RESEARCH TECHNICAL REPORT

SMART Sprinkler Protection for Highly Challenging Fires - Phase 2: Full-Scale Fire Tests in Rack Storage

SMART Sprinkler Protection for Highly Challenging Fires - Phase 2: Full-Scale Fire Tests in Rack Storage

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Executive Summary

Fire hazards in modern warehouses have increased significantly due to the recent development of automatic handling technology. Highly challenging fires (HCFs) are defined as storage and building configurations that currently do not have any protection recommendations. One example of HCFs is high storage of roll paper that exceeds what is covered in current FM Global Property Loss Prevention Data Sheet 8-21, *Roll Paper Storage*. To address HCFs, the concept of a new protection system was proposed and developed with work starting in 2012.

The overall objective of this project is to demonstrate a new sprinkler system that can provide adequate protection for HCFs. The new sprinkler system utilizes the Simultaneous Monitoring, Assessment and Response Technology (SMART), which provides multiple functions including fire detection, fire location, sprinkler activation and fire suppression. In order to evaluate these system functions, a series of experiments was designed and conducted as Phase 1 in the Small Burn Lab at the FM Global Research Campus in West Glocester RI, USA, which included fire detection, sprinkler activation and preliminary fire suppression tests. The experimental results demonstrated that the newly developed system met the design objectives for fire protection purposes. Based on the results in Phase 1, the objective of Phase 2 was set to evaluate the new sprinkler system performance in full-scale tests using standard commodities.

The present work focuses on evaluating SMART sprinkler performance in rack storage configurations. Cartoned unexpanded plastic (CUP) commodities were selected as the fuel. Three tests were conducted with increasing storage height, *i.e.*, 3-, 5- and 7-tier rack storage. The main array in each of the tests was a four-pallet-load long, double-row rack. Two target arrays, each two-pallet-loads long, were placed on each side of the main array. The ignition locations were selected according to the standard full-scale sprinkler test protocol. Ignition was carried out using two half-igniters at the offset location relative to the center of the main fuel array. The protection was provided using sixteen SMART sprinklers. The ceiling sprinkler spacing was 3.05 m x 3.05 m (10 ft × 10 ft) for all tests. For 3-, 5- and 7-tier CUP commodities, the target water densities were 16.3, 26.5 and 36.6 mm/min (0.4, 0.65 and 0.9 gpm/ft^2), respectively. These values were selected based on previous Critical Delivered Flux (CDF) measurements and full-scale tests.

The test results in the present work show that the SMART sprinkler system can provide adequate protection for CUP commodity in rack storage under the tested conditions. Specifically, all fires were suppressed shortly after sprinkler activation; fire damage was limited to the ignition location and the adjacent area directly above ignition; fire sizes were small upon sprinkler activation; the estimated fire locations were sufficiently accurate; and the target water densities were significantly lower (50-56%) than those recommended in current FM Global Property Loss Prevention Data Sheet 8-9, *Storage of Class 1, 2, 3, 4 and Plastic Commodities*. These satisfactory results lay the foundation for evaluating such a system in protecting HCFs in engineering practice.

Abstract

Full-scale suppression tests were conducted to evaluate the performance of SMART sprinkler technology in protecting rack storage fires. The selected fuel was cartoned unexpanded plastic (CUP) commodity representing an intermediate level of fire hazard. The storage height increased from 3 tiers to 5 tiers to 7 tiers in the three tests. The sprinkler activation was initiated by a smoke alarm and a ceiling temperature rise threshold, upon which the fire location was calculated as the thermal centroid based on ceiling temperatures and a group of sprinklers, closest to the calculated fire location, was activated simultaneously. Subsequent fire development was monitored through visual observation as well as ceiling temperature data. Test results show that the SMART sprinklers can provide adequate protection for the CUP commodities stored up to 7-tiers high within a rack storage under the tested conditions. These tests lay the foundation for exploring further applications of the SMART sprinklers in HCFs.

Acknowledgements

The authors would like to thank Ryan Leach, Scott Cook, and Michael Skidmore for conducting all the tests at the FM Global Research Campus; to Scott Ulricksen and Christopher LaButti for installing the instrumentation; and to Jeff Chaffee for reviewing the test plan.

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1. **Introduction**

1.1 Background

Fire hazards in modern warehouses have increased significantly due to recent developments in automatic handling technology. The fire hazards that cannot be covered by existing protection recommendations are defined, in this work, as Highly Challenging Fires (HCFs). One example of HCFs is the very high storage of roll paper that exceeds current protection guidelines within FM Global Property Loss Prevention Data Sheet 8-21, *Roll Paper Storage* [1]. To address this issue, a new protection concept was proposed in 2012 and a prototype system was designed and tested in 2013-2015. The overall objective of this program was to demonstrate a new sprinkler system that can provide adequate protection for selected HCF scenarios.

The new sprinkler system utilizes the Simultaneous Monitoring, Assessment and Response Technology (SMART), which provides multiple functions including fire detection, fire location, sprinkler activation and fire suppression. In the present work, this new protection system is referred as the SMART sprinkler.

In order to evaluate these system functions, a series of experiments was designed and conducted as Phase 1 in the Small Burn Lab at the FM Global Research Campus in West Glocester RI, USA, which included fire detection, sprinkler activation and preliminary fire suppression tests. Fire detection tests were carried out with various fire sizes, fire locations and sprinkler spacing; sprinkler activation tests were conducted using liquid pan fires with different ignition locations; and preliminary fire suppression tests were performed using cartoned unexpanded plastic commodities under different sprinkler activation criteria, ignition sources and locations and sprinkler discharge densities. These experiments were completed and have been documented in a recent technical report [2].

The experimental results show that the use of multi-sensor detection technology, *e.g.*, the combination of smoke and temperature signals can help the SMART sprinklers respond faster and improve fire locating accuracy. The fire location can be determined with reasonable accuracy using a thermal centroid based calculation. The sprinkler activation can be achieved by the control unit through triggering individual sprinklers locally and dynamically, based on the results of fire detection and fire location. Fire suppression, even fire extinguishment, can be achieved with adequate sprinkler discharge densities. In summary, the results from fire detection, sprinkler activation and preliminary suppression tests have shown that the newly developed system meets design objectives for fire protection purposes.

1.2 Objectives

Based on the results of Phase 1, the objective of Phase 2 was set to evaluate the new sprinkler system performance in full-scale tests using standard commodities. In the present work, the focus was on testing SMART sprinkler performance in rack storage fires using a representative commodity. Specifically, the system performance in fire detection, sprinkler activation and suppression effectiveness was assessed with increasing level of fire hazards to provide the design basis for further assessment of the system performance in various high challenge storage configurations.

1.3 Organization of this report

In Chapter 2, experimental methods are described in detail including test commodity, experimental setup, SMART sprinkler system and test procedures and matrix. Chapter 3 presents experimental results from three full-scale fire suppression tests, together with discussions of the SMART sprinkler system performance. Conclusions are drawn and future work is discussed in the last chapter (Chapter 4). Detailed test data for the three full-scale tests are documented in Appendix A.

2. **Experimental method**

2.1 Fire tests using CUP in rack storage

In this work, the performance of the SMART sprinkler system was evaluated in a series of full-scale fire tests using standard commodities in rack storage configurations. All fire tests were conducted with cartoned unexpanded plastic (CUP) commodities. The CUP commodity was selected as representative of an intermediate level of fire hazard. Each pallet load of CUP commodity consisted of eight cartons in a 2 x 2 x 2 matrix placed on a hardwood pallet. Each carton [0.53 m x 0.53 m x 0.53 m (21 in. x 21 in. x 21 in.)] is filled with 125 polystyrene cups in a 5 x 5 x 5 matrix separated by cardboard dividers. The hardwood pallet has a plan area of 1.07 m x 1.07 m (42 in. x 42 in.) and is 0.13 m (5 in.) in height. The nominal dimensions of the pallet load is 1.07 m x 1.07 m x 1.19 m (42 in. x 42 in. x 47 in.). Details of the CUP commodity can be found in Ref. [3].

All suppression tests were set up under the south movable ceiling in the Large Burn Lab (LBL) of the FM Global Research Campus. The key parameters of the test conditions are listed in Table 2-1. Three tests with increasing storage height, *i.e.*, 3-, 5- and 7-tier rack storage, were carried out. Figures 2-1, 2-2, 2-3 and 2-4 show the elevation and plan views of the test setups.

Table 2-1: Test matrix.

No.	Fuel Arrays	Ceiling Height	Aisle Width	Ignition Location	Sprinkler Protection (open sprinkler)
1	Main (1): 2×4, 3T Target (2): 1×2, 3T	9.1 m (30 ft)	1.2 m (4 ft)	Under 1, offset	Pendent K160, 16.3 mm/min (K11.2, 0.4 gpm/ft^2)
2	Main (1): 2×4, 5T Target (2): 1×2, 5T	10.7 m (35 ft)	1.2 m (4 ft)	Under 1, offset	Pendent K200, 26.5 mm/min (K14.0, 0.65 gpm/ft^2)
3	Main (1): 2×4, 7T Target (2): 1×2, 7T	12.2 m (40 ft)	1.2 m (4 ft)	Between 2, offset	Pendent K360, 36.6 mm/min (K25.2, 0.9 gpm/ft^2)

The main array for each test was a four-pallet-load long, open frame, double-row rack. All flue spaces were 15 cm (6 in.). Two target arrays, each two-pallet-loads long, were placed 1.22 m (4 ft) from each side of the main array. The main and target arrays had the same storage height. The ignition locations were selected according to the full-scale sprinkler test protocol based on clearance between top of the commodity and the ceiling, sprinkler orientation and Actual Delivered Density (ADD) measurements of the sprinkler being used. Each ignition event was carried out using two half-igniters at the offset location relative to the center of the main fuel array (see Figure 2-4).

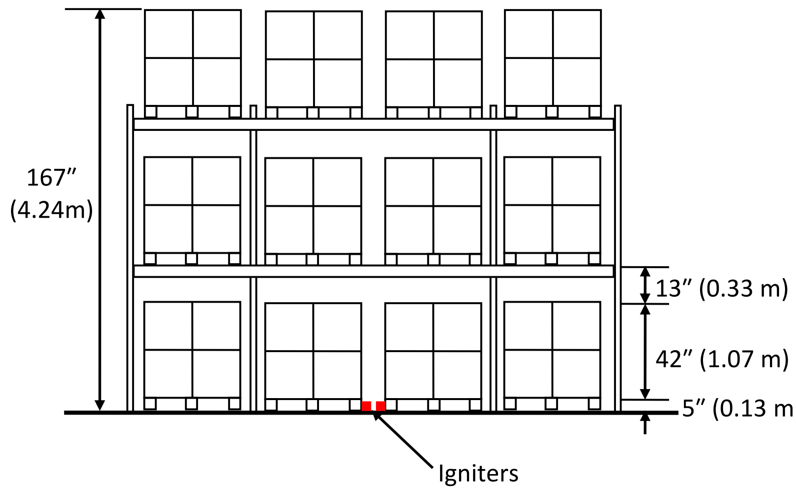

Figure 2-1: Elevation view of 2x4, 3-tier fuel array setup.

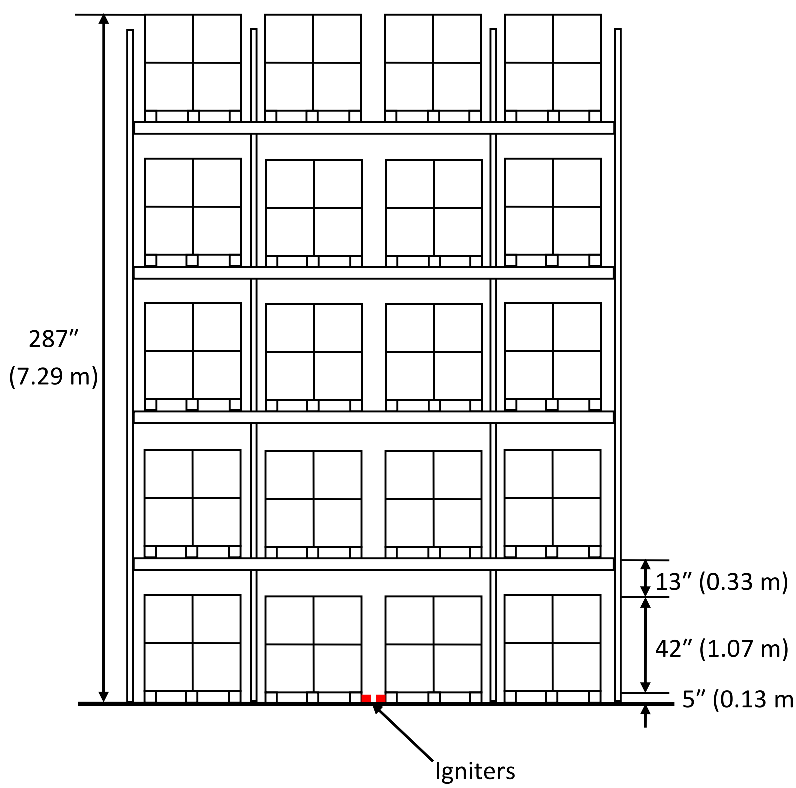

Figure 2-2: Elevation view of 2x4, 5-tier fuel array setup.

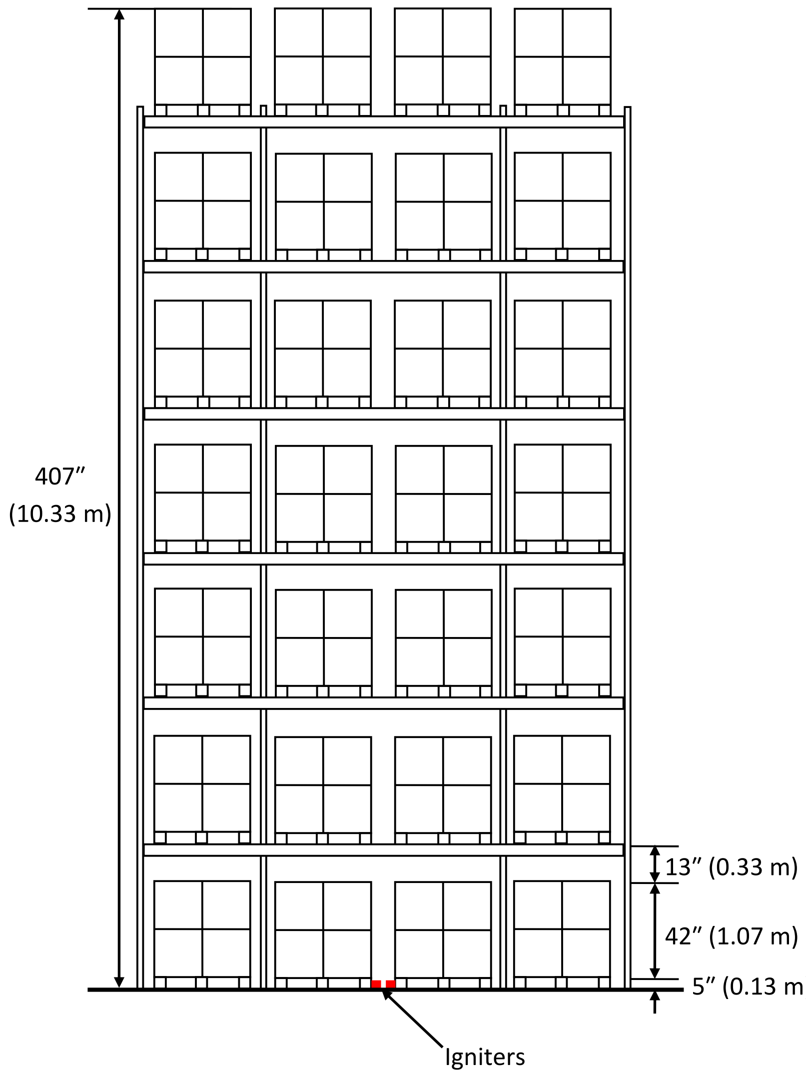

Figure 2-3: Elevation view of 2x4, 7-tier fuel array setup.

The protection was provided using SMART sprinklers. Details of the sprinkler system are discussed in the next section. Due to the complexity associated with SMART sprinkler installation, the fuel array location was adjusted in each test based on the test configuration, while the sprinkler system was fixed on the ceiling after installation. In the present work, a 3.05 m x 3.05 m (10 ft ×10 ft) sprinkler spacing was used for all tests. Figures 2-5, 2-6 and 2-7 show the sprinkler layout and its location relative to the fuel array and ignition. For 3-, 5- and 7-tier CUP commodities, the target water densities were 16.3, 26.5 and 36.6 mm/min (0.4, 0.65 and 0.9 gpm/ft^2), respectively. These values were selected based on Critical Delivered Flux (CDF) measurements [4] and previous full-scale test results. The total water flow rates and operating pressures were determined by calibration of the target water densities with six sprinklers open under no fire conditions.

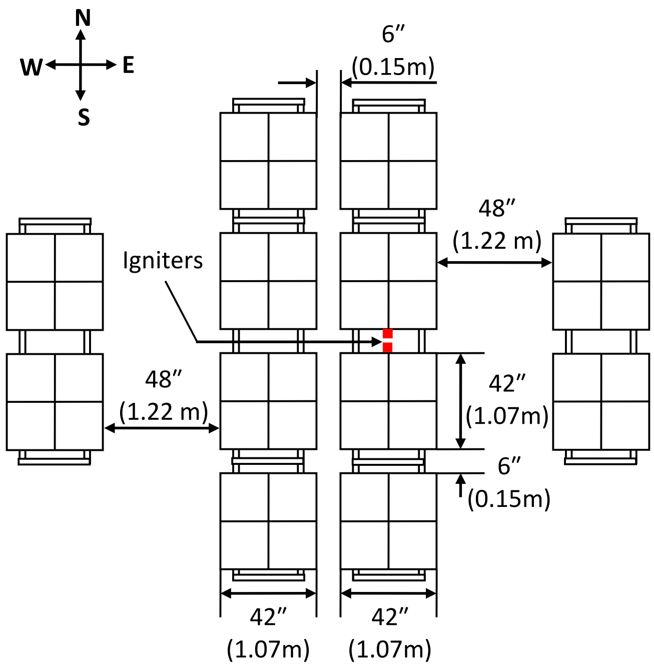

Figure 2-4: Plan view of 2x4, 3- to 7-tier fuel array setup.

2.1 SMART sprinkler system

All rack storage fires in this work were protected by SMART sprinklers installed on the ceiling. Figures 2-8 and 2-9 show the details of the SMART sprinkler system, including the node connection diagram and the valve and sprinkler connection diagram. Details of the development of the SMART sprinklers are documented in a separate report [2]. The output of smoke alarms and type “T” thermocouples were connected into XBEE transceivers so that the control unit could obtain these signals via wireless communication for fire detection. In this work, the fire detection criteria included two thresholds, both of which had to be satisfied: the smoke alarm being triggered, and the ceiling temperature rise exceeding 5 K. It should be pointed out that the use of temperature rise of 5 K is based on previous work [2], especially the preliminary tests in racks storage configurations using the CUP commodities. This detection criterion may be changed for HCFs, especially for those with very fast fire growth rates, to a temperature rate-of-rise to achieve faster detection. Also note that the 5-K temperature rise condition was tested in this work in a well-controlled laboratory environment, and was reached in less than one minute after ignition. Therefore, a time period associated with the temperature rise should be specified for SMART sprinklers in engineering practice to avoid false activation due to ambient temperature change.

When a fire event was detected, the fire location was determined by calculating the thermal centroid based on ceiling temperature data. Then, the control unit sent trigger signals to the XBEEs to activate the solenoid valves of a group of selected sprinklers. The trigger signal from the XBEE was connected to a solid state relay that controlled the solenoid valve power supply (120 VAC). At the same time, the smoke alarm and TC signals were also connected to the Research Campus data acquisition system (RCDAQ) to obtain data for post-test analysis. Figure 2-10 shows the XBEE labels, *i.e.*, sprinkler IDs, on each sprinkler unit.

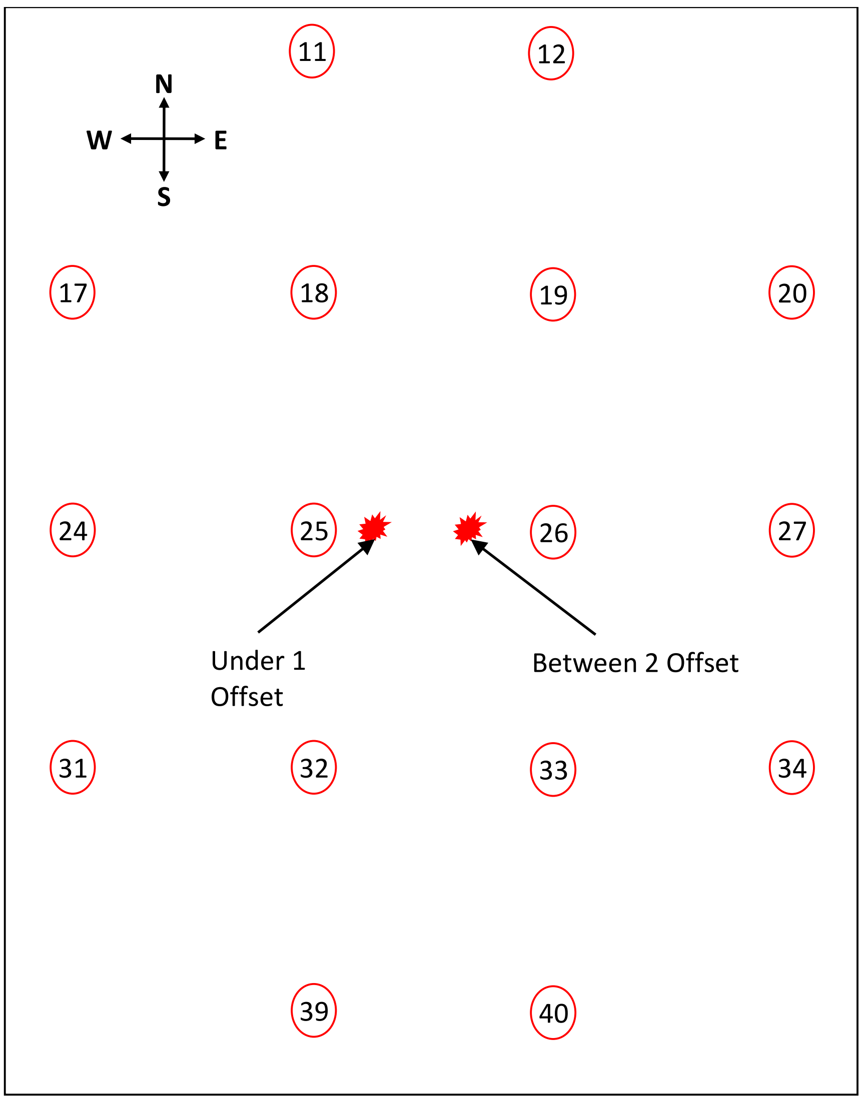

Figure 2-5: Smart sprinkler layout under the south movable ceiling with 3.05 m × 3.05 m (10 ft × 10 ft) spacing.

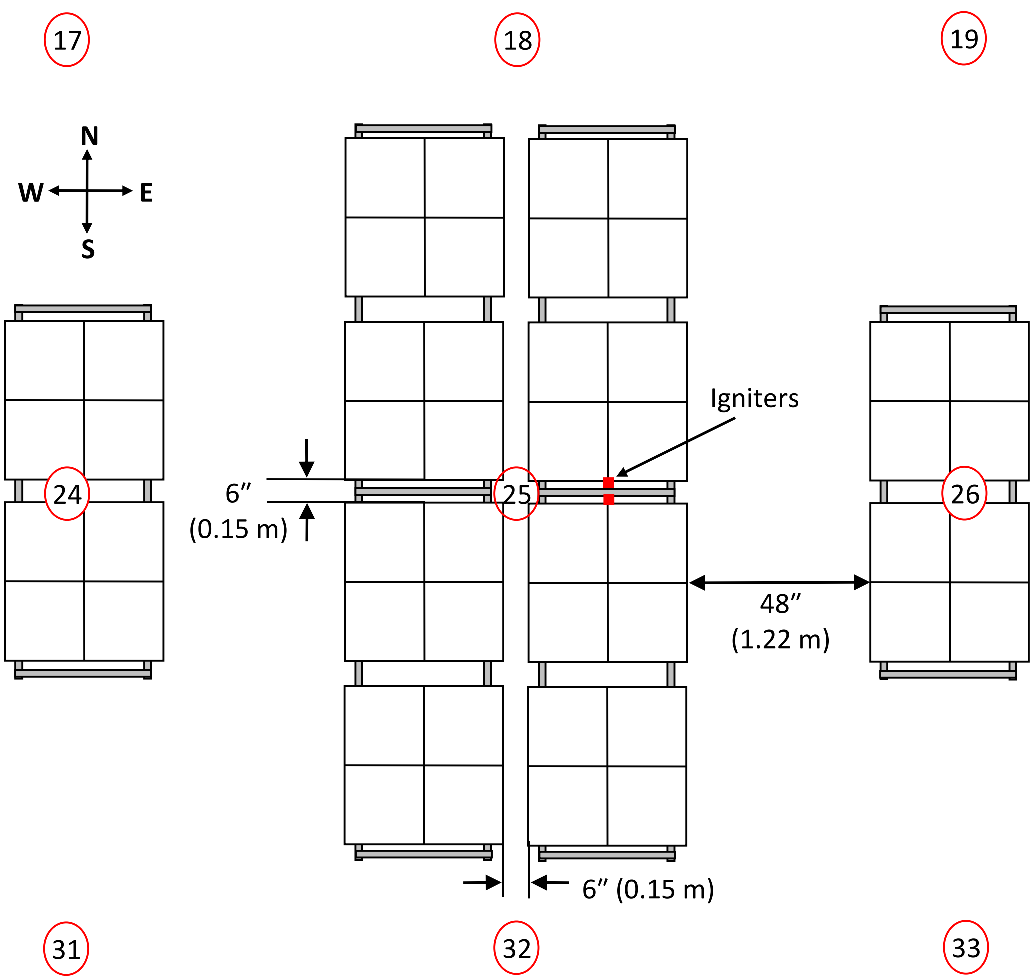

Figure 2-6: Plan view of sprinkler layout and fuel array: Test 1-2, Under 1 Offset.

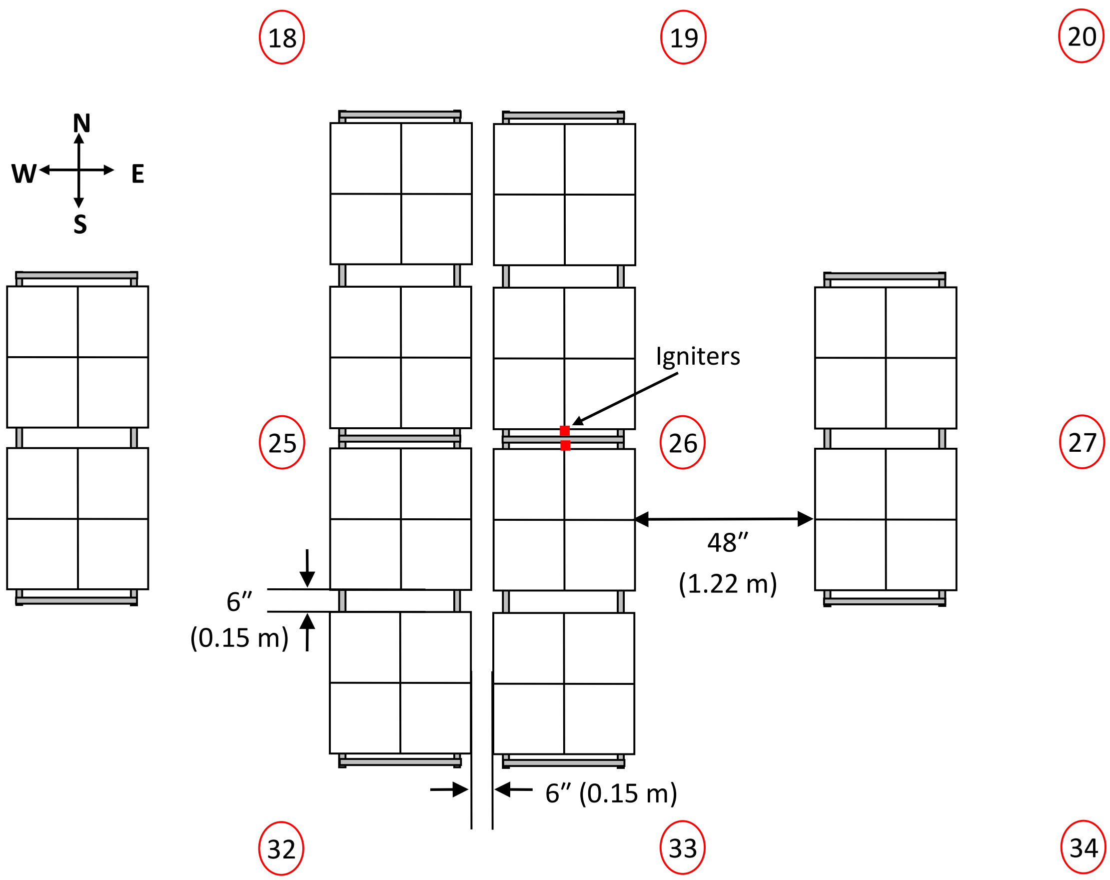

Figure 2-7: Plan view of sprinkler layout and fuel arrays: Test 3, Between 2 Offset.

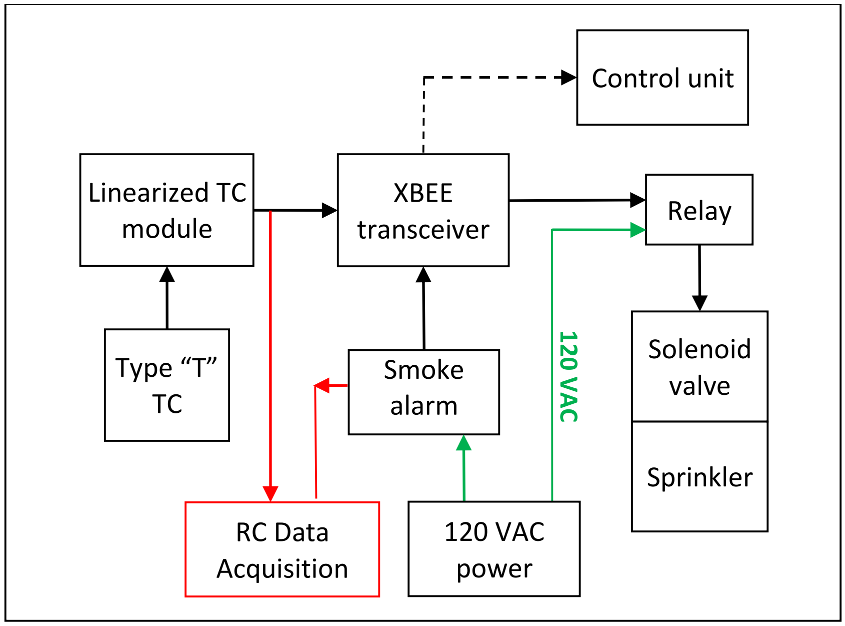

Figure 2-8: Smart sprinkler node connection.

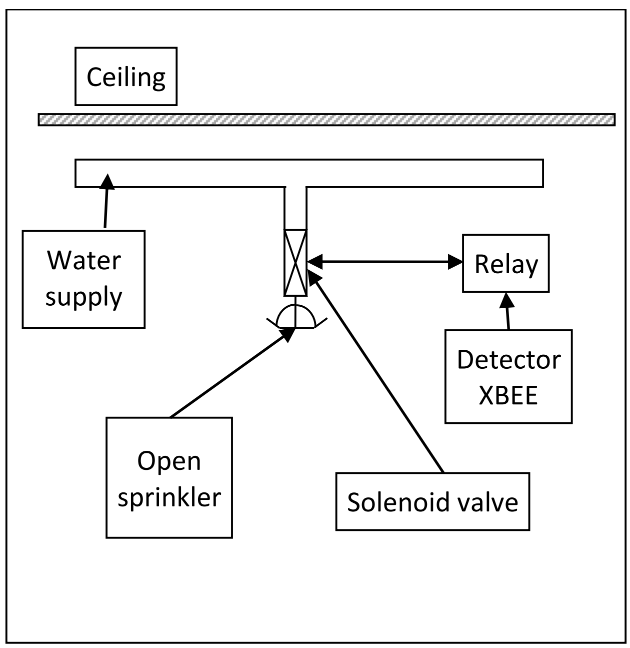

Figure 2-9: Solenoid valve and sprinkler connections.

Figure 2-10: Sprinkler layout under the ceiling: 16 SMART sprinklers (green circles with ID labels below) installed on a grid with 3.05 m x 3.05 m (10 ft x 10 ft) spacing.

Sixteen SMART sprinkler nodes were mounted on the ceiling. For each SMART sprinkler, the inlet of the solenoid valve was connected to the water supply pipe (Figure 2-9); and the open sprinklers were connected to the outlet of the solenoid valve. A metal disk [10 cm (4-in.) dia.] was installed above the sprinkler to block any potential upward water spray impinging on the electronic parts of the SMART sprinkler such as the XBEE. The solenoid valves were in normally-closed position to avoid potential water discharge in case of power interruption.

2.2 Test preparation and procedures

Prior to the first full-scale test, a series of steps was taken to prepare the SMART sprinkler system:

- **Assemble the SMART sprinklers.** Sixteen sprinkler units were assembled by mounting the smoke detector, XBEE transceiver, TC linear module and solid state relay on an electric insulation board. The connections and functions of these components were examined using the system control unit before installation on the LBL ceiling.
- **Install SMART sprinklers.** The SMART sprinkler units were installed under the south movable ceiling at locations shown in Figure 2-10. For each unit, Figures 2-8 and 2-9 were followed to connect the system components and to provide water and power.
- **Check smoke alarms and TCs connections.** Manual checks of alarms and TCs were conducted by pressing the alarm trigger buttons and presenting a heat source to the TCs. The responses were monitored through both the RCDAQ and the wireless control unit.
- **Examine sprinkler activation.** Sprinkler activation was tested multiple times using a wireless control unit. In each test, a random selected fire location was generated by the control unit to activate a group of six solenoid valves close to the fire location.
- **Calibrate water flow rate.** Prior to each test, six sprinklers were activated by the control unit to calibrate the total water flow rate. The position of the control valve as reported by the building control system was recorded for pre-setting the total water flow.
- **Perform system check.** Two pan fire tests were carried out to evaluate the system response before conducting the first full-scale test. In each fire test, a 0.3-m (12-in.) heptane pan fire was placed 6.1 m (20 ft) below the ceiling to trigger the system. Key system functions such as smoke alarm, temperature rise, sprinkler activation and water pressure and flow, were monitored in both the RCDAQ and wireless control unit.

When these steps were completed successfully, the fuel array was set up under the south movable ceiling based on the test conditions listed in Table 2-1. For each test, ambient data were collected for 5 min before ignition. Ignition started at the offset location as shown in Figure 2-4. SMART sprinkler performance was then observed with emphasis on smoke alarm, ceiling temperature rise, sprinkler activation and subsequent fire development. Each test was terminated 20 min after ignition as no further fire development was observed. The results of the three full-scale tests are discussed in the next chapter.

3. Results and discussions

3.1 Test 1 – 2x4, 3-tier CUP in rack storage

Test 1 started with ignition after 5 min of collecting ambient data. The fire grew to about 1.0 m (3.3 ft) tall in 35 s in the vicinity of the ignition location (offset from Sprinkler #25 - ID 0a54). The first smoke alarm was triggered at t = 36 s after ignition at Sprinkler #25 as recorded by the wireless data. The temperature rise above the ambient (ΔT) at Sprinkler #25 (denoted as TC25) is plotted in Figure 3-1 including both wired and wireless data. The temperature rise exceeded 5 K at t = 41 s after ignition. Six sprinklers were activated at 41 seconds as shown in Figure 3-2. Note that, in Figure 3-2, each square represents a sprinkler location denoted by its sprinkler ID, e.g., Node: 0a54 for Sprinkler # 25. The number in each square reports the instantaneous temperature in degree C, *e.g.*, 27.61 ^{o}C at Node: 0a54 (Sprinkler # 25). The dotted circle in Figure 3-2 indicates the calculated fire location. The blue-colored squares stand for the activated SMART sprinklers. From Figure 3-2, it is clear that the calculated fire location was sufficiently accurate. As a result, the activation of six sprinklers provided adequate coverage over the burning zone and adjacent region for pre-wetting the fuel. Similar accuracy of fire location calculation was also observed in the subsequent two tests.

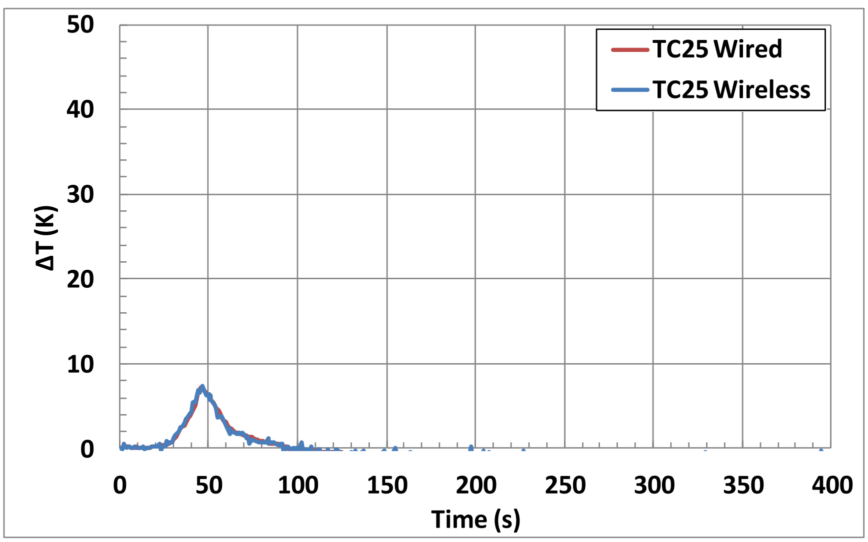

Figure 3-1: Temperature rise near ignition location (Sprinkler # 25) in Test 1.

Upon sprinkler activation, the flames were about 1.5 m (5 ft) tall with flame tips slightly above the bottom of the second tier. The estimated chemical HRR was 80 KW using the flame volume based method [5]. The fire was contained in the vicinity of the ignition location after water application and never propagated beyond the center of the first tier. Figure 3-3 shows different stages of the fire development during Test 1. Note in Figure 3-3, each panel is labeled with time after ignition. The fire test was terminated 20 minutes after ignition with no further fire development. Figure 3-4 shows the plan view of the damage area in the bottom tier based on visual inspection after the test. The fire burned through the commodities by approximately 0.53-0.64 m (21-25 in.) perpendicular to the central flue. As a result, the fire was shielded and thus was contained, but not extinguished.

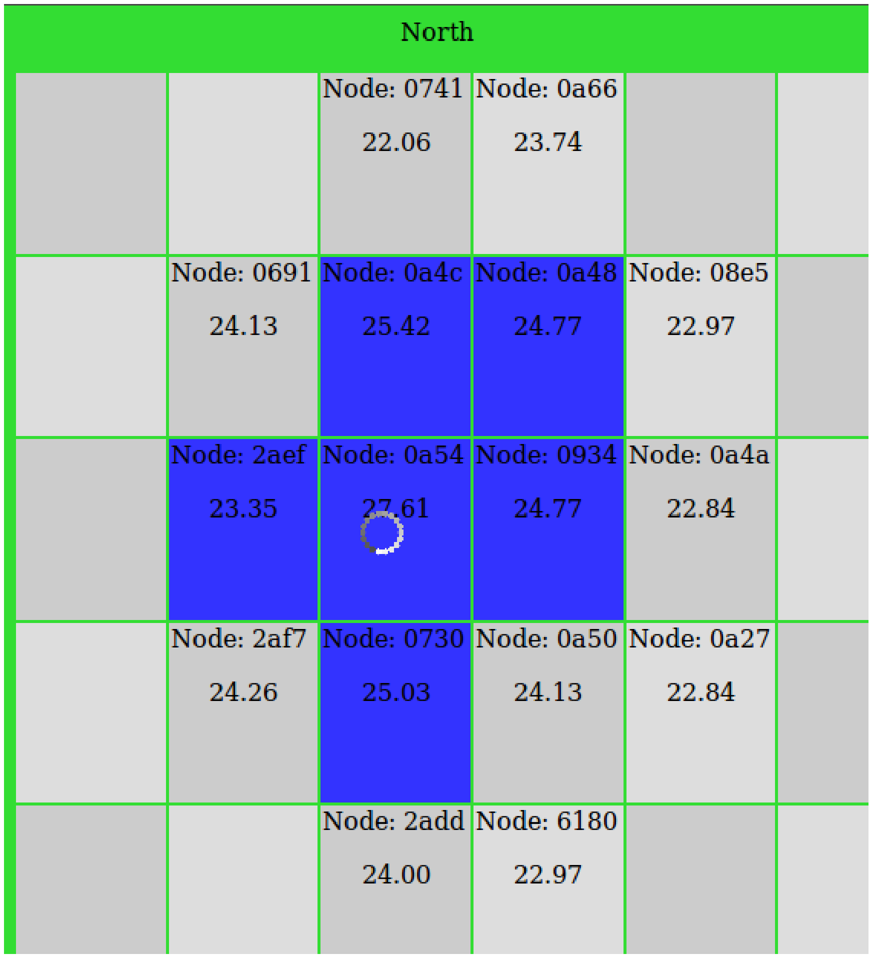

Figure 3-2: Sprinkler activation with under-1 ignition in Test 1.

Taking Figures 3-3 and 3-4 together, the target water density of 16.3 mm/min (0.4 gpm/ft^2) is adequate to achieve well-suppressed protection for this fire scenario. This can also be seen from comparison of current study and previous work using traditional sprinklers. Figure 3-5 shows HRRs measured under the movable ceiling in Test 1 of the present work and a previous test using traditional sprinklers. These two tests used the same setups except that in the previous test, the length of the fuel array was twice (eight pallet load) long and the protection was provided by quick response, traditional sprinklers [K160 L/mm/bar$^{1/2}$ (K11.2 gpm/psi$^{1/2}$)] with a design density of 24.4 mm/min (0.6 gpm/ft^2). It should be pointed out that the HRR measurements under the movable ceiling are not time resolved. Therefore, a more appropriate comparison of the two tests should be the total energy release for the same period of time. Integration of the HRR curves over 20 min after ignition shows that the total chemical energy release in the present work is 60 MJ, significantly less than that (6400 MJ) in the previous test using the traditional sprinkler.

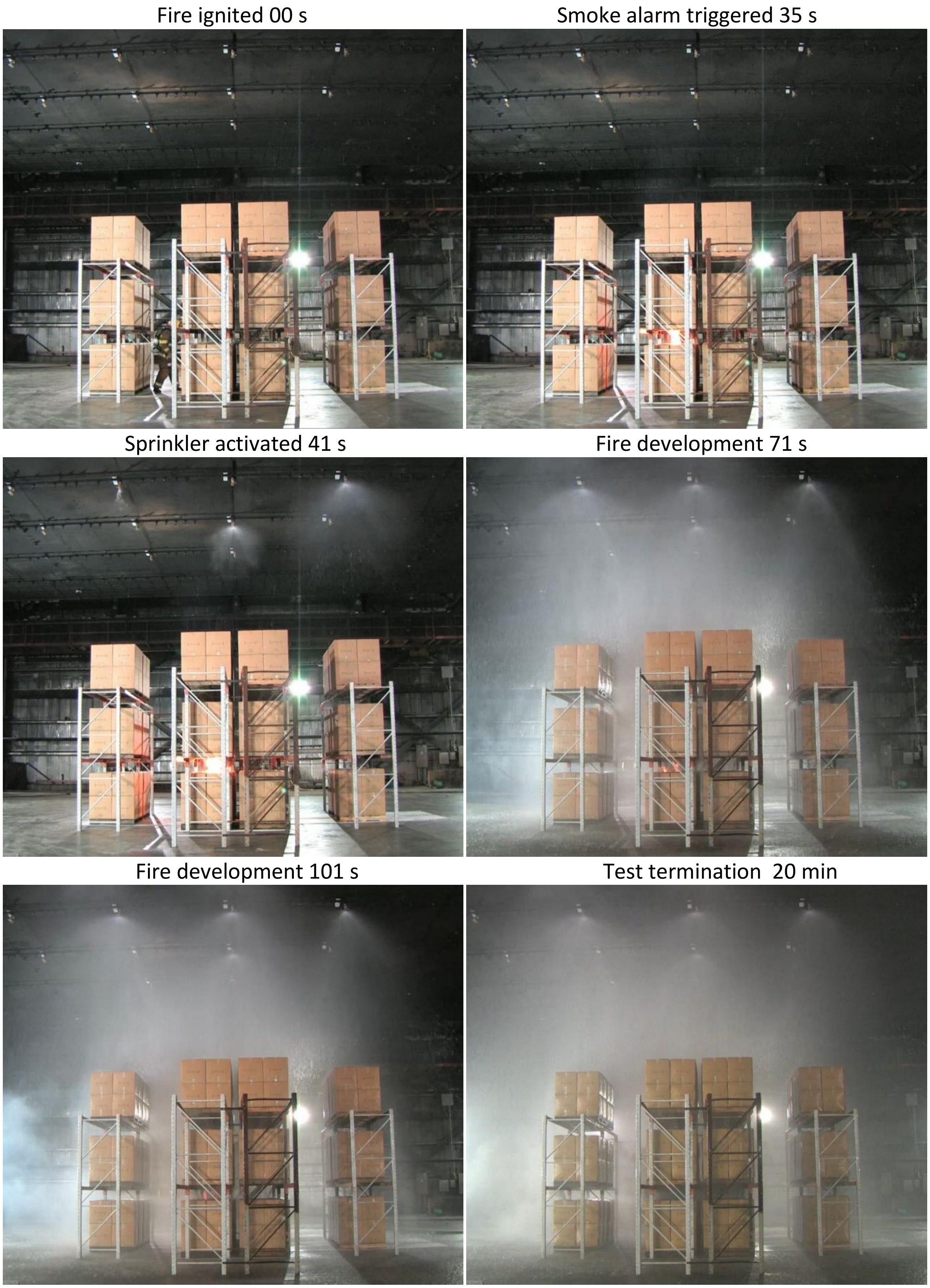

Figure 3-3: Fire development in Test 1 [K160, 16.3 mm/min (K11.2, 0.4 gpm/ft^2)].

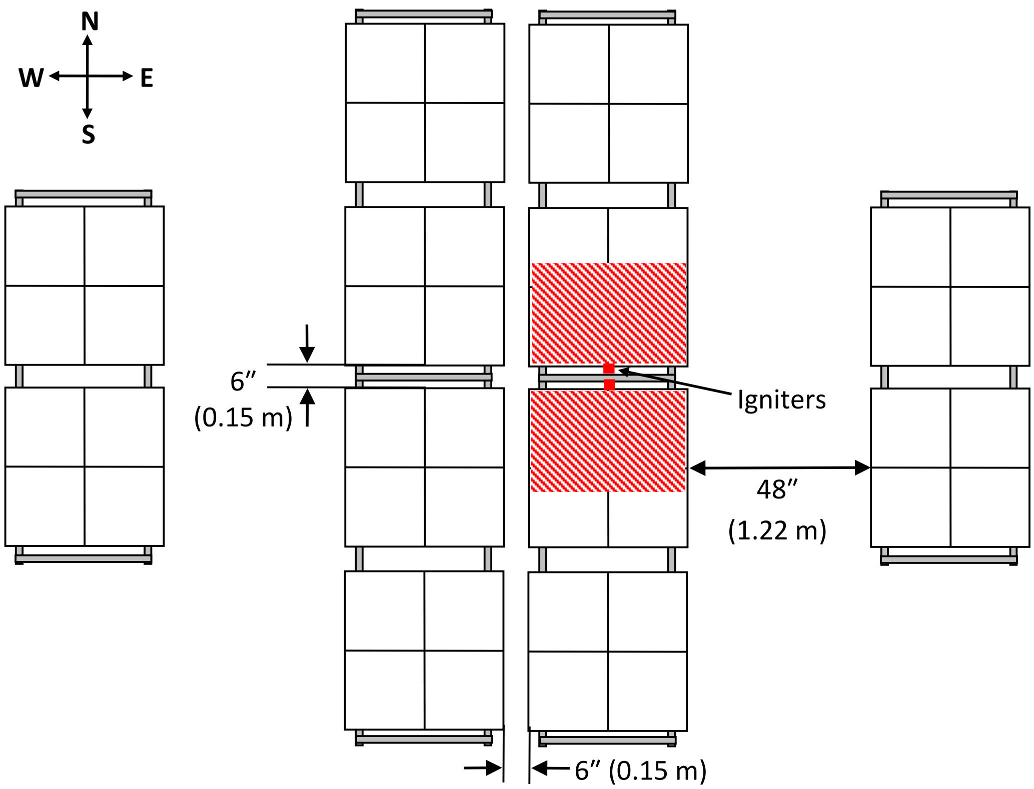

Figure 3-4: Plan view of fire damage (red hachures) limited to the bottom tier in Test 1.

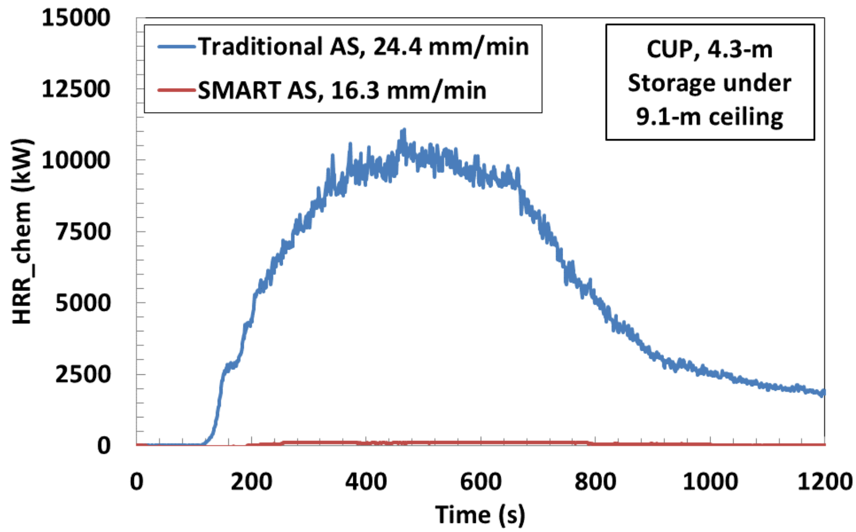

Figure 3-5: HRRs in 3-tier CUP rack storage tests using traditional and SMART sprinklers.

Note that the recommended target water density in FM Global Property Loss Prevention Data Sheet 8-9 [6] is 32.6 mm/min (0.8 gpm/ft^2), which is twice the value used in the present work for the SMART sprinklers. Similar differences were also observed in the next two tests, with target water densities at

54-56% of those recommended in FM Global Property Loss Prevention Data Sheet 8-9 [6]. The reduction of design water density is significant, especially considering situations where water resources are limited.

3.2 Test 2 – 2x4, 5-tier CUP in rack storage

Test 2 followed the same procedure as Test 1. After 5 min of collecting ambient data, the fire was ignited at the offset location close to Sprinkler #25 (see Figure 2-6). The fire grew to about 1 m (3.3 ft) tall in 23 s in the vicinity of the ignition location (offset from Sprinkler #25). The temperature rise at Sprinkler #25 is shown in Figure 3-6. The first smoke alarm was triggered at t = 23 s after ignition. Shortly after the smoke alarm, six sprinklers were activated at t = 34 s as the temperature rise at Sprinkler #25 exceeded 5 K. The sprinkler activation pattern is shown in Figure 3-7, with the blue-colored squares denoting open sprinklers and the dotted circle denoting the calculated fire location. It can be seen that the calculated fire location is sufficiently accurate for the six activated sprinklers to provide water coverage.

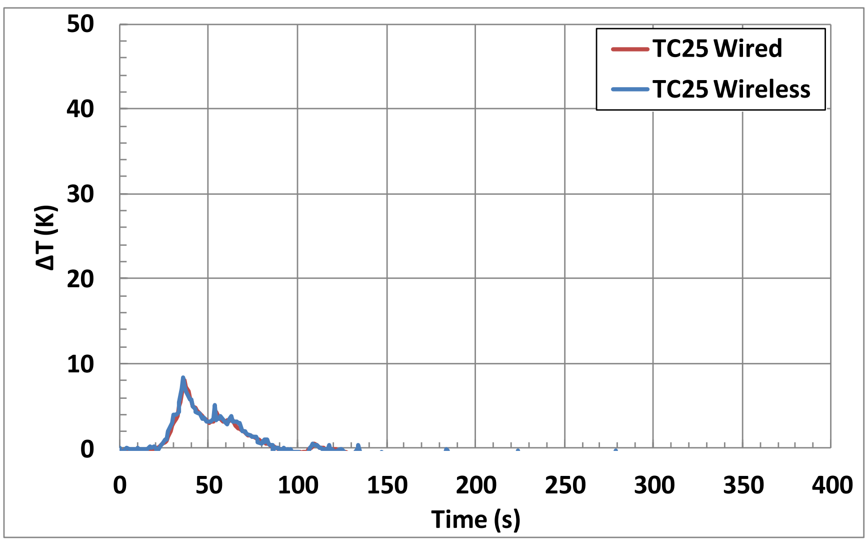

Figure 3-6: Temperature rise near ignition location (Sprinkler # 25) in Test 2.

Upon sprinkler activation, the flame tips were slightly above the second tier. The estimated chemical HRR was 230 KW using the flame volume based method [5]. The fire growth continued and peaked at approximately t = 45 s with flame tips flickering between the third and fourth tier. The estimated fire size at this time was 1.2 MW. Subsequently, the fire size started to decrease. By 30 seconds after sprinkler activation (t = 64 s after ignition), the fire was contained in the flue space above the ignition location in the bottom two tiers and never propagated beyond this region. Figure 3-8 shows different stages of the fire development during Test 2. The fire test was terminated 20 minutes after ignition with no further fire development. Figure 3-9 shows the plan view of the damage area in the bottom two tiers based on visual inspection after the test. The fire burned through the commodities by about 0.5 m (20 in.) in the direction perpendicular to the central flue. As a result, the fire was shielded and thus was suppressed, but not extinguished. The water density in this test [26.5 mm/min (0.65 gpm/ft^2)] is 54% of the value recommended in FM Global Property Loss Prevention Data Sheet 8-9 [6] [48.8 mm/min (1.2 gpm/ft^2)].

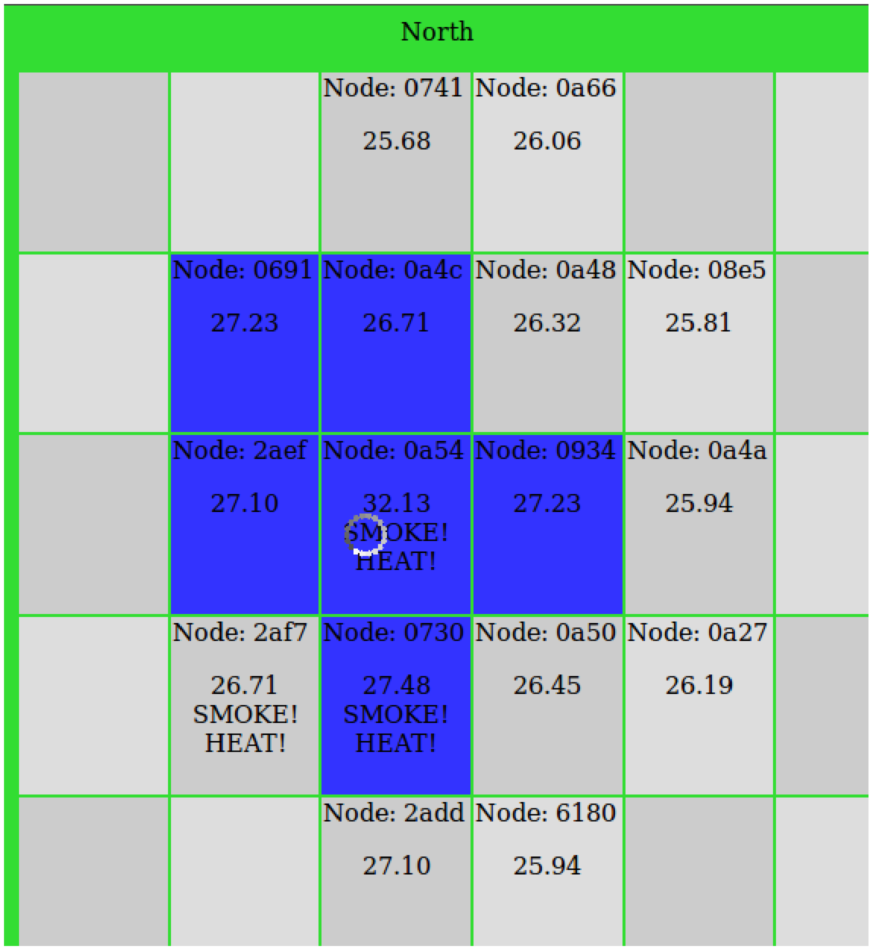

Figure 3-7: Sprinkler activation with under-1 ignition in Test 2.

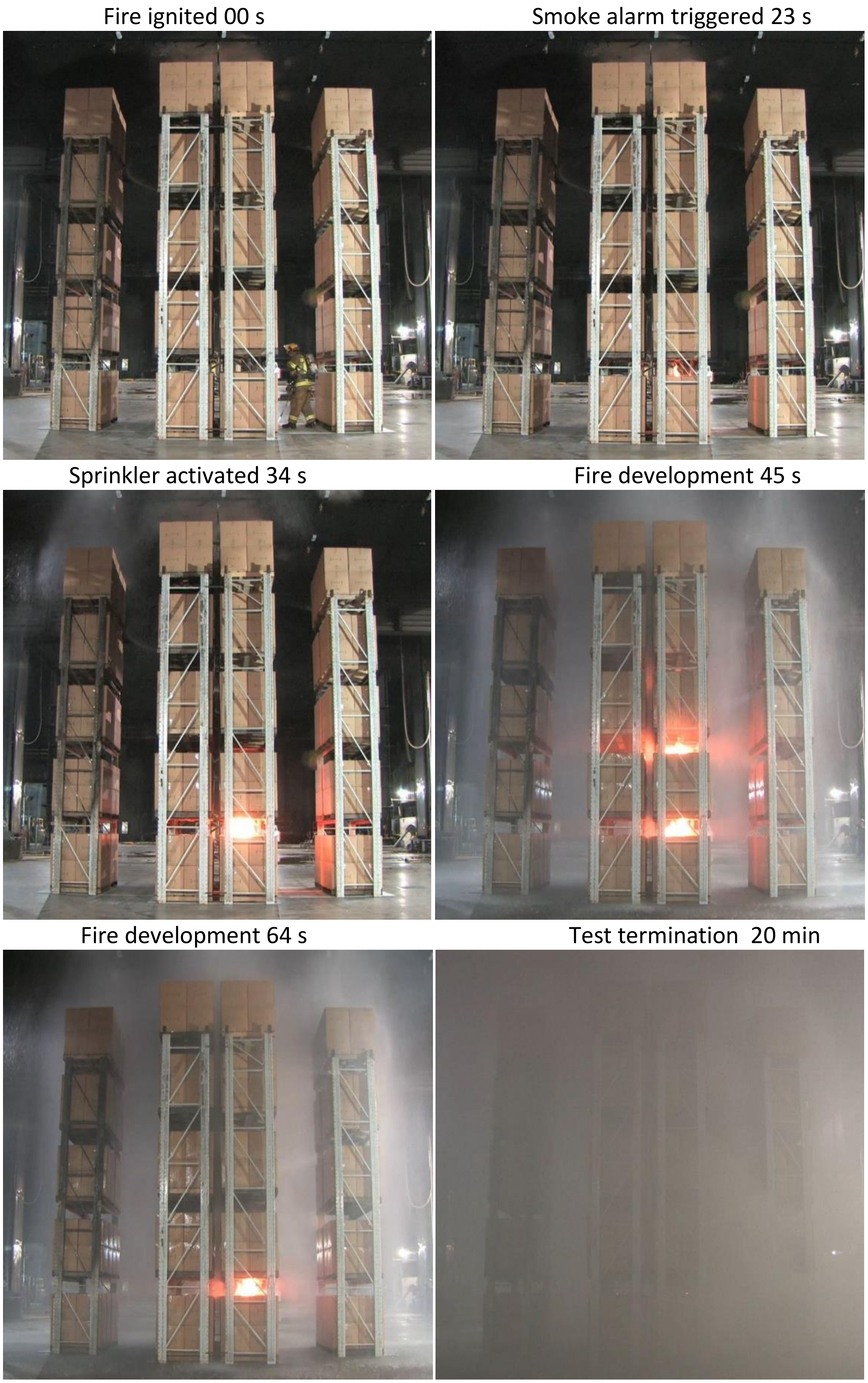

Figure 3-8: Fire development in Test 2 [K200, 26.5 mm/min (K14.0, 0.65 gpm/ft^2)].

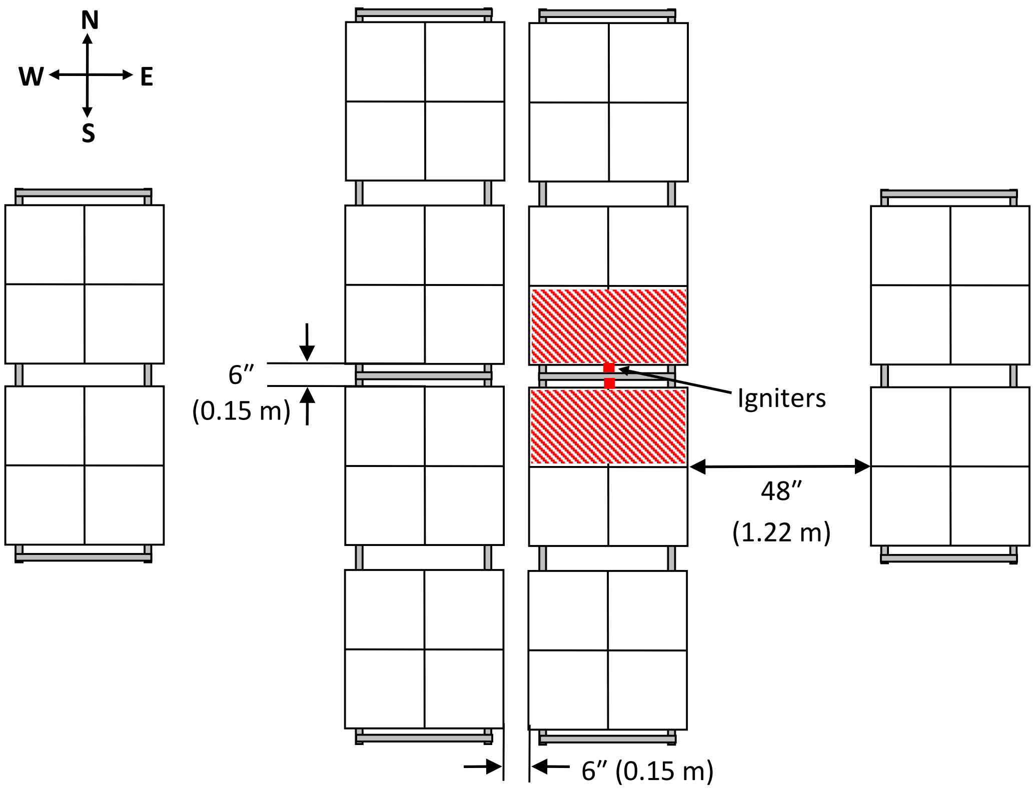

Figure 3-9: Plan view of fire damage (red hachures) limited to the 1st and 2nd tiers in Test 2.

3.3 Test 3 – 2x4, 7-tier CUP in rack storage

In Test 3, the fire was ignited at the offset location between Sprinkler #25 and #26 after 5 min of collecting ambient data. The fire grew to about 2.1 m (7 ft) tall in 32 s directly above the ignition location. The temperature rise at Sprinkler #25 is shown in Figure 3-10. The first smoke alarm was triggered 32 seconds after ignition. Shortly after the smoke alarm, six sprinklers were activated 38 seconds after ignition as shown in Figure 3-11. It can be seen that the calculated fire location is accurate for the six activated sprinklers to provide sufficient coverage.

Upon sprinkler activation, the flame tips were slightly above the third tier [4.9 m (16 ft)]. The estimated chemical HRR was 0.5 MW using the flame volume based method [5]. The fire continued its growth and peaked at approximately 45 s after ignition with flame tips slightly above the bottom of the sixth tier. The estimated fire size at this time was 0.8 MW. The peak ceiling temperature rise also indicated a value of 21 K, about three times the value in Test 1. Subsequently, the fire size started to decrease. By 30 seconds after sprinkler activation (68 s after ignition), the fire was contained in the flue space above the ignition location in the bottom two tiers and never propagated beyond this region. Figure 3-12 shows different stages of the fire development during Test 3. The fire test was terminated 20 minutes after ignition with no further fire development.

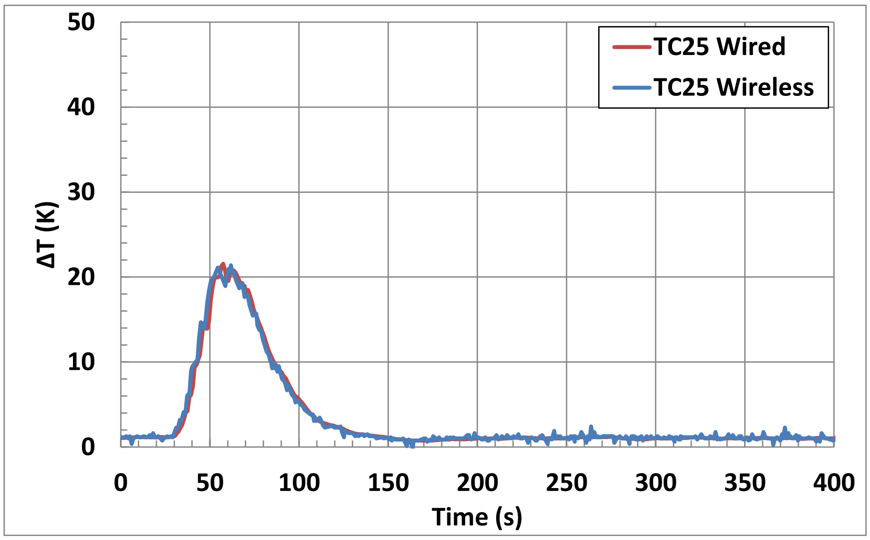

Figure 3-10: Temperature rise near ignition location (Sprinkler #25) in Test 3.

Visual examination after the test showed that the fire damage occurred mainly on the bottom three tiers. As shown in Figure 3-13, each pallet load adjacent to the ignition had about 50% of the pallet load burned out at the bottom tier. The damage fraction reduced to approximately 25% on each side of the ignition flue on the second tier. As for the commodities on the third tier, the carton surfaces adjacent to the ignition flue were cracked open, with very little damage in terms of fuel consumption. The fuel surfaces next to the ignition flue on the fourth tier were also charred on the surface, but the cartons were intact.

Figure 3-14 shows the comparison of the current study using the SMART sprinkler and previous work using a traditional sprinkler. The two plots are HRRs measured under the movable ceiling in Test 3 of the present work and those in previous work. These two tests used the same setups except that, in the previous work, the length of the fuel array was twice (eight pallet load) as long and the protection was provided by quick response, traditional sprinklers [K360 L/mm/bar$^{1/2}$ (K25.2 gpm/psi$^{1/2}$)] with a design density of 65.2 mm/min (1.6 gpm/ft^2). It should be pointed out that the water density in the current work [36.6 mm/min (0.9 gpm/ft^2)] is 56% of the value recommended in FM Global Property Loss Prevention Data Sheet 8-9 [6] [65.2 mm/min (1.6 gpm/ft^2)].

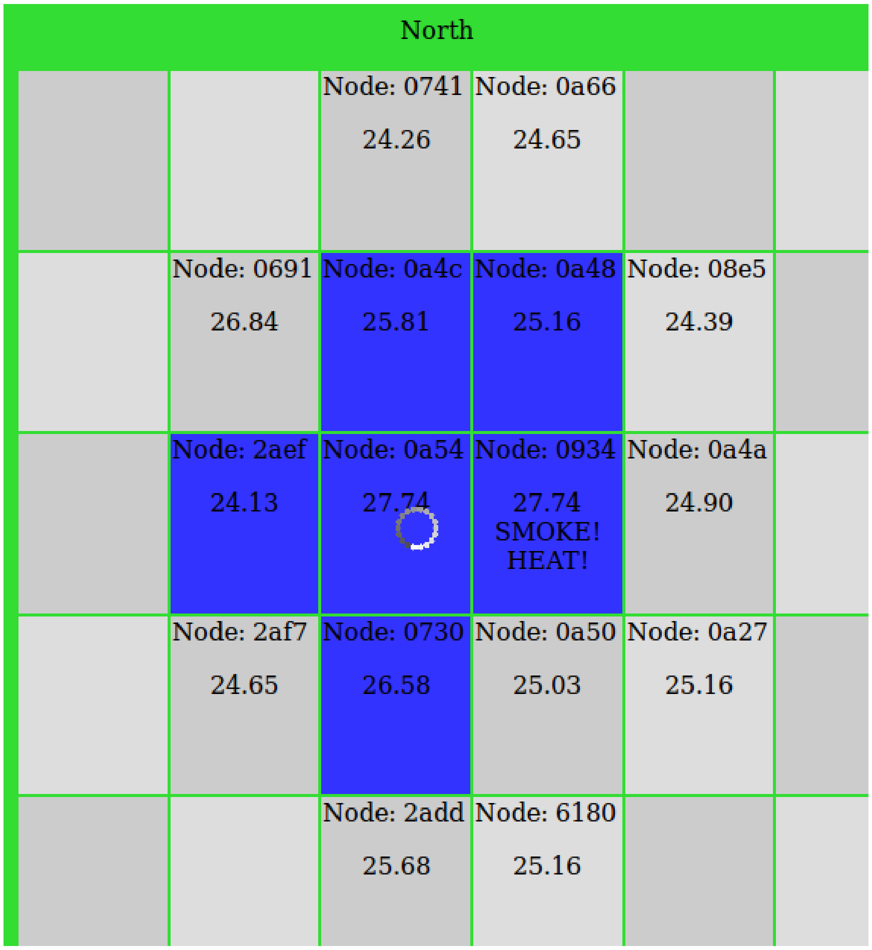

Figure 3-11: Sprinkler activation with between-2 ignition in Test 3.

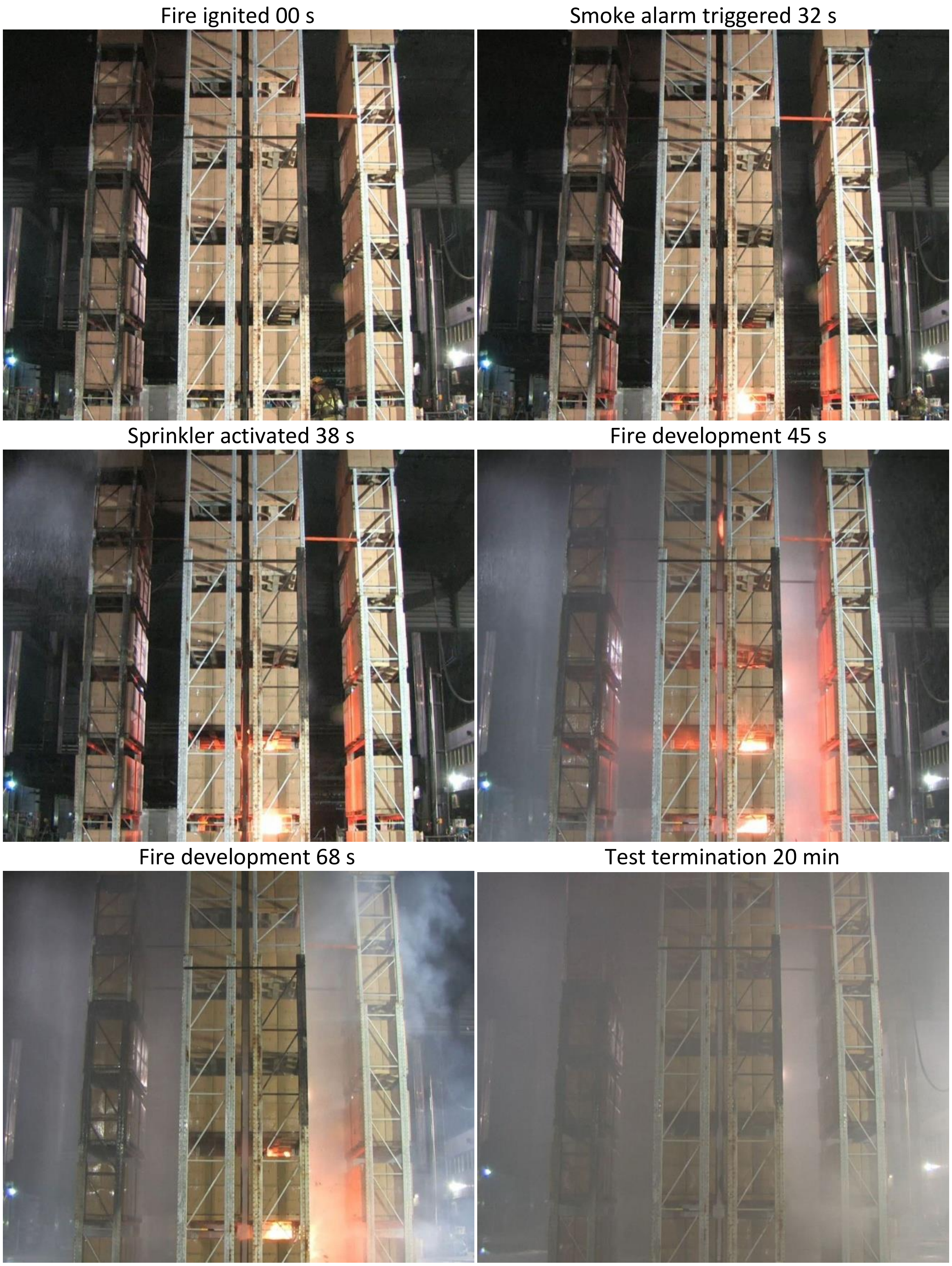

Figure 3-12: Fire development in Test 3 [K360, 36.6 mm/min (K25.2, 0.9 gpm/ft^2)].

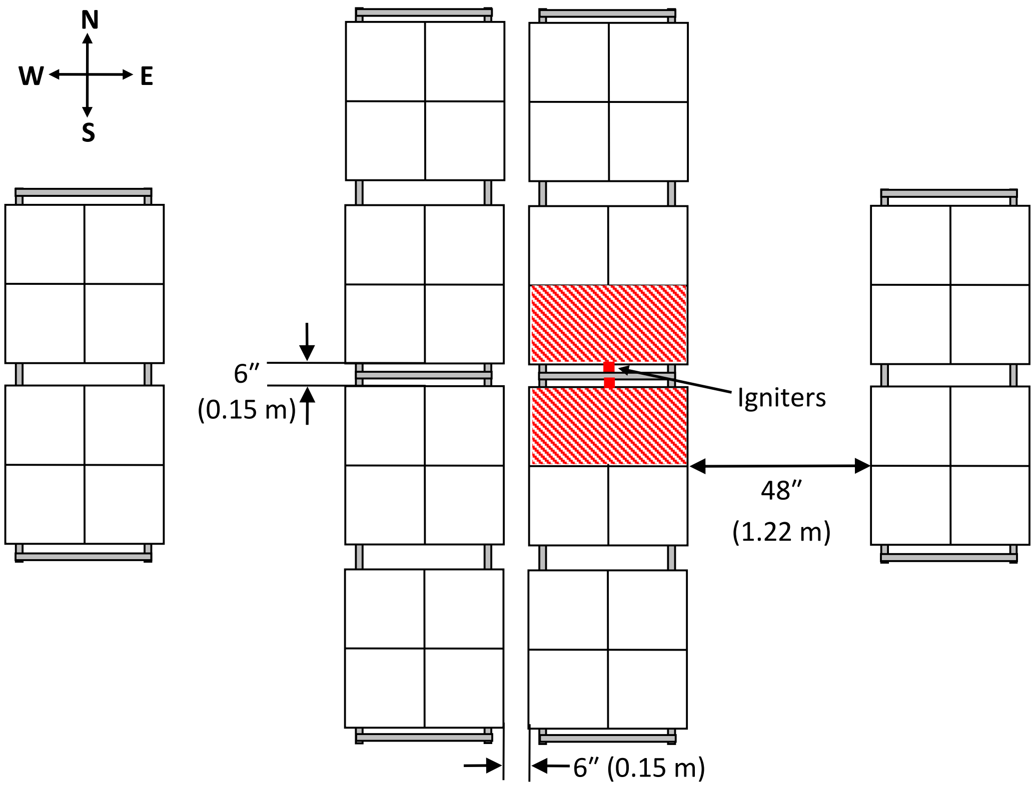

Figure 3-13: Plan view of fire damage (red hachures) at the bottom tier in Test 3.

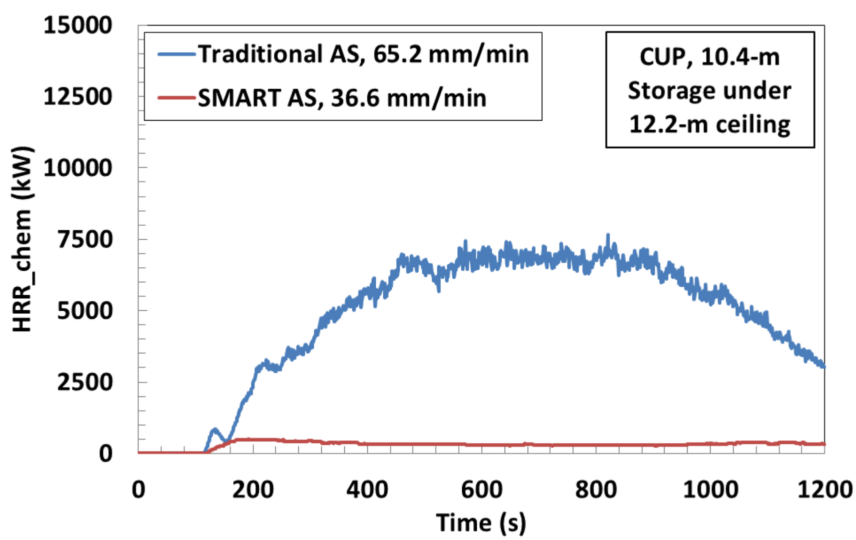

Figure 3-14: HRRs in 7-tier CUP rack storage tests using traditional and SMART sprinklers.

4. Conclusions and future work

Three full-scale tests were conducted to evaluate the performance of the SMART sprinkler technology in protecting rack storage configurations. The selected fuel was CUP commodity, representing an intermediate level of fire hazard. The storage height increased from 3 to 5 to 7 tiers in the three tests. The sprinkler activation was initiated on triggering of a smoke alarm and a ceiling temperature rise of 5 K. This temperature-rise condition was tested in this work in a well-controlled laboratory environment, and was reached in less than one minute after ignition. Therefore, a time period associated with the temperature rise should be specified for SMART sprinklers in engineering practice to avoid false activation due to ambient temperature variation. Following detection, the fire location was calculated as the thermal centroid based on ceiling temperature, and a group of six SMART sprinklers, closest to the calculated fire location, was activated simultaneously. Subsequent fire development was monitored through visual observation as well as ceiling temperature data.

Overall, the test results show that the SMART sprinklers can provide sufficient protection for the CUP commodities in a rack storage configuration under the tested conditions. Specifically,

- All fires were suppressed shortly after sprinkler activation. The fire suppression was observed visually as fire size decreased significantly compared to that upon sprinkler activation. The ceiling temperature data also indicated that the temperature rise never exceeded 22 K.
- Fire damage was limited to the ignition location and adjacent area directly above ignition. Lateral fire spread never exceeded one-pallet load to either side of ignition.
- Fire sizes were small at sprinkler activation. In all three tests, the estimated HRRs were in the range 80-500 kW for 3- to 7-tier rack storage.
- The estimated fire locations were sufficiently accurate. As shown in the sprinkler activation pattern of each test, the fire sprinklers centered on TC25 always opened upon fire detection. One additional sprinkler adjacent to these five sprinklers contributed to an enlarged coverage area.
- The target water densities were significantly lower than those recommended in current FM Global Property Loss Prevention Data Sheet 8-9, *Storage of Class 1, 2, 3, 4 and Plastic Commodities* [6]. On average, the water densities applied in the three tests were 50-56% of those recommended in Ref. [6]. It should be noted that the SMART sprinkler design densities used in this work were actually selected conservatively so that the ceiling temperature remained within the limits of the electronic components [~40 ^{o}C (104 ^{o}F)].

From these results, the performance of the SMART sprinkler system can be deemed satisfactory in protecting up to 7-tier rack storage of CUP commodities. This result lays the foundation for evaluating the system against more challenging fires.

References

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2. Y. Xin, K. Burchesky, J. de Vries, H. Magistrale, X. Zhou, and S. D'Aniello, "Smart Sprinkler Protection for Highly Challenging Fires - Phase 1: System Design and Function Evaluation," FM Global Technical Report, February 2016.

3. FM Approvals LLC., "Approval Standard for Automatic Control Mode Sprinklers for Fire Protection, Class Number 2000," Norwood, MA 02062, USA, March 2006.

4. Y. Xin and F. Tamanini, "Assessment of Commodity Classification for Sprinkler Protection Using Representative Fuels," *Fire Safety Science* , vol. 9, pp. 527-538, 2008.

5. Y. Xin, "Estimation of Chemical Heat Release Rate in Rack Storage Fires Based on Flame Volume," *Fire Safety Journal*, vol. 63, pp. 29-36, 2014.

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Appendix A. Full-scale test data

In the following sections, experimental results are listed for each full-scale test including the normalized thermal centroid deviation (Distance/spacing), the water pressure and flow rate, the smoke alarm response time (t_act) and corresponding temperature rise (ΔT_act) and temperature rise (ΔT) above the ambient value at various sprinkler locations. Note that the normalized thermal centroid deviation was defined in previous work [2] as the ratio of the distance from the thermal centroid location to the ignition location and the sprinkler spacing. It should also be pointed out that not all smoke alarms were triggered in the tests; thus only those triggered are documented herein.

A.1 Test 1

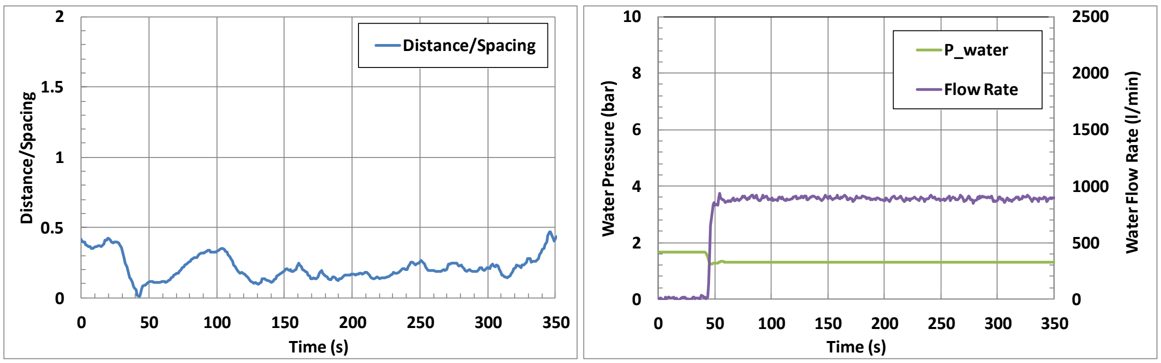

Figure A-1: Calculated thermal centroids and water discharge rate in Test 1.

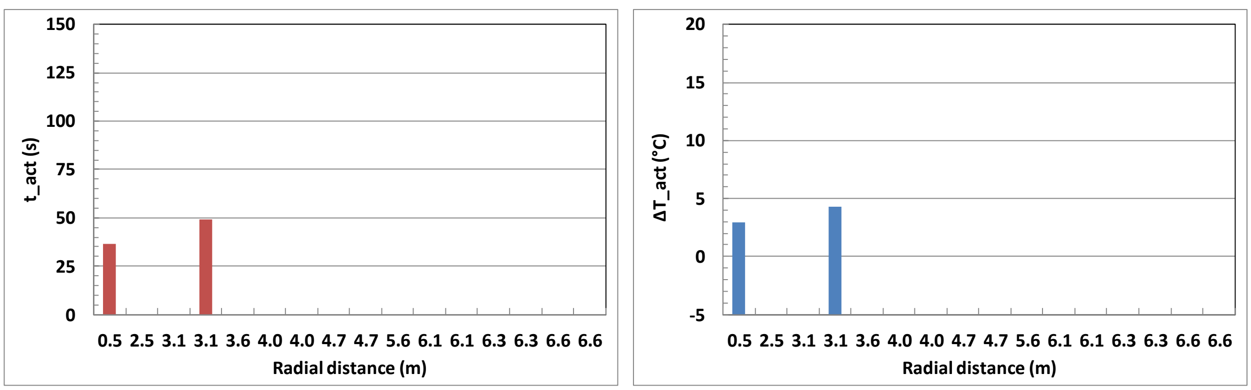

Figure A-2: Smoke alarm activation times and temperature rise in Test 1.

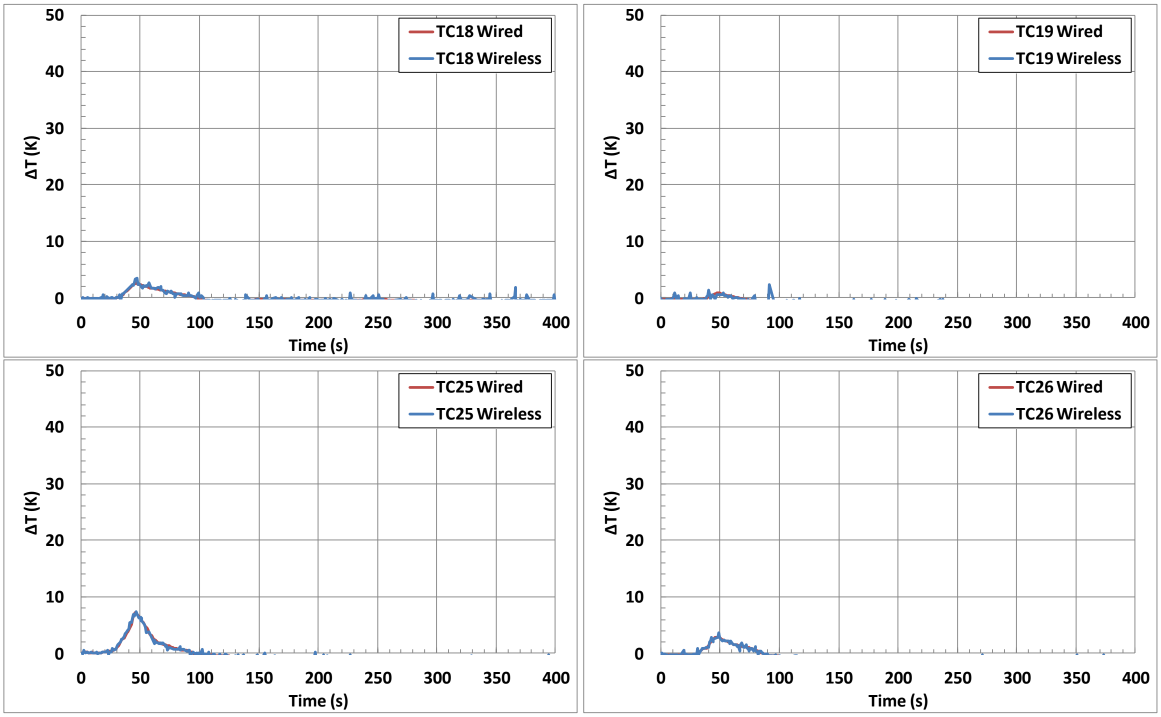

Figure A-3: Temperature rise near ignition location in Test 1.

A.2 Test 2

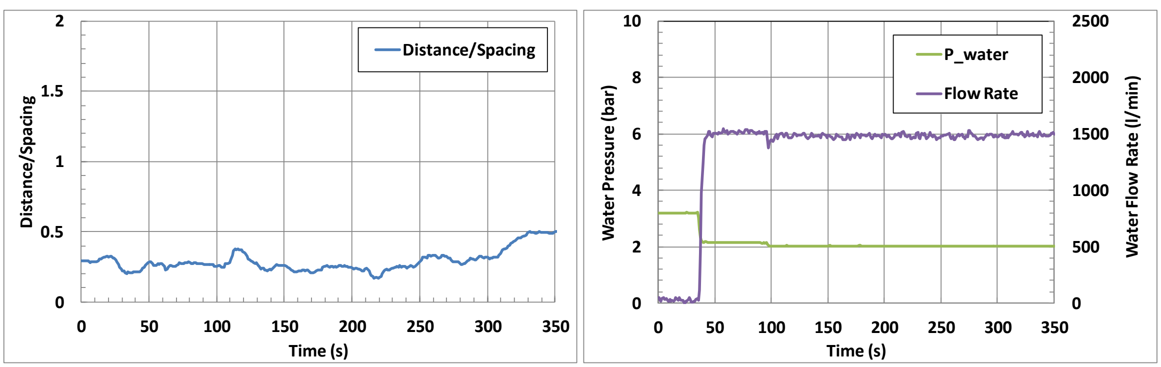

Figure A-4: Calculated thermal centroids and water discharge rate in Test 2.

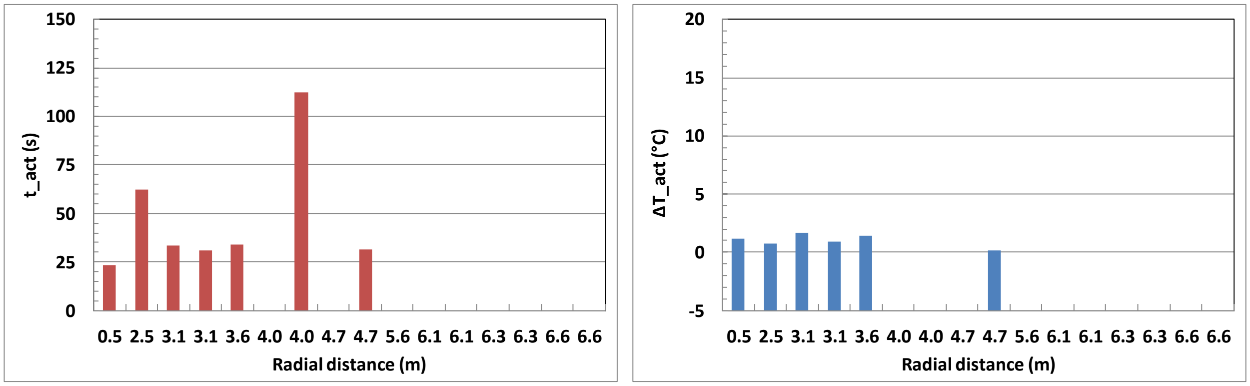

Figure A-5: Smoke alarm activation times and temperature rise in Test 2.

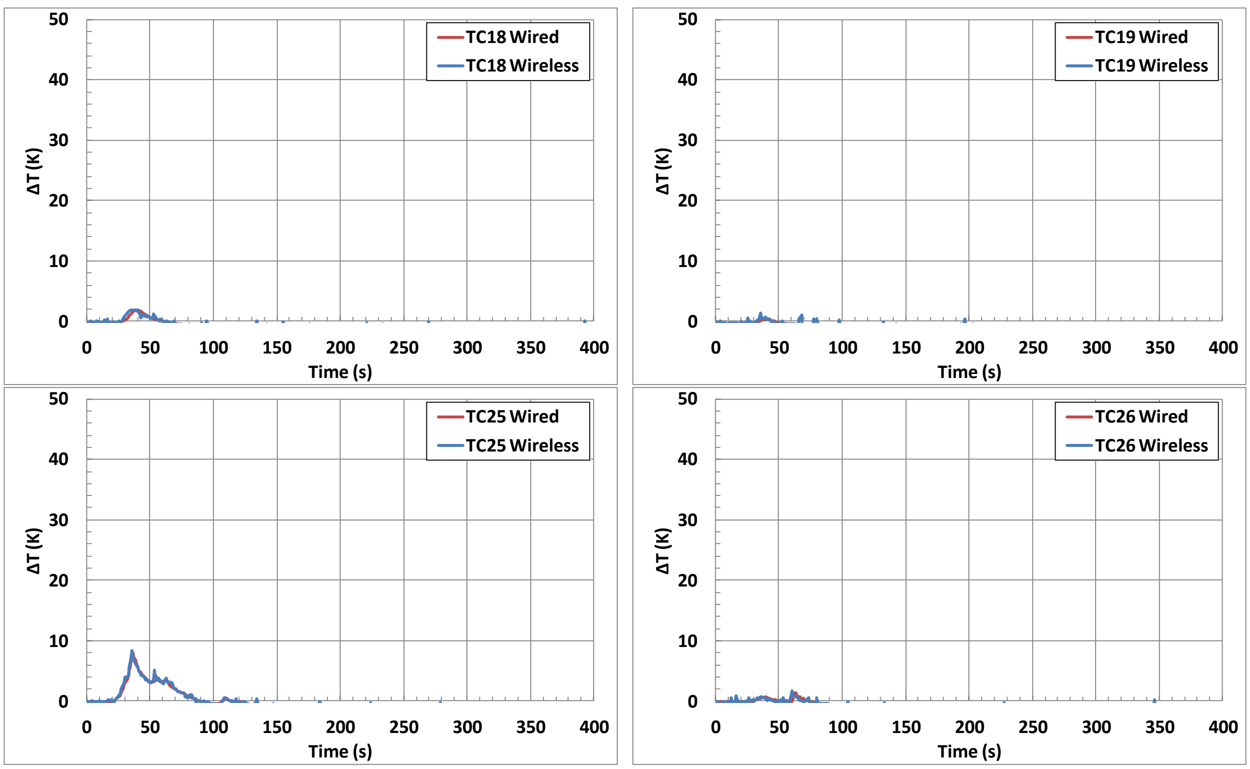

Figure A-6: Temperature rise near ignition location in Test 2.

A.3 Test 3

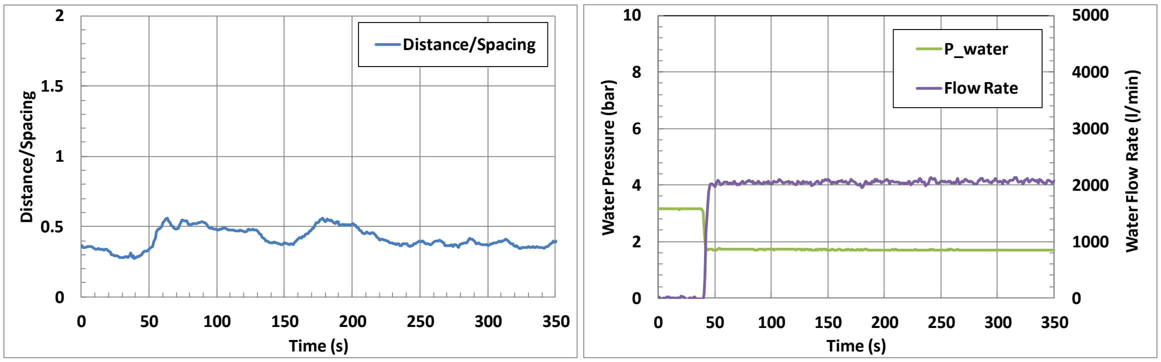

Figure A-7: Calculated thermal centroids and water discharge rate in Test 3.

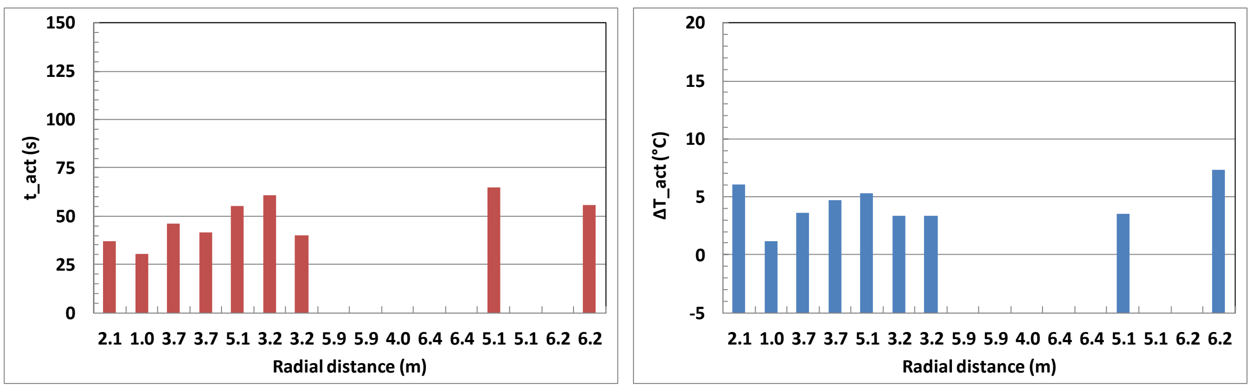

Figure A-8: Smoke alarm activation times and temperature rise in Test 3.

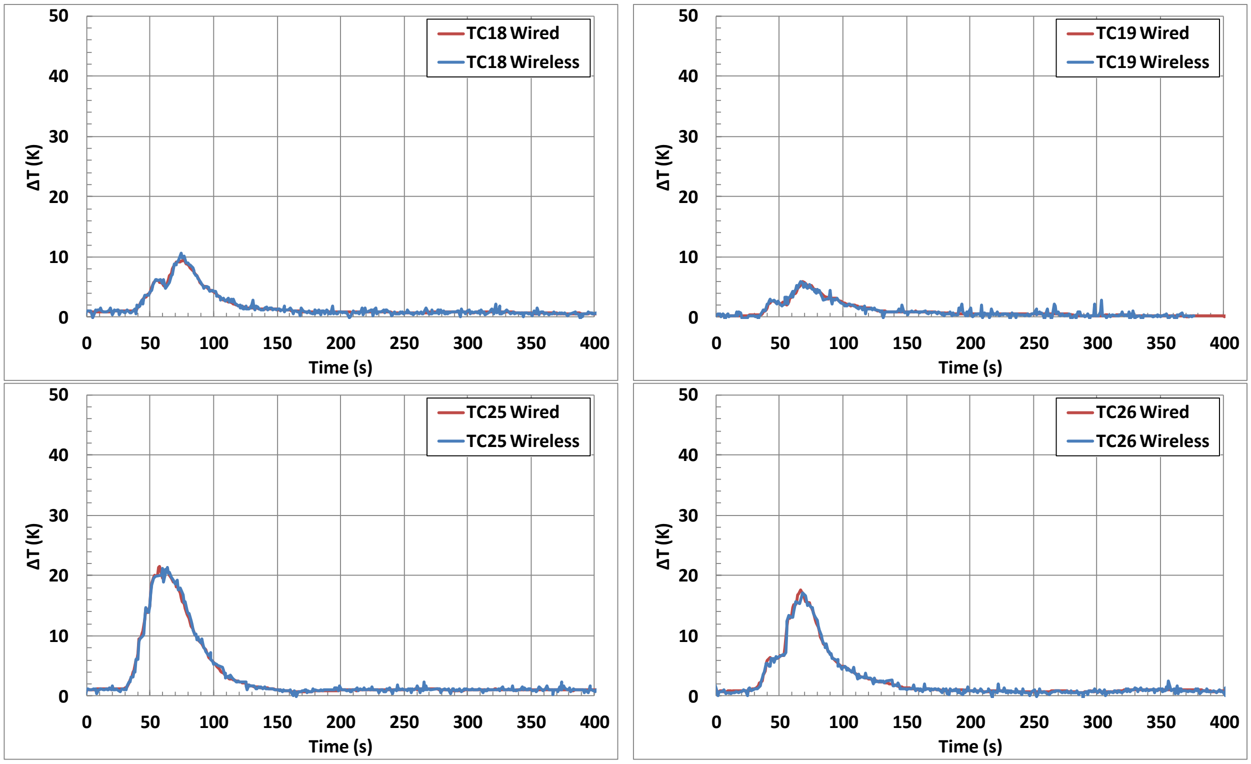

Figure A-9: Temperature rise near ignition location in Test 3.

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