Evaluation of Protection for Plastic Containers Using Sprinkler Systems with 1.0% AFFF and Plain Water

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ABSTRACT: Four large-scale fire tests were conducted to compare an aqueous film forming foam (AFFF) agent against plain water for protection of an on-floor storage arrangement of a plastic container commonly used in automated and manual materials handling. The container used in these tests was a 600 mm × 400 mm × 280 mm open-top, double-wall, polypropylene box. These boxes were stored 4.5 m high under a 10.5 m ceiling. The protection design used fast-response 68°C-temperature-rated K160 sprinklers discharging either 1.0% AFFF agent/water solution or plain water at a discharge density of 30 mm/minute. Initial test parameters, which included fuel and storage configuration, sprinkler system design (sprinkler type, temperature rating, actuation link sensitivity, spacing, and discharge pressure), ignition placement within the storage configuration and the relative positioning of the storage arrangement with respect to ceiling sprinklers were consistent for all tests. The testing procedure involved a format that used an initial test followed by a validation test under the same initial test conditions.

KEY WORDS: warehouse storage protection, sprinklers, sprinklered fire test, AFFF agent, plastic containers, KLT boxes, plastic tote boxes, large-scale fire tests, large-scale fire test repeatability.

INTRODUCTION

FIRE TESTING AND actual fire emergency experience have confirmed that aqueous film forming foam (AFFF) agent improves the effectiveness of plain water on two-dimensional (e.g., a horizontal pool) flammable liquid fires. A similar extinguishment improvement for three-dimensional and solid-fuel fires has not been extensively verified. However, in some instances, European fire protection guidelines [1] recommend AFFF water spray system protection for certain plastic containers in warehouse storage arrangements.

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1042-3915/09/02 0107–18 $10.00/0 DOI: 10.1177/1042391508101983

SAGE Publications, Los Angeles, London, New Delhi and Singapore

The current study includes an assessment of water-only sprinkler protection as a means of evaluating any increased effectiveness related to the use of the 1.0% AFFF agent.

European fire protection for KLT (Kleinladungstrager) plastic boxes[1] utilizes water spray systems for on-floor storages up to 3 m high. AFFF at 1.0–3.0% volume concentration is recommended for storage heights that exceed 3 m and are applicable to on-floor storages up to 4.5 m high. The potential advantage of AFFF systems for this application was assessed by the tests in this program. The AFFF fire protection concept for storages higher than 3 m but less than 4.5 m utilize K160 (see Sprinkler Protection) fast response, upright water spray nozzles installed on 3 m × 3 m spacing with application of 1.0% AFFF at a design density 30 mm/minute. At issue is whether these fire protection requirements provide significantly better fire protection than plain water. US domestic fire protection guidelines typically promote use of water-only, closed-head sprinkler protection whenever possible to reduce system complexity and maintenance requirements. In addition, use of plain water systems avoids the environmental impact issues that may be associated with AFFF systems. To resolve the issue of whether there was an advantage to be gained through use of a 1.0% AFFF/water solution over plain water for KLT boxes, a large-scale fire test scenario was designed using a 4.5 m high storage of KLT plastic boxes under a 10.5 m ceiling.

TEST SETUP AND PROCEDURES

The current study consisted of direct comparisons using a single test scenario, with an initial test followed by a verification (repeat) test for both 1.0% AFFF agent and plain water systems. The initial tests evaluated the AFFF agent (Tests 1 and 2) and were followed by the plain water tests (Tests 3 and 4). The same sprinkler system design (sprinkler characteristics, piping arrangement and discharge density) was used in all four tests.

Facilities

All tests were conducted in the Large Burn Laboratory of the FM Global Research Campus, West Glocester, RI USA under a height-adjustable (to 18.3 m) ceiling set at 10.5 m. At this facility the make-up air to the test volume is drawn into the building through a system of adjustable louvers installed on one wall of the Large Burn Laboratory. The actual air influx to the facility is controlled by the adjustable louvers and the exhaust rate of a wet electrostatic precipitator (WESP) air pollution system. Air extracted from the

[1]Kleinladungstrager, literally means 'small cargo carrier' or small load container.

Figure 1. *Test arrangement – south-west view of main block and west target. (The color version of this figure is available online.)*

test volume, which includes all airborne combustion products from fires, is withdrawn at ceiling level and collected by the WESP. The air ventilation through the test volume was set at $94.4\,m^3/s$.

Test Fuel – KLT Boxes

The open-top plastic container used in these tests is the standard KLT box used in European warehouses for storage of a variety of items including heavy pieces of machinery and automobile parts. The test array consisted of a palletized block storage arrangement of $600\,mm \times 400\,mm \times 280\,mm$ polypropylene plastic KLT boxes (Figure 1). These are open-top, double-wall, solid-deck bottom boxes with an average weight of 4.35 kg each. The boxes were designed to nest vertically and were empty at the start of each test. The topmost boxes for each pallet load were left uncovered.

Each pallet load consisted of 20 KLT boxes in five layers ($2 \times 2 \times 5$ high configuration) stored on a European-style wood pallet.[2] The European pallets were $0.8\,m \times 1.2\,m \times 150\,mm$ with an average weight of 19.4 kg. A single pallet load of KLT boxes had overall dimensions of $0.8\,m \times 1.2\,m \times 1.52$ high.[3]

[2]The European-style wood pallet was softwood (e.g., pine) instead of the hardwood used for domestic pallets and has slightly smaller dimensions.
[3]Includes height of the pallet (150 mm (6 in.)).

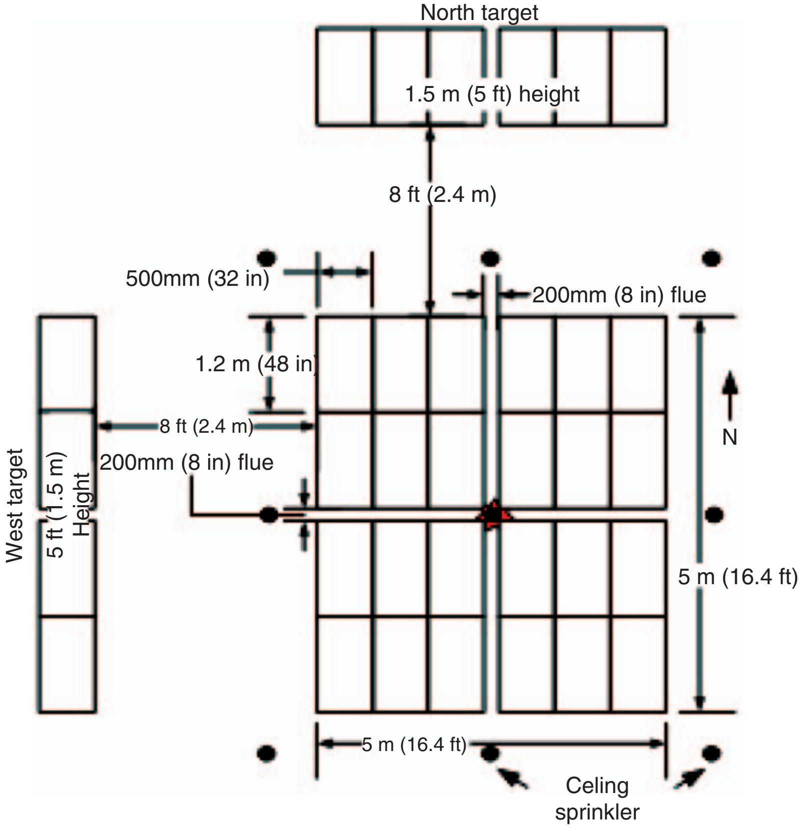


Figure 2. *Plan view of test arrangement with location of the nine (9) ignition zone sprinklers. (The color version of this figure is available online.)*

The test arrangement for these tests (Figures 1 and 2) consisted of a main array and target arrays for all except the initial test (Test 1). The main array was a 5 m × 5 m × 4.5 m high block configuration of 24, three-tier high stacks. Singular longitudinal (north–south) and transverse (east–west) 200 mm wide intersecting flue spaces separated the block into equal quadrants. Each quadrant consisted of 18 pallet loads arranged in a 2 × 3 × 3 pallet load configuration. The stack configuration is shown as Figure 3. In Tests 2, 3, and 4, one-tier high target arrays were placed across 2.4 m (8 ft) aisle spaces directly west and north of the main array. The target arrays were included to assess the potential of fire spread by stack collapse.

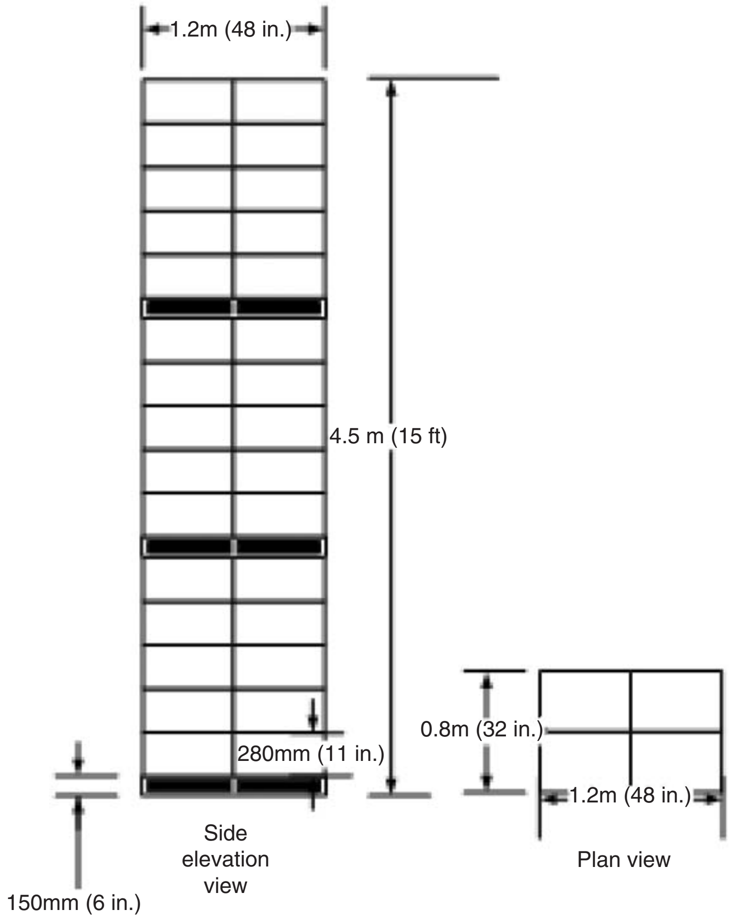


Figure 3. *Single stack configuration of KLT plastic totes.*

Ignition and Test Procedure

The fuel and storage configuration, sprinkler system design (sprinkler type, temperature rating, actuation link sensitivity, spacing, discharge pressure), ignition placement within the storage configuration and the relative positioning with respect to ceiling sprinklers were consistent for all tests. Two tests (Tests 1 and 2) used 1.0% AFFF agent/water as the extinguishing agent; the remaining two tests (Tests 3 and 4) used plain water. The two tests within each agent category consisted of a primary test and a repeat test for confirmation of the initial test result.

The main array was centered directly below a sprinkler at center of the ceiling. Ignition was placed at the base of the pallet loads forming the intersecting flues of the main array. Ignition consisted of four 76 mm long, 76 mm diameter cellucotton rolls each soaked with 118 mL of gasoline and wrapped in a clear polyethylene plastic bag. An igniter was placed at one corner of each of the intersecting flues at the center of the arrangement. The igniters were lighted using a propane torch to begin each test.

Sprinkler Protection and Foam Water System

In all tests, 49 upright type, closed-head sprinklers in a 7×7 grid were installed at the ceiling on a $3\,\text{m} \times 3\,\text{m}$ spacing using nominal 2 in. steel pipe branch lines, which resulted in sprinkler deflectors being 180 mm below the ceiling. The sprinkler was an European-manufactured extra large orifice (ELO) device with nominal 20 mm pipe thread connection and K-factor of 160.[4] It had a 3 mm, 68°C temperature-rated, fast response quartz bulb mechanism with a nominal response time index (RTI)[5] of 35 [2].

The water supply was set to provide a constant 3.2 bar discharge pressure. At this pressure, each operating sprinkler discharged 288 L/minute for an application design density of 30 mm/minute. This application design density was the same for all tests.

The AFFF concentrate was a generic low-expansion (volumetric expansion less than 15 times), fluorinated surfactant foam specifically formulated for use on Class A and B fires [3]. For foam/water tests (Tests 1 and 2) the AFFF agent proportioning system used 1.0% solution concentrate. The proportioning system hardware used in these tests provided an error rate of less than 1% of the desired 1.0% design AFFF injection rate for the system.

Test Instrumentation

Test instrumentation included (1) thermocouples for measuring gas temperatures 0.18 m below the ceiling (designated as 'near- ceiling' in the following) and ceiling steel temperatures at various locations over the test site, (2) ceiling velocity probes at 1.5 m and 3 m radial distances from directly over the center of the main array, (3) heat flux gauges at 1.2 m separation from the east and west faces of the main array at an elevation of 2.3 m, (4) sprinkler system pressure and flow monitoring, and (5) electrical circuits to monitor sprinkler actuation times. In addition, periodic samples of sprinkler discharge were taken during the AFFF agent tests to validate AFFF

[4]The K-factor is the sprinkler nozzle discharge coefficient, which relates the water discharge rate to the discharge pressure and is given in units of $\text{L/minute/bar}^{0.5}$. K-factor equivalent in English units is $11.2\,\text{gpm/psi}^{0.5}$.
[5]RTI provides relative measure of sprinkler sensitivity. Given in units of $(\text{m s})^{0.5}$.

agent concentration. The sampling of sprinkler discharges for Tests 1 and 2 confirmed volume concentrations of $1.0 \pm 0.01\%$ AFFF.

TEST RESULTS

The collected data, test observations and the visual records (video and still photography) were used to assess the effectiveness of the protection systems. The assessment also included three specific criteria, (a) the total number of sprinkler actuations, (b) the maximum ceiling steel temperature over the main array, and (c) the extent of fire damage to the fuel arrays.

The total number of sprinkler operations during a test provides indication of the effectiveness of the system by allowing determination of effective design coverage areas. The maximum allowed coverage area had previously been estimated to be $225\,m^2$ for this scenario. This is the equivalent coverage area of 25 sprinklers installed on $3\,m \times 3\,m$ spacing.

The maximum steel temperature at the ceiling over the array provides indication of the potential for thermally induced failure of structural steel supports. The criterion for this measurement uses a maximum limit of 538°C. This is based upon the assessment that most structural steel begins to lose strength at this temperature. Of course, the failure of steel support members is dependent upon a number of factors including the alloy, length, thickness, unsupported length, and loading.

The extent of fire damage is an important indication of fire protection system effectiveness. For large-scale warehouse fire test evaluations, the test configuration represents a full-scale segment of a much larger facility. In reality, a warehouse would have more available fuel. It is therefore necessary to require that the fire be contained within the test arrangement if the fire protection is to be considered adequate. If the fire is not contained, it is likely that in an actual warehouse, the fire would spread uncontrolled.

A summary of test evaluation criteria is presented as Table 1. Sprinkler actuation sequences are provided in Figures 4–7.

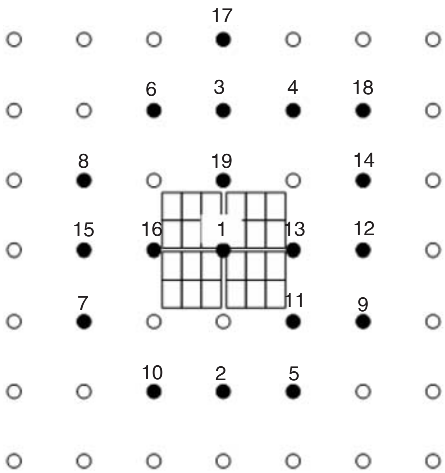
DISCUSSION

Test 1 evaluated the AFFF agent system and Test 2 was a validation (repeat) test conducted under the same initial condition. The only difference between the test setup for Test 1 and Test 2 was the inclusion of target arrays to the north and west in Test 2. The target arrays were used in all remaining tests. Test 3 used a plain water system under the same initial conditions as Test 2. Test 4 was a validation (repeat) test for Test 3.

Fire development in all tests was very similar with flames at the center of the intersecting flues reaching the top of the 4.5 m array at 1 minute

Table 1. Test evaluation criteria – AFFF agent/water tests.

Test number	Agent	Sprinkler operation First	Sprinkler operation total	Sprinkler operation Last	Maximum steel (°C)	Damage extent
1	1.0% AFFF	2:48	19	5:29	97	Within array
2	1.0% AFFF	2:43	19	7:01	81	Within array
3	Water	2:47	16	5:30	79	Within array
4	Water	2:28	16	5:59	81	Within array



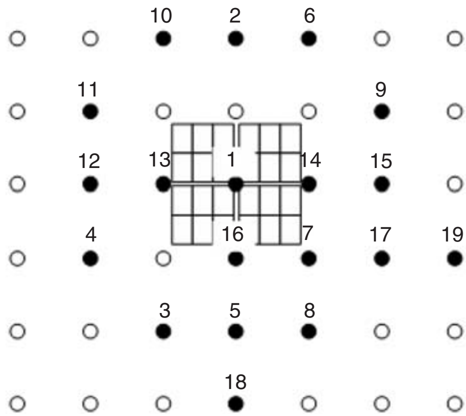
Sprinkler sequence

No.	time	No.	time
1	2:48	11	3:59
2	3:22	12	4:10
3	3:29	13	4:13
4	3:34	14	4:17
5	3:38	15	4:29
6	3:41	16	4:30
7	3:45	17	5:11
8	3:52	18	5:15
9	3:56	19	5:29
10	3:59		

Figure 4. *Sprinkler actuation sequence – Test 1 – AFFF system (filled symbols represent actuated sprinklers).*

55 seconds after ignition in Test 4 and 2 minutes 15 seconds after ignition in Test 2 and Test 3. Flames reached the top of the array at 2 minutes 12 seconds in Test 1. The times for first sprinkler actuations were also consistent with actuation times ranging from 2 minutes 28 seconds (Test 4) to 2 minutes 48 seconds (Test 1) (Table 1).

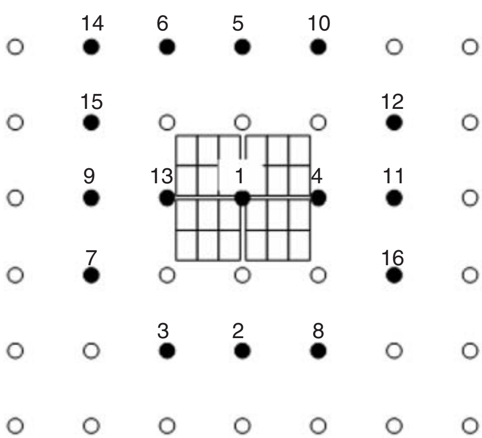
Near-ceiling gas temperature profiles directly over the array are presented in Figure 8. The ceiling steel temperatures directly over the array center are shown in Figure 9. Figures 10–12 present average near-ceiling gas temperatures for all four fire tests at distances of 1.5 m, 6.1 m, and 10.5 m from the center of the ceiling, respectively. These data indicate similar initial fire growth and decay in all tests. There are differences in near-ceiling gas temperature behavior as temperatures fluctuate in response to the variations in the sprinkler actuation sequences (Figures 4–7). The near-ceiling gas temperature profiles indicated that in all four tests fire control had been achieved within 15 minutes (900 seconds) after ignition.



Sprinkler sequence

No.	time	No.	time
1	2:43	11	3:54
2	3:25	12	4:00
3	3:26	13	4:00
4	3:29	14	4:26
5	3:31	15	4:39
6	3:32	16	5:18
7	3:36	17	5:22
8	3:37	18	5:23
9	3:52	19	7:01
10	3:52		

Figure 5. *Sprinkler actuation sequence – Test 2 – AFFF system (repeat of Test 1).*

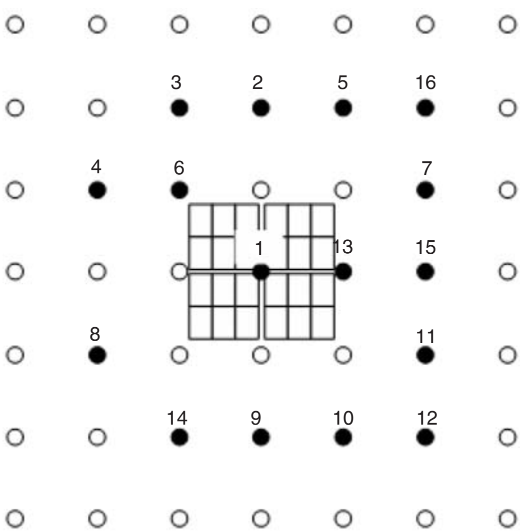


Sprinkler sequence

No.	time	No.	time
1	2:47	11	4:44
2	3:24	12	4:49
3	3:29	13	5:12
4	3:34	14	5:20
5	3:37	15	5:20
6	3:42	16	5:30
7	4:02		
8	4:03		
9	4:11		
10	4:23		

Figure 6. *Sprinkler actuation sequence – Test 3 – plain water system (filled symbols represent actuated sprinklers).*

The four fires also behaved similarly with drastic reductions in fire intensity at about 7 minutes after ignition. The reductions were indicated by significant decrease in the near-ceiling gas temperatures directly over ignition (Figure 8). The averaged readings for near-ceiling thermocouples at radial distances of 1.5 m, 6.1 m, and 10.5 m from the center of the ceiling also



Sprinkler sequence

No.	time	No.	time
1	2:28	11	4:33
2	3:20	12	4:38
3	3:31	13	4:38
4	3:40	14	4:39
5	3:43	15	4:41
6	3:44	16	5:59
7	3:52		
8	4:09		
9	4:10		
10	4:13		

Figure 7. *Sprinkler actuation sequence – Test 4 – plain water system (repeat of Test 3).*

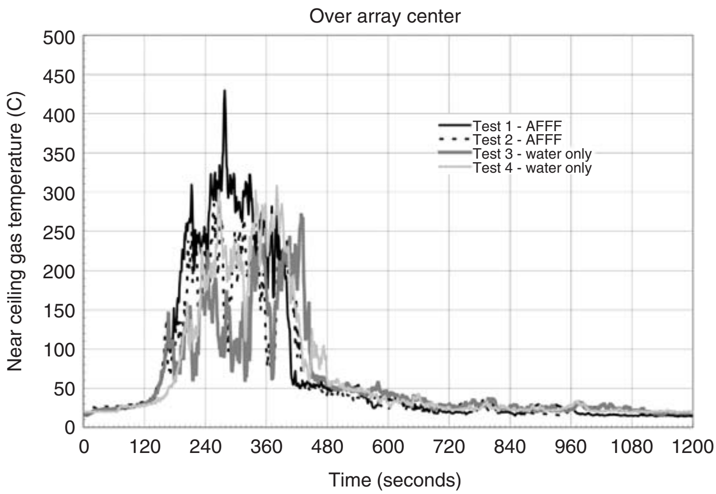


Figure 8. *Near-ceiling gas temperature over ignition.*

show similar decreases in near-ceiling gas temperatures.[6] These results indicate similar fire control in all four tests.

The reductions in fire intensities at 7 minutes after ignition in these four tests could not be linked to a specific sprinkler actuation. In large-scale fire tests the

[6]At each radial distance readings were taken from four thermocouples (east, west, north, and south).

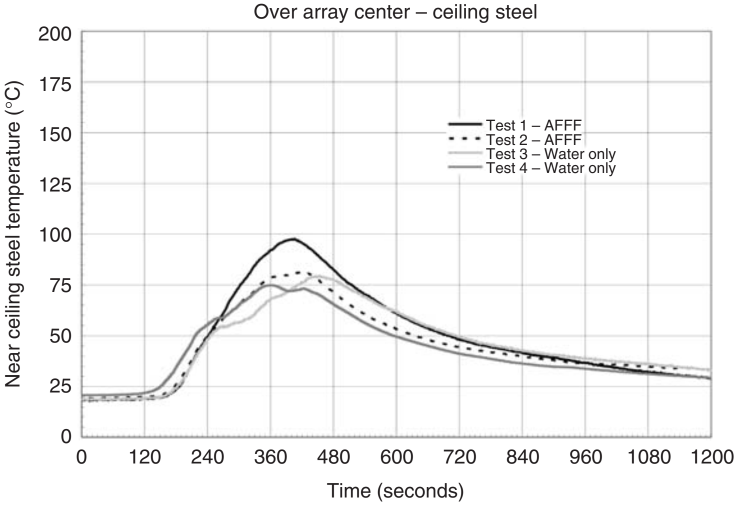


Figure 9. *Ceiling steel temperature over ignition.*

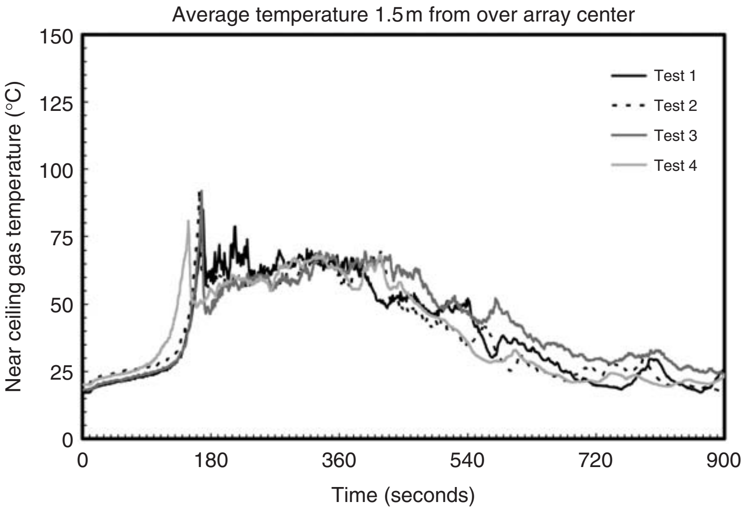


Figure 10. *Average near-ceiling gas temperature at 1.5 m radius.*

actuation of a single sprinkler over the fire zone can sometimes have dramatic impact upon a growing fire resulting in the immediate reduction of near-ceiling gas temperatures. However, in these tests the sprinklers closest over the main array[7] had actuated prior to the time that the fire underwent the reduction

[7]Those sprinklers that would actuate. Not all sprinklers over the arrays actuated during these tests.

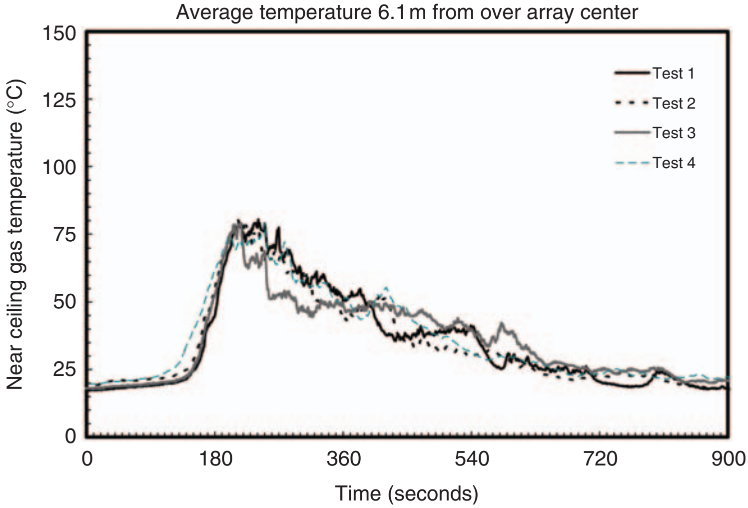


Figure 11. *Average near-ceiling gas temperature at 6.1 m radius. (The color version of this figure is available online.)*

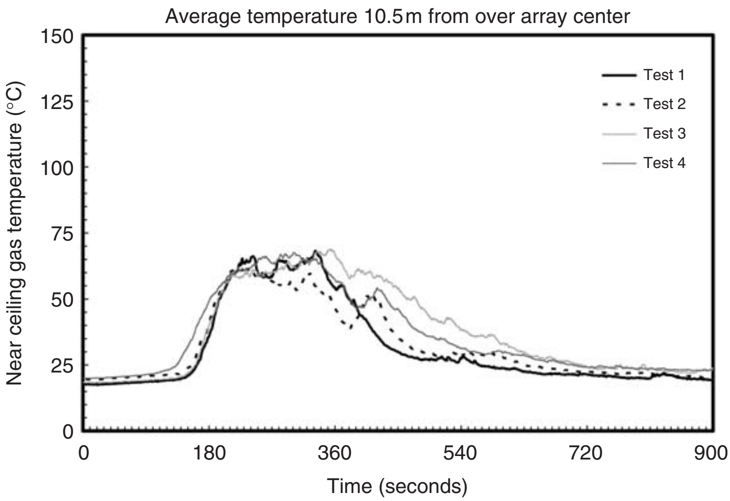


Figure 12. *Average near-ceiling gas temperature at 10.5 m radius.*

in intensity. Therefore, a sprinkler actuation could not be directly linked to the reductions in fire intensity for any of the four fire tests. The reductions in fire intensities were likely due to shifting of the arrays, which occurred at around 6 minutes to 7 minutes after ignition and resulted in narrowing of the vertical flue spaces in upper pallet loads of the block arrangement.

This would produce immediate reduction in near-ceiling gas temperatures as the fire plume was blocked. It is also possible that the uppermost bins, which were open to the sprinkler discharge reached fill capacity at about this time (the same sprinkler discharge rate was used in all tests) and began overflowing down the sides of the arrangement into the internal flues. The cascading of water from the overflowing top tier of KLT boxes down the vertical flues could affect rapid fire control and assist in causing the rapid decrease in ceiling gas temperatures. Because of the limited visibility of the test arrangement at this stage of the tests it was not possible to validate either of these two suppositions.

There was good repeatability for this test series, which provides a degree of confidence for using limited-number large-scale fire tests as a means of developing sprinkler protection guidelines and standards for the fire protection community. For most practical applications, water supply requirements used in industrial fire protection standards reflect the total number of sprinkler actuations during single-scenario, large-scale fire tests such as these. There were 19 sprinkler actuations in both AFFF agent tests (Tests 1 and 2), while both plain water tests (Tests 3 and 4) resulted in 16 sprinkler actuations.

Further, the validation tests showed consistency in the number of sprinklers over the storage arrangement that were actually needed to control the fires. There were nine ignition zone sprinklers in the 3×3 sprinkler arrangement over the array (Figure 2) that discharged water onto the burning array. In the AFFF tests, five of these sprinklers actuated and were responsible for controlling the fires. In the plain water tests, three were needed in each test. For the practical purposes of setting protection guidelines, which specify water supply requirements, these results affirm the legitimacy of the traditional approach of large-scale fire testing.

The data for the four sprinkler tests are not significantly different. Point source gas temperature measurements near the ceiling in the immediate vicinity of the fire in a test with sprinklers can often be misleading because of the influence of water vapor and droplets carried by the fire plume. However, averaged near-ceiling gas temperatures at radial distances away from the center of the array can usually provide an indication of how well a sprinkler system controls a large-scale fire. Figures 10–12 present near-ceiling gas temperatures at horizontal distances of 1.5 m, 6.1 m, and 10.5 m, respectively, from the center of the array. These data indicate comparable, adequate fire control for all four tests.

When the specified test evaluation criteria are applied it is evident that the AFFF/water sprinkler protection system offered no significant improvement in fire control/extinguishment performance over plain water for the scenario tested. Table 1 presents numbers of sprinkler operations, maximum ceiling steel temperatures and extent of fire damage for the four tests conducted in this series.

In terms of the total numbers of sprinkler operations during the test, the two plain water sprinkler fire tests (Tests 3 and 4) yielded a slightly reduced total number of sprinkler operations, i.e., 16 sprinklers versus 19 sprinklers. Further, the operating patterns of sprinkler actuations for Tests 3 and 4 do not include sprinklers in the outer ring of installed sprinklers (Figures 6 and 7), whereas sprinkler actuations in Tests 1 and 2 (Figures 4 and 5) included sprinklers installed in outer rings near the edges of the ceiling. The operation of sprinklers near the edges of the ceiling raises the issue regarding the potential for additional sprinkler actuations under a larger expanse of ceiling.

Maximum (peak) ceiling steel temperatures were analyzed to assess the potential for collapse of roof structural steel support members. None of the four tests exhibited maximum steel temperatures that approached the 538°C temperature set as the acceptable limit for this measurement. The sprinkler protection criteria consisting of K160 sprinklers at a design density of 30 mm/minute provided acceptable ceiling steel protection for both 1.0% AFFF agent/water and plain water systems.

The extent of fire travel during the four fire tests was essentially the same. In all four tests, flames from the fire exited the central flues of the block arrangement at the second- and third-tier pallets and extended onto the outside faces (Figure 13) for a brief period. These flames were eventually extinguished by the sprinkler sprays. No targets were used in Test 1.

Figure 13. *Flames at transverse and longitudinal flue openings (Test 4). (The color version of this figure is available online.)*

However, in tests in which target arrays were used, i.e., Tests 2, 3 and 4, the fires were confined to the block arrangement with no involvement of the target arrays to the west and north across 2.4 m aisles. Fires burned in the collapsed material in the aisles between the main and target arrays, but the targets used in Tests 2, 3 and 4, did not ignite.

There were differences in overall fire damage and post-test clean-up requirements. It was determined that the differences were related to individual test duration. The sprinkler protection system for this scenario was designed for fire control, not fire suppression. In the case of fire control, fires are expected to be contained but not fully extinguished as would be the expectation for fire suppression systems. With a fire control sprinkler system, plant emergency and fire department response are essential factors in limiting fire damage and providing clean-up operations. The differences in post-test cleanup requirements for the four tests can be clearly discerned in Figures 13–16. In this series, all sprinkler operations for each test had occurred by approximately seven minutes after ignition. However, testing periods ranged from 18 minutes for Test 2 to 30 minutes for Test 4. The tests were terminated when it was judged that fire intensity was low and further sprinkler actuations would not occur. Test 4 was allowed to proceed to 30 minutes to investigate the effect of a longer test duration. The longer the test was allowed to proceed, the greater was the post-test damage and clean-up operations. The post-test extinguishment of residual fire for Test 4 was

Figure 14. *Test 1 – post test (view from north-east corner). Test duration: 22 minutes. (The color version of this figure is available online.)*

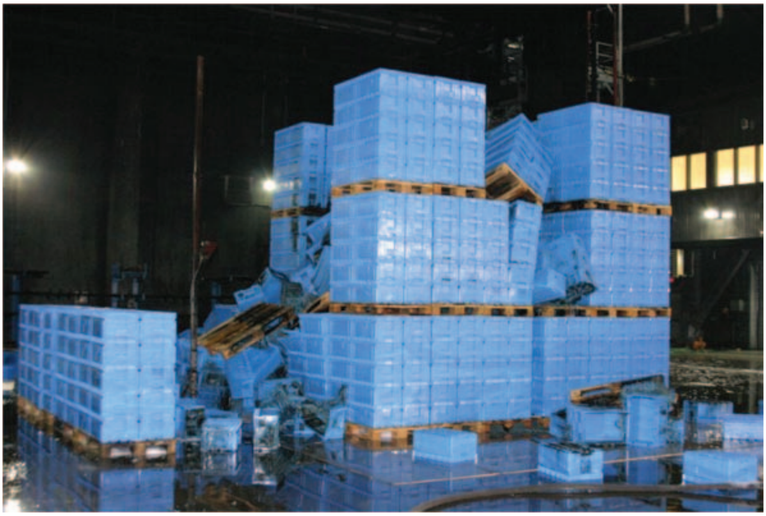


Figure 15. *Test 2 – post test (View from south-west corner). Test duration: 18 minutes. (The color version of this figure is available online.)*

Figure 16. *Test 3 – Post test (view from south-east corner). Test duration: 25 minutes. (The color version of this figure is available online.)*

extensive because of the 30-minute test duration. By the end of Test 4 there had been almost complete collapse of the block arrangement with numerous sites of shielded fires in the piles of collapsed boxes (Figure 17). In Test 2 (Figure 15), the test duration was 18 minutes and three corners of the block

Figure 17. *Test 4 – post test (View from south-east corner). Test duration: 30 minutes. (The color version of this figure is available online.)*

arrangement remained standing as the test was terminated. Clean-up and extinguishment operations were clearly much less extensive than in Test 4.

CONCLUSIONS

The four tests performed in this series involved palletized storage of empty polypropylene plastic KLT boxes stored 4.5 m high under a 10.5 m ceiling. The fire protection for the test scenario consisted of a ceiling-only, wet-pipe sprinkler system incorporating upright type, quick response, 68°C temperature rated ELO sprinklers installed on 3 m $\times$ 3 m spacing. The water supply was set at an operating pressure of 3.1 bar for a design density of 30 mm/minute. The tests were conducted in a format that allowed a primary test and a repeat (validation) test. Tests 1 and 2 used a 1.0% AFFF agent-water agent and Tests 3 and 4 used plain water.

The results of these tests show no significant sprinkler system performance advantage for use of 1.0% AFFF agent over plain water for these type of plastic storage containers when stored and protected as in these tests.

While tests indicate that both 1.0% AFFF and plain water sprinkler protection will provide acceptable fire control for the test scenario, the testing also indicated that a timely secondary manual firefighting response in the form of a plant emergency organization or municipal fire department is a necessary element in limiting fire damage and clean-up operations.

In addition, the testing procedure used for this series showed good repeatability in a large-scale test format. This contributes to the affirmation of this methodology for developing reliable fire protection guidelines and standards used for industrial storage occupancies.

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