RESEARCH TECHNICAL REPORT

Evaluation of Sprinkler Fire Protection of Retail Sales of Consumer Fireworks

FM Global

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Executive Summary

The National Fire Protection Association (NFPA) first provided fire protection guidelines for the retail sales of consumer fireworks in NFPA 1124: Code for the Manufacture, Transportation, Storage, and Retail Sales of Fireworks and Pyrotechnic Articles[i] in 2003. Although extensive literature reviews and fire testing had been conducted to inform the development of the guidelines, the chapters were ultimately withdrawn in 2014. There were concerns that the large-scale fire tests[ii] conducted to assess the fire protection may not be representative of actual retail locations, primarily because a relatively low volume of products on the shelves was tested. FM Global agreed to a request from the National Association of State Fire Marshals (NASFM) to conduct additional fire testing aimed at addressing these concerns. In addition to supporting a need for fire protection guidance in the national code structure, this research also serves the purpose of providing guidance that can be used to enhance FM Global Property Loss Prevention Data Sheet 7-28: Energetic Materials.[iii]

The present study was designed to assess fire protection for retail sales of consumer fireworks in gondola shelving. Two large-scale fire tests were conducted that evaluated the protection guidance that existed in NFPA 1124 prior to its withdrawal and adhered to requirements for storage heights, aisle widths, shelving lengths and flame breaks. Accordingly, the tested consumer fireworks were classified as UN0336 and 1.4G and complied with any limits and requirements of the APA Standard 87-1: Standard for Construction and Approval for Transportation of Fireworks, Novelties, and Theatrical Pyrotechnics[iv] and applicable Code(s) of Federal Regulations[v]. The test design was largely informed by that previously put forth in a concept test plan that was developed in 2011 by the Fire Protection Research Foundation (FPRF)[vi] and at that time agreed upon by NFPA, and NASFM.

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[i] NFPA 1124: Code for the Manufacture, Transportation, Storage, and Retail Sales of Fireworks and Pyrotechnic Articles, National Fire Protection Association, 2003.

[ii] B. L. Badders, "Fire performance evaluation of consumer fireworks retail sales displays incorporating various fire risk mitigation techniques," Southwest Research Institute, San Antonio, TX, Series Report SwRI Project No. 01.13626.01.001, February 12, 2009.

[iii] FM Global, FM Global Property Loss Prevention Data Sheet 7-28: Energetic Materials, Interim Revision October 2017.

[iv] American Pyrotechnic Association, APA Standard 87-1, Standard for Construction and Approval for Transportation of Fireworks, Novelties, and Theatrical Pyrotechnics, Version 12/01/01, Effective 10/01/03, 68 Fed Reg. 48562, Reprinted 1/04.

[v] Code of Federal Regulations. [Online]. https://www.govinfo.gov/app/collection/cfr/2018/

[vi] Aon Fire Protection Engineering Corporation for the Fire Protection Research Foundation, "Sprinkler Protection Criteria for Consumer Fireworks Storage in Retail Facilities," Fire Protection Research Foundation, Quincy, MA, Concept Test Plan September 2011.

Testing was conducted at Southwest Research Institute within the Fire Technology Department. Tests 1 and 2 were practically identical except for the ceiling height and applied water density. Consumer fireworks (500 g fountains) were loaded in four 1.8 m (6 ft) high gondola shelving units, consisting of three levels of solid shelves as well as a single 4.9 m (12 ft) high gondola shelving unit that had five levels of solid shelves; a minimum of 88% of the available shelving volume was occupied with commodity. The shelving units were 7.3 m (24 ft) in length[vii] and separated by 1.2 m (4 ft) wide aisles. Combustible flame breaks were installed longitudinally along the back of each shelving unit as well as transversely within each shelf on 4.9 m (16 ft) spacing. 500 g fountains were assumed to be a reasonable representation of the highest hazard within the ground-based category. The energy density[viii] of the shelving unit, on average, was 50.9 kg/m^3 (3.2 lb/ft^3). Aerial devices were omitted. Both ground-based and aerial devices can contain up to 500 g of chemical composition, the former discharge their energy into a localized volume thus contributing more to the magnitude of the fire than would an aerial that disperses its energy along its trajectory. The potential for remote ignition caused by aerial devices was not addressed in this study since aerials should be contained[ii].

The protection in both tests consisted of sprinklers installed on a 3.0 m x 3.0 m (10 ft x 10 ft) spacing having a K-factor of 80 lpm/bar$^{1/2}$ (5.6 gpm/psi$^{1/2}$), standard response time index and 74°C (165°F) temperature rating. They were installed with their thermal element at 0.3 m (12 in.) below the ceiling. In Test 1 the target discharge density was 8.1 mm/min (0.2 gpm/ft^2) which coincides with Ordinary Hazard (OH), Group 2 protection. Test 2 had a target water density of 12.2 mm/min (0.3 gpm/ft^2) and aligns with Extra Hazard (EH), Group 1 protection. The ceiling height in Tests 1 and 2 was 4.9 m (16 ft) and 9.1 m (30 ft) respectively.

The test results showed that the protection can maintain acceptable flame spread and limit ceiling-level steel temperatures to values that would not threaten structural integrity. However, in both tests excessive sprinkler operations occurred (35 of 36 installed sprinklers in Test 1 and 36 of 36 in Test 2) and a specific demand area cannot be defined for either of the tested conditions.

Previous research[ii] sponsored by the American Fireworks Safety Laboratory (AFSL), as well as the results of the present study likely represent a reasonable range of the hazard spectrum associated with retail sales of consumer fireworks in the United States. The number of sprinkler operations achieved in Tests 1 and 2 of the current study greatly exceeded that of the previous large-scale fireworks tests where 2-4 operations occurred[ii]. Specifically, AFSL Tests 6, 7 and 8[ii] (repeat tests conducted in the previous study) used the same sprinkler protection as Test 1; pertinent differences were the types of consumer firework devices (ground-based, novelties and caged aerials with varying pyrotechnic composition), 4.9 m (16 ft) long and 1.8 m (6 ft) high shelves containing non-combustible flame breaks were partially loaded (estimated to be 50% of shelf volume) with an energy density, on average, of 8.3 kg/m^3 (0.5 lb/ft^3) and

[vii] With the exception of one shelving unit that was 4.9 m (16 ft) in length.

[viii] Energy density is being defined as the total mass of chemical composition (i.e., 500 g per device in Tests 1 and 2) per shelving unit volume.

the ceiling height was 5.2 m (17 ft). The rate of fire development was slower in AFSL Tests 6-8 than in Test 1 as indicated by visual observations and the time to 1st sprinkler operation. Additionally, ceiling-level gas temperatures were approximately steady state at their maximum value when sprinklers operated in AFSL Tests 6-8, whereas they were only 20% of their maximum value at the time of 1st operation in Test 1. In Test 1, eight sprinklers had operated with only a single 1.8 m (6 ft) high shelving unit involved in the fire (the 4.9 m (12 ft) high Side C was ignited at 01:47) compared to a total of 2-4 sprinkler activations with multiple shelving units actively involved in AFSL Tests 6-8. These differences are attributed to the combined effect of device type, shelf loading and energy density; their independent effects cannot be decoupled based on the available data but are most likely attributable to the large difference in energy density. Tests 1-2 and AFSL Test 6-8 shared similar fire damage profiles. Regardless of differences in shelving length and number of sprinkler activations, the fire was able to traverse the length of the shelving unit in lower shelf heights highlighting the shielding effect that solid shelves have on sprinkler water.

While solid shelves pose a challenge to delivering water to combustion regions, the tested protection provided effective pre-wetting to limit flame spread and maintained building structural integrity. Results also indicate that combustible flame breaks can hinder, and in some cases, halt lateral flame spread. The presence of two combustible longitudinal flame breaks separating adjacent shelving units was essential to mitigating flame spread in that direction. Variations in device type, shelf loading and energy density have been shown to have a strong effect on the demand area. Results of Tests 1 and 2, which were selected to be representative of the higher end of the hazard spectrum, do not allow for a specific demand area to be defined. Therefore, it must be assumed that all sprinklers within the area of fire origin will operate and the design area should be equal to the floor area. This approach is achievable for locations with relatively small floor areas (e.g., up to 465 m^2 [5000 ft^2]) but may be impractical for larger areas. If the demand area cannot be equal to the floor area, then it seems reasonable to limit the energy density such that it is in line with that used in previous testing[ii].

Abstract

Two large-scale fire tests were conducted to assess sprinkler protection requirements for retail sales of consumer fireworks stored in gondola shelving. The test design was based on guidance that existed in NFPA 1124: Code for the Manufacture, Transportation, Storage, and Retail Sales of Fireworks and Pyrotechnic Articles prior to withdrawal of the consumer fireworks chapters in 2014. The design was also based on a conceptual test plan previously put forth by the Fire Protection Research Foundation. The results of this study in conjunction with referenced previous research represent a reasonable range of the fire hazard associated with retail sales of consumer fireworks in the United States and provide guidance to design sprinkler protection.

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1. Introduction

1.1 Background

In 1999 the National Fire Protection Association (NFPA) initiated a change in scope to NFPA 1124 [1] expanding it to include the retail sale of consumer fireworks [2] and the new version was published in 2003. In 2007 the NFPA commissioned a study, through the Fire Protection Research Foundation (FPRF) intended to assist the NFPA 1124 Technical Committee in further developing the consumer fireworks guidance in NFPA 1124. This study [3], consisted of a literature review of the hazards associated with the retail sales of consumer fireworks and identified areas for future research. Reference [3] provides a wealth of information on prior fire incidents, fire research and data, hazard data and relevant code provisions. To further support the development of protection recommendations in NFPA 1124, the American Fireworks Standard Laboratory (AFSL) sponsored a series of 12 tests[ix] which were conducted at Southwest Research Institute (SwRI) in San Antonio, Texas between October 2007 and April 2008 [4]. These tests evaluated fire performance of consumer fireworks retail displays incorporating different types of fire risk mitigation techniques and were used to evaluate NFPA 1124 (2006 edition) sprinkler protection requirements for retail sales of consumer fireworks. The validity of this sprinkler protection was subsequently called into question due primarily to the limited size fuel array and low product density (i.e., volume of products on the shelves) used in the testing. Although these factors create valid concerns, it is emphasized that the information generated during the AFSL test series is very useful and was drawn upon to inform the research detailed herein.

In March 2014 Chapters 6 and 7 (i.e., related to the retail sales and storage of consumer fireworks) were withdrawn from NFPA 1124 (2013 edition) [2, 5]. The primary reason for their removal was the judgment of lack of valid fire testing [2]. In February 2015 the National Association of State Fire Marshals (NASFM) formally requested that FM Global undertake research to provide a validated fire protection design for retail sales of consumer fireworks.

In 2011, prior to withdrawing the aforementioned chapters of NFPA 1124 (2013 edition), the FPRF provided a conceptual test plan intended to resolve the outstanding concerns relating to the sprinkler protection requirements [6]. That document provided a site survey of existing consumer firework retail sales locations and established a range of parameters such as typical storage heights and arrangements. Additionally, Reference [6] summarizes the AFSL test series [4] as well as the Battelle Tests [7], and based on the perceived deficiencies in that testing, presented a new research plan. That plan called for a combination of calorimetry testing to identify the highest hazard configuration as well as sprinklered fire tests of both palletized and shelf storage of consumer fireworks. The plan was reviewed and accepted by the FPRF, NFPA and NASFM. The research presented herein used components from the FPRF test

[ix] Hereafter referred to as AFSL tests, AFSL test series or AFSL series.

plan along with existing knowledge to generate a new test plan to validate sprinkler protection for retail sales of consumer fireworks.

1.2 Consumer Firework Codes and Regulations

Consumer fireworks are regulated by the federal government in 16 CFR § 1500 and 1507 [8, 9] and 49 CFR § 171 through 180 [10 - 19]. Consumer fireworks are defined within 49 CFR §173.59 [20] as any finished firework device that is in a form intended for use by the public that complies with any limits and requirements of the American Pyrotechnics Association (APA) Standard 87-1: Standard for Construction and Approval for Transportation of Fireworks, Novelties, and Theatrical Pyrotechnics [21] and the construction, performance, chemical composition, and labeling requirements codified by the U.S. Consumer Product Safety Commission in 16 CFR § 1500 and 1507. A consumer firework does not include firework devices, kits or components banned by the U.S. Consumer Product Safety Commission in 16 CFR 1500.17 [22].

The hazard classification of consumer fireworks is UN0336[x] and 1.4G, where 1.4 is the division number and "G" is the compatibility group letter. The "G" compatibility group is defined as "Pyrotechnic substance or article containing a pyrotechnic substance, or article containing both an explosive substance and an illuminating, incendiary, tear-producing or smoke-producing substance [other than a water-activated article or one containing white phosphorus, phosphide or flammable liquid or gel or hypergolic liquid]". Compatibility group letters are used to specify the controls for transportation, and storage related thereto, of explosives and to prevent an increase in hazard that might result if certain types of explosives were stored or transported together (49 CFR § 173.52 [23]). The Pipeline and Hazardous Materials Safety Administration (PHMSA), an agency within the Department of Transportation (DOT), is responsible for issuing the hazardous materials regulations (i.e., 49 CFR § 171 through 180). The PHMSA defines UN0336 1.4G consumer fireworks as having a small hazard with no mass explosion[xi] and no projections of fragments of appreciable size or range. In the 1.4G class, an external fire will not "cause virtually instantaneous explosion of nearly the entire contents of the package" (per PHMSA). Consumer fireworks (UN0336, 1.4G) do not pose the radiant heat, violent burning, and minor to mass explosion hazard associated with display (i.e., professional) fireworks (i.e., Division 1.1 and 1.3).

These codes and regulations thoroughly ensure that, if a consumer firework is in the United States (US) and/or being transported on US roadways, it meets stringent packaging and safety requirements. Additionally, NFPA 1124 Section 7.2.7 (2013 edition) specifies that retail sales of consumer fireworks that do not comply with the regulations of the U.S. Consumer Products Safety Commission as set forth in

[x] The United Nations (UN) number are four-digit numbers used worldwide in international commerce and transportation to identify hazardous chemical or classes of hazardous materials. They are required for the shipment of hazardous materials.

[xi] The explosive effects are largely confined to the package and no projection of fragments of appreciable size or range is to be expected.

16 CFR § 1500 and 1507 and the regulations of the US DOT as set forth in 49 CFR § 100 through 178 [24], including their related storage and display for sale, shall be prohibited. Therefore, fire tests were conducted with the consumer fireworks in their final sale condition (i.e., fuse covers, packaging, etc.).

NFPA 1124 (2013 edition) provides automatic sprinkler protection requirements for retail sales of consumer fireworks in Section 7.3.6 (a subsection of 7.3, General requirements for All Retail Sales) where it directs the reader to NFPA 13 [25]. The specific wording is as follows:

> An automatic sprinkler system designed and installed in accordance with NFPA 13, Standard for the installation of Automatic Sprinkler Systems, shall be provided throughout permanent consumer fireworks retail sales (CFRS) facilities and stores[xii] in which CFRS are conducted in the following buildings:
>
> (1) New buildings greater than 279 m^2 (3000 ft^2) in area
> (2) Existing buildings greater than 694 m^2 (7500 ft^2) in area

In NFPA 1124 Annex A Section A.7.3.6 (2013 edition) it is stated that “appropriate sprinkler design criteria should be determined based on an engineering analysis prepared by a fire protection engineer”. Further, NFPA 1124 Section 7.5.1.1 (2013 edition), which contains general information on stores, directs the reader to Annex A Section A.7.5.1.1 where it states that “for existing buildings, appropriate sprinkler system criteria should be determined based on an engineering analysis prepared by a fire protection engineer”. In the 2006 edition of NFPA 1124 this guidance is slightly different; Section 7.3.6 is the same as that of the 2013 edition, with the exception that item (1) specifies “new buildings greater than 557 m^2 (6000 ft^2) in area”. Annex A Section A.7.3.6 does not exist in the 2006 edition. Section 7.5.1.1 of the 2006 edition is identical to that of the 2013 edition. However, Annex A Section A.7.5.1.1 of the 2006 edition states the following:

> Preliminary results of recent full-scale fire tests indicate that automatic sprinkler systems designed for an Ordinary Hazard, Group 2 occupancy in accordance with NFPA 13, Standard for Installation of Sprinkler Systems, might be suitable for protecting retail displays of consumer fireworks where the ceiling height does not exceed 3.1 m (10 ft) and might also be adequate for ceiling heights up to 4.9 m (16 ft). This implies that there may be a need to design the sprinkler system in new buildings for an Extra Hazard (EH), Group 1 occupancy for ceiling heights greater than 4.9 m (16 ft). For existing buildings, existing sprinkler systems designed for Ordinary Hazard (OH), Group 2 occupancy should suffice. Until such a time as additional fire testing is completed and more conclusive design criteria can be verified, designers of automatic sprinkler systems for areas where retail sales of consumer

[xii] Refer to Section 1.3.1 of this report for the NFPA 1124 definition of facilities and stores.

fireworks are located may want to consider these design criteria. For additional information contact the American Pyrotechnic Association (APA), PO Box 30438, Bethesda, MD 20824.

NFPA 1124 does not explicitly provide a sprinkler system design for CFRS facilities and stores. In both the 2006 and 2013 editions of NFPA 1124, the reader is directed to NFPA 13 for the sprinkler system design. However, NFPA 13 also does not explicitly provide a system design for consumer fireworks. The International Building Code [26] does, however, define the hazard group of consumer fireworks in Section 307, High Hazard Group H. Consumer fireworks are defined as Hazard Group H-3 in Section 307.3.1, 307.5 and Table 307.1(1) readers are directed to Section 903.2.5 for automatic sprinkler system requirements.

In application, it appears that OH, Group 2 and EH, Group 1 sprinkler protection has been applied to CFRS facilities and stores with the cut-off point between the protection levels being dependent on ceiling height (OH, Group 2 corresponding to ceilings less than 4.9 m [16 ft] and EH, Group 1 corresponding to ceilings greater than 4.9 m [16 ft]).

1.3 Research Background and Assumptions

References [3, 4, 6] provide information concerning the fire hazard associated with retail sales of consumer fireworks and the effect of fire risk mitigation techniques. The following is a brief discussion of some of the pertinent findings as they relate to the research detailed herein.

1.3.1 Types of Retail Facilities

Consumer fireworks are sold in both dedicated CFRS facilities as well as in mixed commodity stores. NFPA 1124 (2013 edition) Section 3.3.29.1 defines a CFRS facility as a permanent or temporary building or structure, CFRS stand, tent, canopy, or membrane structure that is used primarily for the retail display and sale of consumer fireworks. Concerning what NFPA terms stores, NFPA 1124 (2013 edition) Section 7.5.1.1 states that, for the purpose of Chapter 7, stores in which retail sales of consumer fireworks are conducted shall not be considered CFRS facilities as defined in 3.3.29.1 where the following conditions both exist:

(1) The area of the retail sales floor occupied by the retail displays of consumer fireworks does not exceed 25 percent of the area of the retail sales floor in the building or 55.5 m^2 (600 ft^2), whichever is less.
(2) The consumer fireworks are displayed and sold in a manner approved by the AHJ and comply with the applicable provisions of this code, federal and state law, and local ordinances.

Stores are typically a dedicated mixed commodity retail location such as a big-box store; these locations will occasionally provide retail sales of consumer fireworks. Facilities on the other hand, primarily sell fireworks and often do so year-round. Facilities, with a retail area typically ranging from 93 m^2 to 465 m^2 (1,000 ft^2 to 5,000 ft^2) [6, 7] are likely to be much smaller than the retail area of stores which can generally exceed 4650 m^2 (50,000 ft^2).

1.3.2 Types of Displays

Both palletized and gondola shelving were considered for this research. Gondola displays appear to be most prevalent at retail locations. Palletized displays typically contain packaged assortments and can be configured in a number of different ways. Figures 1-1 and 1-2 show two different types of palletized configurations, fenced and quad[xiii], respectively. An example of empty gondola shelving is pictured in Figure 1-3 [27] while an example of gondola shelving with high product density is given in Figure 1-4 [28].

Figure 1-1: Example of fenced palletized arrangement.

[xiii] The fenced configuration has palletized commodity stored in a row while the quad configuration has four pallets stored in a 2 x 2 arrangement.

Figure 1-2: Example of quad palletized arrangement.

Figure 1-3: Example of empty gondola shelving [27].

Figure 1-4: Example of gondola shelves with full product density [28].

1.3.3 Types of Consumer Fireworks Devices

The types of fireworks devices are herein generalized into aerial devices and ground type devices.

1.3.3.1 Aerial Devices

Aerial devices are defined per NFPA 1124 Section C.3.1.2 and include sky rockets, bottle rockets, missile-type rockets, helicopters, aerial spinners, Roman candles, mine and shell devices, and aerial shell kits/reloadable tubes. An aerial firework is a device that is propelled into the air reaching heights of 61 m (200 ft). For example, the definition given for mine and shell devices (NFPA 1124 Section C.3.1.2.5, 2013 edition) is as follows:

> Mine and shell devices are housed in heavy cardboard or paper tube usually attached to a wooden or plastic base and containing not more than 60 g of total chemical composition (lift charge, burst charge, and visible/audible effect composition). Upon ignition, stars, components producing reports containing up to 130 mg of explosive composition per report, or other devices are propelled into the air. The term mine refers to a device with no internal components containing a bursting charge, and the term shell refers to a device that propels a component that subsequently bursts open in the air. A mine or shell device may contain more than one tube, provided the tubes fire in sequence upon ignition of one external fuse. The term cake refers to a dense-packed collection of mine/shell tubes. Total chemical composition including lift charges of any multiple tube devices may not exceed 200 g. The maximum quantity of lift charge in any one tube of a mine or shell device shall

not exceed 20 g, and the maximum quantity of break or bursting charge in any component shall not exceed 25% of the total weight of chemical composition in the component.

The above definition, which is also used in the latest version of the APA Standard 87-1 [21], specifies a maximum limit of 200 g chemical composition. However, it is noted that consumer aerial devices currently on the market may contain up to 500 g of chemical composition.

Both the Battelle and AFSL tests showed that aerial devices (as defined by NFPA 1124 Section C.3.1.2), if ignited and uncontained, will be projected well beyond the ignition area. For example, during a test conducted at SwRI during the AFSL series, a spent aerial device was found outside the test laboratory, having been projected through an air inlet louver. If aerial devices are uncontained, there is a potential for remote ignition. The consequences of remote ignition depend on a number of factors. For instance, if the building floor area is greater than the sprinkler design demand area, then remote ignition has the potential to overtax the sprinkler system by exceeding the demand area. There would be no potential to exceed the demand area of a sprinkler system when it is equal to that of the floor area; however, if remote ignition were to occur, the magnitude of the fire could be increased substantially, which may lead to excessive building temperatures. For CFRS stores and facilities, where the retail area exceeds the sprinkler system design area, it has been considered prudent to put restrictions on the presence of aerial devices. NFPA 1124 Section 7.5.1.2 addresses this hazard for stores (defined in NFPA 1124 Section 7.5.1.1) by prohibiting public access to aerial and audible ground devices (defined in NFPA 1124 Section C.3.1.3) and recommends that the devices be displayed in such a manner as to limit the travel distance of ejected pyrotechnical components. However, AFSL testing has shown that aerial devices are capable of breaking out of a partially caged shelf. Reference [3] compares the behavior of aerial devices to that of aerosols and notes that aerosols require material segregation and passive barriers to contain the projectile hazard. It is noted that the AFSL tests demonstrated proof of concept containment techniques that effectively limited projectile behavior, noting that further development would be required for more practical means of achieving the restraint.

1.3.3.2 Ground Type Devices

Ground and hand-held sparkling devices are defined by NFPA in Section C.3.1.1 and include cylindrical fountains, cone fountains, illuminating torches, wheels and ground spinners. Fountains are composed of a cardboard or heavy paper tube/cone that contains pyrotechnical composition and upon ignition emits a shower of sparks and sometimes a whistling or smoke effect. As with aerials, fountains may contain up to 500 g of chemical composition.

1.3.4 Fuse Covers and Ignitability of Devices

A covered fuse is defined by NFPA 1124 in Section 3.3.22 as a fuse or designed point of ignition that is protected against accidental ignition by contact with a spark, smoldering items, or small open flame. NFPA 1124 Section 7.3.15.5.2 further states that a consumer firework device shall be considered to have a covered fuse if the fireworks device is contained within a packaged arrangement, container, or wrapper that is arranged and configured such that the fuse of the firework device cannot be touched directly by a person handling the firework without the person having to puncture or tear the packaging or wrapper, unseal or break open a package or container, or otherwise damage or destroy the packaging material, wrapping, or container within which the fireworks are contained. NFPA provided specific criteria for fuse cover performance in PYR 1129: Standard Method of Fire Test for Covered Fuse on Consumer Fireworks [29], since withdrawn. Research conducted at SwRI during the AFSL series [4] evaluated four types of fuse covers against three types of ignition tests, namely the open flame ignition test, the hot surface contact ignition test and the incendiary ignition test. The fuse covers assessed were cardboard, corrugated cardboard, aluminized plastic tape and plastic tape. The results varied depending on the fuse cover material and the type of test. This information is provided below to give examples of the types of fuse covers available; more information can be found in Reference [4].

Both the Battelle [7] and AFSL [4] test series assessed the effect of fuse covers on mitigating the fire risk. When fuse covers are omitted, the result is a rapid growing fire; in all cases tested, the entirety of commodity was consumed, regardless of whether or not the storage was protected with automatic sprinklers. AFSL testing showed that use of fuse covers greatly reduces the potential for a sustained fire. The AFSL test series has shown that, for the tested commodity shelf loading, a ground based, fountain type, firework cannot reliably ignite adjacent fireworks when fuse covers are used. Of the eight AFSL tests conducted with fireworks with fuse covers stored in gondola shelving (i.e., Tests 2-9), 50% of them required at least three ignition attempts in order to create a sustained fire. The remaining 50% of the time a sustained fire was achieved on the first ignition attempt (three times with a fountain firework and one time with waste paper in a mesh basket). In the instances where sustained ignition was achieved on the first attempt with the fountain firework, a minimum of 80 seconds was required to ignite adjacent fireworks. Additionally, once a sustained fire was achieved, the fire growth rate was much slower than when fuse covers were omitted. Applicable regulations and codes require that consumer fireworks meet specific safety standards which include proper packaging and fuse covers. Therefore, the fire tests used consumer fireworks that met these requirements.

1.3.5 Flame Breaks

Previous testing [4] has shown that sheet steel flame breaks are effective at decreasing the flame spread in gondola shelf storage. Combustible flame breaks were less effective, allowing the fire to burn through and ignite firework devices on the opposite side of the gondola shelving. NFPA 1124 allows either non-combustible or combustible flame breaks. NFPA 1124 Section 7.3.15.2.2 requires that flame breaks have a minimum 5 minute rating as per PYR 1128, Standard Method of Fire Test for Flame Breaks [30] and, if a combustible flame break, such as plywood or fiberboard, is used, Section 7.3.15.2.2.1 specifies that the flame spread index must be greater than 75 as determined in accordance with ASTM E84, Standard Test Method for Surface Burning Characteristics of Burning Materials [31]. To represent a reasonable worst-case scenario, combustible flame breaks were used in this testing.

1.3.6 Fire Hazard of Palletized vs. Gondola Shelf Storage

The AFSL test series [4] assessed the fire hazard of consumer fireworks on retail sales gondolas as well as palletized arrangements. One can infer the relative fire hazard by comparing AFSL Tests 6, 7 and 8 (repeats of one another using gondola shelving) with AFSL Test 10 (palletized). This assessment is made based on a comparison of fire behavior both prior to and after sprinkler operation. In AFSL Test 10, sustained ignition was achieved on the first attempt with a fountain device. There are no repeat tests by which to base the reliability of this ignition source. However, it may be inferred that the cardboard packing used for the assortments allows for easier ignition than the unpackaged single devices found in gondola shelving. In comparison, AFSL Test 6 required one, and AFSL Tests 7 and 8 each required three ignition attempts to achieve a sustained fire. These results imply that the likelihood of sustained ignition is highly dependent on the ignition source, the specific location of ignition relative to other combustibles and the nature of the other combustibles themselves. For these reasons, it is difficult to draw any general conclusions about the differences in ignitability and fire growth between the gondola and palletized displays. AFSL Tests 6 and 8 each had four sprinkler operations while AFSL Tests 7 and 10 each had two sprinkler operations. Given the test to test variability seen among repeat tests, the difference in number of operations between the two display types seems negligible. Additionally, there were no notable differences in ceiling-level gas temperatures up to the time of first sprinkler operation between the repeat tests of gondola displays nor between gondola and palletized displays.

The key difference in fire hazard between these display types is evident in their respective response to suppression. Following the first sprinkler operation the ceiling-level gas temperatures in AFSL Test 10 exhibited a faster rate of cooling than those in AFSL Tests 6-8. The gondola display, with its solid shelving obstructs sprinkler water from reaching the fire whereas the palletized display allows for direct wetting and pre-wetting to occur. The fire continued to propagate in the gondolas following sprinkler operation. At the termination of the gondola tests there remained residual fire in the bottom shelves, where sprinkler water was obstructed by the shelves, which required manual extinguishment. The post-test damage in the gondola tests was observed to be worst in the bottom two shelves while the top shelf commodity, unobstructed to sprinkler water, sustained comparatively less damage. The post-test damage image of the palletized display [4] shows a mix of burned and unburned commodity; application of sprinkler water was shown to quickly diminish the fire severity and limit subsequent flame spread.

Based on the comparison detailed above it is concluded that gondola shelving presents a greater challenge for the sprinkler protection and therefore was the focus of this research. Test results for the gondola shelf arrangement are assumed to be applicable to palletized arrangements based on the assessment provided above.

1.3.7 Selection of Test Commodity

Previous testing has clearly shown that aerials, if ignited and uncontained, have the potential to be projected well beyond the ignition area [4, 7]. Use of aerial devices in fire testing will create test to test variability and induce uncertainty in the results. This is because once an aerial is ignited, the trajectory, final position and potential to cause remote ignition are highly non-repeatable. In order to produce repeatable and comparable fire tests the use of aerial devices is being omitted. This decision is further substantiated by the reasoning given in Section 1.3.3.1. The test commodity will consist of ground based fountain devices. In terms of energy release potential, both aerial and ground based devices can contain up to 500 g of chemical composition. Further, ground based devices discharge their energy into a localized volume thus contributing more to the magnitude of the fire than would an aerial that disperses its energy along its trajectory.

Additionally, previous testing had used an assortment of consumer fireworks devices [4, 7]. From a practical standpoint, that commodity selection is representative of an actual retail location. However, from a scientific perspective, the use of varied commodity leads to uncertain and unrepeatable results. For instance, if flame spread were to stop at a location on a shelf where two different types of devices abutted one another, one could not definitively conclude whether flame spread was halted by the fire protection system or simply because the adjacent commodity was less prone to ignition.

In order to produce conclusive and repeatable test results a single type of 500 g fountain device was used throughout the test array.

1.3.8 Ignition and Fire Development

Section 1.3.4 contains a discussion related to ignition of consumer fireworks. A consumer firework device proved to be an unreliable source for sustained ignition of non-assortment/single firework devices [4]. On the contrary, waste paper in a wire mesh basket proved a reliable ignition source for the same commodity conditions [4]. In order to provide a reliable and repeatable ignition scenario, the fire tests used two FM Global Standard Full Ignitors as the ignition source; their construction is detailed in Section 2.1

1.4 Objectives and Scope

Using up to two tests, assess the adequacy of specific sprinkler protection for retail sales of consumer fireworks in gondola shelves (refer to Section 2.1 for specific parameters) in buildings up to 4.9 m (16 ft) and 9.1 m (30 ft). Warehouse storage of consumer fireworks is beyond the scope of this work.

2. **Methodology**

The research plan and test design was based largely on previous research [3, 4, 6, 7] and complies with all applicable federal requirements and those of NFPA 1124 (2013 edition) [1] (e.g., storage height, ceiling height, shelving layout and construction, aisle widths, etc.). Prior testing had used partially loaded shelves which had a length of 4.9 m (16 ft). NFPA 1124 (2013 edition) allows for shelving lengths up to 9.8 m (32 ft) before an aisle is required. The current research addressed concerns of the effect of commodity loading (i.e., percent volume of the shelf filled) and the height and length of shelving units and comparisons of results are made in context of these parameters.

2.1 Fire Test Setup

Two fire tests were conducted at Southwest Research Institute, Fire Technology Laboratory, San Antonio, Texas USA.

Both tests used the same shelving layout and predominantly the same commodity layout, with exceptions noted. The storage layout is shown in Figures 2-1 through 2-8. The total floor area of fireworks was equal to 13.9 m^2 (150 ft^2) and was designed to be representative of a section of the retail sales store/facility[xiv]. It consisted of gondola shelving (Sides A-E, with each side considered a “unit”) with solid shelves and combustible flame breaks. Following the requirements of NFPA 1124 (2013 edition), the flame breaks, which were 9.5 mm (3/8 in.) southern pine plywood, had been tested to the PYR 1128: Standard Method of Fire Tests for Flame Breaks [30] meeting the 5 minute requirement. The flame breaks were installed along the back of each shelving unit (i.e., longitudinal flame breaks) forming a barrier between adjacent adjoining shelving units. There were two longitudinal flame breaks separating Sides A and B (one on either side of the 6.4 cm [2.5 in.] wide shelving upright), resulting in a 4.6 cm (1.8 in.) air gap between flame breaks. Side C, D and E each had a single longitudinal flame break; however, the back of Side C was also sheathed with 9.5 mm (3/8 in.) sheet rock to simulate the presence of an interior wall (Figure 2-9). Flame breaks were also installed within each shelf of a given unit (i.e., transverse flame breaks) on 4.9 m (16 ft) spacing, forming a barrier between commodity along the length of the shelf. The location of lateral flame breaks is shown in Figure 2-2 and images of their installation are shown in Figure 2-10. All penetrations from one side of a shelving unit to the other side were blocked by combustible flame break material to mitigate the passage of flames/sparks and/or hot gases; an image of this construction is given in Figure 2-11. Each shelving unit was 1.8 m (6 ft) high except for Side C which had a storage height of 3.7 m (12 ft) to simulate perimeter shelving found along a wall. The aisle widths were 1.2 m (4 ft) throughout. Images of the finished empty shelving units are shown in Figure 2-12.

[xiv] NFPA 1124 (2013 edition) allows for a maximum of 55.7 m^2 (600 ft^2) of retail area within a store.

Both tests used a combination of fountain type devices and empty boxes[xv]. The commodity layout is shown in Figure 2-13. Empty boxes were used in Sides D and E to reduce cost. The empty boxes were single-wall corrugated containerboard boxes, cubic in geometry with each outer side equal to 21 cm (8.4 in.). These boxes met specifications for ASTM D5118 and D3951 [32, 33] and had an Edge Crush Test 32 (ECT 32) [34, 35] rating. Four different models of fireworks devices were used; Type A, B, C and D, differing only slightly in their pyrotechnic displays. Representative images of a single device and its display are shown in Figure 2-14 and its internal components, after discharge, are shown in Figure 2-15. All models had the same physical construction and were cubic in geometry with each outer side equal to 20 cm (8.0 in.). The individual weight of each device, including all components, was 1.60 g ± 0.05 kg (3.5 lb ± 0.1 lb). They each contained eight tubes with a total chemical composition[xvi] of 500 g (1.1 lb); the remaining 1,100 g (2.4 lb) was cellulose material with a trace amount of plastic (red cellophane top) and fuse material. All devices had a discharge duration of 190 seconds under normal conditions and each tube would discharge sequentially in series[xvii].

The firework device layout was selected to allow for test repeatability and direct comparison of results between tests. A total of 2,580 fireworks devices and 406 empty boxes were used in Test 1 and 2,160 devices and 812 empty boxes were used in Test 2; the difference arising from the use of empty boxes in Sides D and E in Test 2. Images of the final construction of the test array are shown in Figure 2-16 through 2-19; all shelving units had commodity loaded two deep. Sides A, B, D and E each had three shelves; the commodity was stored three high on the bottom shelf and two high on the middle and top shelf. This resulted in an air gap between the top of the commodity and the underside of the shelf above equal to 6.4 cm (2.5 in.) for the bottom shelf commodity and 8.3 cm (3.3 in.) for the middle shelf commodity; these are shown pictorially in Figure 2-20(a) and (b). Side C had five shelves; the commodity was stored three high on the bottom four shelves and four high on the top shelf. The air gap between the top of the commodity and the underside of the shelf above was equal to 5.1 cm (2 in.) for all shelves in Side C, as shown in Figure 2-20(c). A minimum of 88% of the total available shelving volume was filled with firework devices.

The energy density of the retail arrangement was 47.6 kg/m^3 (2.97 lb/ft^3) in Sides A and B and 54.3 kg/m^3 (3.39 lb/ft^3) in Side C. The energy density is being defined as the total mass of chemical composition divided by the total volume of the shelving unit. For example, there were 504 devices in Side A, each containing 500 g of chemical composition. Side A was 7.3 m long, 0.4 m deep and 1.8 m high (24 ft x 1.3 ft x 6 ft) resulting in a total shelving unit volume of 5.3 m^3 (187.2 ft^3) and hence the

[xv] Empty boxes represented target commodity and were used to assess flame spread.

[xvi] The chemical composition is defined by the American Pyrotechnics Association as being “all pyrotechnic and explosive composition contained in a fireworks device. Inert materials (such as clay used for plugs or organic matter used for density) are not considered to be part of chemical composition.”

[xvii] The discharge time reduced when exposed to a large fire source, presumably due to multiple ignition locations along the fuse resulting in multiple tubes discharging at once.

stated energy density for Side A. Test 1 was conducted using a design density of 8.1 mm/min (0.2 gpm/ft^2); which is within the range of OH, Group 2 protection[xviii]. The results of Test 1 were used to assist the design of Test 2 which assessed protection under a 9.1 m (30 ft) ceiling. Test 2 was conducted using a design density of 12.2 mm/min (0.3 gpm/ft^2) maintained at the most remote branchline, which is within the range of EH, Group 1[xix] protection. In both tests, pendent sprinklers with a nominal activation temperature of 74°C (165°F), standard response time index (RTI) and K-factor of 80 lpm/bar$^{1/2}$ (5.6 gpm/psi$^{1/2}$) were installed on a 3.0 m x 3.0 m (10 ft x 10 ft) spacing with their thermal element located 0.3 m (12 in.) below the ceiling. Images of the sprinkler and piping system are provided in Figures 2-21 and 2-22, respectively.

Ignition was offset 0.3 m (1 ft) under one sprinkler and was achieved using two FM Global Standard Full Cellucotton Ignitors. Each was contained in a plastic bag and consisted of 113 g (4 oz.) of rolled cotton and 240 mL (8 oz.) of gasoline. The ignitors were placed in the bottom shelf of Side A, 0.3 m (1 ft) east of the transverse flame break where a single device had been removed to accommodate their placement. Images of the cotton material and final ignitor placement are shown in Figures 2-23 and 2-24(a). The ignitors were initiated by application of a propane torch as shown in Figure 2-24(b). An image of the ignitors shortly after being activated is given in Figure 2-25. The live firework device on which the ignitors sat was exposed to the ignition fire. The flames from the ignitors impinged on the shelf above promoting horizontal flame extension along the underside of the shelf which provided ignition potential for adjacent devices.

[xviii] OH Group 2 calls for a sprinkler discharge density of 6.9 mm/min (0.17 gpm/ft^2) over an area of 279 m^2 (3000 ft^2) or 8.2 mm/min (0.20 gpm/ft^2) over an area of 140 m^2 (1500 ft^2) or any value linearly interpolated between the two.

[xix] EH Group 1 calls for a sprinkler discharge density of 11.4 mm/min (0.28 gpm/ft^2) over an area of 279 m^2 (3000 ft^2) or 12.2 mm/min (0.30 gpm/ft^2) over an area of 232 m^2 (2500 ft^2) or any value linearly interpolated between the two.

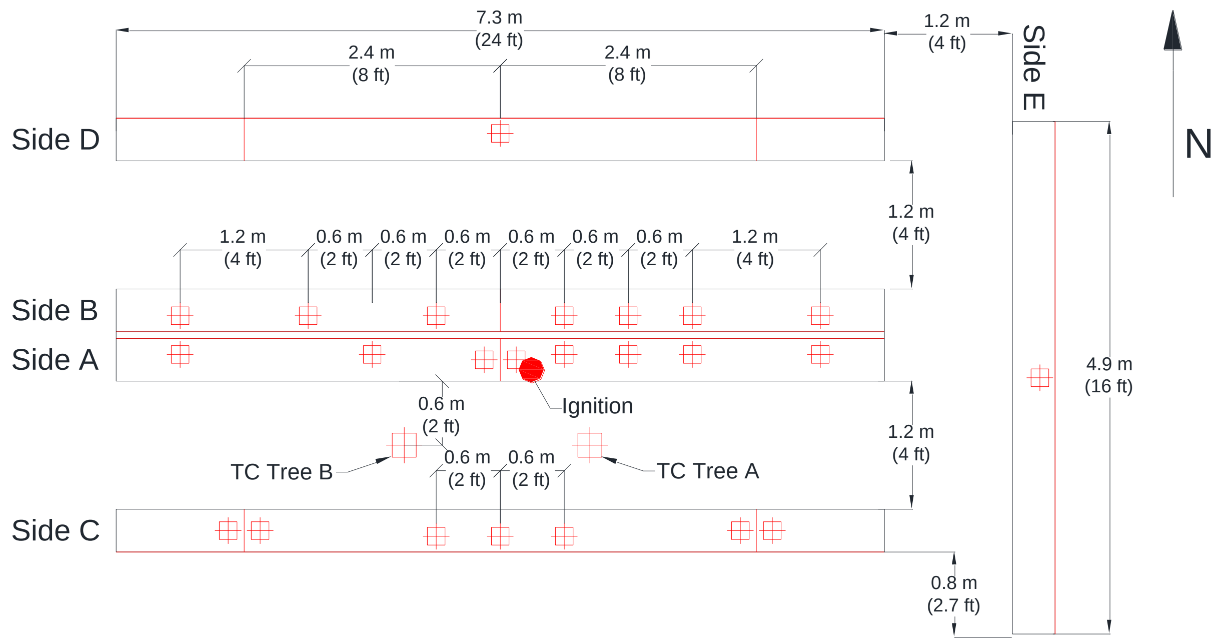


Figure 2-1: Plan view of shelving unit layout indicating nomenclature of sides and with thermocouple locations (red crosses).

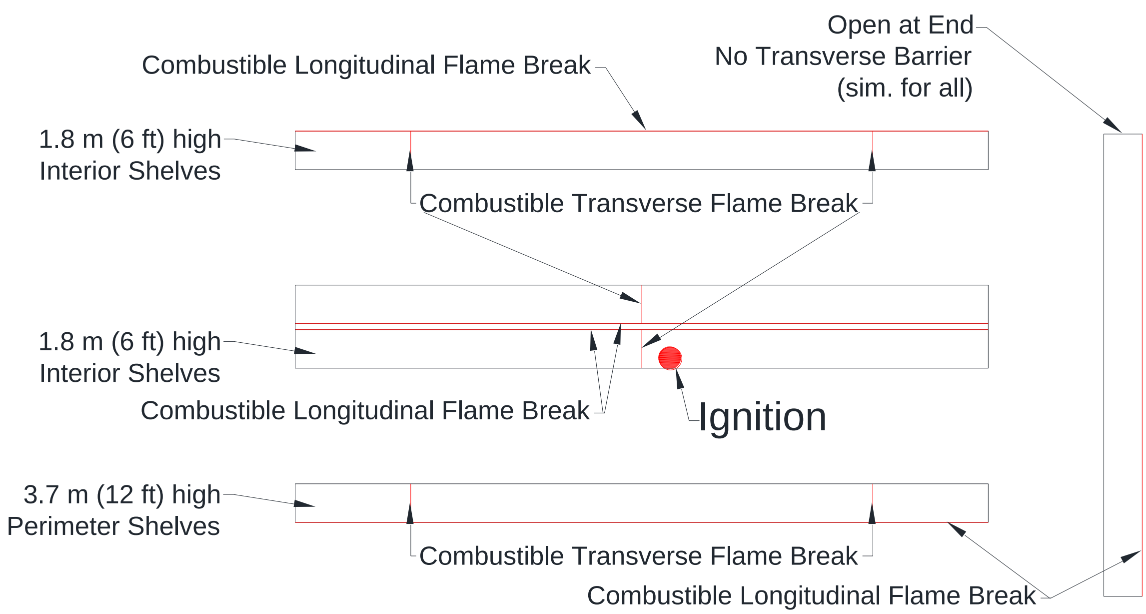


Figure 2-2: Plan view of shelving unit showing flame break locations.

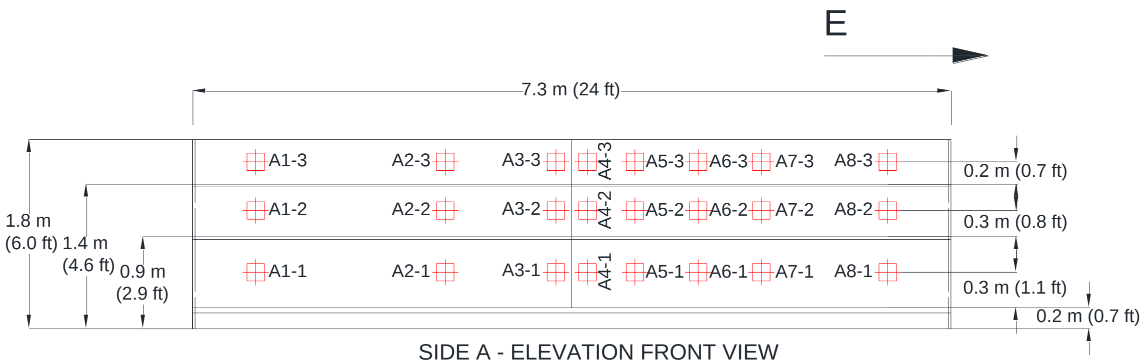


Figure 2-3: Front elevation view of Side A showing shelf height and thermocouple nomenclature and vertical dimensions of locations. Red crosses represent TCs.

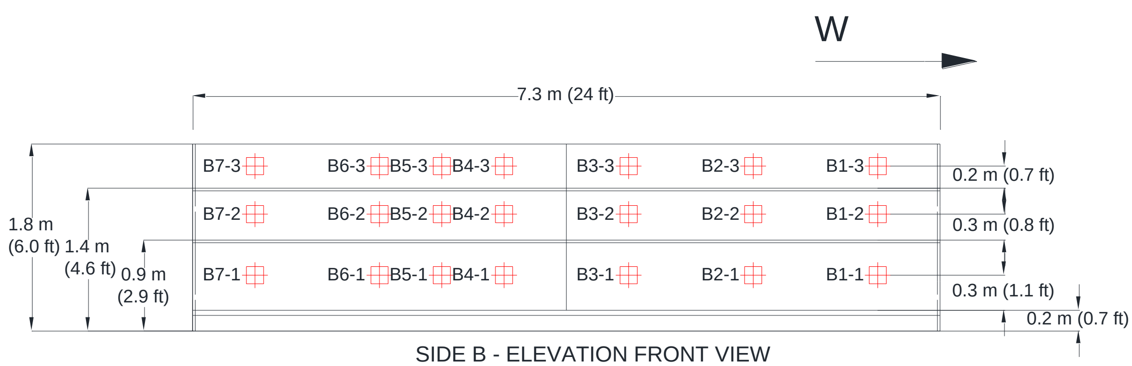


Figure 2-4: Front elevation view of Side B showing shelf height and thermocouple nomenclature and vertical dimensions of locations. Red crosses represent TCs.

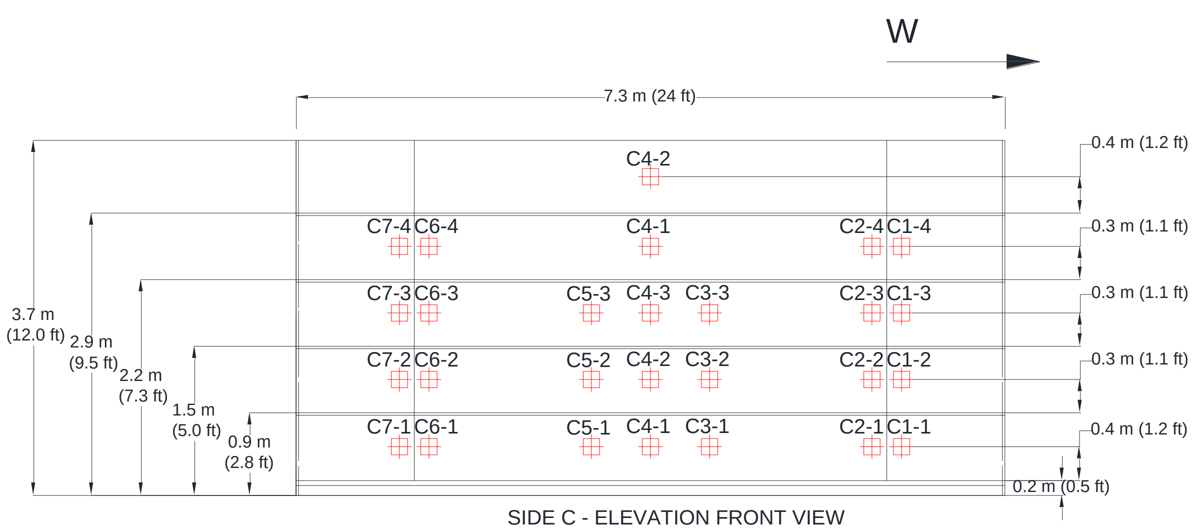


Figure 2-5: Front elevation view of Side C showing shelf height and thermocouple nomenclature and vertical dimensions of locations. Red crosses represent TCs.

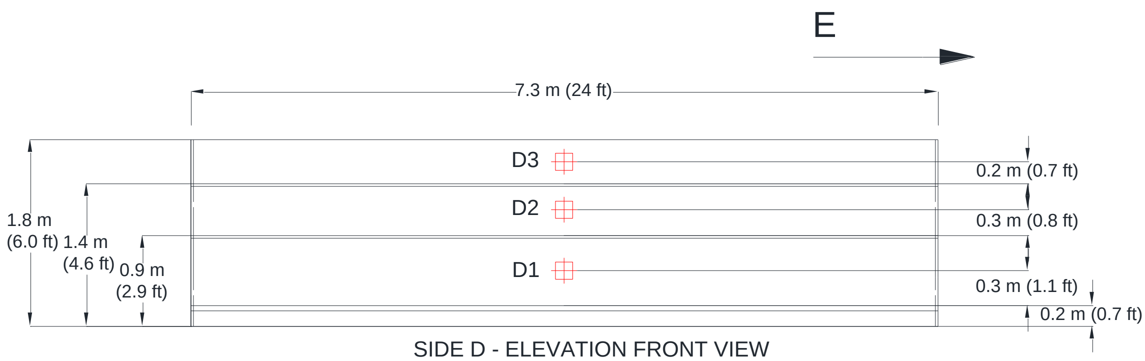


Figure 2-6: Front elevation view of Side D showing shelf height and thermocouple nomenclature and vertical dimensions of locations. Red crosses represent TCs.

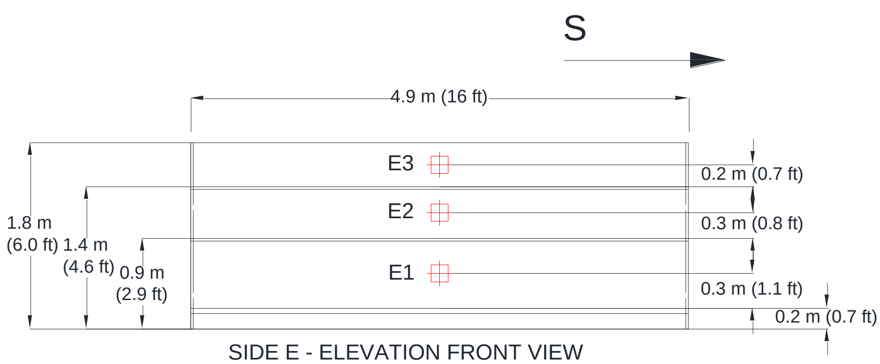


Figure 2-7: Front elevation view of Side E showing shelf height and thermocouple nomenclature and vertical dimensions of locations. Red crosses represent TCs.

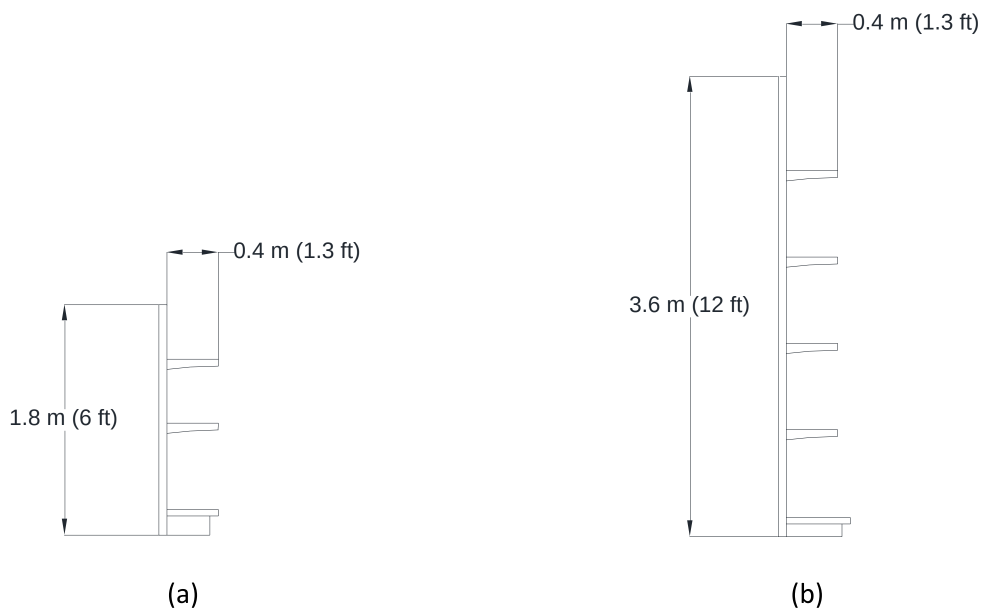


Figure 2-8: Side elevation view of (a) Side A, B, D, and E, and (b) Side C.

Figure 2-9: Sheet rock simulating interior wall on back of Side C.

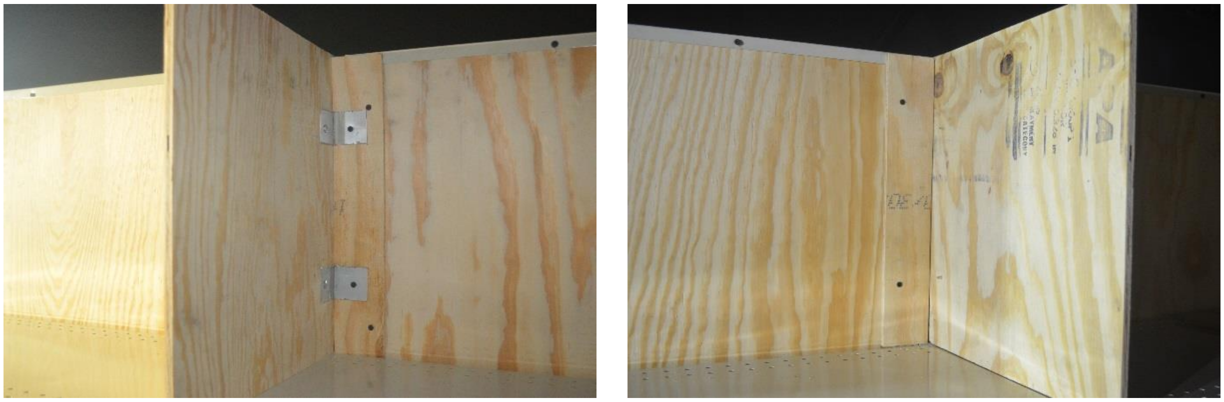


Figure 2-10: Construction of lateral flame break (penetrations at shelving upright covered by sheet of flame break material).

Figure 2-11: Shelving construction showing examples of TC locations, covering of penetrations in rack uprights with flame break material and TC Tree locations.

Figure 2-12: Empty finished shelving units.

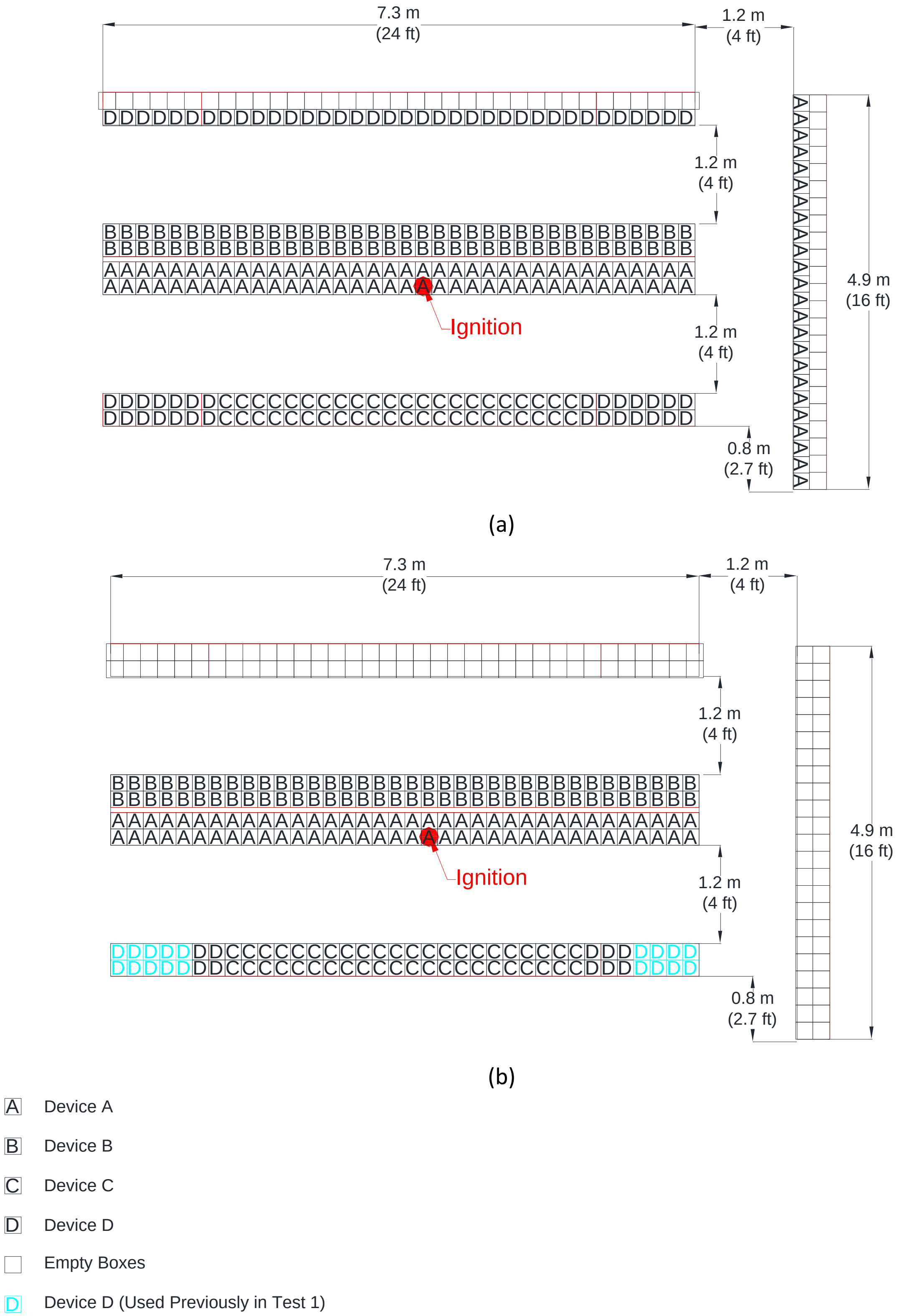
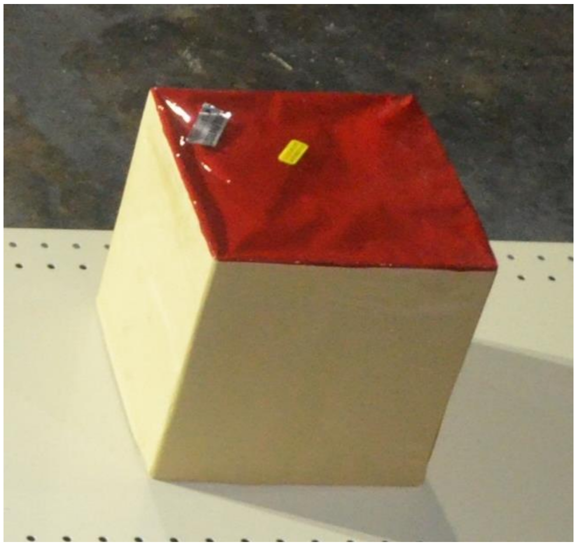


Figure 2-13: Plan view of commodity type location within the test array, (a) Test 1, and (b) Test 2.



(a)

(b)

(c)

Figure 2-14: Single device (a) side and top, (b) cellophane top showing fuse, (c) example of one phase of discharge of device, display reaches approximately 4.9 m (16 ft) high.

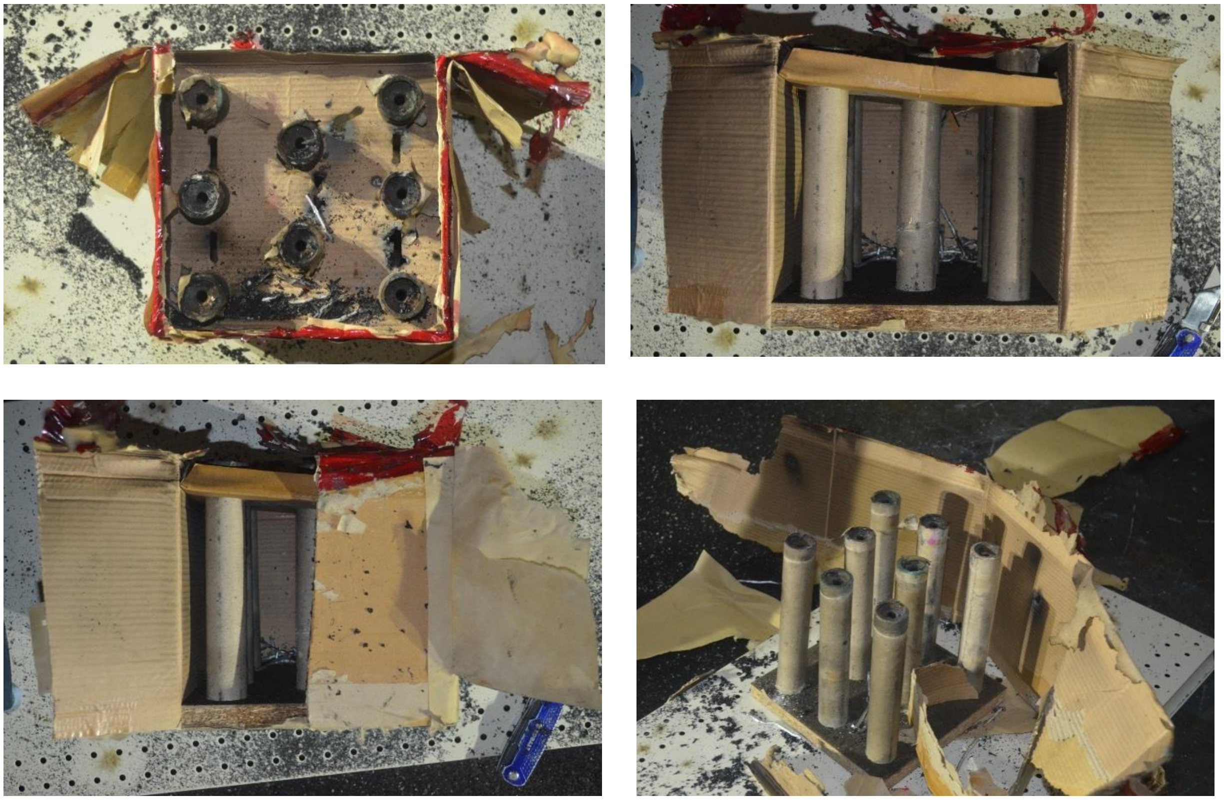


Figure 2-15: Discharged fireworks device that has been deconstructed showing engineered wood product base and cellulose tube and outer construction with red colored cellophane sheet on top.

Figure 2-16: Final construction of test array looking eastward.

Figure 2-17: Final construction of test array looking eastward down ignition aisle (between Sides A and C).

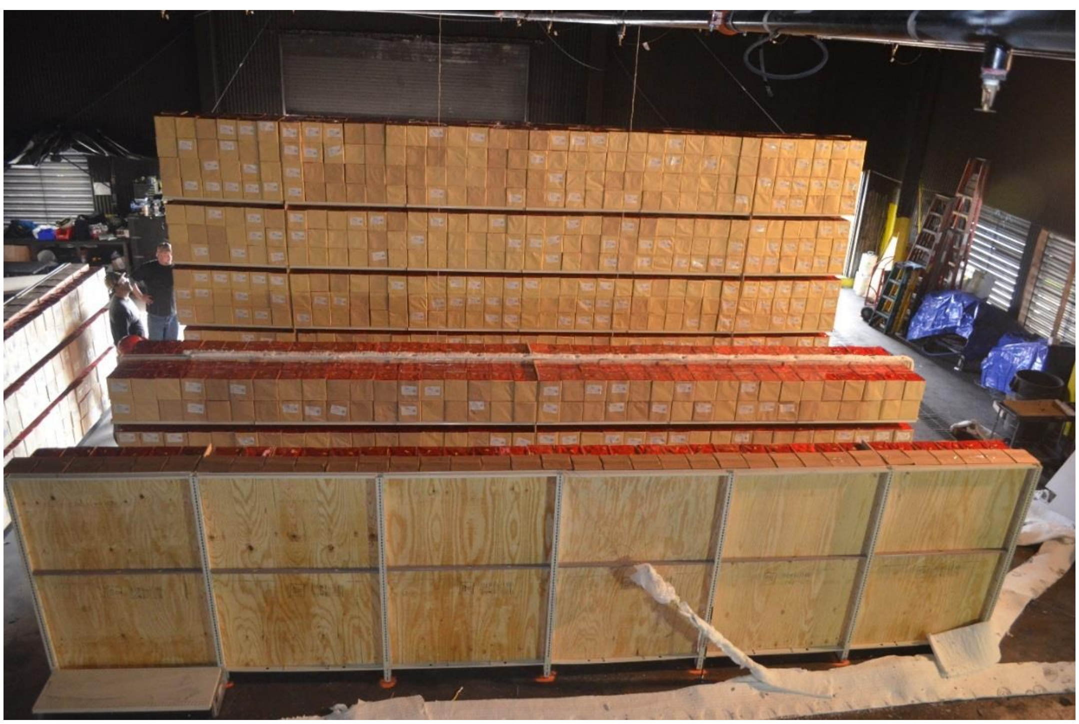


Figure 2-18: Final construction of test array looking southward.

Figure 2-19: Final construction of test array looking westward.

(a) (b) (c)

Figure 2-20: Air gap between top of commodity and underside of shelf above for (a) bottom shelf commodity in Side A, B, D, and E, (b) middle shelf commodity in Side A, B, D, and E, and (c) commodity in all shelves of Side C.

Figure 2-21: Ceiling-level sprinkler: K-factor 80 lpm/bar$^{1/2}$ (5.6 gpm/psi$^{1/2}$), SR, Pendent, 74°C (165°F).

(a) (b)

Figure 2-22: Sprinkler system (a) piping layout showing 10.2 cm (4 in.) cross main on left and 5.1 cm (2 in.) branchlines, (b) installed ceiling-level sprinkler.

Figure 2-23: Standard full cellucotton ignitor (without bag and gasoline).

(a) (b)

Figure 2-24: Ignition within the test array (a) close up showing ignitor placement, (b) ignition by application of propane torch.

Figure 2-25: Initial flames shortly after ignition.

2.2 Documentation and Instrumentation

Documentation for each test included video, still photographs, and recording of visual observations throughout the test. Post-test damage documentation was also recorded. The following instrumentation was installed for each test:

- Sprinklers at 36 locations on a 3.0 m x 3.0 m (10 ft x 10 ft) spacing; their locations are shown in Figure 2-26. In Test 1, all 36 sprinklers were active whereas in Test 2, 17 of the 36 sprinklers were installed but plugged to prevent water flow; this was done as a result of Test 1 to ensure sufficient water availability. The plugged sprinklers were used to determine the potential demand area. The radial water distribution pattern for the plugged sprinklers was assessed to ensure that, had the sprinklers been active, their discharge would not have provided wetting to the array. In Test 1, the nine sprinklers nearest ignition were electronically monitored to determine the operation of each specific sprinkler. In Test 2, the 25 sprinklers nearest ignition were monitored. Unmonitored sprinklers were visually inspected post-test to confirm they had operated.

- Bare-bead, 0.8 mm (20 gage), chromel-alumel (Type-K) thermocouples (TCs), were placed 0.165 m (6.5 in.) below the ceiling. Thermocouples were located alongside each sprinkler location and their nomenclature is presented in Figure 2-26.

- Bare-bead, 0.8 mm (20 gage), chromel-alumel (Type-K) thermocouples (TCs), were installed at various locations within the gondola shelving, each located at the mid-height between shelves. A plan view of the TC locations in shown in Figure 2-1 and front elevation views of each side are shown in Figures 2-3 through 2-7. Images of installed TCs are shown in Figures 2-11 and 2-27; the bead of the TC was positioned 5.1 cm (2 in.) away from the flame break. TCs were placed at approximately the same locations used in previous fireworks testing conducted at SwRI during the AFSL series [4] to allow comparison of test data.

- Bare-bead, 0.8 mm (20 gage), chromel-alumel (Type-K) thermocouples (TCs), were installed in two vertical TC trees within the aisle space between the ignition side of the main array (Side A) and the opposing target array (Side C). Their location is shown in Figures 2-1 (plan view) and 2-28 (elevation view). The TCs were installed on 0.6 m (2 ft) vertical increments from 0.6 m (2 ft) off the floor and up to 4.9 m (16 ft). TC locations are identical to those used in previous fireworks testing conducted at SwRI during the AFSL series [4].

- A pressure transducer ranged 0-3.4 bar (0-50 psig), was installed at the most remote branchline, to assist in maintaining the required sprinkler system flow parameters.

- A magnetic flow meter ranged 4713 lpm (0-1245 gpm), was installed in the 10.2 cm (4 in.) diameter sprinkler system riser.

- Six video cameras were positioned to capture all angles of the test array. A schematic of camera locations is given in Figure 2-29.

Data collected during the test were recorded at a 1 Hz frequency. The moisture content (dry-basis) of the test commodity was controlled by encapsulating the test array in plastic sheeting and placing an appropriately sized dehumidifier in the enclosed environment. The dehumidifying process was maintained for a minimum of 24 hours. Moisture content was measured (dry-basis) just prior to ignition; the average moisture content was 9.5% and 7.4% for Tests 1 and 2, respectively. The moisture content in Test 1 exceeded the 4% to 8% range that is required for wet-pipe sprinklered fire tests conducted at FM Global. As moisture content increases the vertical and lateral flame spread rates decrease therefore, this 1.5% variance likely resulted in a slower fire growth rate than had the moisture content been within range. Additionally, in an actual consumer fireworks facility or store, the moisture content may be less than that tested, which would tend to increase the challenge to the fire protection system.

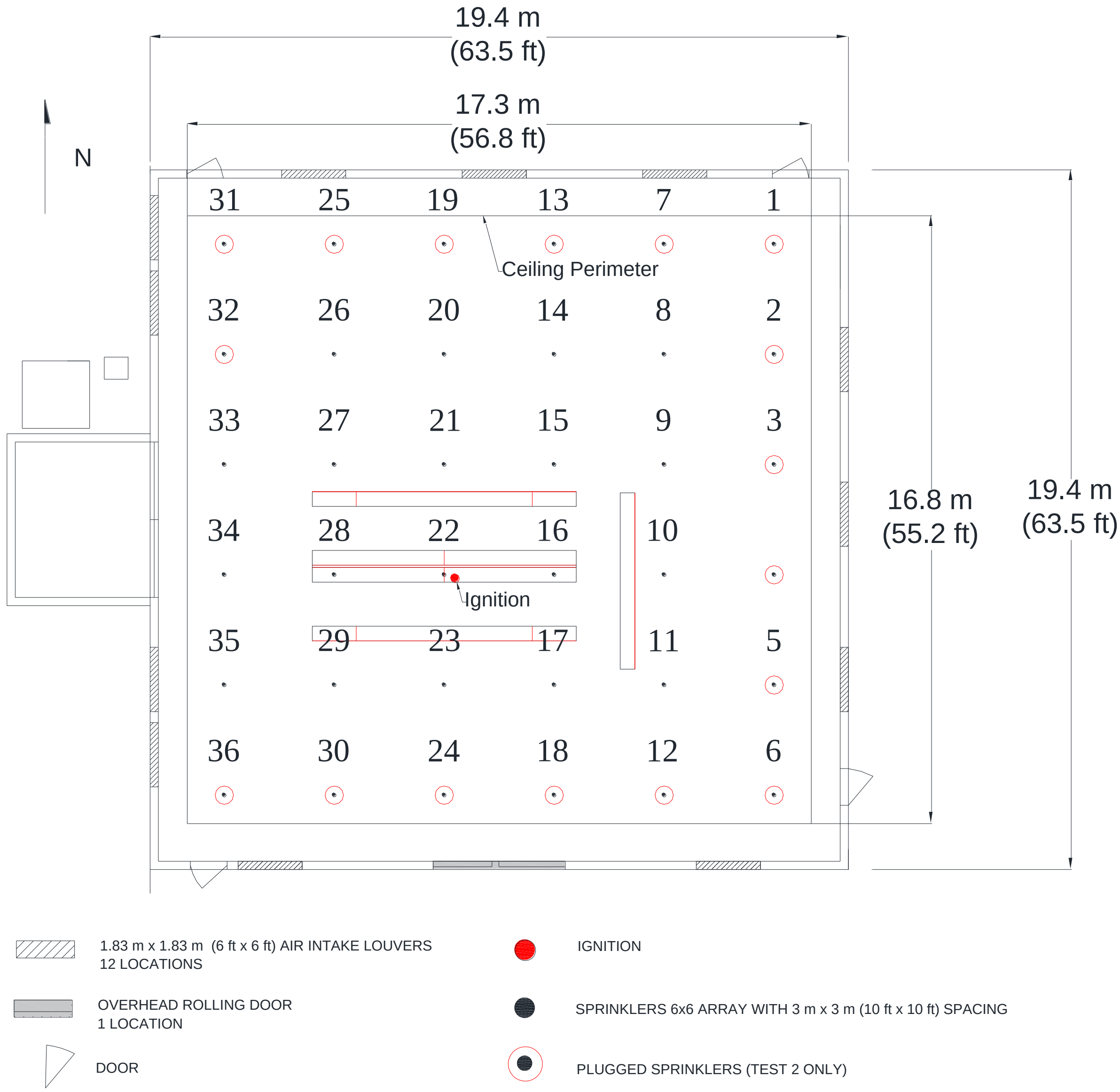
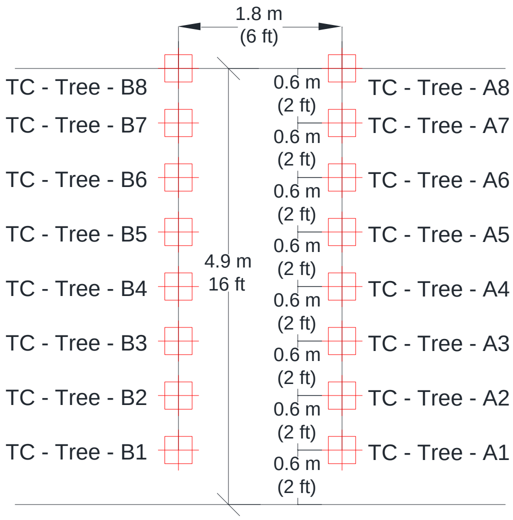
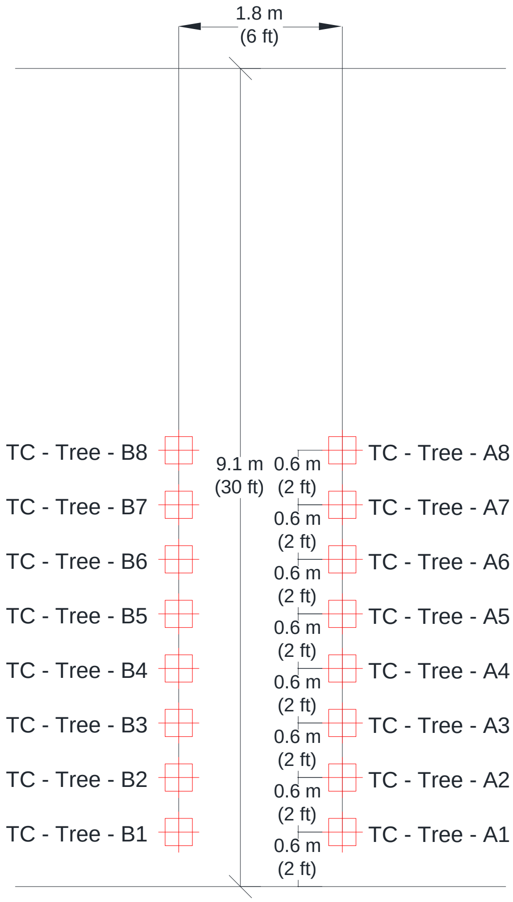


Figure 2-26: Plan view of test array and ceiling-level sprinklers within the laboratory space. Numbering above each sprinkler location is also associated with the TC at each location.

Figure 2-27: TC installation in shelving units (a) TC along perpendicular flame break, (b) TC located on transverse flame break. TCs located such that bead is 5.1 cm (2 in.) from the flame break.



(a)



(b)

Figure 2-28: Front elevation of TC Tree A and B for (a) Test 1 and (b) Test 2.

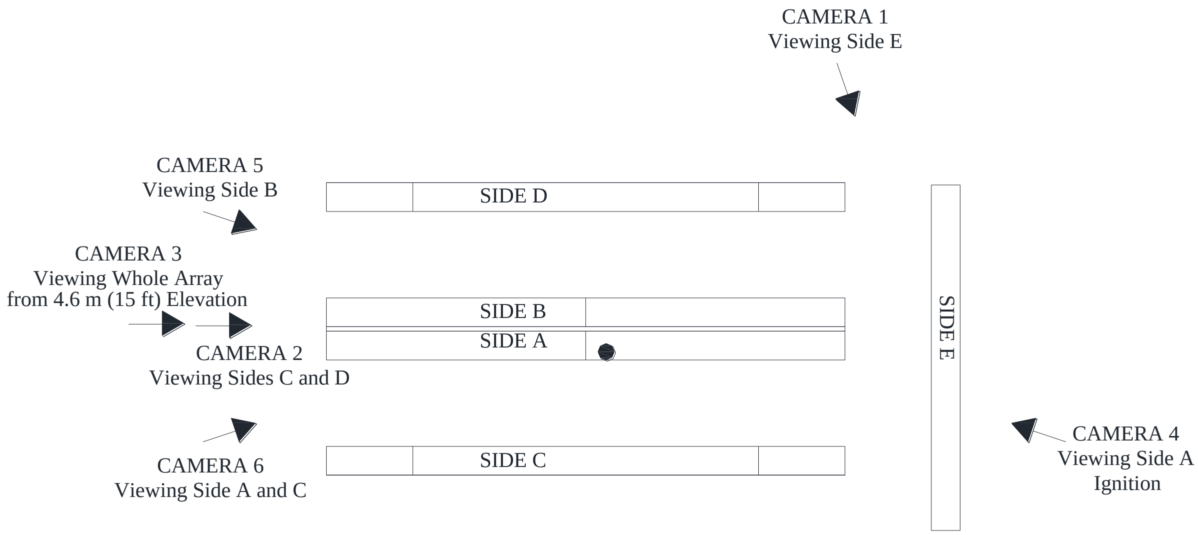


Figure 2-29: Plan view showing video camera locations.

2.3 Test Evaluation Criteria

Determination of a successful test was assessed in relation to the metrics specified below.

1) Fire spread to the extent of the array.
2) Gas temperatures near-ceiling-level maintained at high-levels for a time judged to endanger exposed structural steel.
3) Operation of ceiling-level sprinklers on the perimeter of the ceiling and/or unreasonably high water demand.

Damage needs to be confined to the extent of the fuel array and the extents are defined as the back side of targets Side C, D and E. Flame spread to the back side of the longitudinal flame break (Side D and E) or the sheet rock (Side C) constitute a failure.

Structural steel begins to soften and lose its integrity when exposed to high temperatures over a sufficient duration of time. The maximum allowable ceiling steel temperature is 538°C (1000°F). This threshold is chosen based on an assessment that structural steel loses approximately 50% of its load bearing strength when at this temperature. Ceiling-level steel temperatures were calculated from the measured ceiling-level gas temperatures. The calculation is based on the energy balance on a thermally thin strip of steel, exposed to fire conditions on one side and adiabatic conditions on the other as shown in Eq. (1):

$$\rho\, c_p\, \delta\, \frac{dT_s}{dt} = (h_c + h_R)\left(T_g + T_s\right), \quad (1)$$

where (ρ) is the steel density, (c_p) specific heat, (δ) steel thickness, $(\frac{dT_s}{dt})$ heating rate, (h_c) and (h_R) convective and radiative heat transfer coefficients, respectively, and (T_g) and (T_s) are the gas and steel temperatures. Typical steel property values can be found in literature [36]. The steel thickness was

6.4 mm (0.25 in.). A value of 7,850 kg/m^3 was used for the density and the temperature-dependent specific heat in (J/kg·K) is as follows over the temperature range of interest:

$$c_p = 425 + 0.773\,T - 1.69 \times 10^{-3} T^2 + 2.22 \times 10^{-6} T^3 \qquad \text{if} \qquad 20℃ \leq T < 600℃$$

A value of 25 W/m^2·K was assumed for the convective heat transfer coefficient based on recommended values for compartment fires [36]. The radiative heat transfer coefficient was calculated by manipulating the Stefan-Boltzmann law as shown in Eq (2),

$$h_R = \varepsilon\, \sigma \left(T_g^2 + T_s^2\right)\left(T_g + T_s\right), \tag{2}$$

where ε is the resultant emissivity between the steel and the fire plume, assumed to be equal to one, and σ is the Stefan-Boltzmann constant equal to 5.67 X 10^{-8} W/m^2·K^4. Since the maximum allowable ceiling steel temperature is 538°C (1000°F), this assessment is only conducted for ceiling locations where the maximum gas temperature is greater than 538°C (1000°F). An estimated steel temperature, T_S, with a maximum value greater than 538°C (1000°F) constitutes a failure.

The acceptability of sprinkler operations is determined based on the number and location occurring in the test. The number of sprinkler operations is used to determine the water demands of the system, which is only limited by the local water supply in any given engineering application. Another way to examine the number of sprinkler operations is to compare it to the design area of OH, Group 2 and EH, Group 1 protection in NFPA 13 [25]. It should be pointed out that, when sprinklers operate along the ceiling perimeter, it is difficult to determine whether sprinklers further away would have also operated. Thus, the sprinkler demand area may not be defined directly from the test results and may have to rely on estimation including a conservative safety factor. In practice, sprinkler operations in excess of the number of sprinklers included in the design could potentially tax the sprinkler system beyond its effective capacity. Therefore, perimeter sprinkler operations typically indicate that the water demand may require additional analysis to arrive at a conservative estimation.

3. **Test Results**

Results of the two tests are summarized in this section. A general overview of each test is provided with detailed data presented below. Summaries of test parameters and results are provided in Table 3-1. All times are stated from the start of the fire (i.e., ignition) and are expressed as min:sec unless otherwise noted. Results are presented to provide an overview of the test in terms of the performance criteria. Additional data are presented in the appendices. A fire chronology in the form of a pictorial narrative is provided in Appendix A. Appendix B contains ceiling-level gas temperature data, temperature data measured within the shelving units and TC tree data. Appendix C contains images and descriptions of post-test damage.

3.1 Test 1 Results

The purpose of Test 1 was to determine if 74°C (165°F) rated, K-factor of 80 lpm/bar$^{1/2}$ (5.6 gpm/psi$^{1/2}$), SR, pendent sprinklers providing a discharge density of 8.1 mm/min (0.2 gpm/ft^2) is adequate protection for retail sales of consumer fireworks with ceiling heights up to 4.9 m (16 ft).

3.1.1 Highlights of Fire Development

Flames were visible on the face of Side A at 00:17 and firework sparks were first visible at 00:33. The fire intensity and smoke production were increasing at the time of 1st sprinkler operation (00:57). The fire continued to intensify, and sparks were being projected throughout the test array. Visibility in the lab was partially obscured by smoke and flames extended approximately 1.2 m (4 ft) above the top of Side A when the 2nd and 3rd sprinkler operations occurred at 01:16. Ignition of Side C occurred at 01:47 and the core nine sprinklers had operated by 01:49; their locations were such that their water discharge covered the whole test array. Sparks where witnessed ricocheting off Sides B, C, D, and E. The fire continued to intensify and 35 of 36 installed sprinklers had operated by 02:53; visibility in the lab was heavily obscured with smoke at this time. Ceiling-level gas temperatures began a steady decline at approximately 03:10; sparks continued to be vigorously scattered throughout the test array. All ceiling-level gas temperatures were below 100°C (212°F) at 06:57. The test was terminated at 35:00 and required only minimal manual firefighter intervention to extinguish a few lingering combustion regions.

Table 3-1: Test result summary

Project I.D.	3058934	
Test Number	1	2
Test Date	02/15/2019	03/19/2019
Movable Ceiling Test Site Height (m) [ft]	4.9 (16)	9.1 (30)
Test Commodity / Fuel	500 g fountain consumer firework	
Storage Arrangement	Shelf (Gondola)[1]	
Array Size	Large-Scale	
Nominal Storage Height (m) [ft]	1.8 and 3.7 (6 and 12)	
Flame Break Material	Combustible 10 mm (3/8 in.) southern pine	
Pre-test Site Dry-Bulb Temperature (°C) [°F]	19 (66)	19 (66)
Pre-test Site Relative Humidity (%)	50	44
Pre-test Paper Moisture Content, Surface - Dry Basis (%)	9.5	7.4
Lab Ventilation Rate (m^3/s) [cfm]	Approximately 14.2 (30,000)	
Ceiling-level Sprinkler Protection Details		
Ignition Location with Respect to Sprinklers	Offset 0.3 m (1 ft) Under 1	
Distance from Ceiling to Sprinkler Thermal Element (mm)	305 (12)	
Sprinkler Temperature Rating (°C) [°F]	74 (165)	
Sprinkler Model/Type	Pendent, VK110, SR	
Orifice Diameter (mm) [in.]	13 (0.5)	
Discharge Coefficient (K-factor) (lpm/(bar)^{½}) [gpm/(psi)^{½}]	80 (5.6)	
Sprinkler Spacing (m x m) [ft x ft]	3.0 x 3.0 (10 x 10)	
Discharge Pressure (bar) [psi]	0.9 (13)	2.0 (29)
Nominal Discharge per Sprinkler (ℓ/min) [gpm]	75 (20)	114 (30)
Fire Test Results		
Total Sprinklers Opened	35[2,3]	36[4]
First / Last Sprinkler Operation Times (min:sec)	00:57 / 02:53	01:28 / 02:20[5]
Peak Ceiling-level Gas Temperature (°C) [°F] and Time (min:sec)	929 (1704)	906 (1662)
	@ 03:11	@ 02:33
Maximum One-Minute Average Gas Temperature (°C) [°F]	869 (1596)	812 (1494)
Peak Ceiling-level Steel Temperature (°C) [°F] and Time (min:sec)	450 (842)	326 (610)
	@ 03:55	@ 03:48
Ignition of Side C?	Yes @ 01:47	Yes @ 01:08
Extend of Flame Spread Acceptable?	Yes	Yes
Test Termination - Time After Ignition (min)	35:00	52:00

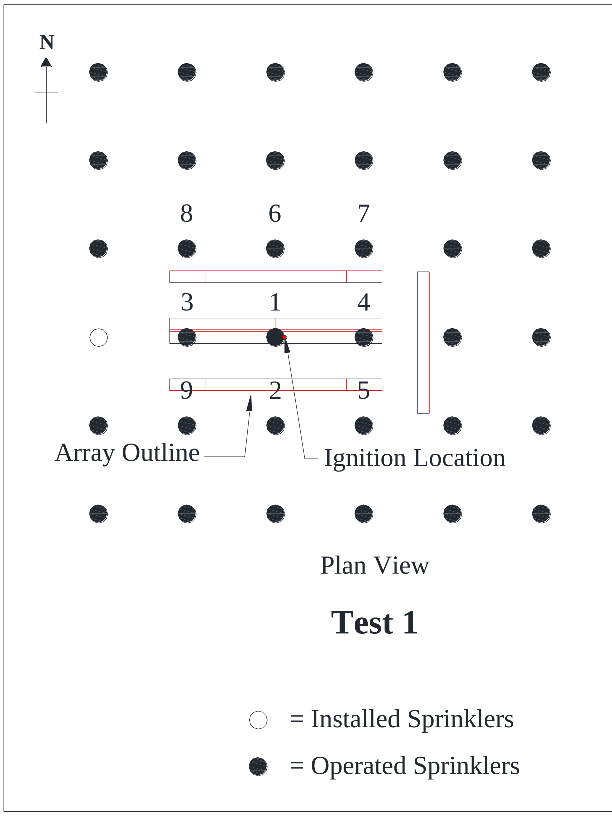
[1] Refer to Section 2.1 for a complete description of the array.
[2] The capacity of the water delivery system was exceeded, and water pressure dropped below the target value until supplemental water was provided. Refer to Section 3.1.2 for details.
[3] 35 of 36 installed sprinklers operated, 21 of which were perimeter operations.
[4] Every installed sprinkler operated, 22 of which were perimeter operations.
[5] The last sprinkler operation time reported here is for the monitored sprinklers. It is not to determine when the plugged unmonitored sprinkler activated.

3.1.2 Results and Damage Assessment

Figure 3-1 shows the sprinkler operation pattern for the nine sprinklers that were monitored. A total of 35 sprinklers operated in the test, 21 of which were perimeter operations therefore the demand area exceeds the plan area covered in the test and cannot be determined definitively. The water flow and pressure data are provided in Figure 3-2. The water flow meter signal was lost at 02:45; however, the continuously increasing volumetric flow rate up to that time indicates that sprinklers were operating in rapid succession with the final operation occurring at 02:53 as suggested by the stabilized water pressure. The water delivery system was overtaxed and water pressure dropped below the target value of 0.9 bar (12.8 psig) at 01:58 reaching a minimum value of (5.6 psig) at 02:53. The water system was supplemented and pressure was gradually increased and was maintained within ± 15% of the target pressure between 07:40 and 31:10. It is not possible to conclude if maintaining the target water pressure would have resulted in fewer sprinkler operations.

A damage assessment was made following test termination and is summarized below; refer to Appendix C for detailed images and descriptions. A plan view of the maximum extent of damage is provided in Figure 3-3 and elevation views for Sides A and C are shown in Figure 3-4, respectively. Sides B, D, and E sustained water damage only, thus the extent of flame spread was within acceptable limits. The fire in Side A burned through the transverse flame breaks reaching both the east and west end in the bottom and middle shelves where the solid shelving shielded the sprinkler water. The fire did not reach the east and west ends in the top shelf of Side A and more commodity remained than in lower shelves presumably due to more exposure to sprinkler water. Fire damage in Side C occurred in all five shelves and was contained between the transverse flame breaks. Fire burned through portions of the longitudinal flame break in Side C but did not penetrate the outer sheet rock. The most damage occurred in the bottom shelf and extent of damage decreased with increasing shelf height.

Ceiling-level gas temperatures exceeding 538°C (1000°F) were measured at six locations. These data have been converted to steel temperature using the methodology given in Section 2.3. The time history of the calculated steel temperatures is given in Figure 3-5. The peak steel temperature was achieved at 03:55 and was equal to 450°C (842°F) which is below the established limit.



Operating Sequence	Time (min:s)
1	00:57
2	01:24
3	01:24
4	01:28
5	01:34
6	01:35
7	01:40
8	01:43
9	01:49

Figure 3-1: Test 1 sprinkler operation pattern. Note that only 9 of 36 sprinklers were electronically monitored for their operation time.

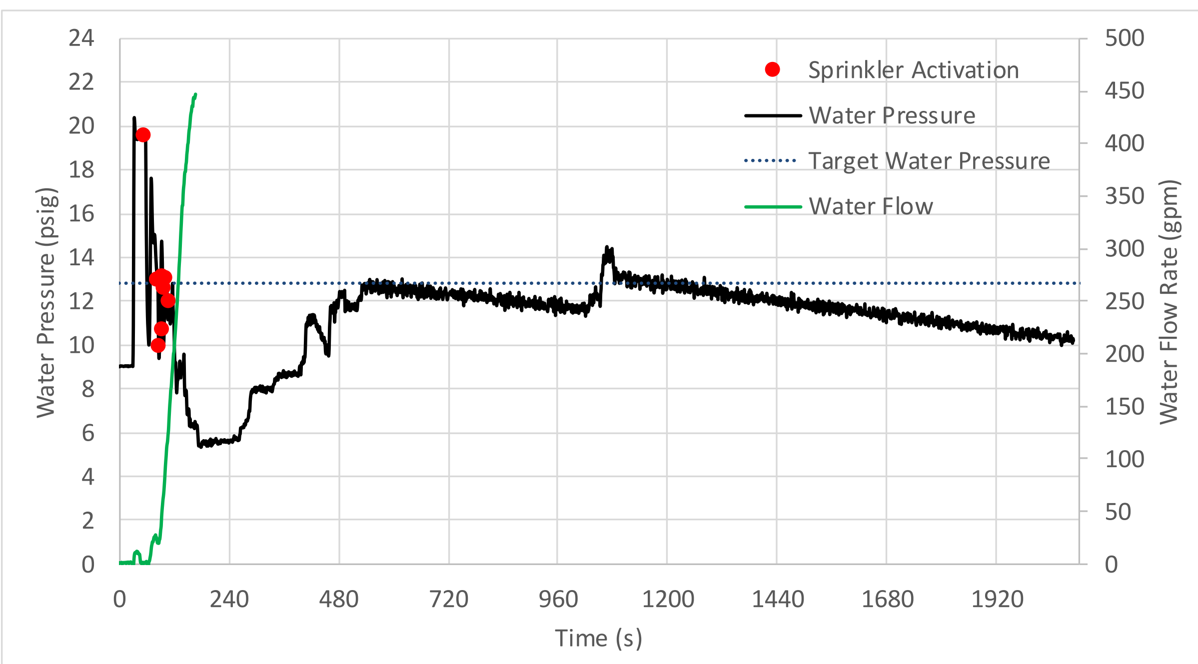


Figure 3-2: Test 1 water pressure and flow rate.

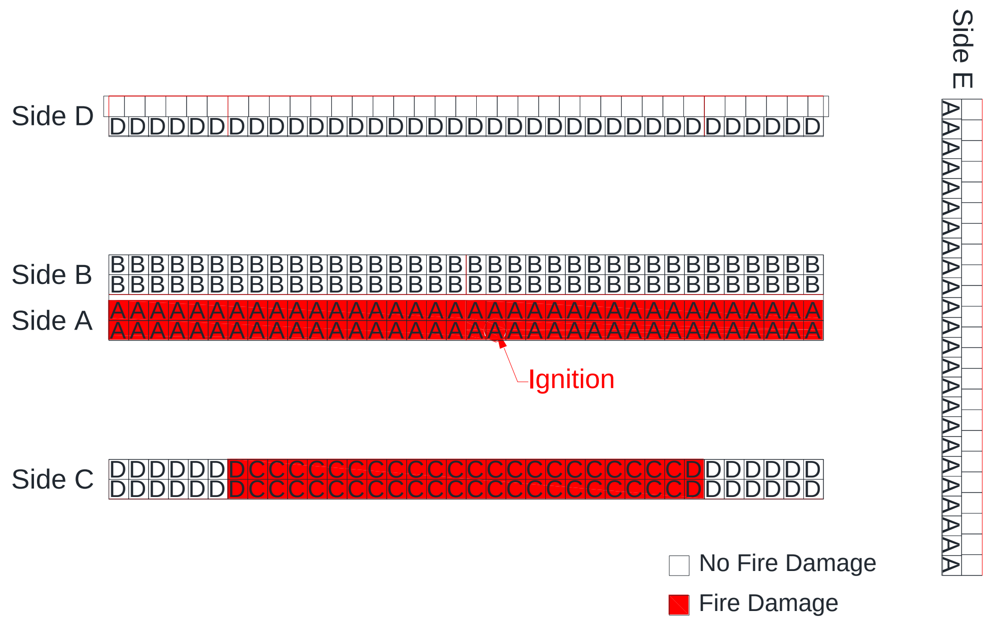


Figure 3-3: Test 1 plan view of maximum extent of fire damage.

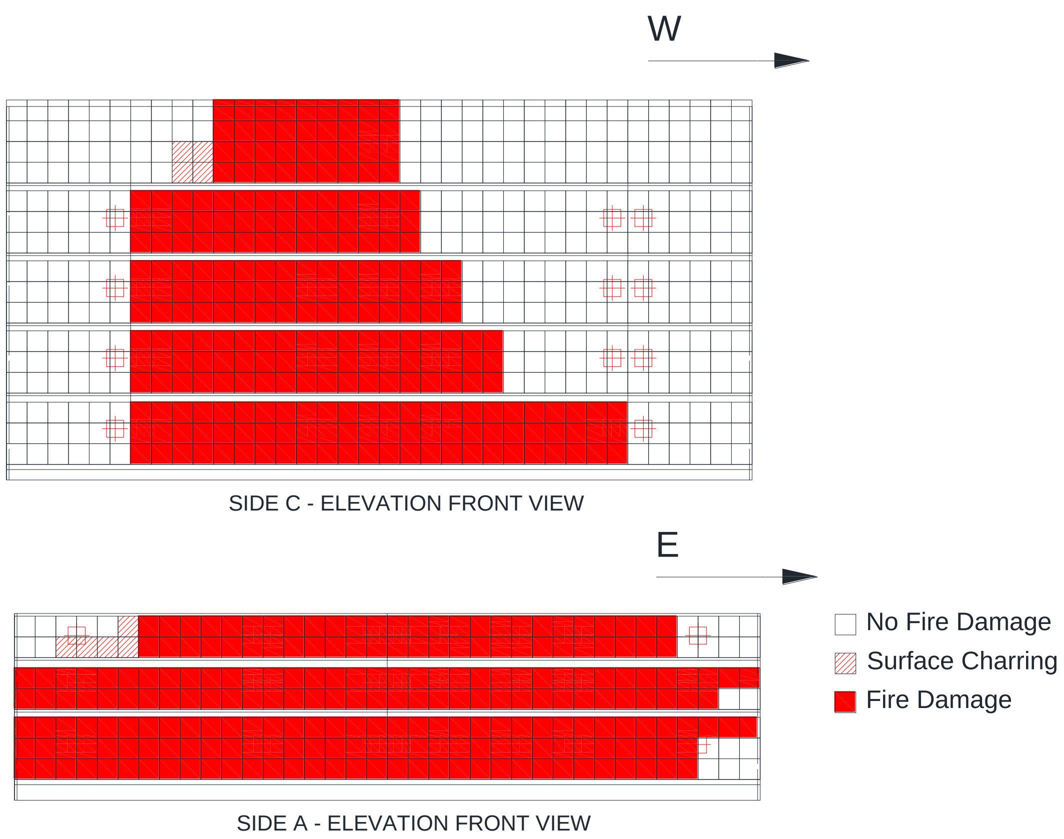


Figure 3-4: Test 1 elevation view of fire damage.

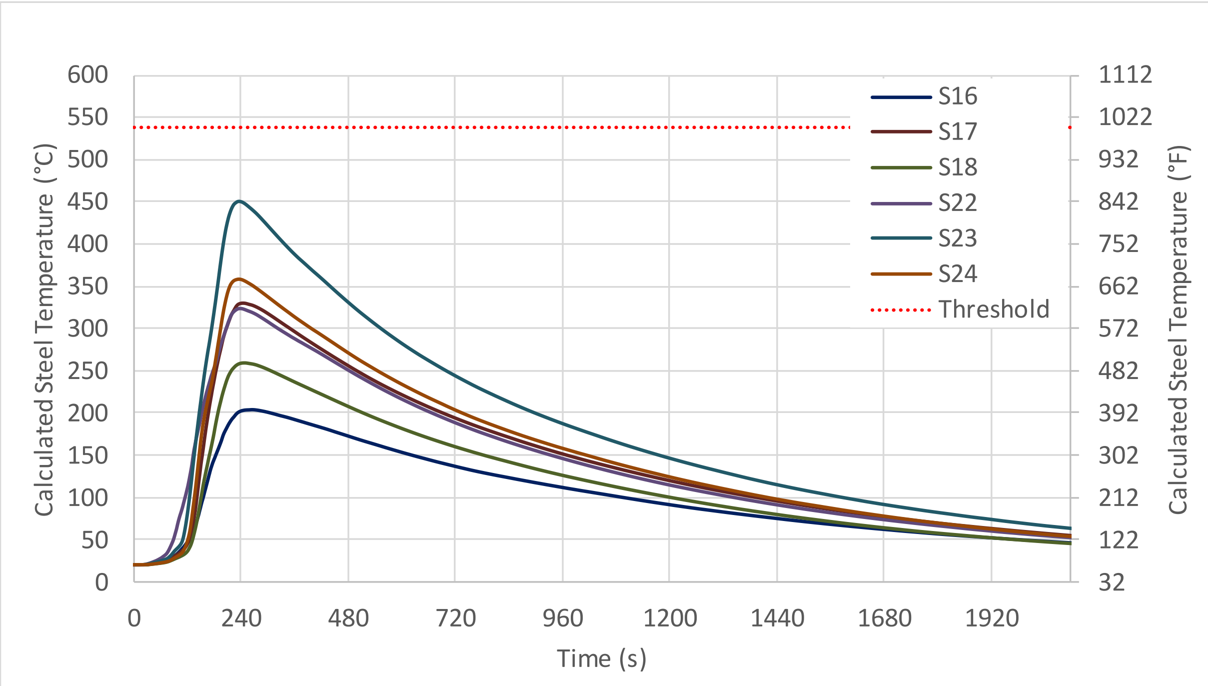


Figure 3-5: Test 1 calculated ceiling-level steel temperatures for locations where gas temperatures exceeded 538°C (1000°F).

3.2 Test 2 Results

Test 2 was identical to Test 1 with the exception that the ceiling height was 9.1 m (30 ft) and the sprinkler discharge density was 12.2 mm/min (0.3 gpm/ft^2)[xx].

3.2.1 Highlights

Flames were visible on the face of Side A at 00:05 and firework sparks were first visible at 00:19. At 01:00 the fire was confined to Side A and flames extended approximately 2.1 m (7 ft) above the top of the commodity; a dense shower of sparks was falling on the top shelf commodity of Side B. Ignition of Side C occurred at 01:19 and the fire continued to intensify with sparks being thrown throughout the test array. At 01:23 the top commodity of Side B began discharging live pyrotechnics. The fire intensity was increasing when the 1st sprinkler operated at 01:28; there was full visibility in the lab and the sprinkler discharge had no noticeable effect on fire intensity. The fire continued to intensify and at least 24 sprinklers activated between 01:44 and 02:20 during which time visibility became nearly fully obscured. Ceiling-level gas temperatures began a rapid decline at approximately 03:40 (refer to Appendix B for temperature data); sparks continued to be vigorously scattered throughout the test array. All ceiling-level gas temperatures were below 100°C (212°F) by 04:20 although TCs in the shelving

[xx] There were also inconsequential differences in the commodity loading in Sides D and E.

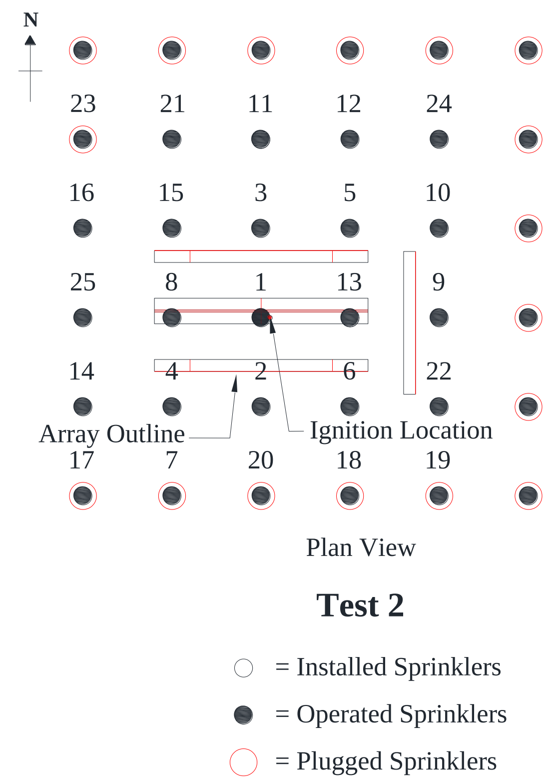
indicated the presence of fire in Sides A and C. The test was terminated at 52:00 and required only minimal manual firefighter intervention to extinguish a few lingering flames.

3.2.2 Results and Damage Assessment

Figure 3-6 shows the sprinkler operation pattern for the 25 sprinklers that were monitored. All 36 installed sprinklers operated, 22 of which were perimeter activations, therefore the demand area cannot be determined, but would have exceeded the requirements for EH, Group 1 protection at a 12.2 mm/min (0.3 gpm/ft^2) density which requires a demand area of 232 m^2 (2500 ft^2). The water flow and pressure data are provided in Figure 3-7. The average water pressure was maintained within ± 3% of the target pressure once all active sprinklers had operated.

A damage assessment was made following test termination and is summarized below; refer to Appendix C for additional details. A plan view of the maximum extent of damage is provided in Figure 3-8 and elevation views for Sides A and C are shown in Figure 3-9. Side B sustained damage to 22 devices located on the top shelf. Sides D, and E sustained water damage only, thus the extent of flame spread is within acceptable limits. The fire in Side A burned through the transverse flame breaks in the bottom and middle shelves and reached both the east and west end in the bottom shelf and the east end in the middle and top shelves. The solid shelving likely contributed to the fires ability to traverse these shelves. As with Test 1, more commodity remained on the top shelf than in lower shelves likely due to more exposure to sprinkler water. Fire damage in Side C occurred in all five shelves. Flame spread did not go beyond the transverse flame breaks on the west; however, fire consumed the eastern transverse flame breaks and reached the east end of Side C in the bottom four shelves.

Ceiling-level gas temperatures exceeding 538°C (1000°F) were measured at seven locations. These data have been converted to steel temperature using the methodology given in Section 2.3. The time history of the calculated steel temperatures is given in Figure 3-10. The peak steel temperature was achieved at 03:48 and was equal to 326°C (610°F) which is below the established limit.



Operating Sequence	Time (min:s)
1	01:28
2	01:44
3,4	01:47
5	01:51
6	01:52
7	01:54
8	01:55
9	01:58
10	01:59
11	02:01
12	02:03
13	02:04
14	02:07
15	02:08
16, 17, 18, 19	02:09
20	02:10
21	02:12
22	02:14
23	02:16
24	02:19
25	02:20

Figure 3-6: Test 2 sprinkler operation pattern. Note that northern and eastern most rows of sprinklers were not electronically monitored for their operation time.

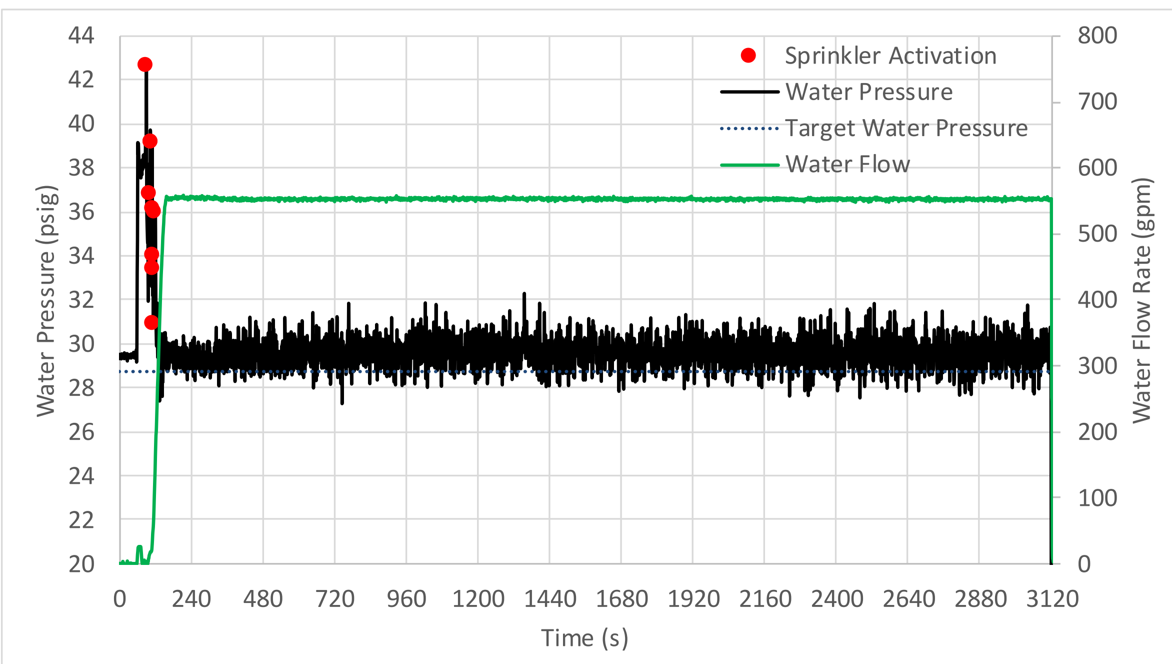


Figure 3-7: Test 2 water pressure and flow rate.

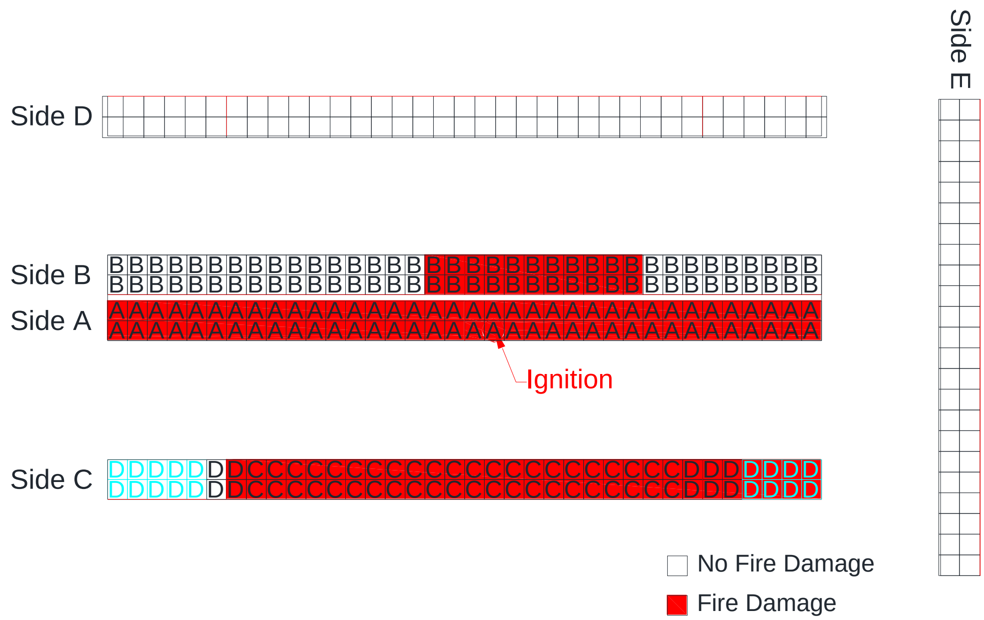


Figure 3-8: Test 2 plan view of maximum extent of fire damage.

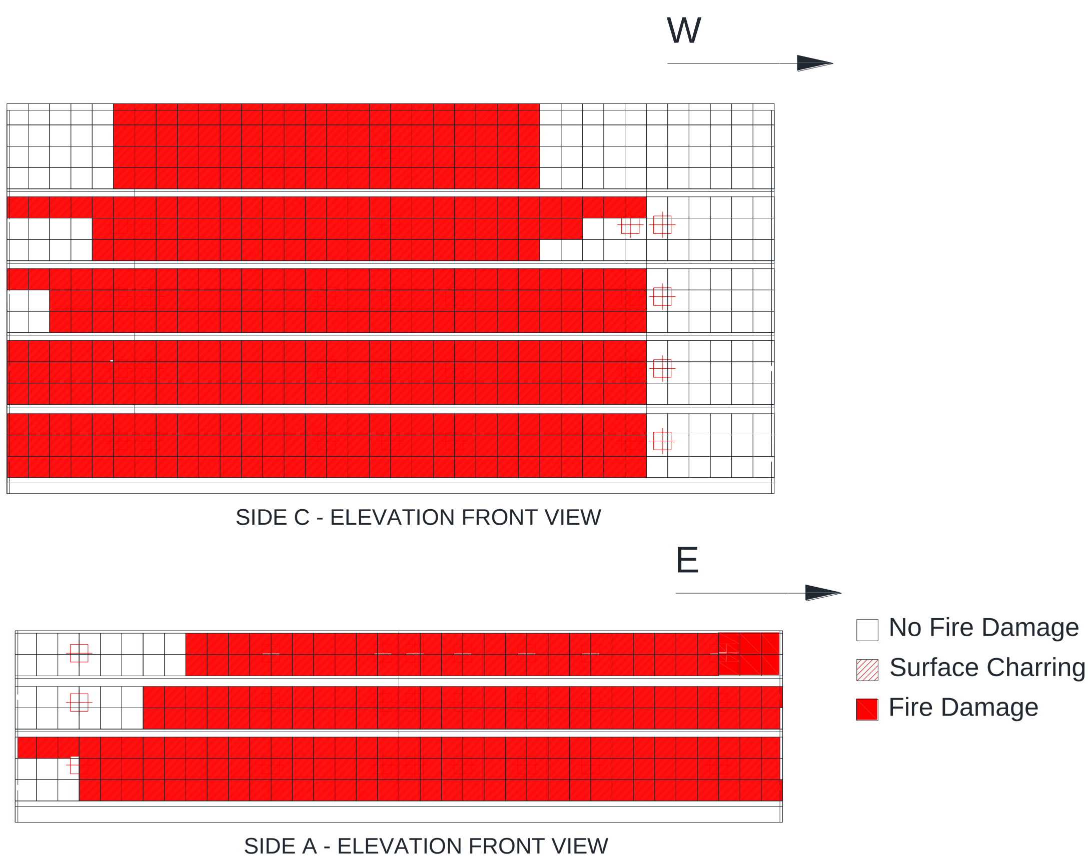


Figure 3-9: Test 2 elevation view of fire damage.

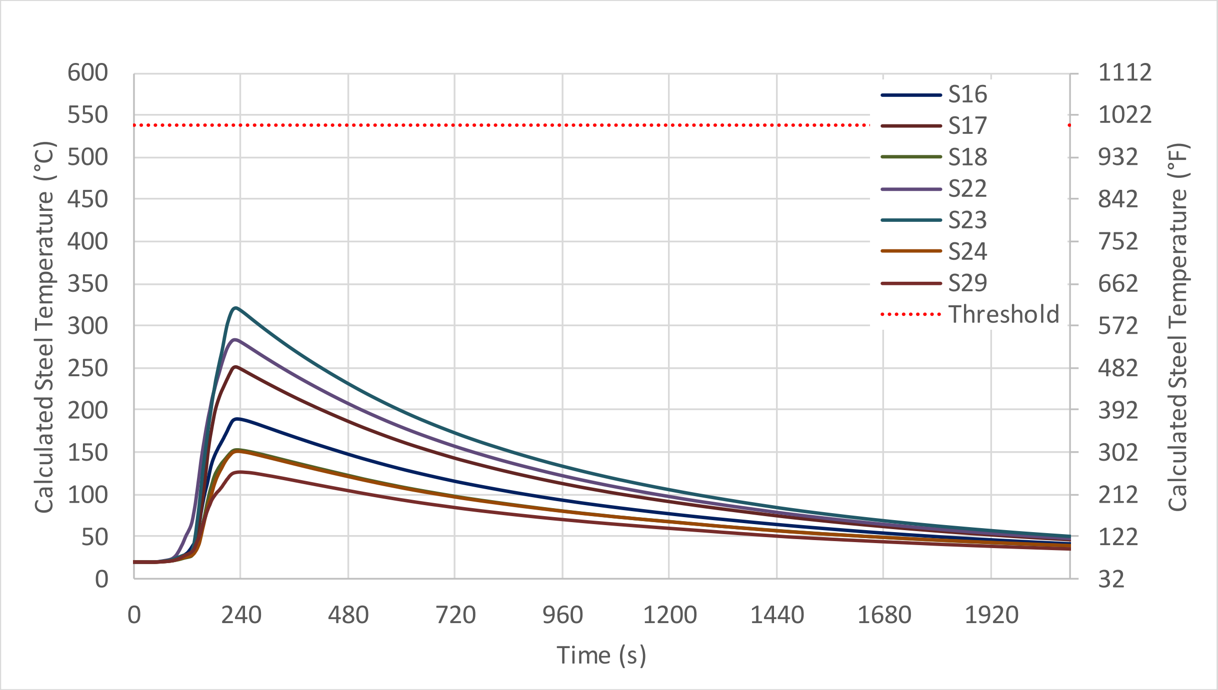


Figure 3-10: Test 2 calculated ceiling-level steel temperatures for locations where gas temperatures exceeded 538°C (1000°F).

4. Discussion

4.1 Performance Evaluation

The results of the two fire tests conducted in the present work show that, for buildings with 4.9 m (16 ft) and 9.1 m (30 ft) high ceilings, the tested fire protection designs are capable of maintaining acceptable flame spread and limiting ceiling-level steel temperatures to values that would not threaten structural integrity in occupancies containing the retail sales of consumer fireworks in gondola shelves. In Test 1, the fire was confined to Sides A and C; the double longitudinal flame break proved essential in preventing flame spread to Side B. The fire did not involve Sides D and E; breaching the longitudinal flame break on these sides would have constituted a failure of the flame spread metric. Ceiling-level steel temperatures reached an estimated maximum value of 450°C (842°F) at 03:55 which is below the 538°C (1000°F) failure threshold. Similarly, in Test 2, the fire was confined to Sides A, B and C (minimal damage to top shelf fireworks on Side B) and therefore the flame spread performance metric was met. Again, the double longitudinal flame break proved essential in preventing flame spread from the back of Side A to Side B. Ceiling-level steel temperatures reached a maximum value of 326°C (610°F) at 03:48, which is below the 538°C (1000°F) failure threshold. In both tests, however, excessive sprinkler operations occurred. In Test 1, 35 of the 36 installed sprinklers activated and in Test 2 all installed sprinklers activated. Because perimeter operations occurred, it is not possible to know exactly how many sprinklers would have operated had the test ceiling been larger. Therefore, a specific demand area cannot be defined for either of the tested conditions but would have exceeded the demand area for OH, Group 2 and EH, Group 1 protection for the supplied discharge density.

4.2 Comparison to Prior Test Results

The number of sprinkler operations achieved in Tests 1 and 2 greatly exceeded the number that operated in similar large-scale fire testing conducted as part of the AFSL test series [4]. AFSL Tests 6, 7 and 8 of Reference [4] were repeats of one another. In AFSL Tests 6, 7 and 8 a total of 4, 2 and 4 sprinklers operated; the sprinkler protection was identical to that used in Test 1 of the present research. Overall these AFSL tests [4] are a good comparison with Test 1 with a few pertinent differences that are hence noted. AFSL Tests 6, 7 and 8 used a variety of different types of fireworks devices[xxi] with varying quantities of pyrotechnical composition per device[xxii], the shelves were partially loaded[xxiii] and had an

[xxi] Ground-based, aerials and novelties.

[xxii] Ranging from 1 g to 500 g per device.

[xxiii] Based on images provided in Reference [4] it is estimate that 50% of the available volume was occupied with commodity sometimes resulting in a free space between the top of commodity and underside of the shelf above that was greater than half the shelf height. This is of interest because it is thought that given a free space of appropriate size, flames channeled along the underside of the shelf will be in close enough contact with adjacent firework devices to cause their ignition.

average energy density of 8.3 kg/m^3 (0.5 lb/ft^3)[xxiv]. In Test 1 all devices were 500 g fountains and a minimum of 88% of the available shelving volume was occupied with commodity resulting in an average energy density of 50.9 kg/m^3 (3.2 lb/ft^3). Additionally, in AFSL Tests 6, 7 and 8 all shelving was 4.9 m (16 ft) in length and 1.8 m (6 ft) high and used non-combustible flame breaks while Test 1 had shelving that was primarily 7.4 m (24 ft) long[xxv] and 1.8 m (6 ft) high with a 3.7 m (12 ft) high shelving unit across the aisle from ignition; flame breaks were combustible. The ceiling height in AFSL Tests 6, 7 and 8 was 5.2 m (17 ft) as opposed to 4.9 m (16 ft) in Test 1. Despite the differences in test set-ups, the primary cause for the disparity in the number of sprinkler operations between AFSL Test 6, 7 and 8 and Test 1 is most likely attributable to the large difference in energy density.

4.2.1 Fire Development

The initial fire development in AFSL Tests 6, 7 and 8 was generally slower than in Test 1. AFSL Test 6 used a firework device for ignition and the fire intensity continuously increased until operation of the 1st sprinkler at 02:45. The fire growth in AFSL Test 6 was faster than that of AFSL Tests 7 and 8. In AFSL Test 7 a wire mesh basket containing 15 sheets of crumpled newspaper was used as the ignition[xxvi] source and took 01:00 to ignite an adjacent firework device. The 1st sprinkler operation did not occur until 15:50 after the ignition of the newsprint. A paper filled basket was also used for Ignition in Test 8[xxvi] and the 1st firework device ignited 02:30 later, followed by additional devices and then a decrease in firework activity. The 1st sprinkler operated 12:56 after ignition of the paper filled basket. The reason for the variability in the fire growth behavior between AFSL Tests 6, 7 and 8 is unknown, however, may have been influenced by minor variations in commodity loading or perhaps by test to test variability in commodity moisture content.

Two standard full ignitors were used to ignite Test 1 and the 1st firework device activated at 00:33 followed by a continuous increase in fire intensity. The fire continued to intensify following the 1st sprinkler operation at 00:57 whereas in AFSL Tests 6, 7 and 8 ceiling-level gas temperatures remained approximately steady state after the 1st operation. Test 1 produced a more rapidly growing fire than AFSL Tests 6, 7 and 8 as evidenced by the time to 1st sprinkler operation. This difference in fire development is likely a result of the energy density. The test set-up with varying firework device types, partial shelf loading and an average energy density of 8.3 kg/m^3 (0.5 lb/ft^3) used in AFSL Tests 6, 7 and 8 may be representative of the lower end of the retail sales of consumer fireworks hazard spectrum[xxvii]. On

[xxiv] This value is calculated based on the total powder weight per test (values reported in Appendix A of Reference [4]) and the total volume of the shelving units used in the tests (i.e., 10.9 m^3 [384 ft^3] for Sides A, B, C and D combined).

[xxv] Side E was 4.9 m (16 ft) long while all others were 7.4 m (24 ft) long.

[xxvi] Two previous ignition attempts using a firework device had failed.

[xxvii] Note that these tests contained aerial firework devices that had been completely caged so as to remain in place if discharged. In this manner the device is being considered to behave more as a ground-based device than an aerial.

the other hand, the 500 g devices, minimum 88% loading and average energy density of 50.9 kg/m^3 (3.2 lb/ft^3) used in Test 1 is likely representative of the higher end of the hazard spectrum for ground-based fireworks. This point is further articulated in the following paragraph which compares the ceiling-level gas temperatures and sprinkler activation times. Some of the data have been interpreted from paper graphs from Reference [4] and all times stated below are approximate.

4.2.2 Ceiling-level Gas Temperatures and Sprinkler Activations

In AFSL Test 6 [4] the first sprinkler operation occurred 00:05 after the target (Side C) ignited. At this time, ceiling-level gas temperatures had just achieved maximum[xxviii] values and were approximately steady-state for 01:45, then began to decline. Although the 2nd through 4th (final) sprinkler operations times were not recorded, it is possible to infer that they had activated within 03:45 of the 1st operation, which is when all ceiling-level gas temperatures were below the sprinkler operating temperature. Similar events occurred in AFSL Test 7 where the 1st sprinkler operated when ceiling-level gas temperatures were at their maximum and steady for 03:15 and dropped below the sprinkler operation temperature 00:15 later and continued to decline. Side C was ignited although the exact time was undetermined. In AFSL Test 8 the ceiling-level gas temperatures reached the same approximately steady state maximum, this time 01:45 *prior* to 1st sprinkler operation. Side C was observed to be burning 01:15 prior to 1st operation. Temperatures dropped below the sprinkler operation temperature 01:45 after 1st operation, which also coincided with the end of quasi-steady state conditions, implying that the remaining three sprinkler operations had occurred.

Contrast these results with those of Test 1 which have been graphically summarized in Figure 4-1. The 1st sprinkler operation occurred when ceiling-level gas temperatures were approximately 20% of their maximum. Following this time, temperatures continued to increase, and sprinklers continued to operate. Side C ignited 00:50 after the 1st operation and at least nine sprinklers were operating about this time. Temperatures continued to increase achieving approximate maximum values 01:15 after the 1st operation (an estimated 20 sprinklers were operating at this time) and remained approximately steady state for the following 00:50 after which time they exhibited a steady decline. 35 of 36 sprinkler had operated within 01:56 of the 1st sprinkler operation. In AFSL Tests 6, 7 and 8, ceiling-level gas temperatures did not increase following first sprinkler operation; and in AFSL Test 8 temperatures had achieved a steady state maximum prior to this operation. Given that the provided fire protection was the same in all tests, these differences indicate that the energy density in Test 1 was a main contributing factor to the disparity of sprinkler activations.

There was no immediate reduction in temperature as a result of sprinkler activations in any of the tests carried out here indicating that the sprinkler protection was doing little to reduce the intensity of the fire. The uniform decline in temperatures followed by the steady state period at their maximum values

[xxviii] Quantitative ceiling-level gas temperatures are not given because a direct comparison between AFSL Tests 6, 7, 8 and Test 1 cannot be made. Ceiling heights were different by 0.3 m (1 ft) and thermocouples were located at different vertical distances from the ceiling. In AFSL Tests 6, 7 and 8 they were located 30 cm (12 in.) below the ceiling (i.e., same elevation as sprinklers) while in Test 1 they were located 17 cm (6.5 in.) below the ceiling.

is likely an indication that the fireworks in the main fire region had been consumed and effective pre-wetting had occurred thus limiting subsequent combustion.

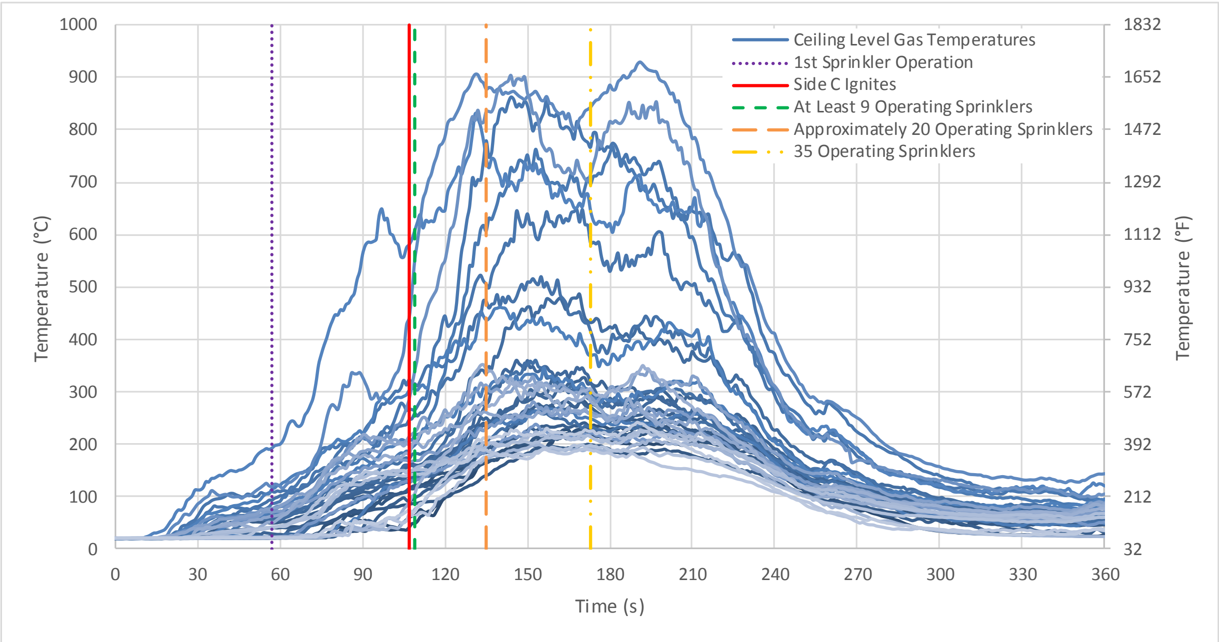


Figure 4-1: Test 1 ceiling-level gas temperatures and relevant events.

4.2.3 Shelving Height

These test results cannot be used to decouple the effect of shelving height from the combustible loading. However, it can be noted that at least eight sprinklers had operated in Test 1 when only the 1.8 m (6 ft) Side A was involved in the fire, whereas in AFSL Tests 6, 7 and 8 the combined fire resulting from the involvement of Sides A, B and C (all 1.8 m [6 ft] high) resulted in a maximum of 4 operations. An additional 26 sprinkler operations occurred in Test 1 after the ignition of Side C (4.9 m [12 ft] high). This comparison cannot be made for Test 2 because Side C ignited prior to 1st sprinkler operation.

4.2.4 Shelving Length

Reference [4] provides a post-test image of damage sustained to Side A in AFSL Tests 6 and 8; it appears to extend the full length of the bottom and middle shelf but not to the top shelf. This is the same sort of damage profile seen in Side A of Test 1. Note that, regardless of differences in shelving length and number of sprinkler activations, the fire was still able to traverse the length of the shelving unit in lower shelf heights highlighting the shielding effect that solid shelves have on sprinkler water. It seems reasonable to assume that fire would also reach the end of a 9.8 m (32 ft) long shelving unit, which is the maximum allowable length per NFPA 1124 (2013 edition) [1]. However, Tests 1 and 2 of the present study have shown that, should this happen, pre-wetting is likely to prevent radiant ignition across a 1.2 m (4 ft) aisle (i.e., fire in Sides A and C did not spread to Side E). In Tests 1 and 2, given the already large demand area, it seems unlikely that shelves up to 9.8 m (32 ft) in length would further increase the demand area. In the case of AFSL Tests 6, 7 and 8 [4], where the number of sprinkler operations was low, it is possible that additional operations may occur as a result of increased shelf length. This seems probable because the fire may propagate beyond the pre-wetted regions and gain intensity. If this were to happen, the total number of sprinkler operations is not expected to be more than double those reported in the tests.

4.3 Palletized Displays in Retail Locations

Previous research [4] showed that sprinkler protection reduced the fire intensity faster in palletized displays than in gondola shelving. The gondola display, with its solid shelving obstructs sprinkler water from reaching the fire, whereas the palletized display allows for direct wetting and pre-wetting to occur. This phenomenon, along with the arguments set forth in Section 1.3.6, suggests that the tested protection will perform the same if not better for palletized displays of consumer fireworks up to the heights tested.

4.4 Increased Protection

It is reasonable to question whether the demand area might be reduced by employing a higher level of protection. Based on the results of Test 1 and 2 it seems unlikely that control mode sprinkler protection will be able to actively suppress the fire (as opposed to pre-wetting adjacent combustible and letting the fire region burn out) and demand area would remain high. It is possible that using larger orifice sprinklers, such as K-factor 200 lpm/bar$^{1/2}$ (14.0 gpm/psi$^{1/2}$) or greater at a water pressure capable of proving enough downward thrust to penetrate the fire plume may result in a reduction in demand area. However, the presence of solid shelves will hinder the delivery of suppression water to the burning surfaces. Thus, the possibility still exists that the fire severity may maintain an intensity for a long enough duration to cause excessive sprinkler operations. Additionally, the use of larger orifice sprinklers at relatively high pressure may not be a practical solution for locations with large retail areas.

5. **Summary**

Two large-scale fire tests were conducted to assess fire protection for retail sales of consumer fireworks in gondola shelving. The tests were designed based on the protection guidance that existed in NFPA 1124 (2013 edition) prior to its withdrawal and adhered to requirements for storage heights, aisle widths, shelving lengths and flame breaks. Accordingly, the tested consumer fireworks were classified as UN0336 and 1.4G and complied with any limits and requirements of the APA Standard 87-1: Standard for Construction and Approval for Transportation of Fireworks, Novelties, and Theatrical Pyrotechnics [21] and applicable Code(s) of Federal Regulations[xxix]. The test design was largely informed by that previously put forth in a concept test plan that was developed in 2011 by the Fire Protection Research Foundation (FPRF) [6] and at that time agreed upon by NFPA, and NASFM.

For the conditions tested, sprinklers with a K-factor of 80 lpm/bar$^{1/2}$ (5.6 gpm/psi$^{1/2}$) and having a standard response time index and temperature rating of 74°C (165°F) installed on a 3.0 m x 3.0 m (10 ft x 10 ft) with their thermal element located 0.3 m (12 in.) below the ceiling are capable of maintaining acceptable flame spread and limiting ceiling-level steel temperatures to values that would not threaten structural integrity when they are designed to provide a minimum discharge density of 8.1 mm/min (0.2 gpm/ft^2) for 4.9 m (16 ft) high ceilings and 12.2 mm/min (0.3 gpm/ft^2) for 9.1 m (30 ft) ceilings. Results of the present study indicate that combustible flame breaks can hinder, and in some cases, halt lateral flame spread. The presence of two combustible longitudinal flame breaks separating adjacent racks was essential to mitigating flame spread in that direction. Additionally, both past [4] and present research has shown that solid shelves pose a challenge to delivering water to combustion regions.

However, all but one (Test 1) and every (Test 2) installed sprinkler operated which precludes the establishment of a specific demand area. Therefore, it must be assumed that all sprinklers within the area of fire origin will operate and the design area should be equal to the floor area. This approach is achievable for locations with relatively small floor areas (e.g., up to 465 m^2 [5000 ft^2]) but may be impractical for larger areas. In similar tests conducted previously [4] a maximum of four sprinkler operations occurred which, when contrasted with the present study, highlights the effect that energy density has on the demand area. Therefore, if the demand area cannot be equal to the floor area, then it seems reasonable to limit the energy density such that it is in line with that used in previous testing documented in Ref. [4].

[xxix] Refer to Section 1.2 for specific details on these Regulations.

References

1. National Fire Protection Association, NFPA 1124 Code for the Manufacture, Transportation, Storage, and Retail Sales of Fireworks and Pyrotechnic Articles, 1998, 2003, 2006, 2013 Edition.

2. National Fire Protection Association. (2014, March) Standards Development Relating to the Storage and Retail Sales of Consumer Fireworks. [Online]. http://www.nfpa.org/Assets/files/AboutTheCodes/1124/FD14_3_31_D14_1_APA_NFPA1124.pdf

3. Schirmer Engineering Corporation for the Fire Protection Research Foundation, "Fire safety in consumer fireworks storage and retail facilities - hazard assessment research project," Fire Protection Research Foundation, Quincy, MA, Literature Review October 2007.

4. B. L. Badders, "Fire performance evaluation of consumer fireworks retail sales displays incorporating various fire risk mitigation techniques," Southwest Research Institute, San Antonio, TX, Series Report SwRI Project No. 01.13626.01.001, February 12, 2009.

5. National Fire Protection Association. (2008, February) NFPA Standards Council contemplates changes to fireworks standard. [Online]. http://www.nfpa.org/news-and-research/news-and-media/press-room/news-releases/2008/nfpa-standards-council-contemplates-changes-to-fireworks-standard

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7. Fireworks Fire Suppression Task Force, Report and Recommendations, 2000, Tests conducted by Battelle for the State of Ohio.

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9. The Code of Federal Regulations, 16 CFR Part 1507 - Fireworks Devices, March 2017.

10. The Code of Federal Regulations, 49 CFR Part 171 - General Information, Regulations, and Definitions, March 2017.

11. The Code of Federal Regulations, 49 CFR Part 172 - Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, Training Requirements, and Security Plans, March 2017.

12. The Code of Federal Regulations, 49 CFR Part 173 - Shippers - General Requirements for Shipping and Packagings, March 2017.

13. The Code of Federal Regulations, 49 CFR Part 174 - Carriage by Rail, March 2017.

14. The Code of Federal Regulations, 49 CFR Part 175 - Carriage by Aircraft, March 2017.

15. The Code of Federal Regulations, 49 CFR Part 176 - Carriage by Vessel, March 2017.

16. The Code of Federal Regulations, 49 CFR Part 177 - Carriage by Public Highway, March 2017.

17. The Code of Federal Regulations, 49 CFR Part 178 - Specifications for Packagings, March 2017.

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21. American Pyrotechnic Association, APA Standard 87-1, Standard for Construction and Approval for Transportation of Fireworks, Novelties, and Theatrical Pyrotechnics, Version 12/01/01, Effective 10/01/03, 68 Fed Reg. 48562, Reprinted 1/04.

22. The Code of Federal Regulations, 16 CFR 1500.17 - Banned hazardous substances, March 2017.

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Appendix A. Fire Chronology and Test Images

The fire chronologies for Tests 1 and 2 are presented in the form of a pictorial narrative using clips of video during the test. In the following figures camera 1 is located on the top left, camera 2 in the top middle, camera 3 in the top right, camera 4 in the bottom left, camera 5 in the bottom middle and camera 6 in the bottom right. The cameras were dual mode and operated in the visible spectrum when ambient light was sufficient. They transitioned to infrared videography when ambient light became low; activating onboard infrared LEDs that projected light onto physical surfaces for illumination and registering heat zones. Refer to Figure 2-29 in Section 2.2 for a plan view of camera locations.

A.1 Test 1

The following section contains images of Test 1 and the captions serve as a fire chronology.

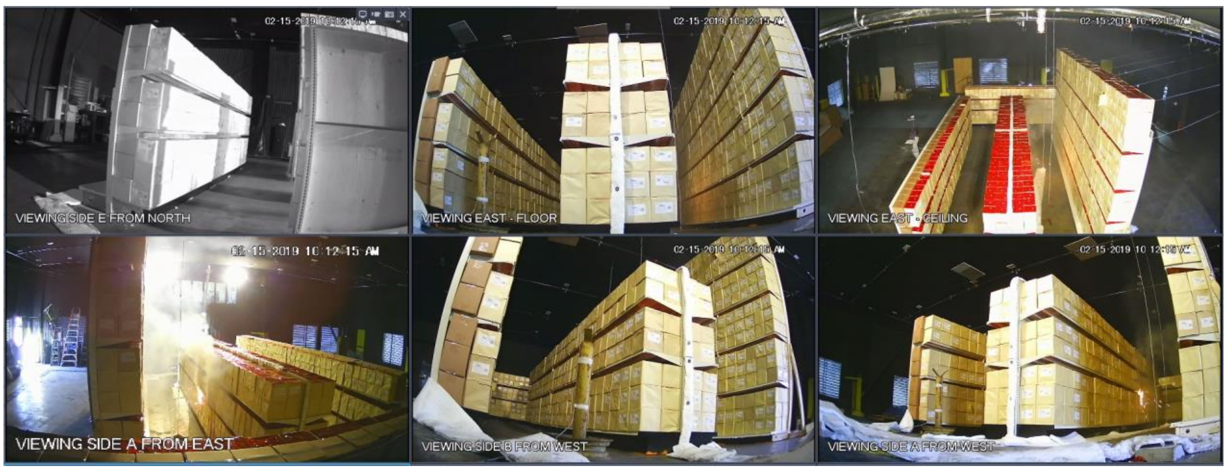

Figure A-1: Test 1 at 00:40: flames present on the face of Side A at ignition location.

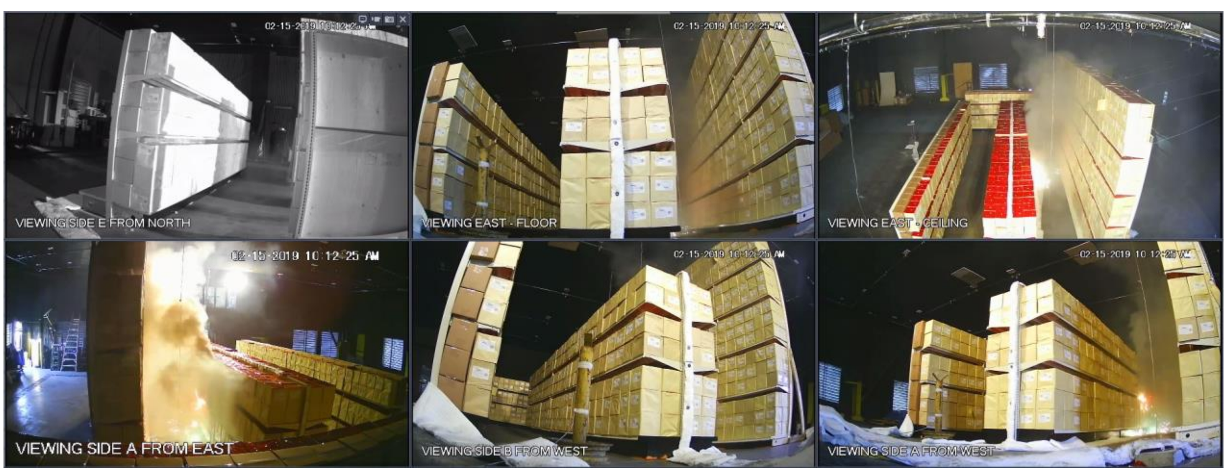

Figure A-2: Test 1 at 00:50: fire and smoke production intensifying in ignition region.

Figure A-3: Test 1 at 01:00: 3 s after 1st sprinkler activation, fire and smoke production intensifying in ignition region.

Figure A-4: Test 1 at 01:10: one sprinkler operating, fire and smoke production intensifying in Side A.

Figure A-5: Test 1 at 01:20: one sprinkler operating, fire and smoke production intensifying in Side A (camera 1 had transitioned from black and white colored infrared to full color due to the luminosity of the fire).

Figure A-6: Test 1 at 01:30: four sprinklers operating, fire and smoke production intensifying in Side A.

Figure A-7: Test 1 at 01:40: at least seven sprinklers operating, fire and smoke production intensifying. Side C ignited at 01:33, camera 1 showing sparks in aisle by Side E.

Figure A-8: Test 1 at 01:50: at least nine sprinklers operating, fire and smoke production intensifying.

Figure A-9: Test 1 at 02:00: sprinklers continue to operate, fire and smoke production intensifying.

Figure A-10: Test 1 at 02:10: sprinklers continue to operate, fire and smoke production intensifying.

Figure A-11: Test 1 at 02:20: sprinklers continue to operate, ceiling-level gas temperatures (refer to Appendix B) are roughly steady state at maximum values.

Figure A-12: Test 1 at 02:30: sprinklers continue to operate; the fire involves Side A and C.

Figure A-13: Test 1 at 03:00: all 35 sprinklers have operated, sparks have been showering the lab since 00:33, visibility is decreasing.

Figure A-14: Test 1 at 03:30: ceiling-level gas temperatures began a rapid decrease at approximately 03:10, visibility continues to decrease.

Figure A-15: Test 1 at 04:00: fire remains confined to Sides A and C, ceiling-level gas temperatures and visibility continues to decrease.

Figure A-16: Test 1 at 05:10: lab visibility completely obscured, camera 1 had transitioned to black and white colored infrared, cameras 2, 5 and 6 showing sparks visible in dark lab space.

Figure A-17: Test 1 at 05:30: lab visibility completely obscured, cameras 1 and 4 are showing black and white colored infrared, cameras 2, 5 and 6 show flames at the west end of Side A in the bottom and middle shelves. Ceiling-level gas temperatures were all below 100°C (212°F) by 06:57. Continuous sparking was witnessed until approximately 10:00 with minor periodic sparking after that. The lab remained obscured until approximately 27:00.

Figure A-18: Test 1 at 28:00: camera 1 in infrared shows water droplets, cameras 2, 5 and 6 show fire damage in bottom and middle shelf of Side A.

Figure A-19: Test 1 at 37:00: 2 minutes after test termination, damage confined to Sides A and C.

A.2 Test 2

The following section contains images of Test 2 and the captions serve as a fire chronology.

Figure A-20: Test 2 at 00:40: flames present on the face of Side A at ignition location.

Figure A-21: Test 2 at 00:50: fire and smoke production intensifying in Side A with flames extending approximately 2.1 m (7 ft) above top of commodity.

Figure A-22: Test 2 at 01:10: fire and smoke production intensifying in Side A.

Figure A-23: Test 2 at 01:20: fire and smoke production intensifying in Side A, sparks being projected throughout lab space and showering down on top of Side B, Side C ignited at 01:19.

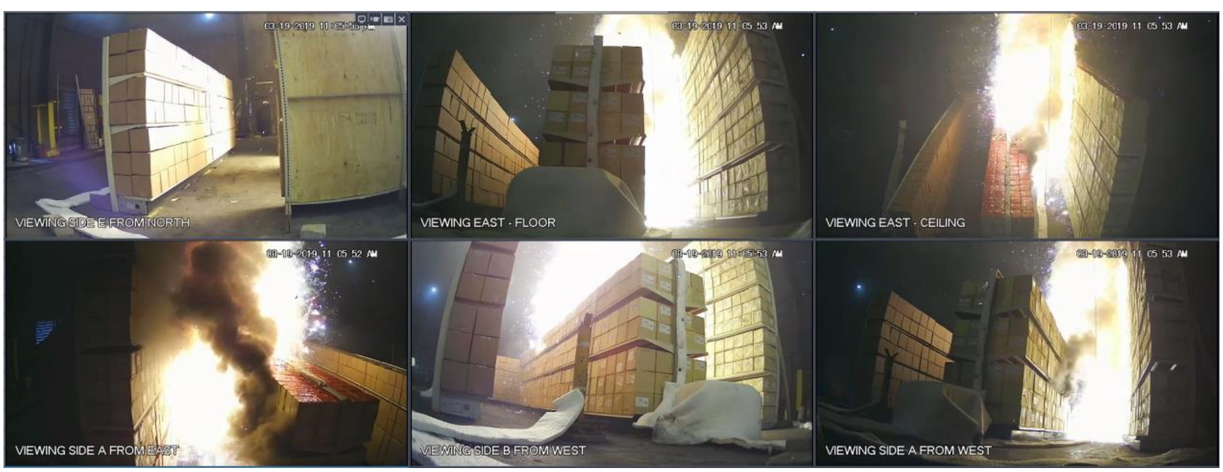

Figure A-24: Test 2 at 01:30: 2 s after 1st sprinkler activation, fire and smoke production intensifying, fireworks on top shelf of Side B became active at 01:23.

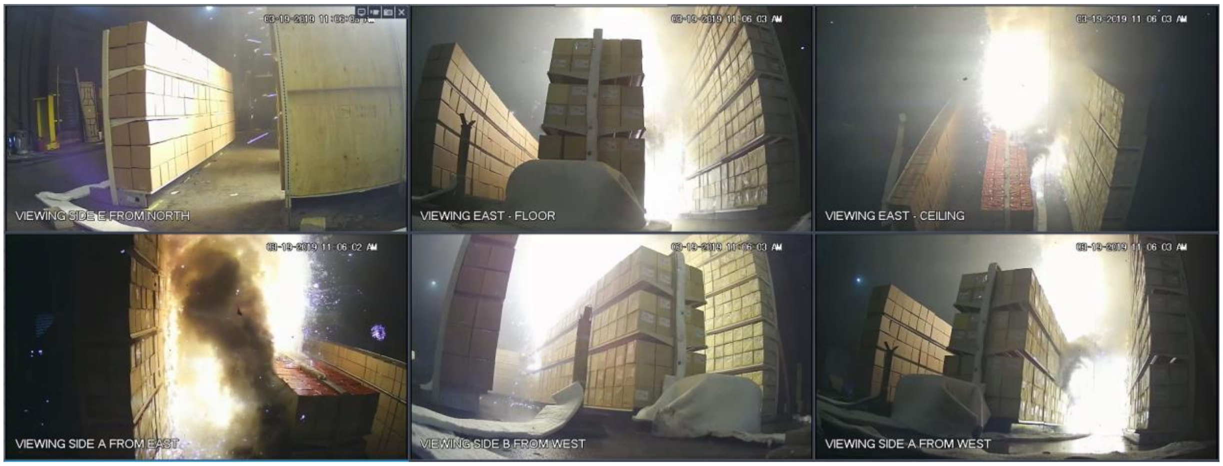

Figure A-25: Test 2 at 01:40: one sprinkler operating and fire and smoke production continue to intensify.

Figure A-26: Test 2 at 01:50: four sprinklers operating and fire and smoke production continue to intensify.

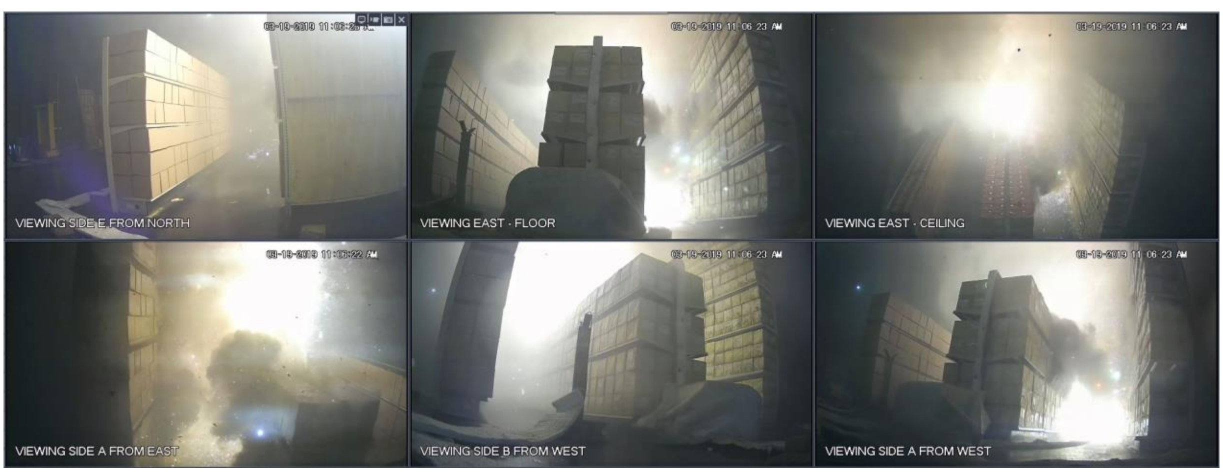

Figure A-27: Test 2 at 02:00: at least 10 sprinklers operating, fire continues to intensify and visibility is becoming obscured.

Figure A-28: Test 2 at 02:10: at least 20 sprinklers operating, fire continues to intensify and visibility is becoming more obscured.

Figure A-29: Test 2 at 02:20: all 25 monitored sprinklers operating (all 36 sprinklers operated during the test, the operating time of the remaining 11 sprinklers was not recorded), ceiling-level gas temperatures (refer to Appendix B) are approaching their peak values, obscuration increases, camera 5 showing example of projectile sparks.

Figure A-30: Test 2 at 02:30: fire confined to Sides A and C, visibility decreasing.

Figure A-31: Test 2 at 02:40: visibility nearly completely obscured.

Figure A-32: Test 2 at 02:50: visibility obscured, after ceiling-level gas temperatures reached an overall maximum at approximately 02:20 temperatures began to gradually decrease and then exhibited a rapid decrease at approximately 03:40, at 04:20 all ceiling-level gas temperatures were below 100°C (212°F), the cameras captured sparking until 05:00 when all visibility was lost.

Figure A-33: Test 2 at 50:00: lab obscuration began to decrease at approximately 45:00, cameras 1 and 4 are in black and white colored infrared mode showing water droplets.

Figure A-34: Test 2 at 52:30: 30 s after test termination, visibility returning, camera 4 infrared showing heat (white in color) in Sides A and C.

Figure A-35: Test 2 at 70:00: 18 minutes after test termination, camera 3 and 4 showing application of firefighter hose stream and damage to Sides A, B and C.

Appendix B. Temperature Data

Temperature data are presented in this section. TCs were installed at the ceiling, within the shelving units and in TC trees located in the aisle between Sides A and C. The measurement locations and nomenclature are detailed in Sections 2.1 and 2.2 in Figures 2-1, 2-3 through 2-7, 2-26 and 2-28. Type K TCs were used throughout and have an operating range of -270°C to 1260°C (-454°F to 2300°F). In some instances, TCs exceeded the maximum range. In other instances, TCs malfunctioned resulting in a non-physical change in signal (e.g., rapid temperature spikes or drops and negative values). Malfunctioning TC data are either noted and/or not plotted.

B.1 Test 1

Temperatures associated with Test 1 are presented in this section.

B.1.1 *Ceiling-level Gas Temperatures*

The time history of the ceiling-level gas temperatures is given in Figures B-1 and B-2 for TC locations (same as sprinkler location) 1-18 and 19-36, respectively. Following ignition, temperatures steadily increased until approximately 02:10 and then exhibited a relatively gradual decreased until 03:10 when their rate of decay increased substantially. Figure B-3 provides a plan view showing the maximum instantaneous and 1-minute average temperature at each location. The highest temperature was achieved at S23 and was equal to 929°C (1704°F).

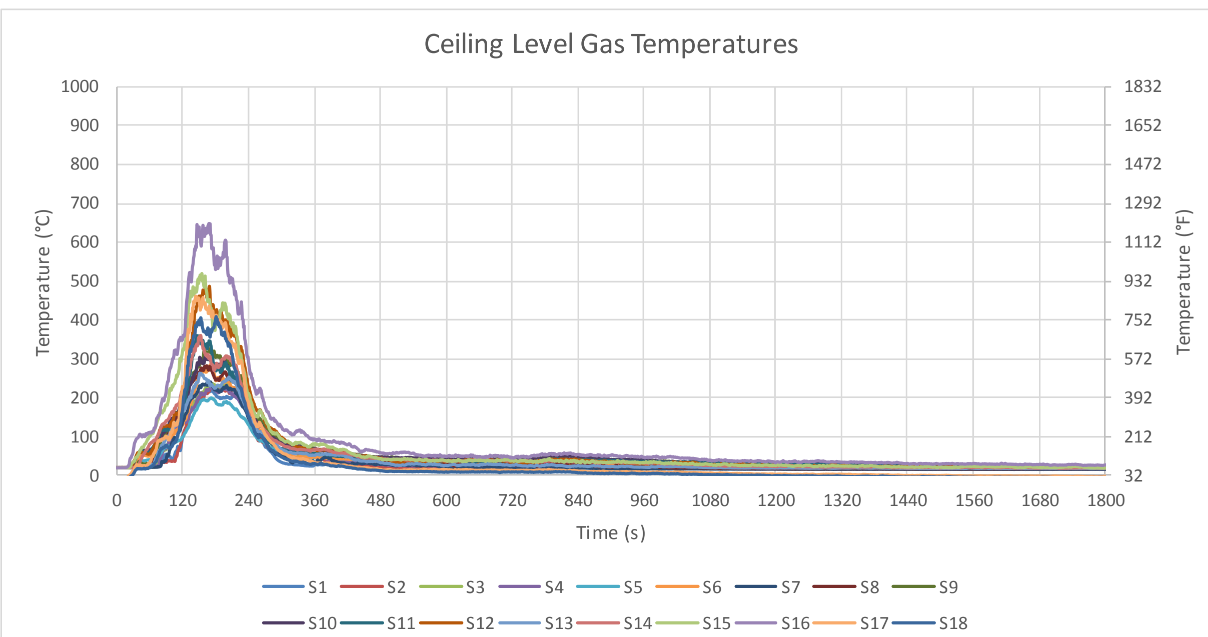

Figure B-1: Test 1 ceiling-level gas temperatures at TC locations 1-18.

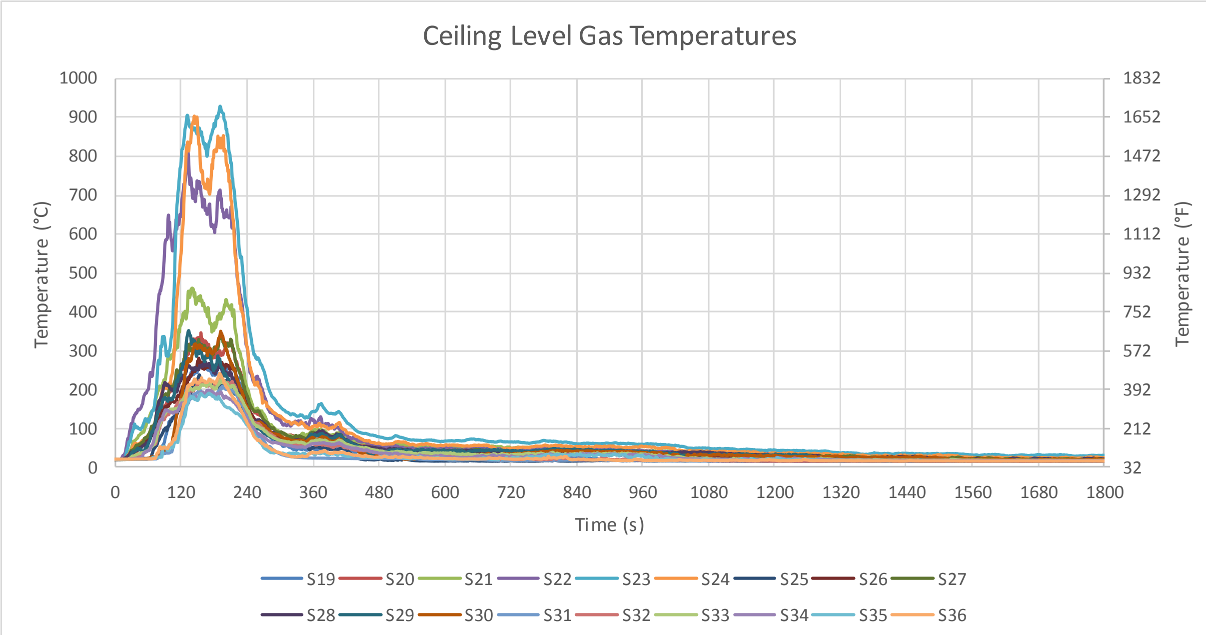

Figure B-2: Test 1 ceiling-level gas temperatures at TC locations 19-36.

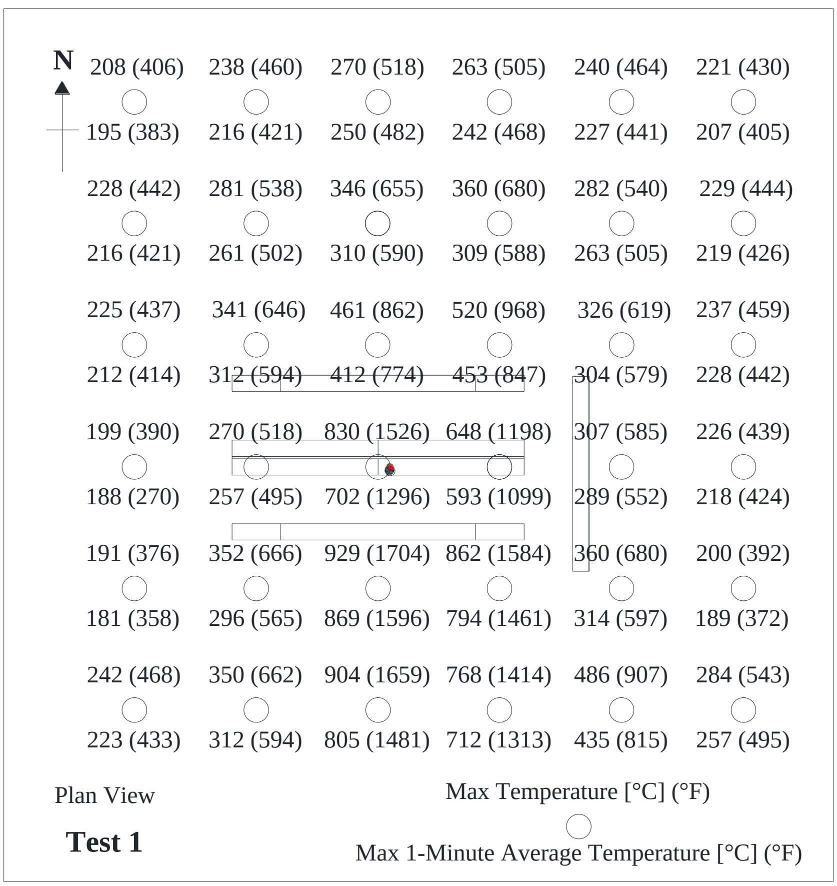

Figure B-3: Test 1 maximum instantaneous and 1-min average ceiling-level gas temperatures.

B.1.2 *Temperature in Shelving Units*

Gas temperature data measured inside the shelving units is presented in this section. For Sides A and C the data are presented both on a per shelf basis as well as per vertical column. This is done for ease of analysis when considering lateral and vertical fire involvement. The reader is cautioned that due to the shelving units confining and channeling the gases, it is not possible to determine if the high temperatures are indicative of gas migration or flame front. In numerous locations the duration of high temperatures measured in the shelves is notably longer than that at ceiling level. There is a trend of generally decreasing duration of high temperatures with increasing shelf height.

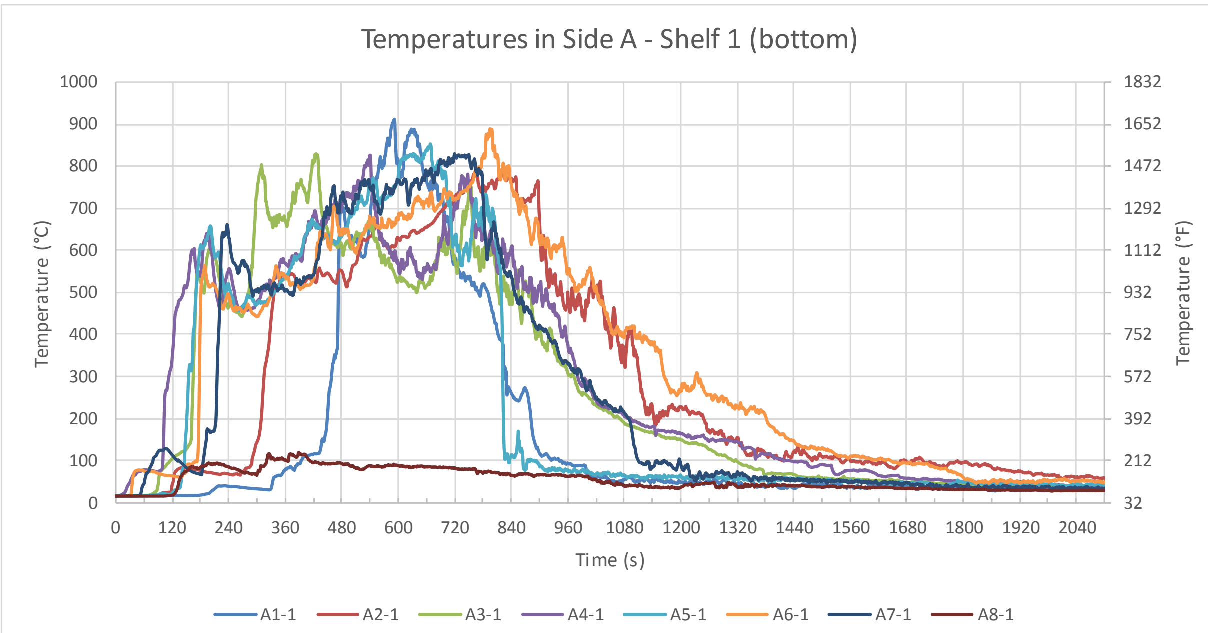

Figure B-4: Test 1 temperatures in Side A: Shelf 1 (bottom) Temperature increase at 05:30 at location A1-1 coincides with visual observation (Figure A-17) of flames reaching west end of Shelf 1.

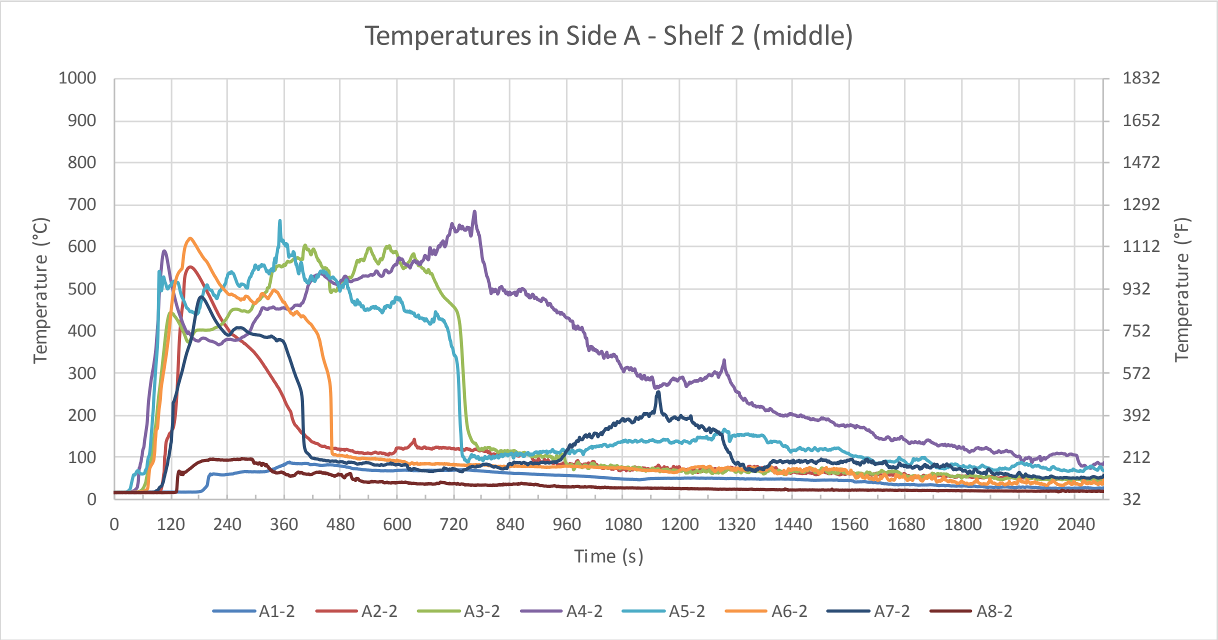

Figure B-5: Test 1 temperatures in Side A: Shelf 2 (middle).

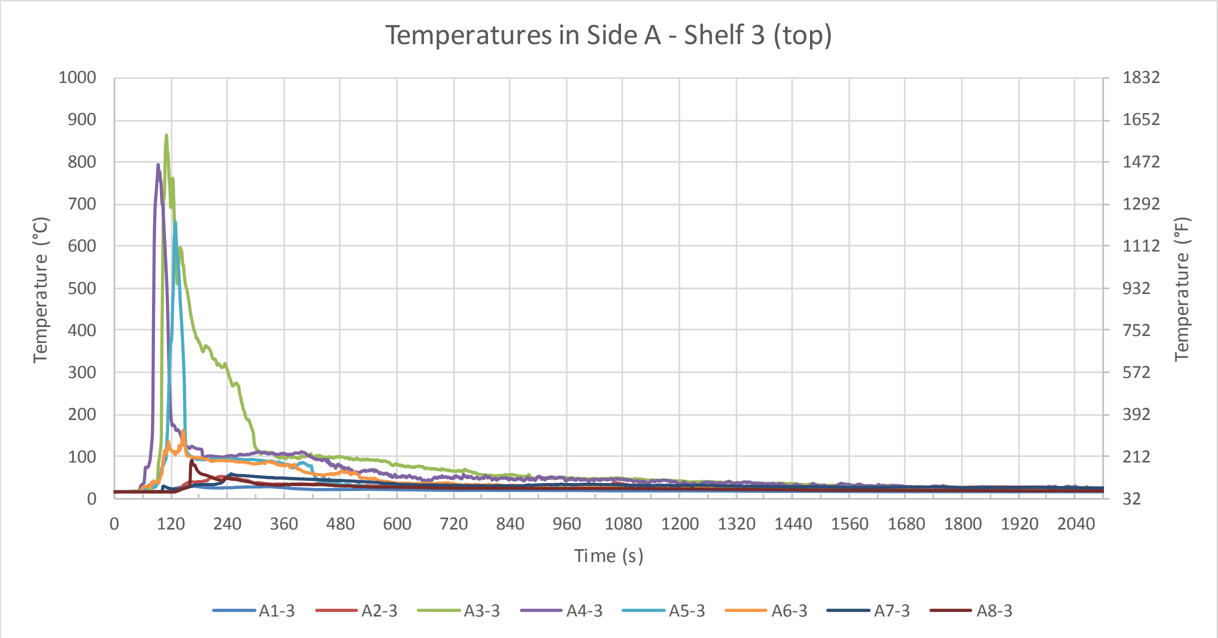

Figure B-6: Test 1 temperatures in Side A: Shelf 3 (top).

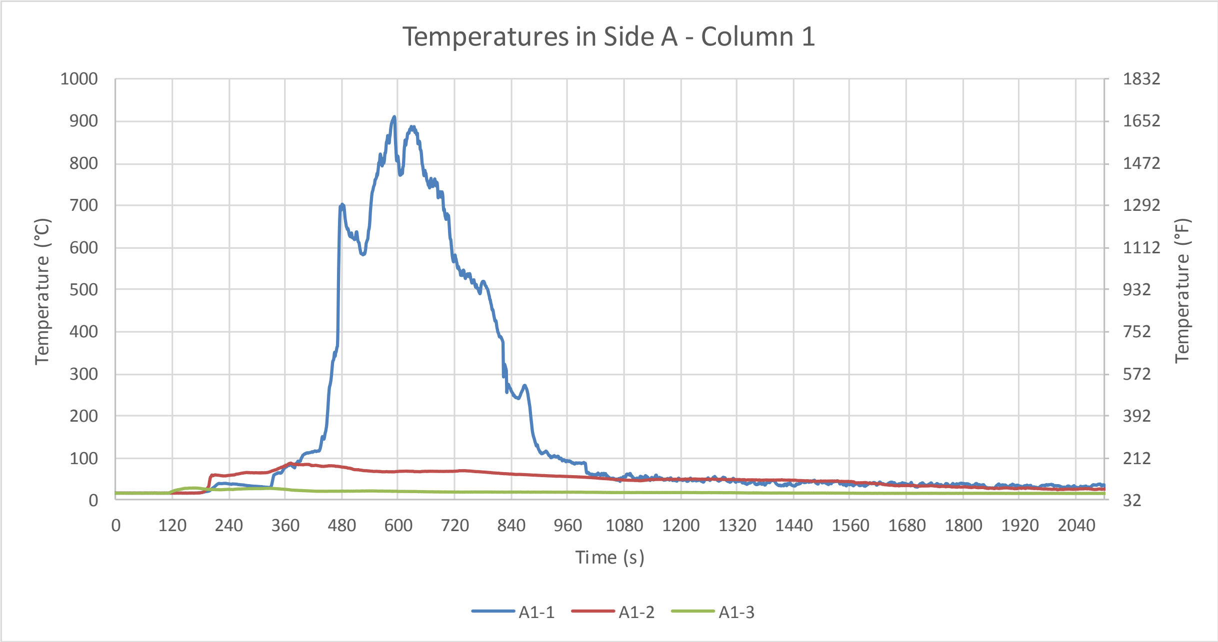

Figure B-7: Test 1 temperatures in Side A: Column 1.

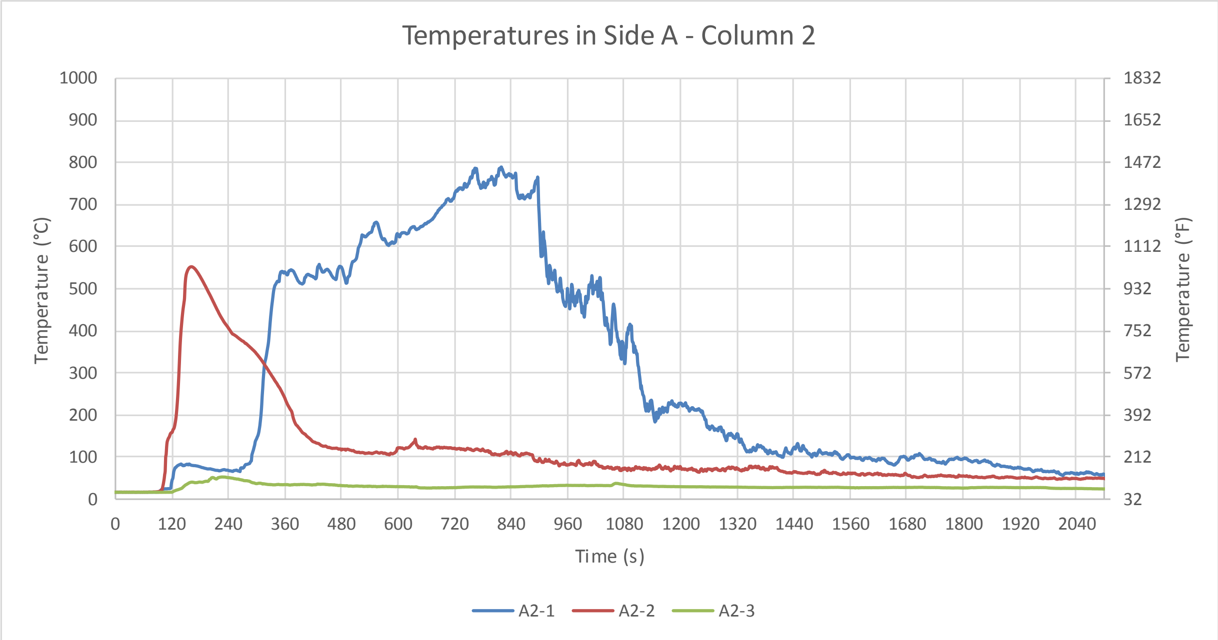

Figure B-8: Test 1 temperatures in Side A: Column 2.

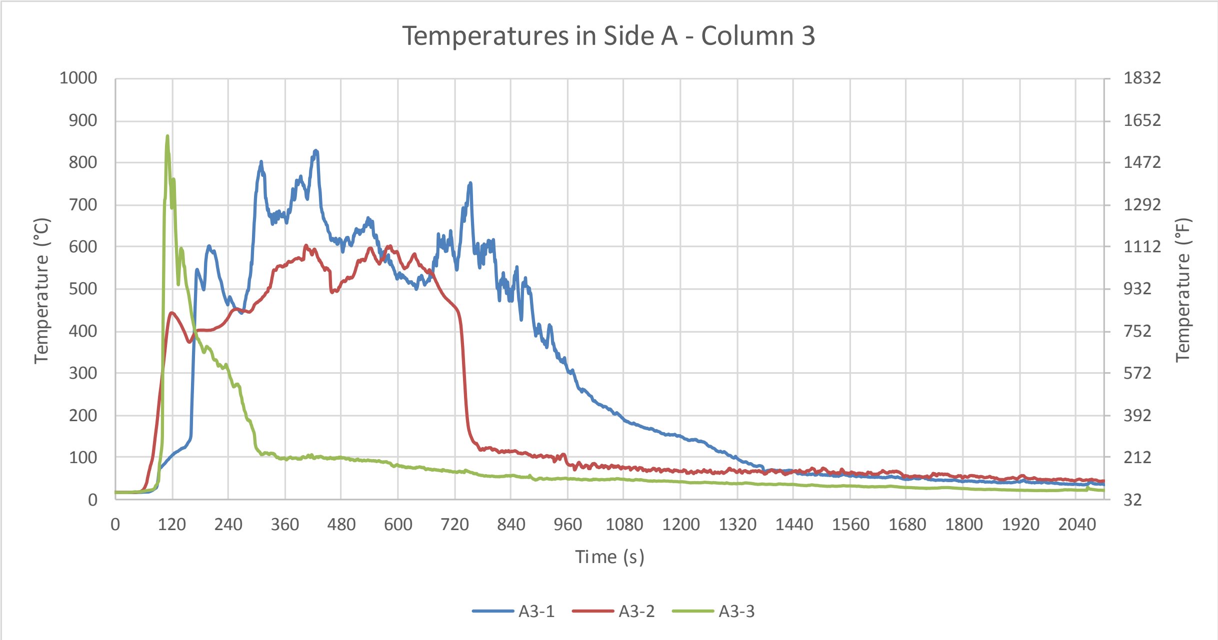

Figure B-9: Test 1 temperatures in Side A: Column 3.

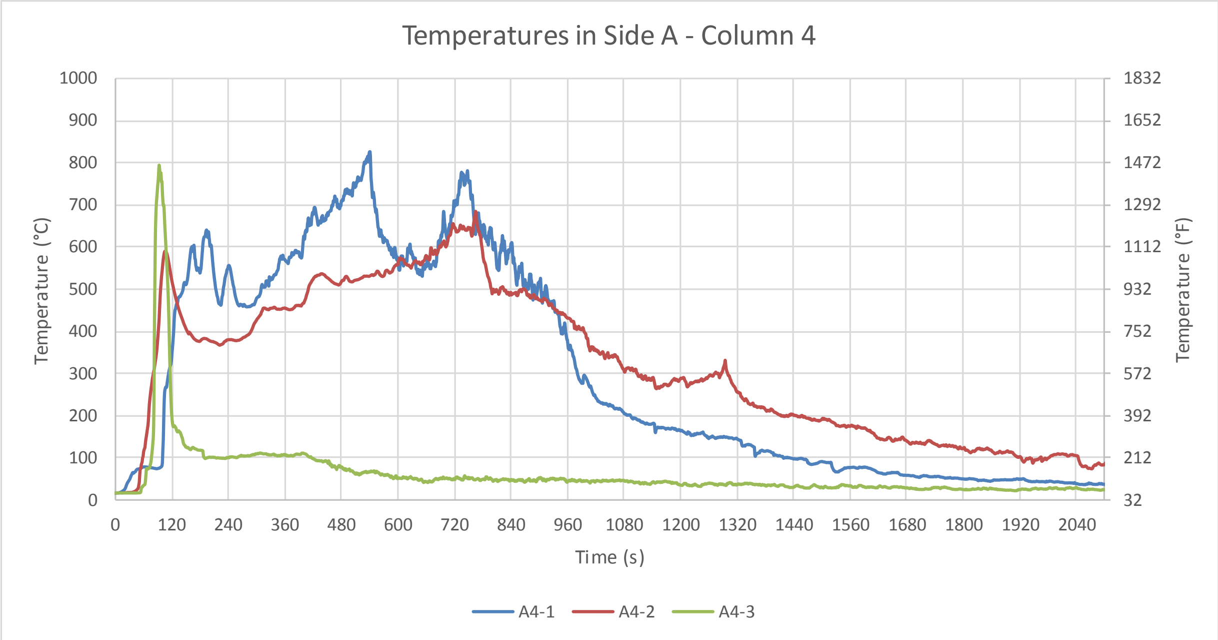

Figure B-10: Test 1 temperatures in Side A: Column 4.

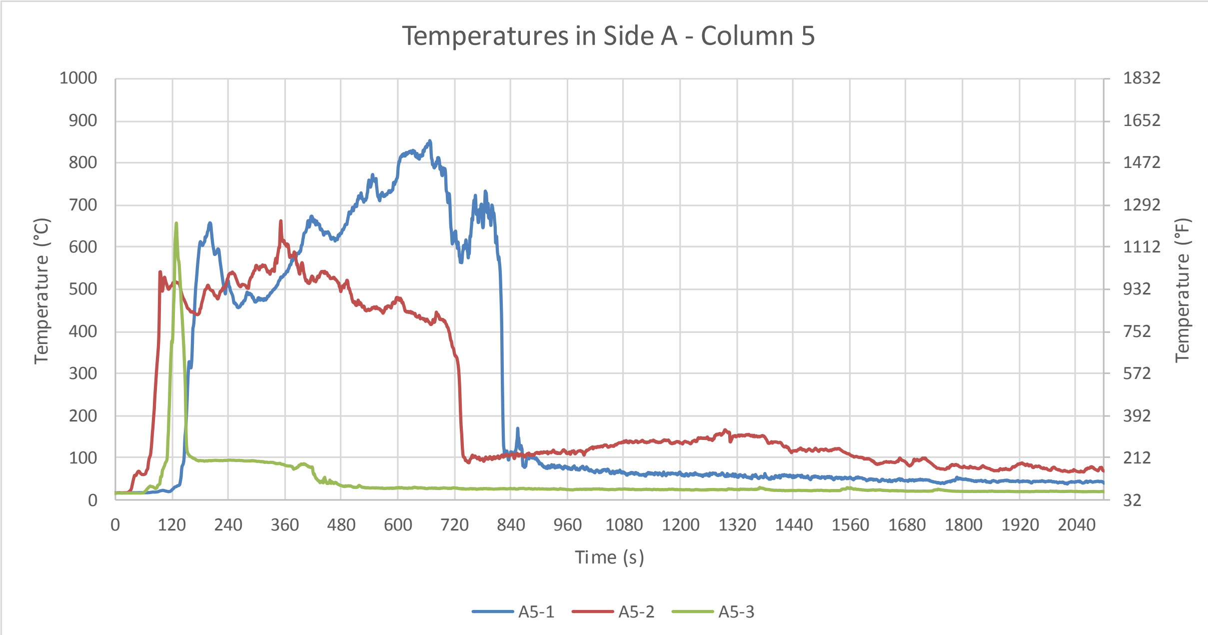

Figure B-11: Test 1 temperatures in Side A: Column 5.

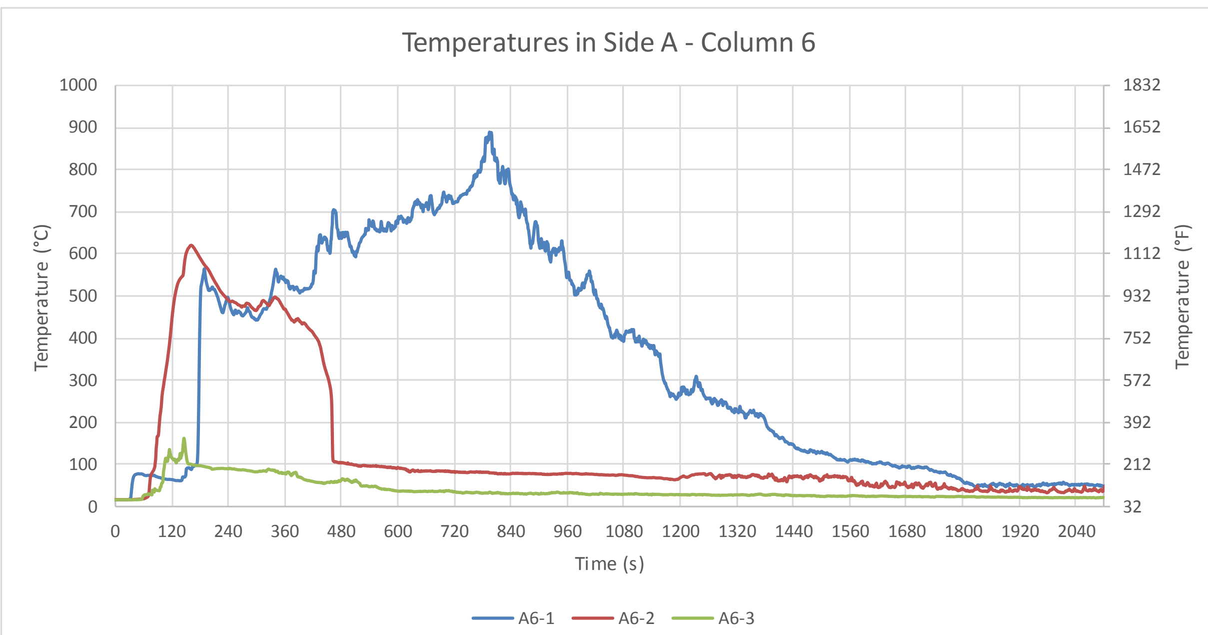

Figure B-12: Test 1 temperatures in Side A: Column 6.

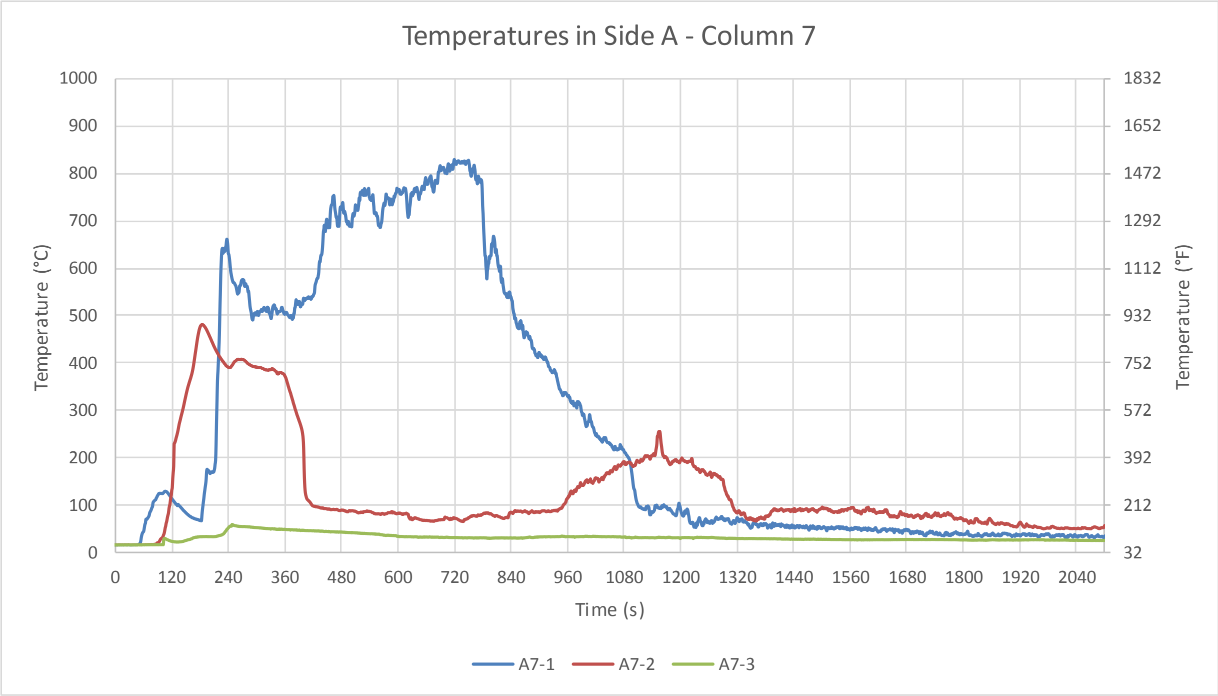

Figure B-13: Test 1 temperatures in Side A: Column 7.

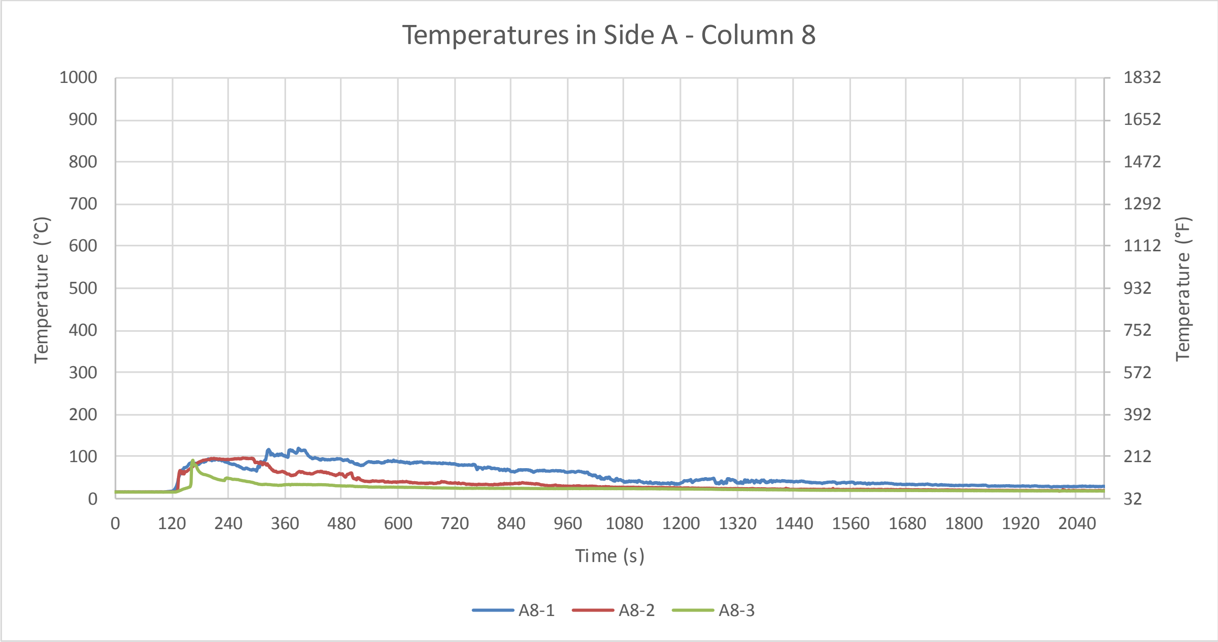

Figure B-14: Test 1 temperatures in Side A: Column 8.

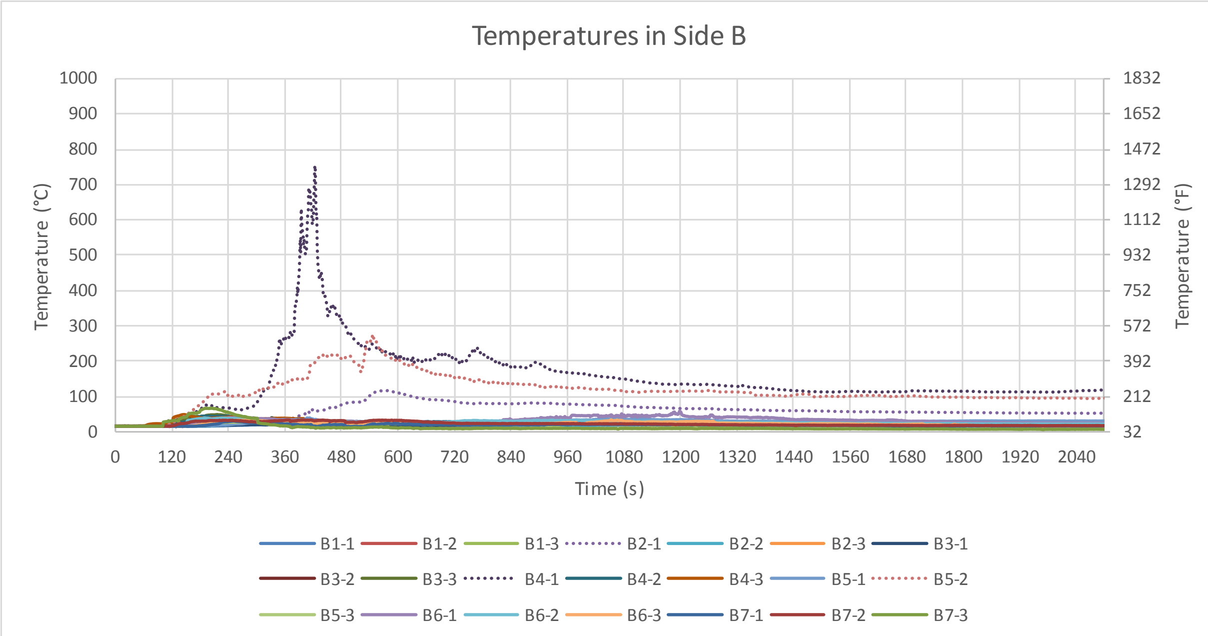

Figure B-15: Test 1 temperatures in Side B. Elevated temperatures are witnessed in the absence of fire on Side B. The longitudinal flame break on Side B had been minorly breached allowing the transport of hot gases. Refer to Section C.1 in Appendix C.

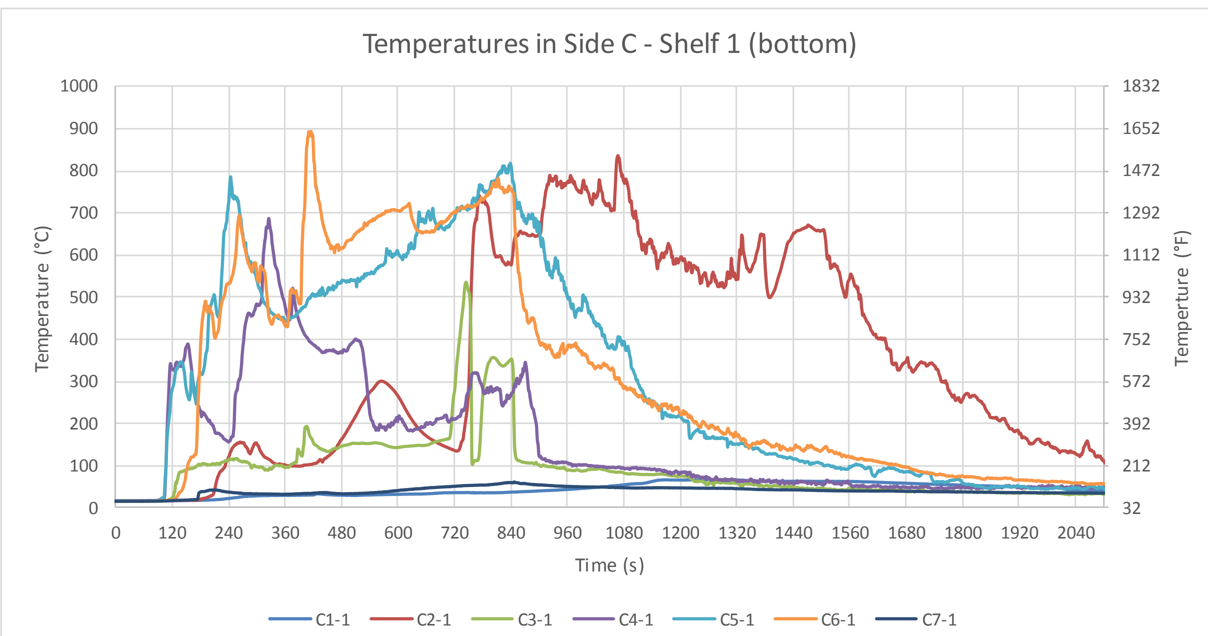

Figure B-16: Test 1 temperatures in Side C: Shelf 1 (bottom).

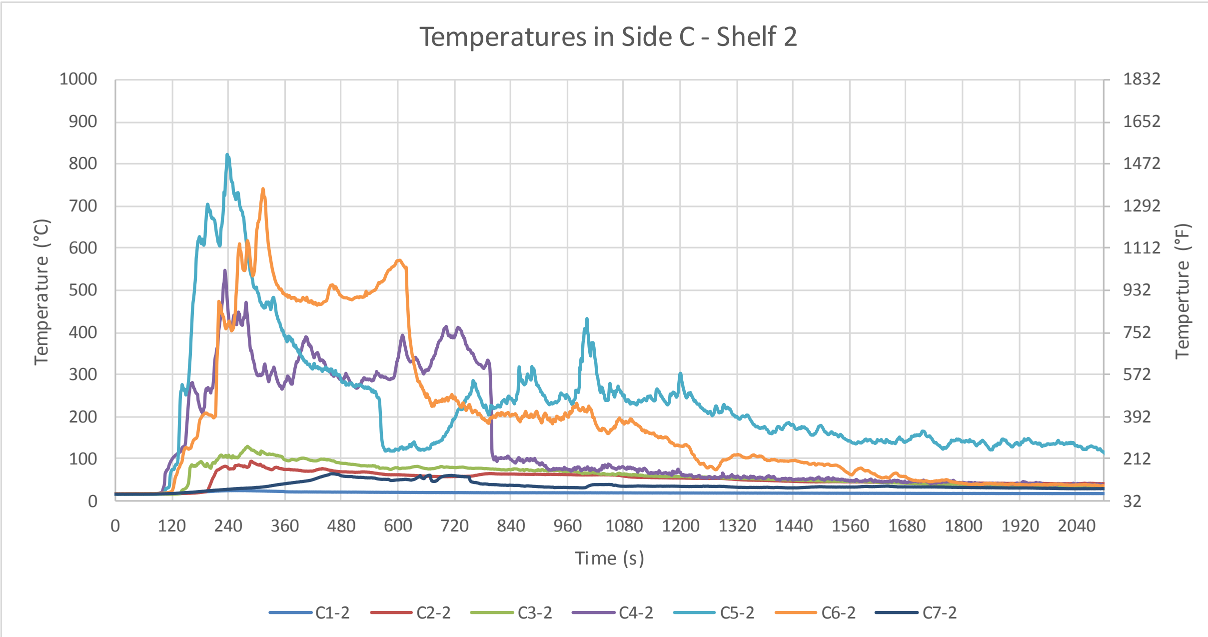

Figure B-17: Test 1 temperatures in Side C: Shelf 2.

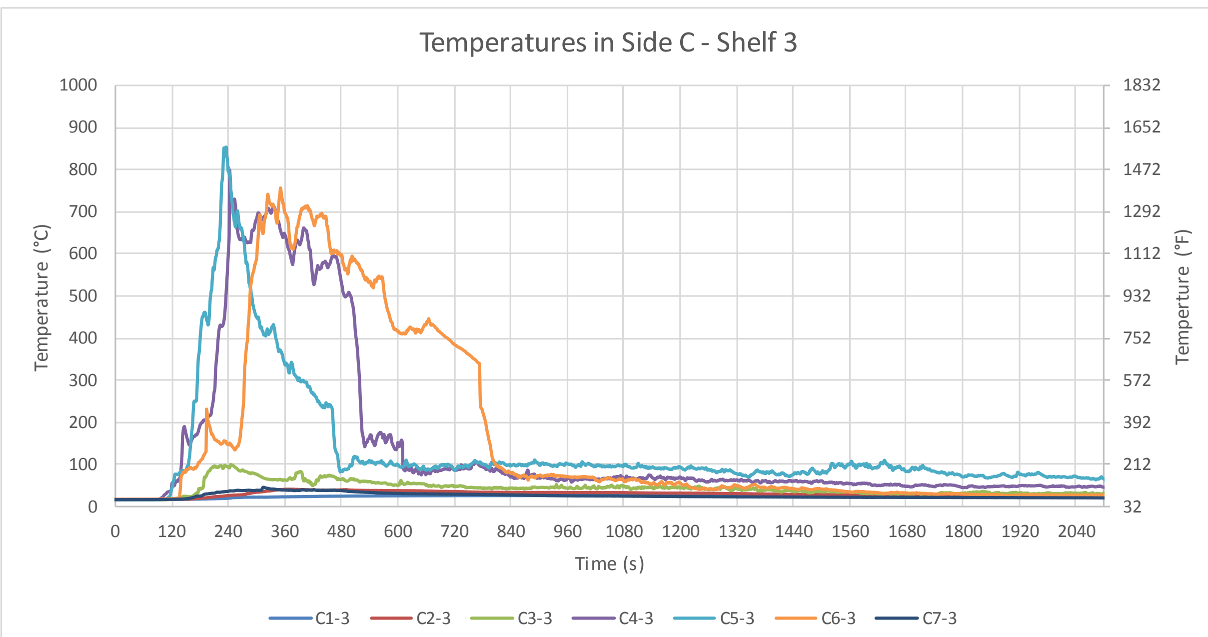

Figure B-18: Test 1 temperatures in Side C: Shelf 3.

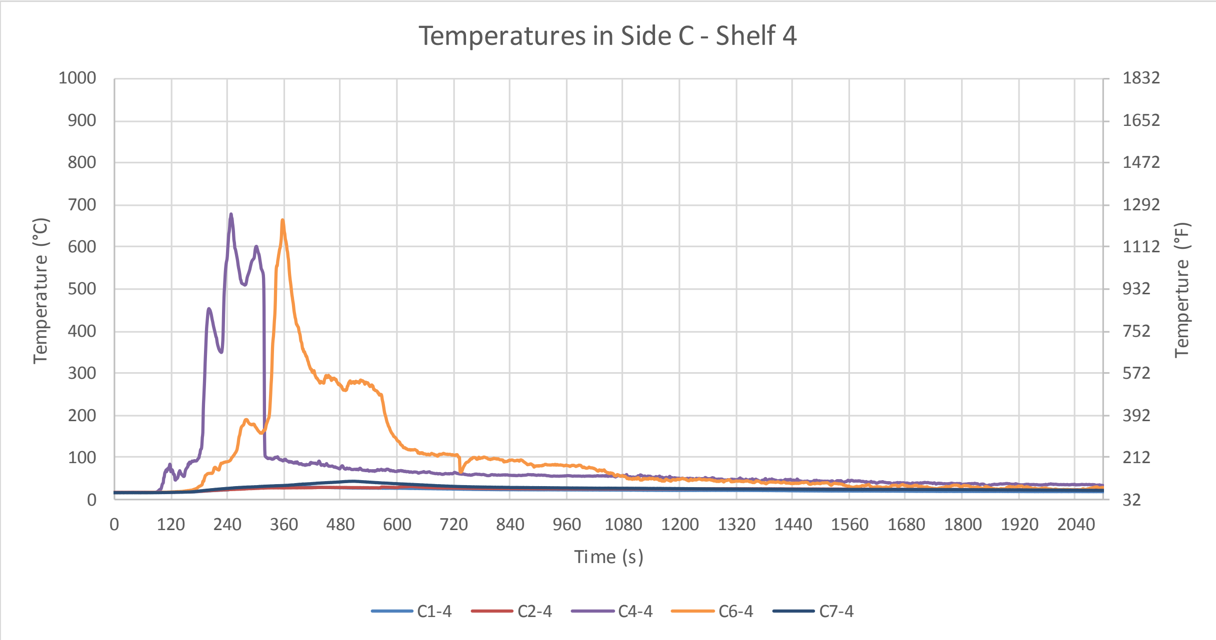

Figure B-19: Test 1 temperatures in Side C: Shelf 4.

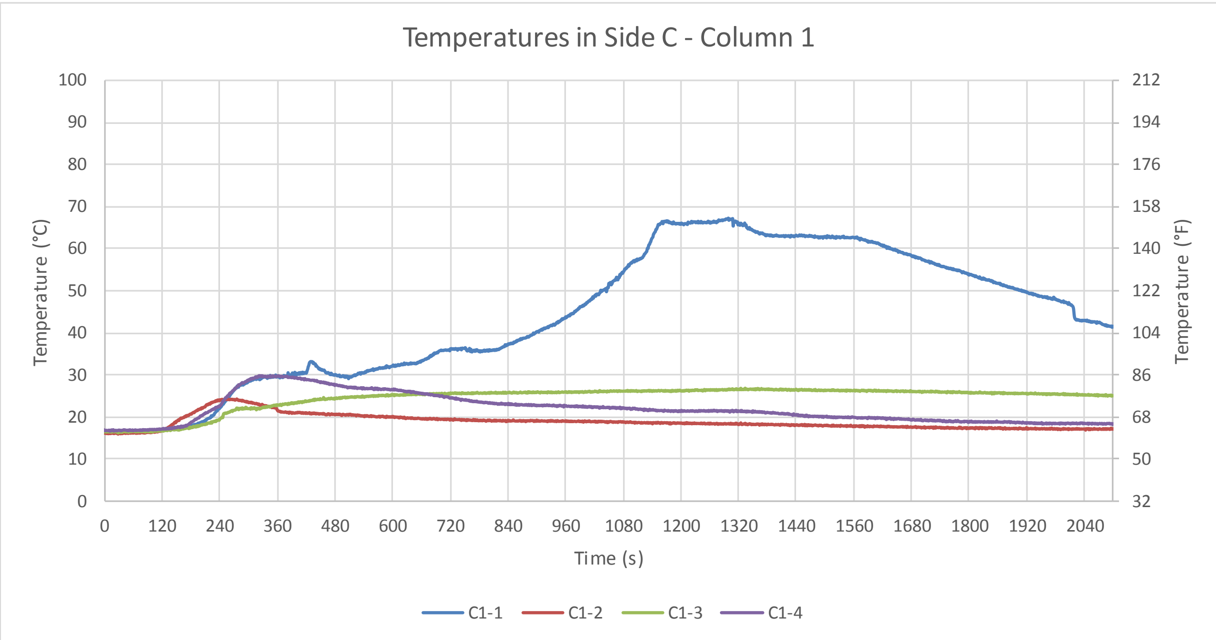

Figure B-20: Test 1 temperatures in Side C: Column 1. Note different temperature scale.

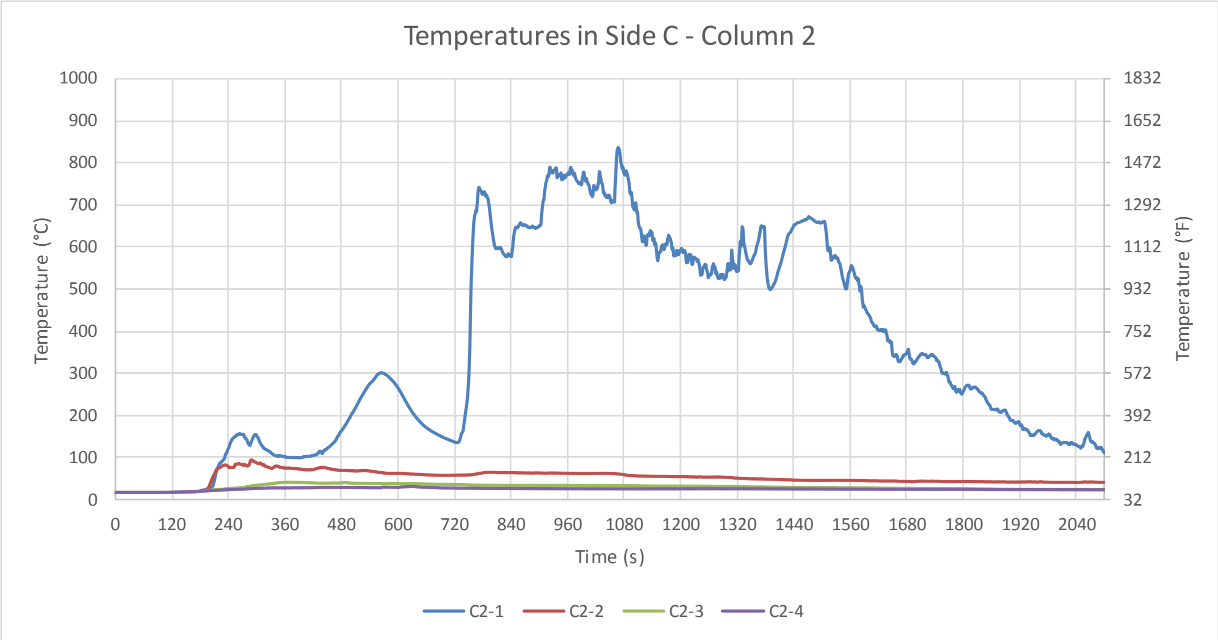

Figure B-21: Test 1 temperatures in Side C: Column 2.

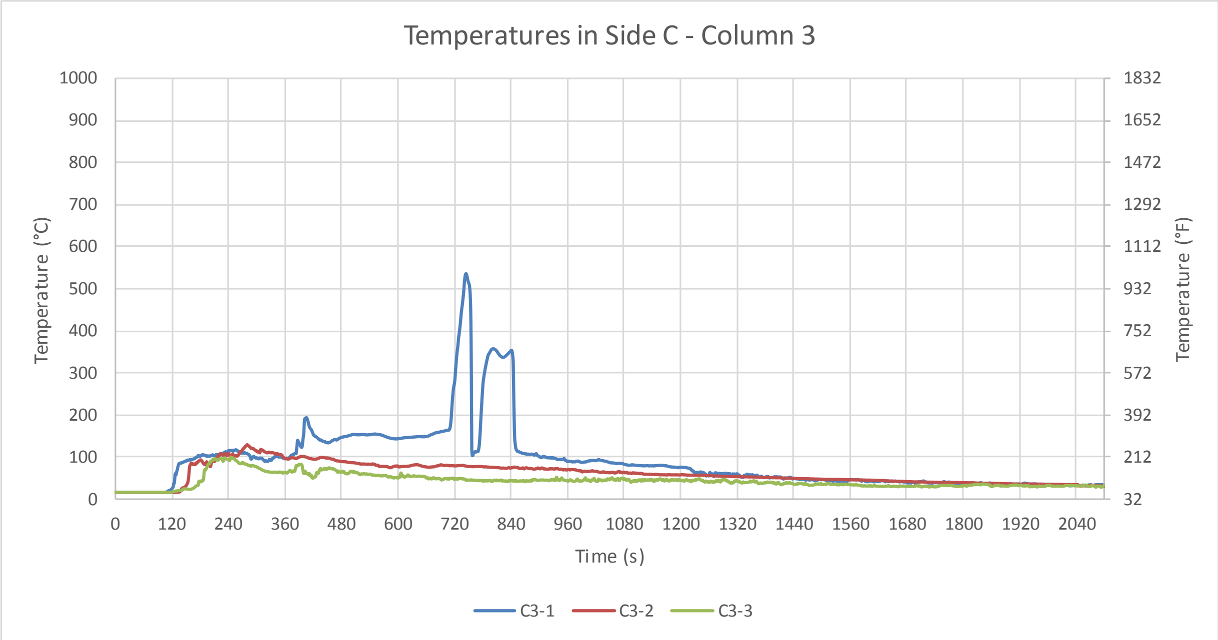

Figure B-22: Test 1 temperatures in Side C: Column 3.

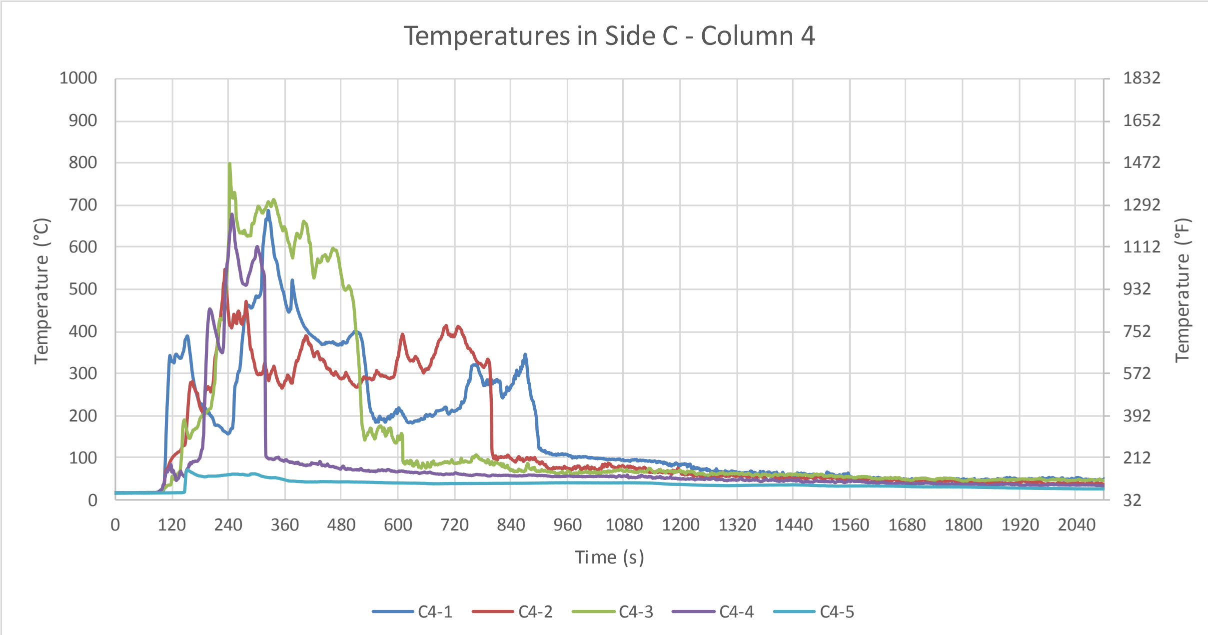

Figure B-23: Test 1 temperatures in Side C: Column 4.

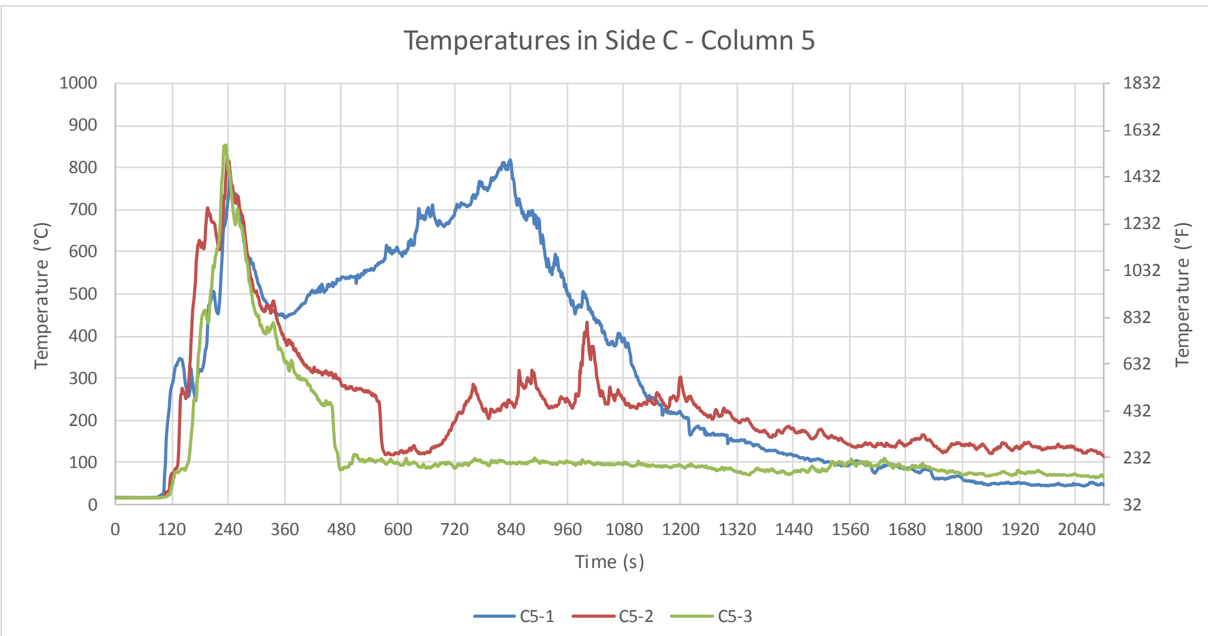

Figure B-24: Test 1 temperatures in Side C: Column 5.

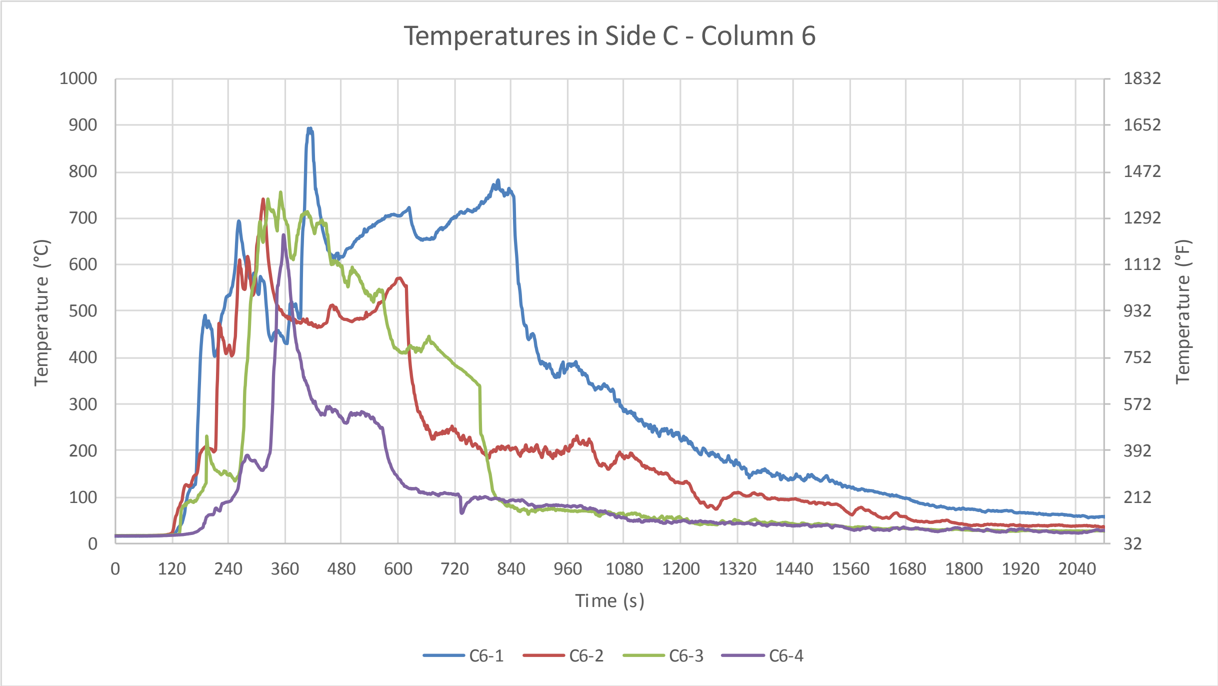

Figure B-25: Test 1 temperatures in Side C: Column 6.

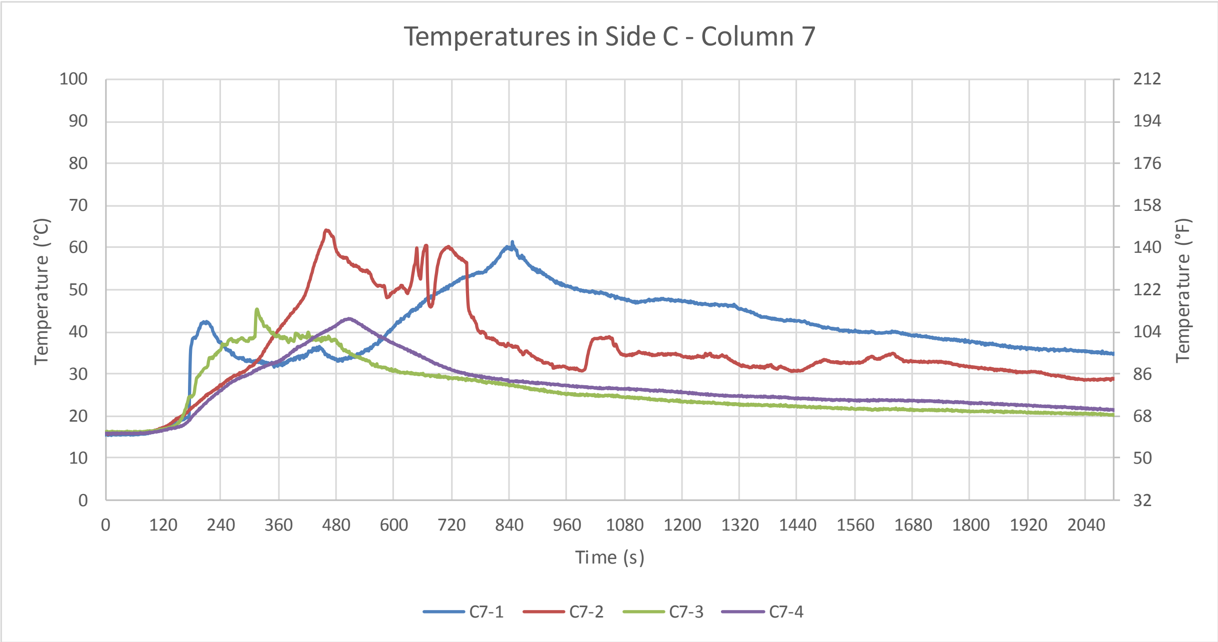

Figure B-26: Test 1 temperatures in Side C: Column 7. Note different temperature scale.

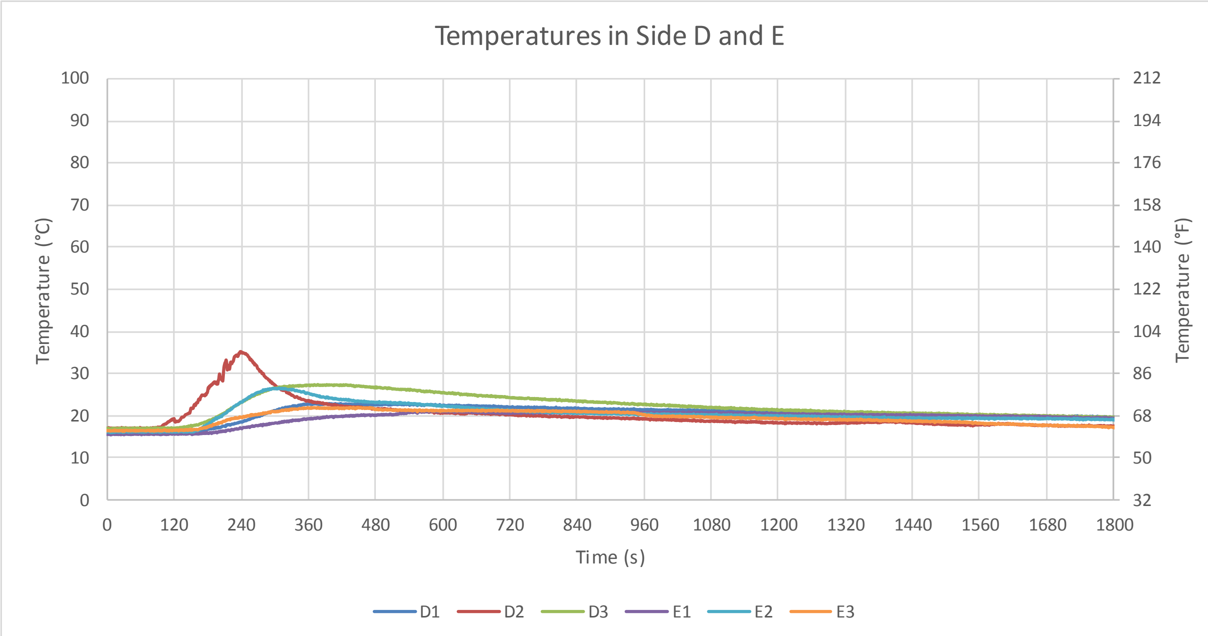

Figure B-27: Test 1 temperatures in Side D and E. Note different temperature scale.

B.1.3 *TC Tree Temperatures*

Figures B-28 and B-29 contain the time history of gas temperatures measured at TC Tree A and B, respectively.

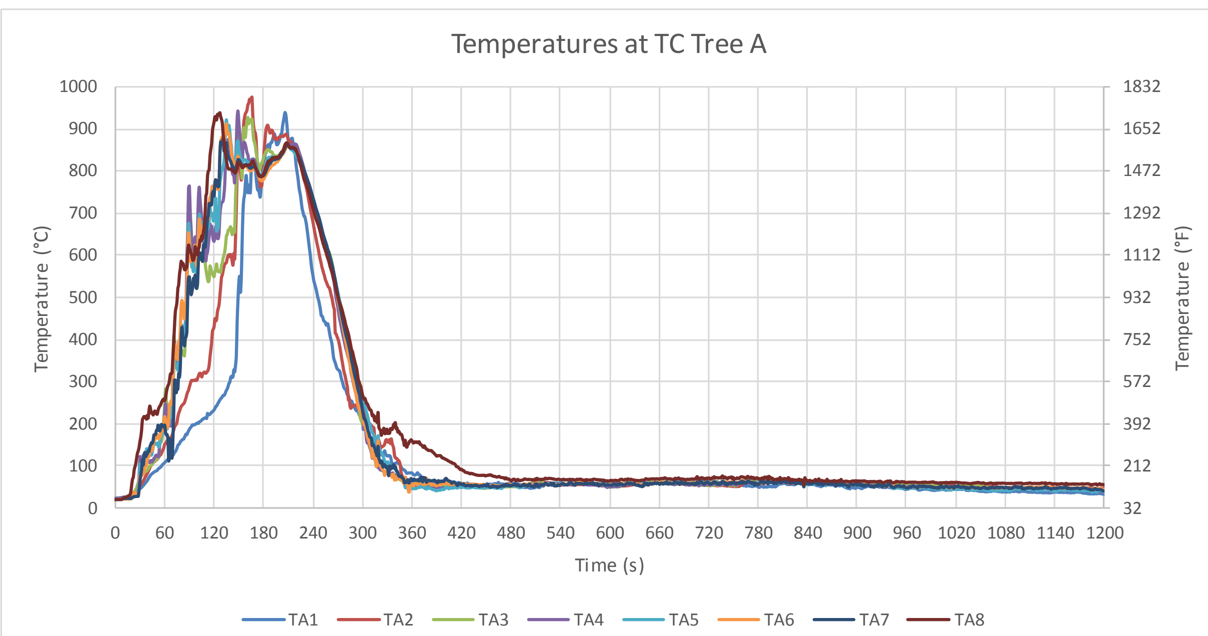

Figure B-28: Test 1 temperatures at TC Tree A. High temperatures are a result of the proximity of the fire to the TC tree and are not indicative of vertical temperature profiles in other regions of the test array.

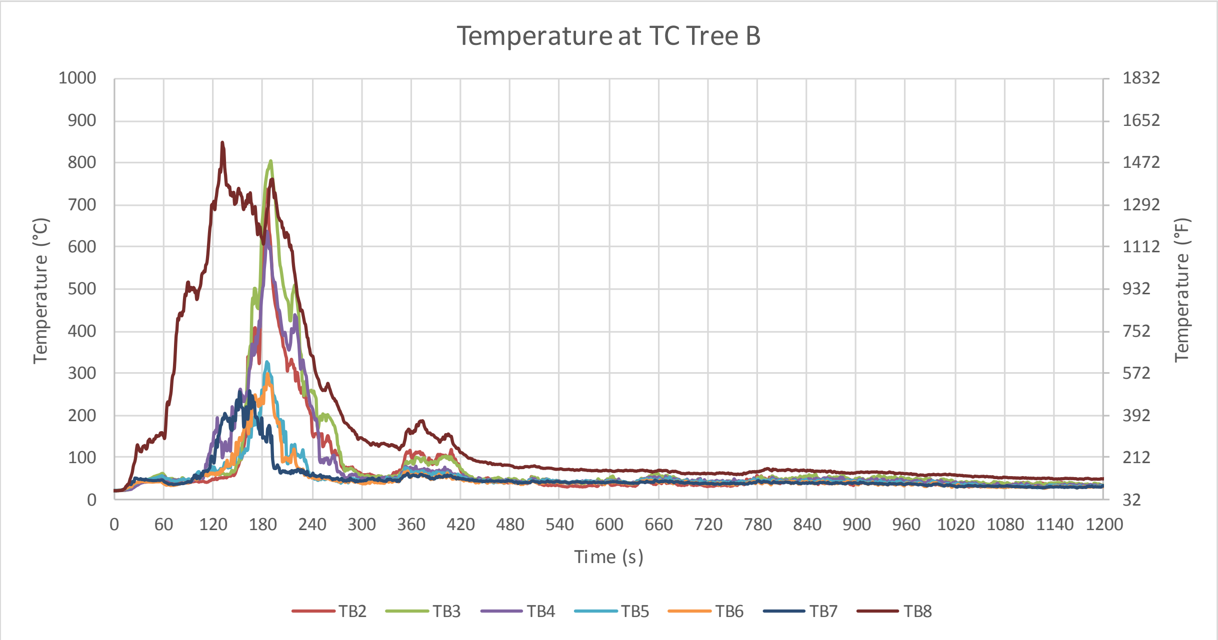

Figure B-29: Test 1 temperatures at TC Tree B. TC TB1 malfunctioned and the data is not presented. Increase in temperature at TB2-TB7 after 01:40 is likely due to the arrival of the flame front. Their magnitude prior to this time are an indication of vertical temperature profiles not directly exposed to the fire plume. In hindsight it would have been advantageous to install a TC tree in the aisle space between Sides B and D to provide gas temperature for regions not directly exposed to the fire.

B.2 Test 2

Temperatures associated with Test 2 are presented in this section.

B.2.1 *Ceiling-level Gas Temperatures*

The time history of the ceiling-level gas temperatures is given in Figures B-30 and B-31 for TC locations (same as sprinkler location) 1-18 and 19-36, respectively. Following ignition, temperatures steadily increased until approximately 02:25 and then exhibited a relatively gradual decrease until 03:40 when their rate of decay increased substantially. Figure B-32 provides a plan view showing the maximum instantaneous and 1-minute average temperature at each location. The highest temperature was achieved at S23 and was equal to 906°C (1663°F).

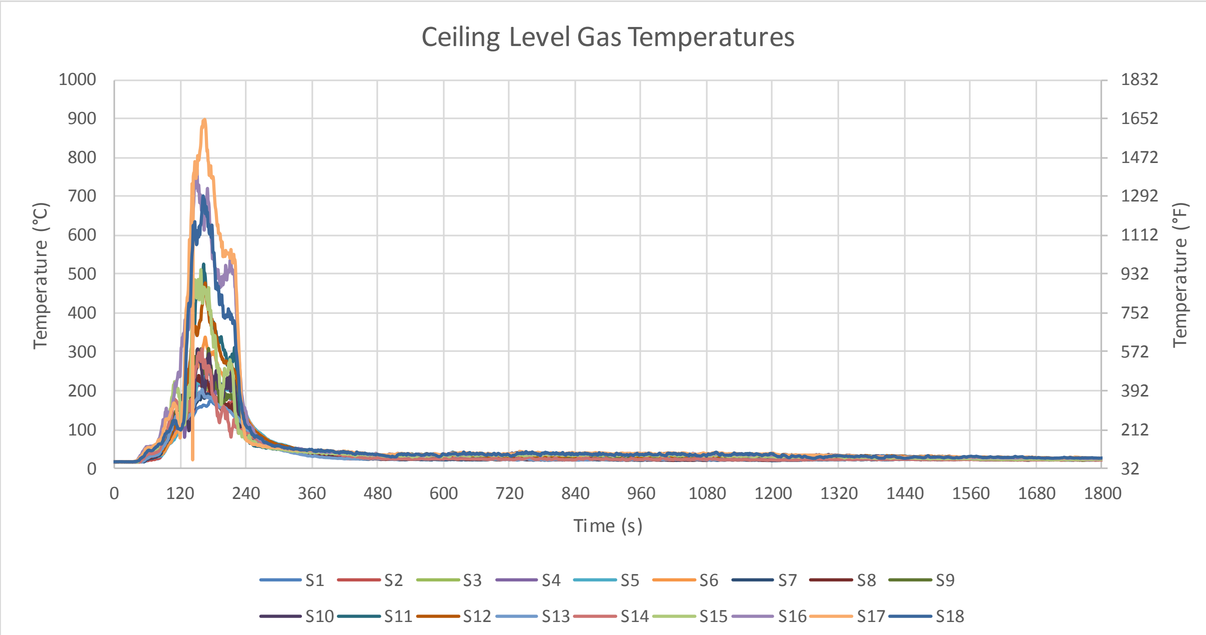

Figure B-30: Test 2 ceiling-level gas temperatures at TC locations 1-18.

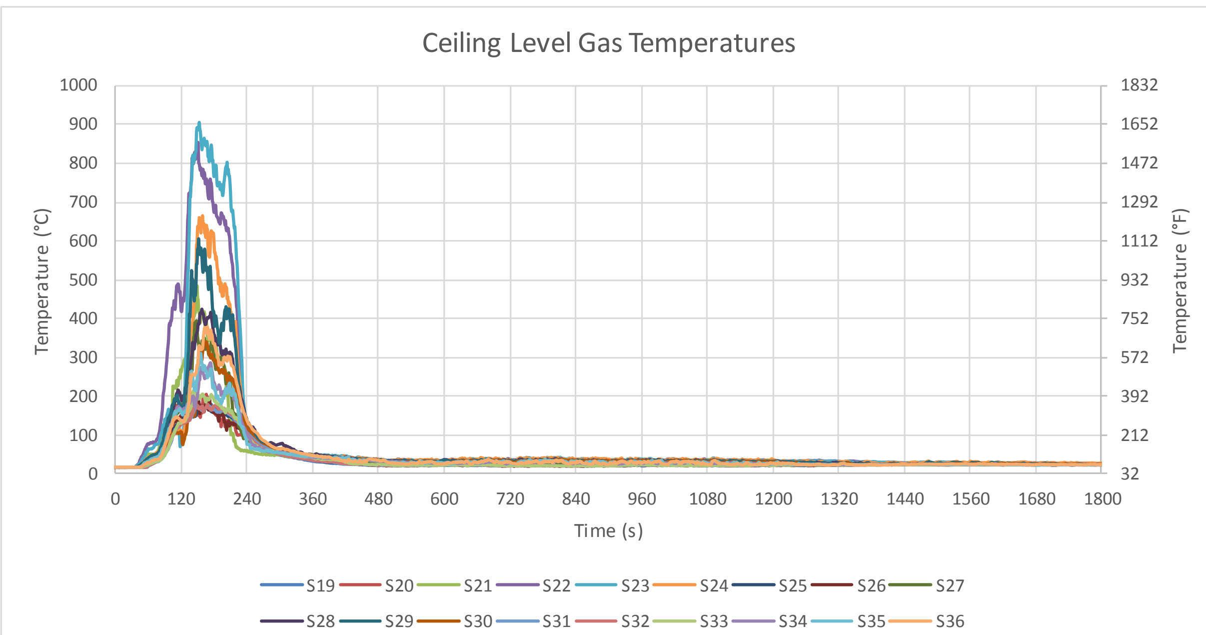

Figure B-31: Test 2 ceiling-level gas temperatures at TC locations 19-36.

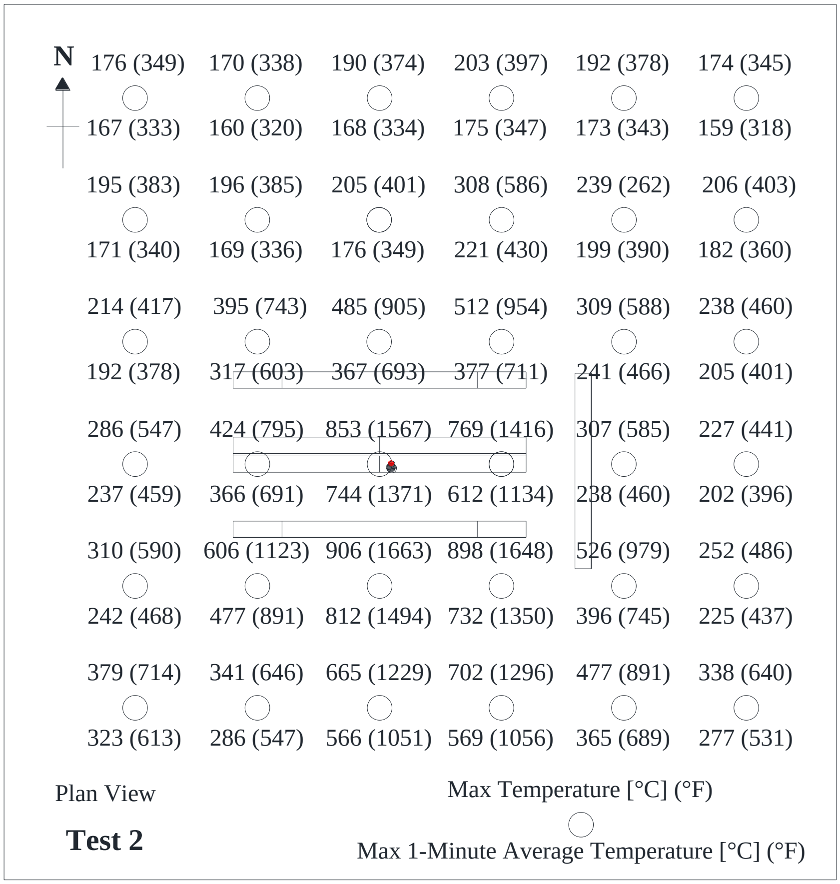

Figure B-32: Test 2 maximum instantaneous and 1-min average ceiling-level gas temperatures.

B.2.2 *Temperature in Shelving Units*

Gas temperature data measured inside the shelving units is presented in this section. For Sides A and C the data are presented both on a per shelf basis as well as per vertical column. This is done for ease of analysis when considering lateral and vertical fire involvement. The reader is cautioned that due to the shelving units confining and channeling the gases, it is not possible to determine if the high temperatures are indicative of gas migration or flame front. In numerous locations the duration of high temperatures measured in the shelves is notably longer than that at ceiling level. There is a trend of generally decreasing duration of high temperatures with increasing shelf height.

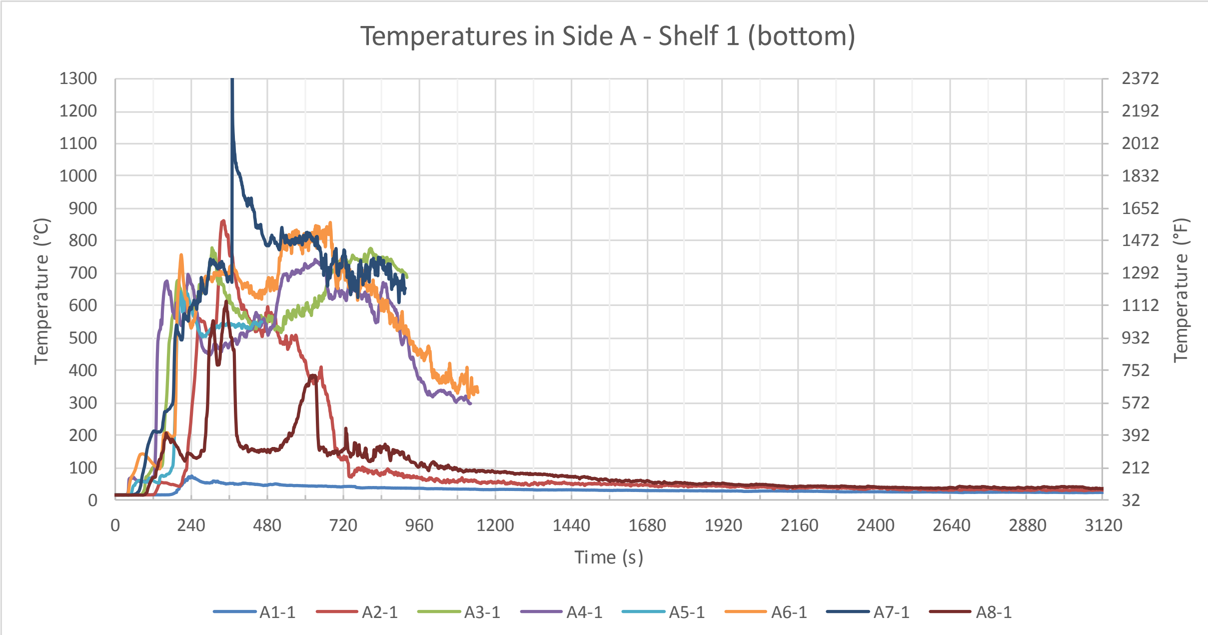

Figure B-33: Test 2 temperatures in Side A: Shelf 1 (bottom). Note that TCs A3-1, A4-1, A5-1, A6-1 and A7-1 malfunctioned during the test and suspect data have not been plotted. A7-1 exceed the maximum rating of a Type K TC at 06:10 after which time the temperature decreased. Their functionality was checked post-test and found to be inoperative. Note different temperature scale.

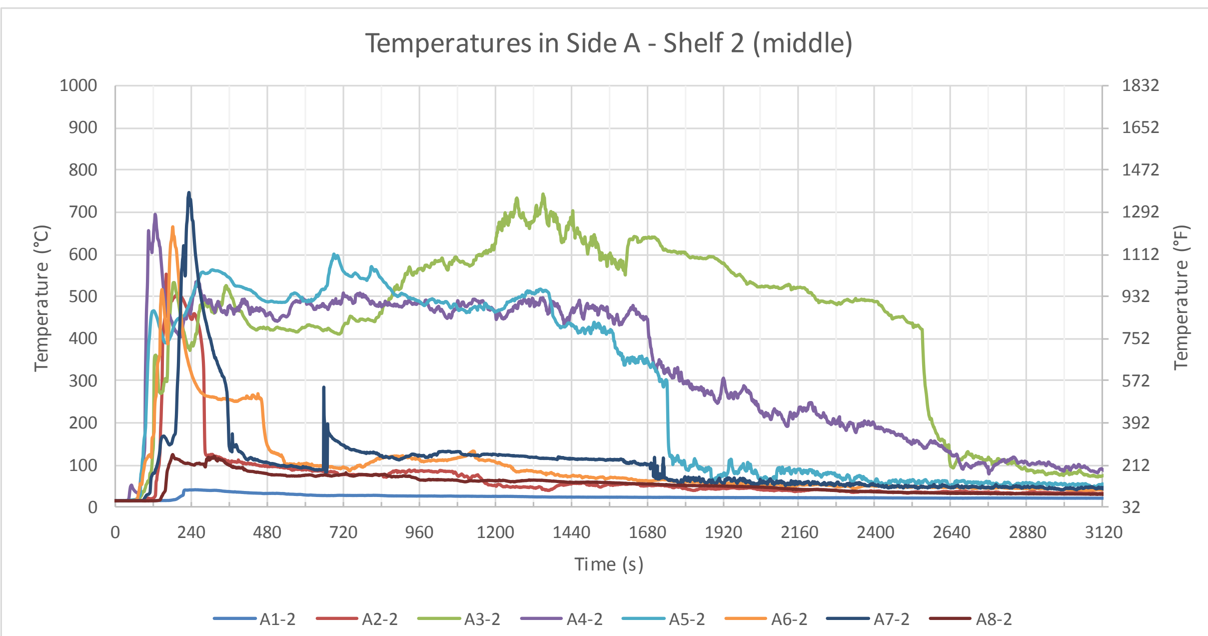

Figure B-34: Test 2 temperatures in Side A: Shelf 2 (middle).

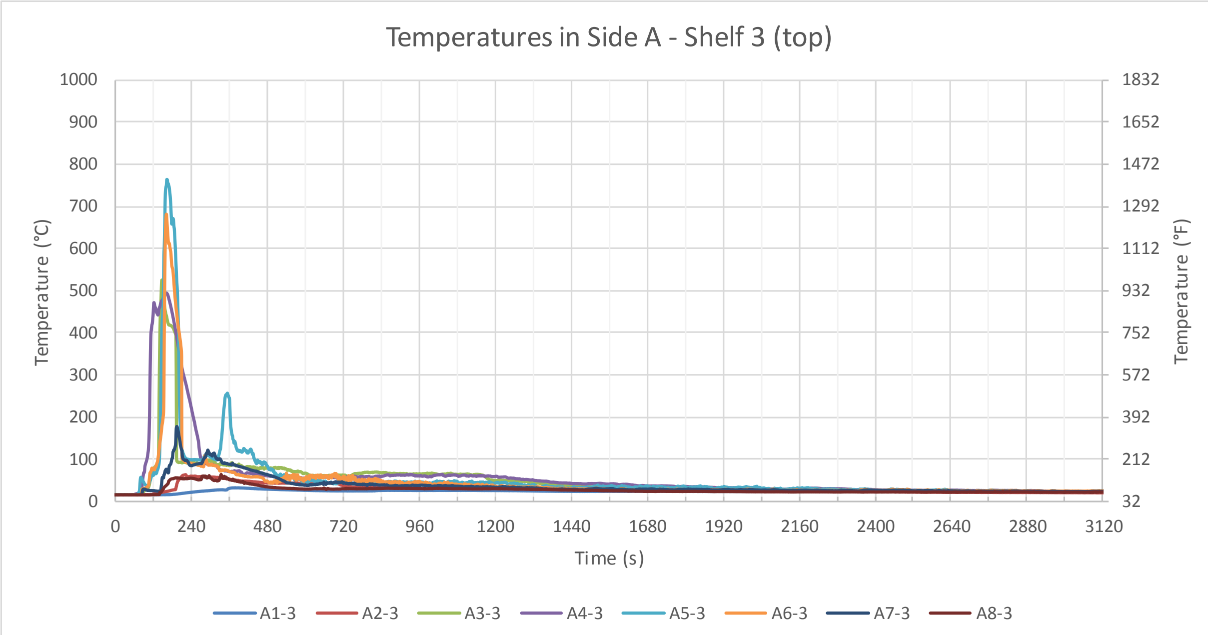

Figure B-35: Test 2 temperatures in Side A: Shelf 3 (top).

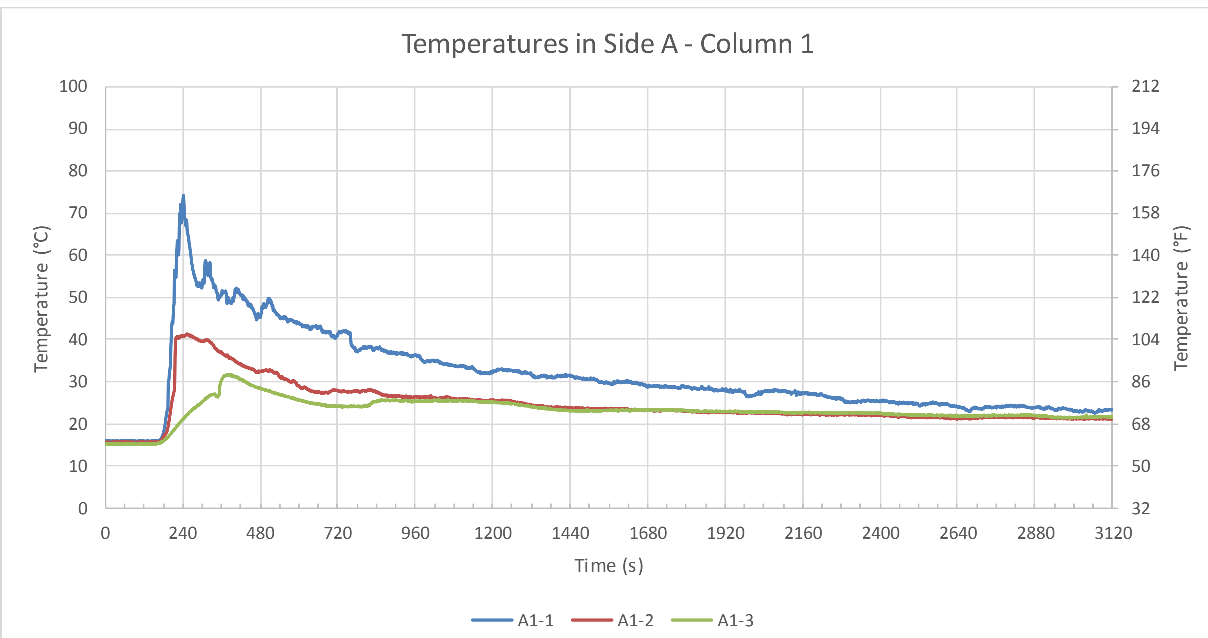

Figure B-36: Test 2 temperatures in Side A: Column 1. Note different temperature scale.

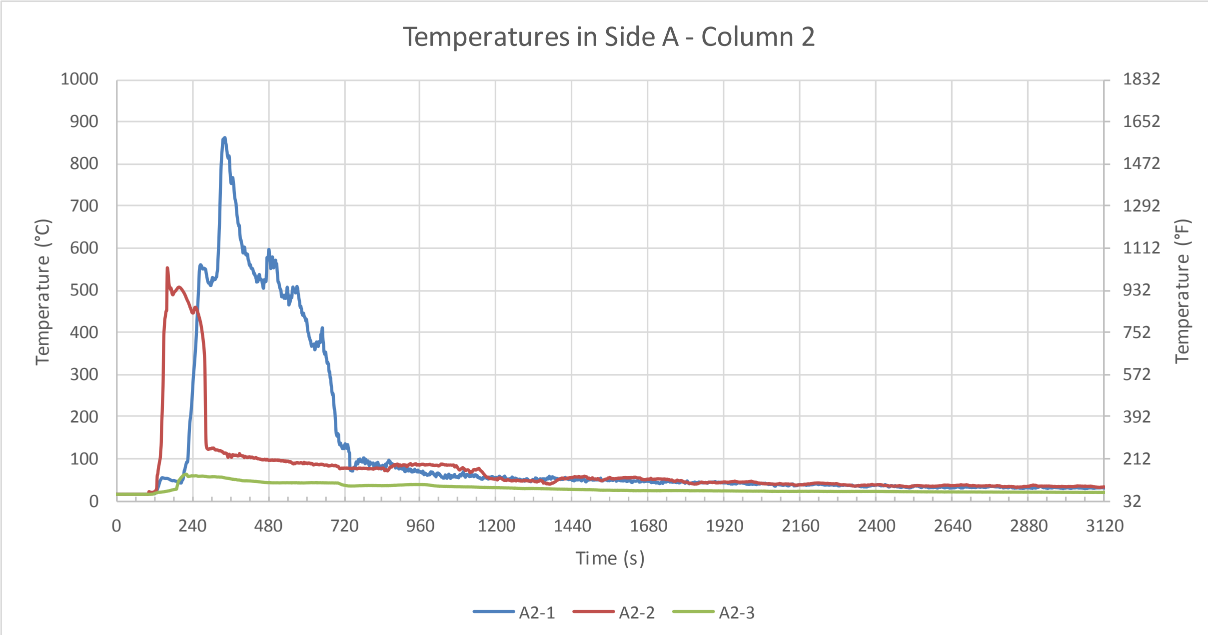

Figure B-37: Test 2 temperatures in Side A: Column 2.

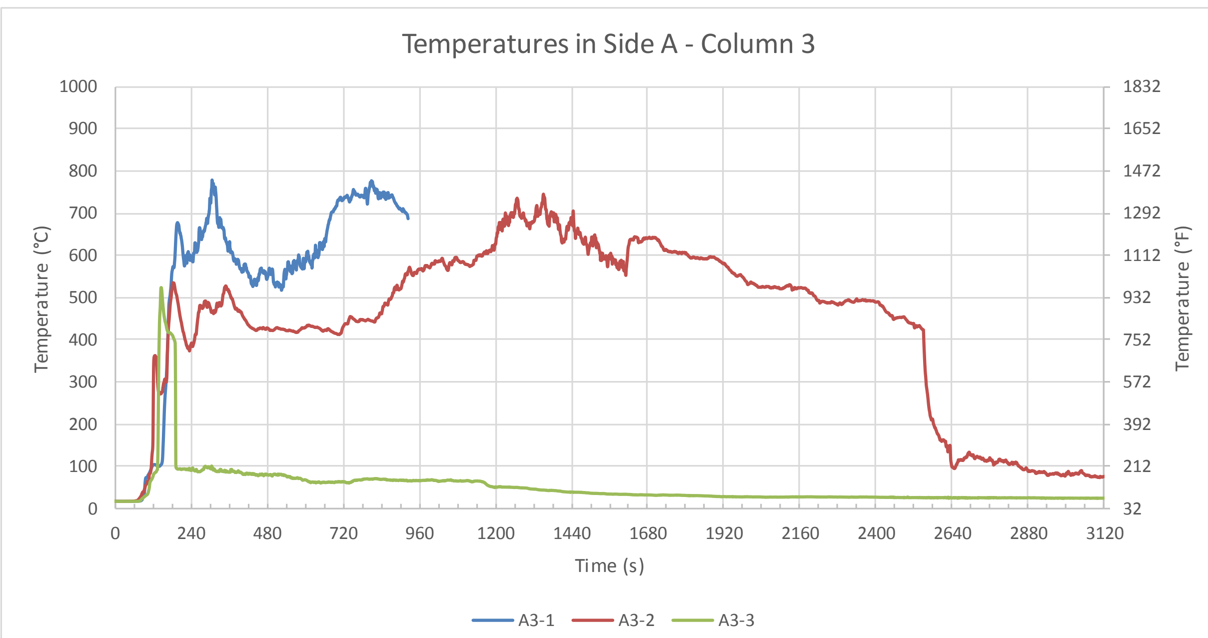

Figure B-38: Test 2 temperatures in Side A: Column 3. Note that TC A3-1 malfunctioned during the test and suspect data have not been plotted. Its functionality was checked post-test and found to be inoperative.

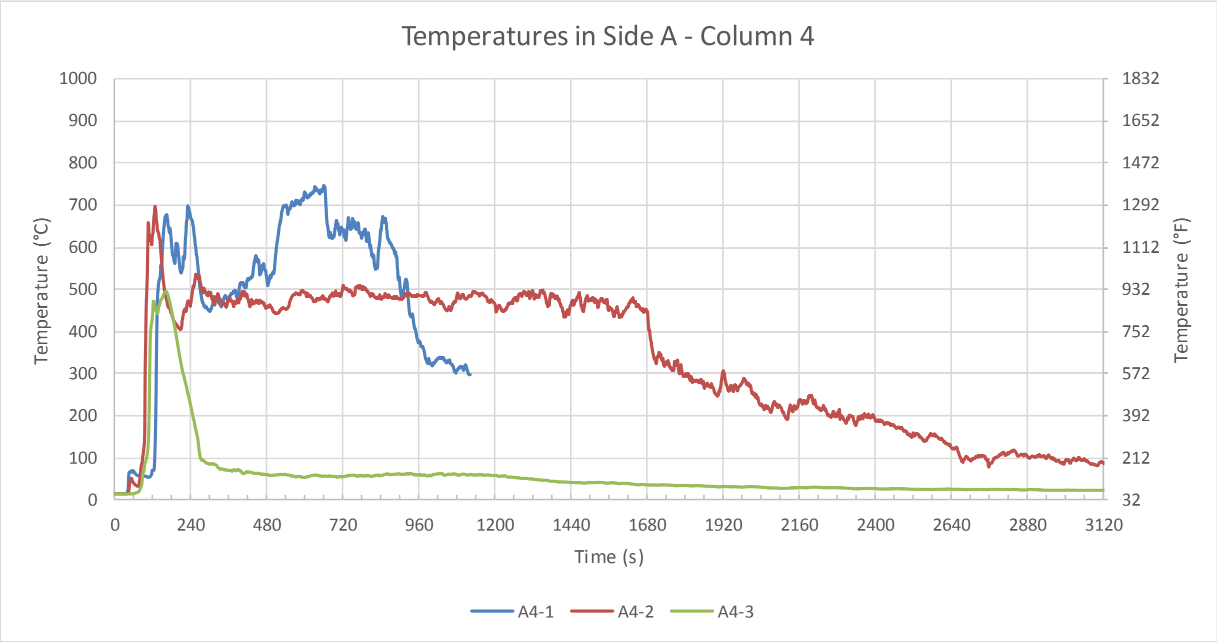

Figure B-39: Test 2 temperatures in Side A: Column 4. Note that TC A4 -1 malfunctioned during the test and suspect data have not been plotted. Its functionality was checked post-test and found to be inoperative.

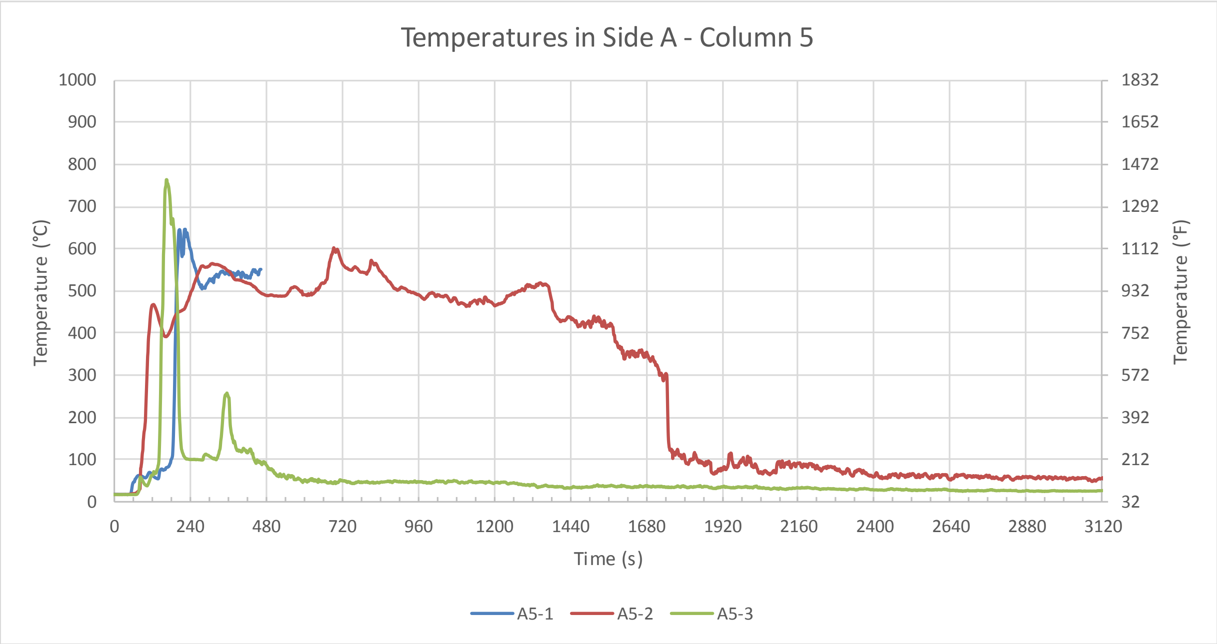

Figure B-40: Test 2 temperatures in Side A: Column 5. Note that TC A5-1 malfunctioned during the test and suspect data have not been plotted. Its functionality was checked post-test and found to be inoperative.

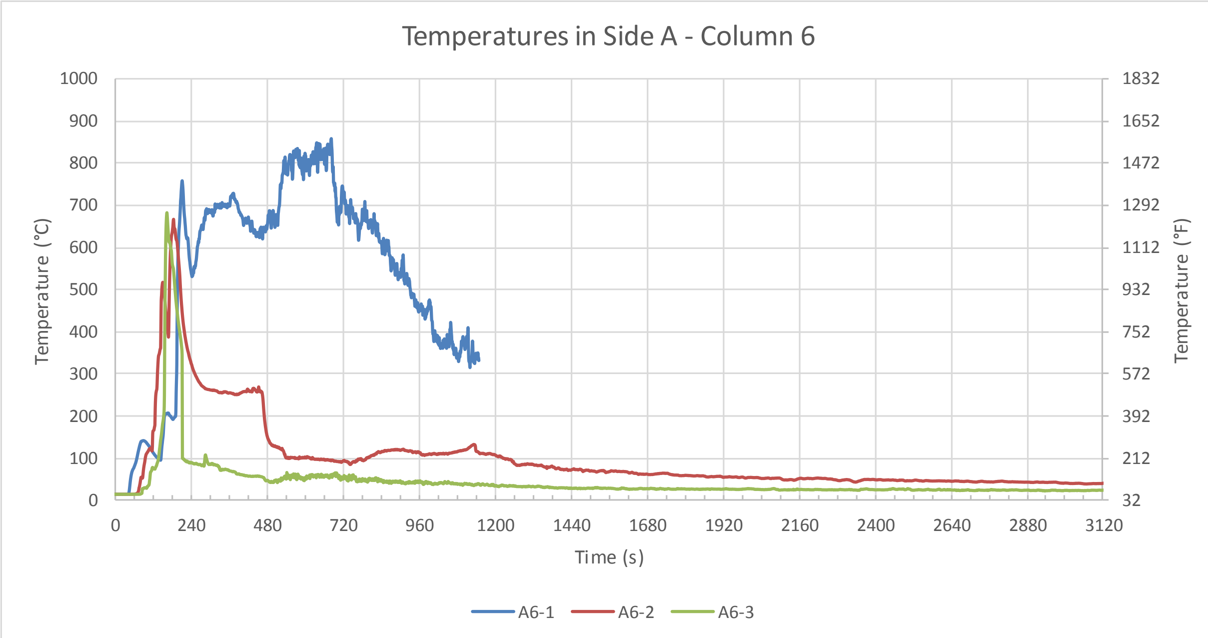

Figure B-41: Test 2 temperatures in Side A: Column 6. Note that TC A6-1 malfunctioned during the test and suspect data have not been plotted. Its functionality was checked post-test and found to be inoperative.

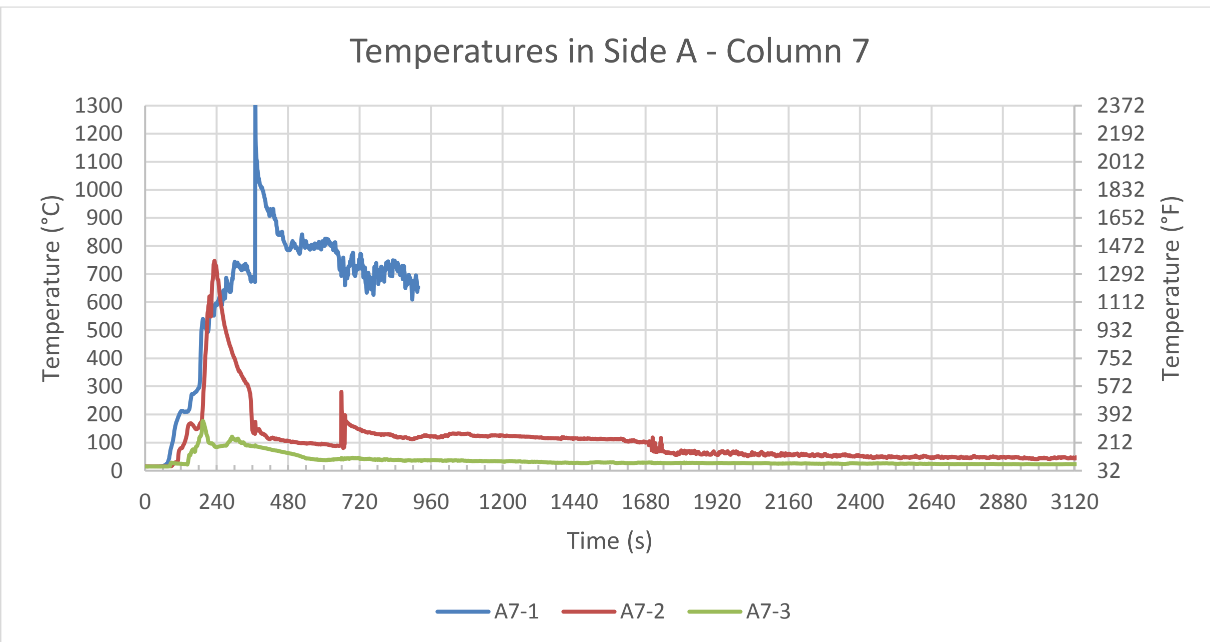

Figure B-42: Test 2 temperatures in Side A: Column 7. Note that TC A7-1 malfunctioned during the test and suspect data have not been plotted, additionally, it exceeded the maximum rating of a Type K TC at 06:10 after which time the temperature decreased. Its functionality was checked post-test and found to be inoperative. Note different temperature scale.

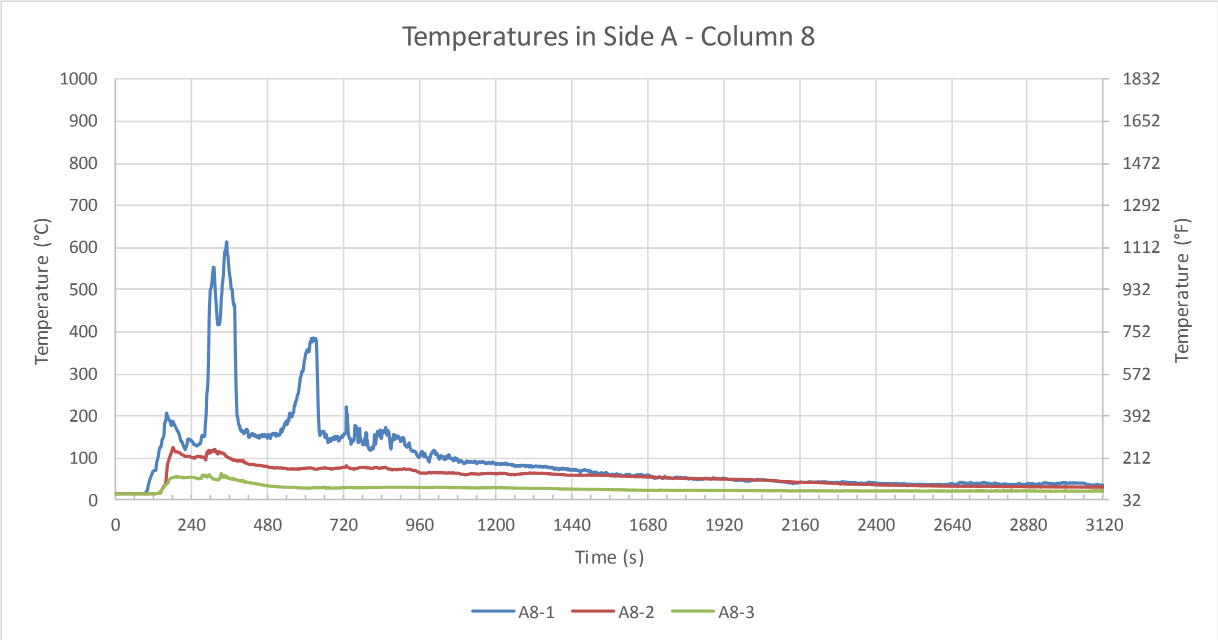

Figure B-43: Test 2 temperatures in Side A: Column 8.

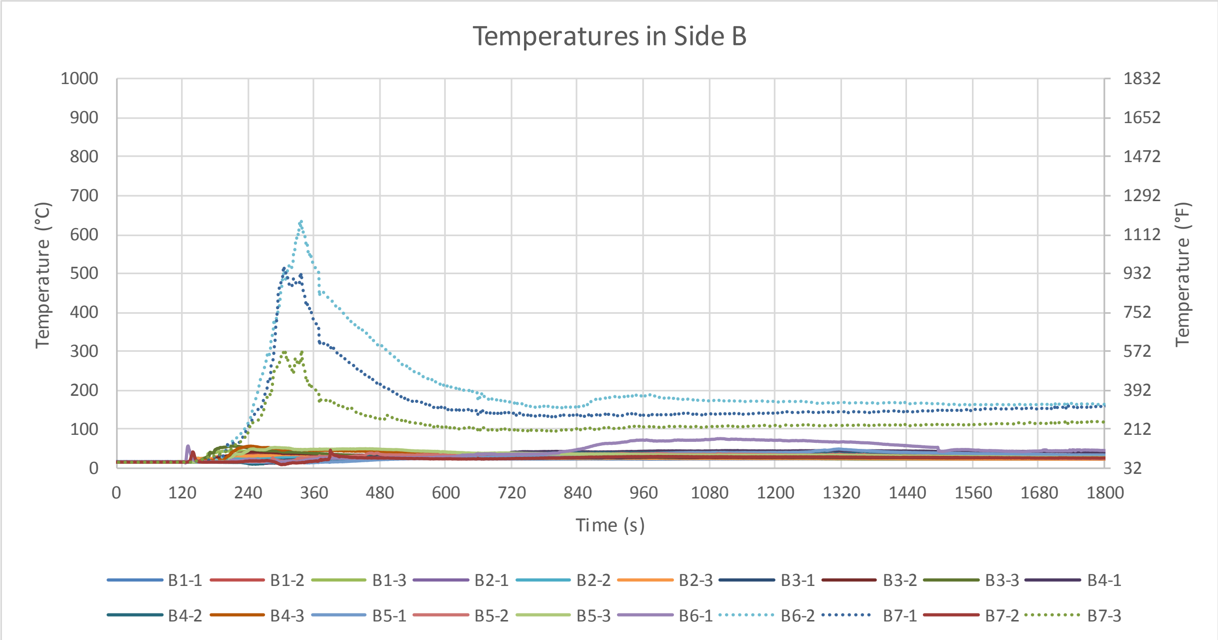

Figure B-44: Test 2 temperatures in Side B. Note that TCs B6-3 malfunctioned during the test and suspect data have not been plotted.

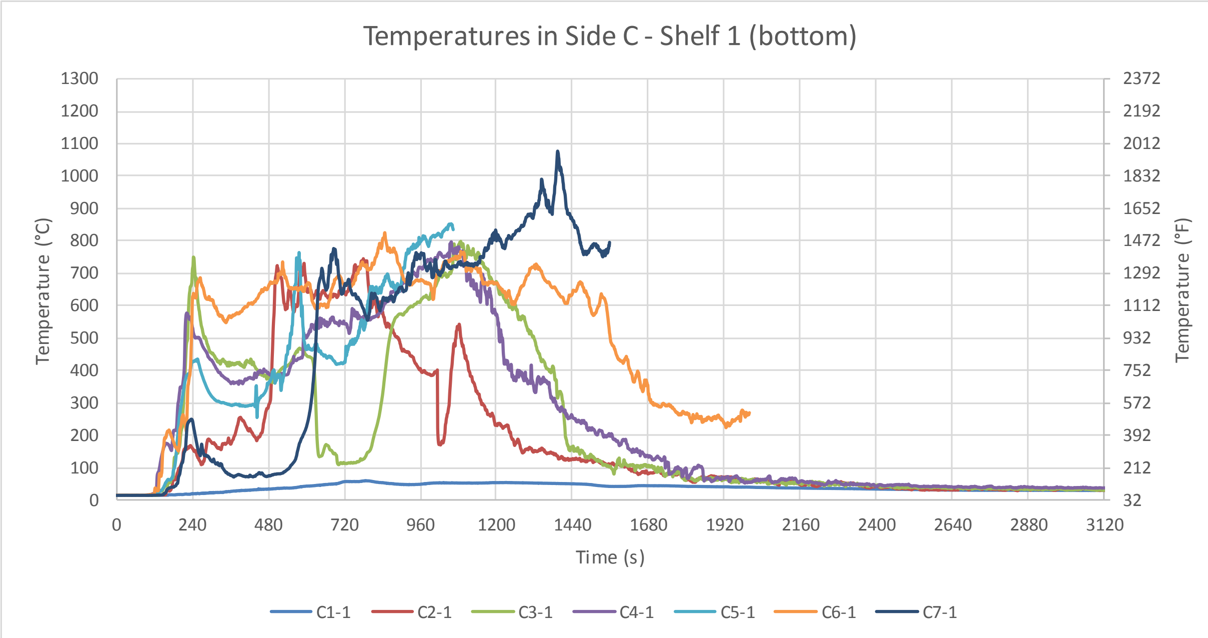

Figure B-45: Test 2 temperatures in Side C: Shelf 1 (bottom). Note that TCs C3-1, C4-1, C5-1, C6-1 and C7-1 malfunctioned during the test and suspect data have not been plotted. Their functionality was checked post-test and found to be inoperative. Note different temperature scale.

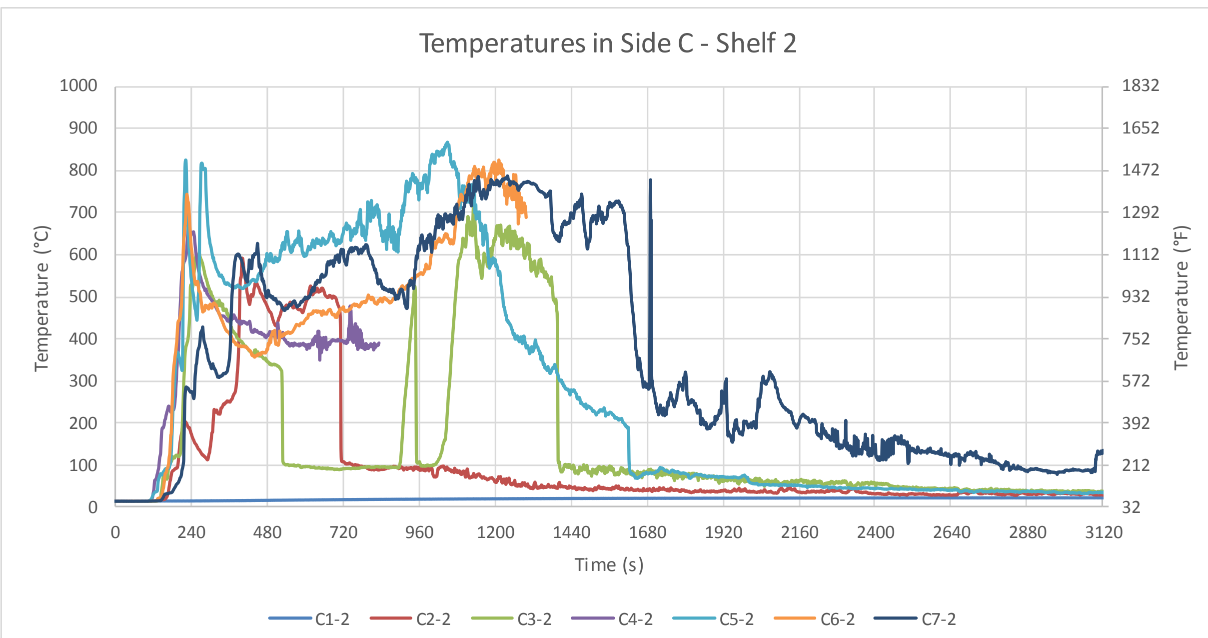

Figure B-46: Test 2 temperatures in Side C: Shelf 2. Note that TCs C4-2, C6-2 and C7-2 malfunctioned during the test and suspect data have not been plotted. Their functionality was checked post-test and found to be inoperative.

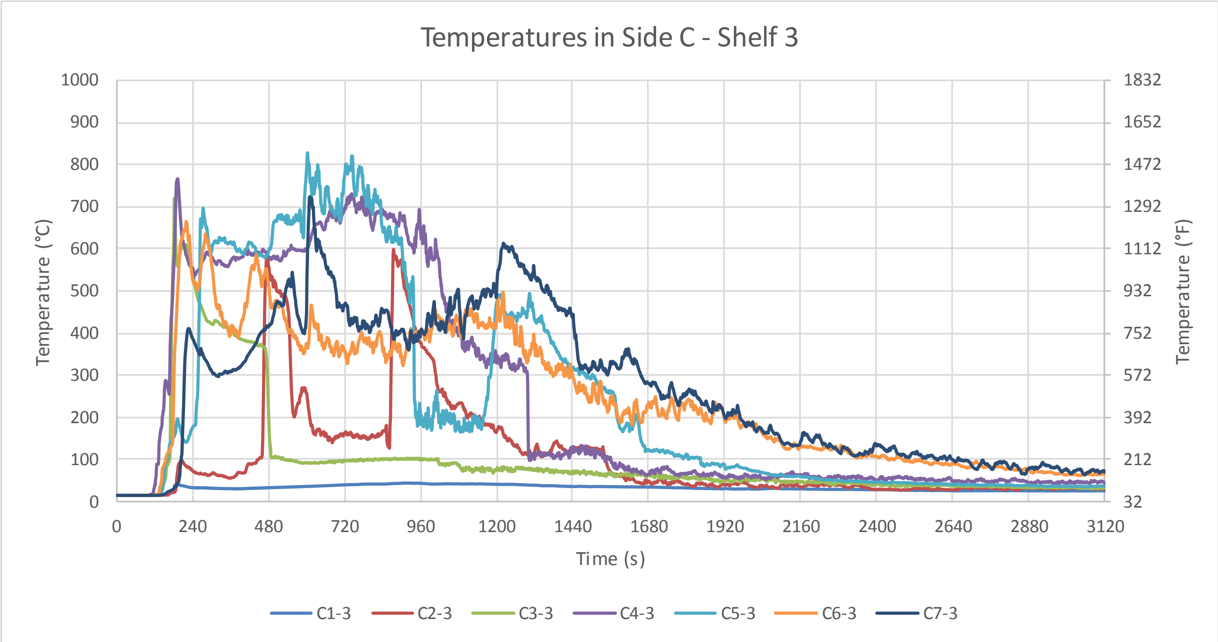

Figure B-47: Test 2 temperatures in Side C: Shelf 3.

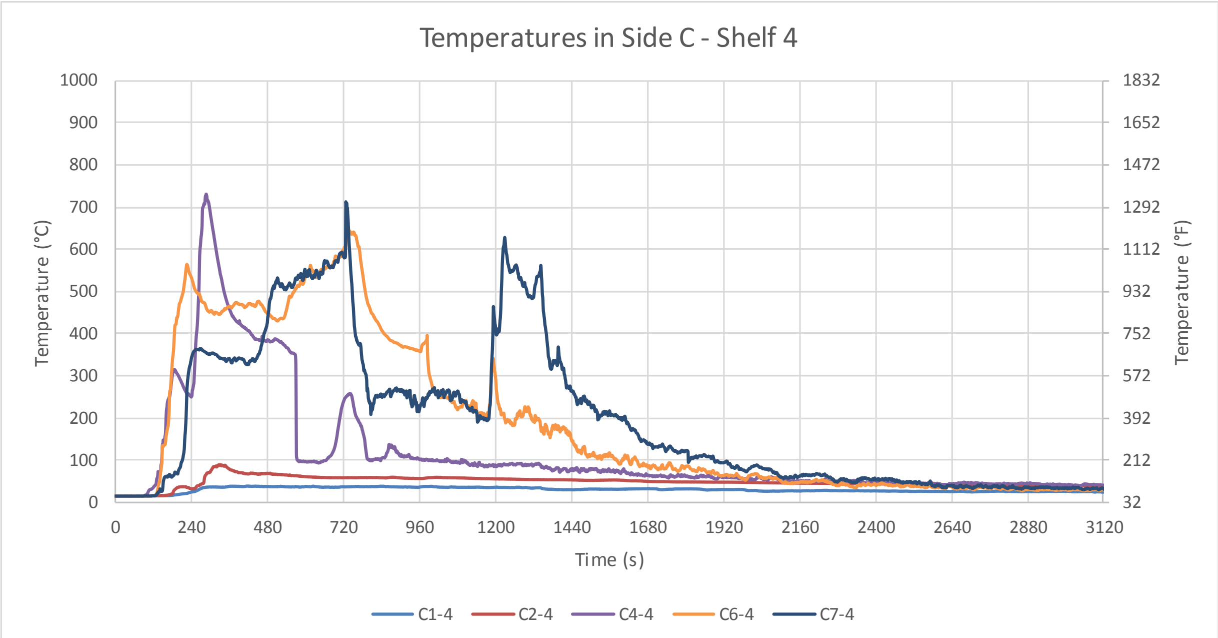

Figure B-48: Test 2 temperatures in Side C: Shelf 4. Note that TC C4-4 malfunctioned during the test and suspect data have not been plotted. Its functionality was checked post-test and found to be inoperative.

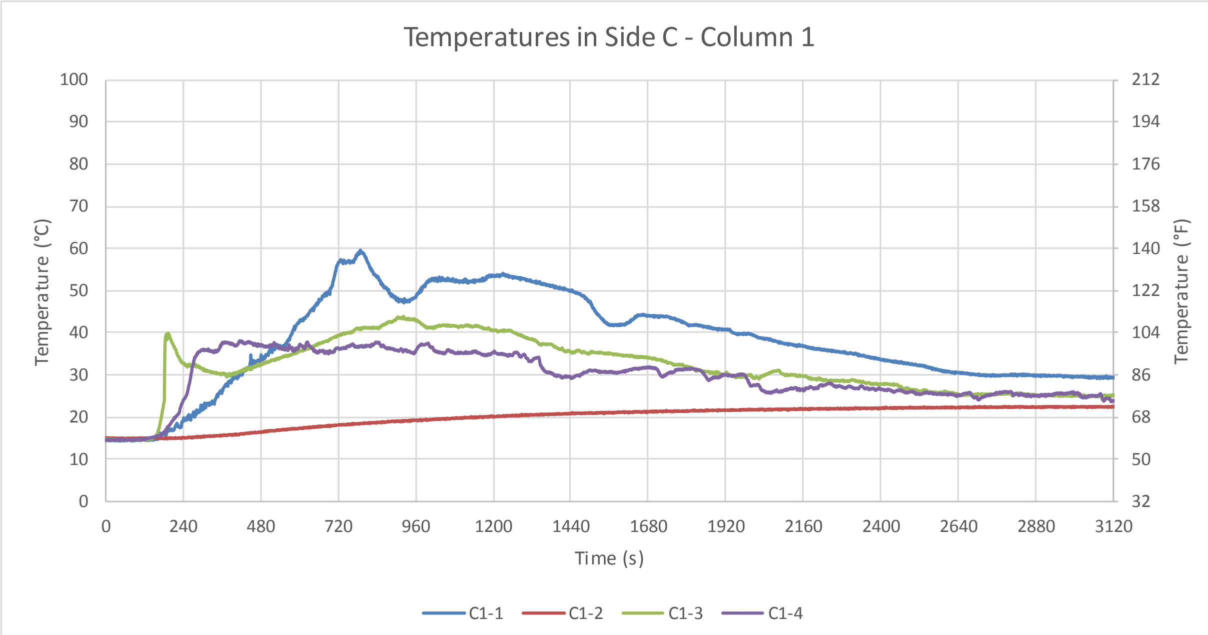

Figure B-49: Test 2 temperatures in Side C: Column 1. Note different temperature scale.

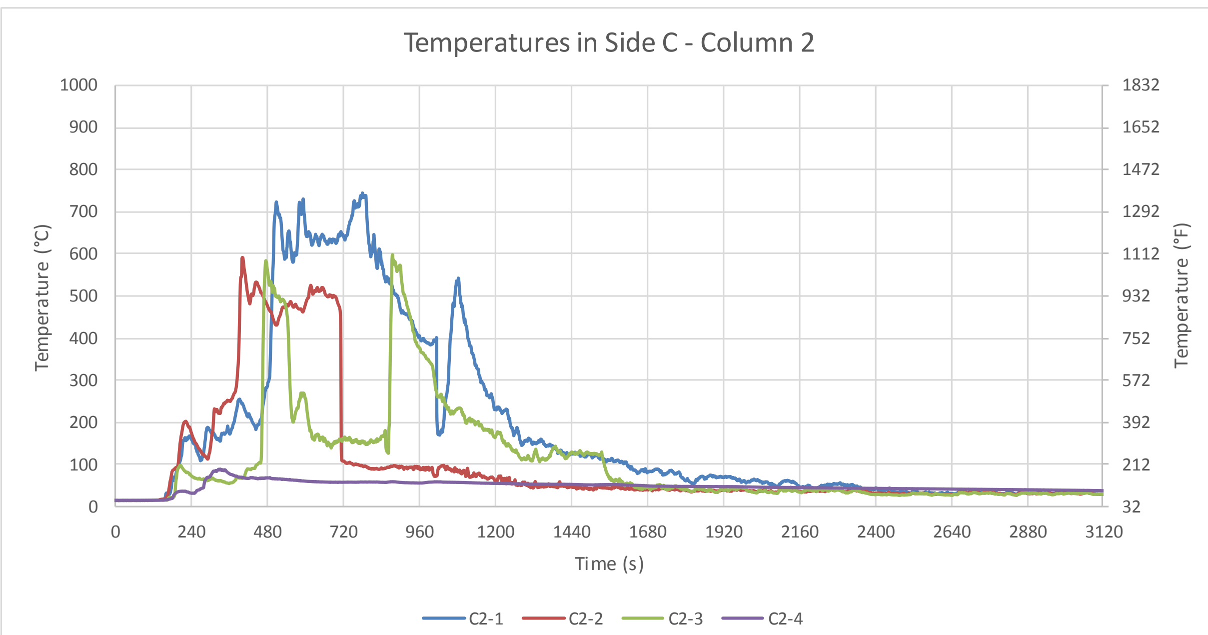

Figure B-50: Test 2 temperatures in Side C: Column 2.

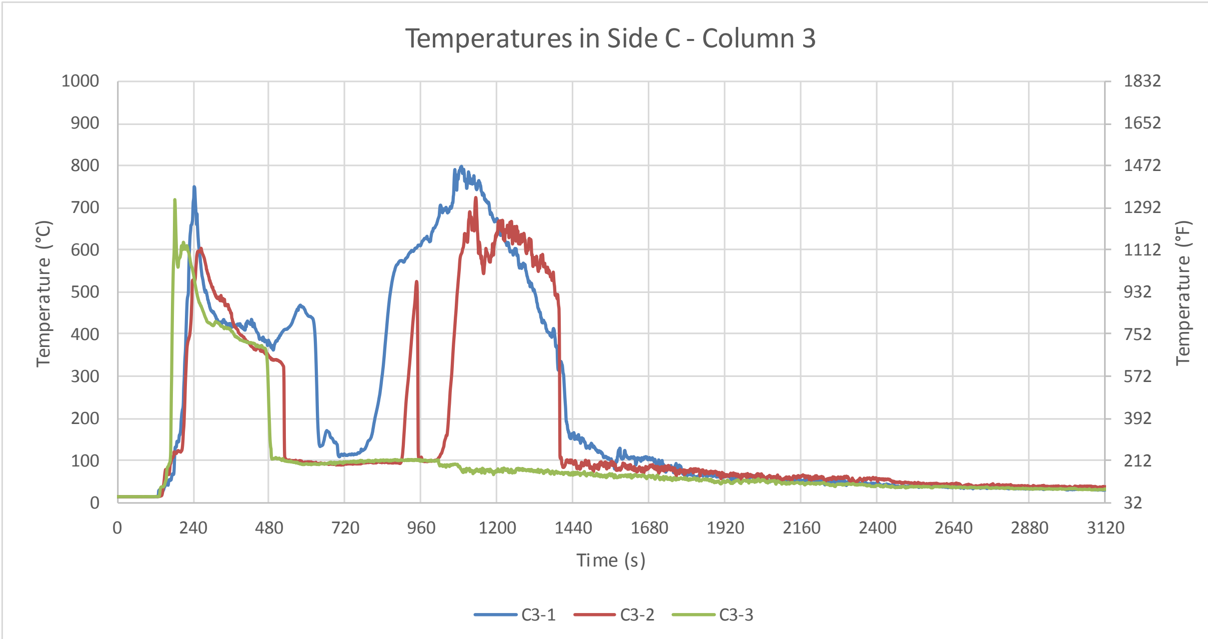

Figure B-51: Test 2 temperatures in Side C: Column 3.

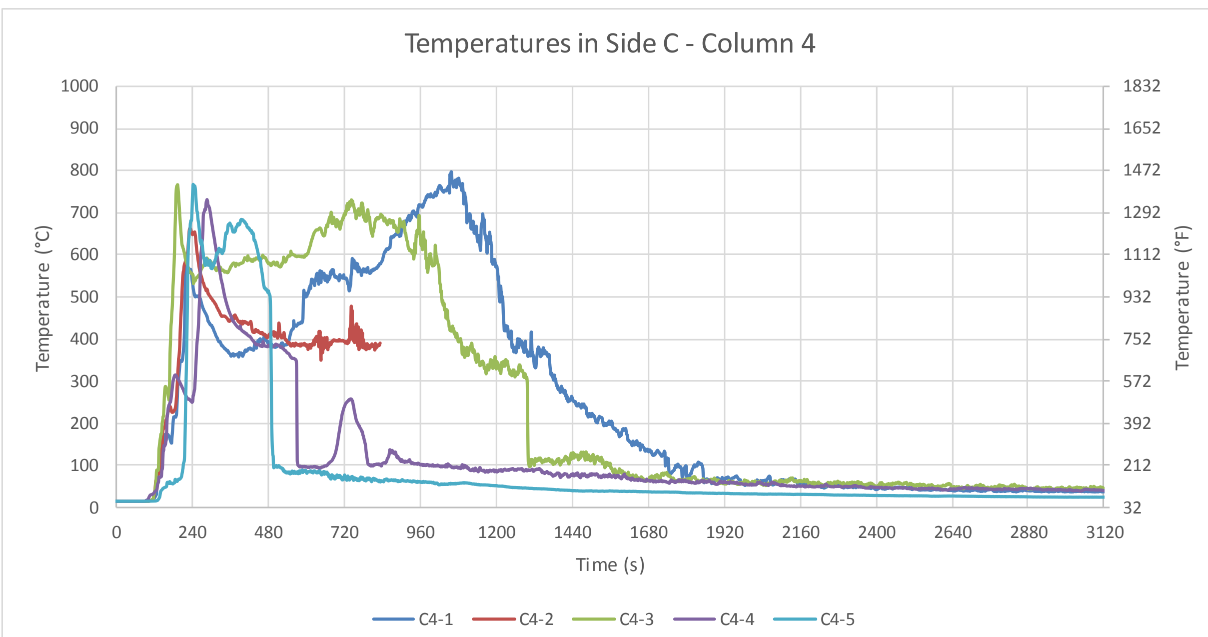

Figure B-52: Test 2 temperatures in Side C: Column 4. Note that TCs C4-1 and C4-2 malfunctioned during the test and suspect data have not been plotted. Their functionality was checked post-test and found to be inoperative.

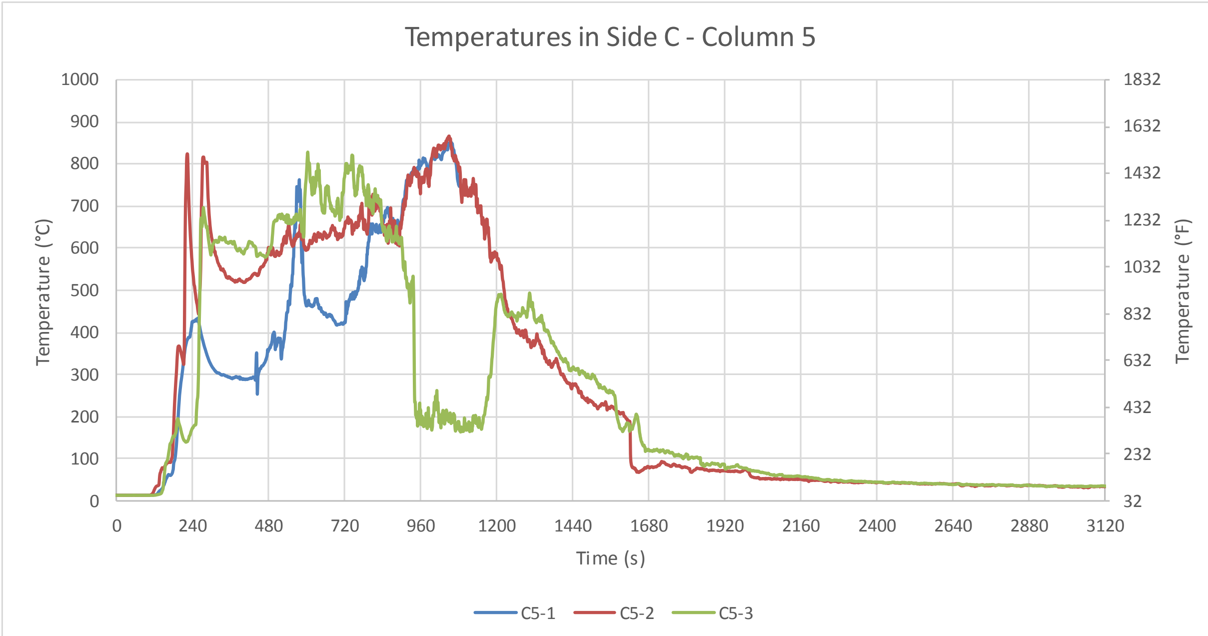

Figure B-53: Test 2 temperatures in Side C: Column 5. Note that TC C5-1 malfunctioned during the test and suspect data have not been plotted. Its functionality was checked post-test and found to be inoperative.

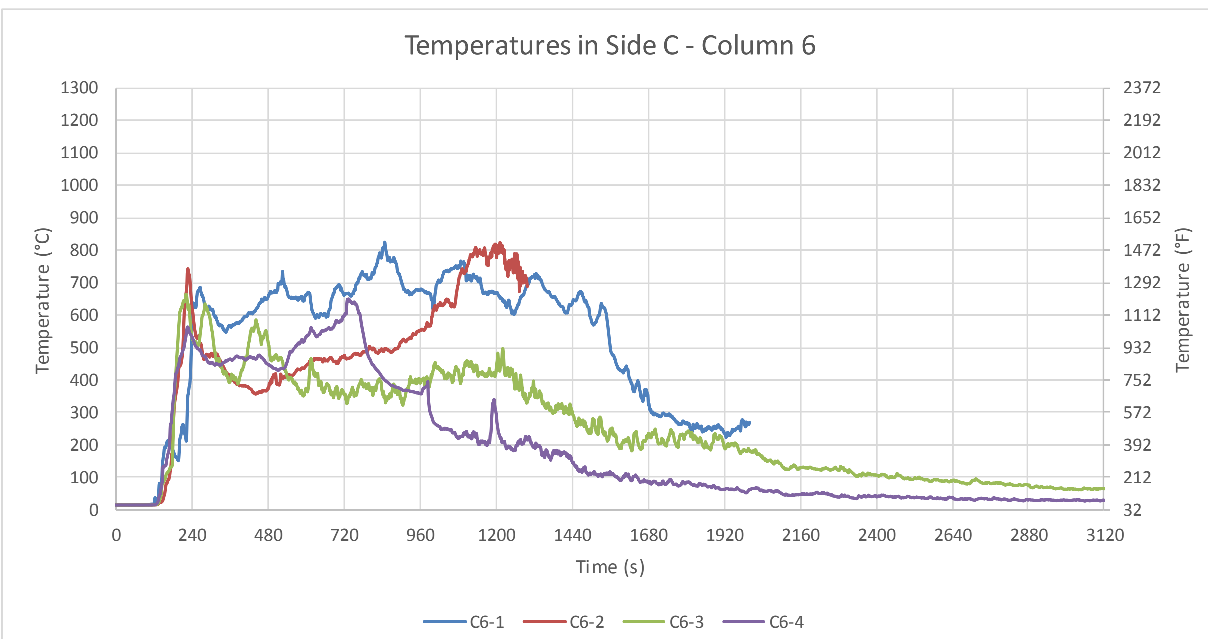

Figure B-54: Test 2 temperatures in Side C: Column 6. Note that TCs C6-1 and C6-2 malfunctioned during the test and suspect data have not been plotted. Their functionality was checked post-test and found to be inoperative.

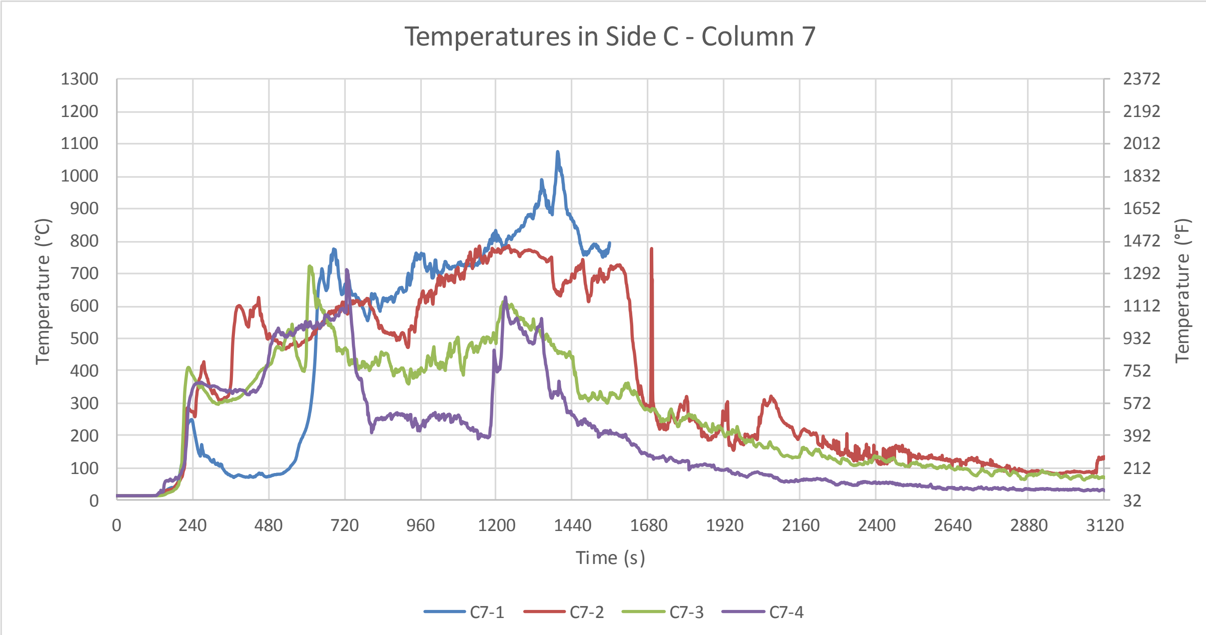

Figure B-55: Test 2 temperatures in Side C: Column 7. Note that TCs C7-1 and C7-2 malfunctioned during the test and suspect data have not been plotted. Their functionality was checked post-test and found to be inoperative.

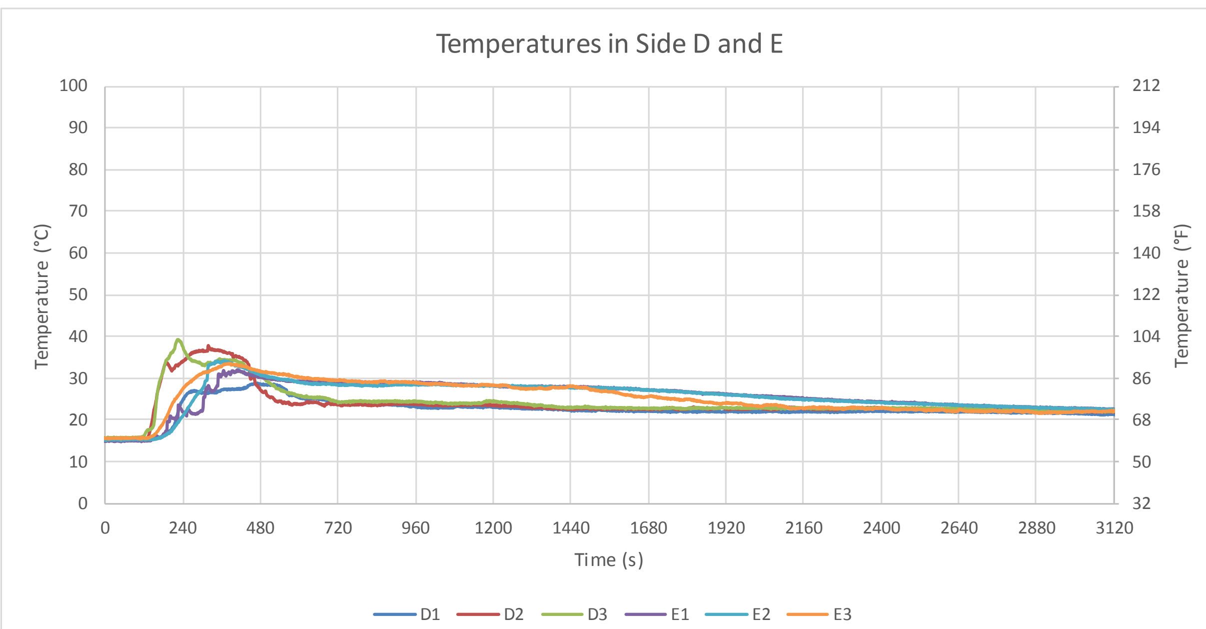

Figure B-56: Test 2 temperatures in Side D and E. Note different temperature scale.

B.2.3 *TC Tree Temperatures*

Figures B-57 and B-58 contain the time history of gas temperatures measured at TC Tree A and B, respectively.

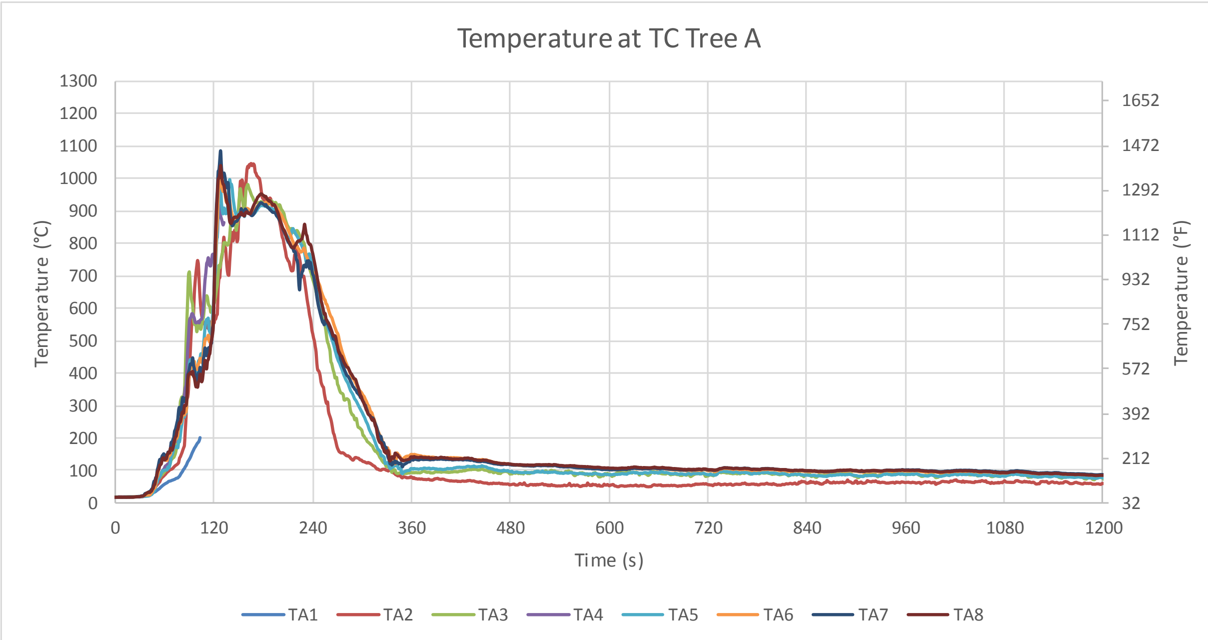

Figure B-57: Test 2 temperatures at TC Tree A. Note that TCs TA1 and TA4 malfunctioned during the test and suspect data have not been plotted. Their functionality was checked post-test and found to be inoperative. High temperatures are a result of the proximity of the fire to the TC tree and are not indicative of vertical temperature profiles in other regions of the test array. Note different temperature scale.

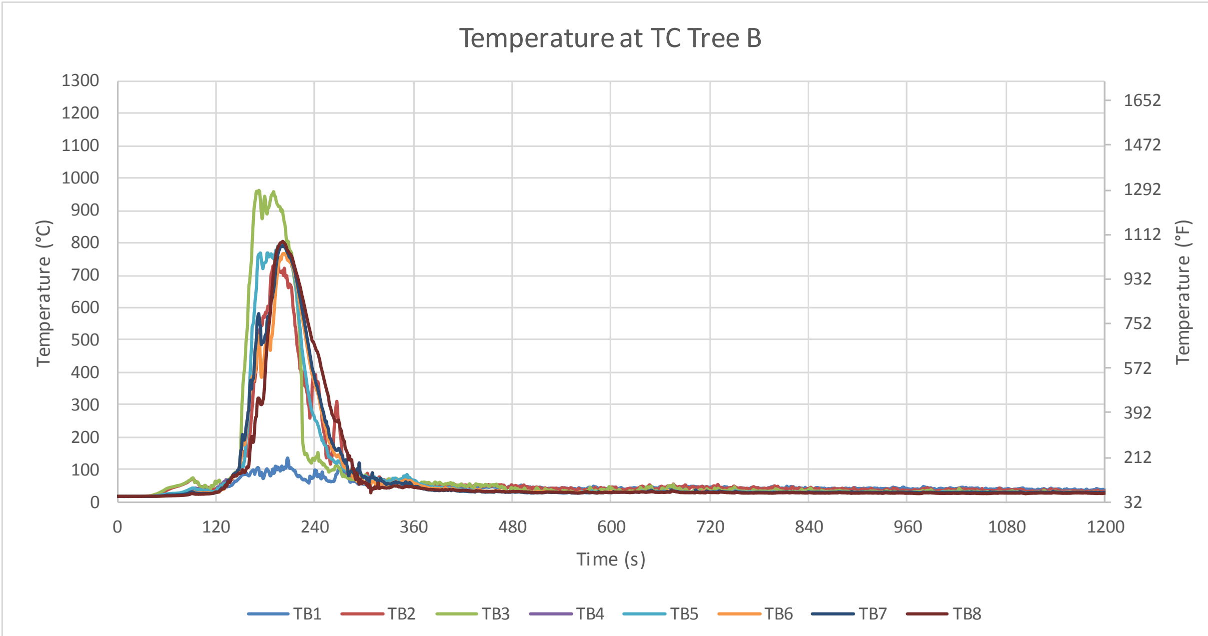

Figure B-58: Test 2 temperatures at TC Tree B. Note that the measured gas temperatures at TB1 in Test 2 are considerably lower than they were in Test 1 when it was located at ceiling-level and measured the ceiling jet temperature. Increase in temperature at TB2-TB7 after 02:00 is likely due to the arrival of the flame front. Their magnitude prior to this time may be an indication of vertical temperature profiles not directly exposed to the fire plume. In hindsight it would have been advantageous to install a TC tree in the aisle space between Sides B and D to provide gas temperature for regions not directly exposed to the fire. Note different temperature scale.

Appendix C. Damage

Post-test damage images are contained herein.

C.1 Test 1

Figure C-1: Test 1 overview of damage looking toward west.

Figure C-2: Test 1 overview of damage looking toward south

Figure C-3: Test 1 overview of damage looking toward east. Commodity shown collapsed into the aisle between Sides A and C.

Figure C-4: Test 1 damage to Sides A (right) and C (left), looking toward west, with collapsed commodity in aisle which occurred during the test and not as a result of firefighting efforts.

Figure C-5: Test 1 damage to Side A looking toward east.

Figure C-6: Test 1 damage to top shelf commodity in Side A vertically aligned with ignition location (which was in bottom shelf).

Figure C-7: Test 1 damage to Side C looking toward west. Transverse flame break located on left of image where commodity remains intact. Center of image shows burn through of longitudinal flame break (sheet rock backing remained intact at test conclusion and was removed post-test).

Figure C-8: Test 1 damage to Side C. Showing back of Side C where sheet rock has been removed post-test to inspect the burn through of the longitudinal flame break.

Figure C-9: Test 1 detail of typical residual commodity in highly effected regions. Specific location in Side C, second shelf.

Figure C-10: Test 1 detail of typical residual commodity in regions where flame spread ceased.

Figure C-11: Test 1 showing example of unburned commodity on one side of flame break and burned commodity on the other. Location in Side C. Note some commodity has been removed as part of the post-test deconstruction process.

Figure C-12: Test 1, west side of Shelves 3, 4 and 5 in Side C showing examples of locations where flame spread ceased in the absence of a flame break. Shelf 3 provides an example of the flame spread that occurs when the flames are channeled along the underside of the shelves.

Figure C-13: Test 1 post-test image of Side B (right) and Side D (left) with Side E at the end of the aisle. These three shelving units sustained water damage only (no fire).

Figure C-14: Test 1 Side B. Front row of commodity has been removed during the post-test deconstruction process to inspect for potential fire damage. Side B sustained no fire damage to the commodity.

(a) (b)

Figure D-15: Test 1 Side B after commodity has been removed showing localized areas of burn through of the longitudinal flame break from fire located in Side A (a) looking westward (b) looking eastward. Detail image shown in Figure C-16.

Figure C-16: Test 1 Side B after commodity has been removed showing localized area of burn through of longitudinal flame break in bottom shelf directly behind ignition location.

Figure C-17: Test 1 Side C (looking westward) after commodity has been removed showing transverse flame breaks intact, localized burn through of longitudinal flame break, and deformation of metal shelves.

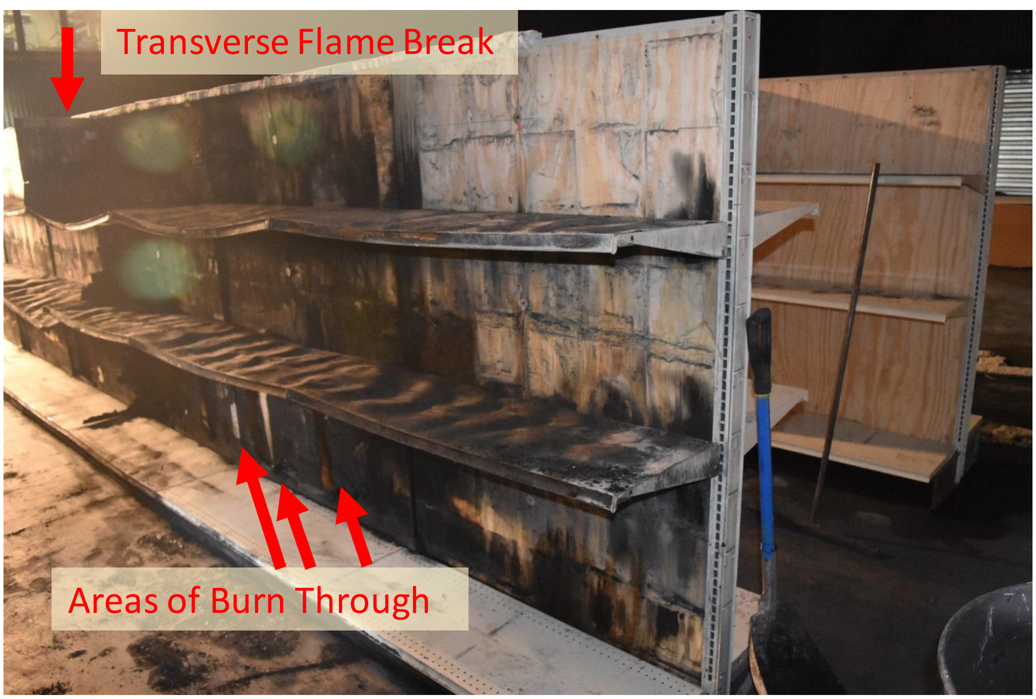

Figure C-18: Test 1 Side A (looking westward) after commodity has been removed showing transverse flame breaks on bottom and middle shelves consumed but intact on top shelf, examples of burn through of longitudinal flame break, and deformation of metal shelves.

C.2 Test 2

Figure C-19: Test 2 damage to Side A looking toward east.

Figure C-20: Test 2 eastern end of Side A.

Figure C-21: Test 2 damage to Sides A (right) and C (left), looking toward east, with collapsed commodity in aisle which occurred during the test and not as a result of the firefighting efforts.

Figure C-22: Test 2 Side C looking toward west, shelves 1-3, showing sheet rock that backs longitudinal flame break which is nearly completely consumed in this region, transverse flame breaks consumed on west, intact on east, fire damage at eastern end in shelves 1-4.

Figure C-23: Test 2 Side C looking toward west, shelves 3-5, transverse flame break on shelves 4 and 5 (top) intact.

Figure C-24: Test 2 Side C looking toward east, shelves 1-3, fire damage reached transverse flame break on shelves 1-3 but did not burn through them.

Figure C-25: Test 2 Side C, east side on left, west on right, shelves 3-5, fire damage reached transverse flame break on west side of shelf 3 but did not burn through and flame front ceased on west side of shelves 4 and 5 prior to reaching transverse flame breaks.

Figure C-26: Test 2 post-test image of Side B (left) and Side D (right) looking westward. Side D sustained water damage only (no fire). Fireworks on the top shelf of Side B sustained fire damage.

Figure C-27: Test 2 shown from aerial perspective with commodity partially removed and highlighting location on Side B where fire damage was sustained.

Figure C-28: Test 2 Side B detail of fire damage, a total of 22 fireworks devices became active in this location.

Figure C-29: Test 2 Side B after commodity has been removed showing localized area of burn through of longitudinal flame break in bottom shelf behind ignition region. See Figure C-30 for a close up image of this burn through.

Figure C-30: Test 2 Side B after commodity has been removed showing localized area of burn through of longitudinal flame break in bottom shelf behind ignition region.

Figure C-31: Test 2 post-test image of Side E which sustained water damage only (no fire).

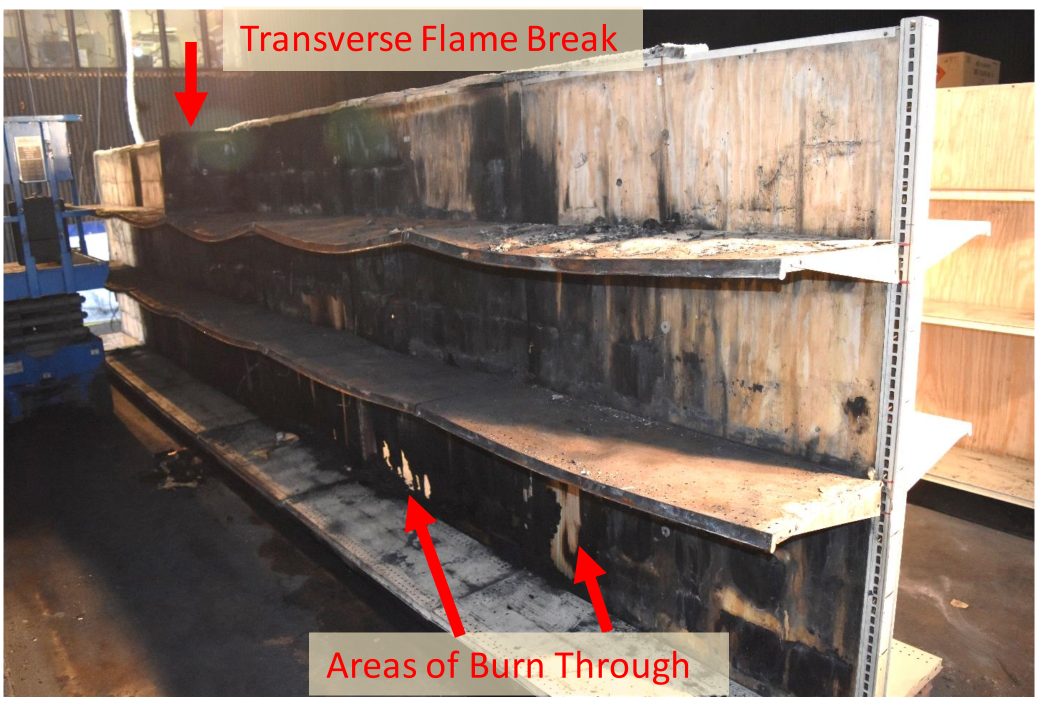

Figure C-32: Test 2 Side A (looking westward) after commodity has been removed showing transverse flame breaks on bottom and middle shelves consumed but intact on top shelf, examples of burn through of longitudinal flame break, and deformation of metal shelves.

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