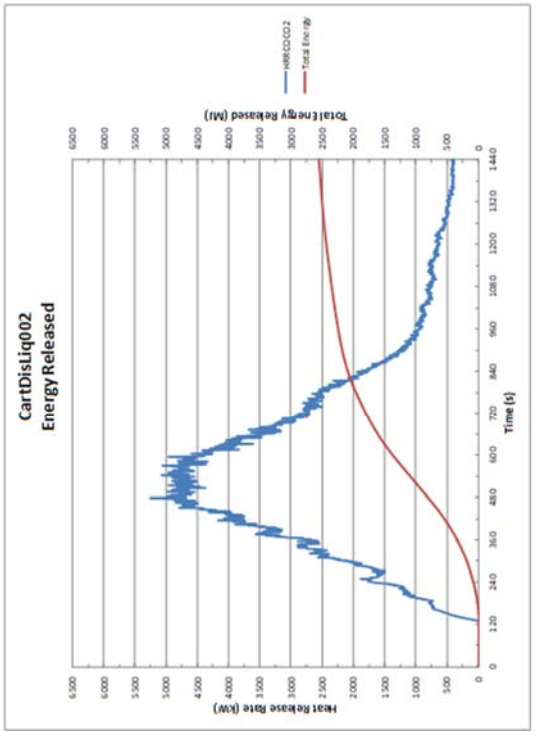
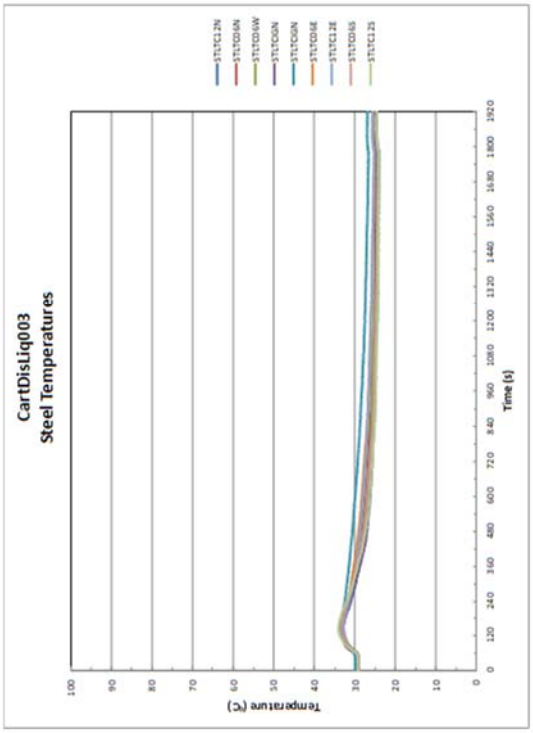
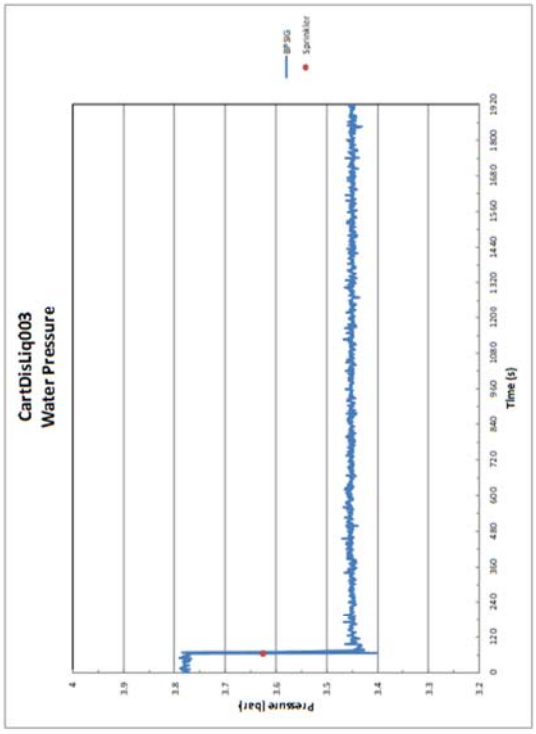
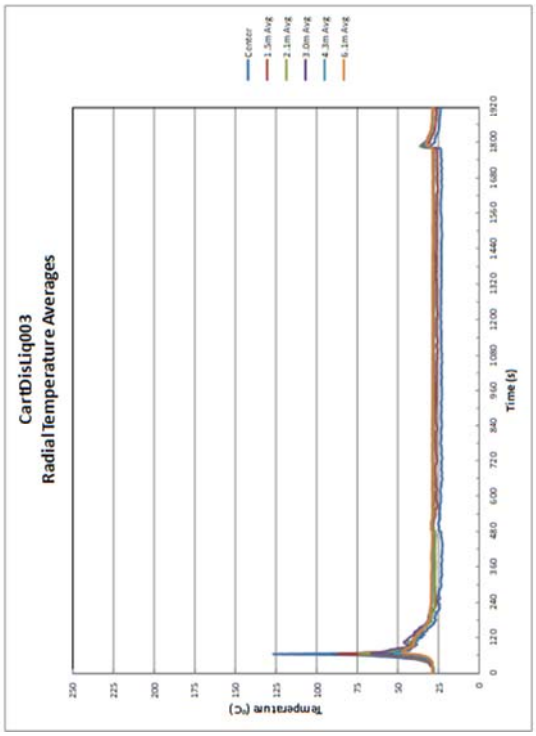


Figure 3-159: Test 2 – Data Plots







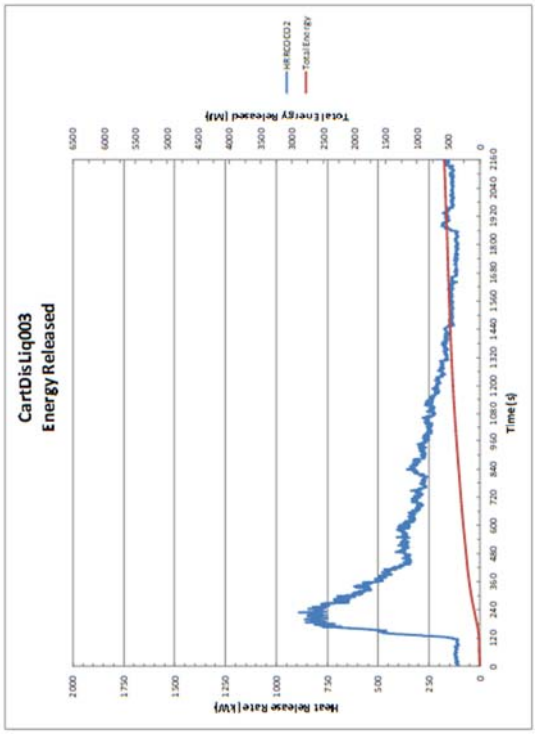


Figure 3-160: Test 3 – Data Plots

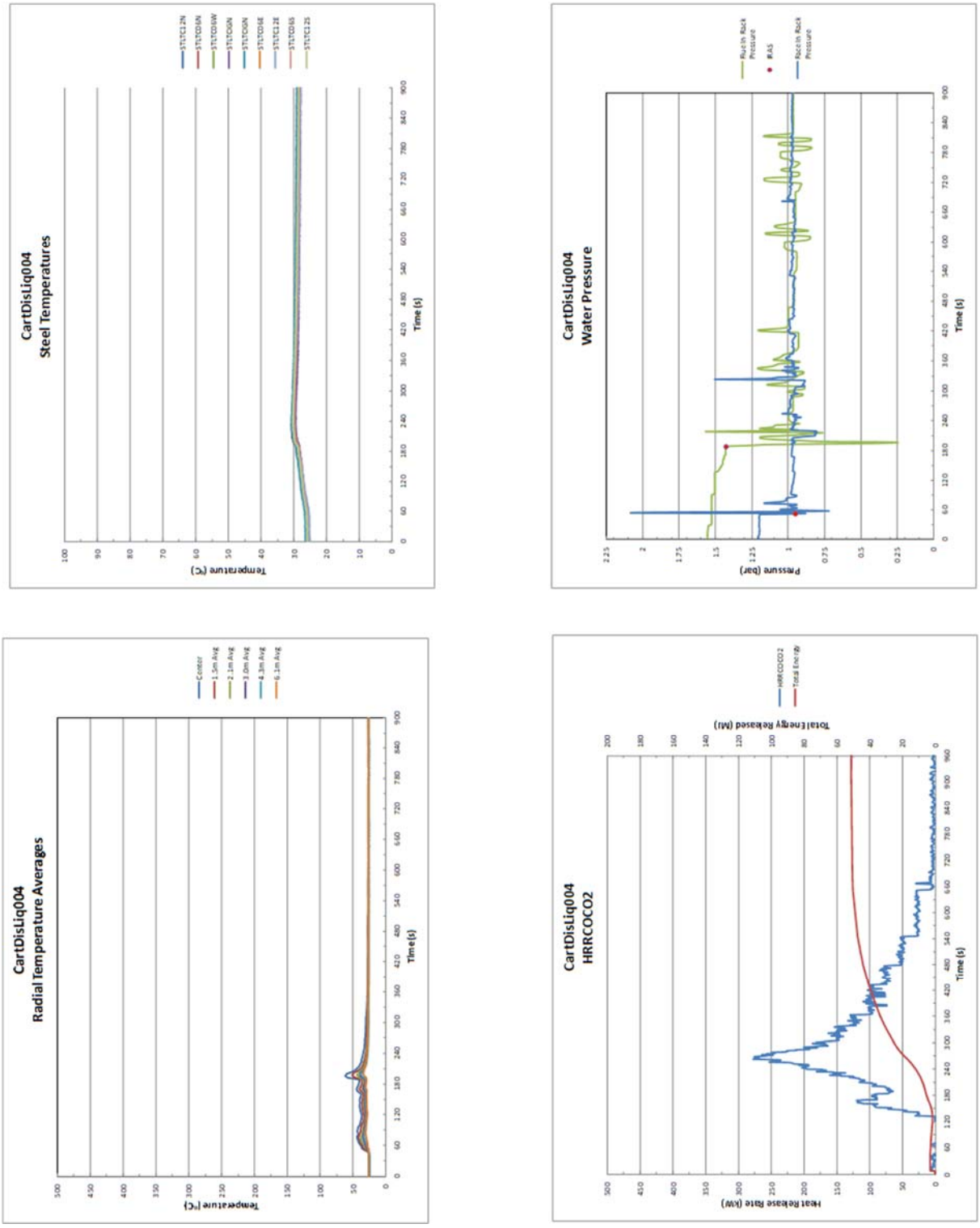


Figure 3-161: Test 4 – Data Plots

3.8.8 Fire Chronologies

Table 3-18: TEST 1 – Fire Chronology / Date: 06-26-2013 / Facing North, Large Burn Lab

Ignition	Comments
0:00	Ignition
0:25	Flames at top of 1st pallet, 4 ft
0:36	Flames observed below 2nd tier pallets
0:48	Plastic starting to peel away from 2nd tier pallets
0:56	Flames below 2nd tier pallets are beneath half of the pallet width
1:00	Flames above the 3rd tier and starting to reach the top of the array
1:06	Flames below 2nd, 3rd, and top tier pallets
1:12	Flames 10 ft above the array
1:18	1st sprinkler operation
1:23	Flames are above the array at the southern end of the array
1:34	Flames knocked down to 5 ft above the array
1:40	Flames still present below pallets of the main array
1:53	Flames on southern end of the array
2:00	Flame heights increase temporarily to 15 ft above array
2:15	Fire below 1st tier pallets have traveled below pallet into the eastern longitudinal flue. Continuing to travel into outermost longitudinal flue. It appears to be an alcohol fire.
2:30	Fire knocked down to only the bottom 2 tiers
2:40	Glass breaking can be heard from within the array
2:49	Very small flames are still present at floor level in the easternmost and westernmost longitudinal flues.
3:11	Fire in center longitudinal flue is 1 pallet in height. Small flames also present below 2nd tier pallets.
3:24	Fire at ground level is below all of the pallets of the main array at the southern end
3:43	Multiple glass bottles break resulting in temporary flare-up
4:00	Upon glass breaking, flare-up in center longitudinal flue. Alcohol contributed to fire at floor level.
4:19	Pallets leaning against each other at top of center longitudinal flue, limiting the flue space at the top.
4:33	More bottles heard breaking
4:33	Two southernmost stacks of each row are leaning towards the center. The three northernmost stacks still appear to be standing straight
5:07	Temperatures at ceiling level are at ambient conditions
5:19	Glass heard breaking within array followed by brief increase in fire intensity

5:44	Observing ceiling sprinkler. Heavy cone of water discharges straight down onto the array. Water is being thrown 10 ft beyond east and west edge of array at floor level.
6:06	Thin smoke is traveling at floor level throughout the lab.
7:00	Glass continues to break in longitudinal flue. Small fire present at the base of the array.
7:16	Fire is no longer observed in the outer longitudinal flues.
7:57	Observing from SW end of the array, no additional fire spread is observed in the western direction.
8:19	Non-essential personnel are being cleared from the test floor due to floor level smoke throughout lab.
10:00	Additional observations will be made from the viewing gallery. Small fire still present in longitudinal flue.
11:10	Flare-ups can still be observed as glass bottles break
12:00	Small fire can be observed at floor level burning below eastern row
15:00	No change to overall conditions
16:15	Small fire observed in western row beneath southernmost pallet.
19:54	Collapse at southern end of the array. Large fires formed at floor level.
20:07	Fire at floor level at southern end of lab floor from the collapsed commodity. Fire traveled beyond the floor drains of the NMC. Fire hose being applied to fire beyond the test pad.
20:34	Additional collapse towards the west
20:55	2 sprinklers operate above commodity at floor level. One sprinkler was on ceiling perimeter
21:27	Discharge pattern from southernmost sprinkler appears to be different than pattern of 1st sprinkler. Possible hang-up of sprinkler.
21:40	Two separate fires are present on test floor. One fire is directly south of the test array and another towards the west.
22:25	Additional collapse of pallets
22:37	Fire towards south end of array is decreasing in intensity, but fire to west is increasing. Flames are 12 ft in height to west.
23:10	3 sprinklers have operated
23:21	No fire observed in main array.
23:35	Fire to west is decreasing in intensity
24:12	Pallet load of main array still standing was easternmost row east of ignition. Stack is leaning and will potentially collapse.
25:08	Fire to west of main array appears to have been mostly extinguished, with minor increases in intensity.
26:09	Ceiling temps back to ambient conditions
26:53	Additional collapse observed
27:07	Tier east of ignition also collapsed, creating small fire at floor level

27:32 Fire appears to be extinguishing quickly.

28:25 Pool fire at southern end of array has reached the drains.

30:00 Test terminated

Table 3-19: TEST 2 – Fire Chronology / Date: 07-15-2013 / Facing North, Large Burn Lab

Ignition	Comments
0:00	Ignition
0:15	Flames traveling up longitudinal flue, 3 ft in height
0:30	Flames at top of 1st tier
0:39	Flames traveling into the 2nd tier and below the 2nd tier pallets
0:50	Flames reaching top of 2nd tier
0:58	Plastic melting away from commodity in the longitudinal flue
1:06	Flames above the top of the array
1:11	1st sprinklers operation
1:17	Flames about 10ft above the array
1:23	Flames on the southern face of the array below the top tier
1:36	Flames about 8ft above the array
1:42	Flames on south face of the array below the 3rd tier
1:50	Flames remain below the 1st and 2nd tier pallets
1:58	Fire is starting to spread northward through the array
2:08	Fire knocked down. Flames are 2-3 ft above the array
2:17	Glass breaking in the array
2:25	The pallet loads on either side of the longitudinal flue have collapsed into each other
2:32	Top of the stacks have collapsed into each other and block the longitudinal flue
2:42	Fire observed in the longitudinal flues east and west of the ignition flue
2:51	Glass continuing to break within the array
3:05	Increase in fire intensity as bottles continue to break. Flames intermittently reaching ceiling level.
3:19	Four sprinklers have operated
3:25	Significant involvement on southern end of the array
3:31	Fire present in all four longitudinal flues of the array
3:39	Fire traveling up western longitudinal flue to the top of the array
3:47	Fire established at the southern end of the array beyond the footprint of the array
3:56	Bottles continue to fall out of the array and break
4:02	Fire above top of the array in the western longitudinal flue. Flames 3 ft above the array
4:28	Fire is involved in southern end of the array as bottles continue to spill from array.

4:35	Pallets beginning to collapse towards the west
4:49	As several bottles spill from the array, fire in longitudinal flue increases in intensity and also contributes to pool fire south of the array
5:00	Eight sprinklers have activated
5:15	Collapse of the stacks at the south end of the array. Four of the stacks have collapsed
5:30	Fire still involved in stacks of main array to the top of the array
5:39	Fire present in collapsed product, but fire is only a few feet in height
5:47	Additional stacks collapse
5:56	Fire is present at extent of the test pad from collapsed commodity and spilled liquid. Fire hoses being applied to prevent further spread beyond the test pad
6:04	Flames above collapsed commodity are 3-4 ft in height. Small pool fires present
6:13	Pool fire present southeast of the main array
6:30	Flames present in eastern most longitudinal flue and extending beyond top of the array
6:56	Twelve sprinklers have operated
7:11	Significant involvement in outermost longitudinal flue
7:27	Majority of fire in collapsed commodity has been significantly diminished if not complexly suppressed
7:50	13 sprinklers have operated
7:59	Commodity has shifted and block the eastern longitudinal flue
8:39	No fire observed in collapsed commodity
8:47	Fire has propagated below the array and has traveled past the easternmost stack of the test array
9:13	Collapse towards east where longitudinal flue fire was present
9:20	Majority of commodity still involved is in commodity collapsed towards the east
9:33	No fire observed in remaining stacks of the test array
9:40	Flames in collapsed commodity are 3-4 ft in height
10:50	Significant collapse of southern end of the array in all direction. Piles of collapsed commodity to west, south, and east.
11:12	Small fires present in collapsed commodity
13:17	No fire present in main array
13:30	Stacks continuing to shift and additional stacks could potentially collapse
15:48	Additional commodity collapsed towards the south. No larger fire was generated from the collapse.
20:00	Test terminated

Table 3-20: TEST 3 – Fire Chronology / Date: 07-15-2013 / Facing North, Large Burn Lab

Ignition	Comments
0:00	Ignition
0:15	Flames traveling up center longitudinal flue, 3 ft in height
0:30	Flames at top of 1st tier pallet
0:40	Flames traveling below 2nd tier pallets
0:45	Flames reaching top of 2nd tier
0:53	Flames above 3rd tier
0:56	Flames above top of the array
0:59	Flames below 2nd and 3rd tier pallets
1:04	1st sprinkler operation
1:14	Flames remain 5-6 ft above array, intensity of the fire is decreasing
1:23	Fire is still observed below 2nd and 3rd tier pallets
1:34	Flames remain 5-6 ft above array
1:42	Corrugated at bottom of array is burning less intensely
1:53	Fire has reached southern end of array at 3rd tier
2:07	Fire has been knocked below the top of the array but is still present in the center longitudinal flue
2:15	Glass breaking within the array
2:24	Fire knocked down into 1st and 2nd tiers of the array
2:40	Small flames still present at bottom on longitudinal flue and below 2nd tier pallets
2:54	White smoke begins to obscure array
2:59	Glass breaking can still be heard within the array
3:13	Small areas of burning can be observed towards southern end of array
3:31	Leaning of stacks on either side of ignition towards the center longitudinal flue
3:52	Boxes at top of center longitudinal flue are touching each other.
4:35	Small fires still present in longitudinal flue at 1st and 2nd tier
4:57	Smoke within lab is less thick, but present entire north ceiling test volume
5:27	Plastic wrap is still intact in longitudinal flues east and west of center
5:52	Small pool fire observed below bottom tier pallets
6:04	Pool fire has traveled beyond longitudinal flue west of center
6:50	Non-essential personnel evacuated

7:28	Several bottles broke towards southern end of array creating small pool fire
7:50	Small pool fire present 1-2 ft in height
8:30	Pool fire to south has been extinguished
9:11	No fires present beyond extent of array. Small fires still present in longitudinal flue
9:51	Bottle continue to break within longitudinal flue creating small increases in intensity, but no pool fires established
10:15	Fire below 1st tier pallets was extinguished and is no longer present
12:00	Bottles continuing to break
13:25	Rows on either side of ignition are leaning on each other. No leaning towards sough
13:50	Stacks are supporting each other preventing collapse
19:00	Bottles still rupturing within the longitudinal flue
29:00	Leaning of stacks on either side of ignition. Row west of western longitudinal flue is also leaning, though no fire is present
29:32	Collapse of material on southern end of array creating small pool fire beyond array.
30:45	Pool fire has been extinguished
32:00	Test terminated

Table 3-21: TEST 4 – Fire Chronology / Date: 08-22-2013 / Facing North, Large Burn Lab

Ignition	Comments
0:00	Ignition
0:20	Glowing observed in center transverse flue
0:24	Flame tips extending above top of 1st tier
0:29	Stretch-wrap is starting to peel back from 1st tier commodity
0:35	Flames extending into 2nd tier
0:45	Flames above the 2nd tier boxes, extending into the 3rd tier
0:51	1st IRAS operation, on east face of array
1:00	Fire still observed impinging into 3rd tier commodity
1:13	Flame intensity decreasing, fire can still be observed above the 2nd tier
1:27	Fire in 1st tier is decreasing in intensity
1:41	Flames cannot be seen above the 2nd tier level
1:47	Flames are still observed above the 1st tier
1:53	Glass bottle broke increasing the fire severity
2:02	Heat can still be observed leaving the 2nd tier, but flames are not visible
2:10	Intermittently see flames extending above the 2nd tier
2:34	Fire still present in center transverse flue. As bottles break, flame extensions are leaving the 1st tier and into the 2nd tier, though short in duration.
3:00	Small fire observed in longitudinal flue.
3:08	2nd IRAS operation.
3:22	Small fire observed at base of longitudinal flue below 1st tier pallets
3:36	Total of 2 IRAS are activated
3:53	Fire is still present below pallets of 1st tier. No fire observed above top of the 1st tier commodity.
4:11	Ceiling temperatures remain below ambient conditions
4:20	Observing discharge pattern of IRAS. Water is traveling horizontal across the 4 ft aisle and water can be observed extending beyond the target array onto the floor east of the target.
5:07	No fire can be observed in center longitudinal flue, or within the 1st tier commodity.
5:25	Observing western aisle, water from IRAS is discharging beyond face of the array and wetting face of west target array.
7:32	East face of the main array, stretch wrap remains on face of the majority of the array.
9:11	No change in test conditions. No fire can be observed within the array.
12:58	Firefighters enter western aisle to observe if any fire is still present within the array.

13:45 Small portion of a pallet at floor level is smoldering.

15:00 Test terminated

4. **Conclusions**

The fire testing provided in this report clearly defines the hazards of ignitable liquids in plastic and glass containers as well as provides very effective protection options for certain liquid-container combinations.

The impact of each test program covered by this report is listed below:

1. Eliminate exclusions in 9.1.4 (NFPA 30) for beverages in up to 1.3 gal containers (3) and medicine, cosmetics, foodstuffs, etc with less than 50% water alcohol in containers up to 1.3 gal (4). [Public Input #109]

   Fire testing provided in Sections 3.6, 3.7, and 3.8 of this report shows the fire hazard of even a diluted alcohol-water mixture is significantly greater than solid commodities covered by NFPA 13. These products need to be included in NFPA 30 to provide effective protection. These products are no longer included in the commodity classifications provided in NFPA 13.

2. Revision of section 12.8 General Purpose Warehouses (NFPA 30). [Public Input #111]

   The available fire protection for the liquid-package combinations provided in the following tables provides a very effective protection level that prevents the formation of any significant pool fires. The storage of these liquid-package combinations can be stored in general purpose warehouses when properly protected. There is no need to provide quantity limits for adequately protected storage. The table below is part of the public proposal to expand the liquid-container combinations that are acceptable in a general-purpose warehouse.

Liquid-Container Combinations Permitted in Protected General-Purpose Warehouses

Liquid Type	Storage Arrangement	Roof Height	Container Size	Container Construction
FP ≥ 450°F (232°C)	Rack	30 ft (Table D.4)	≤ 5 gal (19 L)	Plastic/Glass
		40 ft (new)	≤ 48 oz (1.4 L)	Plastic/Glass
FP ≥ 200°F (93°C)	Rack	unlimited	≤ 5 gal (19 L)	Plastic/Glass
FP ≤ 200°F (93°C)	Rack	unlimited	≤ 2 oz (60 ml)	Plastic/Glass
Ethanol or Isopropanol (100%)	Rack	unlimited	≤ 1 gal (4L)	Plastic/Glass
		30 ft	≤ 6 oz (180 ml)	Plastic/Glass
Ethanol or Isopropanol (50% by volume in water)	Rack	30 ft	≤ 1 gal (4 L)	Plastic/Glass
		unlimited	≤ 59 oz (1.75 L)	Glass/Plastic
	Palletized	40 ft & 30 ft	≤ 59 oz (1.75 L)	Glass
Any flash point, boiling point > 100°F (38°C)	Palletized	30 ft	≤ 5 gal (19 L)	Steel

3. Vegetable oil [FP > 450°F (230°C)] in 48 oz (1.4 L) plastic bottles in cartons and uncartoned. [Public Input #116]

Fire testing provided in Sections 3.1, 3.2 and 3.3 of this report demonstrates the severe fire hazard that is created by the storage of vegetable oil or other oils with flash points greater than 450°F (230°C). In addition it provides effective protection options that prevent the formation of pool fires. Data are also provided that demonstrate the increased hazard of storing this type of product in a tray-pack arrangement (i.e., uncartoned).

4. Low flash point hydrocarbon liquids in 2 oz (59 ml) plastic bottles in cartons. [Public Input #118]

   Fire testing provided in Section 3.4 of this report shows the significant fire hazard that is created by the rack storage of low flash point hydrocarbon liquids in 2 oz (59 ml) plastic bottles in cartons. In addition it provides protection that controls the fire hazard.

5. 99% alcohol in 6 oz (180 ml) plastic bottles in cartons under a 30 ft (9 m) and 40 ft (12 m) roof. [Public Input #119]

   Fire testing provided in Section 3.5 of this report shows that pure alcohol in 6 oz (180 ml) plastic bottles in cartons can be adequately protected using protection levels similar to cartoned unexpanded plastic commodities. The protection prevents the formation of significant pool fires validating the use in a general purpose warehouse.

6. 50-50 isopropyl alcohol-water mixture in 1 gal (3.8 L) plastic bottles in cartons. [Public Input #114, 120]

   Fire testing provided in Section 3.6 of this report shows the significant fire hazard that is created by the rack storage of 50-50 alcohol water mixtures in 1 gal (3.8 L) plastic bottles in cartons. The fire hazard does not resemble any type of solid commodity fire hazard since pool fires will develop and promote the horizontal spread of the fire to adjacent racks. In addition effective protection options are provided that include ceiling only sprinkler design or ceiling + in-rack sprinkler design. The protection level prevents the formation of significant pool fires.

7. 50-50 ethyl alcohol-water mixture in 1.75 L (59 oz) glass bottles in cartons. [Public Input #120, 121]

   Fire testing provided in Sections 3.7 and 3.8 of this report shows the significant fire hazard that is created by the rack and palletized storage of 50-50 alcohol-water mixtures I 1.75 L glass bottles in cartons. In addition effective protection options are provided that include ceiling only sprinkler design or ceiling + in-rack sprinkler design. The protection level prevents the formation of significant pool fires. The ceiling + in-rack sprinkler design allows the use of unlimited ceiling and storage heights.

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