AN EXPERIMENTAL STUDY OF SMART SPRINKLER PROTECTION OF HIGH RACK STORAGE WITH REDUCED WATER DEMAND

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ABSTRACT

A full-scale fire test was conducted in this work to understand how a SMART sprinkler system can provide improvements in terms of lower water demand to current fire protection guidance for standard commodities. The test was conducted using the cartoned unexpanded plastic (CUP) commodity in 12.2m storage under a 13.7m ceiling, aiming at water demand reduction compared to the current recommendations for traditional ceiling-only sprinkler protection. Using linear heat detectors (LHDs) within the rack assembly and six simultaneous sprinkler operations, the water demand was reduced by 77% while successfully controlling the fire. The results of this work demonstrated the potential of reducing water demand using the SMART sprinkler in conjunction with in-rack detection. Future testing and simulations at higher ceiling heights will explore enhanced protection to counteract the effects of increased storage and ceiling height.

INTRODUCTION

Commercial facilities and warehouses are increasingly using high rack arrangements to store supplies and finished products. Protection of these commodities becomes important to minimize business losses and disruptions. Current fire protection guidance[1] for rack storage arrangements usually relies on automatic sprinkler systems. Depending on the configuration, systems consisting of ceiling-only and/or in-rack sprinkler systems are recommended to adequately protect the facility. The ceiling-only option is often preferred to avoid installations of in-rack systems to minimize complexity, high cost and water damage due to accidental activations. Current maximum protectable ceiling height is limited to 13.7m, for cartoned unexpanded plastic (CUP). At this ceiling height, protection guidance states[1] the water demand should be a minimum of 72.5mm/min with 12 sprinkler operations, or 8100 LPM. Such high water demand can be a real challenge for regions with limited water resources, therefore, limits the storage configurations that can be protected.

The goal for this study was to investigate the use of SMART (Simultaneous Monitoring Assessment Response Technology[2]) sprinklers to provide adequate protection of a rack storage arrangement with reduced water demand for ceiling heights of 13.7m and above. To achieve this, a SMART system was simulated by providing simultaneous sprinkler operations controlled by a separate detection method for early activation. Benefits of such a system include elimination of sprinkler skipping, reduced fire size at activation, and improved fire location accuracy, all of which can result in reduced water demand over a traditional system. Simulation of a SMART system provided a means for evaluating protection options without relying on a manufacturer specific system. To simulate a fire detection and sprinkler activation mechanism, in this work, a linear heat detector (LHD) was placed half way up the storage arrangement, providing both an activation signal and fire location. Sprinkler activation was performed manually upon detection by providing water supply to a prescribed number of open sprinklers. The number of prescribed sprinklers simulates the minimum requirement of the protection design, this number may ultimately be increased in engineering applications to include a safety factor.

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The water densities used for testing were estimated based on previous SMART testing at lower storage and ceiling heights[3]. The results of this work aim to provide (1) protection for large storage facilities with low water supply; and (2) insight and motivation to develop SMART sprinkler systems for expanded detection options such as in-rack sensors.

BACKGROUND

The present work aims at utilizing a SMART sprinkler system to define ceiling-only protection performance to reduce the water demand for rack storage of standard commodities. As the first step, CUP (Cartoned Unexpanded Plastic) was selected. Other standard commodities can be evaluated in similar methods subsequently. CUP commodity is widely used in warehouses and the ability to reduce the water demand for ceiling only protection can be of great benefit. The current recommendations for maximum height, 13.7m, ceiling-only level protection of these commodities is 72.6 mm/min, as per widely used industry standard[1]. Two sprinkler options are available at the max ceiling height based on tests using the K360 sprinkler.

SMART sprinkler systems can provide multiple advantages over conventional sprinkler systems. A SMART system can provide individual control of sprinkler activation, thus providing the ability for simultaneous activations. This control eliminates possible sprinkler skipping, which occurs when water discharging from a sprinkler cools the surrounding sprinklers delaying or preventing them from activating. This phenomenon often results in excessive sprinkler operations as sprinklers farther from ignition location provide little or no effective water to control the fire.

A SMART system can place detectors separately from the sprinklers at the ceiling, thus providing additional benefit for tall rack storage configurations. When placed lower in the racks, not just at the ceiling-level, the detectors can more accurately determine the fire location and provide earlier activation. Meanwhile, in-rack detection can also help avoid ventilation impact on ceiling detection. Each of which, could help the system deliver water to the correct location early, minimizing fire growth. Placement of detectors within the rack is significantly simpler than routing water pipes for in-rack sprinklers. Providing protection guidance, without the need for in-racks, at a reduced water demand can be beneficial. When compared to installation of in-rack sprinklers, portability of storage is improved and the likelihood of water damage resulting from accidental sprinkler activation is reduced.

Previous testing of CUP

FM Global conducted numerous fire tests to investigate sprinkler protection of CUP commodities in the past, which formed the basis of Ref. 1. By reviewing the relevant tests, a "between-2" test configuration, i.e., the ignition location selected between two sprinklers in the plan view, was determined to be the worst-case scenario. This scenario showed a larger amount of damage when compared to an "under-1" configuration. Thus the "between-2" configuration with an offset ignition will be used for the testing presented here.

Previous SMART sprinkler testing

Earlier SMART sprinkler system testing on CUP commodity was performed using a 4 x 2 main test array at 3 different tier levels (3, 5 and 7)[3]. The SMART system utilized two detection methods for triggering sprinkler activation: smoke detectors and thermocouples. When smoke was detected, and ceiling temperatures increased by more than 5°C, sprinklers were activated. This metric for temperature rise resulted in activations within a minute of ignition.

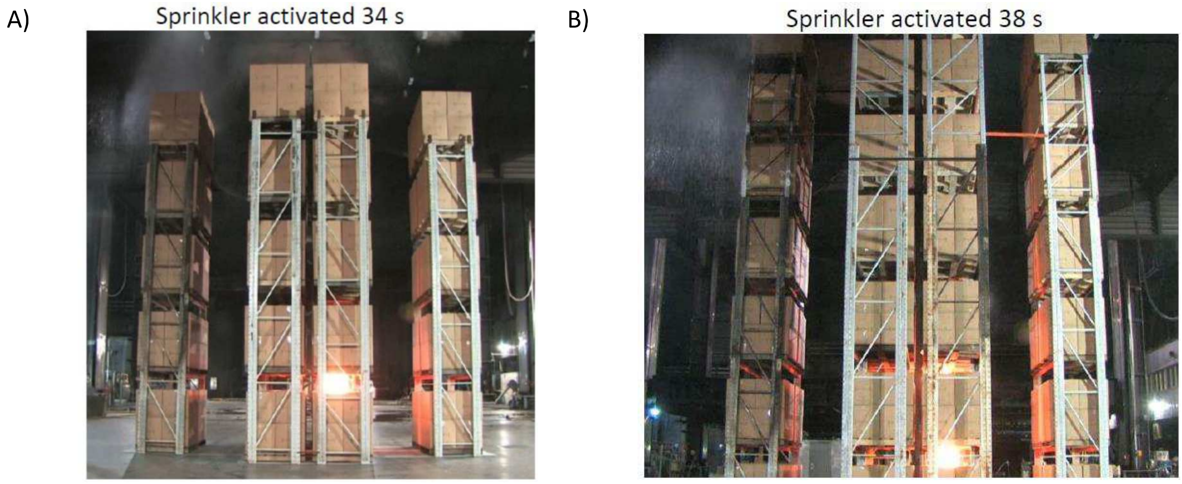

Figure 1: Fire spread at sprinkler activation for previous SMART sprinkler tests[3]; a) fire is below 3rd tier for 5-tier configuration; b) fire is below 4th tier for 7-tier configuration.

Figure 1 shows the state of the fire at sprinkler activation for the previous 5- and 7-tier SMART sprinkler tests [3]. The activation was early enough that fire did not progress to the ceiling by the time the sprinklers activated. The early activation contributed to low water usage at 26.5 and 36.7 mm/min for the 5- and 7-tier tests, respectively[3]. The successful water densities were similar to the critical delivered flux values measured by WAA (Water Application Apparatus) testing[4] as seen in Figure 2. Although the ceiling level protection of the SMART sprinkler testing may still be optimized, the successful control in these tests provides a good starting point for further expansion of the SMART system methodology. The ceiling level water flux values for the 5- and 7-tier SMART sprinkler protection were used to estimate water flux values in this work. Note that, in this work additional detectors half way up the rack will be used to provide early activation and thus the initial flux 32.6 mm/min, labeled as Test 1, will be lower than that of the estimated 8-tier value in Figure 2. The lower value allows for increased damage to the array when compared to the limited damage found in the previous SMART sprinkler testing. Additional details related to detection scheme will follow in the testing configuration section.

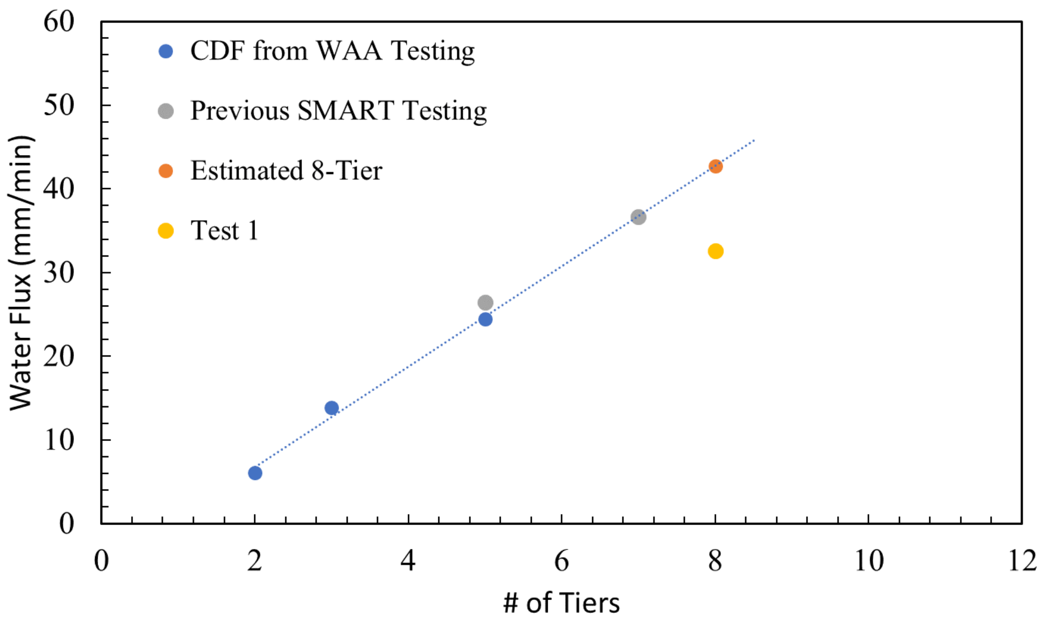

Figure 2: Water density values determined from WAA testing and the previous SMART testing for various tier heights.

EXPERIMENTAL CONFIGURATION

The test configuration for all testing performed was a "between-2" configuration with an offset ignition location. The plan view of the setup is shown in Figure 3a, the array is centered between the two sprinklers with ignition offset to the east. The setup consisted of an 8-tier storage configuration at 12.2m, the elevation view is shown in Figure 3b. The ceiling height was 13.7m, resulting in a ceiling clearance of 1.5m. CUP commodity was used for the entire test setup. The ignition of the commodity was performed using two ignitors. The ignitors were placed on the floor on either side of the rack support between the rack support and the pallets.

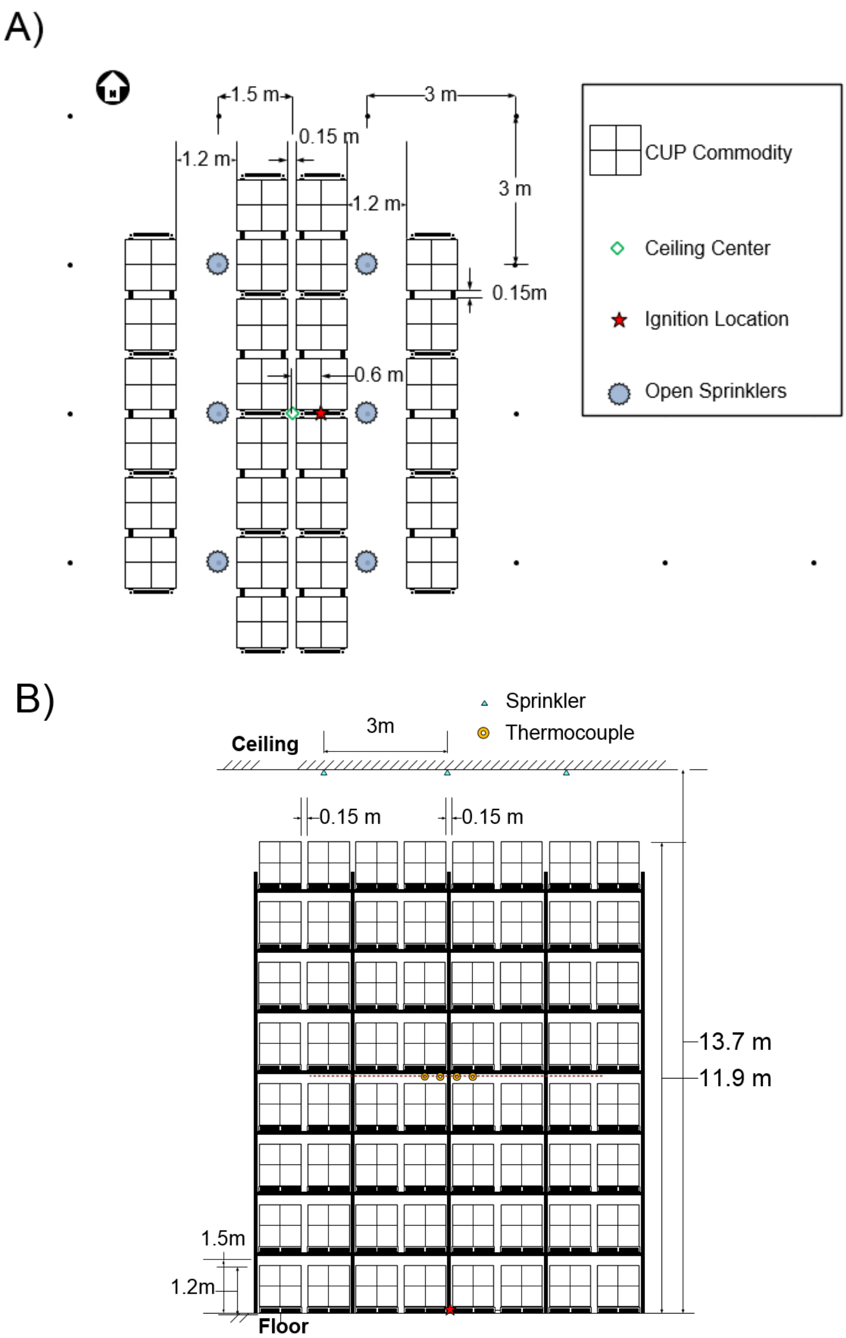

Figure 3: a) Plan view of proposed test setup, utilizing a "between 2" configuration. b) Elevation view of main array used for Test 1: 8 tiers of CUP storage under a 13.7m ceiling.

In-rack detection for activation

To understand the performance and timing advantage of detectors placed within the racks of the commodity, LHDs were installed in a traditional sprinkler test. In this test, LHDs were installed above each of the first 5 tiers of CUP commodity, attached along the rails going north and south. Figure 4 shows the location of these LHDs with the dashed red lines. A side view of one tier shows the LHD placement, red circle, at each rail. Two detectors were placed above the ignition location, towards the east of the main array, while a single line was passed along the main array at the west. The expectation from these setups was to understand how well the LHDs could work when placed within the rack and to determine if detection was possible prior to the fire reaching the ceiling. The LHDs used were Protectowire model PHSC-155-EPC, which have a 68 °C activation temperature and provide activation location based on a current output from a control module (Protectowire Interface Module 530).

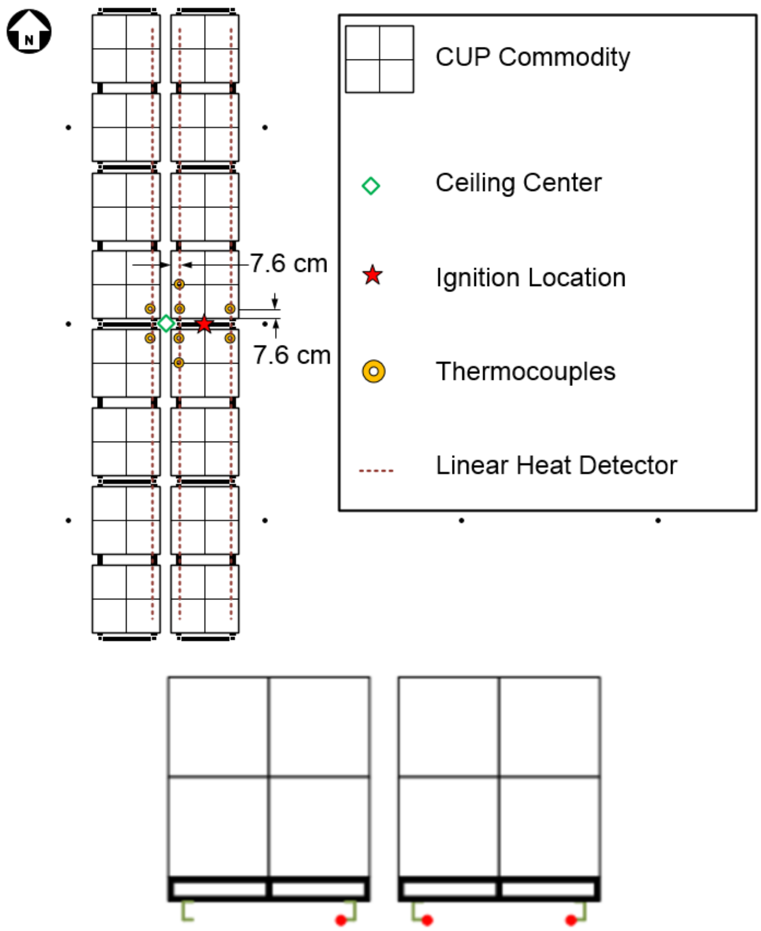

Figure 4: In-rack detection instrumentation showing both thermocouple placement and LHDs, (LHDs placed above first 5 tiers of CUP).

The resultant activation times following ignition are shown in Figure 5 with each color representing a different LHD. Initial observations show two main groups of activation, one group falls within a time window of approx. 45-60 seconds, while the second group falls around 100 seconds after ignition. These two groups represent the LHDs placed on the east and west portion of the main array respectively. The average activation time of LHDs placed along the east portion of the array, above the ignition location was 55 seconds after ignition, a similar time to that of using SMART sprinkler in previous tests[3] with higher ceiling heights, an advantage compared to ceiling activation. Thus, using the LHD provides early activation, minimizing false detections. The longest activation time of the detectors placed above the ignition location occurred at the 4th tier, at 62 seconds. To note, the detectors at the 5th tier activated a little earlier, but within 5 seconds of those at the 4th. The current testing will utilize LHDs placed half way up the storage configuration, above the 4th tier.

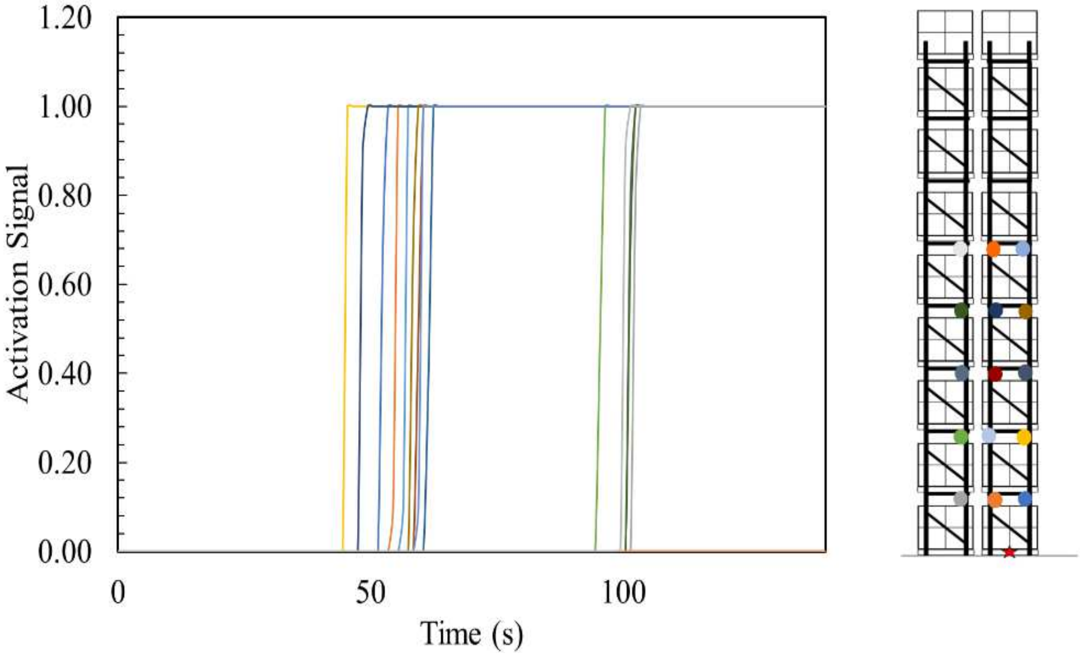

Figure 5: Linear heat detector activation signals from multiple locations and tiers during a traditional sprinkler test. Each color represents a different linear heat detector installed within the array as shown in the side view of the array.

Application of the activation times from the LHDs shows potential for a significant reduction in fire size at detection. The fire would have reached the 6th tier at activation and would not have reached the ceiling.

In addition to providing the activation signal, the LHDs can provide location information for where flame detection occurred. As the LHD is exposed to the fire, the wires within form a junction providing a difference in resistance along the wire, this resistance is related to the length of the wiring. The interface module stores the location of where the break occurred and provides current output to the data acquisition system for active measurement. The module is calibrated based on the length of the wire, the wire is shorted at the control module and at the end of the installed wire to get min and max readings for resistance for accurate stored distance measurements. The current output provided by the control module, however, is for a fixed range of 0-2400m. The large distance unfortunately results in a reduction in dynamic range to the data acquisition system because the wire only spans a distance of 10m length of the main array (less than 1% of the output range). The stored, calibrated distance reading on the PIM (Protectowire Interface Module) unit is most accurate, unfortunately it only stores the last activation which occurs closest to the unit. Thus, the initial activation locations were lost as the fire progressed. For the purposes of this work, the activation signal is most important, the accuracy of fire location is secondary because the fire location is prescribed, and location detection can be improved upon in the future. Thus, the detection approach is suitable for our simulated system. For an actual SMART system, the module could directly communicate with the sprinklers providing the most accurate distance for the first activation prior to any further activations. This may be possible within the onboard module without the reliance on the output signal.

Protection scheme

A localized deluge system was used to simulate SMART sprinkler activation. For the present work, the sprinkler protection consisted of six open sprinklers at pre-determined locations, shown in Figure 3. The six sprinklers were K200 pendent quick response sprinklers (Tyco TY6236) in which the sensible element and plug were removed prior to test start. All water within the piping was allowed to drain into buckets prior to testing to ensure the commodity remained dry.

As stated earlier, the supplied water flux was set based on estimation from the previous SMART sprinkler testing [3] (see Figure 2). However, with the goal of maximizing water reduction, an additional 20% drop in water flux, bringing the value to 32.6 mm/min, was added by expanding the damage threshold of the test array. The data from the previous SMART sprinkler test had minimal damage to the main arrays [3]. As successful protection is defined by preventing aisle jump of the fire and ensuring the fire does not reach the ends of the main array, there is margin in the scaled water fluxes by allowing for more commodity to be consumed.

The water flux in this test, 32.6 mm/min, relative to the previously scaled SMART sprinkler testing is shown in Figure 2 as the point labeled Test 1. Supply pressure for the test was set to 2.27 bar. Water supply was controlled manually for all 6 open sprinklers, which simulated the electronic activation for an actual system. The location and number of sprinklers to activate may be modified for an actual system to incorporate any necessary safety factors.

TEST RESULTS

To begin the test six sprinklers were opened prior to ignition and all the water was drained from the piping. Following ignition, the flame height grew until the first LHD activated at 62 seconds (the next one activated 11 seconds later). The first activation was as expected based on the previous LHD testing. The water was turned on and delivered to the open sprinklers within 10 seconds of the LHD signal. Figure 6 shows the fire development through the early phase of the test. The flame height grew to just above the 4^{th} tier when an activation signal was read from the LHD. The flame height increased by an additional tier prior to water delivery.

Following water delivery, the flame height began to drop and after two minutes of water delivery (~ 200 seconds after ignition) the fire stabilized and burned within the first 4 tiers of the main array. Figure 7 shows a time history of the estimated convective heat release rate (HRR), calculated using flame plume correlations and the ceiling thermocouple data [5]. The estimated convective HRR was between 300 and 400 kW for a period of 7 minutes. Following sprinkler activation these values are only estimates; as the cooling from the sprinklers can cause significant distortion of the calculated HRR, however as there are no additional sprinklers operating during that period, the trend of the curve demonstrates stabilization. Visibly, the size of the fire plume in the array was also consistent over this period. After this period of controlled burning the flame did not spread and the contributing commodity was depleted resulting in the flame height dropping and ultimately subsiding. The peak fire HRR never reached that of a similar traditional test. It appears that the pre-wetting of the surrounding commodity after activation limited the fire growth during the test. Furthermore, due to the lack of spread, the fire duration was driven by the already ignited commodity and the flame height and heat release rate dropped as the commodity was consumed.

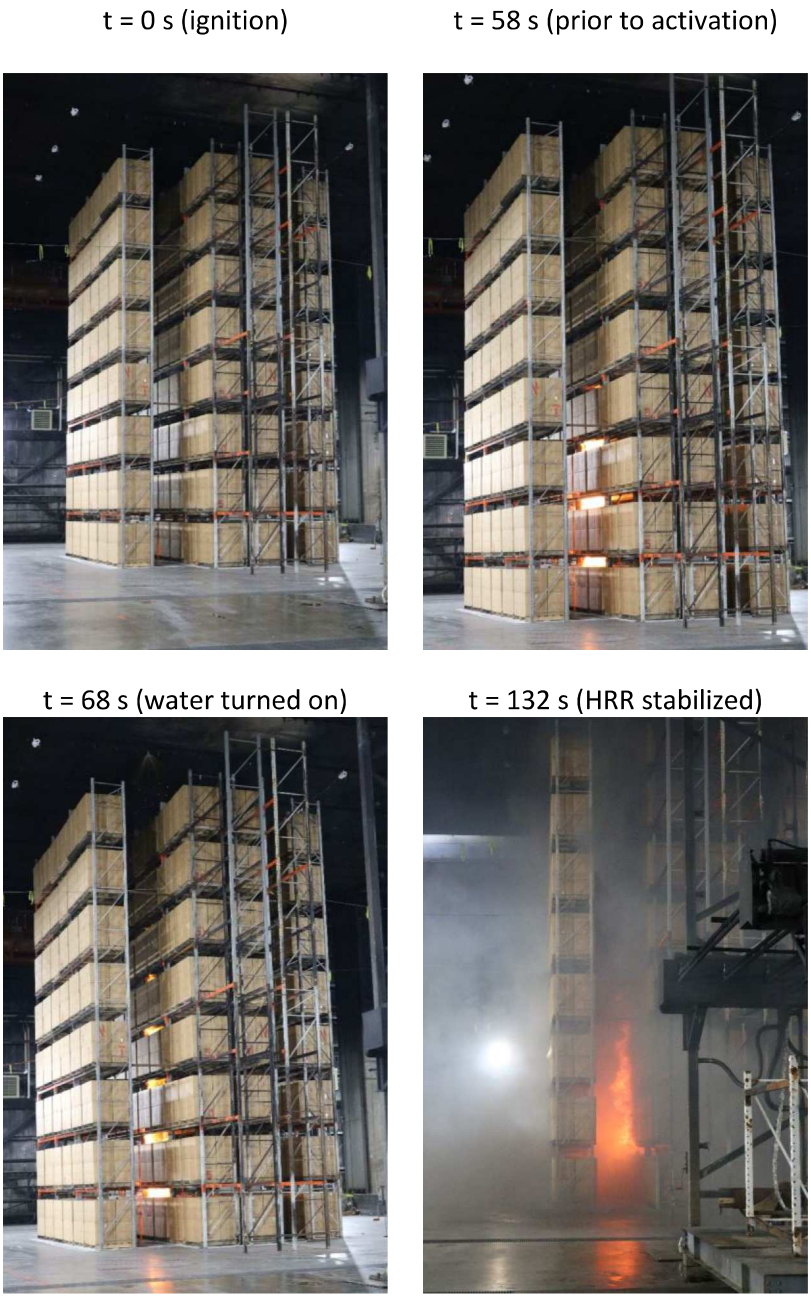

Figure 6: Fire development for 8 tiers of storage with 32.6 mm/min.

Activation of the LHDs was as expected from previous traditional sprinkler testing. The thermocouples at the ceiling were used to compare the LHD activation to the thermocouple-based activation criterion of temperature rise of 5 °C in previous SMART sprinkler testing[3]. When using a temperature rise of 5 °C during a period of one minute occurred at one location at 62 seconds, and 9 locations at a time of 69 seconds. This is just 7 seconds after the LHD activated and is consistent with the earlier findings that the in-rack detectors would activate earlier than the previous SMART system.

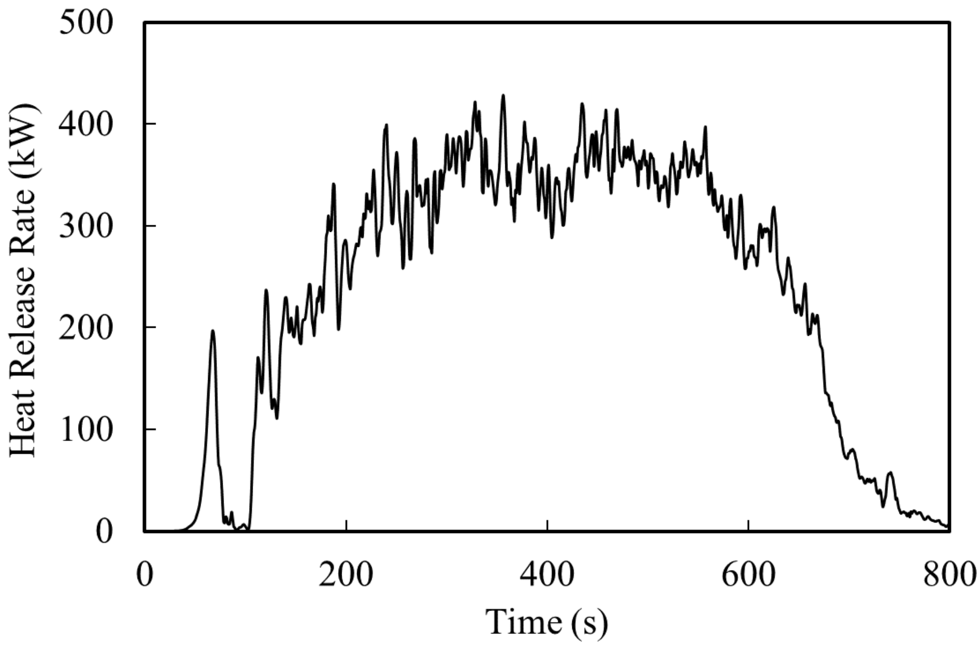

Figure 7: Estimated convective HRR of fire with activation occurring at 62 seconds.

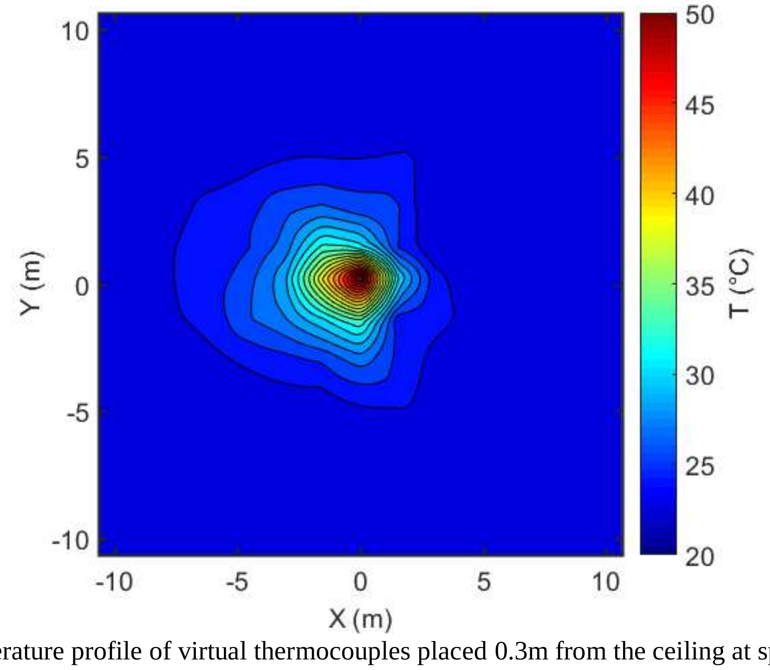

Figure 8: Temperature profile of virtual thermocouples placed 0.3m from the ceiling at sprinkler activation.

From Figure 8, the fire plume location was also at the center of the ceiling with its maximum between the 6 sprinklers which were selected for activation. The damage to the commodity was limited to the main array between the 6 operating sprinklers. Figure 9 shows the damage of the main array when looking from the east side of the array. Damage from the west side was similar but did not span to the 6th tier. There was no fire damage to the target arrays during the test period.

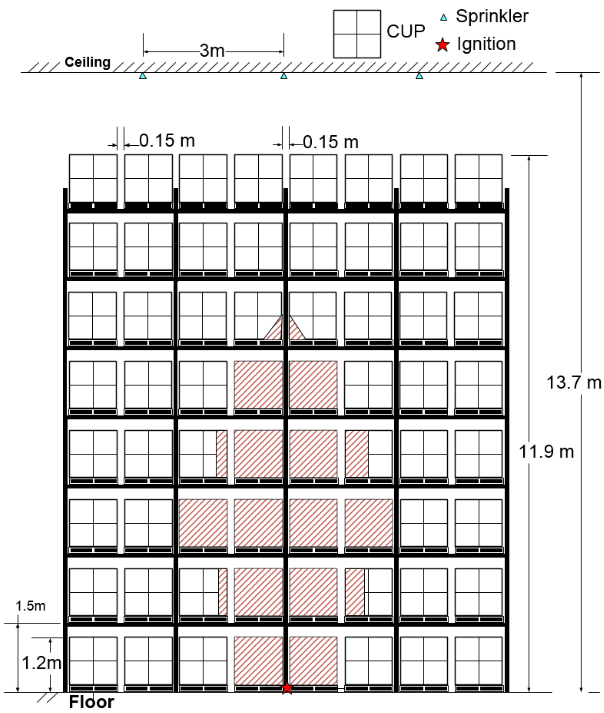

Figure 9: Fire damage of main array represented by red hatch marks (viewed from east). Wooden pallets between each red area were also burned. No fire damage to target arrays was present during testing.

CONCLUSIONS

The test outcome under the 13.7m ceiling showed that scaling the water flow down by 20% relative to results from the previous SMART testing was successful. Additional damage to the main array, relative to the previous SMART testing, did result as expected. However, neither the target arrays or the ends of the main array were reached by fire spread.

Successful protection was aided by early activation, at 62 seconds. The early activation ensured that the flame height was small whereas the non-participating commodity could be prewetted by the sprinklers helping minimize the fire spread. With adequate water density, the fire was contained within the main array and continued burning until the fuel supply was depleted.

Furthermore, both the flame height and HRR remained constant for a duration of approximately 7 minutes while the commodity burned out. During this time there were flames in the aisle space posing a risk to the target arrays. These observations indicate that the water density used in the test is likely close to the critical condition of fire control. Therefore, a slightly higher water density or additional sprinkler activation may be recommended to lower to risk of possible target ignition.

In summary, the results show:

- Quick activation using the in-rack LHD provided early water application to control the fire, while ensuring practical temperature limits for detection.
- Water provided pre-wetting of surfaces before fire could grow and spread with a maximum estimated HRR of 400 kW during the test.
- The delivered water density when using the 6 simultaneously operated sprinklers provided a reduction of water by 77% when compared to the recommendations for traditional protection. Note that additional safety factor should be added to the test results for engineering applications.
- With the fire not growing vertically after sprinkler activation, the fire plume out of the side of the main array may cause target array ignition due to long duration of fire in the 1.2m aisle. This can be addressed by recommending a slightly higher water density or additional sprinkler activation.

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