RESEARCH TECHNICAL REPORT

Impact of a High Volume Low Speed Fan on Sprinkler Performance in Rack Storage Fires

FM Global®

TECHNICAL REPORT

Impact of a High Volume Low Speed Fan on Sprinkler Performance in Rack Storage Fires

By:

Benjamin Ditch

FM Global Research Division

January 2011

Impact of a High Volume Low Speed Fan on Sprinkler Performance in Rack Storage Fires

by

Benjamin Ditch

FM Global Research Division
1151 Boston-Providence Turnkpike
Norwood, MA 02062

DISCLAIMER

EXECUTIVE SUMMARY

An Engineering Standards support project was initiated to evaluate the effect of High Volume Low Speed (HVLS) fans on sprinkler system performance in warehouse scenarios. These fans have diameters up to 7.3 m (24 ft) and are becoming an increasingly popular alternative to standard high speed industrial fans due to their improved energy efficiency. The effect of HVLS fans has yet to be subjected to detailed exploration of the unique and potentially detrimental effect on ceiling level sprinkler protection. Consequently, neither FM Global Property Loss Prevention Data Sheets nor NFPA 13 [i] contains specific installation recommendations or requirements for HVLS fans.

This project was conducted in conjunction with the Property Insurance Research Group (PIRG) and was directed through the National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF). PIRG is comprised of domestic and international property insurance companies with the goal of acquiring general knowledge for issues spanning the property insurance industry. Participation is voluntary and projects are funded by an annual fee. All projects include a technical panel oversight committee including industry experts, consultants and sprinkler association members. FM Global participates in the PIRG as a principal sponsor.

In this study, four large-scale fire tests were conducted by FM Global at the FM Global Research Campus in West Glocester, Rhode Island, USA. The specific scenario addressed was protection of cartoned unexpanded plastic (CUP) commodity using FM Approved quick-response, pendent sprinklers, having a 71^{o}C (160^{o}F) rated link and a K-Factor of 202 L/min/bar$^{1/2}$ (14 gpm/psi$^{1/2}$). Commodity was stored in a double-row open rack arrangement and the ceiling height was set to the maximum allowed in FM Global Property Loss Prevention Data Sheet 8-9 [ii] of 12.2 m (40 ft). A 7.3 m (24 ft) diameter HVLS fan operating at 66 rpm was mounted between the ceiling and the commodity. Within the scope of these tests, it was found that operation of the HVLS fan without any means of shut down caused an unacceptable impairment to the sprinkler system.

[i] National Fire Protection Association Standard 13, "Standard for the Installation of Sprinkler System," 2010.
[ii] "Storage of Class 1, 2, 3, 4 and Plastic Commodities," Data Sheet 8-9, FM Global, May 2008.

However, when shut down of the fan occurred within 1 min 30 s after first sprinkler operation the sprinkler systems performed adequately.

The fan-induced air-flow velocity around and through the ignition bay also was measured for each test array. With only the fan operating, measurements were acquired at multiple elevations spanning from the top of the array to the floor. It was shown that the fan can produce downward air velocities up to 4.5 m/s (14.8 ft/s) at the top of the array with significant penetration, *i.e.*, velocity ≥ 1.0 m/s (3.3 ft/s), several tiers through the array. These data provide insight into the potential affect on sprinkler activation and fire development within the array due to the operating fan. To date, no study has been conducted to measure these air currents for an HVLS fan installed above any type of storage array.

There has been one previous study, coordinated by PIRG, evaluating the effects of an HVLS fan on sprinkler system performance [iii]. This study included two large-scale tests that were conducted at Underwriters Laboratories located in Northbrook, Illinois, USA. Both tests consisted of 6.1 m (20 ft) tall rack storage of cartoned unexpanded plastic (CUP) commodity under a 9.1 m (30 ft) ceiling. Protection was provided by quick-response, pendent sprinklers, having a K-Factor of 202 L/min/psi$^{1/2}$ (14 gpm/psi$^{1/2}$). It was concluded that the presence of an operating HVLS fan did not significantly hinder the ceiling level sprinkler protection. However, it is important to note that ignition for these tests was centered within the array and an evaluation with the ignition offset within the central transverse flue was not conducted. In addition, the protection requirements contained in FM Global Property Loss Prevention Data Sheet 8-9 [ii] allows ceiling-only sprinkler protection for this sprinkler up to 12.2 m (40 ft), which would potentially increase the fire challenge. FM Global participated as a member of the project technical panel for this prior project.

All conclusions in this report are specific to the array configurations used in these tests. The combined effects of a different array height, commodity type, ceiling height, fan diameter/blade shape and speed, etc., are yet to be well understood and may not be inferred from these test

[iii] "HVLS Fans and Sprinkler Operation Phase 1 Research Program," Final Report prepared by Schirmer Engineering Corporation, February 2009.

results alone. Based on the results of the tests presented in this report the following additional conclusions can be made:

- The HVLS fan operating without means of automatic shut down resulted in inadequate sprinkler system performance.
- The HVLS fan centered over the main array, with a clearance from the ceiling to the top of the commodity of 3.0 m (10 ft), resulted in the largest negative impact on the sprinkler system performance.
- For storage with a clearance from the top of the commodity to the ceiling ranging from 3.0 to 7.6 m (10 to 25 ft), fan shut down due to a water flow alarm, *i.e.*, fan shut down less then or equal to 1 min 30 s after first sprinkler operation, allowed for adequate sprinkler system performance.
- The HVLS fan operating at full speed, with a 3.0 m (10 ft) clearance between the top of the commodity and the ceiling:
    - Produced downward air-flow velocities up to 4.5 m/s (14.8 ft/s) at the top of the storage array,
    - Produced significant air-flow velocities, *i.e.*, velocities greater than or equal to 1 m/s (3.3 ft/s), that penetrate up to 4 tiers (6.1 m [20 ft]) through an open frame double-row rack storage array,
    - Created the greatest disturbance to the ceiling gas flow above ignition when the fan was offset 2.2 m (7.1 ft) from the center of the test array.
- The HVLS fan operating at half speed, with a 7.6 m (25 ft) clearance between the top of the commodity and the ceiling, and the fan centered over the array, reduced the peak air velocity reaching the top of the array by approximately 60%.
- The exhaust air system of the FM Global Large Burn Laboratory extracting air at 94 m^3/s (200,000 cfm) generates a negligible air flow across the movable ceiling. The air-flow generated by the HVLS is the dominant disturbance to the ceiling level gas flow.

LARGE-SCALE TEST OVERVIEW

The setup and results for all tests included in this report are shown in Table i and Table ii.

Table i: Test parameters and results, Tests 1 - 3

Project Identification	**0003038945**		
Test Number	**Test 1**	**Test 2**	**Test 3**
Test Date	8/4/2010	8/20/2010	9/3/2010
FM Global Fire Technology Laboratory Test Site	South Movable Ceiling		
Environmental Conditions			
Pre-test Site Dry-Bulb Temperature [°C (°F)]	27 (80)	23 (73)	23 (73)
Pre-test Site Relative Humidity (%)	32	39	38
Outdoor Dry-Bulb Temperature [°C (°F)]	29 (84)	19 (67)	28 (82)
Outdoor Relative Humidity (%)	78	57	64
Main Array Moisture Content [% v/v]	7.7	7.5	7.5
Target Array (East Only) Moisture Content [% v/v]	7.5	7.5	7.4
Fire Test Setup			
Nominal Ceiling Height [m (ft)]	12.2 (40)		
Test Commodity / Fuel	Standard Plastic Commodity		
Fire Type	Double-row rack storage array		
Main Array Dimensions (pallet loads)	2 x 8 x 6		
Target Array Dimensions (pallet loads), East and West	1 x 6 x 6		
Nominal Flue Space Width [mm (in.)]	152 (6)		
Aisle Width [m (ft)]	1.2 (4)		
Main Array Located Below - number of sprinklers	1	4	4
Ignition Location Relative to Rack - offset/non-offset	Offset		
Ignition Location Relative to Sprinkler – centered/offset	Offset		
Fan Diameter [m (ft)] - number of blades	7.3 (24) – 6 blades		
Fan Operating Speed (rpm)	66		
Fan Location Relative to Rack	Offset	Centered	Centered
Fan Hub Installation Level Below Ceiling [mm (in.)]	1270 (50)		
Fan Shut Down Condition	None	None	Water flow¤
Sprinkler Type (Pendent)	Pendent		
Sprinkler Model	Tyco TY6226		
Discharge Coefficient (K-Factor) [*L*/min/(bar)^{½} (gal/min/(psi)^{½})]	202 (14)		
Temperature Rating [°C (°F)]	71 (160)		
Nominal Response Time Index (RTI) [m^{½}s^{½} (ft^{½}s^{½})]	28 (50)		
Spacing [m x m (ft x ft)]	3 x 3 (10 x 10)		
Discharge Pressure [bar (psi)]	5.2 (75)		
Nominal Discharge [*L*/min (gpm)]	454 (120)		
Fire Test Results			
Total Sprinklers Opened	12	12	4
First / Last Sprinkler Operation Times (min:s)	1:28/7:53	1:42/3:57	1:54/2:03
Target Jump – East/West (min:s)	East, 3:09 West, 5:50	East, 2:13 West, no	East, 3:00 West, no
Maximum Steel TC Measurement [°C (°F)] and Time (min:s)	76 (169) @ 5:54	47 (117) @ 4:49	45 (113) @ 4:41
Maximum One Minute Average TC Measurement [°C (°F)] at Time (min:s)	293 (559) @ 4:26	130 (266) @ 3:07	144 (291) @ 1:45
Test Termination - Time After Ignition (min:s)	35:00	25:00	30:00

¤ Fan shut down occurred 1 min 30 s after first sprinkler operation

Table ii: Test parameters and results, Test 4

Project Identification	**0003038945**
Test Number	**Test 4**
Test Date	12/2/2010
FM Global Fire Technology Laboratory Test Site	South Movable Ceiling
Environmental Conditions	
Pre-test Site Dry-Bulb Temperature [°C (°F)]	23 (74)
Pre-test Site Relative Humidity (%)	24
Outdoor Dry-Bulb Temperature [°C (°F)]	2 (36)
Outdoor Relative Humidity (%)	55
Main Array Moisture Content [% v/v]	5.9
Target Array (East Only) Moisture Content [% v/v]	6.3
Fire Test Setup	
Nominal Ceiling Height [m (ft)]	12.2 (40)
Test Commodity / Fuel	Standard Plastic Commodity
Fire Type	Double-row rack storage array
Main Array Dimensions (pallet loads)	2 x 8 x 3
Target Array Dimensions (pallet loads), East and West	1 x 6 x 3
Nominal Flue Space Width [mm (in.)]	152 (6)
Aisle Width [m (ft)]	1.2 (4)
Main Array Located Below - number of sprinklers	4
Ignition Location Relative to Rack - offset/non-offset	Offset
Ignition Location Relative to Sprinkler – centered/offset	Offset
Fan Diameter [m (ft)] - number of blades	7.3 (24) – 6 blades
Fan Operating Speed (rpm)	66
Fan Location Relative to Rack	Centered
Fan Hub Installation Level Below Ceiling [mm (in.)]	1270 (50)
Fan Shut Down Condition	Water flow[¤]
Sprinkler Type (Pendent)	Pendent
Sprinkler Model (Year manufactured)	Tyco TY6226
Discharge Coefficient (K-Factor) [*L*/min/(bar)^{½} (gal/min/(psi)^{½})]	202 (14)
Temperature Rating [°C (°F)]	71 (160)
Nominal Response Time Index (RTI) [m^{½}s^{½} (ft^{½}s^{½})]	28 (5)
Spacing [m x m (ft x ft)]	3 x 3 (10 x 10)
Discharge Pressure [bar (psi)]	5.2 (75)
Nominal Discharge [*L*/min (gpm)]	454 (120)
Fire Test Results	
Total Sprinklers Opened	4
First / Last Sprinkler Operation Times (min:s)	1:39 / 1:42
Target Jump – yes/no (min:s)	No
Maximum Steel TC Measurement [°C (°F)] and Time (min:s)	28 (113) @ 1:46
Maximum One Minute Average TC Measurement [°C (°F)] at Time(min:s)	44 (112) @ 1:42
Test Termination - Time After Ignition (min:s)	30:00

[¤] Fan shut down occurred 1 min 30 s after first sprinkler operation

ABSTRACT

The goal of this project was to evaluate the effect of a High Volume Low Speed (HVLS) fan on the performance of ceiling level sprinkler protection in a warehouse storage scenario. Four large-scale fire tests were conducted with FM Global's Cartoned Unexpanded Plastic (CUP) commodity stored in a rack storage arrangement. It was found that an HVLS fan operating without means of automatic shut down results in inadequate sprinkler system performance. However, adequate protection system performance was achieved when the fan was shut down 1 min 30 s after first sprinkler operation. Increasing the clearance between the HVLS fan and the commodity was also shown to have minimal negative impact on the effectiveness of the sprinkler system.

The results found during this project are specific to the array configurations used in these tests. The combined effects of a different array height, commodity type, ceiling height, fan diameter/blade shape and speed, etc., are yet to be well understood and may not be inferred from these test results alone.

ACKNOWLEDGEMENTS

The author thanks Mr. J. Chaffee, Mr. R. Chmura, Mr. M. Skidmore, Mr. P. Mancini and the entire FM Global Research Campus Large Burn Lab crew for their efforts in conducting the large-scale tests. A special thanks to Mr. C. Labutti, Mr. M. Silva, Mr. S. Ulrickson, and Mr. J. St. Pierre for designing and implementing the specialty air-flow instrumentation.

The author further thanks Kathleen Almand, as head of the Fire Protection Research Foundation, and the members of the Property Insurance Research Group for their insightful discussions. In addition, MacroAir Technologies is gratefully acknowledged for donating the HVLS fans used in this project.

Finally, as always, the efforts of Mrs. Cheryl McGrath in processing this report are greatly appreciated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

High Volume Low Speed (HVLS) fans have become increasingly common as an alternative to smaller traditional industrial fans in many occupancies. Originally developed by Walter Boyd in 1995, HVLS fans move large volumes of air by using large air foil type blades. Increasing the blade range of motion reduces the necessary operating speed while improving the electrical efficiency. Some of the larger fans on the market span 7.3 m (24 ft) and are rated to displace over 175 m^3/s (370,000 cfm) of air while operating at only 65 rpm. This corresponds to a suggested 1,858 m^2 (20,000 ft^2) coverage area or 33.5 m (110 ft) spacing [1].

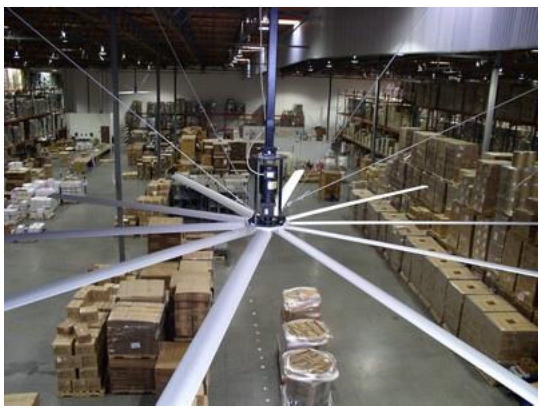


Figure 1-1: HVLS fan in industrial occupancy*

Figure 1-2: Traditional wall-mount industrial fan†

HVLS fan installations are typically mounted on the ceiling above open areas, such as wide aisle spaces or above loading dock areas as shown in Figure 1-1. However, a review by FM Global and Property Insurance Research Group (PIRG) members during this project identified a wide range of fan installations, including high bay rack storage. Depending on environmental conditions, many fans can be designed to blow air downward or upward. In addition, the blade pitch on some models also can be adjusted to maximize efficiency at different operating speeds. The corresponding traditional industrial fans are smaller diameter with the blades often contained within a cage, Figure 1-2. These fans are typically floor-standing or wall-mounted and rely on blade speed to move large volumes of air. Because of the smaller diameter, the displaced air tends to be channeled in a high velocity column in front of the fan.

* Photo courtesy of Macro-Air Technologies Inc, www.macro-air.com.
† Photo courtesy of Schaefer Ventilation Equipment, Versa Kool Model VS36VKWO-B, www.schaeferfan.com/Versa Kool.

2 BACKGROUND

The usage of HVLS fans has predated any detailed exploration of the unique and potentially detrimental effect on ceiling level sprinkler protection. Consequently, neither FM Global Property Loss Prevention Data Sheets nor National Fire Protection Association Standard 13, “Standard for the Installation of Sprinkler System,” [2] contain specific installation recommendations or requirements for HVLS fans.

In 2009, a cooperative research project was conducted to evaluate the impact of HVLS fans on the protection provided by ceiling level sprinklers. Titled “HVLS Fans and Sprinkler Operations – Phase 1 Research Program,” the project was funded by the Property Insurance Research Group (PIRG)* and directed through the National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) [3]. A technical panel oversight committee included FM Global Research staff, industry experts, consultants and sprinkler association members. Schirmer Engineering Corp. was retained to coordinate the testing and prepare a final project report.

The objectives of Phase 1 were to investigate the impact of an HVLS fan on a ceiling level sprinkler system due to 1) obstruction of the sprinkler discharge pattern, and 2) air-flow generated by the fan. The approach included Actual Delivered Density (ADD) testing to determine the effect of fan size and location on the obstruction severity and large-scale testing to evaluate the effect on sprinkler protection in a real-world application. Actual Delivered Density (ADD) tests were conducted at Southwest Research Institute (SwRI) in San Antonio, Texas. The intent was to compare the quantity of discharged water that would reach the top of a test array from an unobstructed sprinkler system versus a sprinkler system obstructed by various static fans. While it was ultimately concluded that no quantifiable information regarding the obstruction provided by an HVLS fan could be provided by ADD testing, observations suggested that the fan alone did not substantially obstruct the sprinkler discharge.

* PIRG is comprised of several domestic and international property insurance companies with the goal of acquiring general knowledge for issues spanning the property insurance industry. Participation is voluntary and projects are funded by an annual fee from PIRG members .

Two large-scale tests were conducted at Underwriters Laboratories located in Northbrook, Illinois. Both tests consisted of 6.1 m (20 ft) tall rack storage of cartoned unexpanded plastic (CUP) commodity under a 9.1 m (30 ft) ceiling. Protection was provided by quick-response pendent sprinklers having a K-Factor of 202 L/min/psi$^{1/2}$ (14 gpm/psi$^{1/2}$) on 3.0 x 3.0 m (10 x 10 ft) spacing. The fan location was varied between the tests, such that either the blade tips or fan hub was located over ignition. It was found that having the fan hub over ignition was the worst-case scenario, resulting in 8 sprinkler operations that controlled the fire.

Under the conditions of the Phase 1 large-scale testing it was concluded that the presence of an operating HVLS fan does not significantly hinder ceiling level sprinkler protection. However, it is important to note that ignition for these tests was centered within the array; an evaluation with the ignition offset within the central transverse flue was not conducted. In addition, the protection requirements contained in FM Global Property Loss Prevention Data Sheet 8-9 [4] allow ceiling-only sprinkler protection for this sprinkler up to 12.2 m (40 ft), which would potentially increase the fire challenge. FM Global participated as a member of the project technical panel for Phase 1 of this project.

For reference, eight other large-scale fire tests have been conducted to evaluate the effect of HVLS fans. These tests were sponsored by either XL Global Asset Protection Service (XL Gaps) or Big Ass Fans Corp. and comprise the remainder of all known tests using HVLS fans. A table detailing the setup and results of these tests was included in the PIRG proposal for this project [5], prepared by Schirmer Engineering Corporation, and reproduced in Appendix H of this report.

Test configurations for this prior work included rack and solid pile storage arrays of CUP or Class 2 commodity, with a nominal height of 4.6 m (15 ft), under a nominal 7.6 m (25 ft) ceiling height. Sprinkler protection was provided by either standard-response sprinklers having a K-Factor of 81 L/min/psi$^{1/2}$ (5.6 gpm/psi$^{1/2}$) or 161 L/min/psi$^{1/2}$ (11.2 gpm/psi$^{1/2}$), or quick-response sprinklers having a K-Factor of 202 L/min/psi$^{1/2}$ (14 gpm/psi$^{1/2}$). Link ratings were either 71 or 141^{o}C (160 or 286^{o}F). Fan size ranged from 6.1 to 7.3 m (20 to 24 ft) diameter with operating speeds from 24 to 63 rpm. The fan operation procedure also varied from being on for the entire test, shut down at first sprinkler operation, or shut down due to advance smoke detection.

Of particular interest was the test labeled as ‘XL Gaps 2007 Test 1’. This test consisted of 4.6 m (15 ft) tall CUP commodity in a palletized solid pile open array under a 7.6 m (25 ft) high ceiling. Protection was provided by standard-response upright sprinklers having a K-Factor of 161 L/min/psi$^{1/2}$ (11.2 gpm/psi$^{1/2}$) and a link rating of 141^{o}C (286^{o}F) on 2.4 x 3.0 m (8 x 10 ft) spacing. The configuration was based on UL 199, “Standard for Automatic Sprinklers for Fire Protection Service” [6]. The fan was operating at 24 rpm (approximately 50% of full speed) and was shut down upon first sprinkler operation. A significant disturbance to the ceiling gas layer and fire plume was observed due to the fan, delaying the initial sprinkler operations. At 8 min after ignition, the test was terminated with a total of 73 sprinkler operations and commodity damage extending to the extremities of the array. Due to concerns raised from this outcome, this test was repeated by Underwriter’s Laboratories in December 2010 and will be reported in the overall Phase 2 Test report to be issued by the Property Insurance Research Group in 2011.

3 REPORT SCOPE AND RATIONAL

This report contains the setup, results and conclusions for the large-scale fire tests conducted by FM Global, as detailed in the Phase 2 proposal by Schirmer Engineering [5]. A total of four large-scale fire tests was conducted focusing on protection of Cartoned Unexpanded Plastic (CUP) commodity with pendent, quick-response, sprinklers having a K-factor of 202 L/min/bar^{½} (14 gpm/psi^{½}). A ceiling height of 12.2 m (40 ft) was selected to be consistent with the maximum ceiling height allowed in FM Global Data Sheet 8-9, using ceiling-only protection [4].

Three tests were initially included in the Phase 2 proposal using the highest storage height possible of 9.1 m (30 ft). The first two tests were intended to establish the worst-case ignition location, under-one or among-four sprinklers, with the fan operating at full speed for the entire test. Unacceptable performance would result in a re-test, except with the fan shut down after first sprinkler operation to simulate a water flow alarm. It is important to note that ignition between two sprinklers was not possible due to an interference between the sprinkler pipes and the desired fan location for the typical test array orientation used by FM Global.

A fourth test was later added using a reduced storage height of 4.6 m (15 ft) to evaluate the sprinkler system performance for a high clearance storage scenario. This test was deemed necessary because the operating fan caused a considerable disturbance of the fire plume, particularly above the array, during the initial three tests. Therefore, the effect of an increased clearance above the array was addressed.

Detailed measurements of the vertical air-flow velocity above the ignition bay were also recorded during each fire test. These measurements were acquired to quantify the magnitude and direction of air-flow generated by the fan. Corresponding measurements also were made at several elevations within the array with only the fan operating. These measurements established the air flow penetration through the array.

4 TEST CONDITIONS AND PROCEDURES

4.1 LARGE BURN LABORATORY

The tests for this program were conducted under the south movable ceiling in the Large Burn Laboratory (LBL) located in the Fire Technology Laboratory at the FM Global Research Campus in West Glocester, Rhode Island, USA. Figure 4-1 is a plan view of the LBL showing the north movable ceiling, the south movable ceiling, and the 20-MW Calorimeter. The air emission control system (AECS) exhaust ducting for each movable ceiling consists of four extraction points, located at the lab ceiling, that merge into a single duct with a cross sectional area of 6.1 m^2 (66 ft^2). Gas concentration, velocity, temperature and moisture measurements are made downstream of the manifold. Beyond the measurement location, the exhaust duct connects to a wet electrostatic precipitator (WESP) prior to the gases venting to the atmosphere. The movable ceilings measure 24.4 x 24.4 m (80 x 80 ft) and are adjustable for heights above the floor ranging from 3.1 to 18.3 m (10 to 60 ft). All tests were conducted at an exhaust rate of 94 m^3/s (200,000 ft^3/min).

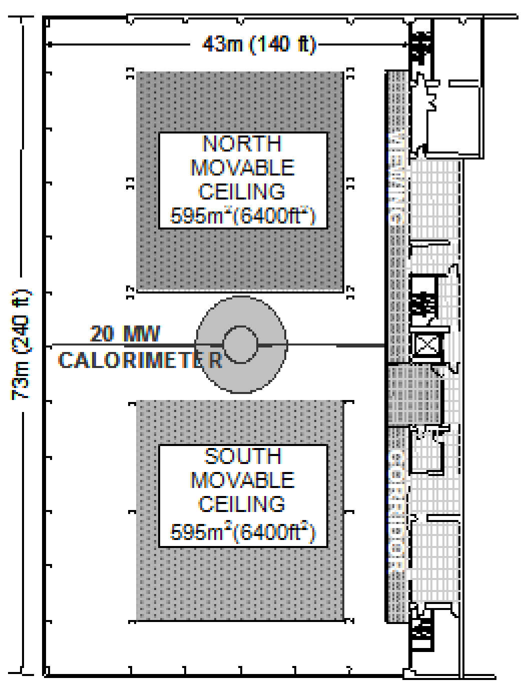


Figure 4-1: Illustration of FM Global Large Burn Laboratory test locations

4.2 TEST COMMODITY

Four rack storage fire tests were conducted using the FM Global Standard Plastic test commodity. This commodity consists of a Cartoned Group A Unexpanded Plastic (CUP), made by rigid crystalline polystyrene cups (empty, 0.47 L, 16 oz.) packaged in single-wall, corrugated paper cartons. Cups are individually compartmentalized with corrugated paper partitions, and are arranged in five layers, with 25 cups per layer, to result in 125 per carton. Eight 0.53-m (21-in.) cube cartons, arranged 2 x 2 x 2, form a pallet load. Overall, the cube unit measures 1.07 m (42 in.) on the outside, and is supported on an ordinary, two-way, slatted deck, hardwood pallet, measuring 1.07 m x 1.07 m x 127 mm (42 x 42 x 5 in.). The total chemical energy for a pallet of the CUP commodity is nominally 1,430 MJ, based on the above masses and the heat of combustion for each material [7]*. A photo of the CUP commodity is provided in Figure 4-2.

Figure 4-2: Photo of cartoned unexpanded plastic (CUP) commodity

The main fuel array consisted of an open-frame, double-row steel rack erected directly on the floor, as shown in Figure 4-3. Each level of the array contained a total of 32 pallet loads of CUP commodity. The array dimensions measure approximately 10.1 m wide x 2.3 m deep (~33 ft x 7.5 ft) in an 8 wide x 2 deep arrangement, Figure 4-4. Single-row target arrays contained six pallet loads of the same commodity across a 1.2 m (4 ft) aisle to the east and west of the main array. Overall the target arrays measured approximately 7.5 m wide x 1.2 m deep (24.5 ft x

* The heat of combustion for each material was multiplied by the mass of the material within a commodity. The referenced heat of combustion for each of the materials are: 12.4 kJ/g (pallet), 14.4 kJ/g (corrugated board, partitions), and 27.5 kJ/g (unexpanded plastic).

3¼ ft). For Tests 1 - 3, a six pallet load high configuration was used, resulting in an approximate 9.1 m (30 ft) high array. For Test 4, a three pallet load high configuration was used, resulting in an approximate 4.6 m (15 ft) high array. The rack storage arrays were oriented perpendicular to the sprinkler pipes, which run east-west across the ceiling.

For all tests, the ceiling height was set at 12.2 m (40 ft) allowing for a minimum 3.1 m (10 ft) clearance between the ceiling and the top of the array. This clearance is different from FM Global's standard clearance for an among-four sprinklers ignition of 1.5 m (5 ft) with the added clearance being necessary to satisfy the fan and sprinkler installation requirements. Specifically, the fan manufacturer requires a minimum installation clearance of 0.9 m (3 ft) between the fan blades and the ceiling. Both FM Global Property Loss Prevention Data Sheet 2-0 [8] and NFPA 13 [2] require a minimum 0.9 m (3 ft) clearance between any obstruction and the stored commodity. The sum of these requirements results in a minimum 1.8 m (6 ft) clearance, which was rounded to the nearest 1.5 m (5 ft) increment, *i.e.,* 3.1 m (10 ft).

Figure 4-3: Typical rack storage array of standard plastic commodity

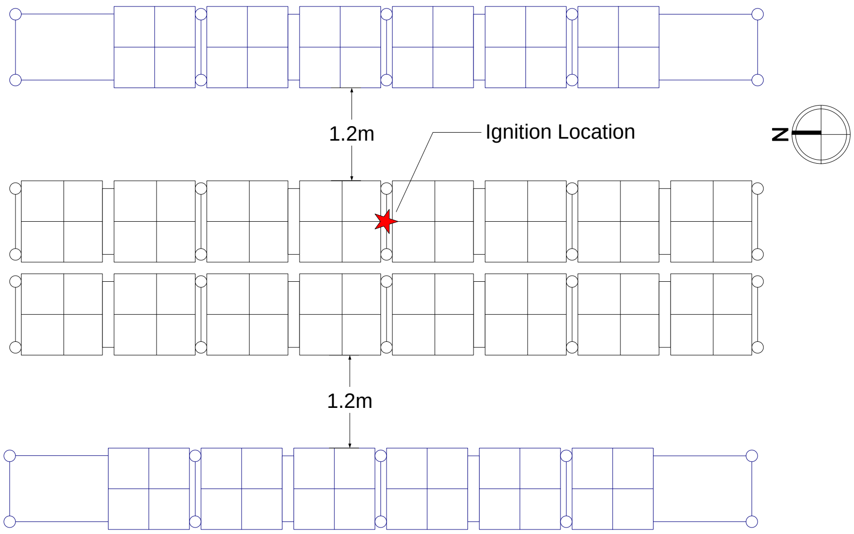


Figure 4-4: Plan view of main and target arrays

4.3 AUTOMATIC SPRINKLER PROTECTION

For each test, the Tyco Fire Products (TYCO) TY6226 sprinkler was used. The sprinkler has a nominal K-Factor of 202 L/min/bar^{½} (14 gpm/psi^{½}) and is an FM Approved, pendent-type, sprinkler with a nominal 18 mm (0.7 in.) diameter orifice and 71^{o}C (160^{o}F) temperature rating. The actuation mechanism was rated at a nominal RTI of 27.6 m^{½}s^{½} (50 ft^{½}s^{½}). Consistent with FM Global standard procedures for a large-scale fire test, each sprinkler was oriented with the sprinkler frame arms parallel to the sprinkler pipe and the sprinkler's heat sensing link facing towards the north.

Figure 4-5: Tyco TY6226 photos

4.4 IGNITION

Ignition was achieved with two FM Global standard half igniters, which are 76 x 76 mm (3 x 3 in.) cylinders of rolled cellu-cotton. Each igniter is soaked in 118 ml (4 oz.) of gasoline and sealed in a plastic bag, Figure 4-6. The igniters were placed in an offset ignition orientation, which is located 0.6 m (2 ft) east of center, in the center transverse flue, between the uprights, of the eastern row of the main array. The igniters were lit with a flaming propane torch at the start of each test and the fires were allowed to develop naturally.

Figure 4-6: Igniters within the rack, located at the rack uprights

4.5 HIGH VOLUME LOW SPEED FAN

4.5.1 Fan Specifications

MacroAir Technologies donated two MaxAir™ MA24XL2006 fans. This fan is a six blade design with an overall diameter of 7.3 m (24 ft). Consistent with previous testing [3], the fan was mounted with the blades 127 cm (50 in.) below the ceiling. The supplied motor was contained in a NEMA-1[*] enclosure and provided 1.5 kW (2 HP). Based on the manufacturer specifications, air displacement of 175 m^3/s (370,000 cfm) is achieved at the maximum speed of 65 rpm. However, validation testing under the installation conditions of this project resulted in a maximum operating speed of 66 rpm. A complete listing of specifications can be found in Appendix G.

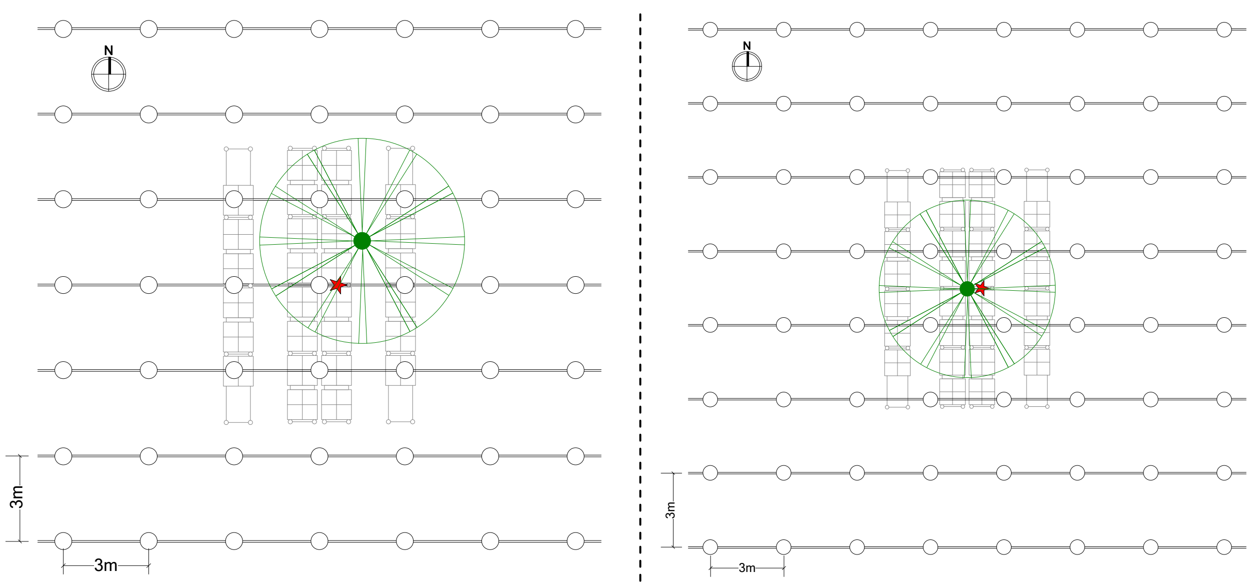
[*] The National American Electrical Association designates NEMA-1 enclosures for general-purpose use indoors and under normal atmospheric conditions. These enclosures protect against dust, light, and indirect splashing but are not dust-tight.

4.5.2 Fan Operation During Fire Tests

During Tests 1 and 2, the HVLS fan was operating at the maximum speed of 66 rpm for the entire test to represent the greatest influence on the performance of ceiling level sprinkler protection. For Tests 3 and 4, the fan was shut down 1 min and 30 s after first sprinkler operation. This sequence, which is consistent with the water flow alarm requirement in NFPA 72 [9], established the benefit of fan shut-down.

4.6 TEST CONFIGURATION OVERVIEW

The configurations for Tests 1 - 4 are shown in Figure 4-7. For Test 1, the main array was centered below one sprinkler and the fan was offset 2.2 m (7.1 ft) to the northeast. For Tests 2 - 4, the main array was centered among four sprinklers and the fan was nominally centered* over the main array. Sprinklers were installed on 3.0 x 3.0 m (10 x 10 ft) spacing. To fit within the extent of the ceiling, a total of 49 sprinklers were installed for Test 1 and 64 sprinklers were installed for Tests 2 – 4. For consistency with common installation practices and manufacturer recommendations, the HVLS fans were always centered among four sprinklers.



Test 1 Configuration

Test 2 - 4 Configurations

Figure 4-7: Sprinkler layout for Tests 1 – 4

* The actual fan placement was offset 0.3 m (1 ft) northeast of the ceiling center due to the presence of the instrumentation used to acquire ceiling steel temperatures.

4.7 DOCUMENTATION AND INSTRUMENTATION

Documentation for each test included video, still photography*, and audio recordings of the visual observations made during the test. The video documentation included three standard definition digital video cameras, one high definition video camera, and an infrared (IR) camera for qualitative assessments of the fire. The three standard definition digital video cameras provided a view of the test from the northeast (main camera) and of both aisle spaces (remote cameras 1 and 2). The high definition and IR camera were located adjacent to the main camera.

Environmental conditions, including relative humidity, dry-bulb temperature, and wet-bulb temperature of the air inside and outside of the lab, were measured just prior to each test as well as continually during each test. In addition, the following standard instrumentation was installed:

- Sprinkler protection was provided at up to 64 locations at the ceiling, as described in Section 4.6. Each sprinkler had its operating mechanism included in an electric circuit to determine operation times.
- Bare-bead, 0.8 mm (20-gage), chromel-alumel thermocouples, placed 165 mm (6-1/2 in.) below the ceiling at 125 locations. These thermocouples have been shown to have a response time index (RTI) of 8 ± 1 $m^{1/2}s^{1/2}$ (14.5 ± 1.8 $ft^{1/2}s^{1/2}$). See Appendix A for specific thermocouple locations.
- Bi-directional probes to measure plume velocity immediately below the ceiling. Probes were located at four orthogonal locations with radial distances from the ceiling center of 2.1 and 4.0 m (7 and 13 ft) [at 0.1 m (0.4 ft) below the ceiling], and 10.4 m (34 ft) [at 0.5 m (1.5 ft) below the ceiling].
- Thermocouples imbedded in a cross-shaped steel angle, made from two 50.8 mm wide x 0.6 m long x 6.35 mm thick (2 in. x 2 ft x 0.25 in.) angle iron segments, attached to the center of the ceiling. Measurements from these thermocouples are referred to as steel temperatures.
- Flow meters and pressure controllers to monitor and control the sprinkler system.

* Photos from individual tests are not provided in this report, but have been archived for future reference.

- Gas analyzers to measure the generation of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC) from the fire and captured in the exhaust, and the depletion of oxygen (O_2) in the test space.

Additional instruments were also installed for this project to measure the air flow immediately above the ignition bay of the main array generated by the building exhaust system and the HVLS fan. A complete description of these instruments is included in Section 4.8.

4.8 AIR-FLOW MEASUREMENTS

4.8.1 Air-Flow Measurements at Top of the Main Array

Air-flow velocities were measured continually at 15 locations 12.7 cm (5 in.) above the top of the main array, surrounding the ignition bay. As shown in Figure 4-8, the measurement locations were separated into three groups: W1 – W5 were 7.6 cm (3 in.) from the main array commodity in the west aisle, C1 – C5 were centered above the longitudinal flue, and E1 – E5 were 7.6 cm (3 in.) from the main array commodity in the east aisle. Each measurement was derived from the combination of a vertically oriented 19 mm (¾ in.) diameter bidirectional probe and a 20-gage exposed bead thermocouple [10], Figure 4-9. The bidirectional probes were connected to Setra Model 2641R25WB2DT1F pressure transducers, which have a range of ± 62.5 Pa (0.25 in. H_20) and a 0.25% accuracy. This method is consistent with FM Global Large Burn Lab practices for near-ceiling gas velocities and the method described by Ingason [11] for fire plume gas velocities within a rack storage array. Only vertical measurements were taken, since bidirectional probes have an angular insensitivity up to 50 degrees.

Measurements were taken under two conditions: 1) with only the fan operating, *i.e.* no fire and 2) with the fan operating during the fire test. These are referred to as ‘cold flow’ and ‘fire test’ measurements in this report, respectively.

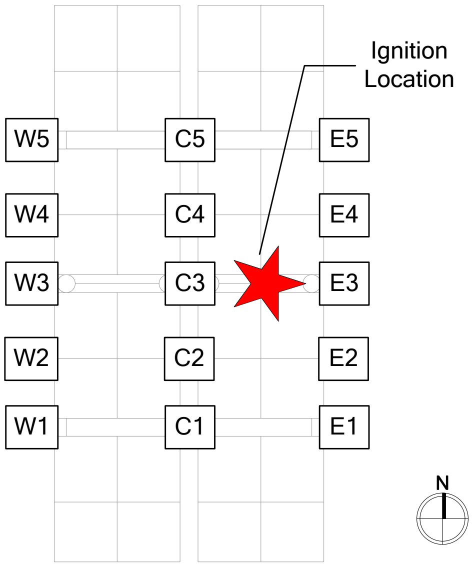


Figure 4-8: Plan view of air-flow measurement instrumentation layout

Figure 4-9: Top view of air-flow instrumentation design

4.8.2 Air-Flow Measurements within Main Array

Additional air-flow velocity measurements were acquired at six elevations within the array with only the fan operating, *i.e.*, no fire. These are referred to as ‘Cold Flow’ measurements in this report. As shown in Figure 4-10, the selected elevations were 12.7 mm (5 in.) above the commodity at tiers one through five and 15.2 mm (6 in.) above the floor. At each elevation, 15 measurements were acquired to correspond with the locations shown in Figure 4-8, resulting in an additional 90 locations for a six-tier high array and 45 locations for a three-tier-high array.

Consistent with the air-flow measurements taken above the top of the array, detailed in Section 4.8.1, the measurement locations were separated into three groups per elevation. Group W1 – W5 were 7.6 cm (3 in.) from the main array commodity in the west aisle, C1 – C5 were centered within the longitudinal flue, and E1 – E5 were 7.6 cm (3 in.) from the main array commodity in the east aisle. At each location data were acquired for five minutes.

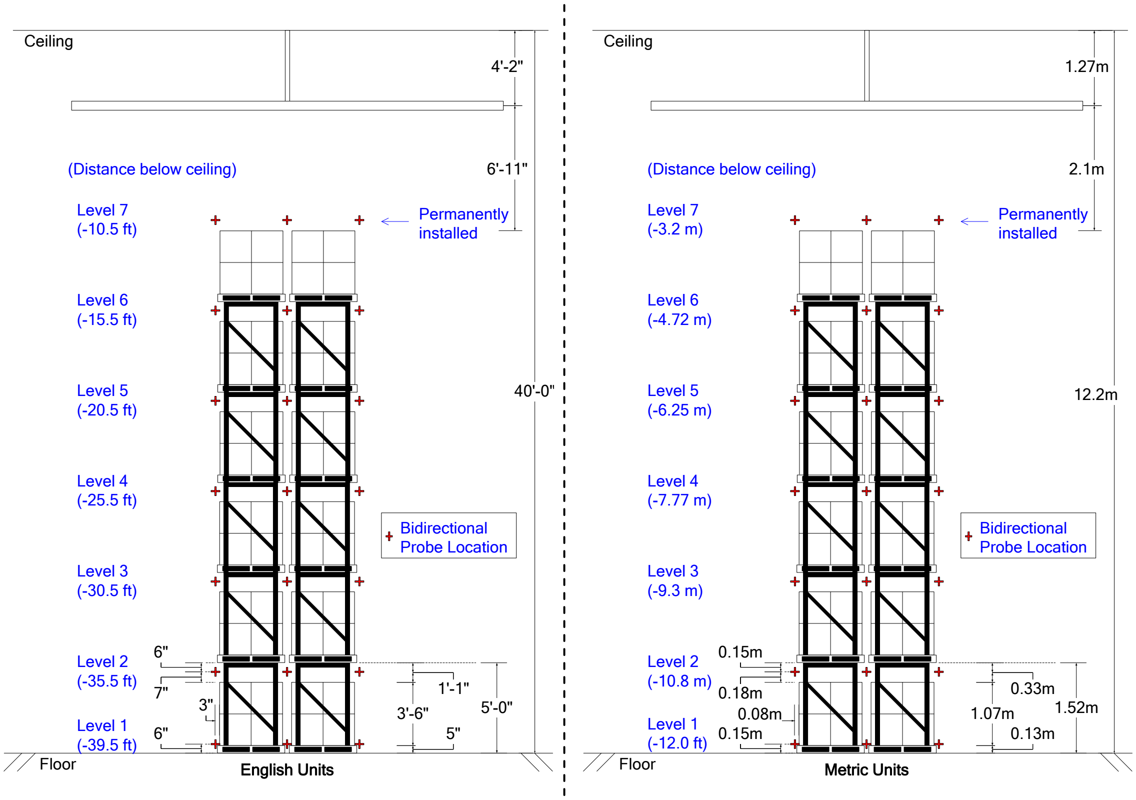


Figure 4-10: Supplementary air-flow measurements within main array for Tests 2 and 3 configuration (English and metric units)

4.8.3 Selection of pressure transducer range

The velocity of a gas flow can be calculated using the combination of a bidirectional probe and thermocouple [12], as

$$V = 0.07\sqrt{T\Delta P} \qquad \text{Eq. 1}$$

where V is the gas velocity in m/s, T is the gas temperature in K, and ΔP is the bidirectional probe pressure differential in Pa.

One can first consider the maximum and minimum pressure transducer range for a fan operating under ambient conditions. From an HVLS fan manufacturer’s website [13], the average air velocity 5.5 m (18 ft) away from a 7.3 m (24 ft) diameter fan is 3.0 m/s (9.8 ft/s). Assuming the peak air velocity is nominally 50% greater, or 9 m/s, the maximum pressure differential is calculated as

$$\Delta P_{fan\_max} = \left(\frac{9[m/s]}{0.07}\right)^2 / 300[K] = 55[Pa].$$

The standard range of Setra bidirectional pressures transducers are: ± 25 to ± 250 Pa at 0.25% accuracy (± 0.1 to ± 1 in H_2O). Using the maximum predicted pressure range of 55 Pa, the selected transducer range was ± 62.5 Pa. This provided an accuracy of ± 0.16 Pa (6.4×10^{-4} in. H_2O), *i.e.*, 62.5*0.0025.

4.9 SPRINKLER SYSTEM PERFORMANCE CRITERIA

Assessment of the system performance was based on the current standard FM Global evaluation criteria for K14 ESFR pendent sprinklers [14]. The primary judgment criteria are the number of sprinkler operations, the extent of fire damage, and the magnitude and duration of steel temperatures. The magnitude of ceiling level TC measurements and total amount of energy released are also considered for comparison between tests, but are not used to evaluate sprinkler system performance.

4.9.1 Sprinkler Operations

In a successful test under these conditions, the total number of sprinkler operations allowed is eight. Additionally, sprinklers along the perimeter of the test ceiling are not allowed to operate. Sprinklers operating at the ceiling perimeter indicate that high temperature gases were present to the edge of the ceiling and could have traveled further along the ceiling, operating additional sprinklers, had they been present.

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

4.9.2 Extent of Fire Damage

Fire damage should be confined within the outermost transverse flues of the main array. Fire jump to the target arrays is permitted, provided the fire does not propagate to the outer faces of the targets. The fire must not display any potential for further propagation at the time of test termination.

4.9.3 Steel Temperature

The maximum 1-min average allowable ceiling steel temperature is 538^{o}C (1,000^{o}F). This criterion is based on the assessment that structural steel loses 50-60 percent of its load-bearing strength upon reaching the 538^{o}C (1,000^{o}F) threshold [15,16]. The loss of strength could cause failure of the ceiling structure resulting in collapse of the roof. Additionally, the maximum instantaneous allowable ceiling steel temperature is 649^{o}C (1,200^{o}F). Ceiling temperatures in excess of these thresholds during a test are taken as an indication of ineffective fire protection. The maximum 1-min average temperature is recorded for every test.

4.9.4 Gas Temperature

Ceiling level thermocouple (TC) measurements are taken at 125 locations on the ceiling, as illustrated in Appendix A. Trends in gas temperatures, as indicated by TC measurements, are analyzed for comparison purposes and to generate temperature contour plots along the ceiling. Additionally, the maximum 1-min average temperature is recorded for every test. The data are not used to evaluate the performance of the sprinkler system.

4.9.5 Total Energy Released

Although time-resolved heat release rates (HRR) cannot be determined from the calorimetry data, an estimate of the total energy release during the test can be obtained. The total energy can be calculated by integrating the chemical HRR curve, calculated from mass flow rate and gas analysis data for CO and CO_2 [7]. Integration under the data curve is possible up to test termination. After the test is terminated, an exponential best fit curve of the decay portion of the test data is used to estimate the tail portion of the HRR and again integrated to provide total energy released. These two values are added to provide a value for the total energy released during the test. This value can be used to estimate the total amount of commodity consumed and can be used as a test-to-test comparison. For error analysis, it is assumed that the total energy up to test termination has ± 10% error and the post test curve fit data have 50% error.

5 TEST RESULTS AND DATA ANALYSIS

This section presents the results of the four large-scale fire tests conducted to evaluate the effect of an HVLS fan on the protection provided by a ceiling level sprinkler system. A summary of the test conditions and results is shown in Table 5-1. A more in-depth description of the test setup can be found in Table i and Table ii of the Executive Summary. In addition, a complete analysis of each test (including time resolved data) can be found in Appendices B - E.

Protection for each test was provided by quick-response, pendent sprinklers, having a 71^{o}C (160^{o}F) rated link and a K-Factor of 202 L/min/bar$^{1/2}$ (14 gpm/psi$^{1/2}$). Sprinklers were installed on 3.0 x 3.0 m spacing (10 x 10 ft) to provide a 48.9 mm/min (1.2 gpm/ft^{2}) density at 5.2 bar (75 psi) over the protected area. The ceiling was set at a height of 12.2 m (40 ft) above the floor.

Tests 1 and 2 were conducted to evaluate the expected worst-case placement of the HVLS fan. For Test 1, the main array was centered below one sprinkler and the fan was offset 2.2 m (7.1 ft) to the northeast. A total of 12 sprinklers operated with the first operation occurring at 1 min 28 s after ignition. Fire spread remained within the confines of the test array; however, extensive damage occurred on both the east and west rows of the main array and the aisle face of both the east and west target arrays. For Test 2, the main array was centered among four sprinklers and the fan was centered[*] over the main array. A total of 12 sprinklers operated with the first operation occurring at 1 min 42 s after ignition. Fire spread remained within the confines of the main array with damage primarily sustained on the eastern row; however, there was extensive damage to the commodity on the backside of the east target array. Both tests exceeded the evaluation criterion for the allowable number of sprinkler operations (Section 4.9.1). Test 2 additionally exceeded the extent of damage criterion (Section 4.9.2) and, therefore, was considered the worst-case configuration.

Test 3 was conducted to evaluate the effect of fan shut down. The configuration was identical to Test 2, except the fan was shut off 1 min 30 s after first sprinkler operation, simulating triggering

[*] The actual fan placement was offset 0.3 m (1 ft) northeast of the ceiling center due to the presence of the instrumentation used to acquire ceiling steel temperatures.

from a water flow alarm. A total of four sprinklers operated with the first operation occurring at 1 min 54 s after ignition. Fire spread remained within the confines of the main array, with damage primarily sustained on the eastern row and minimal damage on the aisle face of the east target array. These results are within the specified levels (Section 4.9) and indicate that fan shut down can allow the sprinkler system to perform acceptably under these conditions.

Test 4 was conducted to evaluate the effect of a high clearance between the top of the stored commodity and the ceiling. The general test configuration was consistent with Tests 2 and 3, except a lower storage height of 4.6 m (15 ft) resulted in a 7.6 m (25 ft) clearance. A total of 4 sprinklers operated with the first operation occurring at 1 min 39 s after ignition and the final occurring at 1 min 42 s after ignition. The fan was shut off 1 min 30 s after first sprinkler operation; all sprinkler operations had occurred by this time. Fire damage was limited to the main array, with no jump to either target array.

Table 5-1: Summary of test setup and results

Configuration and Results	Test 1	Test 2	Test 3	Test 4
Detailed Analysis, Appendix	**B**	**C**	**D**	**E**
Test Configuration				
Commodity	Cartoned Unexpanded Plastic (CUP), Double Row Rack Storage			
Commodity / Ceiling Height [m (ft)]	9.1 / 12.2 (30 / 40)	9.1 / 12.2 (30 / 40)	9.1 / 12.2 (30 / 40)	4.6 / 12.2 (15 / 40)
Main Array Located Below – number of sprinklers	1	4	4	4
Fan Operation	Full speed, Entire test		Full speed, Off at 90s	
Test Results				
Sprinklers Operations	12	12	4	4
Total Energy[†] **[MJ (BTU x 10^3)]**	18,000 ± 2000 (17,000 ± 3,400)	7,500 ± 1,100 (7,100 ± 1,000)	3,500 ± 500 (3,300 ± 500)	750 ± 100 (700 ± 100)
Consumed Commodity [pallet load equivalent]	12.5	5	2.5	0.5
Target Jump (east/west) @ Time [min:s]	East, 3:09 West, 5:50	East, 2:13 West, no	East, 3:00 West, no	East, no West, no
Maximum One-Minute Steel Temperature [^oC (^oF)]	76 (169) @ 5:54	47 (117) @ 4:49	45 (113) @ 4:41	28 (113) @ 1:46
Maximum One-Minute TC Measurement [^oC (^oF)]	293 (559) @ 4:26	120 (266) @ 3:07	144 (291) @ 1:45	44 (112) @ 1:42
Test Termination [min:s]	35:00	25:00	30:00	30:00

[†] To allow for a meaningful comparison of total energy generated, tests were conducted until the fire was largely extinguished (only minimal lingering fire remained) by the sprinkler system.

5.1 SPRINKLER OPERATION PATTERNS

A plan view of the sprinkler operation pattern for each test is presented in Figure 5-1. The location of the test array and the HVLS fan are included for reference. A total of 12 sprinklers operated in Tests 1 and 2, and a total of four sprinklers operated in Tests 3 and 4.

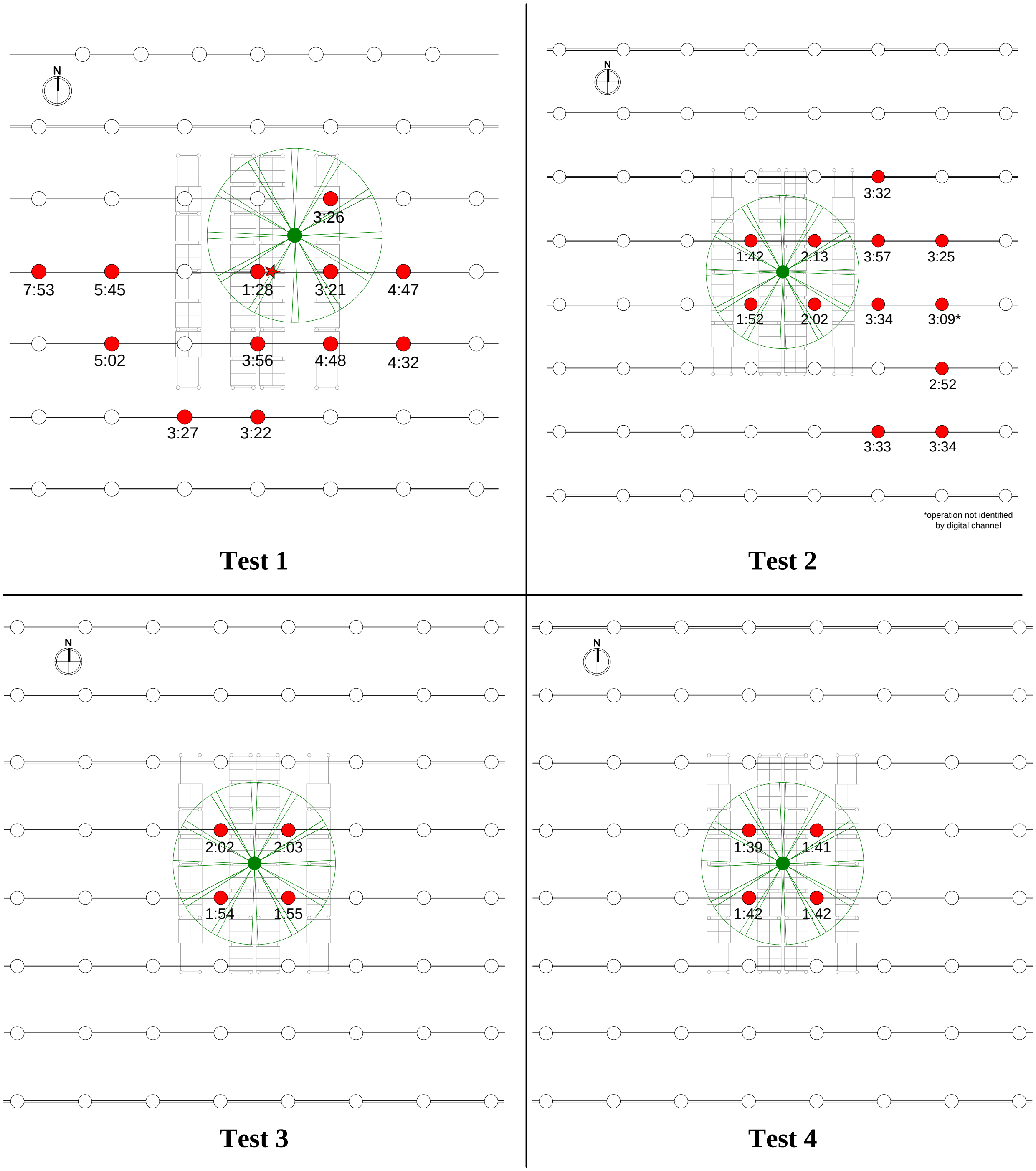


Figure 5-1: Sprinkler operation pattern for Tests 1 - 4

5.2 TOTAL ENERGY

Figure 5-2 presents the total integrated energy produced during Tests 1 - 4. The presented data are based on the generation rates of carbon dioxide and carbon monoxide as described in Section 4.9.5. To allow for a meaningful comparison, each test was conducted until the fire was largely extinguished by the sprinkler system with only small lingering fires remaining. Therefore, the actual duration varies between tests. The estimated total energy for each test was 18,000 ± 2,000 MJ (17,000 ± 3,400 BTU x 10^3) for Test 1, 7,500 ± 1,100 MJ (7,100 ± 1,000 BTU x 10^3) for Test 2, 3,500 ± 500 MJ (3,300 ± 500 BTU x 10^3), and 750 ± 100 MJ (700 ± 100 BTU x 10^3) for Test 4.

The total energy only reflects the quantity of consumed commodity, not the performance of the sprinkler system. Performance of the sprinkler system is based on the evaluation criteria detailed in Section 4.9. For instance, the total commodity consumed was greatest in Test 1, while the negative impact on the sprinkler performance was greatest in Test 2 (based on the potential for fire propagation beyond the test array).

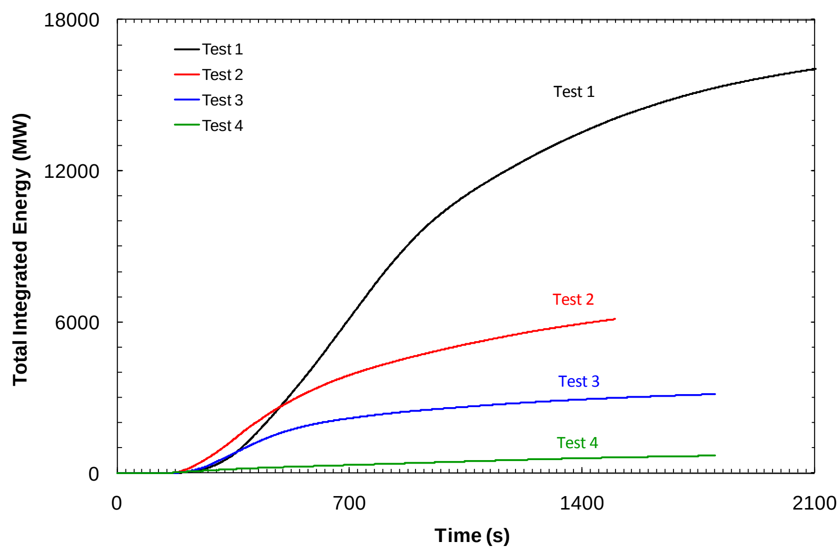


Figure 5-2: Total integrated energy for Tests 1 - 4

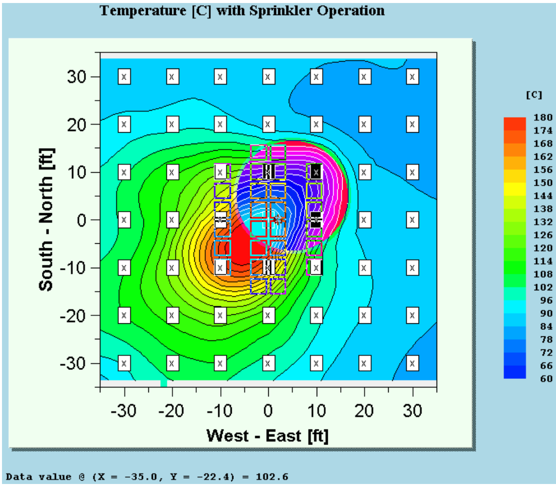
Note that the above graph only includes total energy collected during the fire test. As discussed in Section 4.9.5, the total energy released for each test also includes an estimation of the combustions gases remaining in the laboratory space after the test is terminated.

5.3 CEILING GAS CENTROID AT FIRST SPRINKLER OPERATION

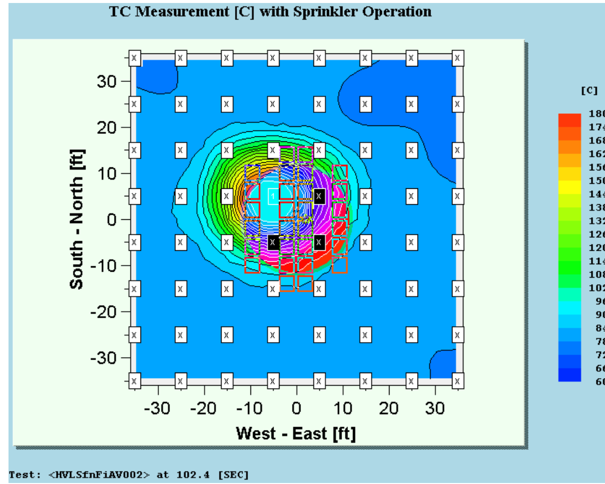
Figure 5-3 presents the ceiling TC measurement contours at first sprinkler operation and the corresponding location of the ceiling gas centroid*, for Tests 1 - 4. Note that the circle towards the center of the figure (noted by inverted colors) indicates the fan location. The time evolution of the two coordinates of the ceiling gas centroid for each test can be found in Appendices B through E.

The departure of the ceiling gas centroid from the ignition location suggests the operating HVLS fan disturbed the fire plume above the stored commodity. For example, the ceiling gas centroid coordinates at first sprinkler operation for Test 1 were 1.3 m south x 2.0 m west (4.3 ft south x 6.6 ft west). This is coincides with the approximate center of the peak TC measurement contours shown in Figure 5-3. Without the fan the ceiling gas centroid would be nominally centered over the ignition location for this test arrangement.

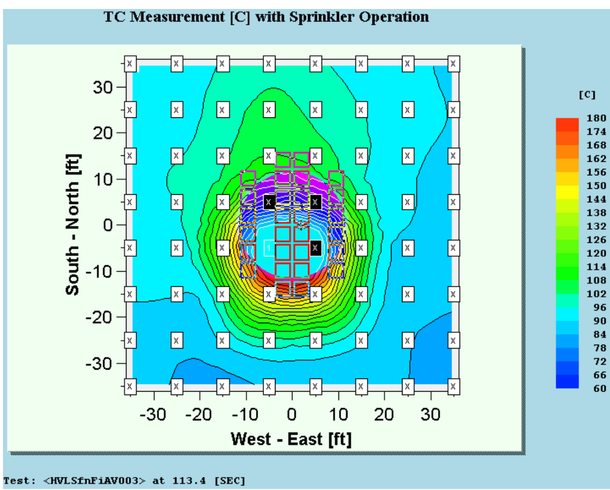
* Centroid refers to the geometric center of the ceiling gas layer produced by the fire, based on summation of normalized magnitude of ceiling TC measurements weighted by location. The position of the centroid is a measure of the axis of the fire plume above the test array.



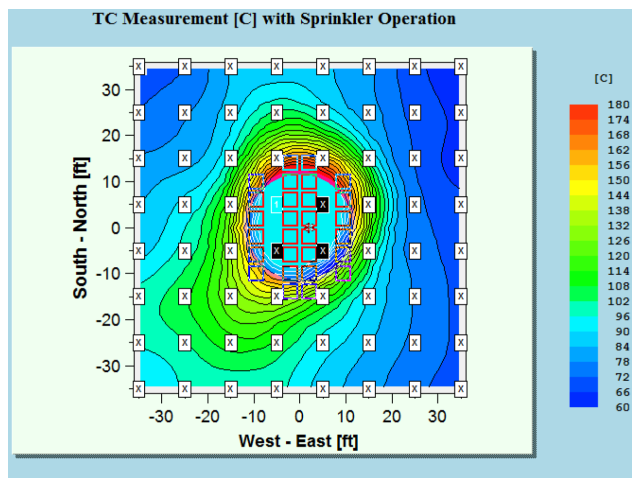
Test 1
[Centroid coordinates: 1.3 m south x 2.0 m west]



Test 2
[Centroid coordinates: 0.7 m north x 1.3 m west]



Test 3
[Centroid coordinates: 0.8 m south x 0.3 m west]



Test 4
[Centroid coordinates: 0.8 m south x 1.1 m west]

Figure 5-3: Contour plots of ceiling TC measurements at first sprinkler operation for Tests 1 – 4

5.4 CEILING AIR-FLOW STABILIZATION

Figure 5-4 presents the ceiling level air velocities under three conditions for Test 1: 1) ambient lab conditions, 2) with only the building control system exhaust fan operating at 94 m^3/s (200,000 cfm), and 3) with the addition of the HVLS fan operating at full speed (66 rpm). Air velocities were measured using bidirectional probes mounted at four orthogonal locations at a radial distance of 2.1, 4.0 and ~10.4 m (7, 13, and ~34 ft) from the ceiling center as described in Section 4.7. As shown, positive values indicate air flow outward from the ceiling center and negative values indicate inward flow.

Under ambient lab conditions, the air flow across the ceiling is minimal with the greatest velocity of ± 0.25 m/s (0.8 ft/s) occurring at the outermost measurement locations of 12.2 m (40 ft). The range of measured flows decreased to ± 0.15 m/s (0.5 ft/s) for the 4.0 m (13.1 ft) and 1.2 m (4 ft) measurement locations. The inclusion of the building control system exhaust fan at -780 s resulted in a negligible change in the air flow. However, the addition of the HVLS fan at -300 s resulted in a significant increase in the air flow at the ceiling, with the disturbance decreasing with distance from the fan. The specific air velocities ranged from -2.9 to 1.1 m/s at a radial distance of 2.4 m (8 ft), -2.1 to -0.8 m/s at a radial distance of 4.0 m (13.1 ft) and -0.3 to 0.6 m/s at a radial distance of approximately 10.4 m (34 ft). Similar results were found for Tests 2 - 4.

These results indicate that the air flow generated by the HVLS has the dominant influence on the ceiling level gas flow prior to the fire.

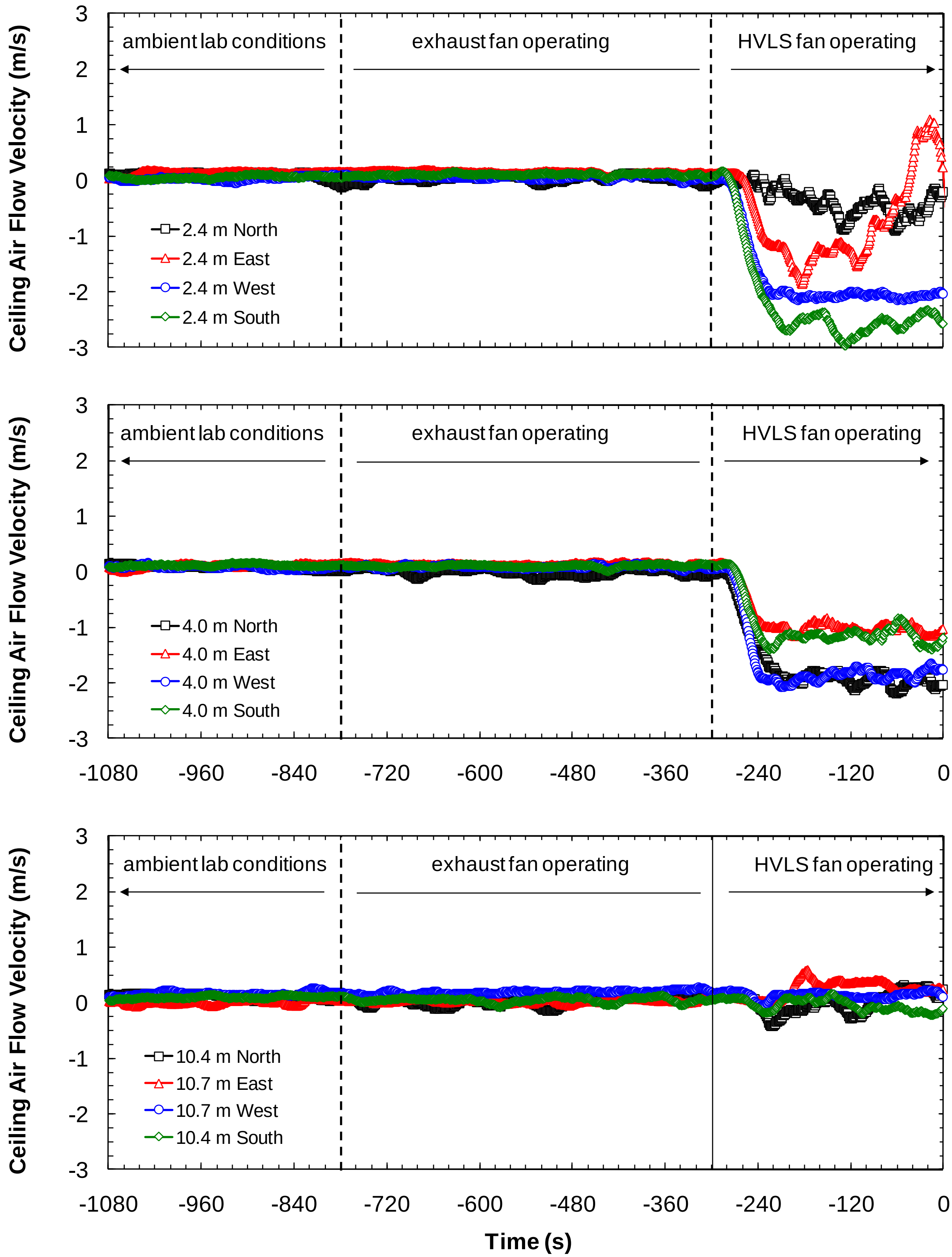


Figure 5-4: Ceiling level air flow resulting from building exhaust only for Test 1

5.5 COLD FLOW AIR VELOCITY AT ARRAY TOP

Table 5-2 presents the average air velocities measured at 12.7 cm (5 in.) above the top of the main array, as described in Section 4.8, for Tests 1 - 4. Air velocities were measured continually at 15 locations that were 13 cm (5 in.) above the top of the main array, surrounding the ignition bay. The measurement locations were separated into three groups: W1 – W5 were 7.6 cm (3 in.) out from the main array commodity in the west aisle, C1 – C5 were centered above the longitudinal flue, and E1 – E5 were 7.6 cm (3 in.) out from the main array commodity in the east aisle.

Figure 5-5 through Figure 5-8 illustrate the data present in Table 5-2. A plan view schematic of the measurement locations relative to the array and the fan is included for reference. As shown, positive values indicate upward flow and negative values indicate downward flow. Each value, which represents an average over a minimum 30-minute duration, was acquired with only the fan operating, *i.e.*, no fire or exhaust air. As discussed in Section 4.8.1, these are referred to as 'cold flow' measurements in this report.

For Test 1, where the fan was offset from the array center, the maximum downward velocity was -4.6 m/s (-15.1 ft/s). Consistent with typical fan air flow, the higher velocities were generally experienced around 50% of the fan blade length. This resulted in higher velocities in the eastern aisle space than in the western aisle space. For the array configuration used in Tests 2 and 3, where the fan was centered over the array, the maximum downward velocity decreased to -3.5 m/s (-11.5 ft/s) and was more evenly distributed between the eastern and western aisle. The decrease can be attributed to the close proximity of the measurement locations to the fan hub, where the fan blades are less efficient. Note that the configuration of Tests 2 and 3 was identical; therefore, cold flow data were only acquired for Test 2.

Test 4 was conducted with the same configuration used in Tests 2 and 3, except the array height was reduced to 4.6 m (15 ft) resulting in a 7.6 m (25 ft) clearance to the ceiling. Measurements were acquired with the fan operating at both full speed (66 rpm) and half speed (33 rpm). With the fan operating at full speed, the air velocities at the top of the array are similar to those experienced with the higher array used in Tests 2 and 3. The maximum downward velocity of

-3.1 m/s (-10.2 ft/s) was measured at the farthest radial distance from the fan hub. This value is within ~10% peak velocity measured during Tests 2 and 3, and indicates that the air velocity did not substantially decrease with the increased clearance. Operating the fan at half speed significantly decreased the air flow, with a maximum downward velocity of -1.3 m/s (-4.3 ft/s) and an average velocity of approximately -0.5 m/s (-1.6 ft/s). This range represents a 60% reduction in the peak air velocity.

Table 5-2: Average cold flow air velocities at top of array for Tests 1 – 4 [negative velocities indicate downward air flow]

Location Identifier	Coordinates* [x,y]	Test 1	Tests 2 and 3†	Test 4	
	m (ft)	m/s (ft/s)	m/s (ft/s)	m/s (ft/s)	
W5	-1.2, 1.2 (-4, 4)	-1.8 (-5.9)	-2.9 (-9.5)	-2.6 (-8.5)	-1.1 (-3.6)
W4	-1.2, 0.6 (-4, 2)	-3.8 (-12.5)	-2.5 (-8.2)	-1.8 (-5.9)	-0.6 (-2.0)
W3	-1.2, 0 (-4, 0)	-4.1 (-13.5)	-3.1 (-10.2)	-2.2 (-7.2)	-0.5 (-1.6)
W2	-1.2, -0.6 (-4, -2)	-2.6 (-8.5)	-3.3 (-10.8)	-1.9 (-6.2)	-0.3 (-1.0)
W1	-1.2, -1.2 (-4, -4)	-0.5 (-1.6)	-3.5 (-11.5)	-3.1 (-10.2)	-0.8 (-2.6)
C5	0, 1.2 (0, 4)	-3.0 (-9.8)	-1.4 (-4.6)	-2.2 (-7.2)	-0.9 (-3.0)
C4	0, 0.6 (0, 2)	-2.0 (-6.6)	-0.6 (-2.0)	-1.3 (-4.3)	-0.5 (-1.6)
C3	0, 0 (0, 0)	-4.2 (-13.8)	-1.3 (-4.3)	-1.5 (-4.9)	-0.3 (-1.0)
C2	0, -0.6 (0, -2)	-4.6 (-15.1)	-1.2 (-3.9)	-1.1 (-3.6)	0.0 (0.1)
C1	0, -1.2 (0, -4)	-1.7 (-5.6)	-2.5 (-8.2)	-2.1 (-3.9)	-0.4 (-1.3)
E5	1.2, 1.2 (4, 4)	-2.6 (-8.5)	-3.0 (-9.8)	-3.0 (-9.8)	-1.3 (-4.3)
E4	1.2, 0.6 (4, 2)	-2.7 (-8.9)	-2.0 (-6.6)	-1.8 (-5.9)	-0.8 (-2.6)
E3	1.2, 0 (4, 0)	-3.0 (-9.8)	-2.1 (-3.9)	-1.7 (-5.6)	-0.7 (-2.3)
E2	1.2, -0.6 (4, -2)	-3.1 (-10.2)	-2.7 (-8.9)	-1.7 (-5.6)	-0.6 (-2.0)
E1	1.2, -1.2 (4, -4)	-4.2 (-13.8)	-3.3 (-10.8)	-2.4 (-7.9)	-0.9 (-3.0)
Array height	-	9.1 m (30 ft)	9.1 m (30 ft)	4.6 m (15 ft)	
Fan Speed	-	66 rpm	66 rpm	66 rpm	33 rpm

* Coordinates are relative to the ceiling center (note that the main array was centered below the ceiling)

† The configuration for Tests 2 and 3 were identical; therefore, cold flow data were only acquired for Test 2

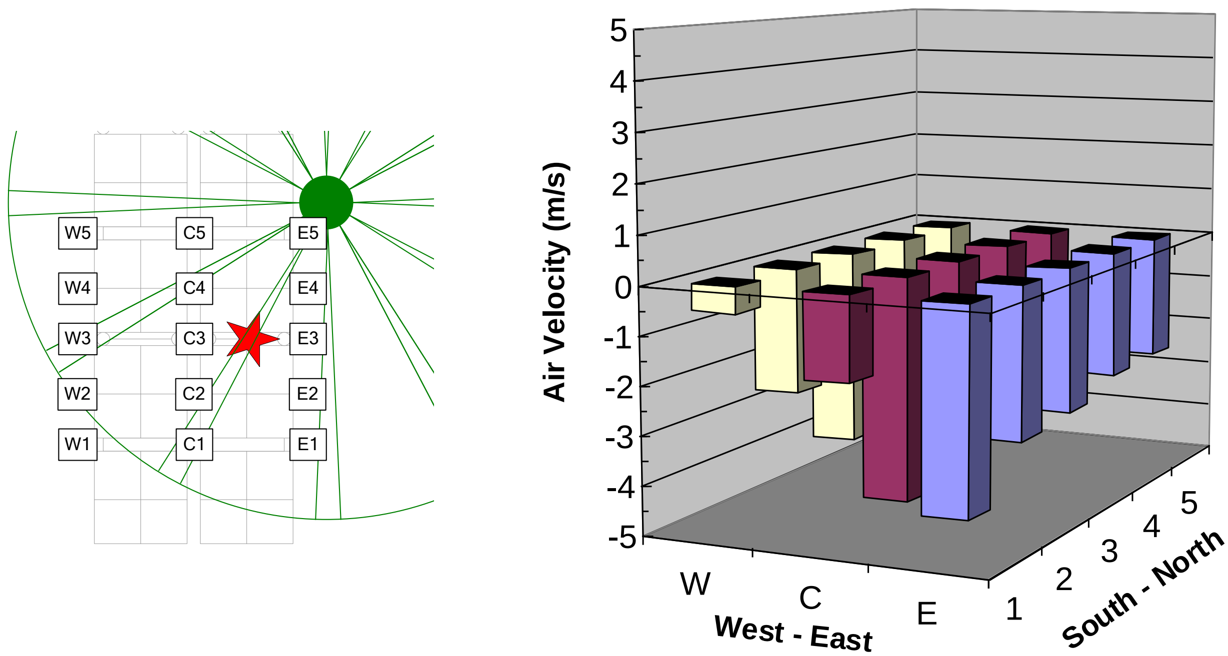


Figure 5-5: Air-flow at top of array [3.2 m (10.5 ft) below ceiling] with fan operating at 66 rpm for Test 1

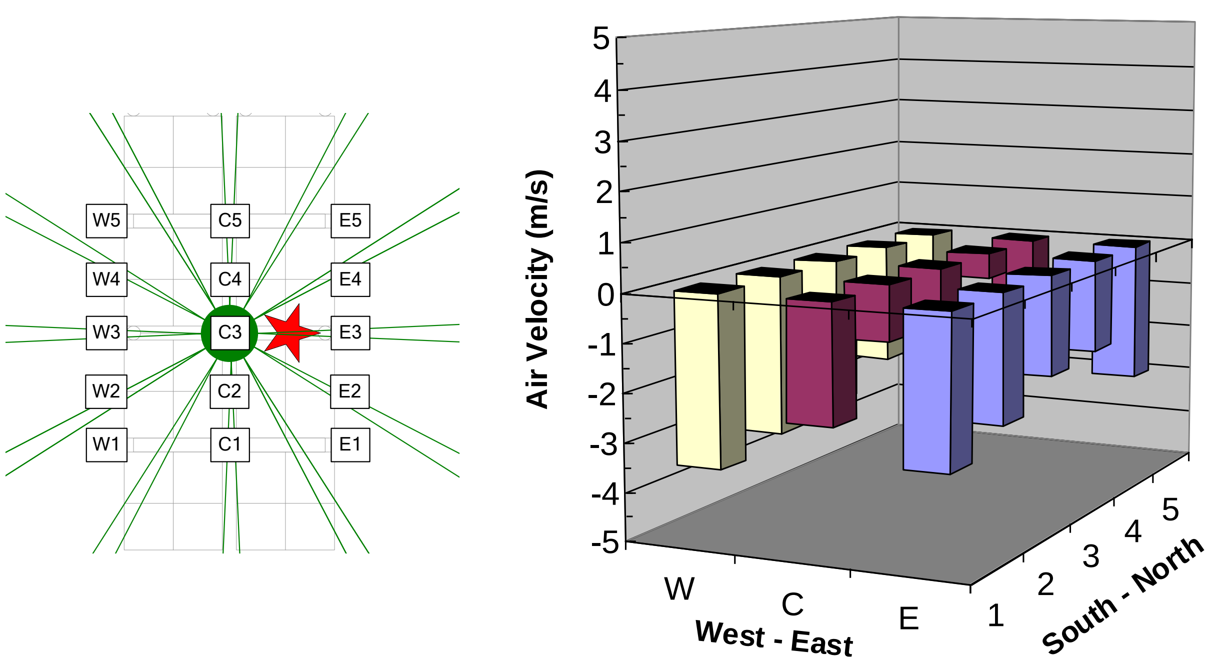


Figure 5-6: Air-flow at top of array [3.2 m (10.5 ft) below ceiling] with fan operating at 66 rpm for Tests 2 and 3

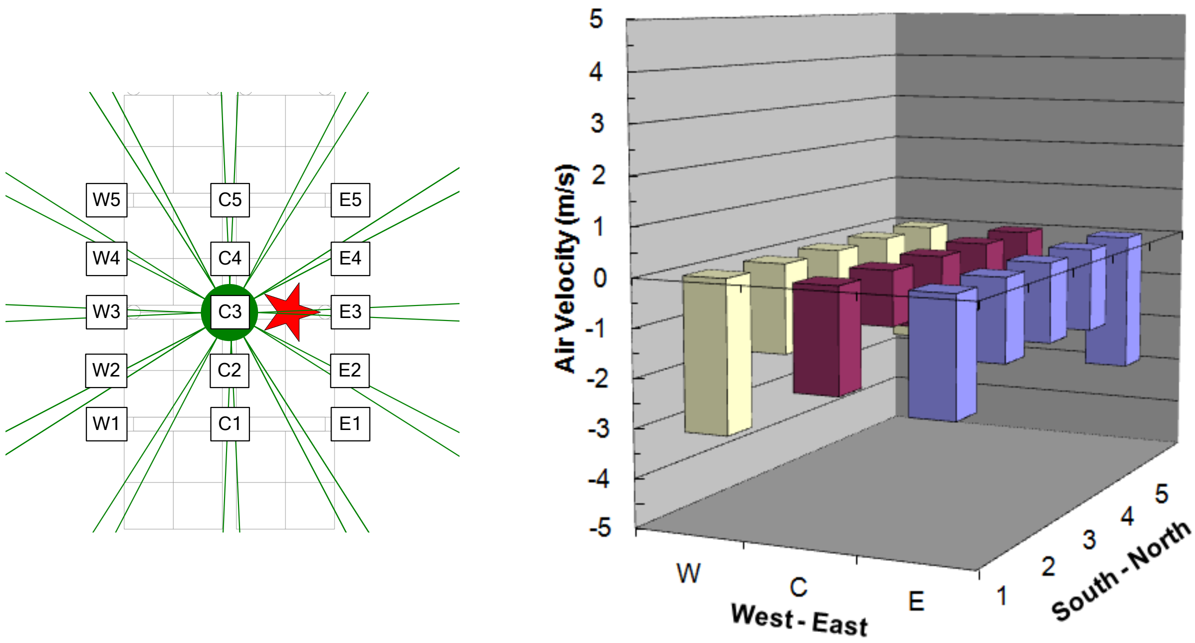


Figure 5-7: Air-flow at top of array [7.8 m (25.5 ft) below ceiling] with fan operating at <u>66 rpm</u> for Test 4

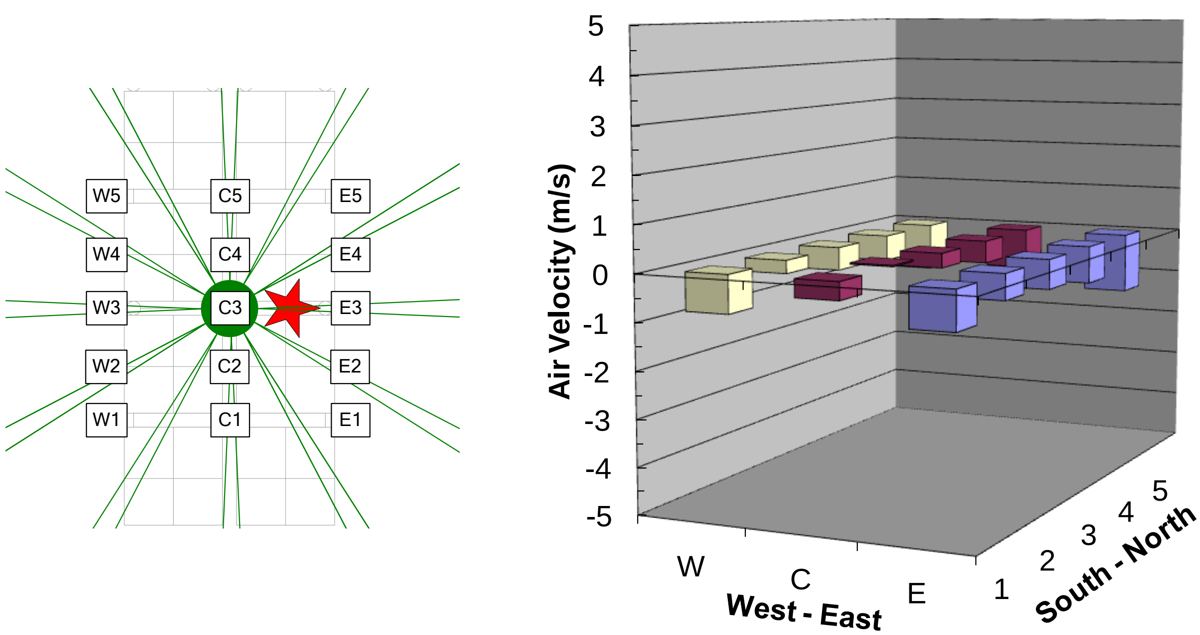


Figure 5-8: Air-flow at top of array [7.8 m (25.5 ft) below ceiling] with fan operating at <u>33 rpm</u> for Test 4

5.6 COLD FLOW AIR VELOCITY THROUGH ARRAY

Table 5-3 through Table 5-6 present the average air velocities measured within the main array for Tests 1 - 4, as described in Section 4.8.2. As shown, positive values indicate upward flow and negative values indicate downward flow. Each value represents a 5-minute average and was acquired with only the fan operating, *i.e.*, no fire or exhaust air. All louvers on the external walls of the test volume and those of the dehumidification system were also closed to mitigate unwanted air movement. For reference, an overview schematic of the instrumentation locations relative to the fan was previously shown in Figure 4-8. The location of the measurement elevations was also shown in Figure 4-10 for a six-tier array. For a three-tier array, only levels one through four are used.

The following analysis assumes that downward air flow velocities less than -1 m/s (3.3 ft/s) are not sufficient to notably affect fire growth. Figure 5-9 illustrates the air flow velocity data for Test 1 (Table 5-3), where the fan was offset from the main array center. These data coincide with the measurements at 15 cm (6 in.) above the array (Figure 5-5 of Section 5.5), where the air flow velocities were greatest in the eastern aisle space and weakest in the western aisle space. A peak downward air velocity of -4.5 m/s (-14.8 ft/s) was measured at the sixth level. Downward air flows greater than -1 m/s (-3.3 ft/s) penetrate to the third level in the eastern aisle and central flue, and the fourth level in the western aisle. The vertical air flow at the lowest two levels of the array was minimal; however, visual observation of the fire test indicated that the air flow at these elevations may be predominantly horizontal due to air sweeping across the floor. Additionally, observations suggest that the upward air flow measured towards the top of the array in the western aisle is due to air currents traveling down the flue spaces, across the top of the commodity, and re-circulating back into the aisle space.

Figure 5-10 illustrates the air flow velocity data for Tests 2 and 3 (Table 5-4), where the fan was centered over the main array. As noted earlier, the configuration for Tests 2 and 3 were identical; therefore, data were only acquired once. Similar to the measurements at 12.7 cm (5 in.) above the array (Figure 5-6 of Section 5.5), the air flow velocities are fairly uniform at the upper levels within the array and a peak velocity of -4.2 m/s (-13.8 ft/s) was measured at the sixth level.

Downward air flows greater than -1 m/s (-3.3 ft/s) penetrated to the third level in the eastern aisle and central flue, and the fourth level in the western aisle. Interestingly, the air flow at the base of the array appears to sweep across the floor and create an updraft as high as 1 m/s (3.3 ft/s) within the central flue space.

Figure 5-11 illustrates the air flow velocity data for Test 4 (Table 5-5 and Table 5-6), which was a high clearance configuration (array height of three tiers) with the fan centered over the main array. Air velocity measurements were acquired with the fan operating at full speed (66 rpm) and half speed (33 rpm) for this test configuration [data for measurement locations C2 – C5 of Level 2 are not shown due to an instrumentation error]. The corresponding air flow velocity data at 12.7 cm (5 in.) above the array can be found in Section 5.5. At 66 rpm, the air flow above the second tier of the array was generally downward and had a magnitude greater than -2.0 m/s (-6.6 ft/s). Note that the peak downward velocity of -2.9 m/s (-9.5 ft/s) represents a 30% reduction compared to Test 2 and 3, which included a taller six-tier array. The air velocity reversed to a slightly upward flow for the lower two measurement levels with an average velocity of ~0.5 m/s (1.6 ft/s) above the first tier and ~0.7 m/s (2.3 ft/s) near the floor. At the lower fan operating speed of 33 rpm, the peak air flow velocities decreased significantly with magnitudes above the third measurement level of approximately -1.0 m/s (ft/s). The velocities decreased further for the lower two measurement levels with magnitudes of 0.3 m/s (1.0 ft/s) or less.

A point of perspective on the results of the analysis of the velocity measurements is provided by previous work by Ingason [11,17], which suggests that the upward gas velocity of a fully developed fire in the flue space of a four-tier, open double-row rack storage array can be up to 10 m/s (33 ft/s)[*]. In those experiments the higher gas velocities were measured at the upper storage tiers and decreased towards the base of the fire, at the lower storage tiers. This suggests that while the HVLS fan displaces the ceiling gas centroid, the air flow within the array is dominated by the buoyancy of the fire.

[*] The actual experiments were a 1:3 scale of a large-scale test, using Froude modeling, and measured an upward flue gas velocity of 6 m/s at 1100 K. (Using a scaling factor of $S^{1/2}$, this value corresponds to 10 [m/s] = $3^{1/2}\cdot 6$ [m/s])

Table 5-3: Average cold flow air velocities through array for Test 1 (metric units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
	m	m/s	m/s	m/s	m/s	m/s	m/s
W5	-1.2, 1.2	-0.5	-0.4	-1.2	-1.4	-1.5	-2.4
W4	-1.2, 0.6	-0.5	-0.1	-0.1	0.3	0.5	0.3
W3	-1.2, 0	-0.5	0.1	-0.1	-1.2	-1.4	-3.8
W2	-1.2, -0.6	-0.3	0.1	0.0	0.2	0.4	0.8
W1	-1.2, -1.2	-0.4	-0.1	-0.3	-0.7	-1.5	-1.1
C5	0, 1.2	0.2	-0.1	-0.4	-1.4	-1.6	-3.5
C4	0, 0.6	0.2	0.1	0.1	-0.5	-2.0	-2.2
C3	0, 0	0.0	0.1	-0.0	-0.6	-2.1	-3.9
C2	0, -0.6	0.3	0.1	0.2	-0.4	-1.5	-2.5
C1	0, -1.2	-0.0	-1.3	-1.4	-1.9	-2.2	-2.9
E5	1.2, 1.2	0.4	0.09	-0.3	-1.9	-3.0	-3.4
E4	1.2, 0.6	0.1	0.19	-1.4	-1.8	-3.4	-3.8
E3	1.2, 0	0.2	-0.05	-1.5	-2.1	-3.1	-3.7
E2	1.2, -0.6	-0.1	-0.39	-1.4	-2.8	-3.8	-4.0
E1	1.2, -1.2	0.0	-0.16	-2.3	-3.5	-4.2	-4.5

Average cold flow air velocities through array for Test 1 (English units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
	ft	ft/s	ft/s	ft/s	ft/s	ft/s	ft/s
W5	-4, 4	-1.6	-1.3	-3.9	-4.6	-4.9	-7.9
W4	-4, 2	-1.6	-0.3	-0.3	1.0	1.6	1.0
W3	-4, 0	-1.6	0.3	-0.3	-3.9	-4.6	-12.5
W2	-4, -2	-1.0	0.3	0.0	0.7	1.3	2.6
W1	-4, -4	-1.3	-0.3	-1.0	-2.3	-4.9	-3.6
C5	0, 4	0.7	-0.3	-1.3	-4.6	-5.2	-11.5
C4	0, 2	0.7	0.3	0.3	-1.6	-6.6	-7.2
C3	0, 0	0.0	0.3	0.0	-2.0	-6.9	-12.8
C2	0, -2	1.0	0.3	0.7	-1.3	-4.9	-8.2
C1	0, -4	0.0	-4.3	-4.6	-6.2	-7.2	-9.5
E5	4, 4	1.3	0.3	-1.0	-6.2	-9.8	-11.2
E4	4, 2	0.3	0.6	-4.6	-5.9	-11.2	-12.5
E3	4, 0	0.7	-0.2	-4.9	-6.9	-10.2	-12.1
E2	4, -2	-0.3	-1.3	-4.6	-9.2	-12.5	-13.1
E1	4, -4	0.0	-0.5	-7.5	-11.5	-13.8	-14.8

Table 5-4: Average cold flow air velocities through array for Tests 2 and 3 (metric units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
	m	m/s	m/s	m/s	m/s	m/s	m/s
W5	-1.2, 1.2	0.5	0.6	-0.8	-1.4	-2.0	-2.9
W4	-1.2, 0.6	0.2	0.3	-0.8	-0.9	-1.3	-2.1
W3	-1.2, 0	0.6	0.6	-0.3	-0.4	-1.0	-2.6
W2	-1.2, -0.6	0.6	0.5	-0.2	-0.6	-0.3	-0.5
W1	-1.2, -1.2	0.6	1.0	-0.2	-1.6	-2.1	-2.7
C5	0, 1.2	0.7	1.0	0.9	-0.4	-1.9	-2.8
C4	0, 0.6	1.0	0.9	0.9	0.1	-1.5	-2.3
C3	0, 0	0.4	0.8	0.7	-0.2	-1.4	-3.1
C2	0, -0.6	0.9	0.6	0.6	-0.5	-1.5	-2.8
C1	0, -1.2	0.5	0.5	-0.1	-1.3	-2.4	-3.3
E5	1.2, 1.2	0.6	0.4	-0.3	-1.2	-2.3	-2.5
E4	1.2, 0.6	0.5	0.3	-0.5	-1.4	-1.6	-1.8
E3	1.2, 0	0.4	0.2	-0.8	-1.4	-1.8	-2.8
E2	1.2, -0.6	0.1	0.0	-1.2	-2.1	-3.2	-3.7
E1	1.2, -1.2	0.3	-0.4	-1.6	-3.0	-4.1	-4.2

Average cold flow air velocities through array for Tests 2 and 3 (English units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
	ft	ft/s	ft/s	ft/s	ft/s	ft/s	ft/s
W5	-4, 4	1.6	2.0	-2.6	-4.6	-6.6	-9.5
W4	-4, 2	0.7	1.0	-2.6	-3.0	-4.3	-6.9
W3	-4, 0	2.0	2.0	-1.0	-1.3	-3.3	-8.5
W2	-4, -2	2.0	1.6	-0.7	-2.0	-1.0	-1.6
W1	-4, -4	2.0	3.3	-0.7	-5.2	-6.9	-8.9
C5	0, 4	2.3	3.3	3.0	-1.3	-6.2	-9.2
C4	0, 2	3.3	3.0	3.0	0.3	-4.9	-7.5
C3	0, 0	1.3	2.6	2.3	-0.7	-4.6	-10.2
C2	0, -2	3.0	2.0	2.0	-1.6	-4.9	-9.2
C1	0, -4	1.6	1.6	-0.3	-4.3	-7.9	-10.8
E5	4, 4	2.0	1.3	-1.0	-3.9	-7.5	-8.2
E4	4, 2	1.6	1.0	-1.6	-4.6	-5.2	-5.9
E3	4, 0	1.3	0.7	-2.6	-4.6	-5.9	-9.2
E2	4, -2	0.3	0.0	-3.9	-6.9	-10.5	-12.1
E1	4, -4	1.0	-1.3	-5.2	-9.8	-13.5	-13.8

Table 5-5: Average cold flow air velocities through array for Test 4 (66 rpm) (metric units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2†	Level 3
	m	m/s	m/s	m/s
W5	-1.2, 1.2	0.8	-0.3	-2.0
W4	-1.2, 0.6	0.6	0.6	-0.6
W3	-1.2, 0	0.5	0.5	-1.9
W2	-1.2, -0.6	0.5	1.0	0.5
W1	-1.2, -1.2	0.7	0.6	-2.4
C5	0, 1.2	0.4	n/a	-2.8
C4	0, 0.6	0.7	n/a	-2.4
C3	0, 0	0.4	n/a	-2.9
C2	0, -0.6	0.6	n/a	-2.2
C1	0, -1.2	0.3	-0.2	-2.9
E5	1.2, 1.2	1.0	0.1	-2.0
E4	1.2, 0.6	0.7	0.6	0.9
E3	1.2, 0	0.4	0.5	-1.9
E2	1.2, -0.6	0.3	0.2	-0.4
E1	1.2, -1.2	1.1	-0.1	-1.4

† No data were acquired for locations C2 through C5 due to an instrumentation error.

Average cold flow air velocities through array for Test 4 (66 rpm) (English units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2†	Level 3
	ft	ft/s	ft/s	ft/s
W5	-4, 4	2.5	-1.1	-6.6
W4	-4, 2	2.1	2.1	-2.0
W3	-4, 0	1.7	1.7	-6.4
W2	-4, -2	1.6	3.2	1.5
W1	-4, -4	2.2	2.1	-7.9
C5	0, 4	1.2	n/a	-9.3
C4	0, 2	2.2	n/a	-7.9
C3	0, 0	1.2	n/a	-9.5
C2	0, -2	2.0	n/a	-7.4
C1	0, -4	0.8	-0.7	-9.6
E5	4, 4	3.4	0.2	-6.7
E4	4, 2	2.2	1.9	2.9
E3	4, 0	1.3	1.5	-6.2
E2	4, -2	0.9	0.8	-1.2
E1	4, -4	3.6	-0.3	-4.6

† No data were acquired for locations C2 through C5 due to an instrumentation error.

Table 5-6: Average cold flow air velocities through array for Test 4 (33 rpm) (metric units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2	Level 3
	m	m/s	m/s	m/s
W5	-1.2, 1.2	0.2	0.1	-0.5
W4	-1.2, 0.6	0.1	0.1	0.0
W3	-1.2, 0	0.1	0.2	-0.2
W2	-1.2, -0.6	0.1	0.3	0.1
W1	-1.2, -1.2	0.1	-0.2	-0.7
C5	0, 1.2	-0.2	-0.2	-1.1
C4	0, 0.6	-0.1	-0.4	-1.1
C3	0, 0	0.0	-0.1	-0.9
C2	0, -0.6	0.1	-0.3	-0.9
C1	0, -1.2	0.2	-0.3	-1.0
E5	1.2, 1.2	0.0	0.2	-0.7
E4	1.2, 0.6	0.1	0.2	-0.3
E3	1.2, 0	0.1	0.2	-0.5
E2	1.2, -0.6	0.0	0.2	-0.6
E1	1.2, -1.2	0.4	-0.1	-0.7

Average cold flow air velocities through array for Test 4 (33 rpm) (English units)

Location Identifier	Coordinates [x,y]	Level 1	Level 2	Level 3
	ft	ft/s	ft/s	ft/s
W5	-4, 4	0.7	0.4	-1.5
W4	-4, 2	0.3	0.4	-0.1
W3	-4, 0	0.5	0.6	-0.6
W2	-4, -2	0.4	0.9	0.4
W1	-4, -4	0.5	-0.7	-2.4
C5	0, 4	-0.6	-0.7	-3.5
C4	0, 2	-0.2	-1.4	-3.7
C3	0, 0	-0.2	-0.5	-2.9
C2	0, -2	0.3	-0.9	-2.9
C1	0, -4	0.5	-1.1	-3.4
E5	4, 4	0.0	0.8	-2.2
E4	4, 2	0.2	0.6	-0.8
E3	4, 0	0.4	0.7	-1.6
E2	4, -2	0.0	0.6	-2.0
E1	4, -4	1.4	-0.4	-2.3

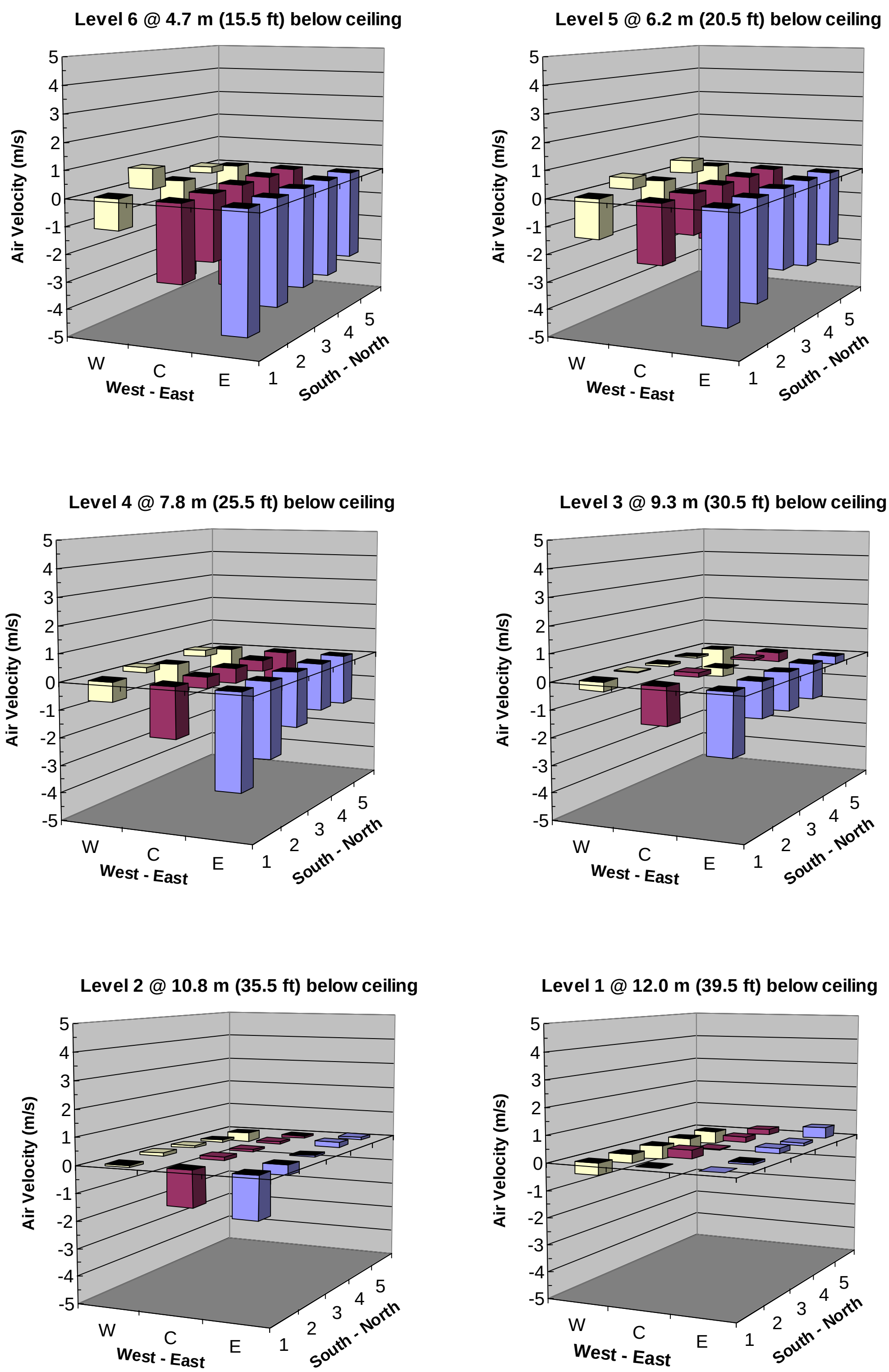


Figure 5-9: Air velocity through array with the fan at 66 rpm for Test 1 [no fire]

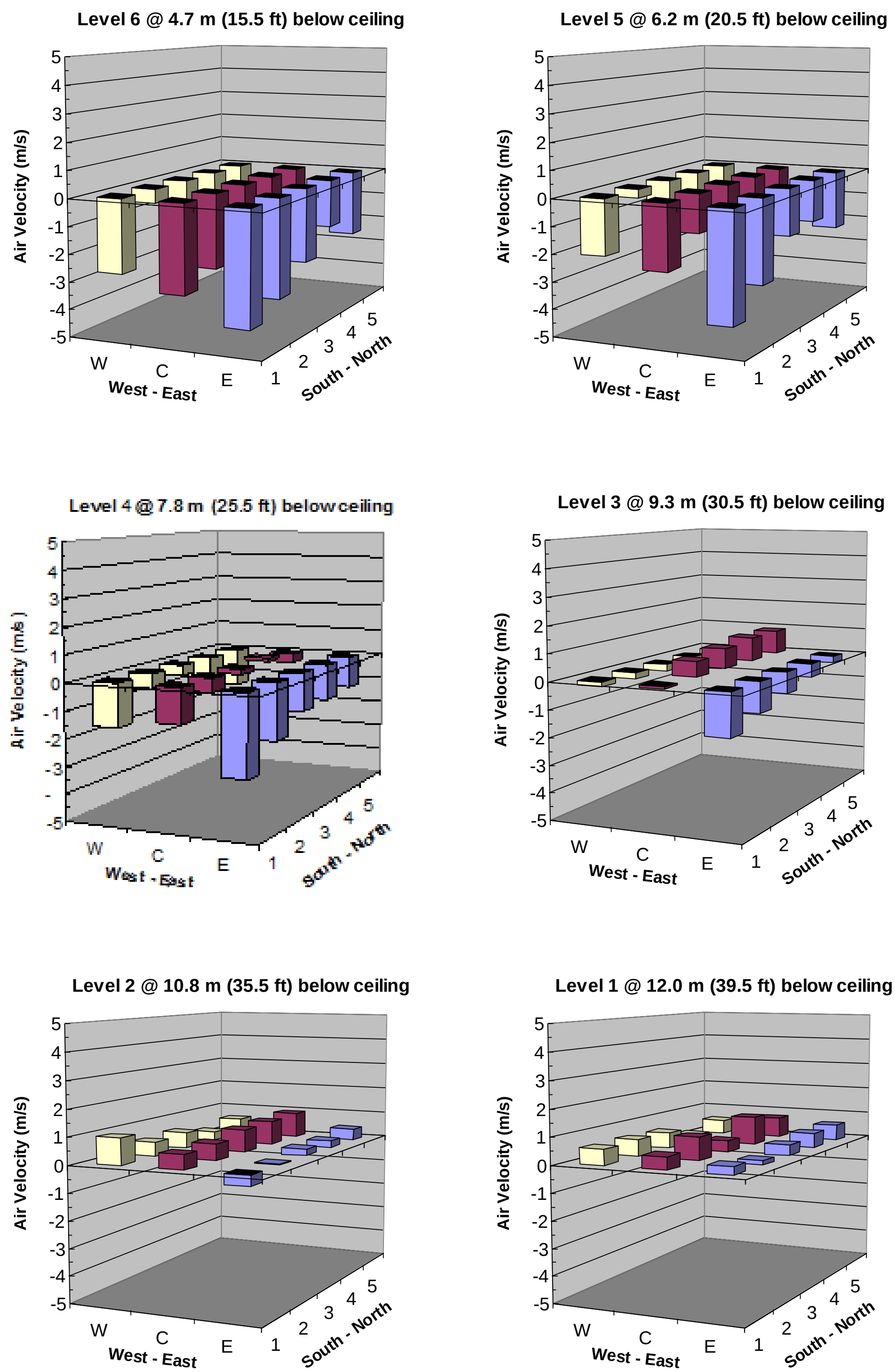
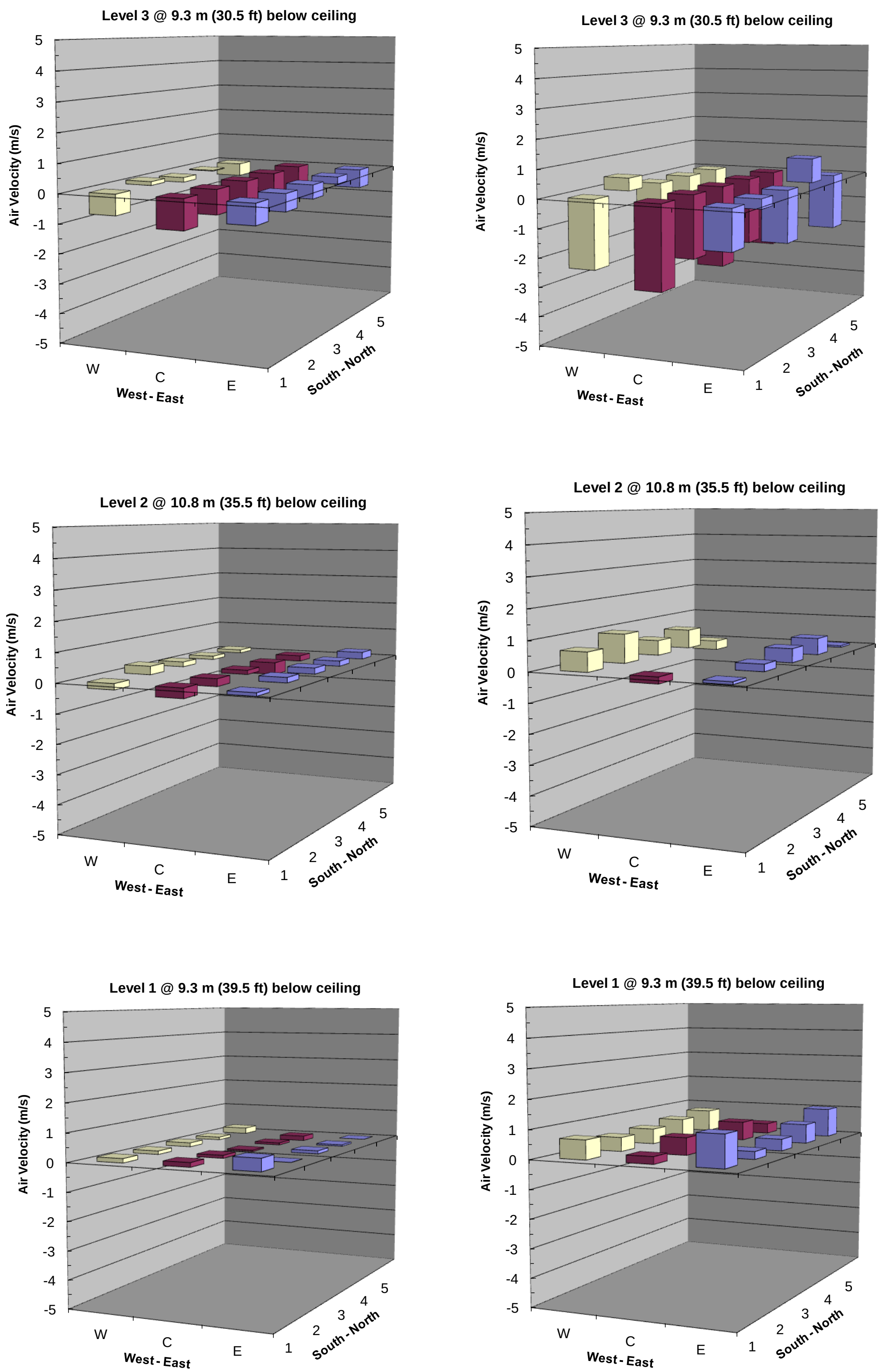


Figure 5-10: Air velocity through array with the fan at 66 rpm for Tests 2 and 3 [no fire]



[Fan at 33 rpm] **[Fan at 66 rpm]**

Figure 5-11: Air velocity through array with the fan at 33 and 66 rpm for Test 4 [no fire]

5.7 FIRE TEST AIR FLOW VELOCITY AT TOP OF ARRAY

Figure 5-12 presents the air velocity measurements taken during Test 1 at the 15 locations above the top of the array over the ignition bay. Each graph contains data from the measurement locations over either the east face of the array, west face of the array, or above the longitudinal flue. As shown, negative values indicate downward air flow. A plan view schematic of the measurement locations relative to the array and the fan is included for reference. Due to an instrumentation error, data are not presented for locations C1 – C3, and C5.

Each graph includes air velocity measurements for three conditions: 1) only the building control system exhaust fan operating at 94 m^3/s (200,000 cfm), 2) the addition of the HVLS fan operating at full speed (66 rpm), and 3) the fire development up to first sprinkler operation. It is important to note that air velocity measurements were not reliable after first sprinkler operation. As discussed in Section 4.8.3, velocity measurements require accurate measurement of the local gas temperature. Operation of a sprinkler results in unknown wetting of the thermocouple, which is typically observed as a significant drop in the calculated velocity and is evident on each graph.

Similar to the cold flow measurements presented in Section 5.5, these data illustrate the strong downward air velocity generated by the fan with peak sustained velocities of over 4 m/s (13 ft/s). After ignition, the buoyant air flow from the fire plume was evident as a net reduction in the downward flow velocity. As the fire grows, the fire plume gases overcome the fan air flow as indicated by upward air velocities at locations W1 – W5 and C4, which coincide with the actual location of the fire plume.

Similar results were observed for Tests 2 through 4 and can be found in Appendices B through E, respectively.

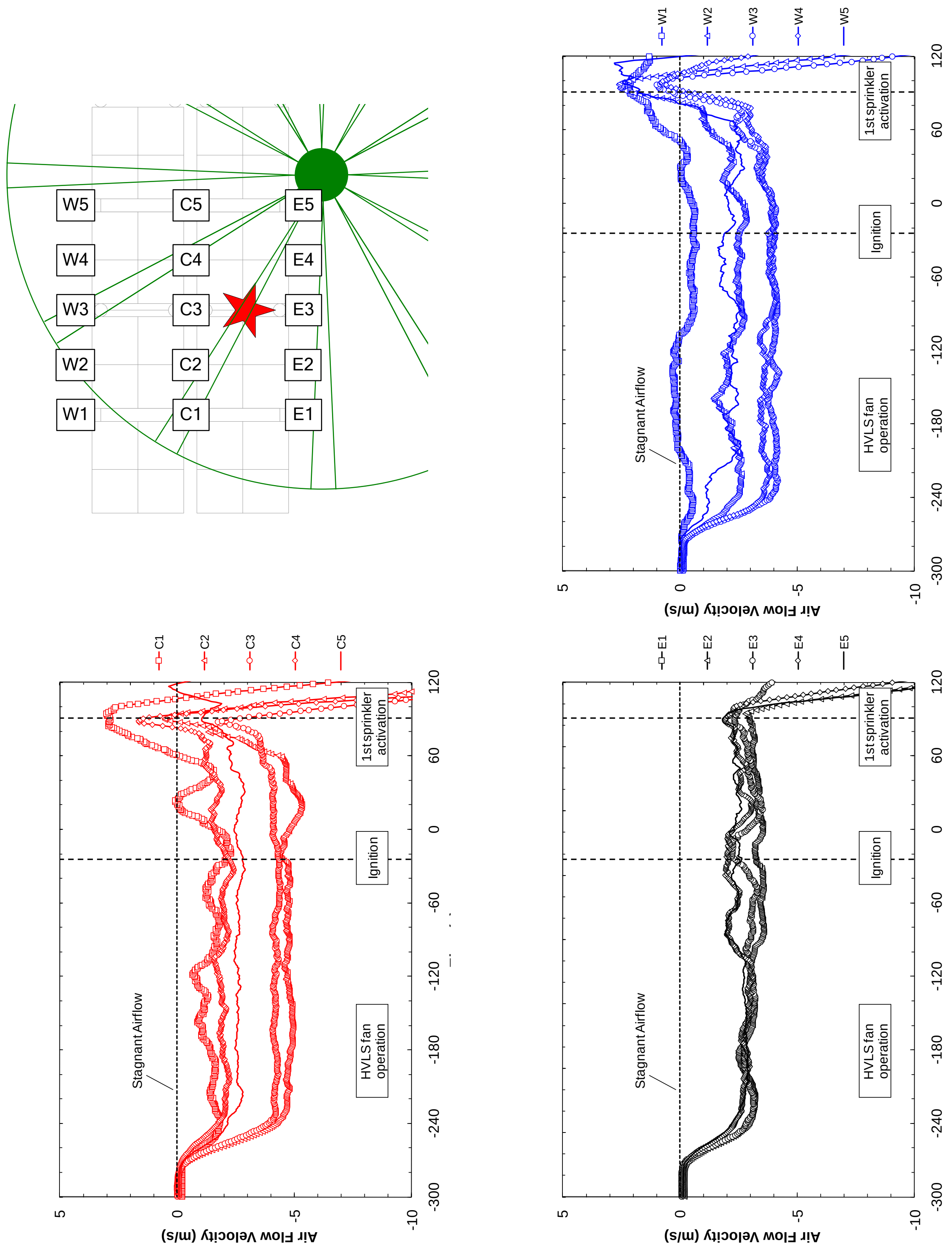


Figure 5-12: Air flow velocities at top of array during Test 1 (until first sprinkler operation)

6 DISCUSSION

All discussion in this report is specific to the array configurations used in the tests. The combined effects of a different array height, commodity type, ceiling height, fan diameter/blade shape and speed, etc, are yet to be understood and may not be inferred from these test results alone.

6.1 FIRE GROWTH RATE COMPARISON – TESTS 2 AND 3

Two tests were conducted indicating that adequate sprinkler system performance can be established by shutting the fan down. The first test, Test 2 of this report, established that the greatest negative impact on the sprinkler system performance occurred when the HVLS fan was centered over the main array. In that test, the fan was operating at full speed for the entire test, resulting in an unacceptable number of sprinkler operations (12) and substantial damage to the backside of the east target array. A subsequent test using an identical array configuration, Test 3 of this report, evaluated the effect of fan shut down 1 min 30 s after first sprinkler operation. In that test, a total of four sprinklers operated and commodity damage was acceptable, indicating adequate sprinkler system performance.

Caution must be used when concluding that fan shut down was the principal factor leading to the acceptable sprinkler system performance exhibited in Test 3. As no statistical analysis can be made from a single test, confidence in the above conclusion can be gained by comparing the initial fire development and the sprinkler operation pattern between Tests 2 and 3. This analysis is prudent despite the good repeatability of the operating sequence of the four sprinklers surrounding ignition, as shown in Section 5.1.

For these tests, the typical method of comparing fire growth rates based on ceiling TC measurements is not reliable due to the high disturbance of the plume gases by the fan. However, the initial fire development can be evaluated based on observation of the fire location within the main array. As shown in Table 6-1, the fire growth leading to first sprinkler operation is very consistent for both tests. The operation times of the initial four sprinklers for each test were also very consistent. In both cases, these sprinklers surrounded the ignition location, which is desirable for an ignition among four sprinklers.

Table 6-1: Comparison of fire development for Tests 2 and 3

Observation	Test 2[†] (min:ss)	Test 3 (min:ss)
Ignition	0:00	0:00
Flames reach bottom of 2nd tier	0:24	0:32
Flames reach bottom of 3rd tier	0:50	0:44
Flames reach bottom of 4th tier	1:00	0:54
Flames reach bottom of 5th tier	1:05	1:03
Flames extend above array	1:15	1:12
1st sprinkler operation	1:42	1:54
2nd sprinkler operation	1:52	1:55
3rd sprinkler operation	2:02	2:02
4th sprinkler operation	2:13	2:03

[†]Eight additional sprinklers operated during Test 2

The fire development leading to the initial sprinkler operations in Tests 2 and 3 is further illustrated in Figure 6-1 and Figure 6-2, respectively. Each figure shows a photograph of the fire at times corresponding to first sprinkler operation in Test 2 (1 min 42 s) and Test 3 (1 min 54 s). Though there is a slight difference in the time of first sprinkler operation, 12 s, it can be seen that the fire development leading to sprinkler operation was consistent.

Ceiling TC measurements can provide insight into the actual location of ceiling gases leading to the initial sprinkler operations. Figure 6-3 and Figure 6-4 present contour plots of the ceiling TC measurements for Tests 2 and 3, respectively. The times shown in each plot are consistent with first sprinkler operation in Test 2 (1 min 42 s) and Test 3 (1 min 54 s). It can be seen for both tests that at 1 min 42 s, the fire plume was similarly located northwest of the ceiling center. In the case of Test 2, this resulted in sprinkler operation of the local sprinkler. However, the corresponding temperatures were slightly lower in Test 3 and that sprinkler did not operate. The plume then moved to the south in both tests by 1 min 54 s, resulting in the operation of the local sprinklers.

Considering the strong disturbance to the ceiling gases caused by the fan, the consistency in fire growth rate and the operation sequence of the first four sprinklers strongly suggests that the shut down of the fan was the driving factor in the improved performance of the sprinkler system in Test 3.

1 min 42 s
[1st sprinkler activation in Test 2]

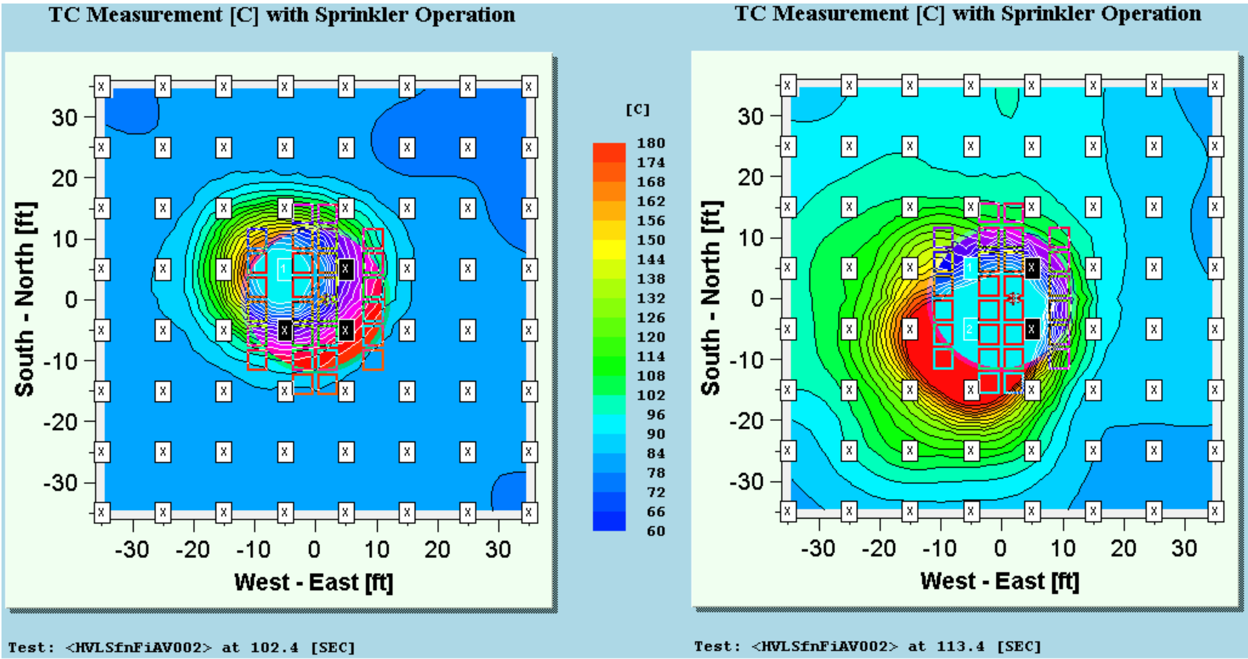
1 min 54 s
[1st sprinkler operation in Test 3]

Figure 6-1: Photos of Test 2

1 min 42 s
[1st sprinkler activation in Test 2]

1 min 54 s
[1st sprinkler operation in Test 3]

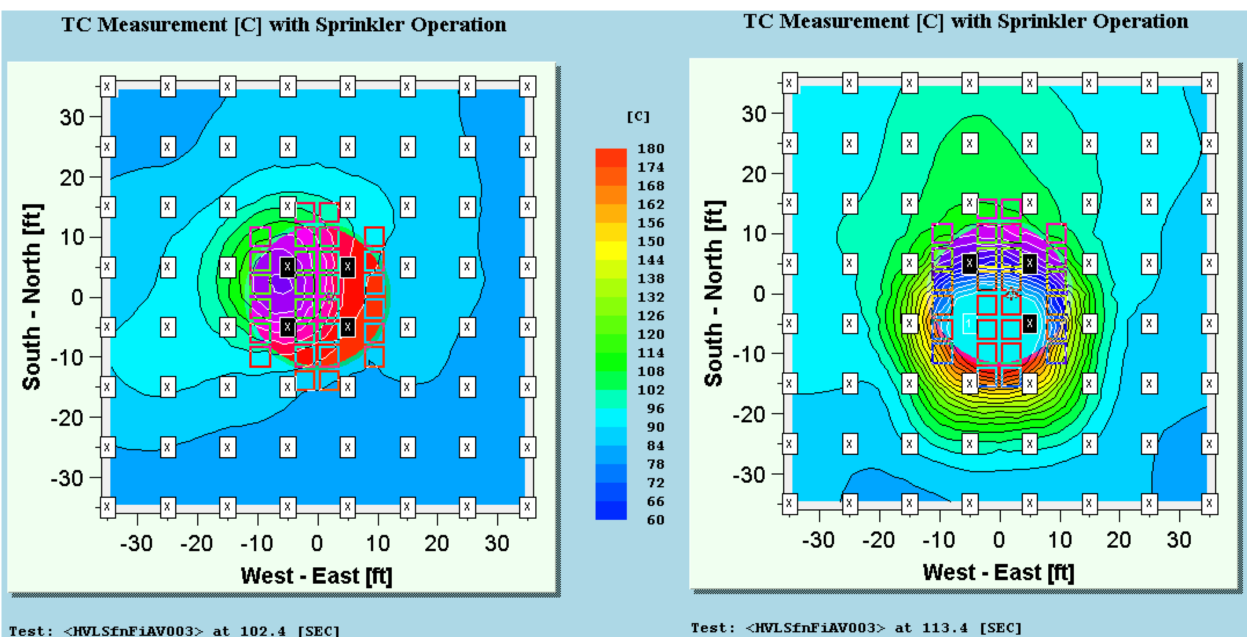
Figure 6-2: Photos of Test 3



1 min 42 s
[1st sprinkler activation in Test 2]

1 min 54 s
[1st sprinkler operation in Test 3]

Figure 6-3: Ceiling TC measurement contour plot for Test 2



1 min 42 s
[1st sprinkler activation in Test 2]

1 min 54 s
[1st sprinkler operation in Test 3]

Figure 6-4: Ceiling TC measurement contour plot for Test 3

6.2 DISPLACEMENT OF FIRE PLUME DUE TO FAN OPERATION

A primary concern with the operation of an HVLS fan installed below a sprinkler system is the deflection of the fire plume leading to operation of sprinklers that are not located over the base of the fire. The ceiling gas centroid at the time of first sprinkler operation can be used as an indicator of deflection of the fire plume. Without an operating HVLS fan the centroid should be positioned over the base of the fire. With an operating HVLS fan, as shown in Section 5.3, the ceiling gas centroid for each test was displaced by the air flow induced by the fan. The specific location for each test, at first sprinkler operation, was:

- Test 1: 1.3 m south x 2.0 m west (4.3 ft x 6.6 ft) [Fan offset from ignition]
- Test 2: 0.7 m north x 1.3 m west (2.3 ft x 4.3 ft) [Fan centered over ignition]
- Test 3: 0.8 m south x 0.3 m west (2.6 ft x 1.0 ft) [Fan centered over ignition]
- Test 4: 0.8 m south x 1.1 m west (2.6 ft x 3.6 ft) [Fan centered over ignition] [High clearance scenario]

Based on these measurements and visual observation, the largest deflection of the fire plume occurred when the fan was offset from the ignition location, Test 1. This test included a 3.0 m (10 ft) clearance from the top of the commodity to the ceiling, which was the minimum included in this project. Centering the fan over ignition only slightly reduced the deflection of the fire plume, regardless of clearance, Tests 2 - 4. It is notable that Tests 2 and 3 included a 3.0 m (10 ft) clearance, while Test 4 included a 7.6 m (25 ft) clearance. Given the significantly greater clearance in Test 4, the HVLS fan had a lesser impact on the fire plume. This result is contradictory to the initial, preliminary hypothesis in Section 3. It is believed this effect of greater clearance lessening the effect of the HVLS fan can be attributed to the decrease in air flow velocity reaching the top of the array as discussed in Section 5.5. The higher clearance also allowed the fire plume to further develop above the array, *i.e.*, increased flame height and gas velocity, before the first sprinkler operated.

7 CONCLUSIONS

All conclusions in this report are specific to the array configurations used in these tests. The combined effects of a different array height, commodity type, ceiling height, fan diameter/blade shape and speed, etc, are yet to be well understood and may not be inferred from these test results alone.

The specific scenario addressed by these tests was protection of CUP commodity using quick-response, pendent sprinklers, having a 71°C (160°F) rated link and a K-Factor of 202 L/min/bar$^{1/2}$ (14 gpm/psi$^{1/2}$). In accordance with the evaluation criteria established in Section 4.9, it was found that operation of an HVLS fan without any means of shut down caused an unacceptable impairment to the sprinkler system. However, when shut down of the fan occurred due to a simulated water flow alarm the sprinkler systems performed adequately.

Based on the results of the tests presented in this report the following conclusions can be made:

- The HVLS fan operating without means of automatic shut down resulted in inadequate sprinkler system performance.
- The HVLS fan centered over the main array, with a clearance from the ceiling to the top of the commodity of 3.0 m (10 ft), resulted in the largest negative impact on the sprinkler system performance.
- For storage with a clearance from the top of the commodity to the ceiling ranging from 3.0 to 7.6 m (10 to 25 ft), fan shut down due to a water flow alarm, *i.e.*, fan shut down less than or equal to 1 min 30 s after first sprinkler operation, allowed for adequate sprinkler system performance.
- The HVLS fan operating at full speed, with a 3.0 m (10 ft) clearance between the top of the commodity and the ceiling:
    - Produced downward air-flow velocities up to 4.5 m/s (14.8 ft/s) at the top of the storage array,
    - Produced significant air-flow velocities, *i.e.*, velocities greater than or equal to 1 m/s (3.3 ft/s), that penetrate up to 4 tiers (6.1 m [20 ft]) through an open frame double-row rack storage array,

  - Created the greatest disturbance to the ceiling gas flow above ignition when the fan was offset 2.2 m (7.1 ft) from the center of the test array.
- The HVLS fan operating at half speed, with a 7.6 m (25 ft) clearance between the top of the commodity and the ceiling, and the fan centered over the array, reduced the peak air velocity reaching the top of the array by approximately 60%.
- The exhaust air system of the FM Global Large Burn Laboratory extracting air at 94 m^3/s (200,000 cfm) generates a negligible air flow across the movable ceiling. The air flow generated by the HVLS is the dominant disturbance to the ceiling level gas flow.

8 REFERENCES

[1] MacroAir specifications, http://www.macro-air.com.

[2] National Fire Protection Association Standard 13 (NFPA 13), "Standard for the Installation of Sprinkler System," 2010.

[3] "HVLS Fans and Sprinkler Operation Phase 1 Research Program," Final Report prepared by Schirmer Engineering Corporation, February 2009.

[4] "Storage of Class 1, 2, 3, 4 and Plastic Commodities," Data Sheet 8-9, FM Global, May 2008.

[5] "Final HVLS Fans Phase II Test Plan for The Fire Protection Research Foundation," Proposal prepared by Schirmer Engineering Corporation, SEC Project No.: 2010033-000, July 2010.

[6] "Standard for Automatic Sprinklers for Fire Protection Service," UL 199, Section 61, 11th Edition, 2005.

[7] A. Tewarson, "Generation of Heat and Chemical Compounds," SFPE Handbook of Fire Protection Engineering, 3rd Edition, Section 3, Chapter 4, pp. 3-82 to 3-161, March 2002.

[8] "Installation Guidelines for Automatic Sprinklers," Data Sheet 2-0, FM Global, March 2010.

[9] NFPA 72, National Fire Alarm and Signaling Code, National Fire Protection Association, Quincy, MA, 2010 Edition.

[10] B.J. McCaffrey and G. Heskestad, "A Robust Bidirectional Low-Velocity Probe for Flame and Fire Application," Combustion and Flame, 26, pp. 125-127, 1976.

[11] H. Ingason, "Plume Flow in High Rack Storages," Fire Safety Journal, Volume 36, pp. 437-457, 2001.

[12] *Flammability Testing of Materials Used in Construction, Transport and Mining* (Vivek B. Apte, ed.), Woodhead Publishing Materials, Cambridge, England, 2006.

[13] Link, Sheila, "How High Volume Low Speed (HVLS) Fans Can Reduce Facility CO2 Emissions," Whitepaper prepared by MacroAir Technologies, 2010.

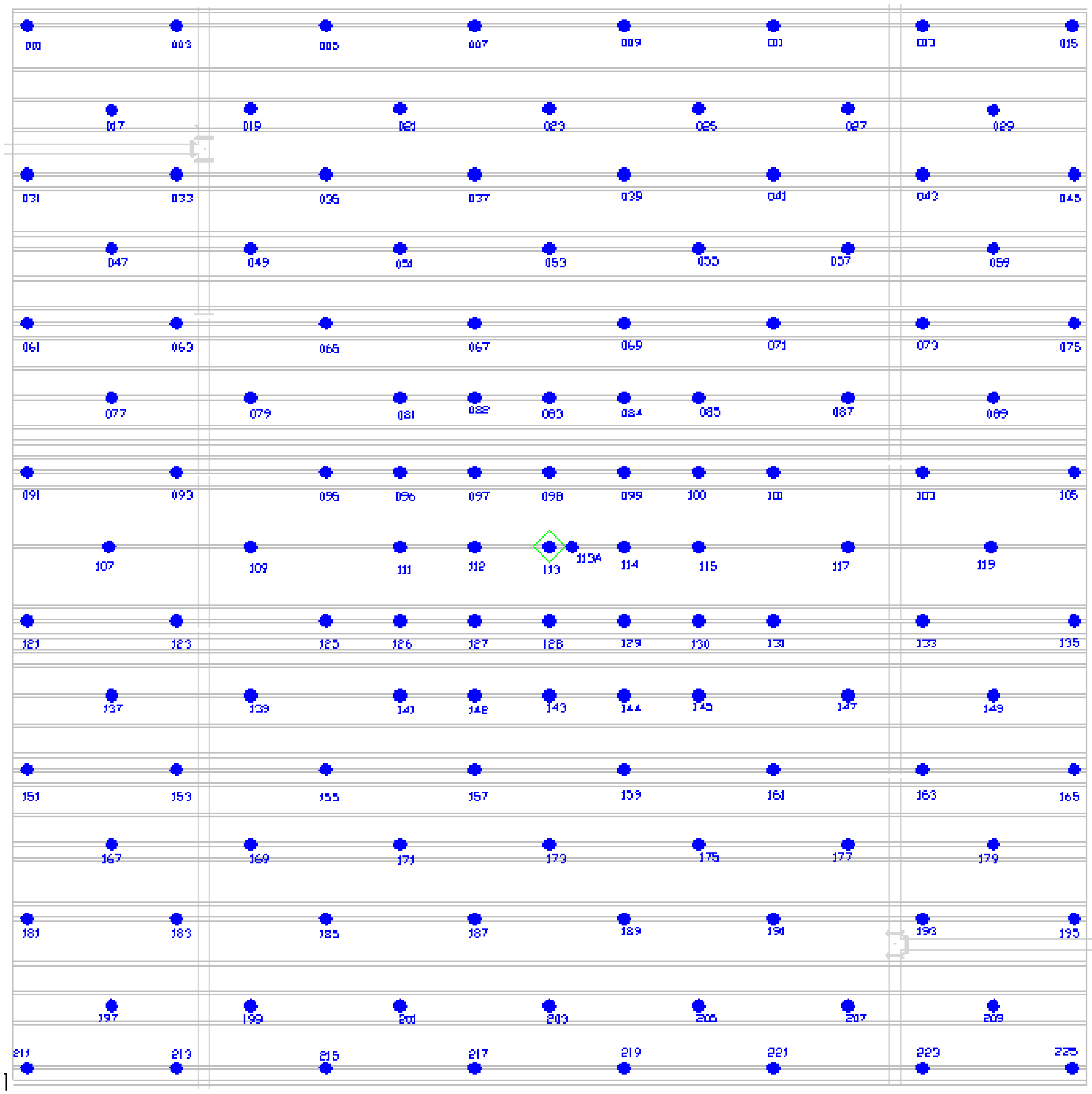
[14] Class Number 2008, "Approval Standard for Suppression Mode [Early Suppression - Fast Response (ESFR)] Automatic Sprinklers," October 2006.

[15] J. Milke, "Analytical Methods for Determining Fire Resistance of Steel Members," SFPE Handbook of Fire Protection Engineering, 3rd Edition, Section 4, Chapter 9, pp. 4-212 to 4-238, 2002

[16] *Specifications for the Design, Fabrication, and Erection of Structural Steel for Building*, American Institute of Steel Construction, New York, 1978.

[17] H. Ingason, "Fire Experiments in a Two Dimensional Rack Storage," BRANDFORSK project 701-917, Swedish National Testing and Research Institute, SP Report 1993:56, 1993.

A APPENDIX A - SOUTH CEILING LEVEL THERMOCOUPLE LAYOUT



Ceiling Thermocouple Layout for Movable Ceiling of Large Burn Lab Reference Key:
● Thermocouple location ◇ Center of Ceiling

B APPENDIX B - TEST 1: DATA, OBSERVATIONS, AND RESULTS

The first test was conducted on August 4, 2010, at 1:30 pm under the South Movable ceiling portion of the Large Burn Lab. Environmental conditions inside the lab were as follows: dry-bulb temperature, 27^{o}C (80^{o}F) and relative humidity, 32%. Weather conditions outside the lab were as follows: dry-bulb temperature, 29^{o}C (84^{o}F) and relative humidity, 78%.

The main fuel array consisted of an open-frame, double-row rack of cartoned unexpanded plastic (CUP) commodity. The array dimensions measured approximately 10.1 m wide x 2.3 m deep (~33 ft x 7.5 ft) in an 8 bay wide x 2 bay deep arrangement. Single-row target arrays contained six pallet loads of the same commodity across a 1.2 m (4 ft) aisle to the east and west of the main array. Overall the target arrays measured approximately 7.5 m wide x 1.2 m deep (24.5 ft x 3.25 ft). For each array, a six pallet load high configuration was used, resulting in an array approximately 9.1 m (30 ft) high. The ceiling was set at a height of 12.2 m (40 ft) above the floor.

The main array was centered under one sprinkler. Ignition was accomplished with two FM Global standard half igniters, offset 0.6 m (2 ft) east in the central transverse flue, located at the rack uprights.

The sprinkler system was comprised of Tyco TY6226 quick-response pendent sprinklers with a K-Factor of 202 L/min/bar$^{1/2}$ (14 gal/min/psi$^{1/2}$) and a 71^{o}C (160^{o}F) rated link. A nominal operating pressure of 5.2 bar (75 psig) was chosen to provide a discharge of 454 L/min (120 gpm) per sprinkler. The sprinklers were installed on 3 x 3 m (10 x 10 ft) spacing, resulting in a 48.9 mm/min (1.2 gpm/ft^{2}) water density at the floor.

The HVLS fan was located among four sprinklers and was offset 2.2 m (7.1 ft) northeast of the array center. This fan was a six blade design with an overall 7.3 m (24 ft) diameter and was operating at the maximum speed of 66 rpm for the entire test.

B.1.1 Test 1 Highlights

The data acquisition system was started with the lab under ambient air flow conditions, *i.e.*, the louvers to the dehumidification system were closed, the louvers on the south end of the west wall were closed, and the louvers on the north end of the west wall were open. After 60 s all instrumentation was zeroed. Data were then collected for 2 min with no air flow in the lab. The exhaust air system was then set to 94 m^3/s (200,000 cfm) and data were collected for 15 min to allow the air flow to stabilize. The HVLS fan was then started and data were collected for an additional 5 min before ignition, again to allow the air flow to stabilize.

After ignition, the initial fire development was within the center transverse flue and flames reached the top of the 1st tier at 30 sec. By 35 s flames reached the 2nd tier and were visibly disturbed by air flow from the fan. Flames then reached the 3rd tier at 1 min 2 s, 4th tier at 1 min 7 s, 5th tier at 1 min 13 s, and extended above the top of the array at 1 min 20 s. The first sprinkler operation, which was centered over the array, occurred at 1 min 28 s. This caused the flames to recede to the 1st and 2nd tier of the ignition bay. The fire then grew laterally with flames reaching the east and west faces of the main array at 2 min 14 s and 2 min 33 s, respectively. The combination of the fan air flow and the sprinkler discharge rapidly filled the lab with smoke obscuring the view of the array. Ignition of the eastern target array occurred at 3 min 9 s and was followed closely by the 2nd sprinkler operation at 3 min 21 s. Ignition of the western target array occurred at 5 min 50 s with a total of 11 sprinklers operating. The 12th and final sprinkler operated at 7 min 53 s. The fire was largely extinguished when the test was terminated by hose stream at 35 min. Damage was contained within the longitudinal extent of the main array and no burning occurred on the backside of either target array.

B.1.2 Test 1 Results

A schematic overview of the sprinkler operation sequence and operation times can be found in Figure B-1. As indicated, the first sprinkler, centered over the main array, operated at 1 min 28 s. The remaining 11 sprinklers operations were spaced over the next 6 min 19 s. A total of 12 sprinklers operated, with the final occurring at 7 min 53 s.

The overall extent of fire damage for Test 1 is represented by the shaded areas in Figure B-2 for the main array and both target arrays. As shown, damage represents visual observation of burning on the outside face of the commodity; no observation of damage within the flue spaces was included. Extensive damage to the commodity occurred on both the east and west rows of the main array and the aisle face of both the east and west target arrays. The fire spread remained within the confines of both arrays.

Figure B-3 shows the near-ceiling TC measurements centered over the main array, and at a radial distance of 1.5 m (5 ft), 3.0 m (10 ft), and 6.1 m (20 ft) from center. The 20-gage thermocouple centered over the main array recorded a peak measurement of 88^{o}C (190^{o}F) and the adjacent 28-gage thermocouple recorded a peak measurement of 120^{o}C (248^{o}F), both coinciding with first sprinkler operation at 1 min 28 s. The peak steel TC measurement of approximately 76^{o}C (169^{o}F) was recorded at 6 min. Steel temperatures shown in the graph represent the average of all nine thermocouples located out to 305 mm (12 in.) in all four directions from center. The thermocouples located 1.5 m (5 ft) and 3.0 m (10 ft) recorded peak TC measurements of 79^{o}C (174^{o}F) to the west and 69^{o}C (156^{o}F) to the south, respectively, at first sprinkler operation. The thermocouples located 6.1 m (20 ft) recorded a peak TC measurement of 201^{o}C (394^{o}F) to the south at 3 min 56 s.

Figure B-4 shows the branch-line water discharge pressure and near-ceiling gas velocities at 2.4 m (8 ft) , 4.0 m (13 ft), and 10.4 m (34 ft) from the main array center. The gas velocities present three distinct lab conditions: 1) until -300 s only the exhaust fan was operating at 94 m^3/s (200,000 cfm), 2) at -300 s the HVLS fan was started, and 3) at 0 s the fire was ignited. For each radial distance, the recorded air velocities with only the exhaust fans operating were ± 0.2 m/s (0.7 ft/s). The addition of the HVLS fan caused a significant disturbance in the air flow, with the effect decreasing with distance from the fan. The negative measurements at the 2.4 m (8 ft) and 4.0 m (13 ft) locations indicate an air flow being drawn toward the fan, *i.e.*, toward the ceiling center. The non-uniformity in the radial distribution was likely a result of the fan being offset within these locations and turbulence in the air flow. Upon ignition, the fire plume gases began traveling outward from the ceiling center. This is observed in most locations as a positive air velocity. At the 10.4 m (34 ft) locations, the effect of the HVLS fan was minimal and the outward flow of fire plume gases was evident. At all three locations, the peak outward air velocity was less then 1 m/s (3.3 ft/s) at first sprinkler operation.

Figure B-5 presents the heat release rate measurements based on the generation rates of carbon dioxide and carbon monoxide (HRR-COCO2), oxygen depletion (HRR-O2), and convection gas flow within the exhaust duct (Convective). Note that the heat release rate calculations do not account for lag and smear of the data, which can be significant, due to complex mixing of the gases above the movable ceiling or transport time through the collection ducts. Based on the HRR-COCO2 measurements, an estimated 18,000 ± 2,000 MJ (17,000,000 ± 3,400,000 BTU) of total energy was released from an equivalent of 12.5 pallet loads of Standard Plastic Commodity.

Figure B-6 presents the time evolution of the two coordinates of the ceiling gas layer centroid. At first sprinkler operation, 1 min 28 s, the coordinates were 1.3 m (4.3 ft) to the south and 2 m (6.6 ft) to the west. This indicates that the fan significantly affected the fire plume, which would be nominally centered under the ceiling without the operating fan. For convenience, Figure B-7 presents the corresponding ceiling TC measurement contours at first sprinkler operation, which show a similar bias toward the southwest. Each measurement is obtained from thermocouples located 152 mm (6 in.) below the ceiling. Note that the circle toward the center of the figure indicates the fan location. Due to an unresolved issue with the contour plot software, the colors within the circle are inverted.

Figure B-8 presents the air velocity measurements taken during the fire test at the 15 locations above the top of the array over the ignition bay. Each graph contains data from the five measurement locations over the east face of the array, west face of the array, or above the longitudinal flue. As shown, negative values indicate downward air flow. A plan view schematic of the measurement locations relative to the array and the fan is included for reference. Due to an instrumentation error, data are not presented for locations C1 – C3, and C5. These data illustrate the strong downward air velocity generated by the fan with peak sustained velocities of over 4 m/s (13 ft/s). After ignition, the buoyant air flow from the fire plume is evident as either a reduction in the downward flow velocity or in some locations an upward air flow. As expected, the upward air velocities are greatest at locations W1 – W5 and C4, which coincide with the actual location of the fire plume.

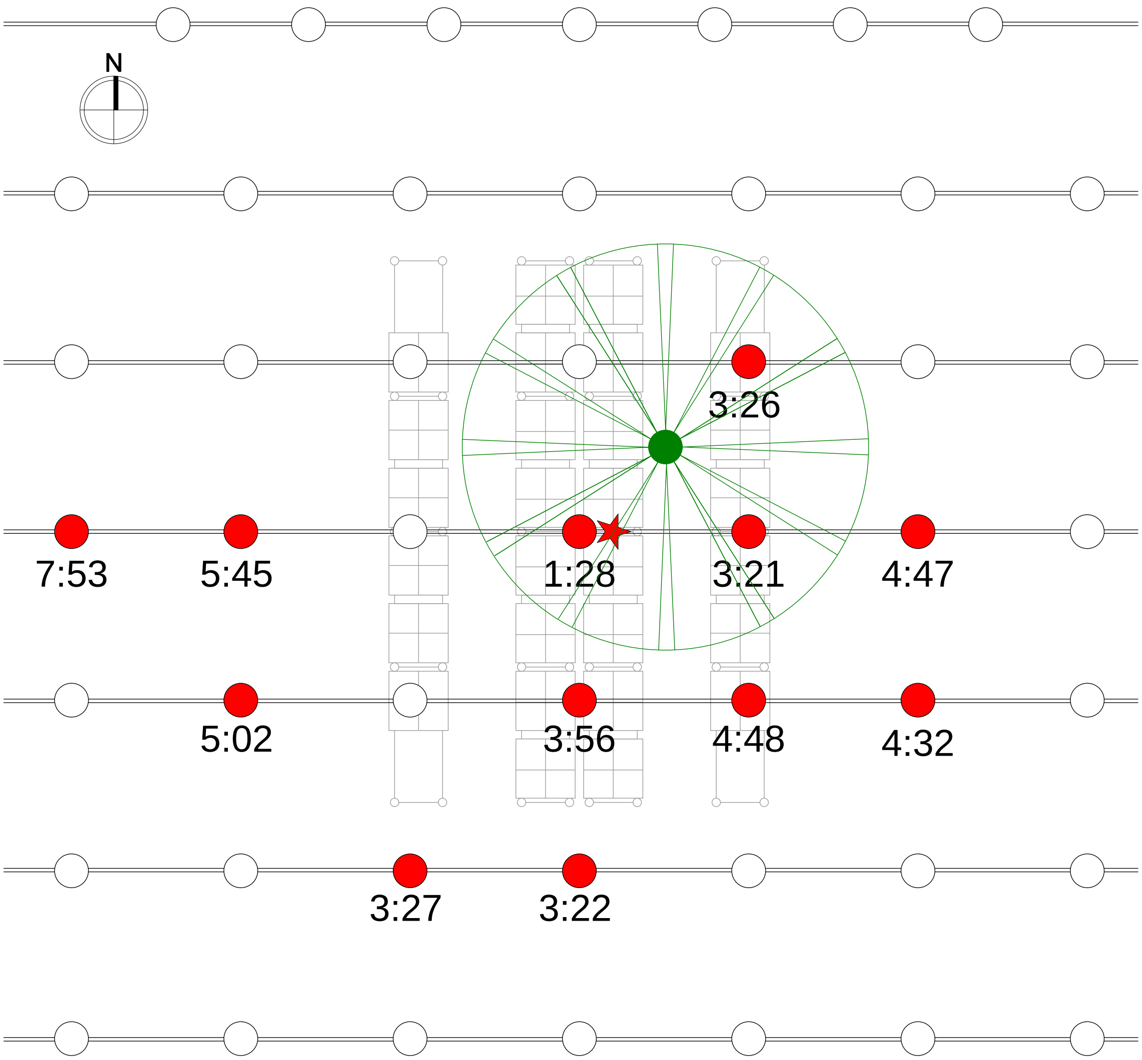


Figure B-1: Plan view of sprinkler operation pattern - Test 1

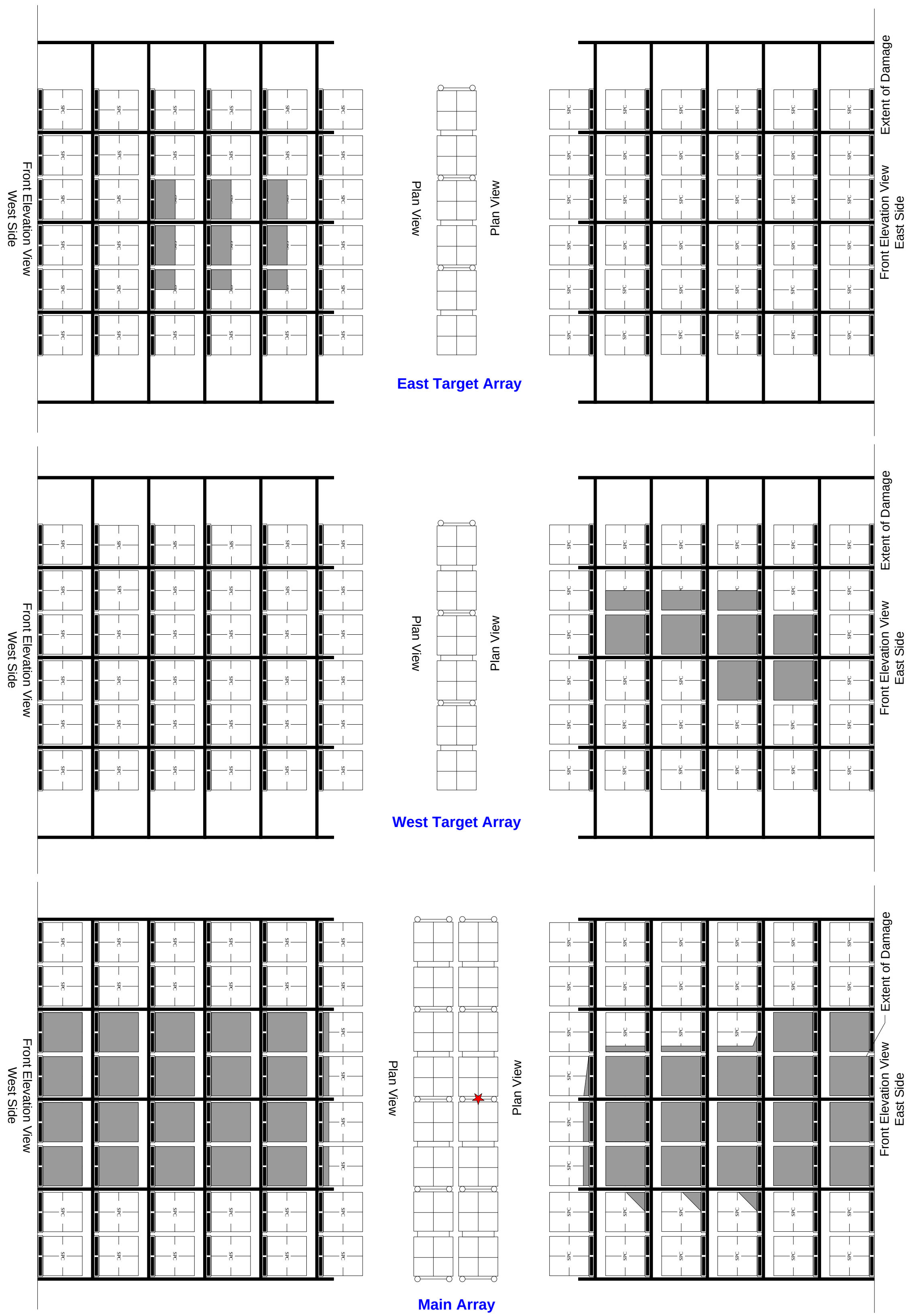


Figure B-2: Damage assessment - Test 1

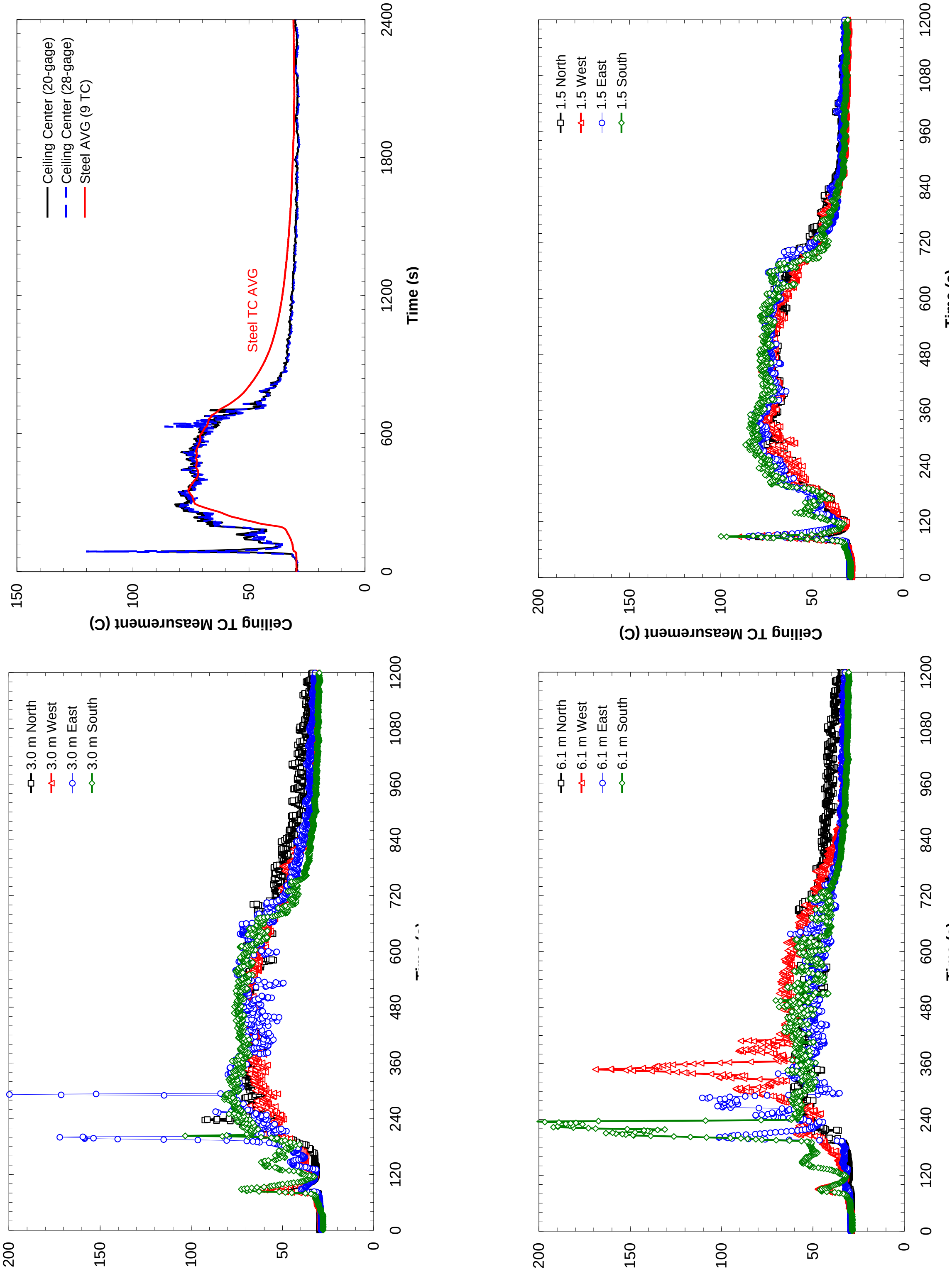


Figure B-3: Various near-ceiling TC measurements - Test 1

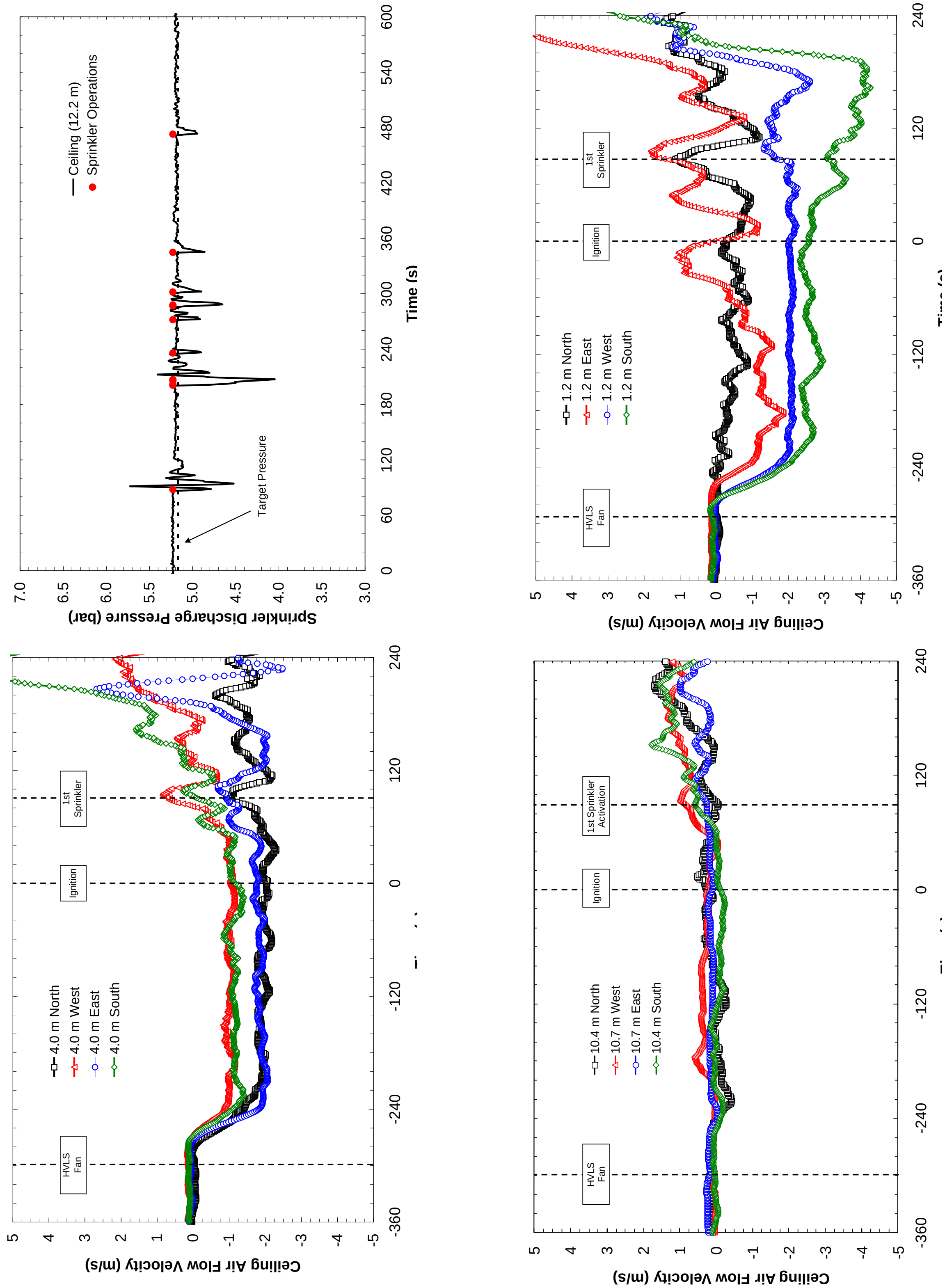


Figure B-4: Data plots – Test 1

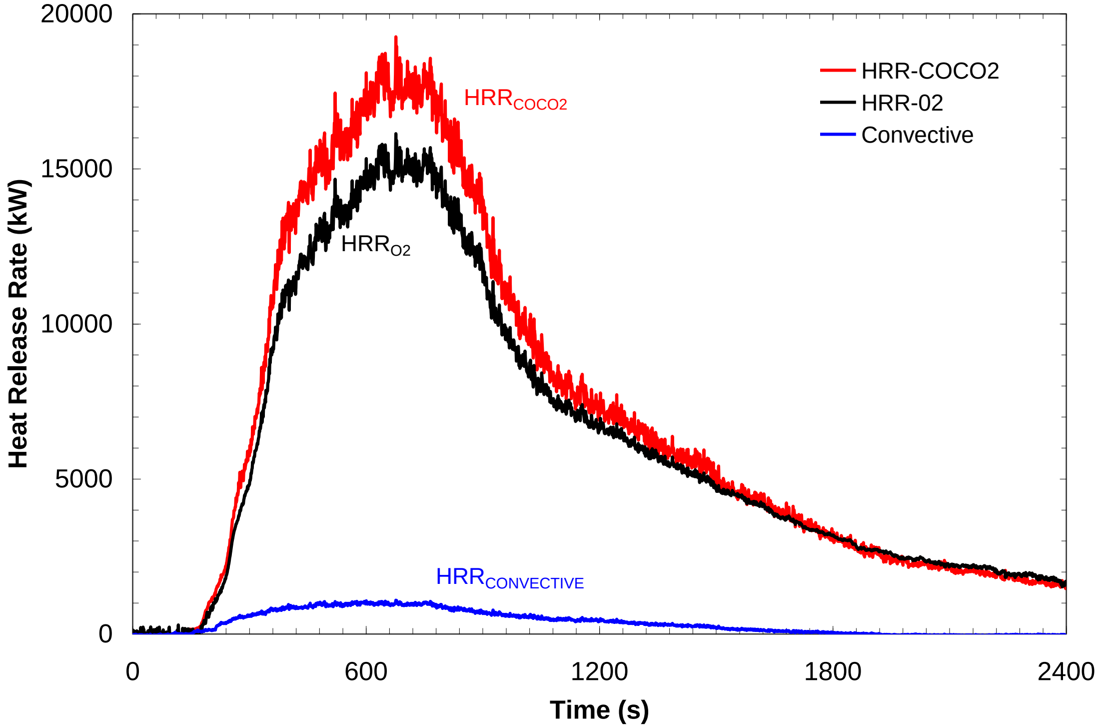


Figure B-5: Heat release rate – Test 1

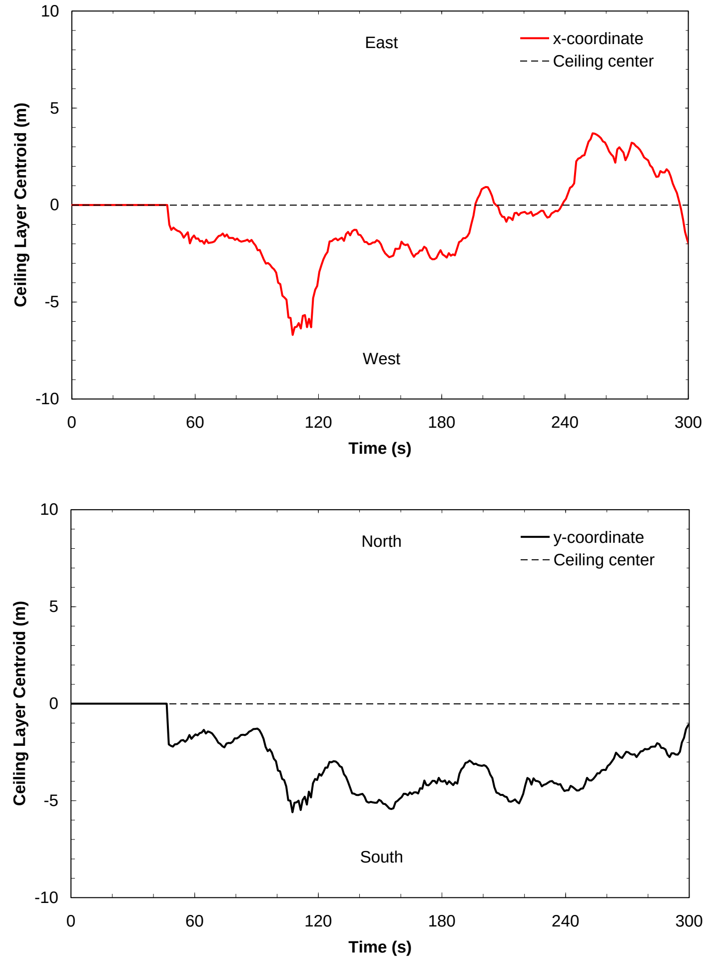


Figure B-6: Time evolution of x- and y-coordinate of ceiling layer centroid – Test 1

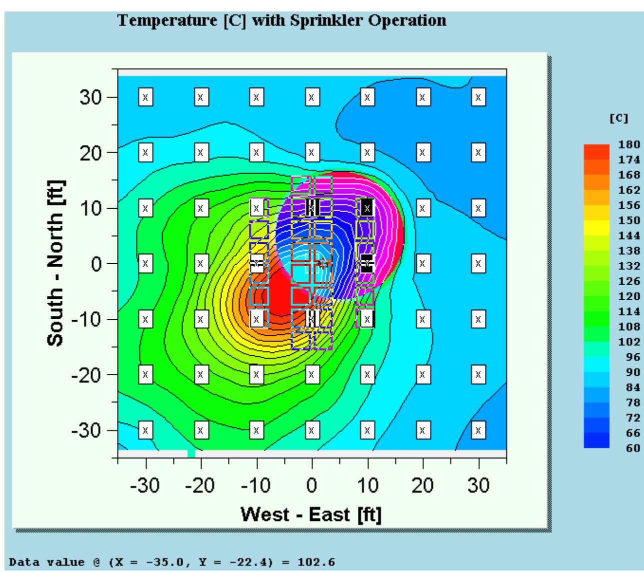


Figure B-7: Ceiling TC contours at first sprinkler operation (1 min 28 s) – Test 1

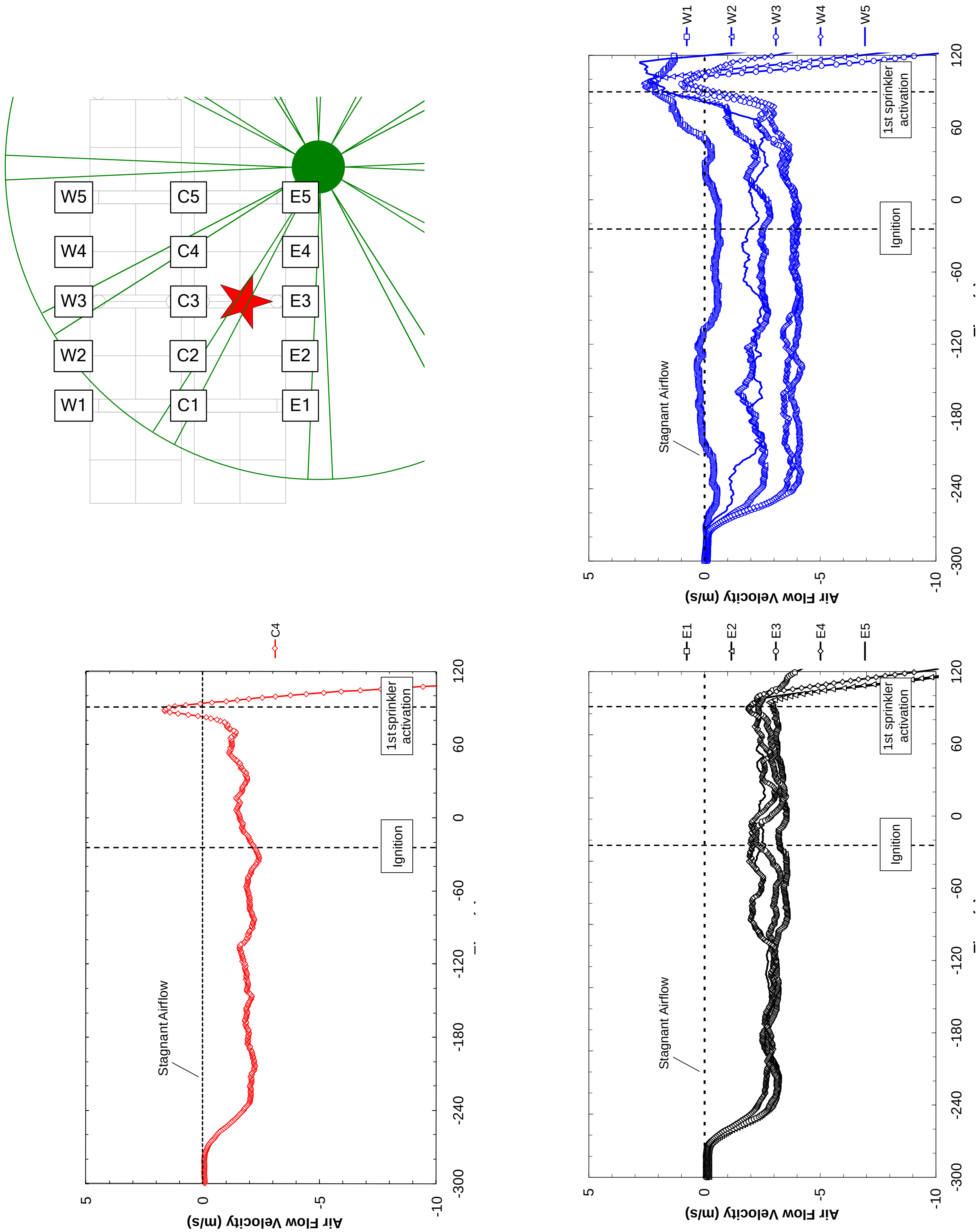


Figure B-8: Air-flow above array at ignition bay – Test 1

C APPENDIX C - TEST 2: DATA, OBSERVATIONS, AND RESULTS

The second test was conducted on August 20, 2010, at 10:30 am under the South Movable ceiling portion of the Large Burn Lab. Environmental conditions inside the lab were as follows: dry-bulb temperature, 23^{o}C (73^{o}F) and relative humidity, 39%. Weather conditions outside the lab were as follows: dry-bulb temperature, 19^{o}C (67^{o}F) and relative humidity, 57%.

The main fuel array consisted of an open-frame, double-row rack of cartoned unexpanded plastic (CUP) commodity. The array dimensions measured approximately 10.1 m wide x 2.3 m deep (~33 ft x 7.5 ft) in an 8 bay wide x 2 bay deep arrangement. Single-row target arrays contained six pallet loads of the same commodity across a 1.2 m (4 ft) aisle to the east and west of the main array. Overall the target arrays measured approximately 7.5 m wide x 1.2 m deep (24.5 ft x 3.25 ft). For each array, a six pallet load high configuration was used, resulting in an array approximately 9.1 m (30 ft) high. The ceiling was set at a height of 12.2 m (40 ft) above the floor.

The main array was centered among four sprinklers. Ignition was accomplished with two FM Global standard half igniters, offset 0.6 m (2 ft) east in the central transverse flue, located at the rack uprights.

The sprinkler system was comprised of Tyco TY6226 quick-response pendent sprinklers with a K-factor of 202 L/min/bar$^{1/2}$ (14 gal/min/psi$^{1/2}$) and a 71^{o}C (160^{o}F) rated link. A nominal operating pressure of 5.2 bar (75 psig) was chosen to provide a discharge of 454 L/min (120 gpm) per sprinkler. The sprinklers were installed on 3 x 3 m (10 x 10 ft) spacing, resulting in a 48.9 mm/min (1.2 gpm/ft^{2}) water density at the floor.

The HVLS fan was located among four sprinklers and was centered over the main array. This fan was a six blade design with an overall 7.3 m (24 ft) diameter and was operating at the maximum speed of 66 rpm for the entire test.

C.1.1 Test 2 Highlights

The data acquisition system was started with the lab under ambient air flow conditions, *i.e.*, the louvers to the dehumidification system were closed, the louvers on the south end of the west wall were closed, and the louvers on the north end of the west wall were open. After 60 s all instrumentation was zeroed. Data were then collected for 2 min with no air flow in the lab. The exhaust air system was then set to 94 m^3/s (200,000 cfm) and data were collected for 15 min to allow the air flow to stabilize. The HVLS fan was then started and data were collected for an additional 5 min before ignition, again to allow the air flow to stabilize.

After ignition, the initial fire development was within the center transverse flue. Flames reached the 2^{nd} tier by 24 s and were visibly disturbed by air flow from the fan. Flames then reached the 3^{rd} tier at 50 s, 4^{th} tier at 1 min, 5^{th} tier at 1 min 5 s, and extended above the top of the array at 1 min 15 s. The first sprinkler operation, which was southeast of ignition, occurred at 1 min 42 s. The remaining three sprinklers surrounding ignition operated at 1 min 52 s, 2 min 2 s, and 2 min 13 s. Ignition of the east target array also occurred at 2 min 13 s and flames quickly extended to the backside of the array by 2 min 50 s. By 3 min 4 s the burning was sustained on the backside of the east target array. The twelfth and final sprinkler operated at 3 min 57 s. The fire was largely extinguished when the test was terminated by hose stream at 25 min. Damage was contained within the longitudinal extent of the main array; however, substantial damage occurred on the backside of the east target array.

C.1.2 Test 2 Results

A schematic overview of the sprinkler operation sequence and operation times can be found in Figure C-1. The first sprinkler, centered over the main array, operated at 1 min 42 s. The remaining 11 sprinklers operations were spaced over the next 2 min 15 s. A total of 12 sprinklers operated, with the final occurring at 3 min 57 s.

The overall extent of fire damage for Test 2 is represented by the shaded areas in Figure C-2 for the main array and both target arrays. As shown, damage represents visual observation of burning on the outside face of the commodity; no observation of damage within the flue spaces was included. The fire spread remained within the longitudinal confines of the main array with damage primarily sustained on the eastern row; however, there was extensive damage to the commodity on the backside of the east target array.

Figure C-3 shows the near-ceiling TC measurements centered over the main array, and at a radial distance of 1.5 m (5 ft), 3.0 m (10 ft), and 6.1 m (20 ft) from center. The 20-gage thermocouple centered over the main array recorded a peak measurement of 203^{o}C (397^{o}F) and the adjacent 28-gage thermocouple recorded a peak measurement of 238^{o}C (460^{o}F), both coinciding with first sprinkler operation at 1 min 42 s. The peak steel TC measurement of approximately 46^{o}C (115^{o}F) was recorded at 4 min 51 s. Steel temperatures shown in the graph represent the average of all nine thermocouples located out to 305 mm (12 in.) in all four directions from center. The thermocouples located 1.5 m (5 ft) and 3.0 m (10 ft) recorded peak TC measurements of 190^{o}C (374^{o}F) to the south and 136^{o}C (277^{o}F) to the south, respectively, at first sprinkler operation. The thermocouples located 6.1 m (20 ft) recorded a peak TC measurement of 151^{o}C (304^{o}F) to the east at 3 min 30 s.

Figure C-4 shows the branch-line water discharge pressure and near-ceiling gas velocities at 2.4 m (8 ft), 4.0 m (13 ft), and 10.4 m (34 ft) from the main array center. The gas velocities present three distinct lab conditions: 1) until -300 s only the exhaust fan was operating at 94 m^3/s (200,000 cfm), 2) at -300 s the HVLS fan was started, and 3) at 0 s the fire was ignited. For each radial distance the recorded air velocities with only the exhaust fans operating were ± 0.2 m/s (0.7 ft/s). The addition of the HVLS fan caused a significant disturbance in the air flow, with the effect decreasing with distance from the fan. This was observed as negative measurements at the 2.4 m (8 ft) and 4.0 m (13 ft) locations in the range of 1 to 2 m/s (3.3 to 6.6 ft/s), which indicate air flow being drawn toward the fan, *i.e.*, toward the ceiling center. The measurements at the 10.4 m (34 ft) locations indicate relatively stagnant air flow during the same timeframe. Upon ignition, the fire plume gases began traveling outward from the ceiling center. This was observed at the 2.4 m (8 ft) locations as a positive air velocity, *i.e.*, away from the ceiling center, with magnitudes up to 4 m/s (13.1 ft/s) near the time of first sprinkler operation. At the 10.4 m (34 ft) locations, the effect of the HVLS fan and the fire plume gas flow was minimal.

Figure C-5 presents the heat release measurements based on the generation rates of carbon dioxide and carbon monoxide (HRR-COCO2) and convection gas flow within the exhaust duct (Convective). Due to an instrumentation failure, no heat release based on oxygen depletion is reported. Note that the heat release rate calculations do not account for lag and smear of the data, which can be significant, due to complex mixing of the gases above the movable ceiling or transport time through the collection ducts. Based on the HRR-COCO2 measurements, an estimated 7,500 ± 1,100 MJ (7,100,000 ± 1,000,000 BTU) of total energy was released from an equivalent of 5 pallet loads of Standard Plastic Commodity.

Figure C-6 presents the time evolution of the two coordinates of the gas layer centroid. At first sprinkler operation, 1 min 42 s, the coordinates are 0.7 m (4.3 ft) to the north and 1.3 m (6.6 ft) to the west. This indicates that the fan significantly affected the fire plume, which would be nominally centered under the ceiling without the operating fan. For convenience, Figure C-7 presents the corresponding ceiling TC measurement contours at first sprinkler operation, which show a similar bias towards the northwest. Each measurement is obtained from thermocouples located 152 mm (6 in.) below ceiling. Note that the circle toward the center of the figure indicates the fan location. Due to an unresolved issue with the contour plot software, the colors within the circle are inverted.

Figure C-8 presents the air velocity measurements taken during the fire test at the 15 locations above the top of the array over the ignition bay. Each graph contains data from the five measurement locations over either the east face of the array, west face of the array, or above the longitudinal flue. As shown, negative values indicated downward air flow. A plan view schematic of the measurement locations relative to the array and the fan is included for reference. These data illustrate the strong downward air velocity generated by the fan with peak sustained velocities up to 3.5 m/s (11.5 ft/s). After ignition, the buoyant air flow from the fire plume is evident as either a reduction in the downward flow velocity or in some locations an upward air flow. The strongest upward air velocities were measured at locations C2 - C4, E3, and E4, which coincide with the actual location of the fire plume.

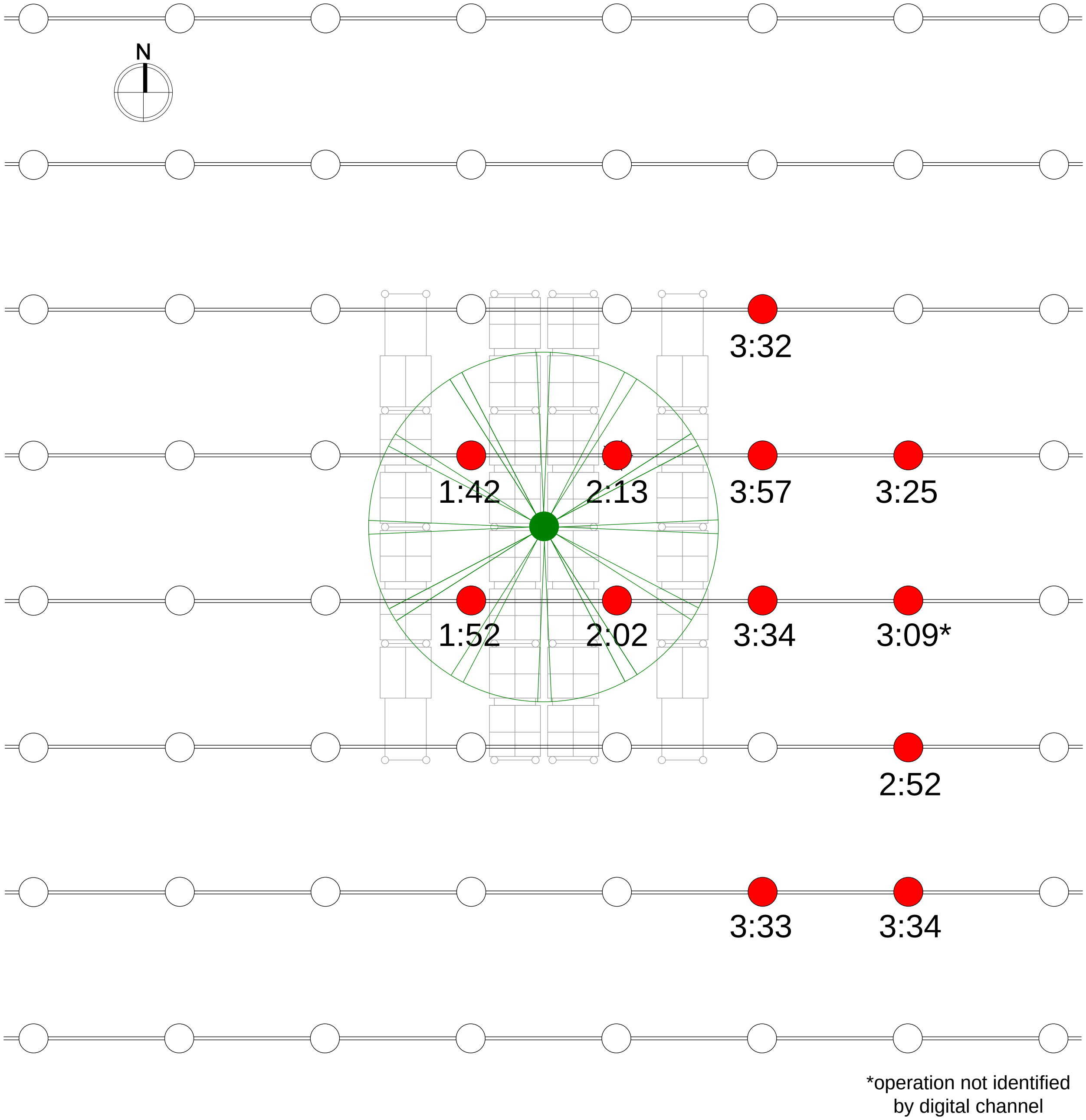


Figure C-1: Plan view of sprinkler operation pattern - Test 2

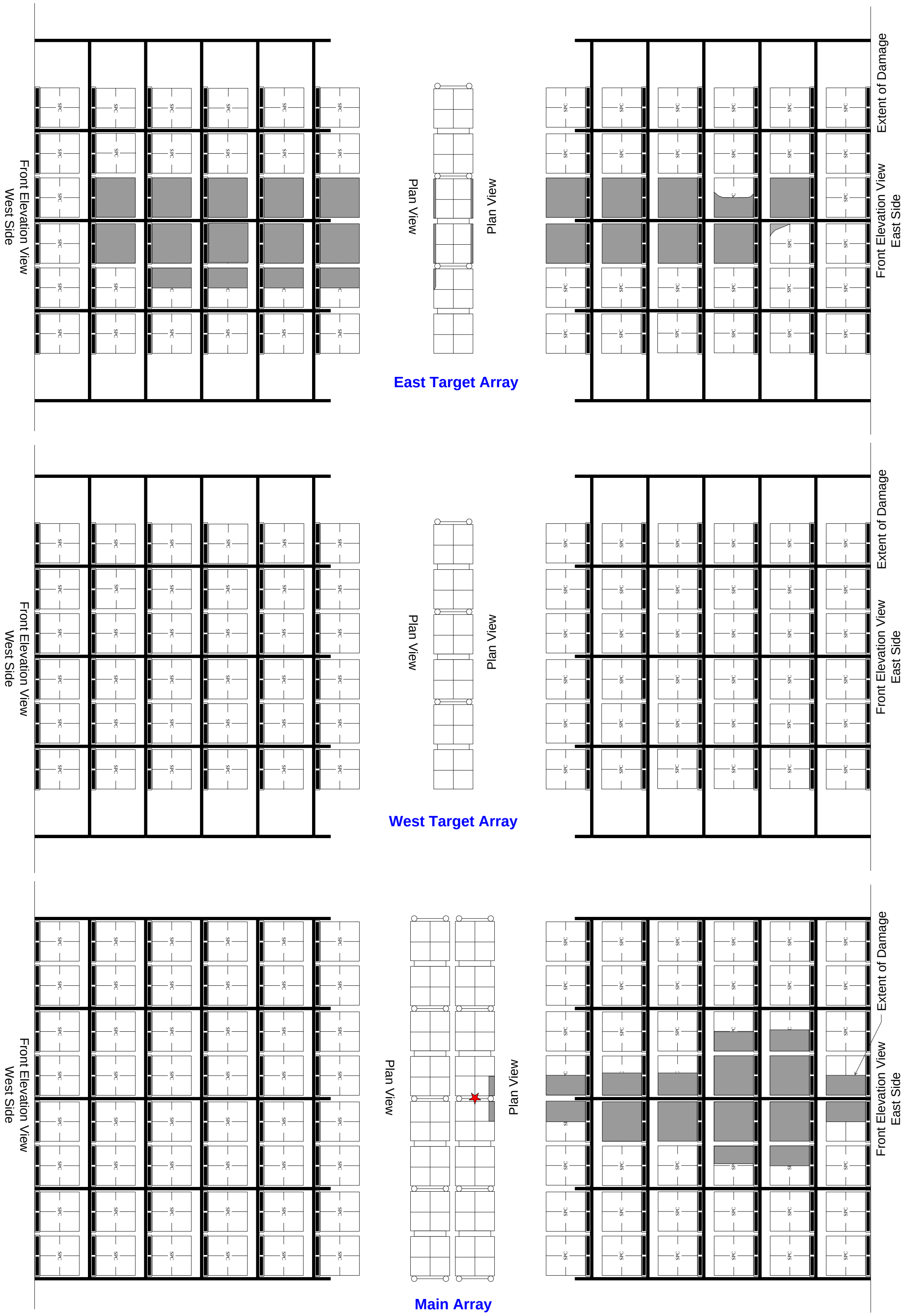


Figure C-2: Damage assessment - Test 2

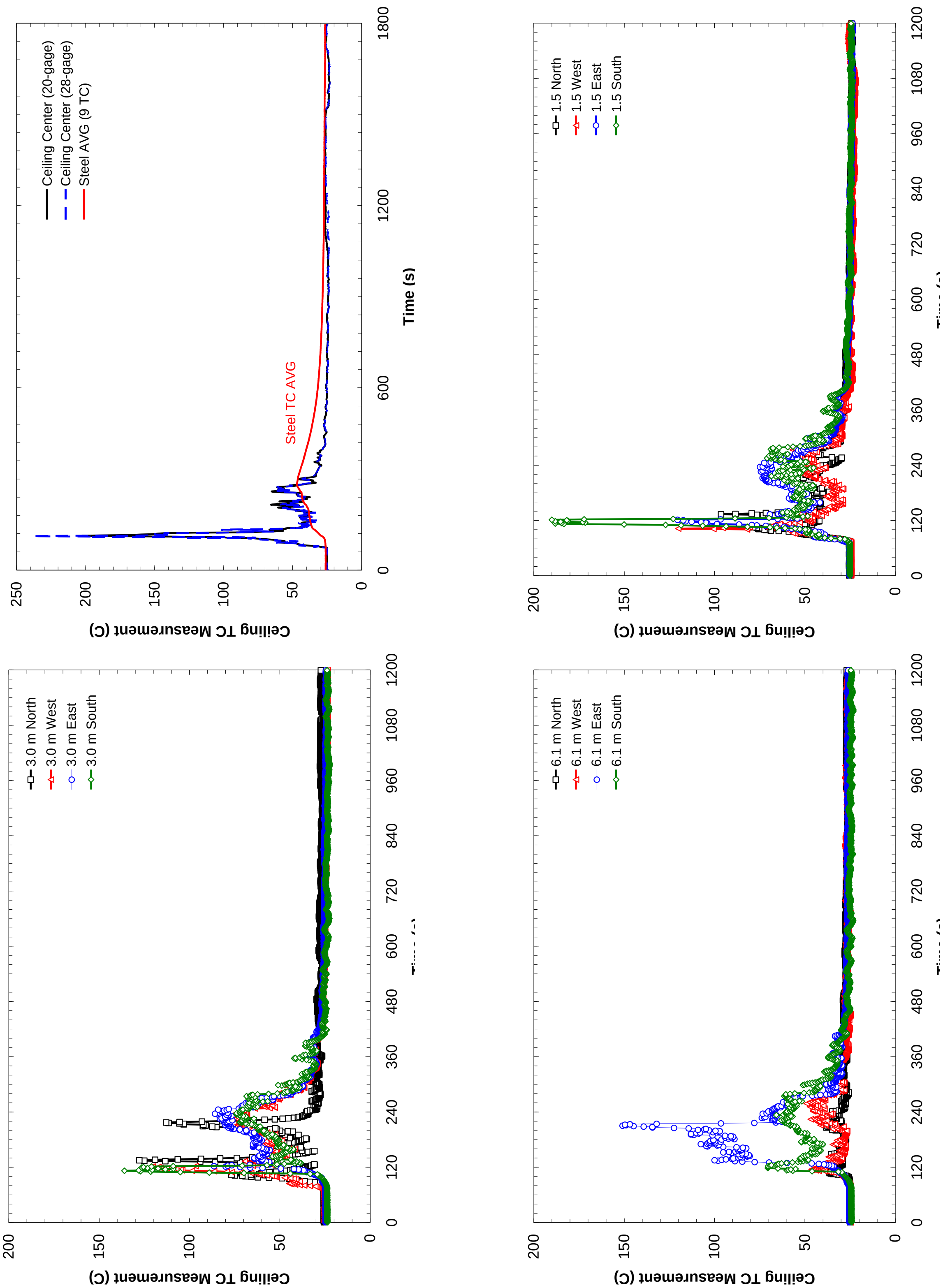


Figure C-3: Various near-ceiling TC measurements - Test 2

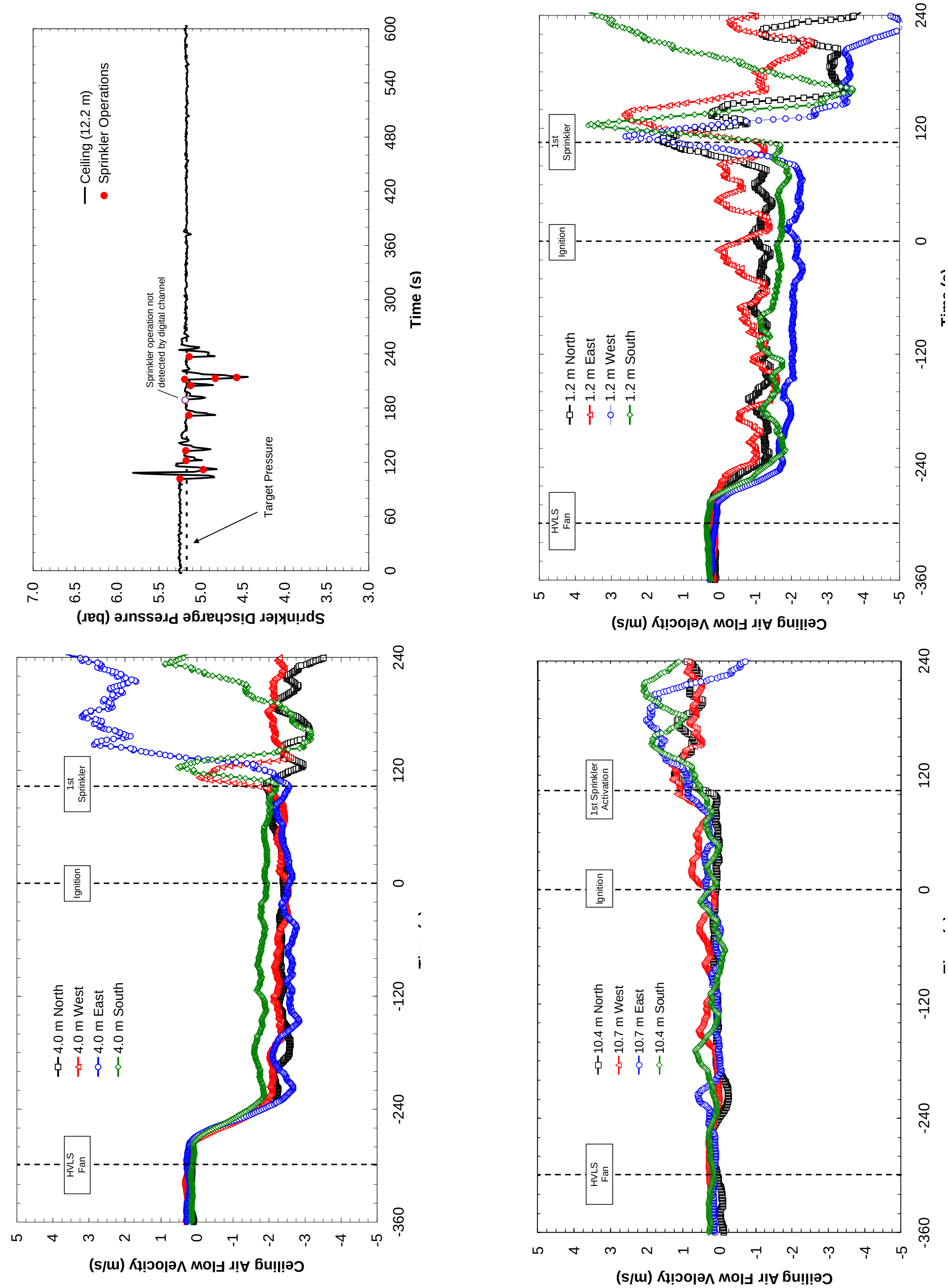


Figure C-4: Data plots – Test 2

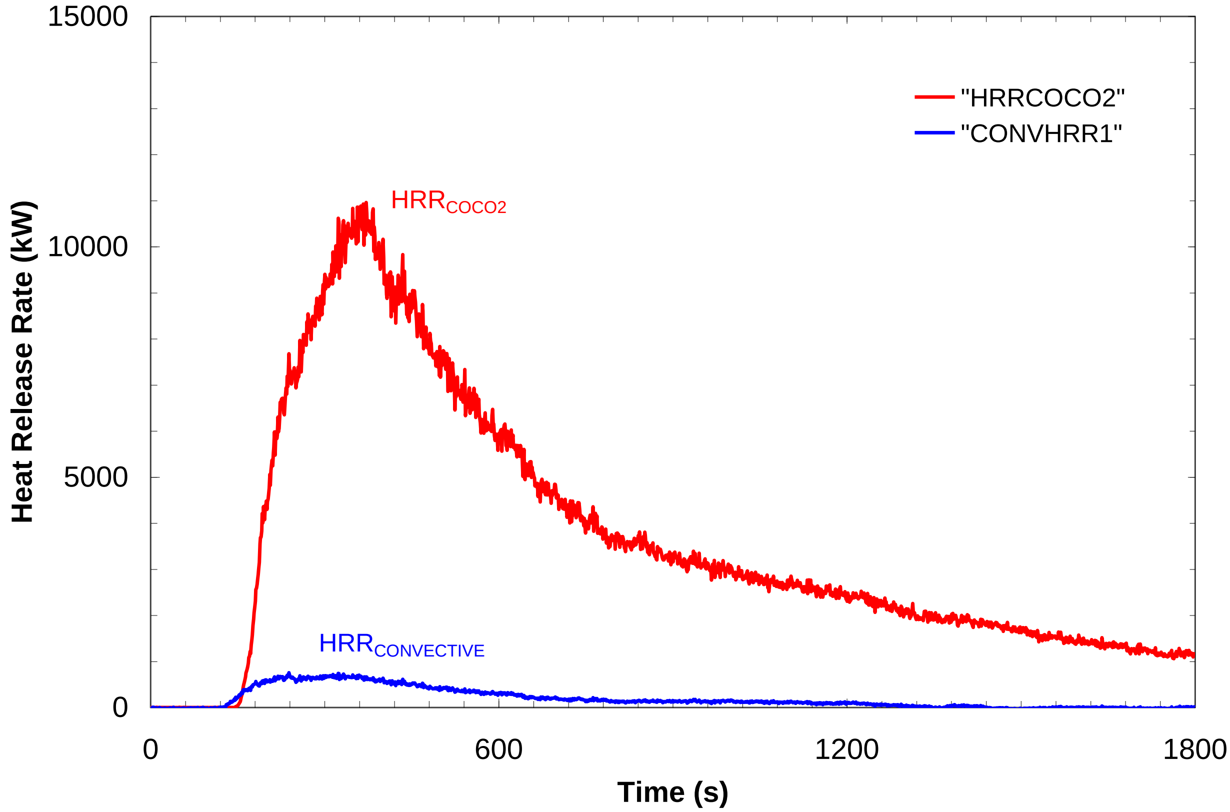


Figure C-5: Heat release rate – Test 2

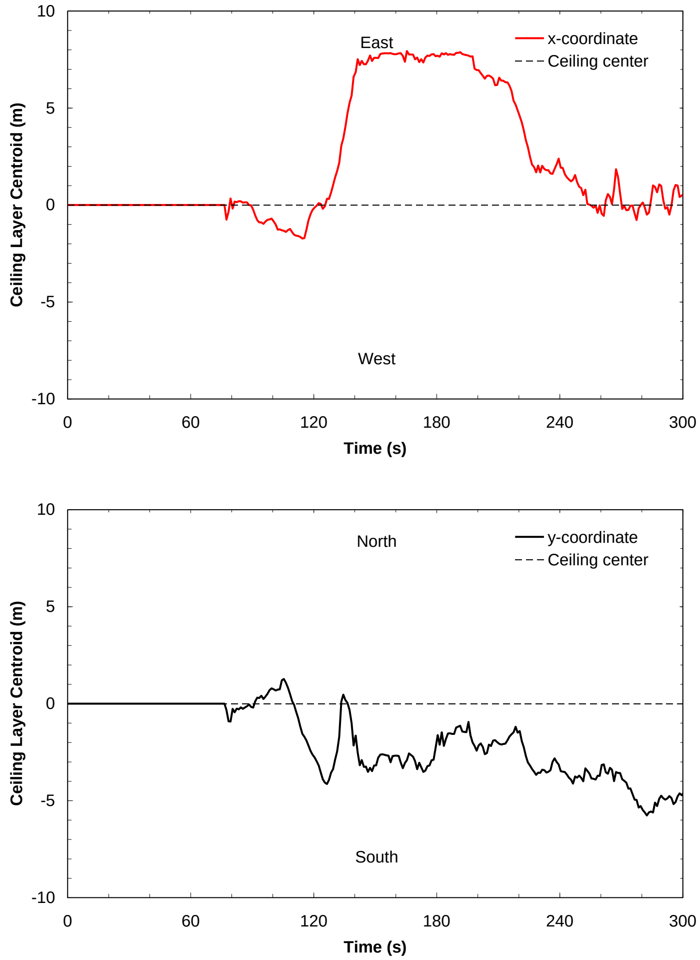


Figure C-6: Time evolution of x- and y-coordinate of ceiling layer centroid – Test 2

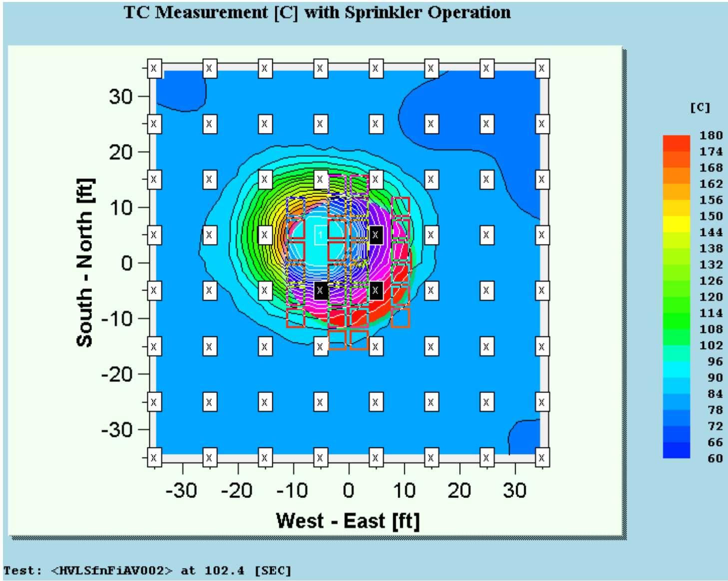


Figure C-7: Ceiling TC contours at first sprinkler operation (1 min 42 s) – Test 2

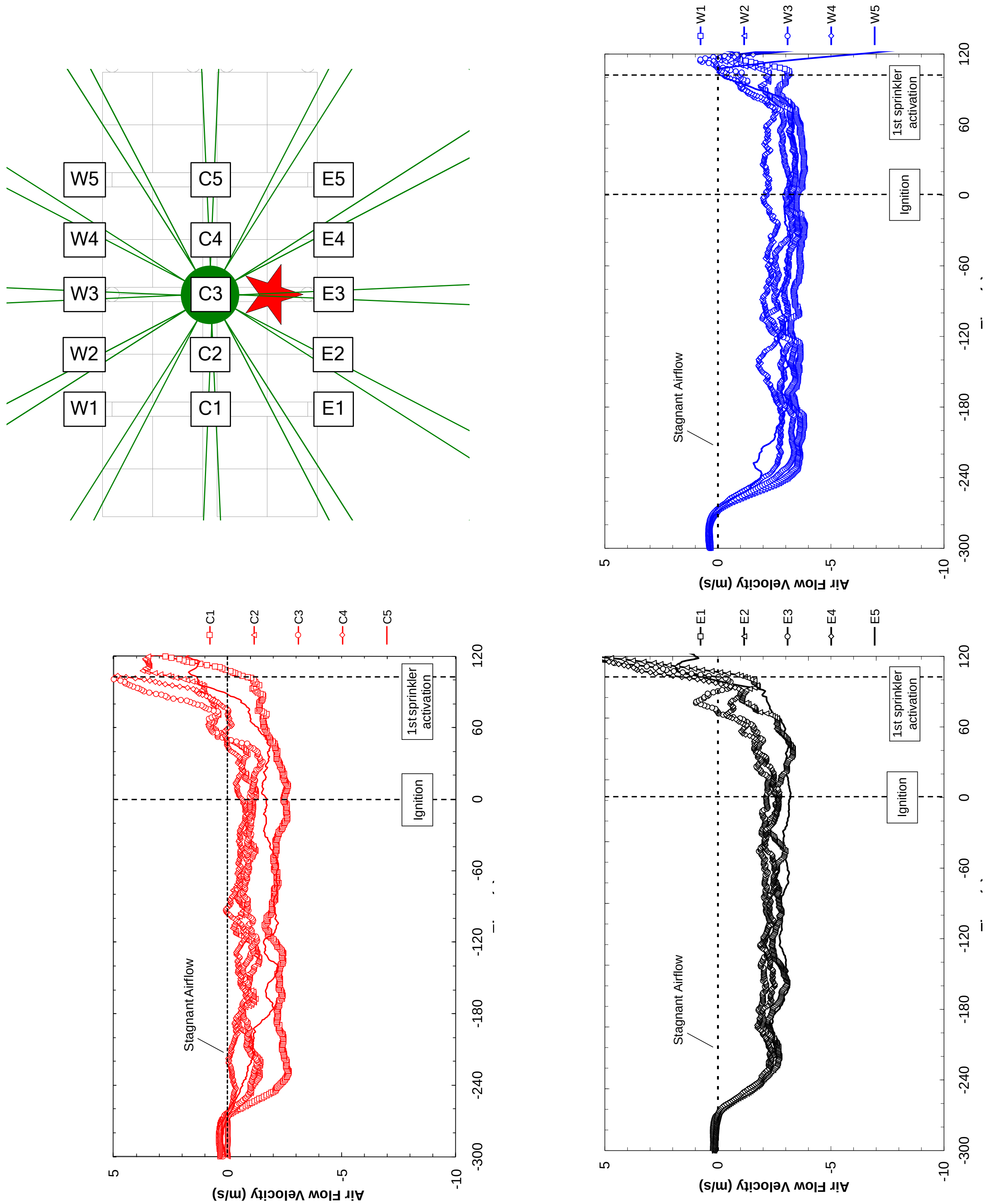


Figure C-8: Air-flow above array at ignition bay – Test 2

D APPENDIX D - TEST 3: DATA, OBSERVATIONS, AND RESULTS

The third test was conducted on September 3, 2010, at 10:30 am under the South Movable ceiling portion of the Large Burn Lab. Environmental conditions inside the lab were as follows: dry-bulb temperature, 23°C (74°F) and relative humidity, 38%. Weather conditions outside the lab were as follows: dry-bulb temperature, 28°C (82°F) and relative humidity, 64%. This test was identical to Test 2, except with the fan was shut off 1 min 30 after first sprinkler operation.

The main fuel array consisted of an open-frame, double-row rack of cartoned unexpanded plastic (CUP) commodity. The array dimensions measured approximately 10.1 m wide x 2.3 m deep (~33 ft x 7.5 ft) in an 8 bay wide x 2 bay deep arrangement. Single-row target arrays contained six pallet loads of the same commodity across a 1.2 m (4 ft) aisle to the east and west of the main array. Overall the target arrays measured approximately 7.5 m wide x 1.2 m deep (24.5 ft x 3.25 ft). For each array, a six pallet load high configuration was used, resulting in an array approximately 9.1 m (30 ft) high. The ceiling was set at a height of 12.2 m (40 ft) above the floor.

The main array was centered among four sprinklers. Ignition was accomplished with two FM Global standard half igniters, offset 0.6 m (2 ft) east in the central transverse flue, located at the rack uprights.

The sprinkler system was comprised of Tyco TY6226 quick-response pendent sprinklers with a K-factor of 202 L/min/bar$^{1/2}$ (14 gal/min/psi$^{1/2}$) and a 71°C (160°F) rated link. A nominal operating pressure of 5.2 bar (75 psig) was chosen to provide a discharge of 454 L/min (120 gpm) per sprinkler. The sprinklers were installed on 3 x 3 m (10 x 10 ft) spacing, resulting in a 48.9 mm/min (1.2 gpm/ft^2) water density at the floor.

The HVLS fan was located among four sprinklers and was nominally centered over the main array. This fan was a six blade design with an overall 7.3 m (24 ft) diameter. The fan was operating at the maximum speed of 66 rpm at the start of the test and was shut off 1 min 30 s after first sprinkler operation.

D.1.1 Test 3 Highlights

The data acquisition system was started with the lab under ambient air flow conditions, *i.e.*, the louvers to the dehumidification system were closed, the louvers on the south end of the west wall were closed, and the louvers on the north end of the west wall were open. After 60 s all instrumentation was zeroed. Data were then collected for 2 min with no air flow in the lab. The exhaust air system was then set to 94 m^3/min (200,000 cfm) and data were collected for 15 min to allow the air flow to stabilize. The HVLS fan was then started and data were collected for an additional 5 min before ignition, again to allow the air flow to stabilize.

After ignition, the initial fire development was within the center transverse flue. Flames reached the 2^{nd} tier by 32 s and were visibly disturbed by the air flow from the fan. Flames then reached the 3^{rd} tier at 44 s, 4^{th} tier at 54 s, 5^{th} tier at 1 min 3 s, and extended above the top of the array at 1 min 12 s. The first sprinkler operation, which was southwest of ignition, occurred at 1 min 54 s, and was immediately followed by the second sprinkler operation at 1 min 55 s southeast of ignition. The remaining two sprinklers surrounding ignition operated at 2 min 2 s and 2 min 3 s. Ignition of the east target array occurred at 3 min. By 5 min, the fire was contained to the lower tiers of the east row of the main array with no observed burning of the east target array. The fire was largely extinguished when the test was terminated by hose stream at 25 min. Damage was limited to the east row of the main array and the aisle face of the east target array.

D.1.2 Test 3 Results

A schematic overview of the sprinkler operation sequence and operation times can be found in Figure D-1. The first sprinkler, centered over the main array, operated at 1 min 54 s. The remaining 3 sprinklers operations, which surrounded the ignition location, occurred by 2 min 3 s.

The overall extent of fire damage for Test 3 is represented by the shaded areas in Figure D-2 for the main array and both target arrays. As shown, damage represents visual observation of burning on the outside face of the commodity; no observation of damage within the flue spaces was included. The fire spread remained within the longitudinal confines of the main array with damage primarily sustained on the eastern row and minimal damage to the commodity on the aisle face of the east target array.

Figure D-3 shows the near-ceiling TC measurements centered over the main array, and at a radial distance of 1.5 m (5 ft), 3.0 m (10 ft), and 6.1 m (20 ft) from center. The 20-gage thermocouple centered over the main array recorded a peak measurement of 183^{o}C (361^{o}F) and the adjacent 28-gage thermocouple recorded a peak measurement of 239^{o}C (462^{o}F), both roughly coinciding with first sprinkler operation at 1 min 54 s. The peak steel TC measurement of approximately 45^{o}C (113^{o}F) was recorded at 4 min 41 s. Steel temperatures shown in the graph represent the average of all nine thermocouples located out to 305 mm (12 in.) in all four directions from center. The thermocouples located 1.5 m (5 ft) and 3.0 m (10 ft) recorded nominally uniform peak TC measurements of 136^{o}C (277^{o}F) and 126^{o}C (259^{o}F), respectively, at first sprinkler operation. The thermocouples located 6.1 m (20 ft) recorded a peak TC measurement of 99^{o}C (210^{o}F) to the east at 3 min 50 s.

Figure D-4 shows the branch-line water discharge pressure and near-ceiling gas velocities at 2.4 m (8 ft), 4.0 m (13 ft), and 10.4 m (34 ft) from the main array center. The gas velocities present three distinct lab conditions: 1) until -300 s only the exhaust fan was operating at 94 m^3/s (200,000 cfm), 2) at -300 s the HVLS fan was started, and 3) at 0 s the fire was ignited. For each radial distance the recorded air velocities with only the exhaust fans operating were ± 0.2 m/s (0.7 ft/s). The addition of the HVLS fan caused a significant disturbance in the air flow, with the effect decreasing with distance from the fan. This effect was observed as negative measurements at the 2.4 m (8 ft) and 4.0 m (13 ft) locations approximately in the range of 0.5 to 2 m/s (1.6 to 6.6 ft/s), which indicates air flow being drawn toward the fan, *i.e.*, toward the ceiling center. The measurements at the 10.4 m (34 ft) locations indicate relatively stagnant air flow during the same time frame. Upon ignition, the fire plume gases began traveling outward from the ceiling center. This was observed at the 2.4 m (8 ft) locations as a positive air velocity, *i.e.*, away from the ceiling center, with magnitudes up to 3 m/s (13.1 ft/s) near the time of first sprinkler operation. At the 10.4 m (34 ft) locations, the effect of the HVLS fan and the fire plume gas flow was minimal.

Figure D-5 presents the heat release measurements based on the generation rates of carbon dioxide and carbon monoxide (HRR-COCO2) and convection gas flow within the exhaust duct (Convective). Due to an instrumentation failure, no heat release based on oxygen depletion is reported. Note that the heat release rate calculations do not account for lag and smear of the data, which can be significant, due to complex mixing of the gases above the movable ceiling or transport time through the collection ducts. Based on the HRR-COCO2 measurements, an estimated 3,500 ± 500 MJ (3,300,000 ± 500,000 BTU) of total energy was released from an equivalent of 2.5 pallet loads of Standard Plastic Commodity.

Figure D-6 presents the time evolution of the two coordinates of the gas layer centroid. At first sprinkler operation, 1 min 54 s, the coordinates are 0.8 m (2.6 ft) to the south and 0.3 m (1.0 ft) to the west. This indicates that the fan significantly affected the fire plume, which would be nominally centered under the ceiling without the operating fan. For convenience, Figure D-7 presents the corresponding ceiling TC measurement contours at first sprinkler operation, which show a similar bias towards the southwest. Each measurement is obtained from thermocouples located 152 mm (6 in.) below the ceiling. Note that the circle towards the center of the figure indicates the fan location. Due to an unresolved issue with the contour plot software, the colors within the circle are inverted.

Figure D-8 presents the air velocity measurements taken during the fire test at the 15 locations above the top of the array over the ignition bay. Each graph contains data from the five measurement locations over either the east face of the array, west face of the array, or within the longitudinal flue. As shown, negative values indicate downward air flow. A plan view schematic of the measurement locations relative to the array and the fan is included for reference. These data illustrate the strong downward air velocity generated by the fan with peak sustained velocities of up to 3.5 m/s (11.5 ft/s). After ignition, the buoyant air flow from the fire plume is evident as either a reduction in the downward flow velocity or in some locations an upward air flow. The strongest upward air velocities were measured at locations C2 - C4 and E2 - E4, which coincide with the actual location of the fire plume.

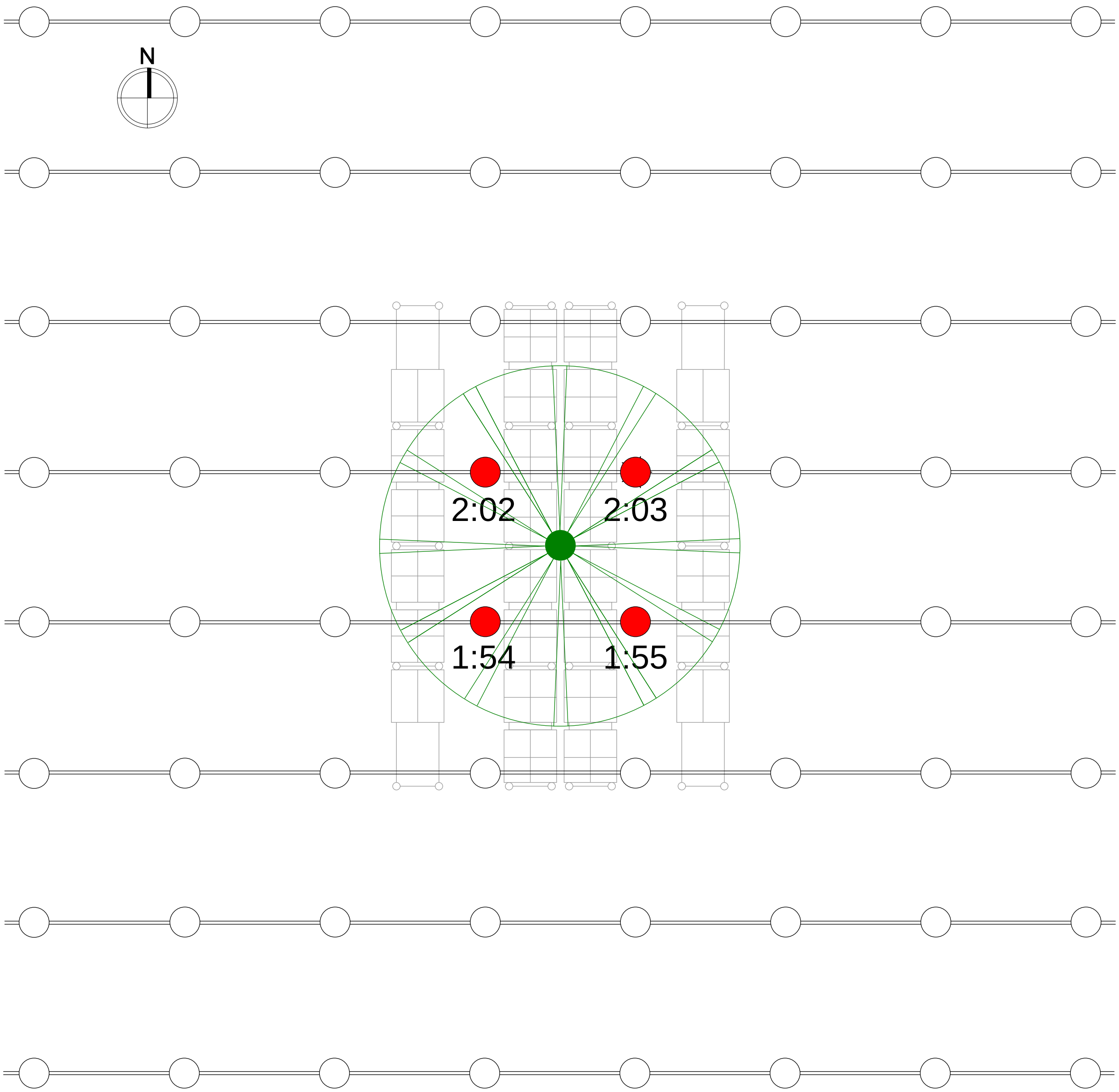


Figure D-1: Plan view of sprinkler operation pattern - Test 3

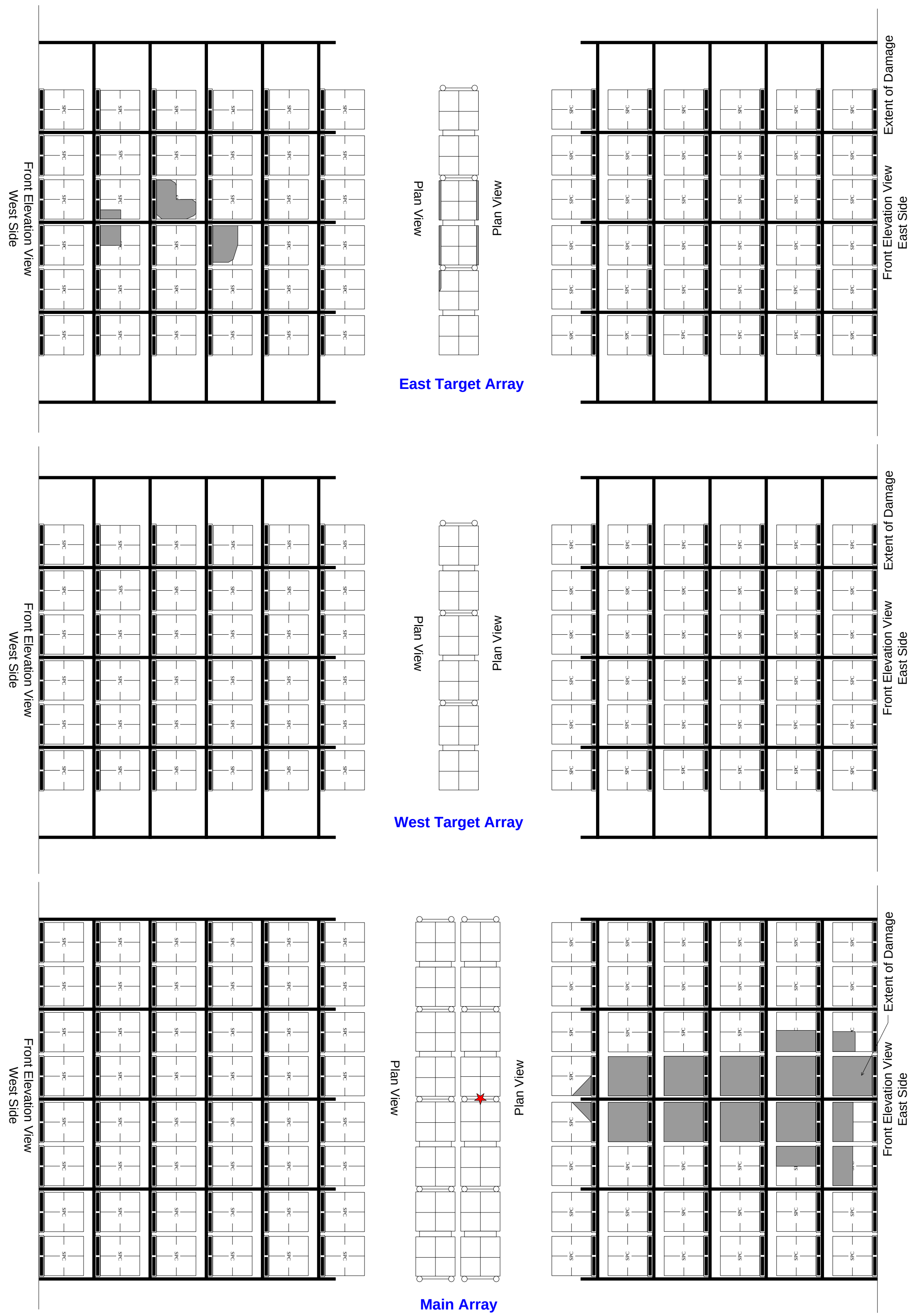


Figure D-2: Damage assessment - Test 3

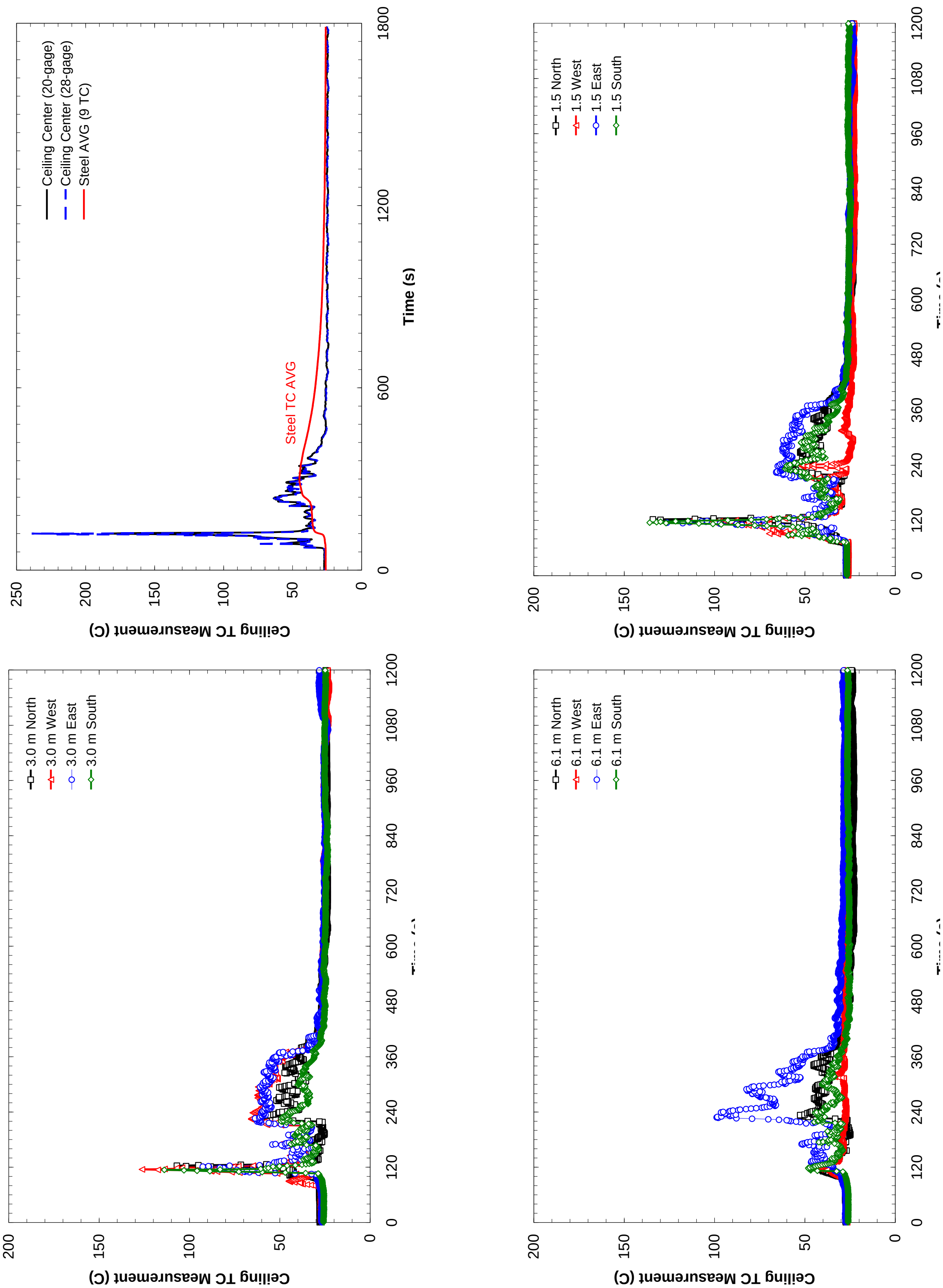


Figure D-3: Various near-ceiling TC measurements - Test 3

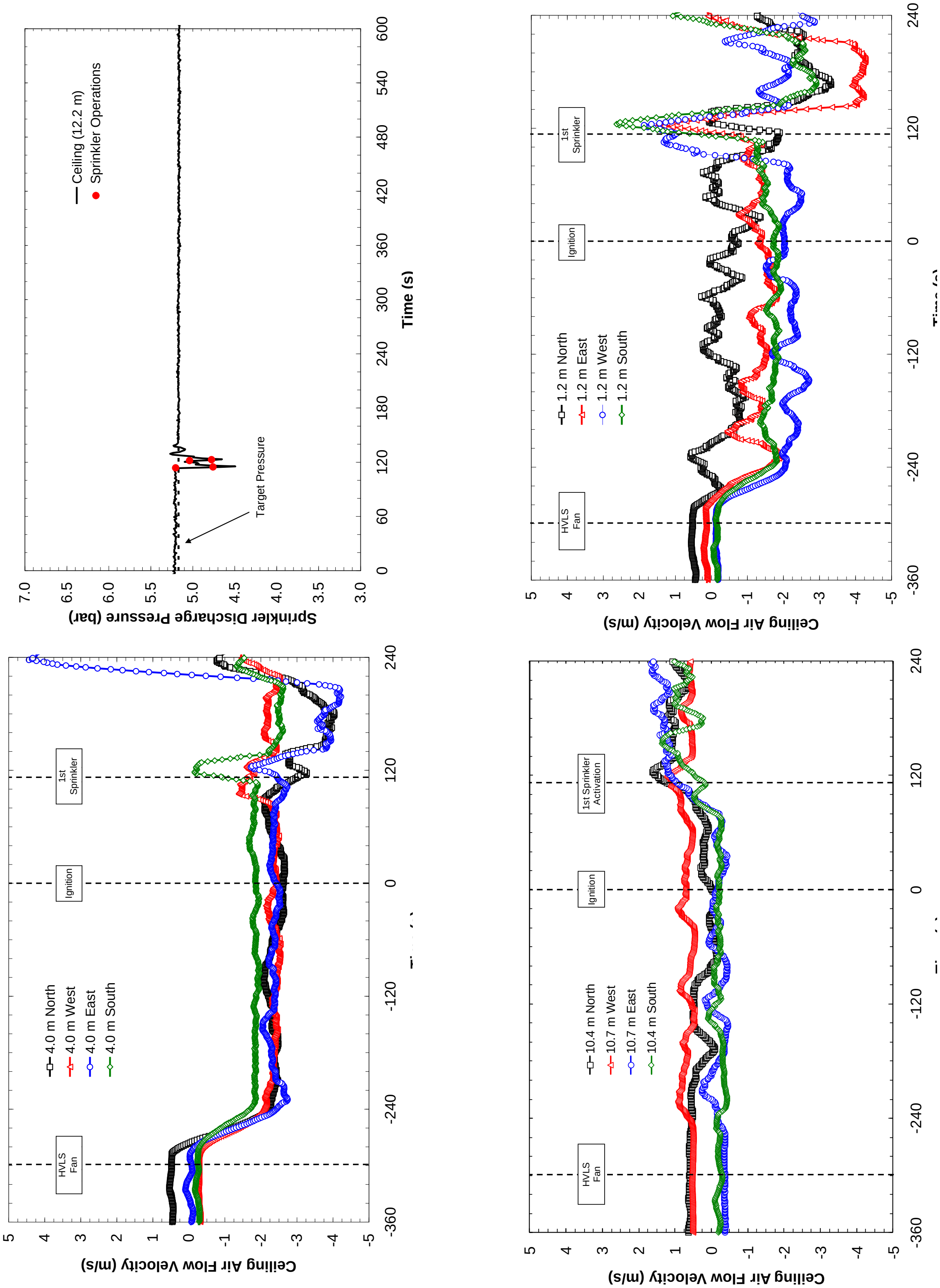


Figure D-4: Data plots – Test 3

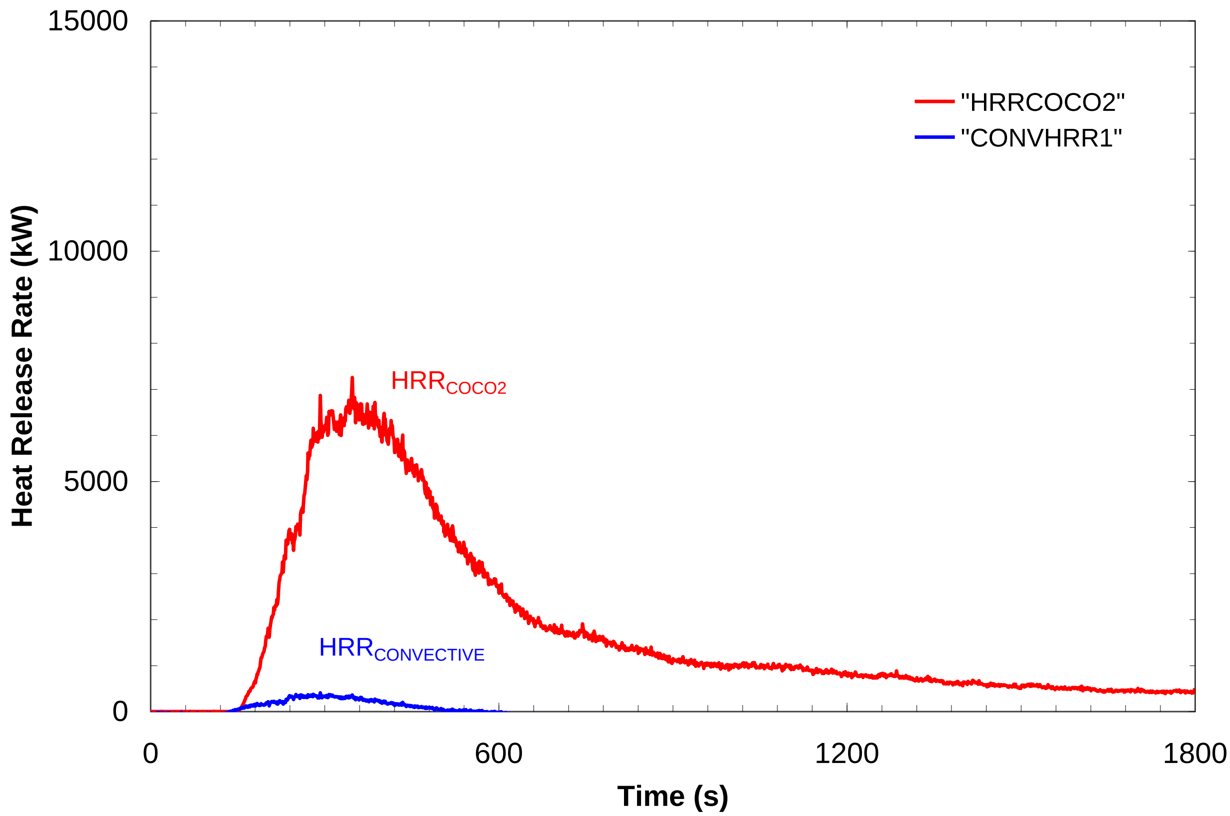


Figure D-5: Heat release rate – Test 3

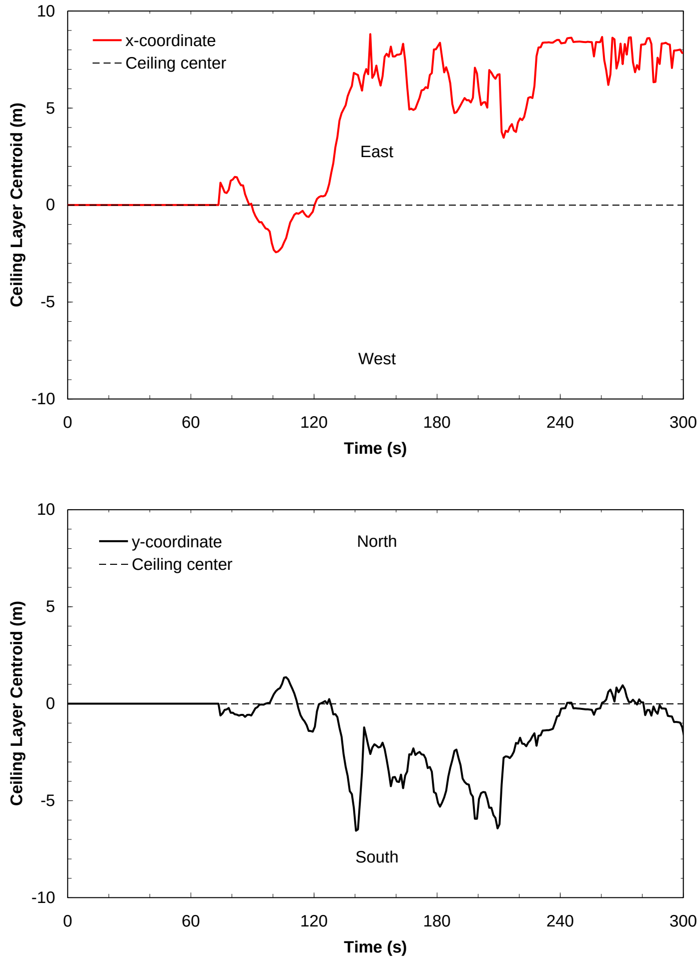


Figure D-6: Time evolution of x- and y-coordinate of ceiling layer centroid – Test 3

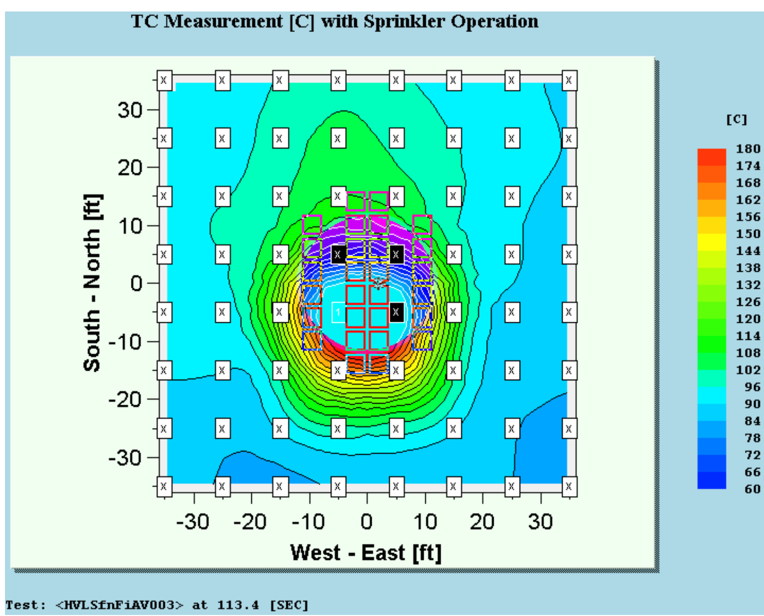


Figure D-7: Ceiling TC contours at first sprinkler operation (1 min 54 s) – Test 3

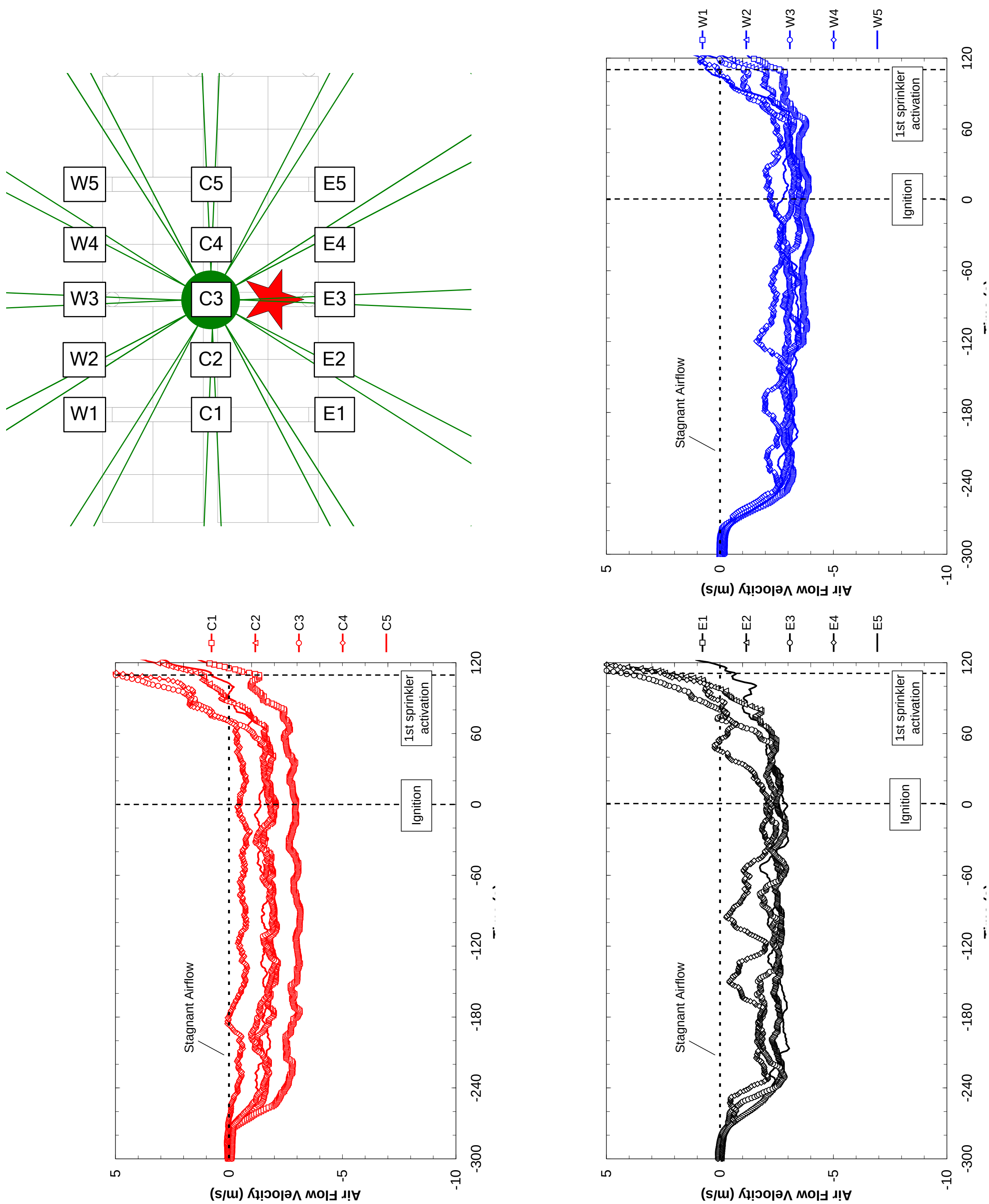


Figure D-8: Air-flow above array at ignition bay – Test 3

E APPENDIX E - TEST 4: DATA, OBSERVATIONS, AND RESULTS

The fourth test was conducted on December 2, 2010, at 9:00 am under the South Movable ceiling portion of the Large Burn Lab. Environmental conditions inside the lab were as follows: dry-bulb temperature, 23°C (74°F) and relative humidity, 24%. Weather conditions outside the lab were as follows: dry-bulb temperature, 2°C (36°F) and relative humidity, 55%. This test was similar to Test 3, except for a reduced storage height of 4.6 m (15 ft).

The main fuel array consisted of an open-frame, double-row rack of cartoned unexpanded plastic (CUP) commodity. The array dimensions measured approximately 10.1 m wide x 2.3 m deep (~33 ft x 7.5 ft) in an 8 bay wide x 2 bay deep arrangement. Single-row target arrays contained six pallet loads of the same commodity across a 1.2 m (4 ft) aisle to the east and west of the main array. Overall the target arrays measured approximately 7.5 m wide x 1.2 m deep (24.5 ft x 3.25 ft). For each array, a three pallet load high configuration was used, resulting in an array approximately 4.6 m (15 ft) high. The ceiling was set at a height of 12.2 m (40 ft) above the floor.

The main array was centered among four sprinklers. Ignition was accomplished with two FM Global standard half igniters, offset 0.6 m (2 ft) east in the central transverse flue, located at the rack uprights.

The sprinkler system was comprised of Tyco TY6226 quick-response pendent sprinklers with a K-factor of 202 L/min/bar$^{1/2}$ (14 gal/min/psi$^{1/2}$) and a 71°C (160°F) rated link. A nominal operating pressure of 5.2 bar (75 psig) was chosen to provide a discharge of 454 L/min (120 gpm) per sprinkler. The sprinklers were installed on 3 x 3 m (10 x 10 ft) spacing, resulting in a 48.9 mm/min (1.2 gpm/ft^2) water density at the floor.

The HVLS fan was located among four sprinklers and was centered over the main array. This fan was a six blade design with an overall 7.3 m (24 ft) diameter. The fan was operating at the maximum speed of 66 rpm at the start of the test and was shut off 1 min 30 s after first sprinkler operation.

E.1.1 Test 4 Highlights

The data acquisition system was started with the lab under ambient air flow conditions, *i.e.*, the louvers to the dehumidification system were closed, the louvers on the south end of the west wall were closed, and the louvers on the north end of the west wall were open. After 60 s all instrumentation was zeroed. Data were then collected for 2 min with no air flow in the lab. The exhaust air system was then set to 94 m^3/s (200,000 cfm) and data were collected for 15 min to allow the air flow to stabilize. The HVLS fan was then started and data were collected for an additional 5 min before ignition, again to allow the air flow to stabilize.

After ignition, the initial fire development was within the center transverse flue. Flames reached the 2nd tier by 34 s and were visibly disturbed by air flow from the fan. Flames then reached the 3rd tier at 43 s and extended above the top of the array by 1 min. At 1 min 10 s the flames extended 1 m (3 ft) above the array and were substantially disturbed (pushed down) by the fan air flow. By 1 min 30 s, the flames extended half way to the ceiling and the fire plume was stable over the ignition area. The first sprinkler operation, which was northwest of ignition, occurred at 1 min 39 s. The remaining three sprinklers (surrounding ignition) operated by 1 min 42 s and the flames receded to the top of the main array by 1 min 47 s. The fan was shut down at 3 min 9 s with burning of the commodity limited to the first tier of the main array. The fire was largely extinguished when the test was terminated by hose stream at 25 min. Damage was limited to the east row of the main array and no target ignition occurred.

E.1.2 Test 4 Results

A schematic overview of the sprinkler operation sequence and operation times can be found in Figure E-1. As indicated, the first sprinkler, centered over the main array, operated at 1 min 39 s. The remaining three sprinklers operations, which surrounded the ignition location, occurred by 1 min 42 s.

The overall extent of fire damage for Test 4 is represented by the shaded areas in Figure E-2 for the main array and both target arrays. As shown, damage represents visual observation of burning on the outside face of the commodity; no observation of damage within the flue spaces was included. The fire spread remained within the confines of the main array with damage primarily sustained on the eastern row and no jump to either target array.

Figure E-3 shows the near-ceiling TC measurements centered over the main array, and at a radial distance of 1.5 m (5 ft), 3.0 m (10 ft), and 6.1 m (20 ft) from center. The 20-gage thermocouple centered over the main array recorded a peak measurement of 178^{o}C (352^{o}F) and the adjacent 28-gage thermocouple recorded a peak measurement of 170^{o}C (338^{o}F), both roughly coinciding with first sprinkler operation at 1 min 39 s. The peak steel TC measurement of 28^{o}C (823^{o}F) was recorded at 1 min 46 s. Steel temperatures shown in the graph represent the average of all nine thermocouples located out to 305 mm (12 in.) in all four directions from center. The thermocouples located 1.5 m (5 ft) and 3.0 m (10 ft) recorded peak TC measurements of 156^{o}C (313^{o}F) to the west and 132^{o}C (270^{o}F) to the east, respectively, at first sprinkler operation. The thermocouples located 6.1 m (20 ft) recorded a peak TC measurement of 60^{o}C (140^{o}F) to the south also coinciding with first sprinkler operation.

Figure E-4 shows the branch-line water discharge pressure and near-ceiling gas velocities at 2.4 m (8 ft), 4.0 m (13 ft), and 10.4 m (34 ft) from the main array center. The gas velocities present three distinct lab conditions: 1) until -300 s only the exhaust fan was operating at 94 m^3/s (200,000 cfm), 2) at -300 s the HVLS fan was started, and 3) at 0 s the fire was ignited. For each radial distance the recorded air velocities with only the exhaust fans operating were ± 0.3 m/s (1.0 ft/s). The addition of the HVLS fan caused a significant disturbance in the air flow, with the effect decreasing with distance from the fan. This was observed at the 2.4 m (8 ft) location as a highly variable measurement ranging from 1.0 to - 2.5 m/s (3.3 to - 8.2 ft/s), indicating flow both toward and away from the fan. The measurements at the 4.0 m (13 ft) locations were approximately in the range of -1.7 to -2.7 m/s (-5.6 to -8.9 ft/s), which indicates air flow being drawn toward the fan, *i.e.*, toward the ceiling center. The measurements at the 10.4 m (34 ft) locations indicate relatively stagnant air flow during the same timeframe. Upon ignition, the fire plume gases began traveling outward from the ceiling center. This was observed at the 2.4 m (8 ft) locations as a positive air velocity, *i.e.*, away from the ceiling center, with magnitudes up to 2.8 m/s (9.2 ft/s) near the time of first sprinkler operation. At the 10.4 m (34 ft) locations, the effect of the HVLS fan and the fire plume gas flow was minimal.

Figure E-5 presents the heat release measurements based on the generation rates of carbon dioxide and carbon monoxide (HRR-COCO2) and convection gas flow within the exhaust duct (Convective). Due to an instrumentation failure, no heat release based on oxygen depletion is reported. Note that the heat release rate calculations do not account for lag and smear of the data, which can be significant, due to complex mixing of the gases above the movable ceiling or transport time through the collection ducts. Based on the HRR-COCO2 measurements, an estimated 750 ± 100 MJ (700,000 ± 100,000 BTU) of total energy was released from an equivalent of 0.5 pallet loads of Standard Plastic Commodity.

Figure E-6 presents the time evolution of the two coordinates of the gas layer centroid. At first sprinkler operation, 1 min 39 s, the coordinates are 0.8 m (2.6 ft) to the south and 1.1 m (3.6 ft) to the west. Given the 7.6 m (25 ft) clearance from the commodity to the ceiling for this test configuration, the location of the ceiling gas centroid indicates that the fan only had a minimal effect on the fire plume, which would be nominally centered under the ceiling without the operating fan. For convenience, Figure E-7 presents the corresponding ceiling TC measurement contours at first sprinkler operation, which show a similar minimal displacement of the fire plume centroid towards the southwest. Each measurement is obtained from thermocouples located 152 mm (6 in.) below ceiling. Note that the circle towards the center of the figure indicates the fan location. Due to an unresolved issue with the contour plot software, the colors within the circle are inverted.

Figure E-8 presents the air velocity measurements taken during the fire test at the 15 locations above the top of the array over the ignition bay. Each graph contains data from the five measurement locations over either the east face of the array, west face of the array, or above the longitudinal flue. As shown, negative values indicate downward air flow. A plan view schematic of the measurement locations relative to the array and the fan is included for reference. These data illustrate the strong downward air velocity generated by the fan with peak sustained velocities of up to -3.3 m/s (-10.8 ft/s). After ignition, the buoyant air flow from the fire plume was evident as either a reduction in the downward flow velocity or in some locations an upward air flow. The upward air velocities were generally greater than 1 m/s (3.3 ft/s) at first sprinkler operation with peak values greater than 5 m/s (16.4 ft/s) measured at locations C3, C4, E2, E4, and W4.

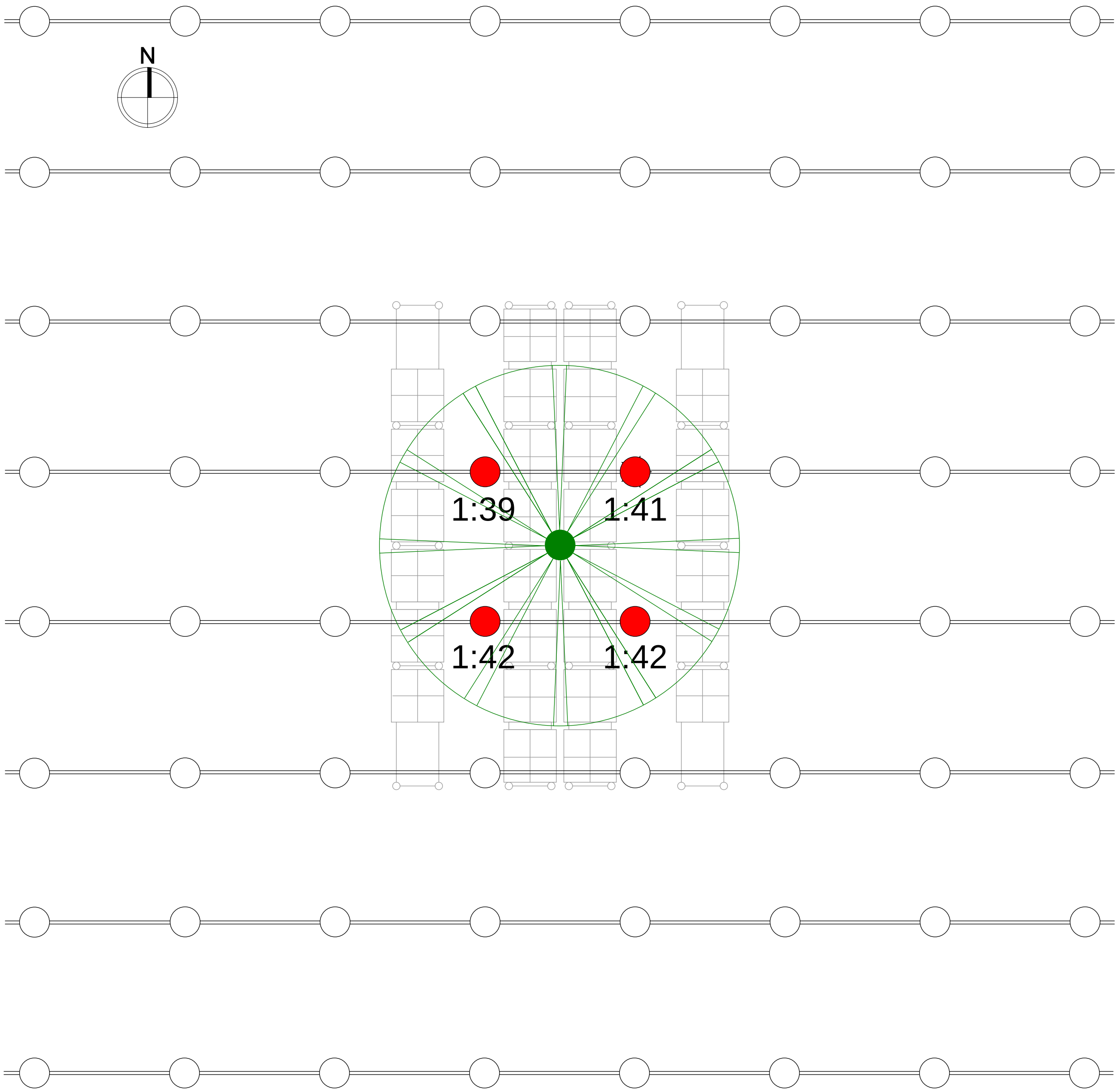


Figure E-1: Plan view of sprinkler operation pattern - Test 4

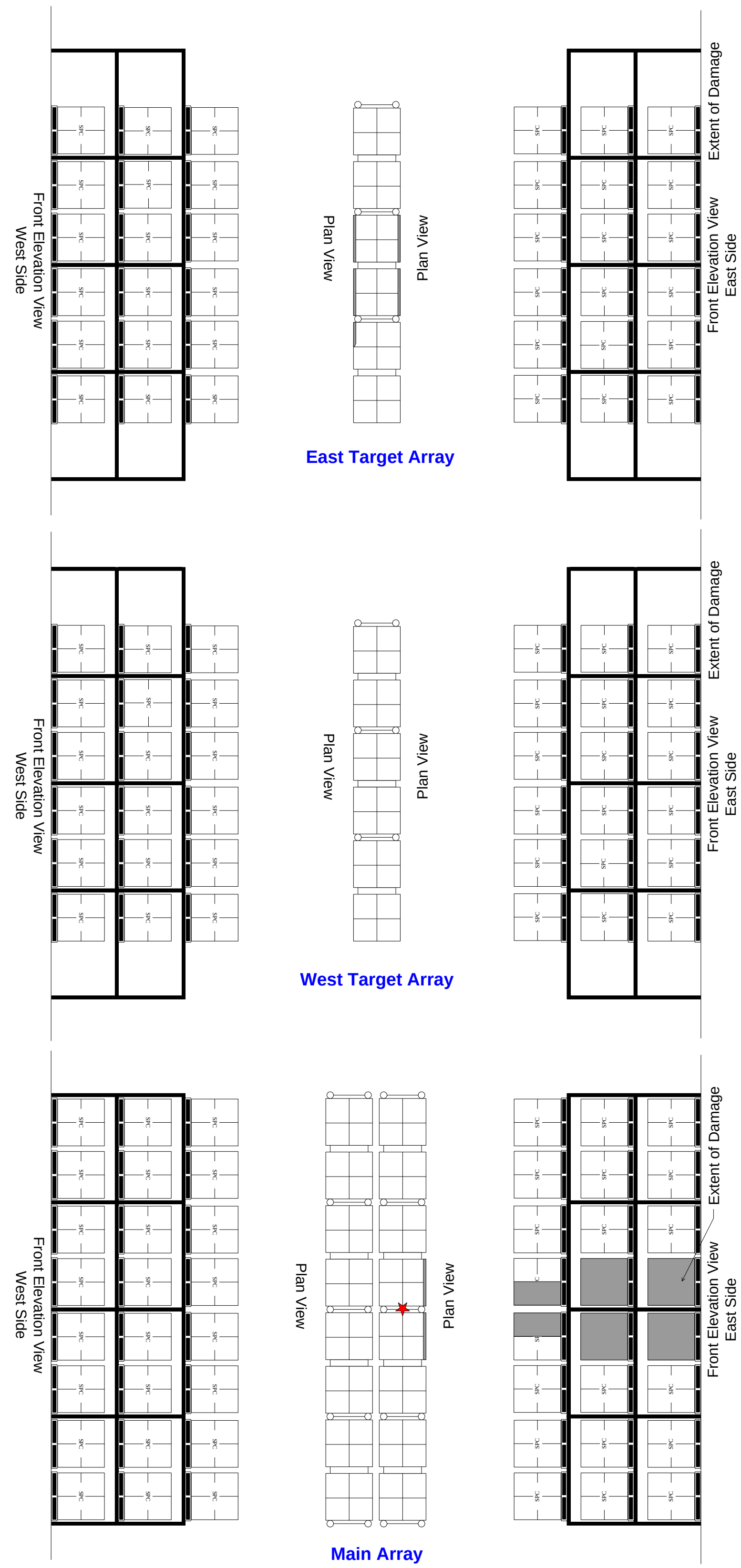


Figure E-2: Damage assessment - Test 4

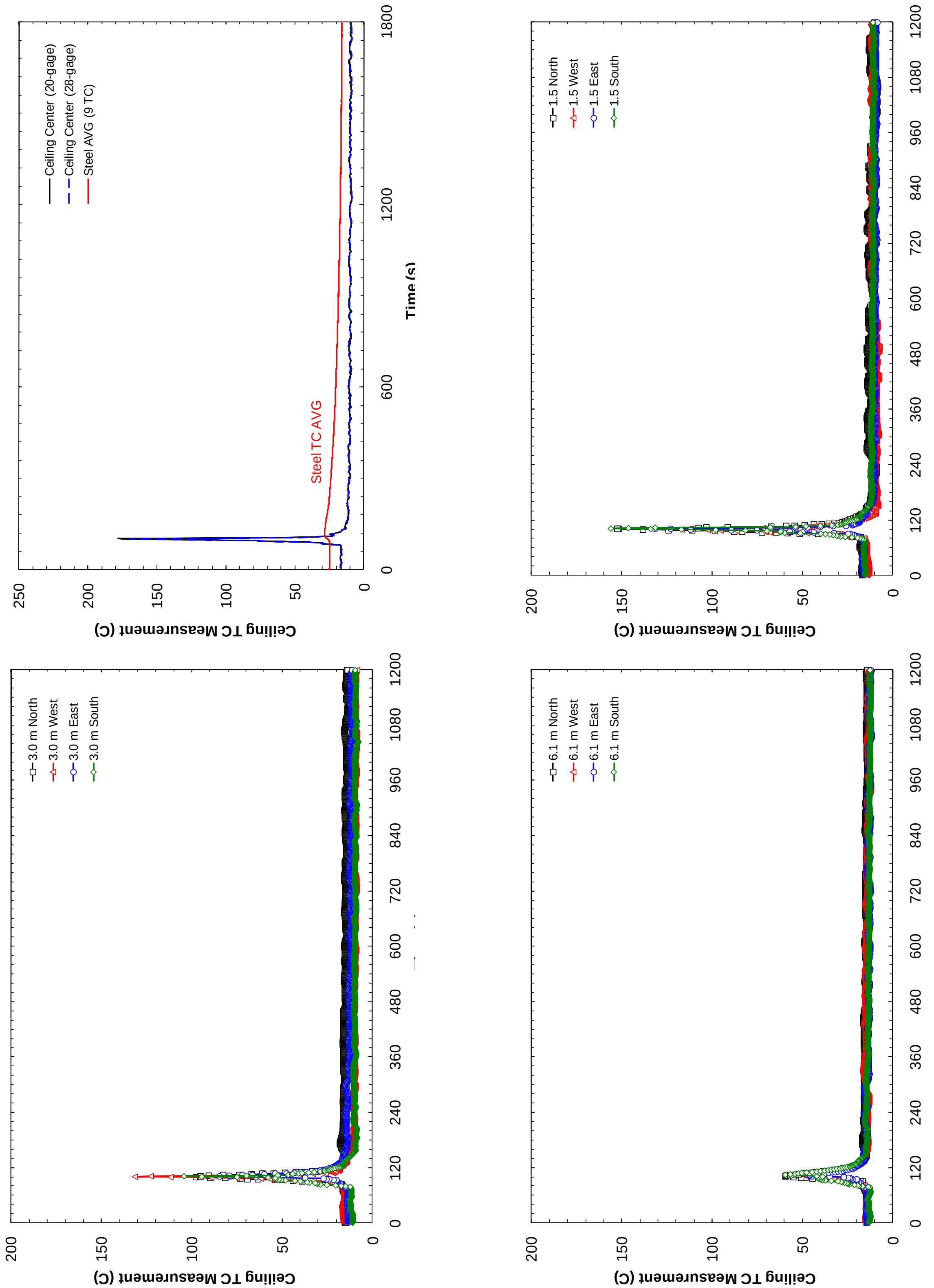


Figure E-3: Various near-ceiling TC measurements - Test 4

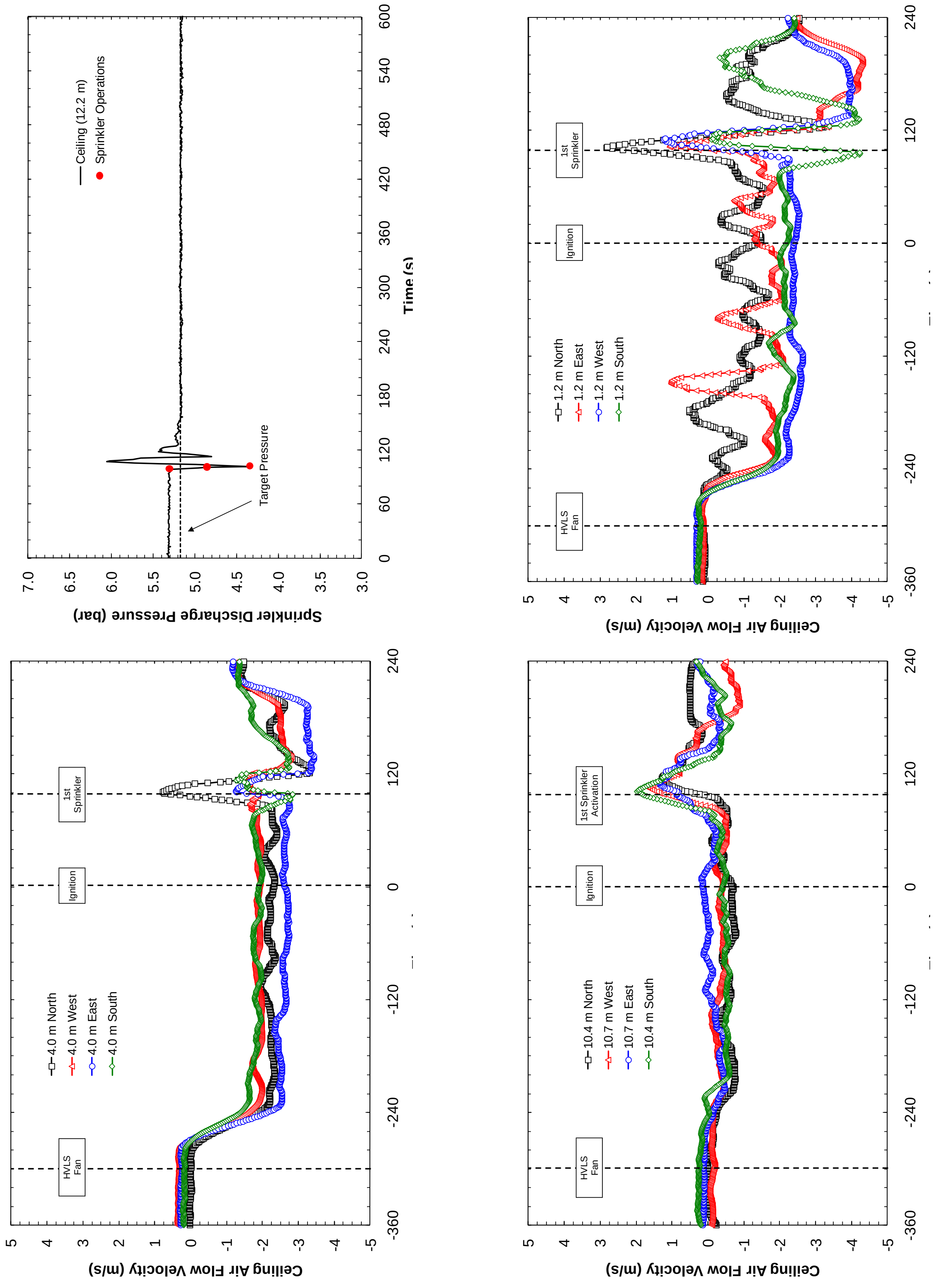


Figure E-4: Data plots – Test 4

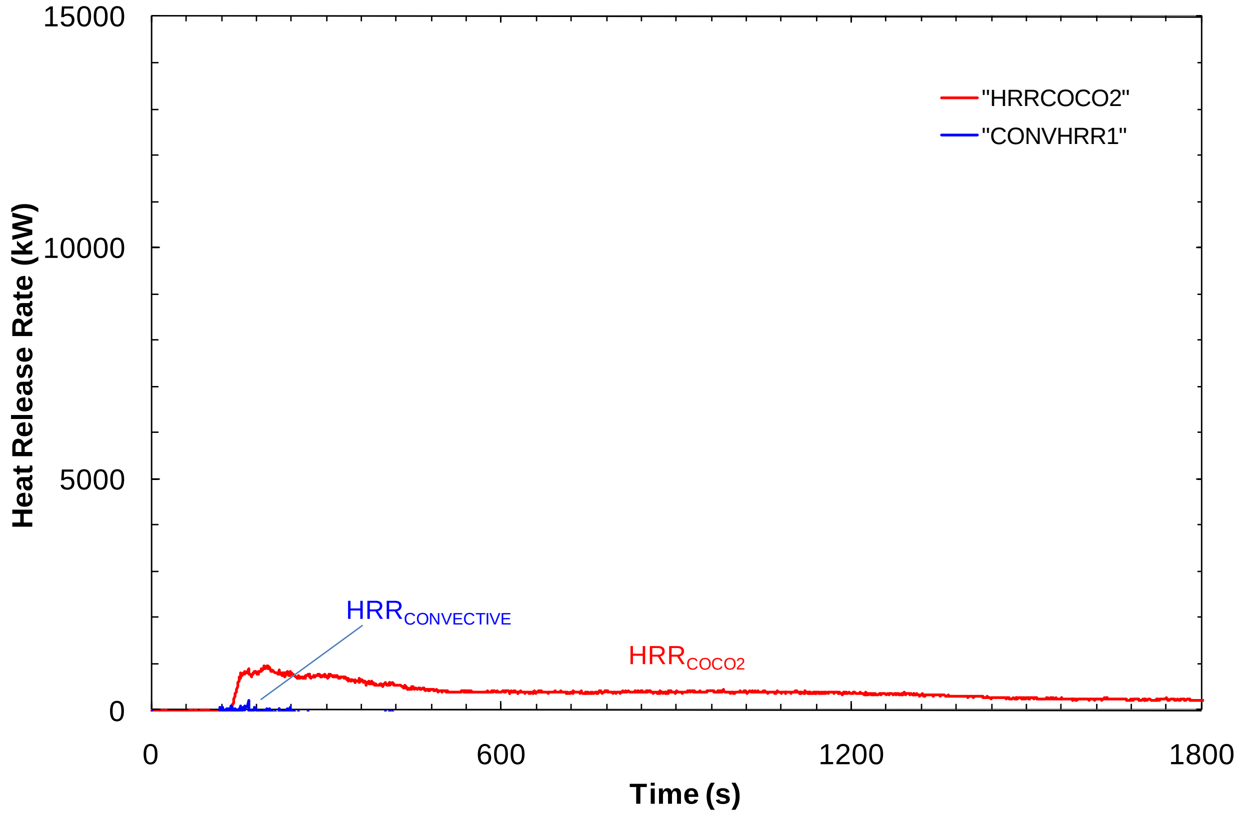


Figure E-5: Heat release rate – Test 4

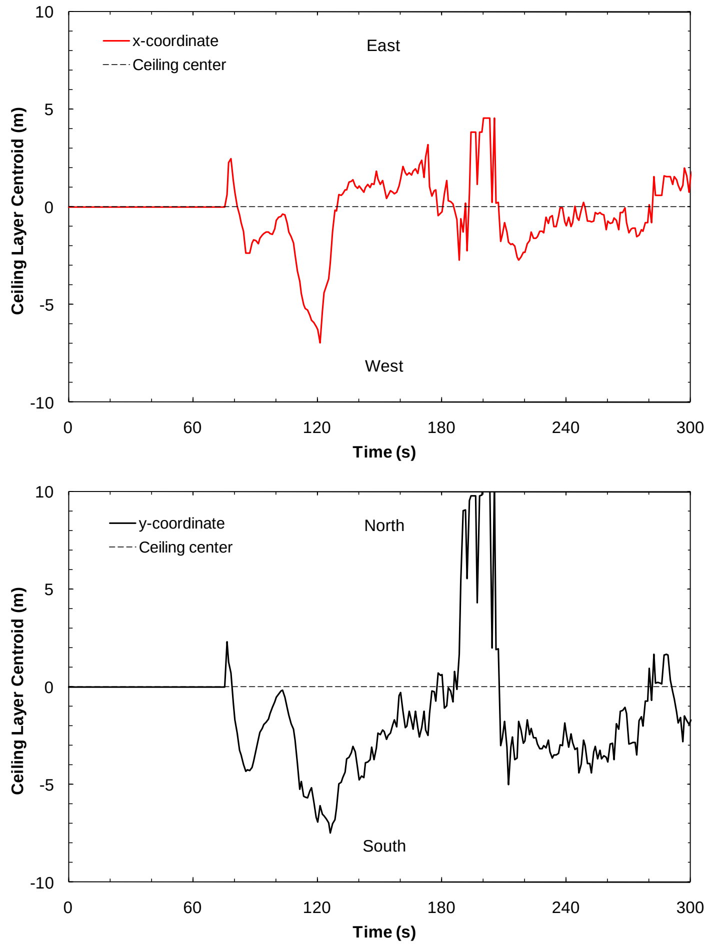


Figure E-6: Time evolution of x- and y-coordinate of ceiling layer centroid – Test 4

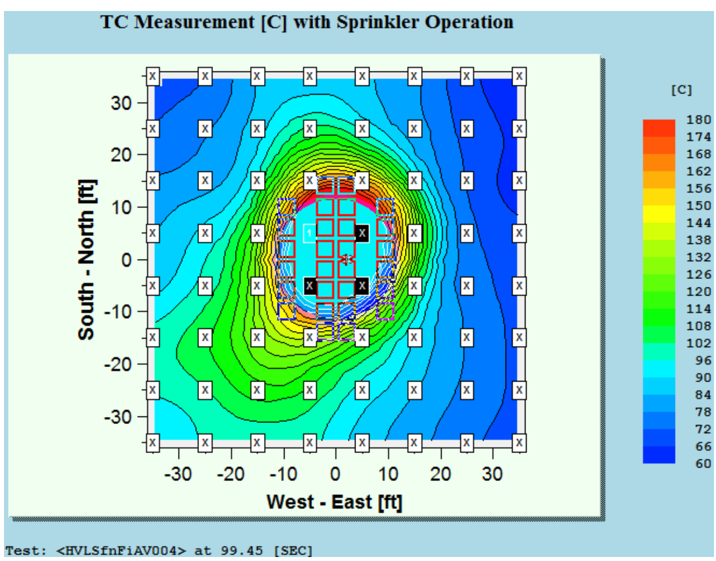


Figure E-7: Ceiling TC contours at first sprinkler operation (1 min 39 s) – Test 4

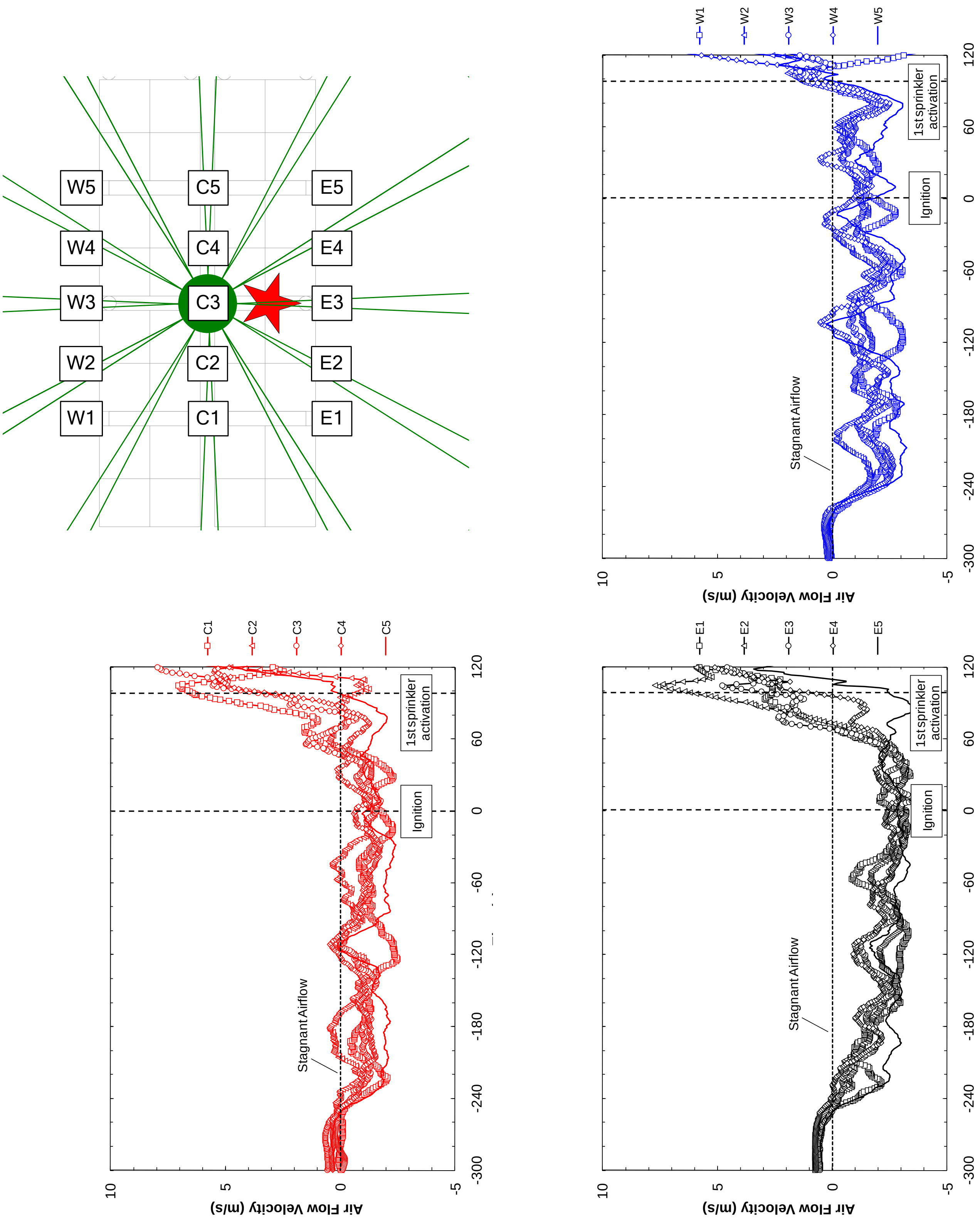


Figure E-8: Air-flow above array at ignition bay – Test 4

F APPENDIX F – FIRE CHRONOLOGIES

F.1 TEST 1 – FIRE CHRONOLOGY

Date: 5 August, 2010
Observer: Benjamin Ditch

Time (mm:ss)	Observation
	DAQ engines, + 60 s and Lin0 (zeroes bidirectional probes)
-22:13	Test start, no air flow in lab (dehumidifier vents closed, louvered walls closed, fan off)
-20:13	Start exhaust air, 200K cfm (time allotted to stabilize air flow)
-5:13	HVLS fan on (time allotted to stabilize air flow)
0:00	Ignition, rack uprights, offset 2-ft east
0:30	Flames visible above 1st tier
0:35	Flames reach 2nd tier, visibly disturbed by fan air flow
1:02	Flames reach 3rd tier
1:07	Flames reach 4th tier
1:13	Flames reach 5th tier
1:20	Flames extend above main array, contained to ignition flue
1:28	1st sprinkler operation, centered over main array
1:40	Flames recede to 1st and 2nd tier of ignition bay
2:14	Flames reach east face of main array at 2nd tier
2:15	Exiting lab due to smoke (fan increasing smoke spread in lab), observations made from cameras viewing east and west aisles and IR camera
2:33	Flames reach west face of main array at 2nd tier
3:09	Flames on east face of main array extend to 2nd and 3rd tier, Ignition of east target array at 3rd tier
3:21	2nd sprinkler operation, centered over east target array
3:27	5 total sprinklers operations
3:30	Flames in east aisle from tiers 2 - 5
4:17	Flames on west face of main array extend to tiers 2 - 4
4:50	Flames on west face of main array extend to tiers 2 - 5
5:45	11 total sprinkler operations
5:50	Ignition of west target array at 2nd and 3rd tier
7:53	12th and final sprinkler operation
35:00	Test terminated by hose stream; 12 sprinkler operations; substantial damage to east and west side of main array, fire jump to both east and west targets, no damage to backside of targets or ends of main array, fan appears to be operating fine

F.2 TEST 2 – FIRE CHRONOLOGY

Date: 20 August, 2010
Observer: Benjamin Ditch

Time (mm:ss)	Observation
	DAQ engines, + 60 s and Lin0 (zeroes bidirectional probes)
-22:10	Test start, no air flow in lab (dehumidifier vents closed, louvered walls closed, fan off)
-20:10	Start exhaust air, 200K cfm (time allotted to stabilize air flow)
-5:10	HVLS fan on (time allotted to stabilize air flow)
0:00	Ignition, rack uprights, offset 2-ft east
0:12	Boxes replaced in array (moved for ignition)
0:24	Flames reach 2nd tier, visibly disturbed by fan air flow
0:50	Flames reach 3rd tier
1:00	Flames reach 4th tier
1:05	Flames reach 5th tier
1:15	Flames extend above main array, contained to ignition flue
1:30	Flames extend 3 -4 ft above array, visibly disturbed by fan air flow (appear to be forced west)
1:42	1st sprinkler operation
1:52	2nd sprinkler operation
2:02	3rd sprinkler operation
2:13	4th sprinkler operation, flames contained to eastern aisle, burning along west face of main array at tiers 2 – 6, ignition of east target array at 2nd and 3rd tier
2:50	Flames extend to backside of east target array at 4th tier, additional sprinkler operation
3:04	Commodity on backside of east target now burning at 4th tier
3:15	Flames/burning at 3rd and 4th tiers on backside of east target, overall fire size appears to be increasing
3:34	11 total sprinkler operations, flames on backside of east target at tiers 3 – 6
3:45	Exiting lab due to smoke, array completely obscured
3:57	12th and final sprinkler operation
4:15	Fan appears to be operating fine
6:30	Comments from IR camera: Flames appear to be contained to main and eastern target array, no judgment possible for backside of east target
8:30	No change
25:00	Test terminated by hose stream; 12 sprinkler operations; damage to main array contained to east row only, fire jump to east target only, substantial damage to backside of east target

F.3 TEST 3 – FIRE CHRONOLOGY

Date: 2 September, 2010
Observer: Benjamin Ditch

Time (mm:ss)	Observation
	DAQ engines, + 60 s and Lin0 (zeroes bidirectional probes)
-22:39	Test start, no air flow in lab (dehumidifier vents closed, louvered walls closed, fan off)
-20:39	Start exhaust air, 200K cfm (time allotted to stabilize air flow)
-5:39	HVLS fan on (time allotted to stabilize air flow)
0:00	Ignition, rack uprights, offset 2-ft east
0:11	Boxes replaced in array (moved for ignition)
0:32	Flames reach 2nd tier, visibly disturbed by fan air flow
0:44	Flames reach 3rd tier
0:54	Flames reach 4th tier
1:03	Flames reach 5th tier
1:10	Flames reach 6th tier
1:12	Flames extend above main array, contained to ignition flue
1:26	Flames extend 2-3 ft above array, visibly disturbed by fan airflow (appear to be forced west)
1:40	Flames burning on the east aisle face of main array at tiers 2 -6
1:54	1st sprinkler operation, southwest of ignition
1:55	2nd sprinkler operation, southeast of ignition
2:02	3rd sprinkler operation, northwest of ignition
2:03	4th (final) sprinkler operation, north east of ignition, flames contained to eastern aisle, burning along west face of main array at tiers 2 – 6
2:40	Grayish smoke filling lab space a partially obscuring view of array
3:00	Ignition of east target array at 3rd tier across from ignition bay
3:24	Fan shut down (1st sprinkler + 90 s)
5:00	Fire contained to lower tiers of east, no remaining flames observed on east target
8:10	Fire completely obscured by white smoke, exiting test floor
8:35	Observation from IR camera, fire contained to tiers 2-4 of main array, no burning on east or west target array
25:00	Test terminated by hose stream; 4 sprinkler operations; damage to main array contained to east row only, fire jump to east target only causing minimal damage

F.4 TEST 4 – FIRE CHRONOLOGY

Date: 2 December, 2010
Observer: Benjamin Ditch

Time (mm:ss)	Observation
	DAQ engines, + 60 s and Lin0 (zeroes bidirectional probes)
-22:09	Test start, no air flow in lab (dehumidifier vents closed, louvered walls closed, fan off)
-20:09	Start exhaust air, 200K cfm (time allotted to stabilize air flow)
-5:09	HVLS fan on (time allotted to stabilize air flow)
0:00	Ignition, rack uprights, offset 2-ft east
0:10	Boxes replaced in array (moved for ignition)
0:34	Flames reach 2nd tier, visibly disturbed by fan air flow
0:43	Flames reach 3rd tier
1:00	Flames extend above main array, contained to ignition flue
1:10	Flames extend !3 ft above array, visibly disturbed by fan air flow (appear to be forced downward)
1:30	Flames extended half way to ceiling (~ 13 ft above array). Fire plume stabilized over ignition area)
1:39	1st sprinkler operation, northwest of ignition
1:41	2nd sprinkler operation, northeast of ignition
1:42	3rd and 4th (final) sprinkler operation, southeast and southwest of ignition
1:47	Flames reduced to top of main array
1:54	Flames largely extinguished with main array burning primarily at first tier only
3:09	Fan shut down (1st sprinkler + 90 s), minimal burning on first tier of main array only
25:00	Test terminated by hose stream; 4 sprinkler operations; damage to main array contained to east row only, no fire jump to target arrays

G APPENDIX G – HVLS FAN SPECIFICATIONS

Build: February 2010

THRUST
"102 lbf"

MA24XL2006

MaxAir™ Family

General

Model Number	MA24XL2006
Diameter	24 FT / 7.32 Meters
Blade Style	WhisperFoil XL
Number of Blades	6
Nominal Horsepower	2.0 HP / 1.5 Kw
Hanging Weight (average)	236 LBS / 107.0 Kg
Shipping Weight (Including MCP, Mounting Hardware) (average)	436 LBS / 197.8 Kg
Power Unit Pallet Dimensions / Weight	36" X 36" X 36" / 268 lbs / 0.914 X 0.914 X 0.914 Meters / 121.67 Kg
Blade Pallet Dimensions / Weight	140" X 29" X 18" / 191 lbs / 3.6 X .74 X .46 Meters / 86.8 Kg

Performance (at max speed)

Displacement (fwd, blowing down)	376,804 CFM / 10669.9 CMS
Displacement (rev, blowing up)	263,763 CFM / 7468.9 CMS
Maximum Speed	65 RPM
Power Usage @ Max. Speed	1.65 KW
Efficiency @ 75% Max. Speed	232.60 CFM/Watt / 6.59 CMS/Watt
Maximum Effective Area	20,000 SQ FT / 1858.1 m^2
Typical Industrial Spacing	110 FT / 33.52 Meters

Construction

Frame	Black Powder Coat / Welded A36 Steel Fabrication
Hybrid Hub	356 T-6 Cast Aluminum
Blade Struts (Invertible)	Black Anodized / 6061 T-6 Aluminum
Blades	Anodized / 6063-T6 Aluminum
Blade End Caps	ABS Plastic

Safety Components

Blade Retaining Links (6)	Zinc Plated / 10 GA A569 Steel
Safety Cable	Galvanized / 1/4" x 7 x 19 Steel Aircraft Grade Cable
Guy Wires	Galvanized / 1/8" x 7 x 19 Steel Aircraft Grade Cable
Safety Link Extenders (6)	Zinc Plated / 10 GA A569 Steel
Rotor Retaining Ring	Zinc Plated / 3/16 A569 Steel

Mounting Hardware

Standard Mount	Universal I-Beam Clamp w/ Swivel Joint and a 7.5" Drop
Glulam Mount (Optional)	Brackets w/ Swivel Joint & 7.5" Drop
Extra Wide / Thick I-Beam Mount (Optional)	Consult Factory
Additional Drop Extensions (Optional)	Up to 10 FT in 1 FT Increments

Motor

HP	2.0 / 1.5 Kw
Phase	3
Volts	208-230/460 3Ø
Insulation Class	F

Gearbox

Type	2-Stage Helical
Service Interval	Lubed For Life

Motor Control Panel (MCP)

Standard Power	208-230V 1Ø or 3Ø, 460-480V 3Ø
Enclosure	NEMA 1
Disconnect Switch	20-25 Amp, Lockable
Remote Control Wall Mounted Switch NEMA 4X	Fwd/Off/Rev w/Speed Control Knob
RF Line Filter	Built In
VFD Motor Drive Cable	25 Feet / 7.62 Meters
Remote Cable	100 Feet / 30.48 Meters
Special Wiring (Thermostats, fire alarm interface, networking etc.) (Optional)	Consult Factory
Enclosure (Optional)	NEMA 4/ 4x
50hz Operation (Optional)	
Line Reactor (480V Only) (Optional)	

Warranty

Motor, Gearbox & Control Panel	12 YRS.*
Blades, Hub & Mounting System	Limited Lifetime

*Labor Allowance to Remove and Replace in 1st Year

Contact MacroAir for full Warranty Details. Specifications are subject to change.

H APPENDIX H – SUMMARY OF HVLS FAN TESTING TO DATE

SUMMARY OF HVLS FAN FIRE TESTING TO DATE (7/20/10)

FIRE TEST DATE	FPRF 10/8/08	FPRF 10/10/08	XL GAPS 6/1/09	XL GAPS 6/1/09	XL GAPS 2007 Test 1	XL GAPS 2007 Test 2	XL GAPS 2007 Test 3	BIG FAN 5/5/08	BIG FAN 5/5/08	BIG FAN 9/11/08
PARAMETERS										
Storage Type	Double-Row Rack	Double-Row Rack	Double-Row Rack	Double-Row Rack	Palletized Open Array	Palletized Open Array UL 199 (Ord Haz)	Palletized Open Array UL 199 (Ord Haz)	Palletized Open Array	Palletized Open Array	Palletized Open Array
Commodity Type	Cartoned, Unexpanded Group A Plastic	Cartoned, Unexpanded Group A Plastic	Cartoned, Unexpanded Group A Plastic	Cartoned, Unexpanded Group A Plastic	Cartoned, Unexpanded Group A Plastic	Standard Class II Commodity Baseline Test- No Fan	Standard Class II Commodity	Cartoned, Unexpanded Group A Plastic Baseline Test- No Fan	Cartoned, Unexpanded Group A Plastic	Cartoned, Unexpanded Group A Plastic W/VESDA
Nominal Storage Height (ft)	20	20	15	15	15	12	12	15	15	15
Nominal Ceiling Height (ft)	30	30	25	25	25	22	22	26	26	26
Nominal Clearance (ft)	10	10	10	10	10	10	10	11	11	11
Aisle Width (in.)	48	48	48	48	N/A	NA	NA	N/A	N/A	N/A
Longitudinal/Transverse Flue (in.)	6/6	6/6	6/6	6/6	12	6	6	12	12	12
Ignition Location	Between 2 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers	Between 4 Sprinklers
Sprinkler Type/Temperature Rating (°F)	ESFR/165	ESFR/165	CMDA/286	CMDA/286	CMDA/286	CMDA / 165	CMDA /165	ESFR/165	ESFR/165	ESFR/165
Deflector to Ceiling (in.)	14	14	12	12	3	2	3	12	12	12
Nominal Sprinkler Discharge Coefficient K (gpm/psi½)	14.0	14.0	11.2	11.2	11.2	5.6	5.6	14.0	14.0	14.0
Density/Nominal Sprinkler Discharge Pressure (psi)	50	50	0.60 gpm/sq ft	0.60 gpm/sq ft	0.60 gpm/sq ft	0.20 gpm/sq ft	0.20 gpm/sq ft	50	50	50
Sprinkler Spacing (ft x ft)	10 x 10	10 x 10	10 x 10	10 x 10	8 x 10	10 X 12	10 X 12	10 x 10	10 x 10	10x10
Fan Size (ft)	24	24	24	24	24	NA	24	NA	20	20
Fan Location	15-ft South of Ignition	Above Ignition	15-ft South of Ignition	15-ft South of Ignition	8-ft South of Ignition	NA	9-ft 10-in South of Ignition	NA	12-ft South of Ignition	12-ft South of Ignition
Fan Distance Below Ceiling (in.)	50	50	50	50	60	NA	60	NA	48	48
HVLS Fan Speed (rpm)	63	63	24	24	24	NA	24	NA	47	47
HVLS Fan Operation	On	On	Off at Sprinkler Operation	Off at Sprinkler Operation	Off at Sprinkler Operation	NA	On	NA	Off at Sprinkler Operation	Off at VESDA Alarm
RESULTS										
Length of Test (hr:min:s)	00:32:00	00:32:00	00:30:00	00:30:00	00:08:00	00:30:00	00:30:00	01:10:00	00:32:00	00:30:00
First Ceiling Sprinkler Operation (min:s)	01:00	00:49	01:56	01:53	03:26	01:14	01:57	01:31	02:00	01:50
Last Ceiling Sprinkler Operation (min:s)	01:04	04:48	05:34	03:31	07:35	03:40	03:51	02:16	02:45	01:58
Number of Operated Ceiling Sprinklers	2	8	9	10	73	21	26	4	4	4
Peak Gas Temperature at Ceiling Above Ignition (°F)	250	237	1335	1294	988	732	674	295	300	305
Maximum 1 Minute Average Gas Temperature at Ceiling Above Ignition (°F)	131	201	1083	1002	953	634	614	240	75	180
Peak Steel Temperature at Ceiling Above Ignition (°F)	109	145	378	471	519	289	346	130	220	135
Maximum 1 Minute Average Steel Temperature Above Ignition (°F)	106	142	309	295	408	288	344	125	75	120
Fire Spread Across Aisle	No	No	No	No	NA	NA	NA	NA	NA	NA
Fire spread to the Ends of the Array	No	No	No	No	Yes	No	Yes	No	No	No
	TYCO ESFR-1 165°-F	TYCO ESFR-1 165°-F	?	TYCO ESFR-1 165°-F	TYCO ESFR-1 165°-F			Viking VK500	Viking VK500	Viking VK500

S:\SNDGO\PROJECTS\2010 Projects\2010033 HVLS Fans & Spr Interaction Phase II (Opp 2010056)\Reports\App A - Summary of HVLS Fan Fire Testing to Date 7.20.10.doc

Table duplicated from reference 5 and prepared by Schirmer Engineering Corporation.