RESEARCH TECHNICAL REPORT

Summary Report of Fire Testing Involving Distilled Spirits in Wooden Barrels – for NFPA 30

Summary Report of Fire Testing Involving Distilled Spirits in Wooden Barrels

(Document prepared in support of code changes)

Extracted and edited by

John A. LeBlanc
Chief Engineer's Group
FM Global

For

NFPA 30 Flammable and Combustible Liquid Code

July 2022

Disclaimer

The research presented in this report, including any findings and conclusions, is for informational purposes only. Any references to specific products, manufacturers, or contractors do not constitute a recommendation, evaluation or endorsement by Factory Mutual Insurance Company (FM Global) of such products, manufacturers or contractors. FM Global does not address life safety or health issues. The recipient of this report must make the decision whether to take any action. FM Global undertakes no duty to any party by providing this report or performing the activities on which it is based. FM Global makes no warranty, express or implied, with respect to any product or process referenced in this report. FM Global assumes no liability by or through the use of any information in this report.

Table of Contents

Table of Contents i
List of Figures iv
List of Tables vi
1. Introduction 1
1.1 Background 1
1.2 Organization of this Report 1
1.3 Report Correlation with the Various Public Comments 1
2. FM Global Test Facilities Information 2
3. Test Summaries 3
3.1 Protection for Rack-Stored Distilled Spirits in Oak Barrels / Jaap de Vries / January 2018 3
3.1.1 Test Overview 3
3.1.2 Single Barrel Tests 3
3.1.2.1 Barrel Specifications 3
3.1.2.2 Test Setup and Discussion 5
3.1.3 Large-scale Tests 6
3.1.3.1 Test Evaluation Criteria 6
3.1.3.2 Rack Setup and Dimensions 7
3.1.3.3 Open Area Fraction (OAF) 10
3.1.3.4 Fuel Loading 10
3.1.3.5 Sprinkler Protection 11
3.1.3.6 Ignition Source and Location 14
3.1.4 Test Results 14
3.1.4.1 Result Summary 14
3.1.4.2 Test 1 14
3.1.4.2.1 Fire Chronology 14
3.1.4.2.2 Sprinkler Activation Sequence 15
3.1.4.2.3 Extent of Fire Damage 15
3.1.4.2.4 Maximum Steel and Gas Temperatures at the Ceiling 16
3.1.4.3 Test 2 16
3.1.4.3.1 Fire Chronology 16
3.1.4.3.2 Sprinkler Activation Sequence 16
3.1.4.3.3 Extent of Fire Damage 17
3.1.4.3.4 Maximum Steel and Gas Temperatures at the Ceiling 17

3.1.4.4 Test 3 18
3.1.4.4.1 Fire Chronology 18
3.1.4.4.2 Sprinkler Activation Sequence 18
3.1.4.4.3 Extent of Fire Damage 19
3.1.5 Summary and Conclusions 19
3.1.6 Fire Chronologies 20
3.1.6.1 Test 1 20
3.1.6.2 Test 2 20
3.1.6.3 Test 3 21
3.1.7 Selected Photographs 22
3.1.7.1 Test 1 22
3.1.7.2 Test 2 23
3.1.7.3 Test 3 24
3.2 Palletized Distilled Spirits Storage Protection / Jaap de Vries / May 2012 25
3.2.1 Test Summaries 25
3.2.2 Test Commodity 25
3.2.2.1 Wooden Pallets 25
3.2.2.2 Wooden Barrels 26
3.2.2.3 Simulated Distilled Spirits 28
3.2.3 Large-scale Fire Test Setup, Procedure, and Results 29
3.2.3.1 Test 1 Setup 29
3.2.3.2 Test 2 and Test 3 Setup 31
3.2.3.3 Test 4 Setup 32
3.2.3.4 Automatic Ceiling Sprinklers 33
3.2.3.5 Ignition 33
3.2.3.6 Test Configuration Overview 34
3.2.3.7 Instrumentation 35
3.2.3.7.1 Standard Instrumentation 35
3.2.3.7.2 Liquid Loss Measurements 36
3.2.4 Large-scale Fire Test Results 37
3.2.4.1 Results Overview 37
3.2.4.1.1 Test 1 37
3.2.4.1.2 Test 2 37
3.2.4.1.3 Test 3 38
3.2.4.1.4 Test 4 38

3.2.4.2 Steel Temperatures 39
3.2.4.3 Leakage of Water or Ignitable Liquid 39
3.2.5 Discussion 40
3.2.5.1 Sprinkler Activation 40
3.2.5.2 Liquid Leakage 41
3.2.5.3 Flue Spaces 41
3.2.6 Conclusions 42
3.2.7 Fire Chronologies 43
3.2.7.1 Test 1 43
3.2.7.2 Test 2 43
3.2.7.3 Test 3 44
3.2.7.4 Test 4 45
3.2.8 Dry Pipe Protection for Palletized Storage 46
3.2.8.1 Prior Testing 46
3.2.8.2 Discussion 47
3.2.8.3 Conclusions 48
4. Code Change Conclusions 49
16.10 Distilled Spirits in Wooden Barrels 49
16.10.1 Palletized Storage Arrays 49
16.10.2 Rack Storage Arrays 51
16.10.3 In-Rack Sprinkler Layouts 52
16.10.3.1 Abbreviations Used in Fire Protection Tables 52

List of Figures

2-1: Illustration of FM Global Large Burn Laboratory test locations. 2
3-1: Description and dimensions of wooden barrels used for testing (Units in inch [cm]). 5
3-2: Single-barrel test setup. 5
3-3: Empty barrel heat release rate and effect of initial moisture content. 6
3-4: Tests 1 and 2 configuration elevation view (a), and plan view (b). Dimensions are in inches [centimeter]. 8
3-5: Test 3 configuration in elevation view (a), and plan view (b). Dimensions are in inches [centimeter]. 8
3-6: Photograph of array used in Tests 1 and 2 before ignition, taken from the West side of the array (a). Test 3 photograph at a slightly different angle also taken from the West side of the array (b). 9
3-7: Location of alcohol filled barrels (shown in red) inside the array used during Tests 1 and 2. 10
3-8: Location of alcohol filled barrels (shown in red) inside the array used during Test 3. 10
3-9: Position of fuel array with respect to the ceiling sprinklers. The ignition pan shown as a red square is centered among 4 sprinklers (Tests 1 and 2). 12
3-10: Position of fuel array with respect to the ceiling sprinklers. The ignition pan shown as a red square is centered among 4 sprinklers (Test 3). 13
3-11: In-rack sprinkler location and spacing shown in a plan view (a) and an elevation view (b). 13
3-12: Ignition pan location for Tests 1 and 2 (a). Ignition pan location for Test 3 (b). 14
3-13: Sprinkler activation pattern (a) and timing (b) for Test 1. 15
3-14: Post-test images from Test 1 of affected barrels showing charring at heads (a) and on the staves (b). 15
3-15: Maximum steel (solid red line) and gas (solid black line) temperatures. Test 1. 16
3-16: Sprinkler activation pattern (a) and timing (b) for Test 2. 17
3-17: Post-test images from Test 2 of affected barrels showing charring at heads (a) and on the staves (b). 17
3-18: Maximum steel (solid red line) and gas (solid black line) temperatures. Test 2. 18
3-19: Sprinkler activation pattern (a) and timing (b) for Test 3. 18
3-20: Post-test images from Test 3 of affected barrels showing charring at heads (a) and on the staves (b). 19
3-21: Dimensions (in inches) of hardwood pallets used in this study. 25
3-22: Description of wooden barrel components. 27
3-23: Flash point dependency on volume fraction of alcohol in water. 28
3-24: Schematic of array setup used for Test 1. Core sixteen barrels are marked by a 30
3-25: Image of storage arrangement for Test 1. 30
3-26: Schematic of array setup used for Test 2 and 3, tier 1-3. 31
3-27: Schematic of array setup used for Test 2 and 3, tier 4-7. 31
3-28: Image of the array setup used for Test 2. 32
3-29: Schematic of Test 4, Tier 1. 32

3-30: Schematic of Test 4, Tiers 2-5. 33
3-31: Schematic of Test 4, Tiers 6-7. 33
3-32: Ignition process at time 0, 10, and 30 s (Test 2). 34
3-33: Sprinkler layout for large-scale fire Test 1. Forty-nine (49) sprinklers were placed on a 10 x 10 ft (3.0 x 3.0 m) spacing. 34
3-34: Sprinkler layout for large-scale fire Test 2 and 3. Sixty-four (64) sprinklers were placed on a 10 x 10 ft (3.0 x 3.0 m) spacing. 35
3-35: Sprinkler layout for large-scale fire Test 4. Sixty-four (64) sprinklers were placed on a 10 x 10 ft (3.0 x 3.0 m) spacing. 35
3-36: Plenum used for distributing cooling water (left). Lead wires to hydrostatic pressure transducers wrapped in water-cooled jackets (right). 36
3-37: Lead wires to hydrostatic pressure transducers wrapped in water-cooled jackets running through the western and eastern flues. 36
3-38: Sprinkler operation patterns in Tests 1-4. 38
3-39: Steel temperatures at the ceiling location above ignition. 39
3-40: Test 4 measured leakage (gallons) using a dipstick. 40
3-41: Flue space arrangements for Tests 1-3 (left) and Test 4 (right) 42

List of Tables

3-1: Large-scale fire test summary, Tests 1-3. 4
3-2: Properties of white oak used for the barrels. 5
3-3: Summary of array dimensions for Tests 1, 2, and 3. 9
3-4: Protection summary for Tests 1, 2, and 3. 11
3-5: Result summaries for Test 1, 2, and 3. 14
3-6: Large Scale Fire Testing Summary, Tests 1-4. 26
3-7: Properties of white oak barrels used in this study. 27
3-8: Properties of simulated distilled spirits. 29
3-9: Large-scale fire test result summary. 37

1. **Introduction**

1.1 Background

The contents of this report are being submitted to support Public Comment 61 NFPA 30-2021 and is associated with Public Input 175.

This report was compiled from two (2) full-scale fire test programs conducted by FM Global. The test work spans from 2011 through 2016. It was aimed at defining adequate fire protection for the storage of palletized or rack-stored wooden barrels (≤92 gal [350 L]) of distilled spirits. This testing was conducted with barrels filled with simulated distilled spirits (75% v/v denatured alcohol).

The ceiling height for the rack storage testing was 40 ft (12.2 m) and protection was provided by wet-pipe sprinklers, dry-pipe sprinklers, or a combination of dry-pipe ceiling sprinklers and dry-pipe in-rack sprinklers.

The ceiling height for the palletized testing was 30 ft (9.1 m) and protection was provided by wet-pipe sprinklers. Analysis is provided to extend the protection options to dry-pipe systems.

1.2 Organization of this Report

As noted above, this report contains documentation from two (2) full-scale fire test programs, which are presented in Section 3.0. Each section is fully self-contained. Not all the tests that may have been carried out in a particular research program are included. Only tests that are related to the public comments are in this report. Resulting gaps in test numbering ensure that the content is maintained as written by the original author.

1.3 Report Correlation with the Various Public Comments

Public Comment 61-NFPA 30 2021 proposes a new section to Chapter 16 covering the protection of palleted and rack storage of distilled spirits in wooden barrels.

2. FM Global Test Facilities Information

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 66 ft^2 (6.1 m^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 80 ft x 80 ft (24.4 m x 24.4 m) and are adjustable for heights above the floor ranging from 10 ft to 60 ft (3.1 m to 18.3 m). All large-scale tests are conducted at an exhaust rate of 200,000 ft^3/min (94 m^3/s). The lab is provided with an advanced humidity control system to ensure testing consistency. The system circulates up to 104,000 ft^3/min (49 m^3/s) of air and removes up to one ton (900 kg) of water per hour.

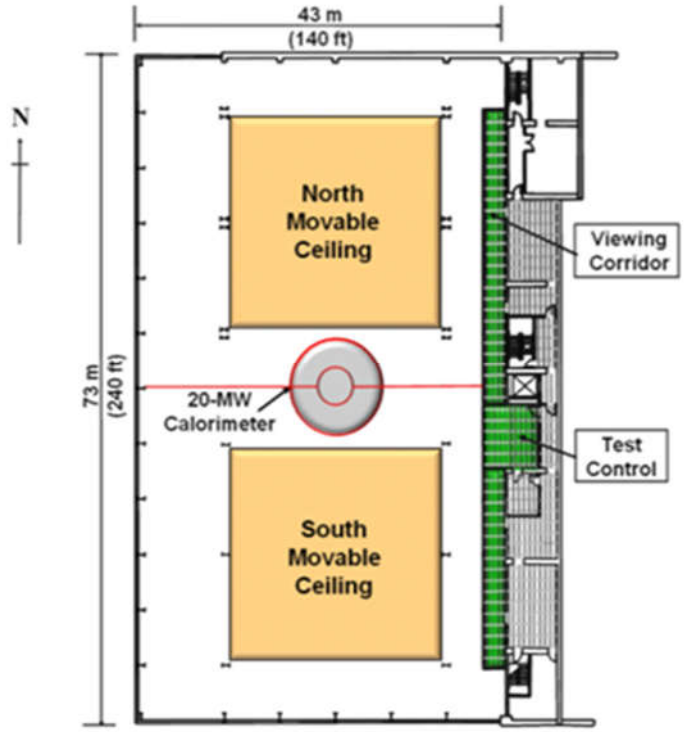


Figure 2-1: Illustration of FM Global Large Burn Laboratory test locations.

3. Test Summaries

3.1 Protection for Rack-Stored Distilled Spirits in Oak Barrels / Jaap de Vries / January 2018

3.1.1 Test Overview

The objective of this study was to develop adequate protection for rack-stored distilled spirits with 75% or greater alcohol content stored in oak barrels with a capacity less than 92 gal (350 L) under 40 ft (12.2 m) ceilings using a wet-pipe or dry-pipe ceiling-only sprinkler system. An additional objective was to evaluate the adequacy of the protection provided by a single tier of dry-pipe, in-rack automatic sprinklers.

In this study single barrel fire tests and three large-scale fire tests were conducted to assess sprinkler protection adequacy. All barrels in this study had a capacity of 59 gal (225 L). The simulated distilled spirits had a 75% (by volume) alcohol content.

The test facility used for this program is described in Section 2. A summary of the three large-scale fire tests is provided in Table 3-1.

3.1.2 Single Barrel Tests

3.1.2.1 Barrel Specifications

All single barrel and large-scale tests were conducted with 59-gallon (225-Liter), Bordeaux-style, French-oak barrels. The material properties and dimensions of the barrels are listed in Table 3-2. A graphical depiction of the barrels is shown in Figure 3-1. The wooden barrels used during these tests are representative of those typical of the industry.

Table 3-1: Large-scale fire test summary, Tests 1-3.

Test Number	Test 1	Test 2	Test 3
Test Date (mm/dd/yyyy)	05/26/2016	06/08/2016	04/26/2017
FM Global Fire Technology Laboratory Test Site	South Movable Ceiling		
Environmental Conditions			
Pre-test Inside Temperature (°F [°C])	73 [23]	66 [19]	57 [14]
Pre-test Inside Relative Humidity (%)	52	54	99
Outdoor Temperature (°F [°C])	75 [24]	60 [16]	49 [9]
Outdoor Relative Humidity (%)	51	64	68
Fire Test Setup and Protection			
Nominal Ceiling Height (ft [m])	40 [12]		
Commodity	Oak Barrels, 225L, Bordeaux Style		
# Empty barrels	188	188	237
# Simulated distilled spirits Filled barrels (75% denatured alcohol)	82	82	87
Storage Arrangement	Rack-stored		
Array Nominal Size – LxWxH (*ft x ft x ft* [m x m x m])	16.5 x 28.5 x x30.9 [5.0 x 8.7 x 9.4]		
Vertical Tier Separation (in [m])	42 [1.1]		
Main Flue Space Width (in [cm])	9 [23]		
No. of Storage Levels	9		
Clearance to Ceiling (ft [m])	9 [2.7]		
Ignition Centered Below (*No. Ceiling Sprinklers*)	4	4	4
Ignition Location Relative to Rack – offset/non-offset	Centered (pool) – non-offset		
Protection Ceiling			
Sprinkler Orientation – upright/pendent (dry/wet)	Pendent (wet)	Upright (dry)	Upright (dry)
Discharge Coefficient (K-factor) (*gpm/psi$^{1/2}$* [lpm/bar$^{1/2}$])	14 [200]	16.8 [240]	11.2 [160]
Sprinkler Response	Quick	Standard	Standard
Temperature Rating (°*F* [°C])	165 [74]	286 [141]	286 [141]
Spacing (ft x ft [m x m])	10 x 10 [3.0 x 3.0]		
Discharge Pressure (psig [barg])	37 [2.5]	25 [1.7]	7 [0.5]
Discharge Density [*gpm/ft^2* (mm/min)]	0.85 [35]	0.85 [35]	0.30 [12]
Protection In-rack Sprinklers			
Sprinkler Orientation – upright/pendent (dry/wet)	None		Upright (dry)
Discharge Coefficient (K-factor) (*gpm/psi$^{1/2}$* [lpm/bar$^{1/2}$])			8.0 [115]
Sprinkler Response			Quick
Temperature Rating (°*F* [°C])			165 [74]
Spacing on line (ft [m])			4 [1.2]
Discharge Pressure (psig [bar])			32 [2.2]
Discharge Flow (gpm [lpm])			45 [170]
Fire Test Results			
First/Last Ceiling Sprinkler Operation (min:s)	1:03/3:20	1:49/2:30	2:16/3:19
Total Ceiling Sprinklers Opened	4	15	3 (In-rack sprinklers)
Peak Gas Temperature (°*F* [°C]) and Time (min::s)	497 [258] @ 1:03	1783 [973] @2:06	750 [399] @ 3:17
Maximum Steel Temperature (°*F* [°C]) and Time (min:s)	178 [81] @ 7:45	477 [248] @ 2:43	197 [92] @ 3:17
Test Termination – Time After Ignition (min:s)	30:00	10:00	12:00

Table 3-2: Properties of white oak used for the barrels.

Oak Wood Properties	
Density (Dried), lb/*ft*^{3} (kg/m^3)	*35.0* (560)
Theoretical Heat of Combustion, *BTU/lb* (kJ/g)	*7,360* (17.1)
Barrel Dimensions	
Capacity, gal (L)	59 (225)
Length, in. (cm)	37 (94)
Head diameter, in. (cm)	23 (58)
Bilge diameter, in. (cm)	27 (68)
Hoops	6
Bung hole diameter, in. (cm)	2 (5)

Figure 3-1: Description and dimensions of wooden barrels used for testing (Units in inch [cm]).

3.1.2.2 Test Setup and Discussion

Five single-barrel tests were conducted. A line propane burner was used as the fire exposure. The line burner was placed above a collection pan (10 ft x 10 ft [3.0 m x 3.0 m]). In this study, the line burner allowed leaked ethanol to form a pool on its own and contribute to the overall heat release rate. A picture of the test setup is shown in Figure 3-2.

Figure 3-2: Single-barrel test setup.

All experiments were carried out underneath the 5-MW Fire Products Collector (FPC). In this setup, gases are sampled from the main duct and pulled to the gas sampling cabinet (GSC).

Five single-barrel tests were conducted, three empty and two filled with 75%/25% (by mass) denatured alcohol / water mixture. The empty barrels were plugged and sealed prior to each test. The propane gas flow was fixed to 7.1 cfm (200 lpm), resulting in a fire exposure of 300 kW. The moisture content of the

oak wood was controlled by varying the drying period after completely submerging the barrel in water for a set period. Figure 3-3 (a) shows the test results for the three empty-barrel free-burn tests. As can be seen, the HRR initially increases to a maximum of approximately 100 kW. After 8 minutes, the barrel surface starts to char and the HRR decreases. In all three cases, the barrels remained intact for the complete 40-minute test duration. The empty-barrel tests revealed two findings: first, the barrels do not contribute significantly to the overall HRR; second, the barrel moisture content does not strongly affect the burning rate.

The HRR profiles for the two alcohol-filled barrel tests are shown in Fig. 3-3 (b). The measured HRR from the leaked content is significantly higher than the peak HRR measured during the empty-barrel tests. In the first test, a pool fire was observed roughly 2.5 minutes after ignition. In the second test, leakage was not observed until after 7.5 minutes. The peak HRR from the leaked alcohol was roughly 1500 kW. This value would be expected to increase with a collection pan of a larger surface area leading to a larger pool of spilled liquid. The measured HRR of 1500 kW equates to roughly 161 kW/m^2, a value that is notably lower than the one reported in the literature of 374 kW/m^2 for pure alcohol in large pan fires. This discrepancy is due in part to the dilution level (75%) of the alcohol and to the partial obstruction of radiant heat feedback to the burning liquid by the barrel. Taking Fig. 3-3 (a) and (b) together, clearly the leakage of alcohol is the dominant factor contributing to the fire size.

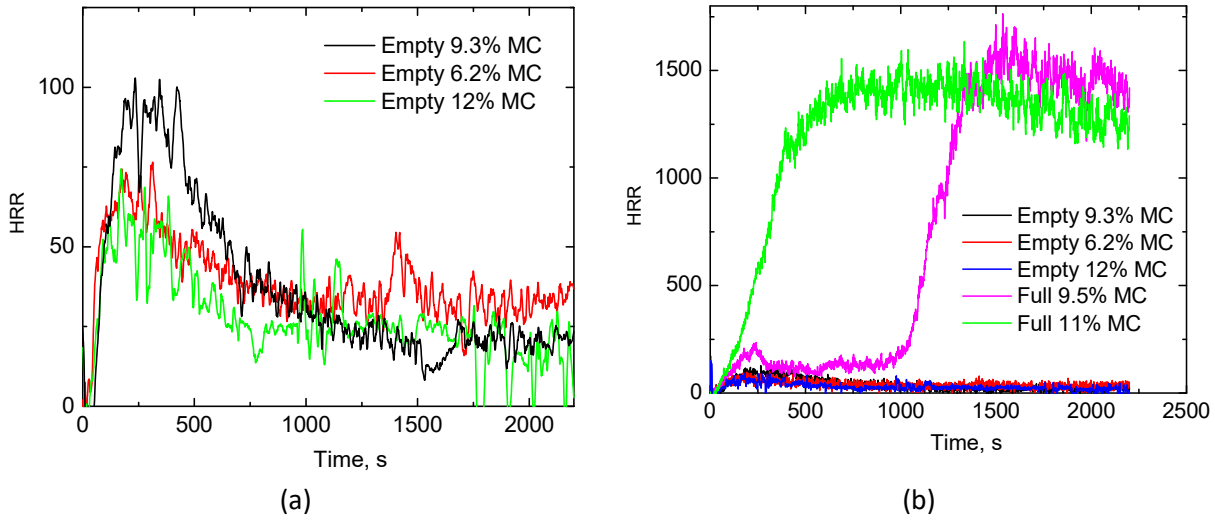


Figure 3-3: Empty barrel heat release rate and effect of initial moisture content.

3.1.3 Large-scale Tests

3.1.3.1 Test Evaluation Criteria

When dealing with ignitable liquids, the evaluation of fire test results involves the consideration of five key areas. They are:

- Number of Sprinklers Operated
  - This is a measure of what the needed water supply will be. Large sprinkler operating areas may not represent a viable sprinkler design.
- Sprinkler Operation Along the Edge of Ceiling Perimeter

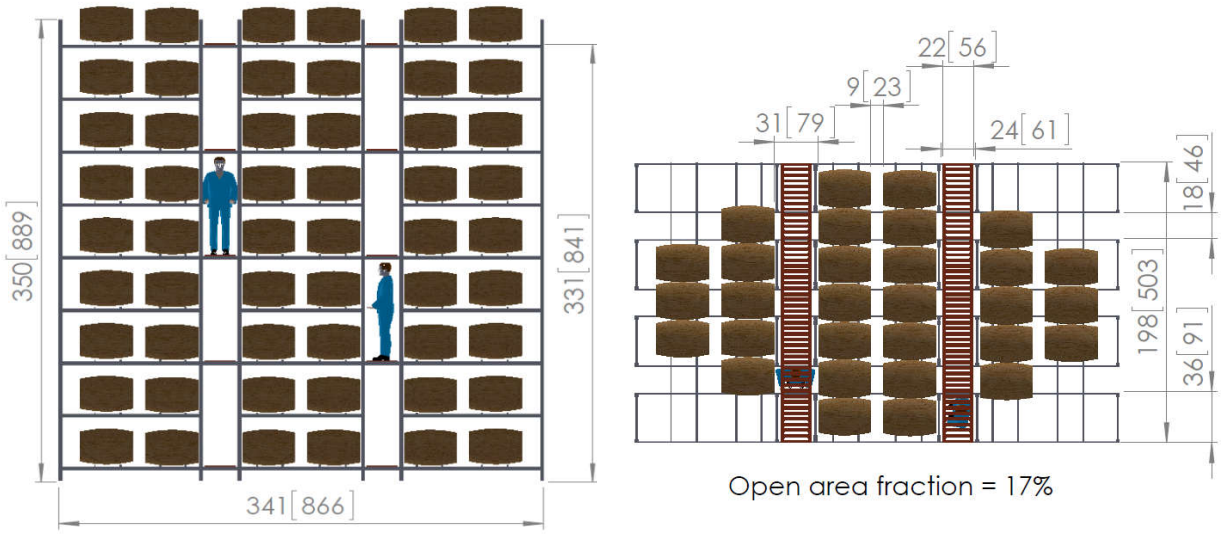
- All test facilities have limitations in producing a meaningful fire test. Beyond having a large enough volume to represent a large building volume, it is important to recognize that operation of any sprinkler in the last ring of sprinklers indicates that more sprinkler beyond could operate.

- Extent of Fire Damage
  - Fire testing arrays have limitations due to available fuel quantities. The fire spread must be contained within the fuel footprint in the array.
- Steel Temperatures
  - The ceiling temperatures created during a fire represent the level of thermal assault the building structural elements will see. Steel structures will lose strength if heated to temperatures above 1000°F (540°C). Target steel temperatures directly above a storage array must not exceed a one-minute average of 1000°F (540°C) or a recorded temperature of 1200°F (650°C).
- Pile Collapse
  - This is unique to liquids storage arrays. A pile collapse can result in a large release of liquid and a significant increase in pool fire size.

3.1.3.2 Rack Setup and Dimensions

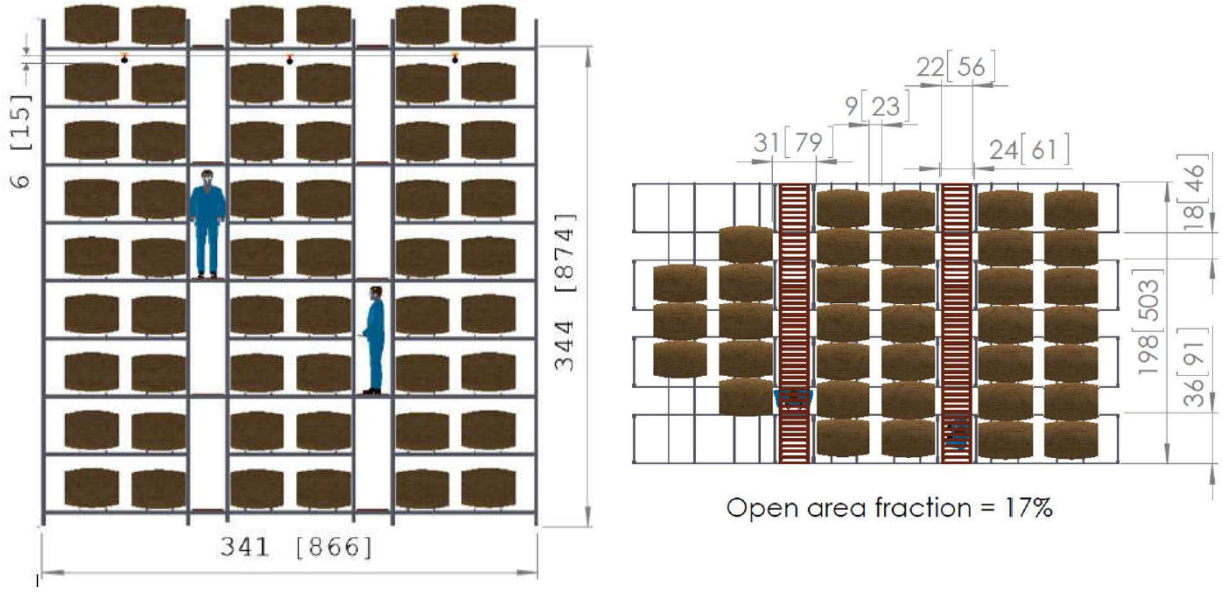
The first two large-scale fire tests (Test 1 and Test 2) had identical array dimensions and fuel loading. Side and plan views of the arrays used for these two tests are shown in Figures 3-4 (a) and (b), respectively. Test 3 used the same rack as the first two tests, but barrels were added on the North facing side of the array favoring the offset ignition towards the North. A side view and plan view of the array used for Test 3 are shown in Figs. 3-5 (a) and (b), respectively. Photographs of the arrays for Tests 1 and 2 and for Test 3 are shown in Figs. 3-6 (a) and (b), respectively.

For all three tests, the main multi-row, rack-stored array was 9 tiers high. The test array racks measured 28.5 ft (8.7 m) wide, 17 ft (5.2 m) deep, and 30.8 ft (9.4 m) high. Two 31 in. (79 cm) walkways were located on either side of the center two rows. The remaining flue spaces were 9 in. (23 cm) wide. Each tier was 42 in. (107 cm) high. All the test details are provided in Table 3-3. The ignition locations for these tests are shown in Figs. 3-9 and 3-10.



(a) (b)

Figure 3-4: Tests 1 and 2 configuration elevation view (a), and plan view (b). Dimensions are in inches [centimeter].



(a) (b)

Figure 3-5: Test 3 configuration in elevation view (a), and plan view (b). Dimensions are in inches [centimeter].

(a) (b)

Figure 3-6: Photograph of array used in Tests 1 and 2 before ignition, taken from the West side of the array (a). Test 3 photograph at a slightly different angle also taken from the West side of the array (b).

Table 3-3: Summary of array dimensions for Tests 1, 2, and 3.

Test Number	Test 1	Test 2	Test 3
Test Date (mm/dd/yyyy)	05/26/2016	06/08/2016	04/26/2017
FM Global Fire Technology Laboratory Test Site	South Movable Ceiling		
Fire Test Setup			
Commodity	59-gal (225-L) Bordeaux Style Oak Barrels		
Alcohol % (by volume)	75%		
Total Alcohol in Test (gal [L])	3380 [12,800]		3588 [13,580]
# Alcohol Filled Barrels	82		87
# Empty Barrels	188		237
Open Area Fraction (OAF)	17%		
# of Storage Levels	9		
Horizontal Layout	3x5x7x7x5x3		3x5x7x7x7x7
Array Outside Dimensions Width x Depth x Height (ft [m])	28.5 x 17 x 30.8 [8.7 x 5.2 x 9.4]		
Aisle Width (in. [cm])	31 [79]		
Flue Width (in. [cm])	9 [23]		
Array Height (ft [m])	33 [10]		
Vertical Tier Spacing (in. [cm])	42 [106]		
Ceiling Height (ft [m])	40 [12.2]		
Ignition Location Relative to Rack	Centered Among 4 Sprinklers		
Ignition Spill Fluid	~96%% Ethanol		
Ignition Pan Size (in. x in. [cm x cm])	72 x 72 [183 x 183]		
Ignition Spill Size (gal [L])	20 [76]		

3.1.3.3 Open Area Fraction (OAF)

Custom rails were used to create a rack geometry with an open area fraction (OAF) close to 17%. The OAF is defined as the percentage of unobstructed projected area established from a plan view of the array. The OAF indicates how effectively the delivered water can pass through the array and is considered a meaningful way to characterize this important parameter.

3.1.3.4 Fuel Loading

For Tests 1 and 2, the array consisted of 270 barrels, of which 82 were filled with simulated distilled spirits (SDS). For Test 3, the overall fuel loading was slightly higher, consisting of 324 total barrels of which 87 were filled with SDS.

For Tests 1 and 2, the total quantity of ethanol used per test was 3,380 gal (12,800 L). The positioning of the alcohol-filled barrels is shown in red in Fig. 3-7. The bottom four tiers contained 16 alcohol-filled barrels per tier. Tiers 5-7 contained 6 alcohol-filled barrels per tier. For safety, the top tiers had empty barrels. For Test 3, the amount of SDS was 3588 gal (13,580 L). The positioning of the SDS-filled barrels during Test 3 is shown in red in Fig. 3-8. For the third test, the bottom 4 tiers contained 15 SDS-filled barrels. Tiers 5-7 contained 9 SDS-filled barrels, while the top two tiers had empty barrels.

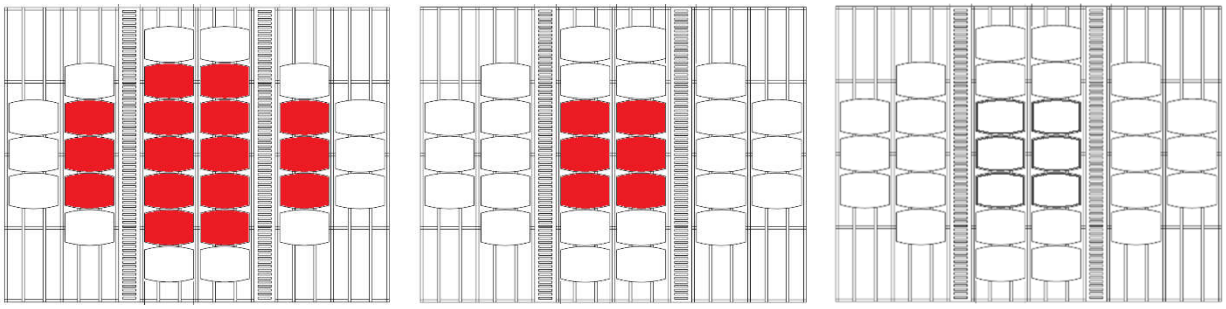


Figure 3-7: Location of alcohol filled barrels (shown in red) inside the array used during Tests 1 and 2.

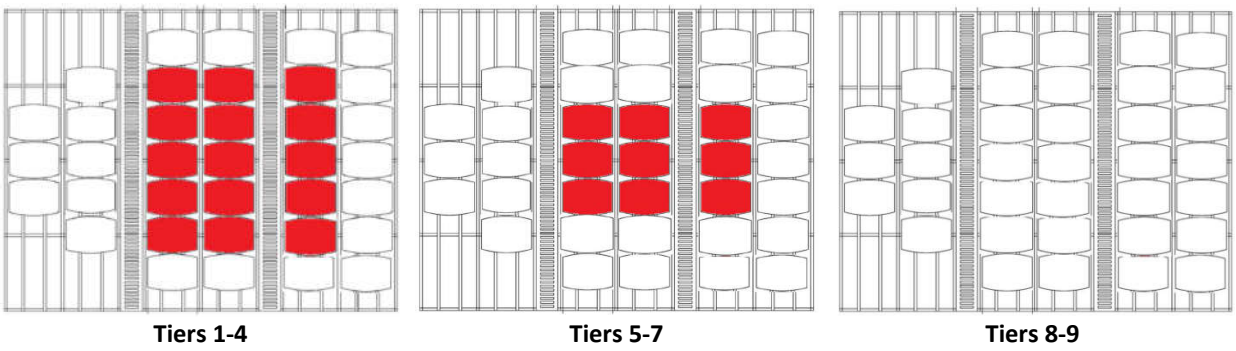


Figure 3-8: Location of alcohol filled barrels (shown in red) inside the array used during Test 3.

3.1.3.5 Sprinkler Protection

Tests 1 and 2 were conducted with 40 ft (12.2 m) high ceiling-only sprinkler protection. Test 3 included ceiling and in-rack sprinklers. A summary of the protection specifications is provided in Table 3-4. Ceiling sprinkler numbering, spacing and location relative to the fuel array are illustrated in Figs. 3-9 and 3-10. The ignition pan was centered among 4 sprinklers in both tests. Previous palletized tests showed very early activation if the ignition source was centered under one sprinkler . For that reason, the more conservative option of centering the ignition pan among four sprinklers was chosen here.

Table 3-4: Protection summary for Tests 1, 2, and 3.

Test #	Test 1	Test 2	Test 3	Test 3 (In-rack sprinklers)
Sprinkler Orientation – Upright/Pendent	Pendent	Upright		
Water Delivery System / Delay (Seconds)	Wet-pipe	Dry-pipe (40)		
Sprinkler Spacing (ft x ft [m x m]) or online (in-rack sprinkler)	10x10 [3.1 x 3.1]			1.2 [4]
Discharge Coefficient (K-factor) (*gpm/psi$^{1/2}$* [lpm/bar$^{1/2}$])	14.0 [200]	16.8 [240]	11.2 [160]	8.0 [115]
Temperature Rating (^{o}F [^{o}C])	165 [74]	286 [141]	286 [141]	165 [74]
Sprinkler Response	Quick	Standard	Standard	Quick
Sprinkler Deflector Location (in. [cm])	12 [30]		12 [30]	6 [15]
# of Sprinklers Installed	64			13
Discharge Pressure (psig [bar])	37 [2.6]	25 [1.7]	7 [0.5]	32 [2.2]
Per Sprinkler Discharge (gpm [L/min])	85 [322]		30 [114]	45 [170]
Design Density (gpm/ft^2 [mm/min])	0.85 [35]		0.30 [12]	N/A

For Test 1, the pendent ceiling sprinklers with a K-factor of 14.0 gpm/psi$^{1/2}$ (200 lpm/bar$^{1/2}$) were installed on a 10 ft x 10 ft (3.0 m x 3.0 m) spacing. These quick response (QR) sprinklers had a temperature rating of 165^{o}F (74^{o}C). The discharge pressure was set to 37 psi (2.5 bar) resulting in a discharge density of 0.85 gpm/ft^2 (35 mm/min). The water discharge density was based on work in a separate study.

For Test 2, the upright ceiling sprinklers with a K-factor of 16.8 gpm/psi$^{1/2}$ (240 lpm/bar$^{1/2}$) were also installed on a 10 ft x 10 ft (3.0 m x 3.0 m) spacing. These standard response (SR) sprinklers had a temperature rating of 286^{o}F (141^{o}C). The discharge pressure was set to 25 psi (1.7 bar) resulting in a discharge density of 0.85 gpm/ft^2 (35 mm/min). This test used a dry-pipe system with a water delivery delay time set to 40 seconds.

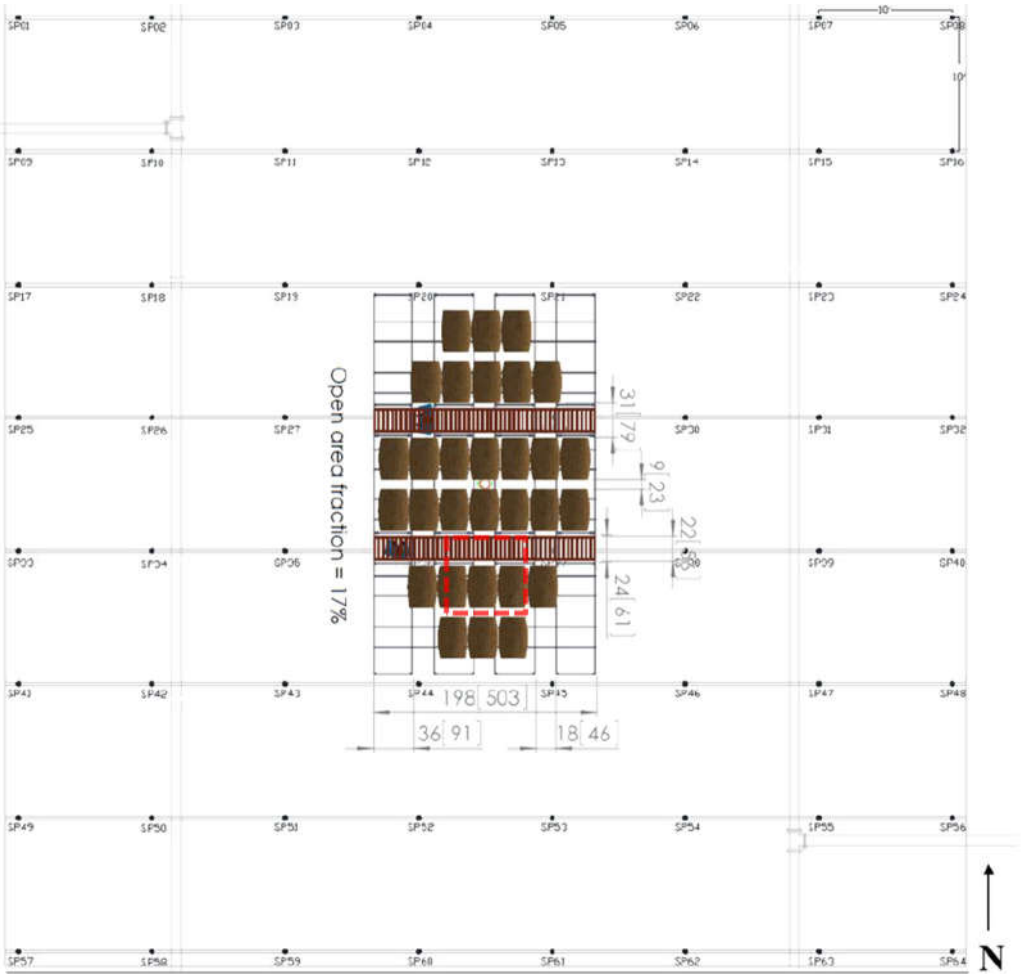


Figure 3-9: Position of fuel array with respect to the ceiling sprinklers. The ignition pan shown as a red square is centered among 4 sprinklers (Tests 1 and 2).

Finally, for Test 3, both ceiling and in-rack sprinklers were installed. The ceiling protection consisted of upright ceiling sprinklers with a K-factor of 11.2 gpm/psi$^{1/2}$ (160 lpm/bar$^{1/2}$) installed on a 10 ft x 10 ft (3.0 m x 3.0 m) spacing. These standard response (SR) sprinklers had a temperature rating of 286°F (141°C). The discharge pressure was set to 7 psi (0.48 bar) resulting in a discharge density of 0.3 gpm/ft^2 (12 mm/min). Like Test 2, a dry-pipe system was used with a water delivery delay time set to 40 seconds. Test 3 also included a single layer of in-rack sprinklers. The in-rack sprinkler protection consisted of upright sprinklers with a K-factor of 8.0 gpm/psi$^{1/2}$ (115 lpm/bar$^{1/2}$) installed on a 4-ft (1.2-m) on-line spacing. These quick response (QR) sprinklers with a temperature rating of 165°F (74°C) were installed 6 in. (15 cm) from the top of the eighth tier as shown in Fig. 3-11 (a) and (b). The discharge pressure was set to 32 psig (2.2 bar) resulting in a per-sprinkler-flow of 45 gpm (170 lpm).

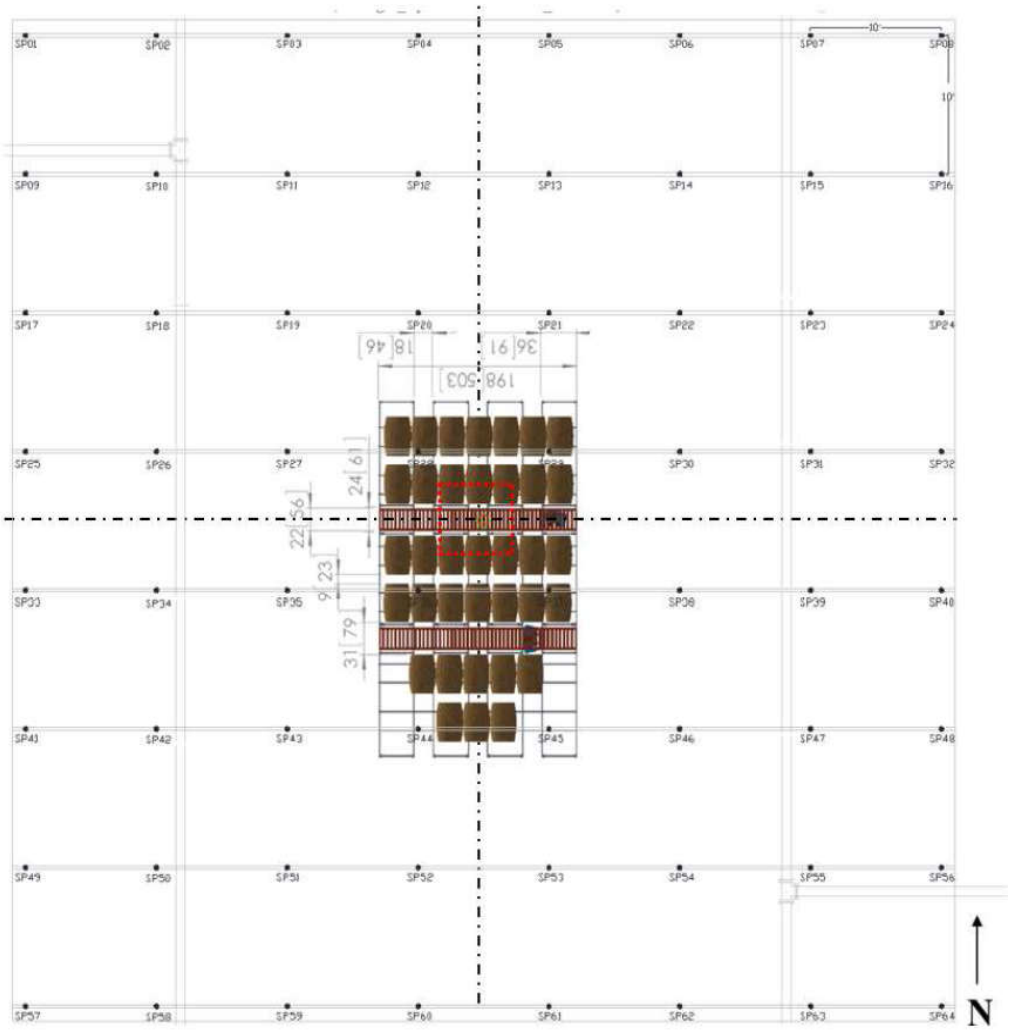
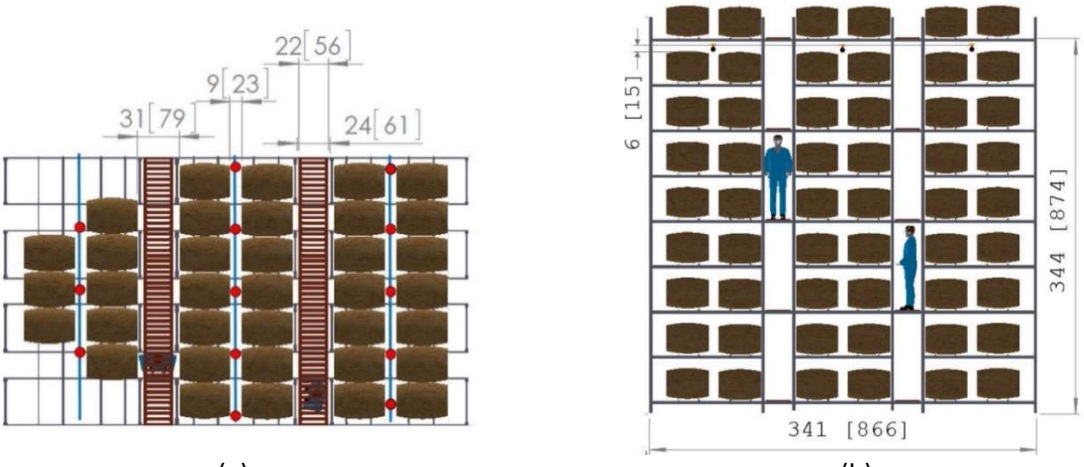


Figure 3-10: Position of fuel array with respect to the ceiling sprinklers. The ignition pan shown as a red square is centered among 4 sprinklers (Test 3).

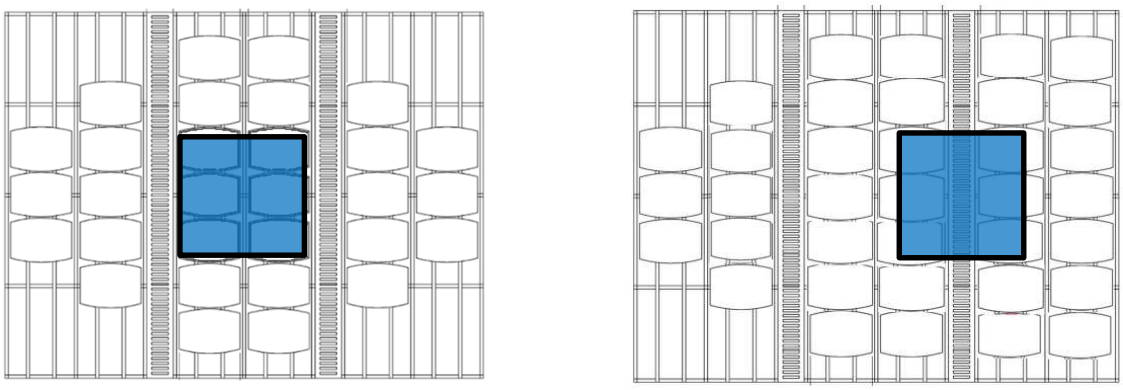


(a) (b)

Figure 3-11: In-rack sprinkler location and spacing shown in a plan view (a) and an elevation view (b).

3.1.3.6 Ignition Source and Location

For all three tests, the ignition fuel loading consisted of a 20-gallon (76-liter) confined spill (6 ft x 6 ft [1.8 m x 1.8 m]) of 100% ethanol. For Test 1 and 2, the pan was centered at the bottom of the array (see Fig. 3-12 (a)). For Test 3, the pan location was offset towards the North and centered with respect to the catwalk (shown in Fig. 3-12 (b)).



(a) (b)

Figure 3-12: Ignition pan location for Tests 1 and 2 (a). Ignition pan location for Test 3 (b).

3.1.4 Test Results

3.1.4.1 Result Summary

A summary of the main test results is presented in Table 3-5. Detailed fire chronologies are given in Section 3.1.6 and selected images are provided in Section 3.1.7.

Table 3-5: Result summaries for Test 1, 2, and 3.

Test Outcome			
Test	Test 1	Test 2	Test 3
First/Last Ceiling Sprinkler Operation (min:s)	1:03/3:20	1:49/2:30	2:16/3:19
Total Ceiling Sprinklers Opened (in-rack sprinklers)	4	15	(3)
Peak Gas Temperature (°F [°C]) @ Time	497 [258] @ 0:63	1783 [973] @2:06	750 [399] @ 3:17
Maximum Steel TC Measurement and Time (°F [°C])	178 [81] @ 7:45	477 [248] @ 2:43	197 [92] @ 3:17
Test Termination – Time After Ignition (min:s)	30:00	15:00	12:00

3.1.4.2 Test 1

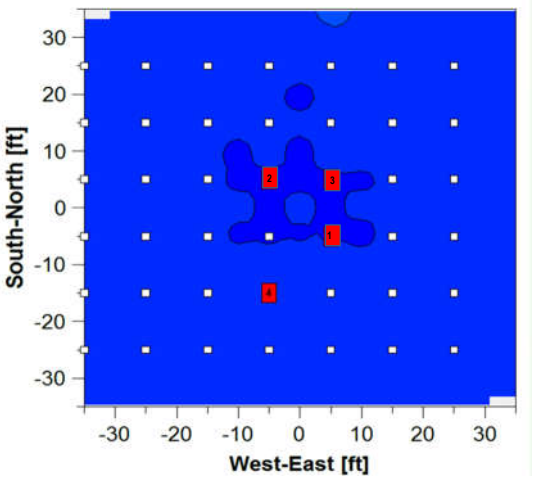
3.1.4.2.1 Fire Chronology

After ignition, flames quickly reached up to the third tier. About 20 seconds into the test, vertical fire growth was observed in the center of the array, reaching the fourth tier after 30 seconds. The fire continued to grow vertically until flames were seen above the array 60 seconds after ignition. At 1:03 (min:sec), three sprinklers opened in quick succession, reducing the flame height to the bottom six tiers. For the next two minutes, the fire remained steady in the core of the array up to the fifth tier. At 3:20, a fourth sprinkler activated and the fire further reduced in size. At 6:15, a small pool fire was visible on the

west side of the array indicating that some of the barrels were leaking. After 9 minutes, this pool fire was diluted and extinguished by the sprinkler water. The fire reduced further in size and was nearly extinguished at 12 minutes after ignition. Small flames remained at the original ignition location for the next 10 minutes. At 22 minutes after ignition, the fire was fully extinguished, and no flames were visible. The test was terminated 30 minutes after ignition.

3.1.4.2.2 Sprinkler Activation Sequence

In total, four sprinklers activated during Test 1. The sprinkler activation pattern is shown in Fig. 3-13.



(a)

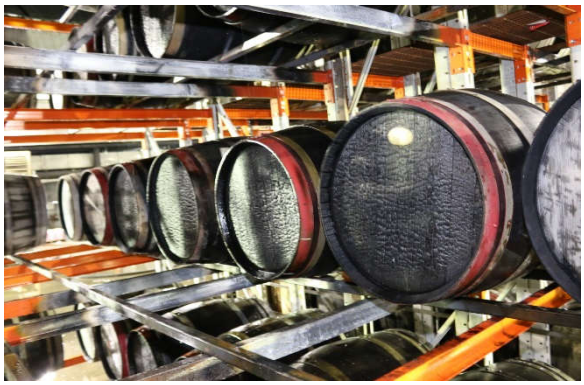
Sequence	Head Number	Activation Time (min:sec)
1	HEAD37	01:03
2	HEAD28	01:03
3	HEAD29	01:04
4	HEAD44	03:20

(b)

Figure 3-13: Sprinkler activation pattern (a) and timing (b) for Test 1.

3.1.4.2.3 Extent of Fire Damage

The damage was mostly contained to the barrels in the bottom four tiers facing the main flue. The most severe charring was observed on the barrel heads facing the main longitudinal flue. Pictures of the charred barrels are shown in Fig. 3-14.



(a)

(b)

Figure 3-14: Post-test images from Test 1 of affected barrels showing charring at heads (a) and on the staves (b).

3.1.4.2.4 Maximum Steel and Gas Temperatures at the Ceiling

Both maximum steel and gas temperatures for Test 1 are shown in Fig. 3-15 (a). The steel temperature (red solid line) is obtained from embedded thermocouples inside a steel cross centered on the ceiling. The gas temperature (black solid line) was measured via ceiling mounted thermocouples. The maximum gas temperature, 497°F (258°C), was measured 63 seconds after ignition. The maximum steel temperature, 178°F (81°C), was observed 7 minutes and 45 seconds after ignition.

At 13:20, only very small flamelets were witnessed at floor level. The test was terminated at 20:00 with the fire completely suppressed.

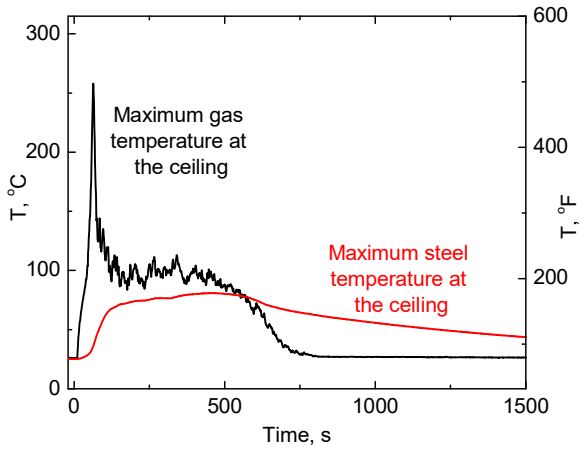


Figure 3-15: Maximum steel (solid red line) and gas (solid black line) temperatures. Test 1.

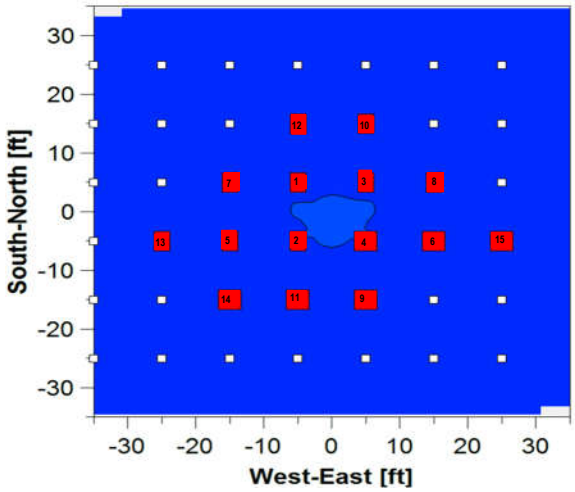
3.1.4.3 Test 2

3.1.4.3.1 Fire Chronology

The initial fire growth during Test 2 was nearly identical to that in Test 1. After ignition of the alcohol inside the ignition pan, flames quickly reached up to the third tier. The fire remained steady above the ignition pan for the first 35 seconds. After 50 seconds, the fire started to grow vertically, and flames reached the fifth tier. After 1 minute, flames reached the seventh tier. At 1:15 (min:sec), flames were observed above the array. From 1:30 until water delivery, steady flames were impinging onto the ceiling. The first sprinkler activated at 1:49. Within the following 40 seconds (the dry-pipe delay time) an additional 14 sprinklers activated. At 2:30, water was delivered to all 15 opened sprinklers and the fire size quickly reduced to the bottom six tiers above the ignition pan. After 4 minutes, the fire reduced to the region just above the ignition pan. At 5:40 the fire was fully suppressed.

3.1.4.3.2 Sprinkler Activation Sequence

The sprinkler activation pattern is shown in Fig. 3-16. Selected ceiling temperature contours are presented in Appendix D.

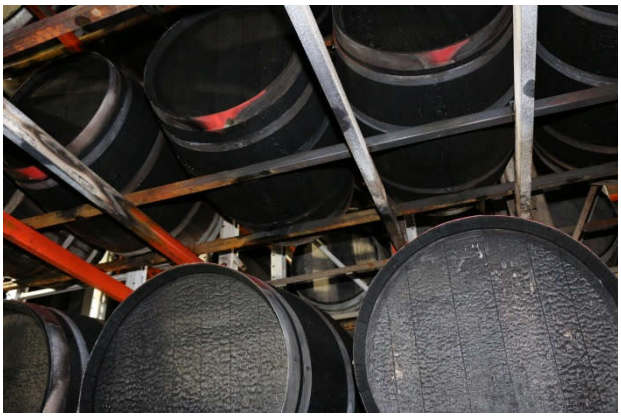


(a)

Sequence	Head Number	Activation Time (min:sec)
1	HEAD28	01:49
2	HEAD36	01:51
3	HEAD29	01:56
4	HEAD37	02:01
5	HEAD35	02:02
6	HEAD38	02:07
7	HEAD27	02:12
8	HEAD30	02:13
9	HEAD45	02:16
10	HEAD21	02:16
11	HEAD44	02:18
12	HEAD20	02:20
13	HEAD34	02:24
14	HEAD43	02:27
15	HEAD39	02:30

(b)

Figure 3-16: Sprinkler activation pattern (a) and timing (b) for Test 2.



(a)

(b)

Figure 3-17: Post-test images from Test 2 of affected barrels showing charring at heads (a) and on the staves (b).

3.1.4.3.3 Extent of Fire Damage

Like Test 1, the damage was mostly contained to the barrels in the bottom four tiers. Charring was most severe for the barrel heads facing the main longitudinal flue. Pictures of the charred barrels are shown in Fig. 3-17 . The total damage assessed after Test 2 was less than that observed after Test 1.

3.1.4.3.4 Maximum Steel and Gas Temperatures at the Ceiling

Both maximum steel and gas temperatures are shown in Fig. 3-18 (a). The maximum ceiling temperatures was observed directly above the ignition location and reached about 1783°F (973°C) 2 minutes and 6 seconds after ignition (directly before the water delivery). The maximum steel temperature of 477°F (247°C) was reached at 2 minutes and 43 seconds after ignition.

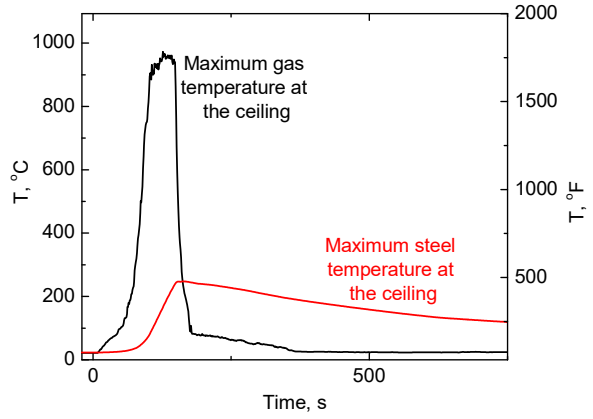


Figure 3-18: Maximum steel (solid red line) and gas (solid black line) temperatures. Test 2.

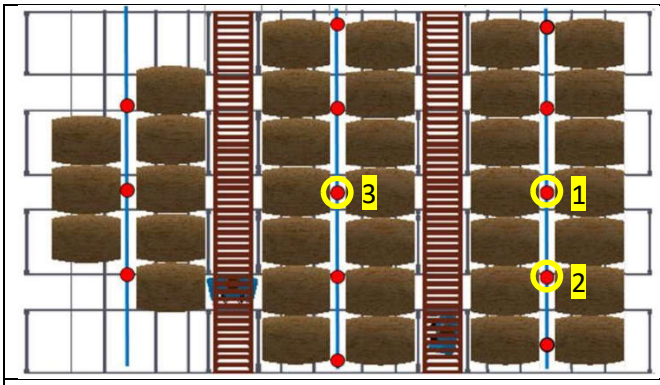
3.1.4.4 Test 3

3.1.4.4.1 Fire Chronology

The initial fire growth was like that of Test 1 and Test 2. After initiation of the alcohol pool fire in the ignition pan, flames quickly reached up to the third tier. About 20 seconds into the test, vertical fire growth was observed in the center of the array reaching the fourth tier. Compared to the first two tests, vertical fire growth started later and flames were seen above the array at 1:43 (min:sec) after ignition. The first in-rack sprinkler activated at 2:18 after ignition. The second and third in-rack sprinkler activated at 3:02 and 3:18, respectively. Water began discharging from the sprinklers at 3:02. The fire slowly reduced in size over the next 2 minutes. Five minutes after ignition and 2 minutes after water delivery to the activated sprinklers, the fire reduced to the bottom three tiers. A weak pool fire was seen towards the southeast side of the array at 6:00. At 8 minutes after ignition, flames were no longer visible. The test was terminated at 12:00.

3.1.4.4.2 Sprinkler Activation Sequence

No ceiling sprinklers activated during Test 3. The pattern and timing of the three in-rack sprinklers that operated are shown in Fig. 3-19 (a) and (b).



(a)

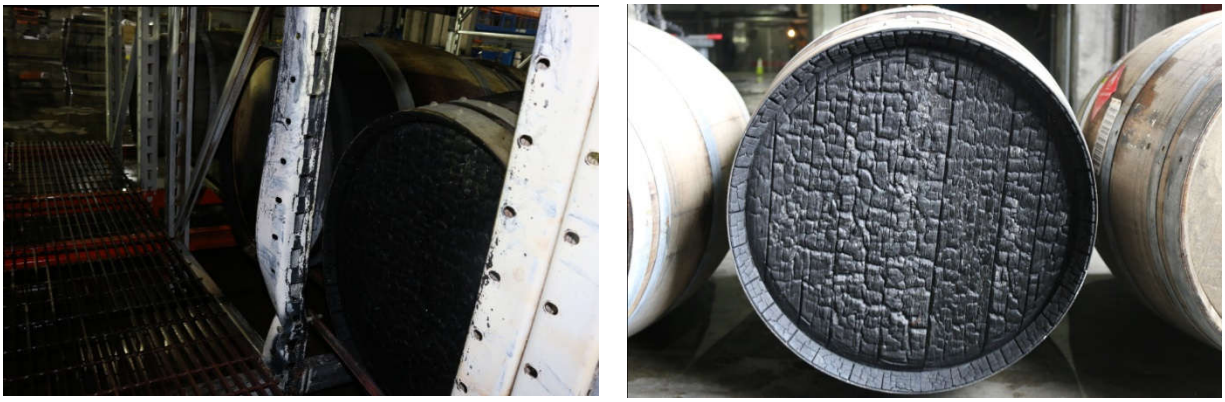
Sequence	Head Number	Activation Time (min:sec)
1	IRAS HEAD11	02:16
2	IRAS HEAD10	03:03
3	IRAS HEAD06	03:19

(b)

Figure 3-19: Sprinkler activation pattern (a) and timing (b) for Test 3.

3.1.4.4.3 Extent of Fire Damage

The damage was mostly contained to the barrels in the bottom three tiers facing the main flue. The most severe charring was observed on the barrel heads facing the main longitudinal flue. Pictures of the charred barrels from Test 3 are shown in Fig. 3-20.



(a) (b)

Figure 3-20: Post-test images from Test 3 of affected barrels showing charring at heads (a) and on the staves (b).

3.1.5 Summary and Conclusions

This study investigated sprinkler protection options for nine-tier high, rack storage of distilled spirits under a 40 ft (12.2 m) high ceiling. The test work included single-barrel heat release rates (HRR) and leak measurements and three large-scale fire tests. All barrels in this study were built from oak and had a capacity of 59 gal (225 L). The simulated distilled spirits (SDS) had a 75% (by volume) alcohol content.

Three large-scale fire tests, Tests 1, 2, and 3, were carried out. Test 1 was conducted with wet-pipe, ceiling-only quick response sprinklers installed on a 10 ft x 10 ft (3.0 m x 3.0 m) spacing, using sprinklers with a K-factor of 14.0 gpm/psi$^{1/2}$ (200 lpm/bar$^{1/2}$) and a temperature rating of 165°F (74°C). The ceiling density was set to 0.85 gpm/ft^2 (35 mm/min), by using a discharge pressure of 37 psi (1.7 bar). Test 1 resulted in four sprinkler activations, fully suppressing the fire after 20 minutes.

Test 2 used an identical rack configuration as Test 1. The protection was changed to a 40 second delayed dry-pipe system. Standard response sprinklers with a K-factor of 16.8 gpm/psi$^{1/2}$ (240 lpm/bar$^{1/2}$) and a temperature rating of 286°F (141°C) were installed on a 10 ft x 10 ft (3.0 m x 3.0 m) spacing. The ceiling density was equal to that in Test 1, 0.85 gpm/ft^2 (35 mm/min), at a discharge pressure of 25 psi (2.5 bar). Test 2 resulted in 15 sprinkler activations, fully suppressing the fire within 10 minutes.

Finally, Test 3 investigated the protection provided by both ceiling and in-rack automatic sprinklers. The ceiling protection was provided by a 40-seconds delayed, dry-pipe system using standard response sprinklers with a K-factor of 11.2 gpm/psi$^{1/2}$ (160 lpm/bar$^{1/2}$) and a temperature rating of 286°F (141°C), installed on a 10 ft x 10 ft (3.0 m x 3.0 m) spacing. Ceiling density was set to 0.3 gpm/ft^2 (12 mm/min). In-rack sprinkler protection was provided by 40-second delayed dry-pipe fed quick response sprinklers with a K-factor of 8.0 gpm/psi$^{1/2}$ (115 lpm/bar$^{1/2}$) and a temperature rating of 165°F (74°C) spaced 4 ft

(1.2 m) on-line. In-rack sprinkler water flow was set to 45 gpm (170 L/min). Test 3 resulted in three in-rack sprinkler activations fully suppressing the fire within 8 minutes.

3.1.6 Fire Chronologies

3.1.6.1 Test 1

Time (mm:sec)	Observation
00:00	Ignition
00:10	Fire from the ignition pan reaches the third tier.
00:20	Fire is starting to mover vertically.
00:30	Fire reaches the fourth tier.
00:40	Fire is starting to move vertically reaching the fifth tier.
00:50	Fire is starting to move vertically reaching the seventh tier.
01:00	Flames seen above the 9-tier array.
01:03	First sprinkler activates.
01:03	Second sprinkler activates.
01:04	Third sprinkler activates.
01:30	Flames are reduced to the bottom six tiers.
02:00	Flames are reduced to the bottom five tiers. Steady flames inside the main flue.
02:30	More smoke and steam development, no significant reduction in fire size.
03:20	Fourth sprinkler activates.
04:00	Narrow column fire centered inside the array reaching the fifth tier.
05:00	Narrow column fire centered inside the array reaching the sixth tier.
06:15	Fire becomes more translucent. A small pool fire is seen on the West side of the array.
09:13	Pool fire on the West side is extinguished due to the sprinkler water flow.
09:00	Fire is reducing in size.
12:00	Fire is all but extinguished.
12:30	Small flame is visible above the third tier in the center of the array.
22:00	Fire completely extinguished.
30:00	Test termination.

3.1.6.2 Test 2

Time (mm:sec)	Observation
00:00	Ignition
00:10	Fire from the ignition pan reaches the third tier.
00:20	Fire is starting to move vertically.
00:30	Fire reaches the fourth tier.
00:40	Fire is starting to move vertically reaching the fifth tier.
00:50	Fire is starting to move vertically reaching the seventh tier.
01:00	Flames seen above the 9-tier array.
01:30	Flames seen above the array impinging on the ceiling.
01:49	First sprinkler activates.
01:51	Second sprinkler activates.
01:56	Third sprinkler activates.

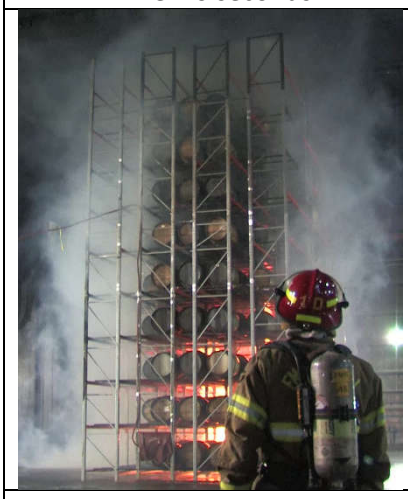
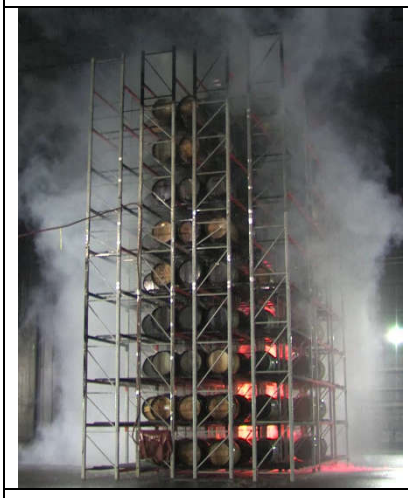
02:01	Fourth sprinkler activates.
02:02	Fifth sprinkler activates.
02:07	Sixth sprinkler activates.
02:12	Seventh sprinkler activates.
02:13	Eighth sprinkler activates.
02:16	Ninth sprinkler activates.
02:16	Tenth sprinkler activates.
02:18	Eleventh sprinkler activates.
02:20	Twelfth sprinkler activates.
02:24	Thirteenth sprinkler activates.
02:27	Fourteenth sprinkler activates.
02:30	Fifteenth sprinkler activates.
02:35	Water arrives at the open sprinkler heads.
02:45	Fire quickly reduces in size.
05:00	Fire is extinguished.
10:00	Test termination.

3.1.6.3 Test 3

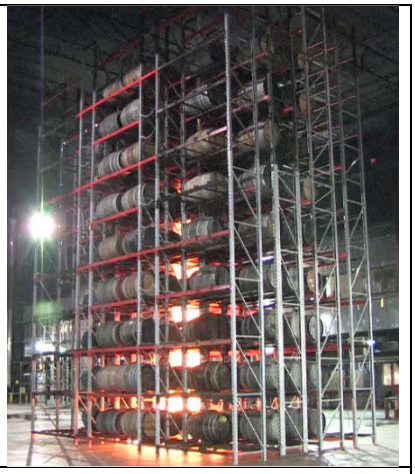
Time (mm:sec)	Observation
00:00	Ignition.
00:10	Fire from the ignition pan reaches the third tier.
00:20	Fire is starting to move vertically.
00:30	Fire reaches the fourth tier.
01:10	Fire is starting to move vertically reaching the fifth tier.
01:30	Fire is starting to move vertically reaching the seventh tier.
01:00	Flames seen above the 9-tier array.
02:16	First in-rack sprinkler activates.
02:30	Flames seen above the array impinging on the ceiling.
03:03	Second in-rack sprinkler activates.
03:03	Water arrives at the open sprinkler head.
03:19	Third in-rack sprinkler activates.
03:30	Fire reduces in size.
06:00	Small pool fire visible.
08:00	Fire is extinguished.
12:00	Test termination.

3.1.7 Selected Photographs

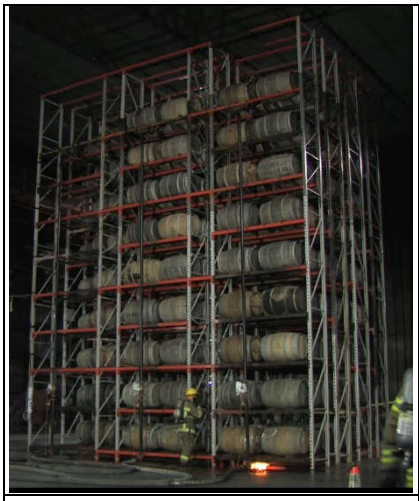
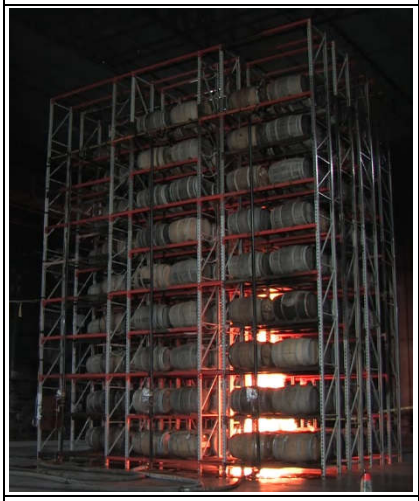
3.1.7.1 Test 1

Time = 0 seconds	0:30	1:00
		
2:00	3:00	5:00
		
7:00	9:00	10:00

3.1.7.2 Test 2

		
Time = 0 seconds	0:30	1:00
1:30	2:00	2:30
3:00	5:00	10:00

3.1.7.3 Test 3

		
Time = 0 seconds	0:45	1:30
		
2:30	3:30	4:30
5:30	5:00	8:00

3.2 Palletized Distilled Spirits Storage Protection / Jaap de Vries / May 2012

3.2.1 Test Summaries

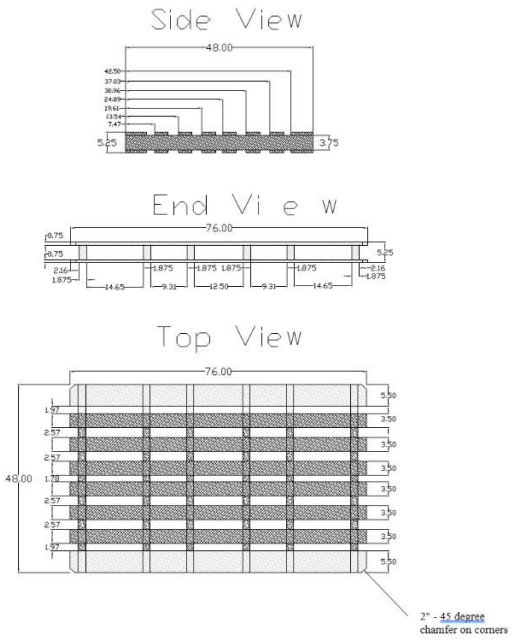
The objective of this study was to determine if barrels filled with a solution of denatured alcohol in water (75% by volume) stored in 7-tier-high palletized arrays can be protected using wet pipe, ceiling sprinkler protection only. Particularly, the effect of adding 6-in. (15-cm) flue spaces to improve water transport down the array was explored. Water penetration within these storage configurations has been identified as one of the major problems in providing adequate ceiling level sprinkler protection.

The test facility used for this program is described in Section 2. A summary of the four tests is provided in Table 3-6.

3.2.2 Test Commodity

3.2.2.1 Wooden Pallets

The pallet design for this testing was representative of the pallets used in the industry. Two different materials are used for pallets in the distilled-spirits industry. These materials are soft wood (Sitka spruce) and hardwood (oak). While soft wood pallets are more common in the industry, hard wood pallets were used due to the lack of availability of the former. Each pallet was dried for at least 7 days inside a kiln. Detailed dimensional drawings of the pallet are shown in Figure 3-21.



3-21: Dimensions (in inches) of hardwood pallets used in this study.

Table 3-6: Large Scale Fire Testing Summary, Tests 1-4.

Test Number	Test 1	Test 2	Test 3	Test 4
Test Date (mm/dd/yyyy)	6/2/2011	6/15/2011	6/24/2011	7/20/2011
FM global Fire Technology Laboratory Test Site	North Movable Ceiling			
Environmental Conditions				
Pre-test Inside Temperature (ºF [ºC])	65 [18]	67 [19]	65 [18]	71 [22]
Pre-test Inside relative Humidity (%)	38	52	80	37
Outdoor Temperature (ºF [ºC])	66 [19]	66 [19]	62 [17]	79 [26]
Outdoor Relative Humidity (%)	37	55	90	54
Main Array Moisture Content (% v/v)	8-10	9-11	9-12	9-11
Fire test Setup				
Nominal Ceiling Height (ft [m])	30 [9.1]			
Commodity	Wooden Barrels			
Water filled	189	210	210	178
Simulated Whiskey Filled (75% denatured alcohol)	0	0	0	32
Storage Arrangement	Palletized			
Array Nominal Size – LxWxH (ft x ft x ft [m x m x m])	*12.7 x 13 x 27* [3.9 x 4.0 x 7.3]			13.2 x 12 x 27 [4.0 x 3.7 x 7.3]
Nominal Pallet Load Height (in [m.])	41.3 [1.04]			
Nominal Flue Space Width (in [mm])	6 [152]			
No. of Storage Levels	7			
Clearance to Ceiling (ft-in [m])	5-11 [1.8]			
Ignition Centered Below (*No. Ceiling Sprinklers*)	1	4	4	4
Sprinkler Orientation – upright/pendent	Pendent			
Discharge Coefficient (K-factor) (*gpm/psi$^{1/2}$* [lpm/bar$^{1/2}$])	25 [360]		14 [200]	
Sprinkler Response	Quick		Quick	
Temperature Rating (°F [°C])	165 [74]			
Spacing (ft x ft [m x m])	10 x 10 [3.0 x 3.0]			
Discharge Pressure (psig [bar])	16 [1.09]		18.3 [1.25]	
Discharge Density (gpm/ft^2 [mm/min])	1.0 [41]		0.6 [24]	
Fire test Results				
First/Last Ceiling Sprinkler Operation (min:s)	1:56	4:17/6:51	5:12/7:17	3:56/5:25
Total Ceiling Sprinklers Opened	1	3	5	5
Peak Gas Temperature (°F [°C])	224 [107]	378 [192]	421 [233]	509 [265]
Maximum One Minute Average TC Measurement and Time (°F [°C])	143 [61.7] @ 1:32	308 [153] @ 5:55	334 [168] @ 5:00	365.6 [185] @ 4:28
Maximum Steel TC Measurement and Time (°F [°C])	88 [31] @ 2:25	154 [68] @ 7:42	176 [80] @ 9:36	209 [98] @ 13:13
Test Termination – Time After Ignition (min:s)	20:00	20:00	30:00	26:00

3.2.2.2 Wooden Barrels

Each white-oak barrel has a volumetric capacity of 54 gal (204 liters). Dimensions of a barrel are 36 in. (91 cm) tall, with a head-hoop diameter of 21 in. (53 cm). The diameter at the bilge is 24 in. (61 cm).

Each barrel weighs approximately 110 lbs (50 kg) unused and 125 lbs (57 kg) when used. An image of a barrel with associated terminology is shown in Figure 3-22.

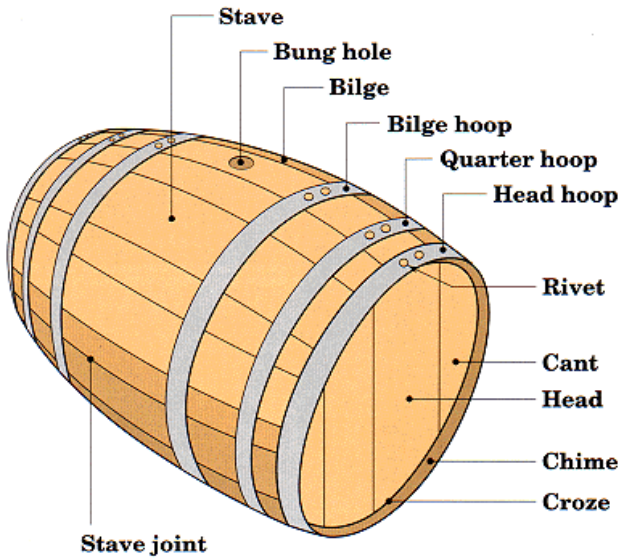


Figure 3-22: Description of wooden barrel components.

A summary of the physical properties of each barrel is given in Table 3-7.

Table 3-7: Properties of white oak barrels used in this study.

Oak Wood Properties	
Formula	$CH_{1.7}O_{0.72}N_{0.001}$
Density (Dried) (lb/ft^3 [kg/m^3])	35.0 [560]
Theoretical Heat of Combustion (*BTU/lb* [kJ/g])	7,348 [17.1]
Pallet Properties	
Volumetric Capacity (gal [L])	53 [201]
Weight (Used) (lbs [kg])	125 [57]
Moisture Content	6%
Fire Loading (kBTU [MJ])	808 [855]

Extensive testing was conducted previously to gain understating of the types of failures and critical failure times of wooden barrels. From these tests, the following conclusions were drawn:

1. Single-barrel fire tests are not representative of the fire dynamics and thermal loads seen in large-scale fires.
2. Leakage times were reduced from 17 minutes to less than 4 minutes between a single barrel and large(er) scale fire tests.
3. Barrel leakage occurs prior to the pallets losing structural integrity and potential for collapse.
4. The main leakage starts when the steel hoops are heated up, expand, and reduce tension on the staves. Leakage typically occurs at the bottom croze where the staves and head come together.

5. During large-scale tests, leakage starts at about the time of first sprinkler operation when using quick response, 165°F (74°C) sprinklers.

3.2.2.3 Simulated Distilled Spirits

Simulated distilled spirits, used in this study (for Test 4 only), consisted of 75% (by volume) of denatured alcohol in water. The effect of alcohol content on closed-cup flash point is shown in Figure 3-23 with data taken from previous work.

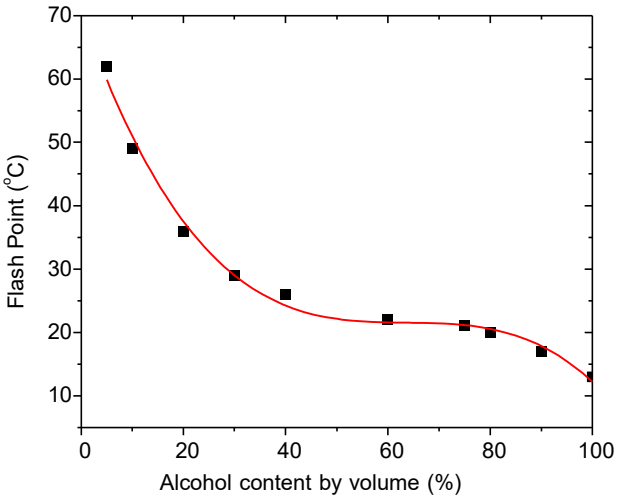


Figure 3-23: Flash point dependency on volume fraction of alcohol in water.

Properties of the simulated whiskey are summarized in Table 3-8. The denatured alcohol (CDA 19) used in this study consist of three individual components: ethanol, methyl- isobutyl-ketone, and heptane. Since 95% of denatured alcohol is made up of ethanol, the closed-cup flash point of a 75% aqueous solution is taken from previous work and assumed to be representative for solutions with water and CDA-19. Note that the theoretical heat of combustion of 75% simulated distilled spirit is 6960 BTU/lb (16.2 kJ/g), which is 59% of the heat of combustion of pure ethanol. At the tested concentration, the closed-cup flash point is 70°F (21°C) which means that these mixtures will easily ignite at room temperature.

Table 3-8: Properties of simulated distilled spirits.

Properties (Denatured Alcohol)	
Density (lb/ft^3 [kg/m^3])	48.9 [784]
Theoretical Heat of Combustion (BTU/lb [kJ/g])	11758 [27.7]
Components (Denatured Alcohol)	
Ethanol (C_2H_5OH)	95.5%
Density (lb/ft^3 [kg/m^3])	49.2 [789]
Theoretical Heat of Combustion (BTU/lb [kJ/g])	11758 [27.7]
Methyl isobutyl ketone ($C_6H_{12}O$)	3.5%
Density (lb/ft^3 [kg/m^3])	50.1 [802]
Theoretical Heat of Combustion (BTU/lb [kJ/g])	10400 [24.2]
Heptane (C_5H_{12})	1%
Density (lb/ft^3 [kg/m^3])	42.6 [684]
Theoretical Heat of Combustion (BTU/lb [kJ/g])	18932 [44.6]
Mixture (Simulated Distilled Spirit)	
Concentration of Denatured Alcohol (%)	75
Water (%)	25
Density (lb/ft^3 [kg/m^3])	53 [849]
Theoretical Heat of Combustion (BTU/lb [kJ/g])	7598 [17.9]
Flash-point, Closed Cup (°F [°C])	70 [21]

3.2.3 Large-scale Fire Test Setup, Procedure, and Results

Four large-scale fire tests were performed for this study. This chapter describes the test setup, procedures, instrumentation, and results. The pass/fail performance criteria used to evaluate the test results have been provided in Section 3.1.3.1.

3.2.3.1 Test 1 Setup

A side view and plan view schematic of Test 1 is shown in Figure 3-24. An actual image of the test setup is shown in Figure 3-25. For Test 1, each tier consisted of 6 pallets holding a total of 27 barrels; as a result, 42 pallets and 189 barrels were used for this test bringing the total fire loading to 240 MBTU (253 GJ). Each barrel was filled with 50 gal (190 L) of water. Each pallet load weighed 3,368 lbs (1,528 kg). The total mass per palletized stack was 23,580 lbs (10,696 kg).

Each array was 156 in. (3.96 m) wide, 152 in. (3.86 m) long, and 24 ft (7.3 m) high. Two 6 in. (15.2 cm) flue spaces were created in the east-west direction. The ceiling height was set to 30 ft (9.1 m) leaving a 70.8 in. (1.8 m) clearance from the top of the array. The open area fraction of the core 16 barrels (shown in Fig. 4-4) was 17.1%.

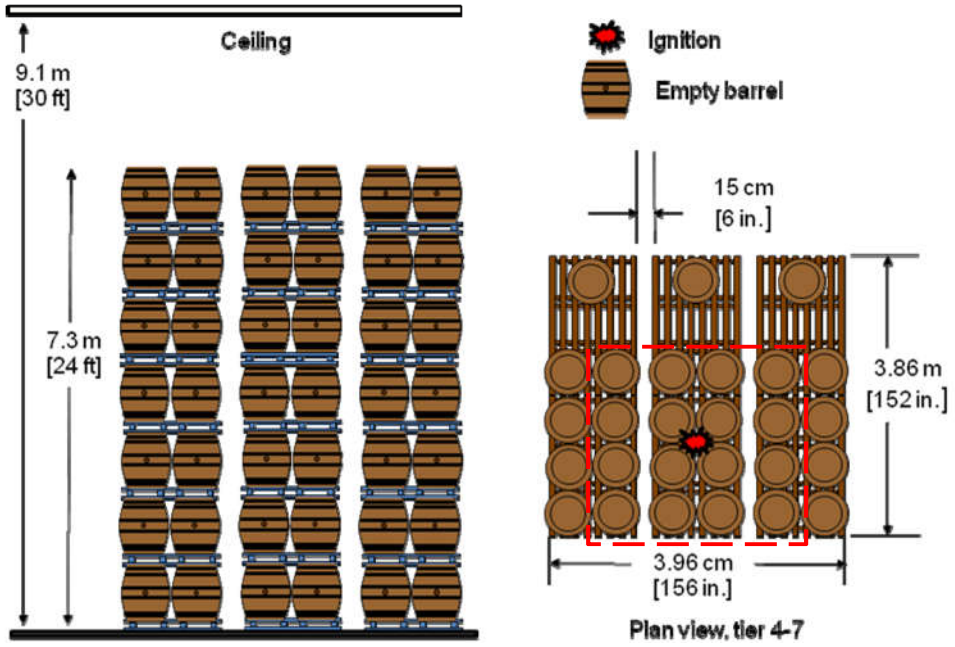


Figure 3-24: Schematic of array setup used for Test 1. Core sixteen barrels are marked by a dotted red line.

Figure 3-25: Image of storage arrangement for Test 1.

3.2.3.2 Test 2 and Test 3 Setup

The test array setup and commodity used for Tests 2 and 3 were the same as those of Test 1; however, an extra barrel was placed on the north side of the array for added stability. The increase in fire loading caused by these 21 barrels is 22 MBTU (18 GJ) bringing the total fire loading to 261 MBTU (275 GJ). A side view and plan view of Test 2 and 3 setup can be seen in Figs. 3-26 and 3-27. The location of the barrels instrumented with pressure transducers is shown. Only the first three tiers were instrumented. An image of the test setup is shown in Fig. 3-28.

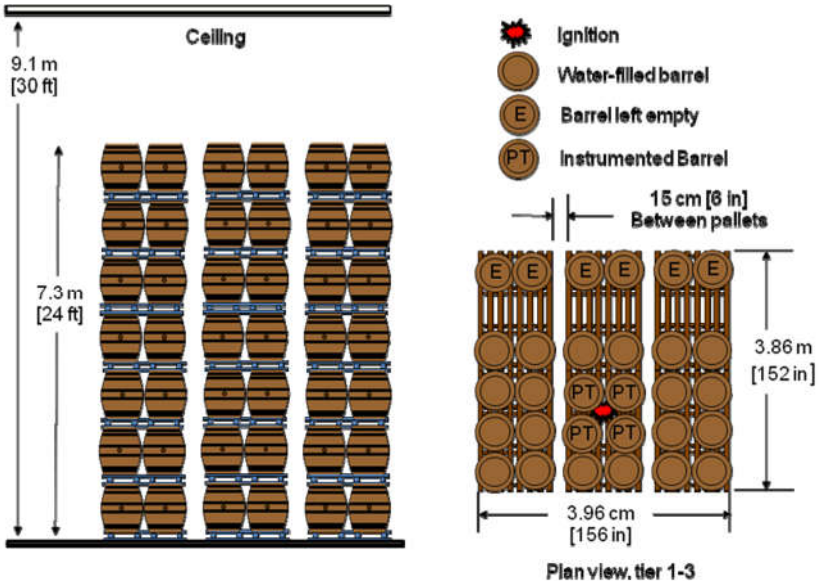


Figure 3-26: Schematic of array setup used for Test 2 and 3, tier 1-3.

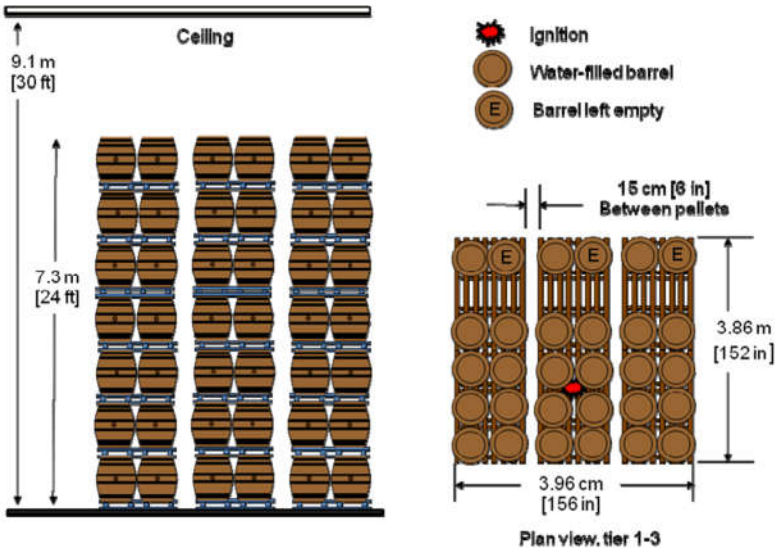


Figure 3-27: Schematic of array setup used for Test 2 and 3, tier 4-7.

Figure 3-28: Image of the array setup used for Test 2.

3.2.3.3 Test 4 Setup

The array dimensions for Test 4 were slightly different than those of Tests 2 and 3. For Test 4, a single flue was present running East-West. This change was made to more closely match array arrangements in the field. With the single 6-in. flue, the total open area fraction within the core 16 barrels was 10.3% which is 40% less than for Tests 2 and 3 and 52% more than for a closed array with no flues. For Test 4, 32 barrels were filled with simulated distilled spirits. The remaining 178 barrels were filled with water. Properties of the distilled spirits were presented in Table 3-8 of Section 3.2.2.3. The use of simulated distilled spirits raised the fire loading of Test 4 by 32% or 83 MBTU (88 GJ) bringing the total to 344 MBTU (363 GJ). A schematic of Test 4 is shown in Figs. 3-29, 3-30, and 3-31.

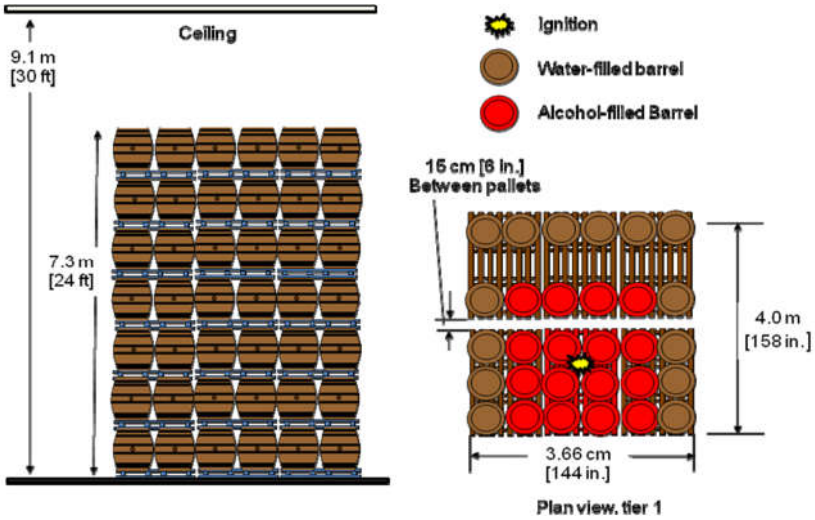


Figure 3-29: Schematic of Test 4, Tier 1.

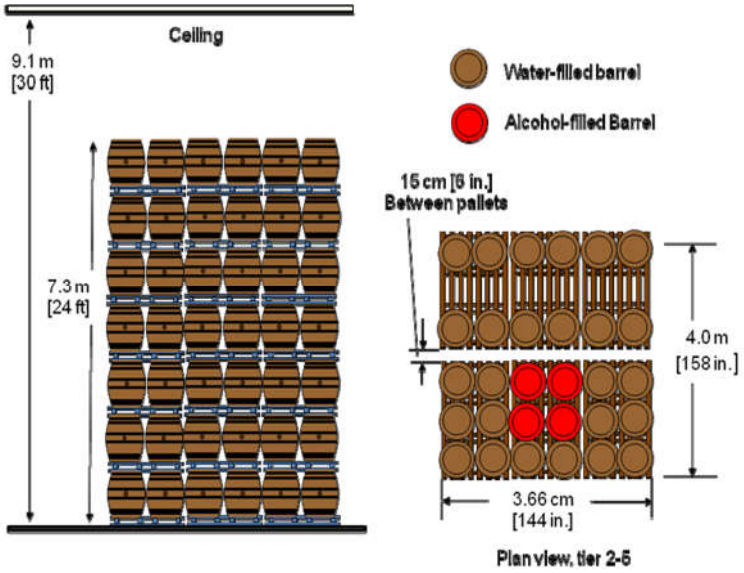


Figure 3-30: Schematic of Test 4, Tiers 2-5.

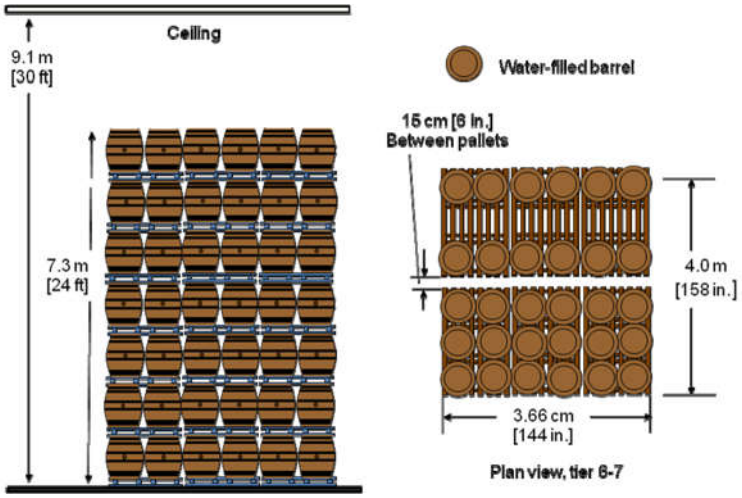


Figure 3-31: Schematic of Test 4, Tiers 6-7.

3.2.3.4 Automatic Ceiling Sprinklers

The sprinkler used for Test 1 and 2 were pendent quick response sprinklers with a K- factor of 25.2 gpm/psi$^{1/2}$ (360 lpm/bar$^{1/2}$). For Test 3 and Test 4, pendent quick response sprinklers were used and had a K-factor of 14 gpm/psi$^{1/2}$ (200 lpm/bar$^{1/2}$).

3.2.3.5 Ignition

Ignition was accomplished the same way for all four large-scale fire tests. The ignition and initial fire exposure consisted of a 2 gal (7.6 L) spill of 100% denatured alcohol poured underneath the 4 barrel footprint located in the core of the array. The initial spill was constrained to the core area by means of a steel pan. The alcohol was ignited with a propane torch. An image of the ignition process at times 0, 10, and 30 s after ignition is shown in Figure 3-32. For Test 1 the ignition was centered underneath one sprinkler. For Tests 2-4, ignition was among four sprinklers.

Figure 3-32: Ignition process at time 0, 10, and 30 s (Test 2).

3.2.3.6 Test Configuration Overview

A plan view of Test 1 underneath the north movable ceiling is shown in Figure 3-33. The spill ignition was centered under one sprinkler. Forty-nine (49) sprinklers were installed for Test 1. Tests 2-4 had 64 sprinklers installed and ignition occurred among 4 sprinklers. For Tests 2 and 3 a plan view is shown in Figure 3-34 and for Test 4 in Figure 3-35.

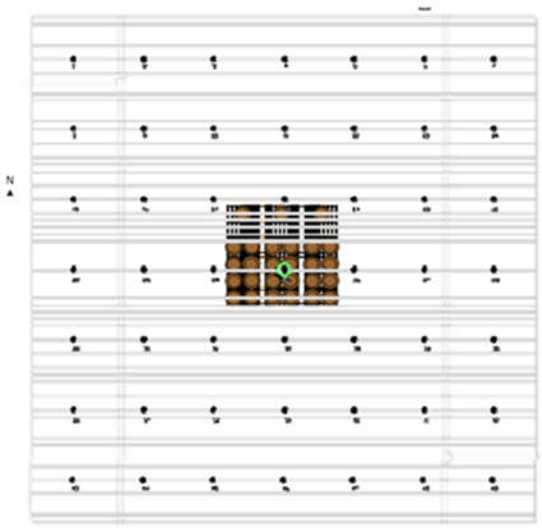


Figure 3-33: Sprinkler layout for large-scale fire Test 1. Forty-nine (49) sprinklers were placed on a 10 x 10 ft (3.0 x 3.0 m) spacing.

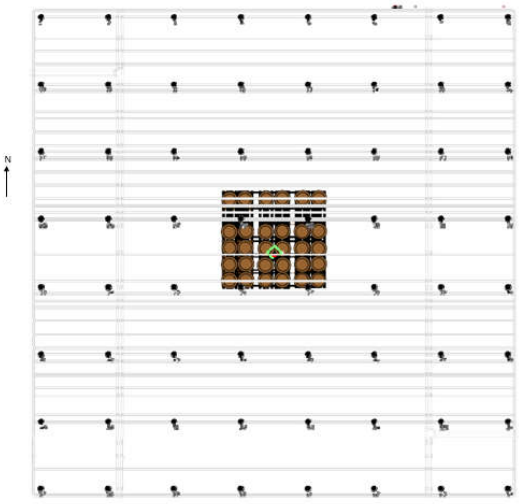


Figure 3-34: Sprinkler layout for large-scale fire Test 2 and 3. Sixty-four (64) sprinklers were placed on a 10 x 10 ft (3.0 x 3.0 m) spacing.

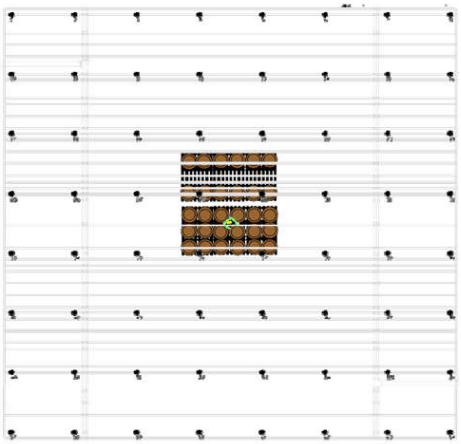


Figure 3-35: Sprinkler layout for large-scale fire Test 4. Sixty-four (64) sprinklers were placed on a 10 x 10 ft (3.0 x 3.0 m) spacing.

3.2.3.7 Instrumentation

Prior and during each test, inside and outside temperature and humidity were measured using fixed relative humidity sensors and thermocouples. The moisture fraction of the wooden pallets and barrels was tested and recorded before each test using a moisture meter. Standard instrumentation was installed for Tests 1-4 (see subsections below). In addition, special submerged pressure transducers were used within some of the barrels for the first three tests to measure loss of liquid.

3.2.3.7.1 Standard Instrumentation

- All sprinklers were outfitted with an electric circuit attached to the operating mechanism; therefore, operating times of each sprinkler could be determined.

- A total of 125, bare-bead, type-K (chromel-alumel), thermocouples with a diameter of 0.8 mm (20-gage) are permanently placed 6.5 in. (165 mm) below the ceiling. These thermocouples have a known response time index (RTI) of 14.5 $ft^{1/2}s^{1/2}$ (8 $m^{1/2}s^{1/2}$).
- Four bi-directional probes to measure plume velocity were placed 3.9 in. (10 cm) or 19.7 in. (50 cm) below the ceiling.
- Steel temperatures at the ceiling were measured using 9 embedded thermocouples inside a cross-shaped 1/4-in. (6.35-mm) thick steel angle. Temperatures measured by these thermocouples provide an indication of the effect of the fire plume on the steel ceiling structure.
- Both flow meters and pressure controllers were used to monitor and control the sprinkler system.

3.2.3.7.2 Liquid Loss Measurements

Twelve submersible hydrostatic pressure sensors were used to measure liquid losses from the barrels during each test. Wiring from the transducers to the data acquisition system was protected by a fireproof jacket; in addition, the wires were water-cooled. A picture of the pressure transducer wiring is shown in Figs. 3-36 and 3-37.

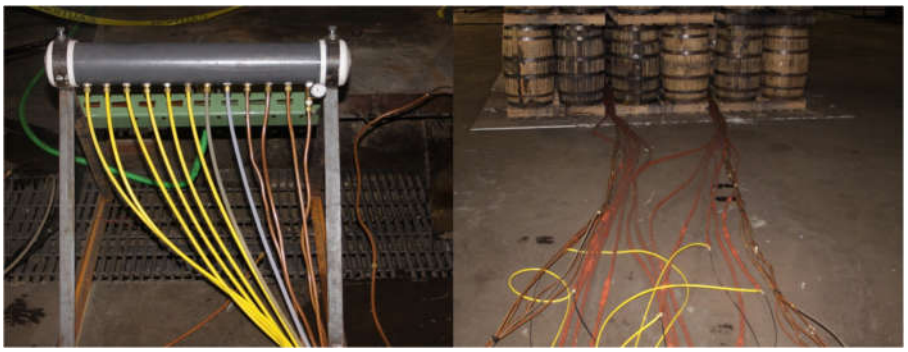


Figure 3-36: Plenum used for distributing cooling water (left). Lead wires to hydrostatic pressure transducers wrapped in water-cooled jackets (right).

Figure 3-37: Lead wires to hydrostatic pressure transducers wrapped in water-cooled jackets running through the western and eastern flues.

3.2.4 Large-scale Fire Test Results

This section presents the results of the four large-scale fire tests performed in this study. For quick reference, a summary of the test results is shown in Table 3-9.

Table 3-9: Large-scale fire test result summary.

Test Number	Test 1	Test 2	Test 3	Test 4
FM Global Fire Technology Laboratory Test Site	North Movable Ceiling			
Test Configuration				
Commodity	Wooden Barrels			
Water-filled	189	210	210	178
Simulated Whiskey Filled (75%)	0	0	0	32
Nominal Ceiling Height (m [ft])	30 [9.1]			
Array Nominal Size - LxWxH (ft x ft x ft [mxmxm])	12.0 x 12.7 x 27.0 [3.7 x 3.9 x 7.3]			
Fire test Results				
First/Last Ceiling Sprinkler Operation (min:s)	1:56	4:16/6:50	5:16/7:17	3:56/5:25
Total Ceiling Sprinklers Opened	1	3	5	5
Peak Gas Temperature (°F [°C])	224 [107]	378 [192]	421 [233]	509 [265]
Maximum One Minute Average TC Measurement and Time (°F [°C])	143 [61.7] @ 1:32	308 [153] @ 5:55	334 [168] @ 5:00	365 [185] @ 4:28
Maximum Steel TC Measurement and Time (°F [°C])	88 [31] @ 2:25	154 [68] @ 7:42	176 [80] @ 9:36	209 [98] @ 13:13
Test Termination – Time After Ignition (min:s)	20:00	20:00	30:00	26:00

3.2.4.1 Results Overview

Plan views of the sprinkler operation patterns for Tests 1-4 are shown in Fig. 3-38.

3.2.4.1.1 Test 1

For Test 1, the ignition pan was centered under one sprinkler. The first sprinkler operated after 1 minute and 54 seconds, after which the flames were immediately reduced to the first tier. Some light charring was observed within the first three tiers; however, all charring occurred at the surface. Damage to the barrels was marginal. Post-fire damage assessment showed no fire spread towards the north of the array. No flames were observed on the outside of the array.

3.2.4.1.2 Test 2

For Test 2, the ignition pan was placed among 4 sprinklers. This delayed activation of the first sprinkler by 2 minutes and 20 seconds compared to Test 1. As a result, the extent of fire damage was greater for Test 2 compared to Test 1. Charring was mostly limited to barrels inside the core of the array. Pallets facing north were marginally affected by the fire, showing only slight charring on the barrels facing the core of the array. The east and west target arrays showed some charring from the barrels facing the core. Flames were never seen coming out of the eastern, western, or northern face of the array. Some pallets located within the core of the array were partially burned and/or charred; however, the core pallet stack never shrank in overall height due to pallets losing their structural integrity.

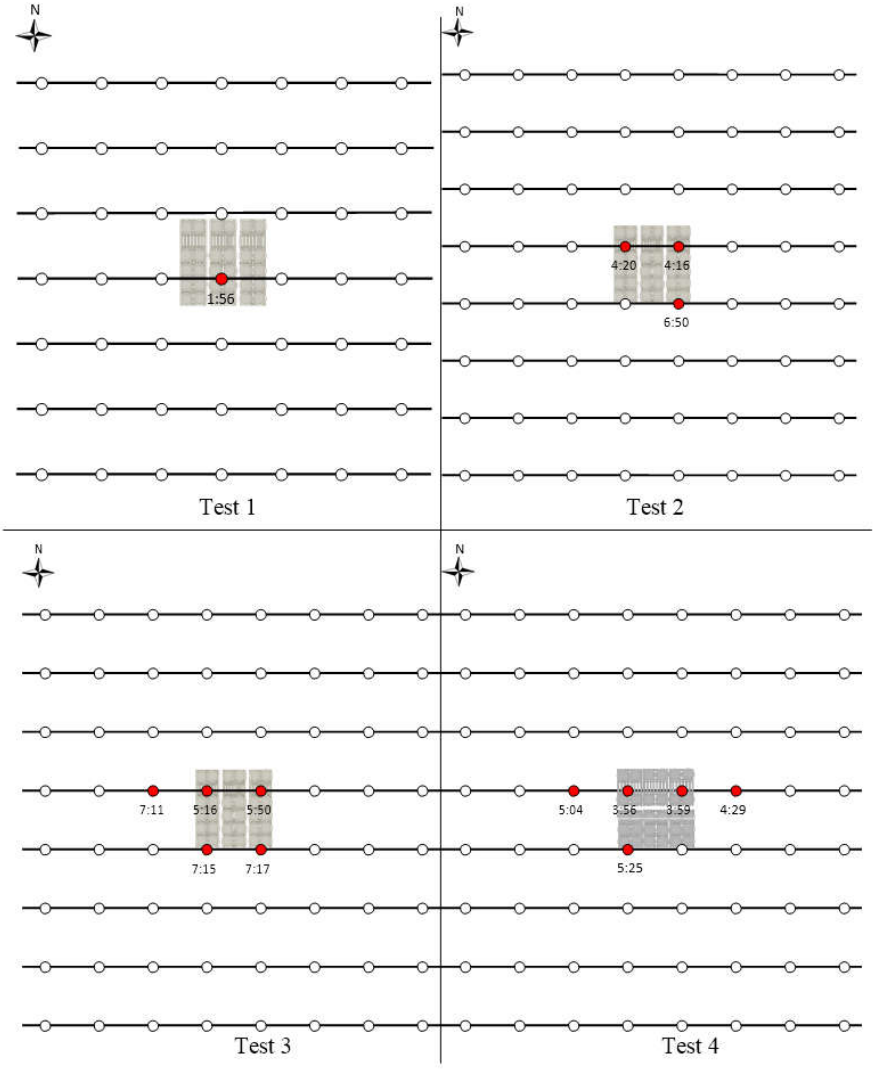


Figure 3-38: Sprinkler operation patterns in Tests 1-4.

3.2.4.1.3 Test 3

For Test 3, the ignition pan was placed among 4 sprinklers. First sprinkler activation occurred after 5 minutes and 12 seconds. During Test 3, the fire burned more intensely compared to Test 2; also, more time was required to suppress the fire; however, no barrel leakage was observed at any point. Charring of the barrels was confined to the core of the array or to barrels facing the core. The fire never spread to the northern, western, or eastern side of the array. Significant burning was observed on the southern side. The core array shrank a few inches due to pallet burning; however, the palletized stack never seemed in danger of collapse.

3.2.4.1.4 Test 4

Test 4 used the same protection and ignition location as Test 3. During Test 4, 32 barrels were filled with simulated distilled spirits consisting of 75% (by vol) denatured alcohol in water. The first sprinkler operated at 3 min and 53 sec. Significant burning was observed on the southern side of the array; also, a small 11 ft^2 (1 m^2) pool fire formed at the southern side of the array. Significant charring was observed after the test. Some leakage of the alcohol-filled barrels was observed in 5 of the 32 barrels using post-

test dipstick measurements. Moderate to significant (1/4 in. (6.3 mm) deep) charring was observed on the core barrels or barrels facing the core. Fire never spread north, and northern facing pallets/barrels seemed unaffected by the fire. Significant structural damage was observed with pallets in the core of the array. The core stack shrunk by as much as 5-7 in. (13-18 cm) before the test was over. Fire was controlled and close to being suppressed. Test 4 had to be terminated after 26 minutes due to filling of the drains, which were closed to prevent ethanol getting into the water treatment system of the test facility.

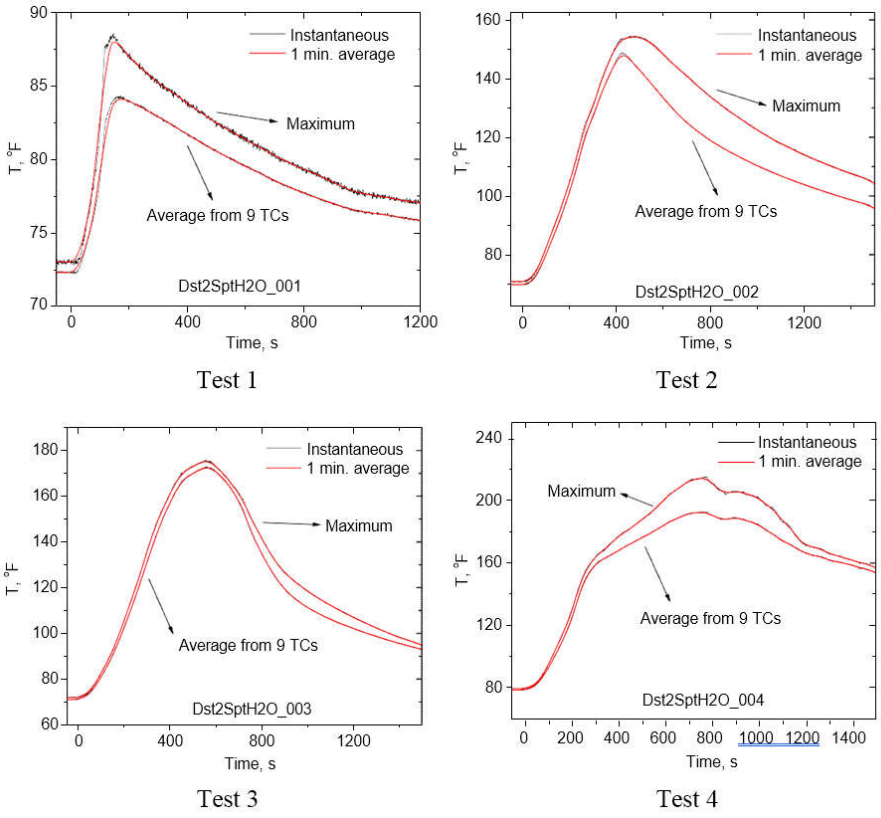


Figure 3-39: Steel temperatures at the ceiling location above ignition.

3.2.4.2 Steel Temperatures

Steel temperatures measured at the ceiling are critical for evaluation of the building integrity during a test. Temperature measurements were taken from a steel cross. The maximum one-minute average steel temperature cannot exceed 1000°F (540°C). The instantaneous temperature cannot exceed 1200°F (650°C). Both instantaneous and one-minute average temperature measurements for Tests 1-4 are shown in Figure 3-39. The maximum allowable steel temperature was not reached in any of the tests.

3.2.4.3 Leakage of Water or Ignitable Liquid

Leakage of barrels was measured in-situ using 12 submersible pressure transducers placed in the 4 core barrels above the ignition pan. Other leakage measurements included weighing of the barrels and dipstick measurements. Submersible pressure sensors were used for Tests 1-3 only. Test 4 had denatured-alcohol-filled barrels in the core of the array and did not utilize pressure sensors. It was

important to understand the amount of leakage and location of leakage before running Test 4 because any water release in Test 4 would impact the results.

In Test 1 there was no leakage due to the short duration of the test. In Test 2, a very minor amount of leakage that is likely within the accuracy of the measurements was seen (approximately 2.3 gal (9 L) spread over 12 barrels). In Test 3, there was no measurable leakage.

In Test 4 leakage was measured after the test using a dipstick. Low dip stick measurements were seen for five barrels. The liquid levels measured for these five barrels are shown in Fig. 3-40 within the red circles. Barrels filled to capacity with 75% by volume alcohol-water solutions are represented by the dark-grey circles. Water-filled barrels are represented by the light-grey circles. None of the water filled barrels lost any of their contents. The total lost volume was 103 gal (390 L). From the approximate measurements one can say that none of the barrels failed catastrophically and that most leaks were gradual. A small pool fire was observed on the south side of the palletized array. In addition, some blue flames were observed from the viewing gallery on the lab floor North/North-West of the array.

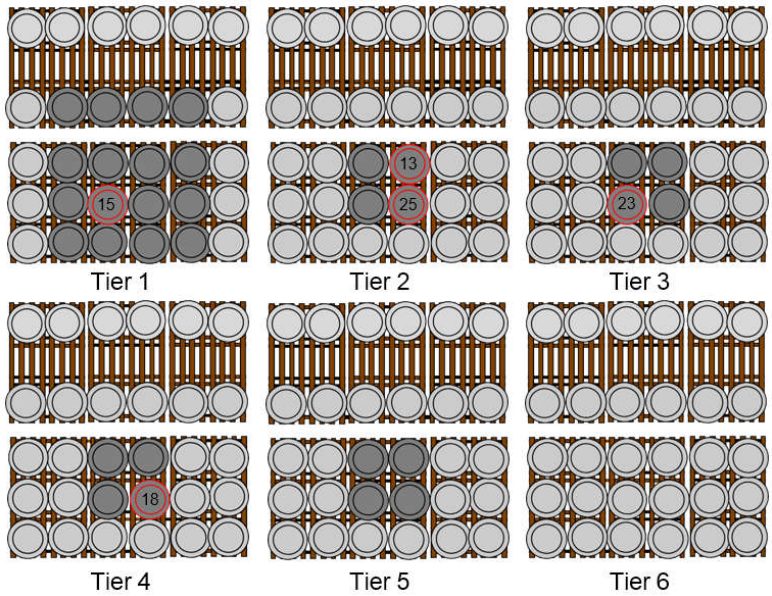


Figure 3-40: Test 4 measured leakage (gallons) using a dipstick.

3.2.5 Discussion

The discussion of the results will focus on the pass/fail criteria for each test. All four tests met the pass/fail criteria presented in Section 3.1.3.1.

3.2.5.1 Sprinkler Activation

The number of sprinklers that activated for Test 1-4 were 1, 3, 5, and 5, respectively. None of the activated sprinklers were located on the perimeter of the ceiling. No sprinkler skipping was observed during these tests. Due to the ignition location in Test 1, the first sprinkler opened after only 1 min 56 s. For Tests 2-4 the first sprinkler opened at 4:17, 5:12, and 3:56, respectively. Test 2, 3, and 4 all end up using 300 gpm (1100 L/min) of flow. During Test 2, this flow was accomplished through three K25.2

sprinklers discharging at 100 gpm (380 L/min) each. During Tests 3 and 4, five K14 sprinklers discharged at 60 gpm (230 L/min) each.

3.2.5.2 Liquid Leakage

A fundamental concern when dealing with distilled spirits of high alcohol content is leakage adding to the overall heat release rate and fire spread. Tests conducted in this study took particular care in trying to measure the leak rate using two methods: (1) by installing submersible pressure sensors inside the barrels, and (2) by measuring the liquid levels inside the barrels before and after each test. During Test 1, the barrels were sealed and not vented; consequently, the air above the liquid surface was allowed to heat up and expand. The pressure sensors showed unusable readings during this test. Test 2 and 3 used vented barrels, which gave pressure readings that could be used for the intended purpose. From the pressure sensors as well as post-test liquid level measurement, no leakage was seen during these two tests.

Test 4 used alcohol-filled (32) as well as water-filled (178) barrels. In addition, the flue width was altered during Test 4. A small pool fire was observed on the south side during this test after approximately 15 minutes; also, small blue flames were seen on the north side of the array. Post-test dipstick measurements showed that 5 barrels had liquid loss. However, barrels continued to leak after test termination, and dipstick measurements were taken 24 to 48 hours after the test was performed. As a result, it was not possible to determine how much liquid was lost during the test separate from losses after termination until the time the measurement was performed. Test 4 was suppressed by ceiling sprinklers alone and showed only small flames inside the core of the array at test termination (26 min). The spilled liquids did not spread the fire across the main flue. None of the water-filled barrels surrounding the core leaked and did not aid in the suppression process. The overall integrated energy release was the greatest for Test 4; however, this result might have been caused by a slightly unfavorable sprinkler activation pattern. The spilled liquids could have inhibited the suppression process, causing delayed fire control compared to Test 3.

3.2.5.3 Flue Spaces

Figures 3-24 shows the different flue spaces that were used during the large-scale fire tests. For Test 1-3, two North-South flues (6 in. [15 cm]) were used. For Test 4 a single East-West flue of the same size was used. The open area fraction for the core 16 barrels for Test 1-3 was 17.1%. For Test 4, with the single flue, this fraction was reduced to 10.3%. None of the large-scale fire tests showed any leakage from barrels separated from the core by a flue. It is not expected that the reduction in open area fraction significantly contributed to the increase in overall fire activity seen for Test 4; however, based on damage assessments, flue spaces do seem to limit the spread and subsequent damage caused by the fire.

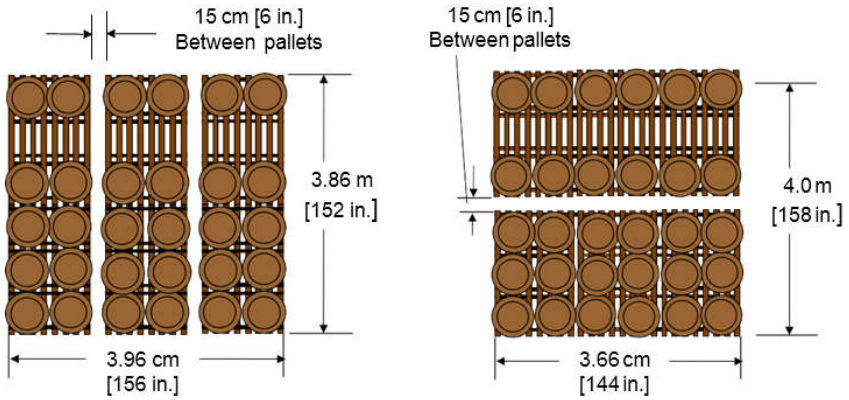


Figure 3-41: Flue space arrangements for Tests 1-3 (left) and Test 4 (right).

3.2.6 Conclusions

The particular scenario tested in this study was palletized 7-tier-high whiskey barrels with added flue space(s). Ceiling protection was provided by either pendent sprinklers with a K-factor of 14 gpm/psi$^{1/2}$ (200 lpm/bar$^{1/2}$) or pendent sprinklers with a K-factor of 25.2 gpm/psi$^{1/2}$ (364 lpm/bar$^{1/2}$). All sprinklers were placed on 10 ft x 10 ft (3.0 m x 3.0 m) spacing. Both sprinklers had a temperature rating of 165°F (74°C) and quick response links. Based on pre-set sprinkler performance criteria, all four large-scale fire tests passed; however, some leakage of ignitable liquids was observed during Test 4.

Based on all testing performed in this study, the following conclusions can be drawn:

- A barrel cannot withstand a drop from a 7-tier-high (±20 ft [6.1 m]) palletized array. Upon impact with a concrete floor the barrel will disintegrate and form a substantial pool of liquid (172 ft^2 [16 m^2]).
- A single barrel can sustain direct fire exposure over 360° of its perimeter for approximately 15 min. After 15 min, the barrel will leak at a slow rate.
- Ignition of a palletized array of whiskey barrels with a 6-in. (15 cm) longitudinal flue, centered under one sprinkler, facilitates early activation of that sprinkler due to a strong chimney effect.
- All large-scale fire tests suppressed or at least controlled the fire before test termination.
- No excessive damage other than some surface charring was seen for barrels separated from the ignition core by a 6-in. (15-cm) flue space.
- Leakage from alcohol-filled barrels resulted in multiple small pool fires during Test 4.
- None of the water-filled barrels during any of the tests leaked.
- During all four large-scale fire tests, loss of structural integrity of the pallets due to the fire resulted in vertical shrinkage of the array. No collapse was observed during any of these tests.

3.2.7 Fire Chronologies

3.2.7.1 Test 1

Time (min:sec)	Observation
00:00	Ignition.
00:02	Pan fire lit, flames reach about 3-4 ft within the core of the main array.
00:30	Flames reach the top of the 2nd tier.
01:10	Small pool fire visible at the first tier in the Southern and Northern flue.
01:20	Flames reach the top of the 3rd tier.
01:25	Smoke seen above the array impinging on the ceiling.
01:30	Flames seen into the 4th tier.
01:56	First sprinkler (25) operation. (sprinkler located above ignition)
02:15	Flames reduced to within the first tier.
02:30	Minimum flames visible within the first tier.
03:10	No flames visible.
03:30	Outside of barrels are wetted by a continues film.
04:00	Smoke only seen from the east side.
05:00	Fire seems completely extinguished.
15:00	Test terminated (fire suppressed)

3.2.7.2 Test 2

Time (min:sec)	Observation
00:00	Ignition
00:05	Flames visible above the ignition pan within the 1st tier.
00:30	Flames visible in the 2nd tier.
01:00	Flames visible above the 2nd tier.
01:10	Flames have reached the top of the 3rd tier. Light smoke development seen impinging on the ceiling directly above ignition.
01:35	Moderate smoke formation at the ceiling, ceiling layer formed. Significant burning within the first 3 tiers.
01:45	Flames reaching the top of the 4th tier.
02:40	Flames visible in the eastern and western flues within the first 3 tiers.
03:10	Flames seen at the top of the 4th tier.
03:30	Flames and burning seen at the southern face of the array. Flames have reached the 5th tier with the core of the main array.
04:00	Flames in the eastern flue have reached the 6th tier.
04:10	Flames seen above the array.
04:17	1st srinkler opens
04:21	2nd sprinkler opens
05:00	Significant fire within the core of the array up to the 5th tier. Flames are seen in the eastern flue up to the 7th tier and in the western flue up to the 5th tier.
06:00	Flames in the eastern flue have reached the top of the array.
06:50	Third sprinkler operates.

07:15	Flames in the eastern flue reduced to the fifth tier.
07:45	Flames in core and flues reduced to the 4th tier. Moderate to severe smoke and vapor development dominated on the east side.
08:30	Continuous water film seen on the outside of the barrels.
09:10	Flames in western flue no longer visible, eastern flue shows flaming around the 3rd tier.
10:30	Flames in the eastern flue no longer visible.
12:30	Only small flames visible within the core above the 2nd tier and at the ignition pan.
14:30	Only small flames visible at the bottom ignition pan.
19:00	Still only small flames visible at the bottom ignition pan.
20:00	Test terminated (fire suppressed)

3.2.7.3 Test 3

Time (min:sec)	Observation
00:00	Ignition
00:05	Fire located above the ignition pan in the first tier.
00:30	Flames above the 1st tier.
01:00	Flames reaching the top of the 2nd tier.
01:20	Flames reaching the top of the 3rd tier.
01:25	Some flames visible in the eastern and western flue at the 1st tier.
01:35	Light smoke column impinging on the ceiling directly above ignition.
02:10	Flames seen inside the 4th tier.
02:20	More moderate smoke development impinging on the ceiling
03:00	Flames have reached the top of the 5th tier. Flames are also observed on the southern face of the array at the 2nd tier level.
03:45	Moderate flame development inside the eastern and western flue at the 2nd and 3rd tier.
04:20	Glowing particles seen with smoke hitting the ceiling.
04:45	Flames seen in the eastern and western flue at tiers 1-5.
05:00	Flames seen above the array, impinging on the ceiling.
05:12	1st sprinkler operation.
05:25	Flames reduced to within the first 6 tiers.
05:48	2nd sprinkler operation.
06:50	Flames seen with the core and the southern face at all 7 tiers.
07:10	3rd sprinkler operates.
07:15	4th sprinkler operates.
07:17	5th sprinkler operates.
08:00	Moderate to severe smoke and steam development. Top view of the array obstructed. Still severe flames seen with all 7 tiers.
09:00	Most of the array obscured by steam and smoke.
10:10	Array completely obscured by steam and smoke.
12:00	Array still completely obscured by steam and smoke.
13:45	Part of the top of array becomes visible
15:00	Array appears sporadically from behind smoke and steam, no flames visible.
16:00	Solid film of water seen flowing down the outside of the barrels.
18:00	Most of the array visible. No flames observable.
20:00	Fire completely suppressed.
22:00	Most remaining steam and smoke seen at the eastern side of the array.

30:00	Test terminated. Hose stream applied.

3.2.7.4 Test 4

Time (min:sec)	Observation
00:00	Ignition
00:15	Fire contained inside the ignition pan flames reaching the bottom of the 2nd tier.
01:00	Early fire development mostly in the core of the array, light smoke formation coming out of the top of the array above ignition.
01:10	Flames have reached the bottom of the 3rd tier.
01:20	Small flames seen in the eastern and western flues.
01:50	Flames have reached the 4th tier.
01:55	More moderate smoke development seen on top of the array impinging on the ceiling.
02:20	Significant burning of the palled on the southern face of the array within the first three tiers.
03:20	Flames reached the 6th tier.
03:30	Flames seen above the array.
03:56	1st sprinkler operation.
03:59	2nd sprinkler activation.
04:20	Steady fire remains on the southern face of the array.
04:29	3rd sprinkler activation.
04:55	Steady fire inside the eastern and western side of the core stack.
05:00	Flames seen above the array.
05:04	4th sprinkler operation.
05:25	5th sprinkler operation.
06:00	Flames still seen above the array.
07:00	Pallets appear to be burning on the southern face.
09:00	Core pallets seem to have burned and the central stack has shifted downwards by approximately 6 in. (15 cm).
10:00	Intense burning remains on the eastern side of the core stack.
11:00	Significant smoke and steam formation one the eastern and western side of the array.
13:00	Fire intensity reduced barrel all seem wetted from the outside still fire remains inside the core of the array, particularly on the eastern side.
14:00	Small 5.4 ft^2 (0.5 m^2) pool fire can be observed on the southern side of the array.
14:30	Pool fire has increased to approximately 11 ft^2 (1 m^2).
17:00	Fire intensity reduced, still flames seen within the core of the array; also, a 11 ft^2 (1 m^2) pool fire is seen on the southern side of the array.
18:30	Core stack within the array has shrunk by approximately 12 in. (30 cm).
20:00	Pool fire has reduced in size to approximately 5.4 ft^2 (0.5 m^2).
22:00	Fire on the eastern side of the core stack mostly suppressed.
23:30	Some flames still visible within the core of the array, mostly within the first 3 tiers.
26:00	Test terminated. Hose stream applied. (Fire mostly suppressed)

3.2.8 Dry Pipe Protection for Palletized Storage

The main performance difference between wet and dry sprinkler systems is delayed water delivery. This delay is due to the additional transport time required for water to travel through the system piping to the activated sprinkler(s), as well as the additional time before sprinkler activation due to the slower response and higher activation temperature of sprinklers typically used with a dry system. The water transport delay is usually on the order of 20-40 s, whereas the activation delay depends on the sprinkler response characteristics of the wet and dry systems being compared, as well as the fire growth characteristics for the configuration of interest. Overall effects of the delayed water delivery include:

(1) No cooling is provided to the ceiling layer gases during the water delivery delay, typically resulting in a greater number of activated sprinklers for a dry system as compared to a wet system. As a result, a dry system requires a greater design water demand to accommodate this increase in number of activated sprinklers.

(2) The fire continues to grow during the water delivery delay so that its size at the time of water delivery may be significantly greater for a dry system as compared to a wet system for commodities that experience rapid fire growth. As a result, a dry system may require a greater sprinkler design density to achieve equivalent protection to a wet system for a given commodity and storage configuration.

3.2.8.1 Prior Testing

Previous testing of distilled spirits stored in oak barrels included single-barrel leakage tests, cold-flow water-transport tests, and large-scale fire tests. The relevant large-scale fire tests include Test 4 (palletized test program – see Section 3.2.3.3), and Tests 1 and 2 (rack storage test program – see Sections 3.1.3.2 and 3.1.3.2).

The available testing experience yielded the following conclusions:

- The heat release rate of a leaking oak barrel storing distilled spirits is dominated by burning of the leaking distilled spirits, whereas heat release from the barrel is relatively small and is not significantly affected by the moisture content of the wood.
- When leakage of a barrel occurs due to fire exposure, that leakage is typically slow, on the order of 0.5-1.0 gpm (2-4 lpm), occurring due to thermal expansion of the barrel hoops after direct fire exposure over 2.5-7.5 min. The time to leakage and leakage rate do not vary significantly with storage orientation of the barrel or the relative size or location of the exposure fire so long as the barrel is partially or totally immersed in the fire.
- Catastrophic failure of barrels is unlikely to occur due to fire exposure but can occur due to collapse of storage and the impact of falling barrels striking the floor.
- Initial fire growth through a storage array of dry oak barrels is typically slow but can be influenced by the size of the ignition source. For a test involving a large ignition source in a rack storage array, first sprinkler activation occurred after approximately 1-2 min. For a test involving a smaller ignition source in a palletized storage array, first sprinkler activation occurred after approximately 4-5 min.

- Transport of sprinkler water through a palletized storage array is typically slow. From a cold-flow water transport test, the time delay before steady water delivery at the base of a 7-tier high palletized storage array of oak barrels was approximately 4-5 min.
- In equivalent rack-storage test configurations, the fire size at time of water delivery was significantly larger for the dry sprinkler system test as compared to the wet sprinkler system test, owing to continuing fire growth over an 82 s total water delivery delay. That delay did not affect adequacy of the protection but led to the activation of 11 additional sprinklers.

3.2.8.2 Discussion

Based on available testing experience, it is apparent that initial fire growth in a palletized storage array of oak barrels storing distilled spirits is relatively slow, leading to first sprinkler activation on the order of 4-5 min after ignition in those tests. It is likewise apparent that water transport through a palletized storage array after sprinkler activation is relatively slow, leading to steady water delivery at the base of the storage array approximately 4-5 min after sprinkler activation in those tests. Failure of an oak barrel due to fire exposure is also relatively slow, with leakage of stored distilled spirits occurring after approximately 2.5-7.5 min of immersed fire exposure in the tested conditions. These time scales are all greater than the time scale associated with the water delivery delay of a typical dry sprinkler system (60-120 s, consisting of both activation and transport delays).

Due to the relatively slow fire growth and the relatively slow water transport, it is reasonable to expect that the performance adequacy of a sprinkler system protecting palletized storage of distilled spirits in oak barrels may not be significantly affected by water delivery delay. Therefore, a similar sprinkler design (operating pressure, orifice size, and design density) may provide adequate protection performance using either a wet or dry sprinkler system for this type of storage. This is consistent with available testing experience for rack storage, where similar sprinkler designs were shown to be effective for both wet and dry systems, provided the dry system accommodates additional water demand to account for the increased number of sprinkler activations.

From available testing experience for the rack storage configuration, a dry system with an 82 s total water delivery delay had 15 ceiling sprinkler activations compared to 4 activations for an equivalent test configuration using a wet system. Since the initial fire growth in a palletized array is slower than that in a rack storage array, it is reasonable to expect that fire growth during the water delivery delay in a palletized array will be less than that in a rack storage array. By extension, the increase in number of sprinkler activations due to water delivery delay is expected to be less for a palletized array than a rack storage array. Given the baseline result of 5 sprinkler activations in the palletized storage test with wet sprinkler protection, and considering that 11 additional sprinklers activated between the wet and dry rack storage tests, the number of sprinklers required for fire control in palletized storage with dry sprinkler protection may be reasonably expected to be greater than 5 and less than 16.

Based on these considerations, existing protection recommendations for wet sprinkler protection of palletized storage of distilled spirits in oak barrels may be reasonably extended to dry sprinkler protection of the same commodity in the same storage arrangement, including a design water demand for at least 16 active sprinklers plus applicable safety factors. Importantly, since no large-scale testing

has been conducted to validate this protection guidance, additional safety factors may be necessary to ensure enough water supply is provided in the design.

An additional significant consideration for protection adequacy of palletized storage of distilled spirits in oak barrels is the prevention of stack collapse and catastrophic failure of the barrels. Based on testing experience, it is expected that array collapse may lead to catastrophic failure of falling barrels upon striking the floor, leading to a large unconfined pool of spilled distilled spirits and a resulting large pool fire. This large pool fire would be unlikely to be adequately controlled by installed sprinkler protection. Collapse of a palletized storage array of distilled spirits in oak barrels was not observed to occur in recent testing, however significant fire damage to core array pallets was observed, resulting in shrinkage of the core stack by as much as 5-7 in. (13-18 cm). From the available testing experience, it is not possible to determine whether the water delivery delay for a dry sprinkler system as compared to a wet sprinkler system will significantly affect the structural stability, or loss thereof, of a palletized storage array of distilled spirits in oak barrels during a fire.

3.2.8.3 Conclusions

Existing protection recommendations based on large-scale testing for wet sprinkler protection of palletized storage of distilled spirits in oak barrels may be reasonably extended to dry sprinkler protection of the same commodity in the same storage arrangement, so long as the design water demand is increased to accommodate at least 16 sprinkler activations plus applicable safety factors to account for water delivery delay in the dry system. Providing the standard safety factor of 1.5, the final sprinkler demand should be 24.

4. **Code Change Conclusions**

Proposed new Section 16.10.

16.10 Distilled Spirits in Wooden Barrels
16.10.1 Palletized Storage Arrays

16.10.1.1 Limit palletized storage arrays to a maximum of 7 pallets high.

16.10.1.2 Maintain a minimum flue space of 6 in. (152 mm) between adjacent pallets as shown in Figure 16.10.1.2

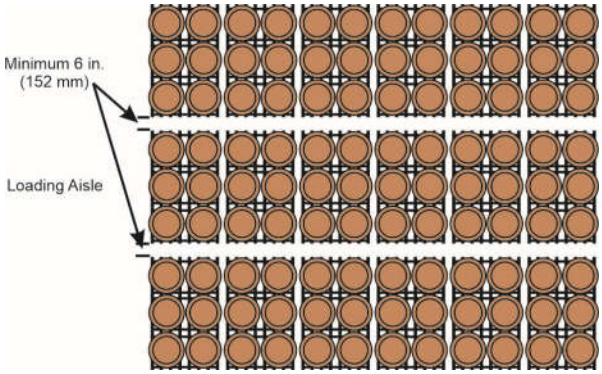


Figure 16.10.1.2. Minimum flue space between palletized storage arrays.

16.10.1.3 Arrange palletized storage using one of the options below:

A. Provide a draft curtain along the side of palletized storage facing the loading aisle as shown in Figure 16.10.1.3.A.

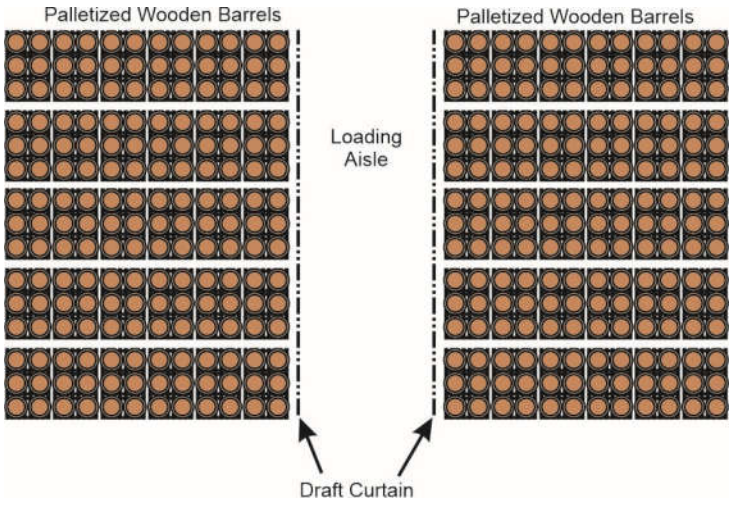


Figure 16.10.1.3.A Loading aisle draft curtain arrangement

B. Provide a trench drain on each side of the loading aisle as shown in Figure 16.10.1.3.B arranged to remove any spilled distilled spirits in the aisle space out of the building and prevent it from spreading into the barrel storage area.

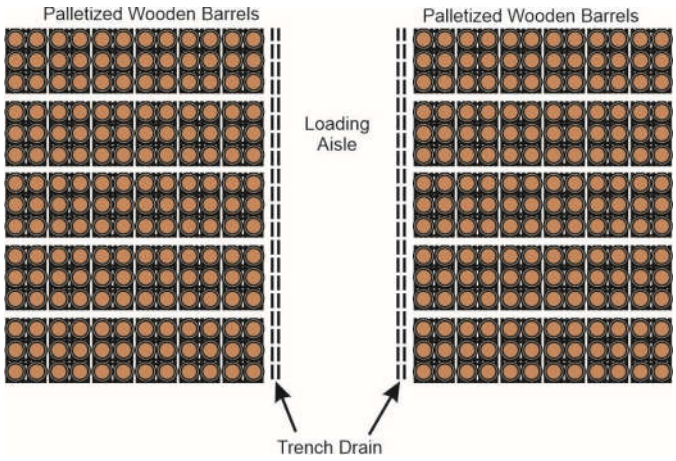


Figure 16.10.1.3.B Loading aisle trench drain arrangement

16.10.1.4 Band the barrels on each pallet to prevent barrels from falling off the pallet during transportation and loading into the storage array.

Table 16.10.1.5. Palletized Storage of Distilled Spirits with up to 75% Alcohol by Volume in Wooden Barrels

Protection Area	System Type	Ceiling Height ft (m)	Storage Height ft (m) / # drums	Ceiling Sprinkler Protection		
				Response / Nominal Temperature Rating / Orientation	K-factor gpm/psi$^{1/2}$ (L/min/bar$^{1/2}$)	Design, # of Sprinklers @ Pressure psi (bar)
Barrel Storage	Wet	30 ft (9 m)	24 ft (7.3 m) / 7 drums	QR / Ordinary / Pendent	14.0 (200)	12 @ 18 (1.25)
	Dry			SR / High / Upright	16.8 (240)	24 @ 13 (0.9)
Loading Aisle w/ Draft Curtain	Wet / Dry		NA	SR / High / Any	5.6 (80)	100 @ 13 (0.9)
					≥ 8.0 (115)	100 @ 7 (0.5)
Loading Aisle w/ Trench Drains	Provide the palletized storage design across the entire roof area (i.e., storage area and loading aisle)					

16.10.1.5 Protect palletized storage arrangements in accordance with Table 16.10.1.5 and the following criteria:

A. The protection applies to alcohol-water mixtures up to 75% alcohol and wooden barrel sizes of 53 – 130 gal (200 – 500 L).

B. Provide a 500 gpm (1900 L/min) hose stream allowance.

C. Provide a water supply that can deliver the total sprinkler and hose stream demand for a duration of at least one hour.

D. The Barrel Storage system and Loading Aisle system do not need to be hydraulically balanced.

E. If a dry sprinkler system is permitted, provide water delivery within 40 seconds to the most remote 4 sprinklers.

16.10.2 Rack Storage Arrays

16.10.2.1 Arrange rack storage arrangements with on-side wooden barrels to provide at least a 17% open area fraction within the rack storage array. See Figure 16.10.2.1.

A. Flue spaces between adjacent rows of barrels of at least 8 in. (20 cm) wide should provide the needed open area fraction.

B. If walkways are provided between barrels, use materials that are noncombustible and 70% open.

C. If solid combustible walkways are used, provide sprinkler protection below the walkways.

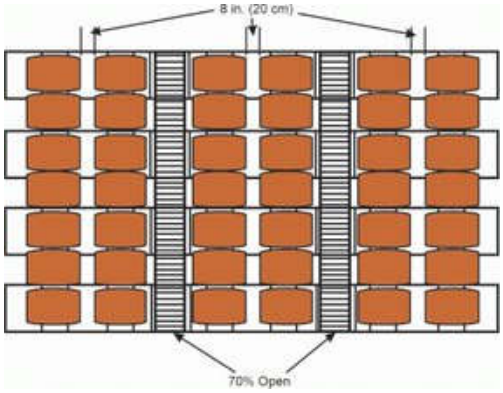


Figure 16.10.2.1. Flue space and walkway layout for on-side barrel storage in racks.

16.10.2.2 Arrange rack storage arrangements with on-end wooden barrel to provide at least 6 in. (15 cm) transverse and longitudinal flue spaces.

16.10.2.3 Protect rack storage arrangements in accordance with Table 16.10.2.3 and the following criteria:

A. Any rack type is acceptable if the needed open fraction and flue spaces are provided.

B. The protection applies to alcohol-water mixtures up to 75% alcohol and wooden barrel sizes of 53 – 130 gal (200 – 500 L).

C. Provide a 500 gpm (1900 L/min) hose stream allowance.

D. Provide a water supply that can deliver the total sprinkler and hose stream demand for a duration of at least one hour.

E. If a dry sprinkler system is permitted, provide water delivery within 40 seconds to the most remote 4 sprinklers.

Table 16.10.2.3. Rack Storage of Distilled Spirits in Wooden Barrels

Barrel Arrangement	Sprinkler System Type	Maximum Ceiling Height ft (m)	Maximum Storage Height ft (m) / # Barrels	Minimum Aisle Width ft (m)	Ceiling Sprinkler Protection			In-Rack Sprinkler Protection			
					Response / Nominal Temperature Rating / Orientation	K-factor gpm/psi$^{1/2}$ (L/min/bar$^{1/2}$)	Design, # of Sprinklers @ Pressure psi (bar)	Layout	Response / Nominal Temperature Rating	K-factor gpm/psi$^{1/2}$ (L/min/bar$^{1/2}$)	Design Flow gpm (L/min) (Note 3)
On-Side	Wet	40 (12)	33 (10) / 9 barrels		QR / Ordinary / Pendent	14.0 (200)	12 @ 37 (2.5)	None			
					SR / High / Any	≥ 11.2 (160)	20 @ 7 (0.48)	Fig 16.10.3.1E/F	QR / Ordinary / Any	8.0 (115)	45 (170)
	Dry	40 (12)	33 (10) / 9 barrels		SR / High / Upright	16.8 (240)	24 @ 25 (1.7)	None			
					SR / High / Upright	≥ 11.2 (160)	20 @ 7 (0.48)	Fig 16.10.3.1E/F	QR / Ordinary / Upright	8.0 (115)	45 (170)
On-End	Wet	30 (9.1)	25 (7.6) / 5 barrels	8 (2.4)	SR / High / Any	≥ 11.2 (160)	50 @ 7 (0.48)	Fig 16.10.3.1 A-D	QR / Ordinary / Any	≥ 8.0 (115)	6 @ 25 (95) [one level] 12 @ 25 (95) [greater than one level]

16.10.2.4 When possible, provide a curb between the loading aisle and the racks. This is to help prevent a spill from a dropped barrel spreading under the rack storage.

16.10.2.5 If barrels are filled/emptied in place while in storage, i.e. alcohol is transferred, then apply FM Global Property Loss Data Sheet 7-32. The protection recommendations above remain applicable provided that the maximum anticipated spill is equivalent to the volume of one barrel.

16.10.3 In-Rack Sprinkler Layouts

16.10.3.1 Abbreviations Used in Fire Protection Tables

- QR = Quick response sprinkler
- SR = Standard response sprinkler
- NA = Not applicable
- DRR = Double-row rack, ≤ 9 ft (2.7 m) wide
- Ordinary = Nominal 165°F (74°C) temperature rating
- High = Nominal 286°F (141°C) temperature rating

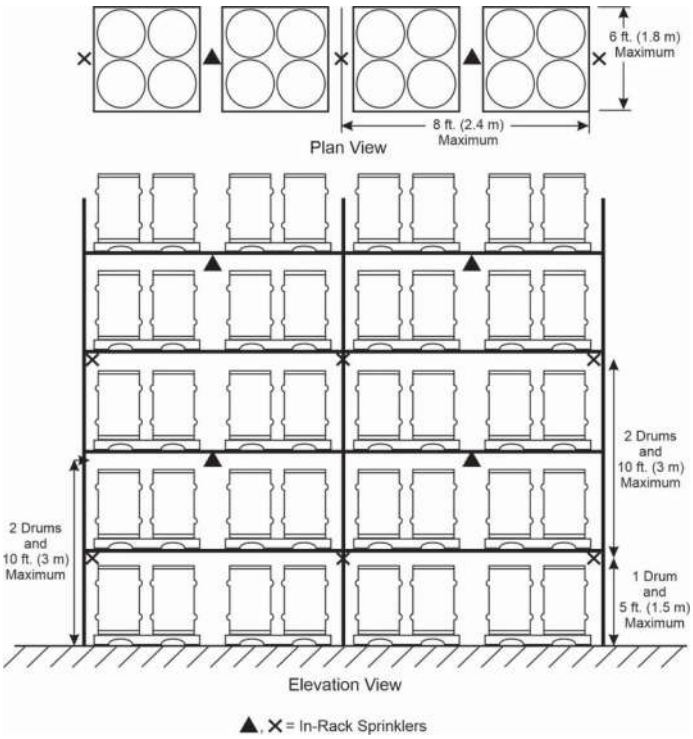


Fig. 16.10.3.1A. Single Row Rack Sprinkler Layout – drum protection scheme

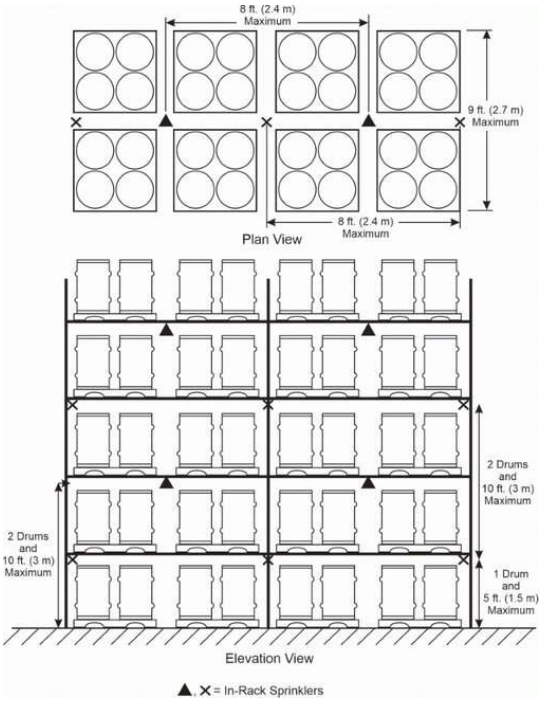


Fig. 16.10.3.1B. Double row rack sprinkler layout - drum protection scheme

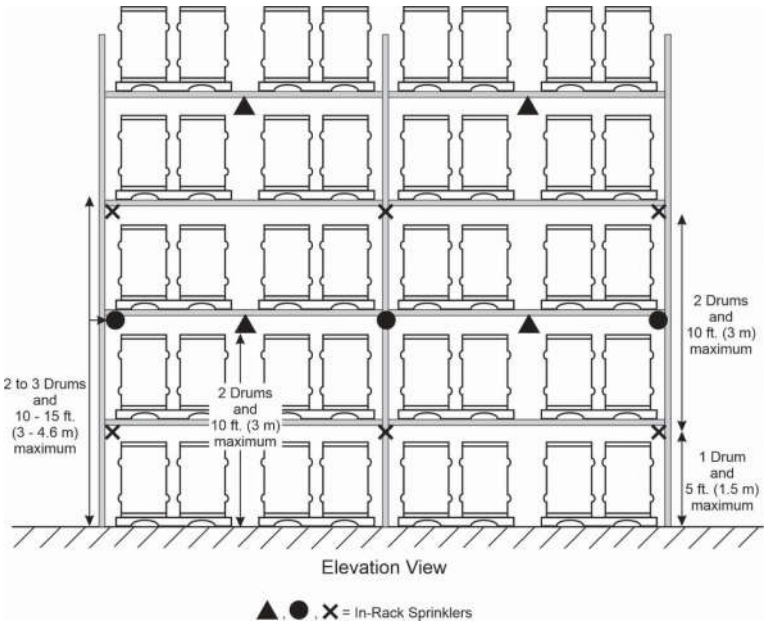


Fig. 16.10.3.1C. Multiple row rack sprinkler layout - drum protection scheme (elevation view)

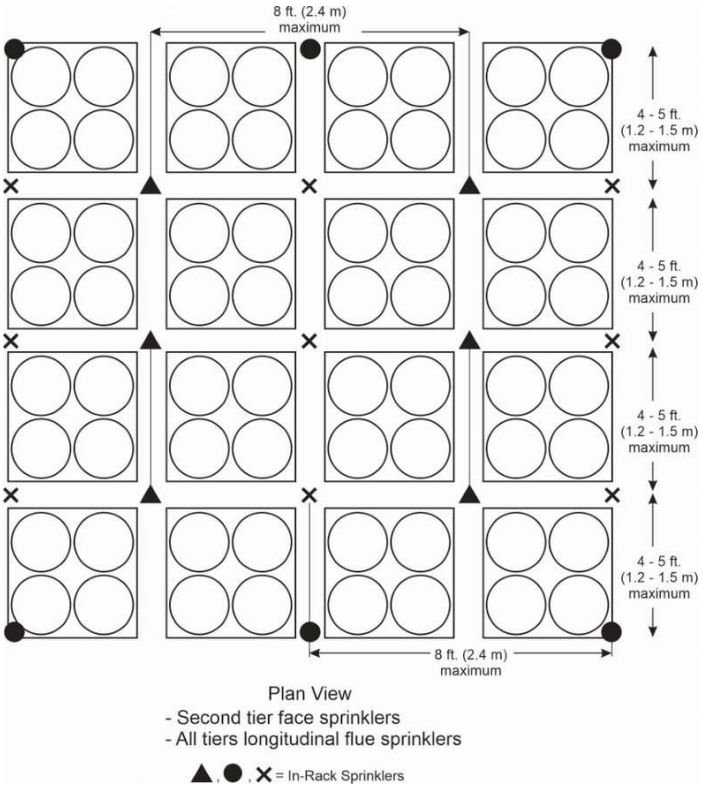


Fig. 16.10.3.1D. Multiple row rack sprinkler layout - drum protection scheme (plan view)

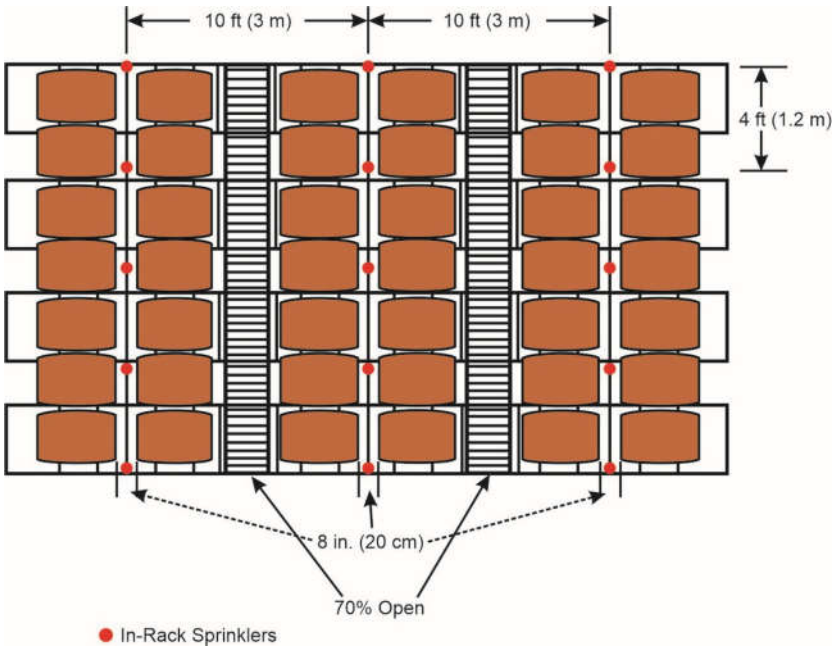


Figure 16.10.3.1E. In-Rack sprinkler layout for distilled spirits in wooden barrels (plan view)

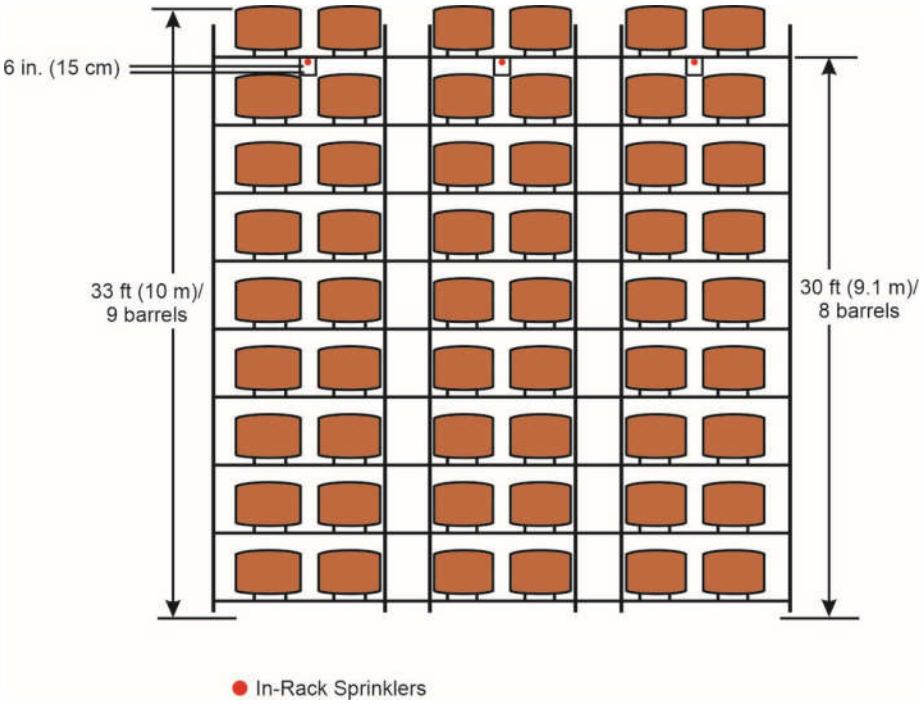


Figure 16.10.3.1F. In-Rack sprinkler layout for distilled spirits in wooden barrels (elevation view)

Printed in USA © 2022 FM Global
All rights reserved.
https://www.fmglobal.com/research-and-resources/standards-and-certification/code-support-reports