RESEARCH TECHNICAL REPORT

Development of Protection Recommendations for Li-ion Battery Bulk Storage: Sprinklered Fire Test

FM Global

Development of Protection Recommendations for Li-ion Battery Bulk Storage: Sprinklered Fire Test

Prepared by

Benjamin Ditch

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FM Global
1151 Boston-Providence Turnpike
Norwood, MA 02062

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Disclaimer

Executive Summary

A project was conducted to determine fire protection guidance for warehouse storage of cartoned Li-ion batteries. The methodology for this project consisted of a comparison of the free-burn flammability characteristics of a large-format polymer pouch Li-ion battery to FM Global standard commodities and previously tested small-format Li-ion batteries in a rack storage array. A large-scale fire test then assessed the performance of ceiling-level sprinkler protection. The goal of the experimental approach was to maximize the application of the successful large-scale fire test result. For example, adequate sprinkler protection established in a large-scale test may be applied to all Li-ion batteries that are shown in the reduced-commodity evaluation to pose a hazard less than or equal to that of the battery used in the large-scale test.

A supplemental task involved assessing the impact of internal ignition within a pallet load of batteries versus the external ignition typically used in large-scale fire testing. An assessment of the effectiveness of sprinkler water at suppressing a fire at a later stage of battery involvement than could be achieved in the large-scale test was also conducted. Both of these tasks reinforce the sprinkler protection guidance resulting from the successful large-scale fire test.

This project was conducted in partnership with the Property Insurance Research Group (PIRG) and in collaboration with the Fire Protection Research Foundation (FPRF). The previous two phases of the project included a use and hazard assessment report[i] and a series of reduced-commodity fire tests comparing the flammability characteristics of several Li-ion batteries and FM Global standard cartoned commodities[ii, iii]. These tests showed that bulk storage of small-format Li-ion batteries (*i.e.*, 2.6 Ah) exhibits similar fire growth leading to first sprinkler operation as cartoned commodities. Further, it was determined that the time required for involvement of Li-ion batteries in a fully developed fire is on the order of five minutes. These conclusions provided the basis for sprinkler protection recommendations for small-format Li-ion batteries in bulk storage, with the goal of suppressing the fire before the anticipated time of involvement of Li-ion batteries. The current project evaluated ceiling-only sprinkler protection based on large-scale sprinklered fire test experience of cartoned Li-ion batteries.

The Li-ion battery available for this project was a 20 Ah, 3.3 V, polymer pouch battery with lithium iron phosphate ($LiFePO_4$) chemistry. The battery dimensions were 160 mm × 230 mm × 7.25 mm (6 in. × 9 in. × 1/3 in.) and the state-of-charge (SOC) was nominally 50%. Packaging consisted of corrugated containerboard cartons, where each carton contained 20 batteries separated by 10 levels of nested

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[i] C. Mikolajczak, M. Kahn, K. White, and R. Long, "Lithium-Ion Batteries Hazard and Use Assessment," Report prepared for the Fire Protection Research Foundation, June 2011.

[ii] B. Ditch and J. de Vries, "Flammability Characterization of Lithium-ion Batteries in Bulk Storage," FM Global Technical Report, March 2013.

[iii] R. Thomas Long Jr., R. T. Long Jr., J. Sutula, and M. Kahn, "Li-ion Batteries Hazard and Use Assessment Phase IIB: Flammability Characterization of Li-ion Batteries for Storage Protection," Report prepared for the Fire Protection Research Foundation, 2013.

plastic dividers. This packaging and battery layout was consistent with the previously tested small-format Li-ion polymer batteries[ii, iii].

All test evaluations were conduct by FM Global at the FM Global Research Campus in Rhode Island, USA. The report findings are only valid under the following conditions:

- Storage height up to 4.6 m (15 ft)
- Ceiling height up to 12.2 m (40 ft)
- Bulk-packaged 20 Ah polymer pouch batteries in corrugated board cartons with heavy plastic dividers at nominally 50% state-of-charge (SOC).

The flammability characteristics of the selected 20 Ah Li-ion polymer pouch battery were compared to those of FM Global's standard commodities and previously tested small-format Li-ion batteries[iv,v]. This test, referred to as "reduced-commodity," was used to estimate the fire hazard present at the time of first sprinkler operation in a sprinklered warehouse fire scenario. Measurements focused on the fire development of each commodity and the time of battery involvement for the Li-ion products during a free-burn rack storage fire test. Based on the result of the test presented in this report, and building upon Reference[ii], the following conclusions can be made:

- The cartoned 20 Ah large-format battery used in the present study represented a higher hazard than the previously tested 2.6 Ah small-format batteries (cylindrical and polymer pouch). This conclusion is based on the following test results indicating that the large-format battery contributed to the overall fire severity closer to the predicted time of sprinkler operation than the small-format batteries:
    - The predicted time of sprinkler operation was similar for all cartoned Li-ion batteries and FM Global standard commodities included in this project. This result supports the assumption that for three-tier-high, open-frame racks, the carton packaging dominates the fire development leading to first sprinkler operation.
    - Under free-burn conditions, the 20 Ah Li-ion polymer pouch battery used in this project contributed to the overall severity of the rack storage 2 min 30 s (150 s) after igntion, versus 5 minutes for the previously tested 2.6 Ah cylindrical and polymer pouch batteries in Phase 2.
- The product packaging, e.g., corrugated board containers and dividers, was identified as a key factor driving the hazard in Li-ion batteries in storage. While the corrugated board cartons were

[iv] B. Ditch and J. de Vries, "Flammability Characterization of Lithium-ion Batteries in Bulk Storage," Technical Report, March, 2013. Available at www.fmglobal.com/researchreports.

[v] R. T. Long Jr., J. A. Sutula, M. J. Kahn, "Lithium Ion Batteries Hazard and Use Assessment Phase IIB - Flammability Characterization of Li-ion Batteries for Storage Protection," Fire Protection Research Foundation Report, 2013.

shown to dominate the initial fire growth, the plastic content within the cartons was shown to be a driving factor in the overall commodity hazard, in particular:

- Cartoned batteries containing significant quantities of plastics exhibited a similar rapid increase in the released energy due to plastics involvement early in the fire development.
    - For the large-format 20 Ah Li-ion polymer pouch batteries used in this project, the heavy plastic dividers contributed to the overall severity of the fire before involvement of the batteries.
    - For the power tool packs, tested in Phase 2[vi], the heavy plastic case of the battery pack dominated the fire hazard and there was no observable contribution from the batteries.
- Cartoned batteries containing minimal plastics (*e.g.,* the small-format Li-ion cylindrical and polymer batteries tested in Phase 2) exhibited a slower increase in energy release and a delay in the battery involvement due to heating of the batteries. In this case the plastic dividers represented a lesser combustible load than the heavy plastic dividers used for the 20 Ah polymer pouch battery.

Caution should be taken when extending the results of the testing presented in this report beyond the specific combination of packaging and battery listed. Changes in the components of the packaging can significantly impact the flammability characteristics of cartoned Li-ion batteries. One key aspect of the packaging driving the fire hazard is the divider used to separate the batteries within the cartons. Potential divider materials represent a wide range of fire properties and include liner board, fiber board, thin or heavy plastic, and expanded foam[vii]. Even for the same battery, changing the liner material can significantly impact the fire hazard. Changes in the Li-ion battery can also have a similar effect on the overall hazard of the cartoned product. For instance, high SOC has been shown to increase the likelihood and severity of thermal runaway[viii]. The quantity of electrolyte, which is the main combustible source, is a function of the battery capacity and can also vary with the battery format (e.g., cylindrical or polymer pouch). Thus even for the same packaging, changes in the battery can impact the fire hazard. A new flammability assessment should be conducted when potentially significant changes to the cartoned product are encountered.

The performance of ceiling-level sprinkler protection was then assessed with a large-scale sprinklered fire test of the large-format 20 Ah polymer pouch batteries. The test was conducted using a three-tier-

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[vi] B. Ditch and J. de Vries, "Flammability Characterization of Lithium-ion Batteries in Bulk Storage," Technical Report, March, 2013. Available at www.fmglobal.com/researchreports.

[vii] M.M. Khan, A. Tewarson, and M. Chaos, "Combustion Characteristics of Materials and Generation of Fire Products," in *SFPE Handbook of Fire Protection Engineering*, P. DiNenno, Ed. Quincy, Massachusetts, New York: Springer, 2016, ch. Section 3, Chapter 4, pp. 1143-1232.

[viii] P. Ribiere, S. Grugeon, M. Morcrette, S. Boyanov, S. Laruelle, and G. Marlair, "Investigation on the Fire-Induced Hazards of Li-ion Battery Cells by Fire Calorimetry," *Energy and Environmental Science*, vol. 5, pp. 5271-5280, 2012. DOI: 10.1039/clee02218k.

high rack-storage array, which represents storage up to 4.6 m (15 ft) high. Protection was provided by quick-response, pendent sprinklers, having a 74°C (165°F) rated link with a K-factor of 320 L/min/bar$^{1/2}$ (22.4 gpm/psi$^{1/2}$) under a 12.2 m (40 ft) ceiling. In accordance with the established evaluation criteria, the following conclusions can be made:

- Storage up to 4.6 m (15 ft) under ceiling heights up to 12.2 m (40 ft) was adequately protected by a fire protection system comprised of pendent sprinklers having a K-factor of 320 L/min/bar^{½} (22.4 gpm/psi^{½}), with a nominal 74°C (165°F) temperature rating and a nominal RTI of 27.6 m^{½}s^{½} (50 ft^{½}s^{½}), installed on 3.0 m × 3.0 m (10 ft × 10 ft) spacing at an operating pressure of 2.4 bar (35 psig). This conclusion is based on one sprinkler operation extinguishing a large-scale test fire without manual intervention.

- Protection guidance established from the large-scale fire test can be reasonably applied to the small-format (i.e., 2.6 Ah cylindrical and polymer pouch) Li-ion batteries previously tested for this project. This conclusion is based on the results of the reduced-commodity test indicating that the cartoned large-format battery used in this project represented a higher hazard in the reduced-commodity test than the previously tested small-format batteries.

Three supplemental evaluations were then included to reinforce the sprinkler protection guidance resulting from the successful large-scale fire test. The first evaluation assessed the likelihood and impact of ignition resulting from thermal runaway of one or more batteries within a carton. The effectiveness of sprinkler water at suppressing a fire at a later stage of battery involvement than was achieved in the large-scale test was then conducted. Finally, literature data were reviewed to compare the minimum water application rate needed to prevent flame spread along the carton packaging versus the sprinkler protection used in the large-scale test. Based on the results of the tests presented in this report, the following conclusions can be made:

- For all small- and large-format Li-ion batteries used in this project, the development of a rack storage fire leading to sprinkler operation should be similar for both an ignition scenario where the fire initiates inside or outside of the carton. This conclusion is based on the following test results:
    - Thermal runaway of the 20 Ah polymer pouch battery used in this project did not result in battery-to-battery propagation within the carton. Experimental data have shown that thermal runaway of up to three batteries simultaneously within a single carton did not propagate to the adjacent batteries within the same carton.
    - There is not sufficient air within a carton to support combustion of a single 20 Ah polymer pouch battery. Thus, the fire propagation primarily occurs outside of the carton. In addition, review of literature data has shown that battery-to-battery

propagation following thermal runaway of small-format cylindrical batteries occurs after the carton has breached[ix].

- Once an external fire is present, flame propagation along the carton material will dominate the fire development leading to sprinkler operation and will occur before the batteries contribute to the overall fire severity.

- The sprinkler system used in the large-scale fire test was sufficient to protect against a fire where the Li-ion batteries were contributing more to the overall fire severity than occurred in the large-scale test. This conclusion is based on the following analysis:
  - Intermediate-scale testing, designed to delay the application of protection water until the batteries were contributing to the overall fire, confirmed the adequacy of sprinkler protection guidance resulting from the successful large-scale fire test.
  - In addition, review of literature data provided in Reference [x] has shown that a lower sprinkler discharge rate than used in the large-scale fire test can also control or suppress fire development along corrugated board cartons.

The best protection recommendations based on current knowledge, for each Li-ion battery included in this project, are summarized below. All ceiling-level sprinkler protection should be installed in accordance with FM Global Property Loss Prevention Data Sheet 2-0 (DS 2-0), *Installation Guidelines for Automatic Sprinklers*, January 2014. The protection recommendations are:

- Li-ion polymer pouch batteries (*i.e.*, capacity up to 20 Ah at ≤ 50% SOC) and Li-ion cylindrical batteries (*i.e.,* capacity up to 2.6 Ah at ≤ 50% SOC):
  - For a single unconfined pallet load of batteries stored on the floor to a maximum of 1.5 m (5 ft) high, protect as an HC-3 occupancy per FM Global Property Loss Prevention Data Sheet 3-26, *Fire Protection Water Demand for Nonstorage Sprinklered Properties*, July 2011. Additionally, maintain a minimum of 3.0 m (10 ft) separation between adjacent combustibles.
  - For batteries stored solid pile, palletized, or in racks up to 4.6 m (15 ft) under a ceiling up to 12.2 m (40 ft) high, protect with quick-response, pendent, sprinklers with a 165°F (74°C) nominal temperature rating. Protection options include:
    - K320 L/min/bar$^{1/2}$ sprinklers @ 2.4 bar (K22.4 @ 35 psi). The water flow demand should allow for 12 sprinkler operations.

[ix] H. Webster, "Flammability Assessment of Bulk-Packed, Rechargeable Lithium-Ion Cells in Transport Category Aircraft," U.S. Department of Transportation Federal Aviation Administration, DOT/FAA/AR-06/38, September 2006.

[x] S. Thumuluru and Y. Xin, "An Experimental Study of Pre-Wetting on Fire Propagation in Parallel Panels," in *Proceedings of the 13th International Fire Science and Engineering Conference (INTERFLAM 2015)*, Windsor, UK, 2013, pp. 317-326.

        - K360 L/min/bar$^{1/2}$ sprinklers @ 2.4 bar (K25.2 @ 35 psi). The water flow demand should allow for 12 sprinkler operations

    - For batteries stored higher than 4.6 m (15 ft) or ceiling heights greater than 12.2 m (40 ft), store batteries in racks and protect with Scheme A per Section D.2.2.1 of FM Global Property Loss Prevention Data Sheet 7-29, *Ignitable Liquid Storage in Portable Containers*, April 2012 (DS 7-29).

- Li-ion power tool packs (*i.e.,* comprised of 18650-format cylindrical batteries with a total pack capacity up to 26 Ah at ≤ 50% SOC):

    - Protect in-process storage of power tool packs as an HC-3 occupancy per FM Global Property Loss Prevention Data Sheet 3-26, *Fire Protection Water Demand for Nonstorage Sprinklered Properties*, July 2011. Limit in-process storage area to 19 m^2 (200 ft^2) and one pallet high. Additionally, maintain a minimum of 2.4 m (8 ft) separation between adjacent combustibles.

    - For power tool packs stored up to 4.6 m (15 ft) high under a ceiling up to 12.2 m (40 ft), protect as FM Global standard cartoned unexpanded plastic (CUP) commodity per FM Global Property Loss Prevention Data Sheet 8-9, *Storage of Class 1, 2, 3, 4 and Plastic Commodities*, FM Global, July 2011.

    - For power tool packs stored higher than 4.6 m (15 ft) or ceiling heights greater than 12.2 m (40 ft), store batteries in racks and protect with Scheme A per Section D.2.2.1 of DS 7-29.

Storage beyond the above listed conditions, including battery characteristics (*e.g.*, SOC, quantity of electrolyte, and format) and packaging components (e.g., cartons and dividers), requires a more robust protection scheme to account for several unknowns that can negatively affect protection effectiveness. Fire Protection Scheme A combines in-rack automatic sprinklers (IRAS) and horizontal barriers for protection of high-hazard commodities, such as rack storage of ignitable liquids or level 3 aerosols. Complete specifications and drawings can be found in Section D.2.2.1 of DS 7-29. Similar specifications can be found in Section E.2 of FM Global Property Loss Prevention Data Sheet 7-31, *Storage of Aerosol Products*, January 2012. This system design is expected to provide the highest level of protection required for storage of the Li-ion batteries tested in this project and can be applied to array configurations beyond the scope of this project.

Abstract

Protection recommendations for warehouse storage of cartoned Li-ion batteries have been developed through fire testing and comparison to analogous commodities with similar hazard characteristics. A unique approach was developed that incorporated four different fire test evaluations, ranging from small- to large-scale, with the goal of extending the application of a successful large-scale fire test to additional types of Li-ion batteries. A reduced-commodity test evaluated the flammability characteristics of large-format, 20 Ah Li-ion polymer batteries, compared to FM Global's standard commodities and previously tested small-format Li-ion batteries. The performance of ceiling-level sprinkler protection was then assessed with a large-scale sprinklered fire test of the large-format 20 Ah polymer pouch batteries. Two supplemental tasks reinforced the sprinkler protection guidance resulting from the large-scale fire test. The impact of internal ignition within a pallet load of batteries versus the external ignition typically used in large-scale fire testing was assessed through small-scale testing. Finally, the effectiveness of sprinkler water at suppressing a fire at a later stage of battery involvement than could be achieved in the large-scale test was assessed through intermediate-scale testing. Where applicable, best protection recommendations based on current knowledge have been provided.

Acknowledgements

The author thanks Mr. R. Chmura, Mr. J. Chaffee, Mr. M. Skidmore and the entire FM Global Research Campus crew for their efforts in conducting the fire tests. There were several testing phases included in this project that utilized the talented personnel of many laboratories. The diligent oversight of project safety and hazardous material disposal by Mrs. J. Pitocco ensured personnel safety throughout this project.

The author greatly acknowledges the discussion and input from the FM Global Engineering Standards group. Their expertise in loss prevention allowed for definitive protection recommendations, improving the practical application of this work.

The author further thanks Ms. Kathleen Almand, of the Fire Protection Research Foundation, and the members of the Property Insurance Research Group for their insightful discussions. In addition, the funding provided by PIRG members and other sponsors for the procurement of Lithium-ion batteries and disposal services was essential to the economic feasibility of this project.

Finally, the author would like to thank Ms. Denise Staplins for processing this report.

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1. **Introduction**

Fire protection guidance for warehouse storage of lithium ion (Li-ion) batteries presently remains a relatively unexplored topic within the fire protection community. At the same time, demand for Li-ion batteries continues to grow for applications such as electric and hybrid electric vehicles, consumer electronics, and energy storage systems. This is highlighted by a 2013 report that forecasted the global Li-ion battery market will increase from US$11.7 billion in 2012 to US$33.1 billion by 2019 [1]. As manufacturing capacity grows to meet the new global demand, so too will the volume of batteries stored in warehouses.

The fire hazards inherent to Li-ion battery technology are well documented in many overview documents [2, 3, 4, 5] and through experimental studies [6, 7, 8, 9, 10, 11, 12, 13]. The unique potential for thermal runaway reactions to spread a fire differentiates Li-ion batteries from typical ordinary combustible materials found in warehouse storage. As a result, neither *FM Global Property Loss Prevention Data Sheets* nor National Fire Protection Association Standard 13, "Standard for the Installation of Sprinkler Systems," [14] currently contain specific, research based, sprinkler installation recommendations or requirements for Li-ion battery storage. Consequently, the existing approach for sprinkler protection often relies on designs for high-hazard commodities, *e.g.,* automatic in-rack sprinklers [15].

This report describes part of a multi-phase project conducted in conjunction with the Property Insurance Research Group (PIRG) and in collaboration the Fire Protection Research Foundation (FPRF). The previous two phases of the project included a use and hazard assessment report [16] and a series of reduced-commodity fire tests comparing the flammability characteristics of several Li-ion batteries and FM Global standard cartoned commodities [17, 15]. These tests showed that bulk storage of small-format Li-ion batteries exhibits similar fire growth leading to first sprinkler operation as cartoned commodities. Further, it was determined that the time required for involvement for Li-ion batteries in a fully developed fire is on the order of five minutes. These conclusions provided the basis for developing sprinkler protection recommendations for small-format Li-ion batteries in bulk storage, with the goal of suppressing the fire before the anticipated time of involvement of the batteries. The current project evaluates ceiling-only sprinkler protection based on large-scale sprinklered fire test experience of Li-ion batteries.

A consultancy company, Exponent Inc., was retained by FPRF to provide a detailed description of the batteries and prepare a summary report of the project findings [18].

FM Global donated the resources associated with conducting the research program, including storage and cleanup of the Li-ion batteries. The batteries used in the test were donated by a private supplier. Disposal and recycling services were donated by a waste management company specializing in disposal of Li-ion batteries. The balance of the costs, which included program management services, was supplied by PIRG.

2. **Experimental Program**

The methodology for this project consisted of a comparison of the free-burn flammability characteristics of the available large-format Li-ion polymer pouch battery to FM Global standard commodities and previously tested small-format Li-ion batteries in a rack-storage array. A large-scale fire test then assessed the performance of ceiling-level sprinkler protection. The goal of this experimental approach was to maximize the application of the successful large-scale fire test result. For example, adequate sprinkler protection established in a large-scale test may be applied to all Li-ion batteries that are shown in the reduced-commodity evaluation to pose a hazard less than or equal to that of the battery used in the large-scale test.

A supplemental task for this project involved assessing the impact of internal ignition within a pallet load of batteries versus the external ignition typically used in large-scale fire testing. A separate task assessed the effectiveness of sprinkler water at suppressing a fire at a later stage of battery involvement than can be achieved in the large-scale test. Both of these tasks reinforced the adequacy of sprinkler protection guidance resulting from the successful large-scale fire test.

2.1 Test Facility

Testing for this program was primarily conducted in the Large Burn Laboratory located in the Fire Technology Laboratory at the FM Global Research Campus in West Glocester, Rhode Island, USA. Figure 2-1 is a plan view of the LBL showing the north movable ceiling, the south movable ceiling, and the 20-MW Fire Products Collector (FPC).

The 20-MW FPC, used for the reduced-commodity test described in Section 3, consists of an 11 m (36 ft) diameter inlet that tapers down to a 3.0 m (10 ft) diameter duct. The inlet to the 20-MW FPC is at an elevation of 11.3 m (37 ft). Gas concentration, velocity, temperature, and moisture measurements are made within the FPC duct. Beyond the measurement location, the exhaust duct connects to a wet electrostatic precipitator (WESP) prior to the gases venting to the atmosphere. The air exhaust rate was set to 71 m^3/s (150,000 ft^3/min).

The north movable ceiling, used for the large-scale fire test described in Section 4, is smooth, flat, and horizontal. The ceiling measures 24.4 m x 24.4 m (80 ft x 80 ft) and is adjustable for heights above the floor ranging from 3.0 m to 18.3 m (10 ft to 60 ft). The air emission control system (AECS) exhaust ducting consists of four extraction points, located at the lab ceiling, that merge into a single duct with a cross sectional area of 6.1 m^2 (66 ft^2). Gas concentration, velocity, temperature, and moisture measurements are made downstream of the manifold. Beyond the measurement location, the exhaust duct connects to a wet electrostatic precipitator (WESP) prior to the gases venting to the atmosphere. The air exhaust rate was to 94 m^3/s (200,000 ft^3/min).

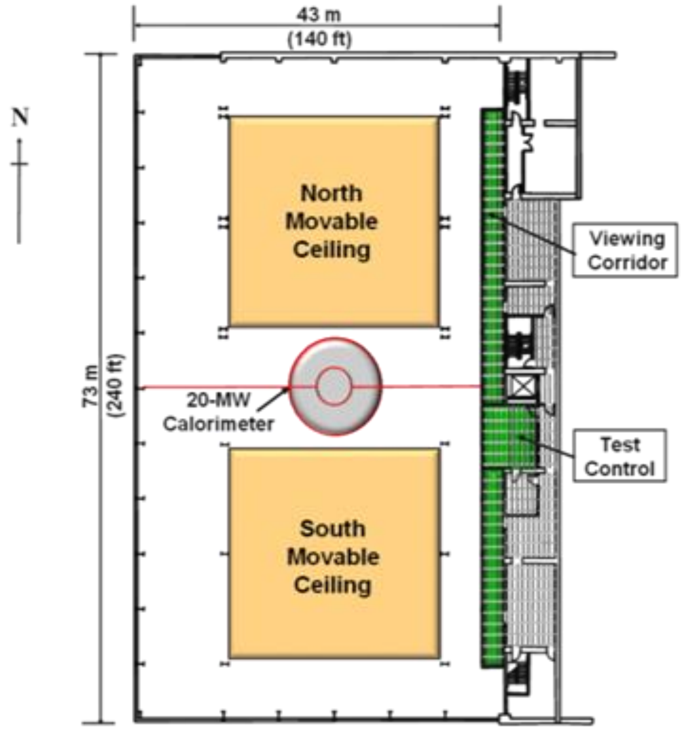


Figure 2-1: Illustration of FM Global Large Burn Laboratory test locations.

2.2 Li-ion Battery Test Commodity

The Li-ion battery available for this project was a 20 Ah polymer pouch battery and the specifications are shown in Table 2-1. The battery is constructed by stacking alternating layers of electrodes, which are then enclosed in foil pouches with heat-sealed seams, Figure 2-2.

It is important to note that the 20 Ah battery used in this project contained approximately 7% electrolyte per total mass of the battery. This represents a similar combustible loading compared to the smaller capacity Li-ion batteries (*i.e.*, 2.6 Ah) used in the previous study, which contained approximately 5% electrolyte for the cylindrical battery and 8% for the polymer pouch battery [15]. The listed state-of-charge is consistent with the typical storage condition for each battery.

The packaging, as received from the supplier, consisted of a 430 mm × 330 mm × 150 mm (16.75 in. x 12.81 in. x 5.75 in.) corrugated containerboard carton. Each carton contained 20 batteries separated by nested polystyrene plastic dividers, Figure 2-3. This packaging and the battery layout is consistent with the previously tested small-format Li-ion polymer batteries [15].

The pallet load design consisted of 56 cartons arranged among seven levels of eight cartons each for a total of 1,120 batteries per pallet load, Figure 2-4. Consistent with the pallet design received from the supplier, the cartons are arranged in a "doughnut shape," resulting in an open area at the center of pallet. The orientation of the cartons alternated each level for stack stability and to ensure consistency in the battery layout on all sides of the pallet load. The overall dimensions of the pallet load were 1,080 mm x 1,080 mm x 1,020 mm tall (42.5 in. x 42.5 in x 40.25 in.).

Table 2-1: Lithium-ion battery specifications. *[courtesy of Exponent, Inc.]*

Specification	Value
Voltage	3.3 V
Capacity	20 Ah
Dimensions	7.25 mm x 160 mm x 227 mm (0.3 in. x 6.3 in. x 8.9 in.)
Mass	490 g (1.1 lb)
Chemistry	Lithium iron phosphate ($LiFePO_4$)
Approximate Electrolyte Mass	34 g (0.08 lb)
Approximate State-of-Charge	50%

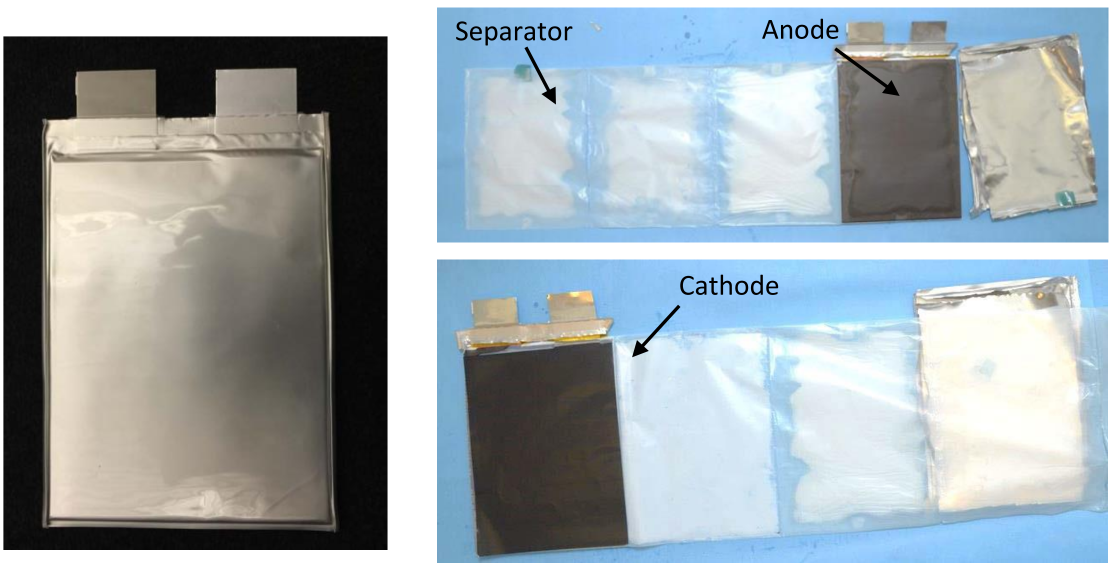


Figure 2-2: Li-ion polymer pouch battery; outside foil pouch shown on left, internal components shown on right. *(images courtesy of Exponent, Inc.)*

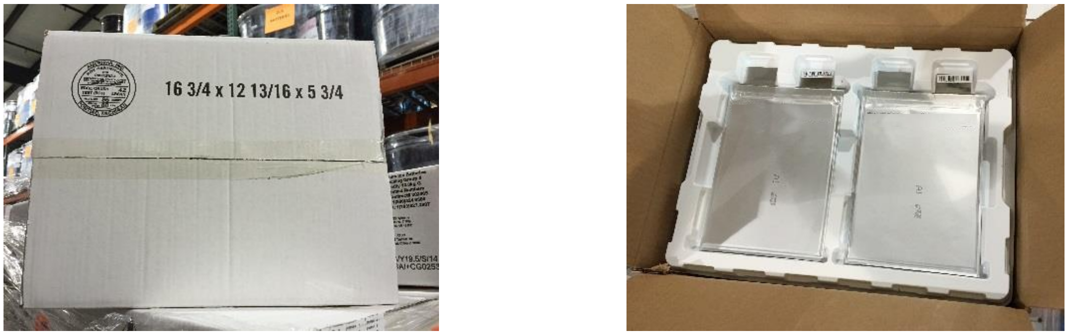


Figure 2-3: Packaging images; individual carton shown on left and top view of packaging shown on right.

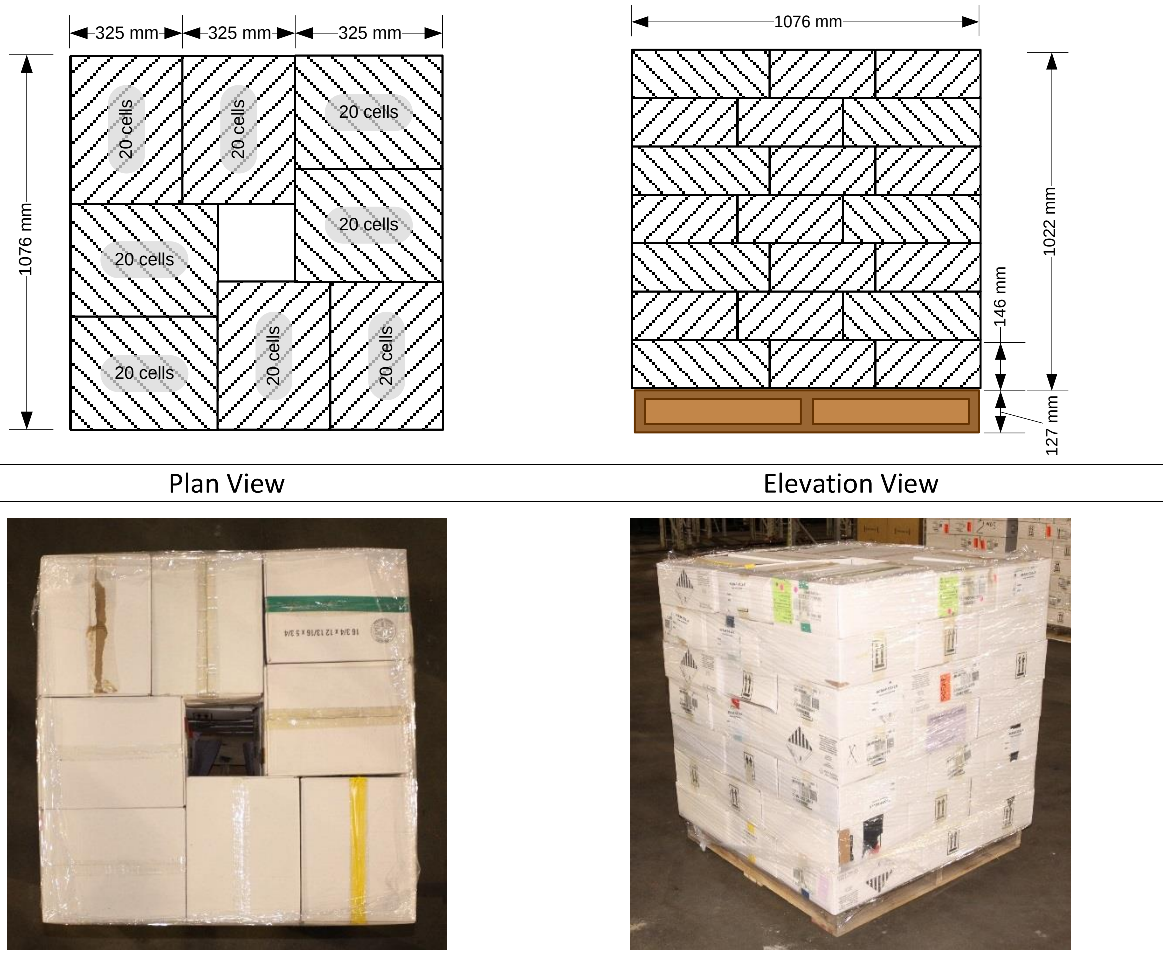


Figure 2-4: Li-ion polymer pouch battery pallet layout; top view shown on left and elevation view shown on right.

As shown in Table 2-2, the combustible loading per carton of batteries is 86 ± 3.5 MJ. When supported on an FM Global standard wood pallet, the combustible weight of the commodity is approximately 177 kg (390 lb); of this total the cartoned Li-ion battery commodity is 155 kg (340 lb) and the pallet 22 kg (50 lb). The total chemical energy per pallet load is nominally 5,105 ± 117 MJ, based on the above masses and the heat of combustion for each material listed in Section 2.3.

Table 2-2: Combustible load per carton of batteries.

Component	Individual Weight (kg)	Quantity per Carton (ea)	Weight per Carton (kg)	Energy* (MJ)
Carton	0.6	1	0.6	8.3 ± 0.2
Plastic Divider	0.15	10	1.5	58.3 ± 1.5
Electrolyte	0.35	20	0.7	19.6 ± 2.0
		Total:	2.8	86 ± 3.7

* Heat of combustion and uncertainty values are listed in Section 2.3.

2.3 Heats of Combustion

Table 2-3 contains average chemical heat of combustion values for each component of the test commodities. These are average values for each material type and up to 5% variance can be expected with the exception of the Li-ion battery electrolyte. The heat of combustion value for diethyl carbonate (DEC) was used as a representative estimate for electrolyte as it has been shown to be similar to other organic carbonate solvents typically found in Li-ion battery electrolyte [9]. The exact composition of the Li-ion battery electrolytes is unknown, therefore a variance of ±10% was assumed.

Table 2-3: Heat of combustions for test commodities.

Material	Chemical Heat of Combustion, kJ/g (BTU/lb)	Representative Material	Reference
Wood pallet	12.4 ± 0.3 (5,300 ± 130)	Red oak	[19]
Corrugated and paper board	14.4 ± 0.4 (6,200 ± 170)	Newspaper	[19]
Unexpanded plastic	27.5 ± 0.7 (11,800 ± 300)	Polystyrene	[19]
Electrolyte	20.9 ± 2 (9,000 ± 860)	Diethyl carbonate	[20]

2.4 Carton Combustion Parameters and Moisture Content

FM Global carefully controls the material properties of the corrugated board cartons used for construction of all standard cartoned commodities. Testing of the flammability characteristics is conducted with the fire propagation apparatus (FPA) [21]. Among the measurements are the thermal response parameter (TRP)[i] and time to ignition under different heat flux exposures [22]. Measurements for the carton material from the Li-ion batteries were within the benchmark values for the carton material used for FM Global's Class 2 standard commodity. Therefore, all commodities included in this

[i] TRP is a quantification of the ignition resistance of a material and relates the time to ignition to the net heat flux.

evaluation were expected to have a similar initial fire growth rate, before involvement of material contained within the cartons.

In addition, the commodity moisture content of the outer cartons was controlled to within 6.0% ± 2% on a dry basis for each test.

3. **Reduced-Commodity Test**

This section presents the results of the reduced-commodity fire test conducted to evaluate the relative flammability characteristics of the large-format 20 Ah Li-ion polymer pouch battery compared to FM Global's standard commodities and previously tested small-format Li-ion batteries [15].

3.1 Test Configuration

3.1.1 Overview

The test configuration was designed to capture the fire growth characteristics leading to sprinkler operation in a warehouse storage scenario. As shown in Figure 3-1, the array consisted of a three-tier-high, open-frame, single-row steel rack with overall dimensions of approximately 2.4 m long × 1.2 m wide × 4.3 m tall (8 ft × 3.25 ft × 14 ft). This array size was used to represent rack storage up to 4.6 m (15 ft), assuming nominally 1.5 m (5 ft) per tier.

The bottom tier of the array consisted of a non-combustible product (metal liner) supported on a wood pallet. The non-combustible product was constructed to maintain the FM Global standard 1.07 m × 1.07 m × 1.07 m (42 in. × 42 in. × 42 in.) commodity dimensions and representative airflow around the commodity. The upper two tiers consisted of pallets loads of cartoned Li-ion batteries also stacked to maintain the standard FM Global pallet load dimensions.

A summary of the pallet load design can be found in Section 2.2. The total chemical energy of the entire reduced-commodity test array is 21,000 ± 480 MJ, *i.e.,* four pallet loads of commodity plus two additional wood pallets under the first-tier non-combustible product (5,105 x 4 + 278 x 2 ≈ 21,000 MJ).

It should be noted that the pallet design for previous reduced-commodity testing only had test commodity lining the ignition flue of the test array [15]. The increased availability of test commodity for this project allowed for the entire pallet load to be comprised of cartoned Li-ion batteries. Increasing the quantity of batteries allows for greater lateral spread, thus longer duration for sprinkler operation predictions. No impact on the time of battery involvement is expected because battery involvement is predominantly due to the thermal exposure at the ignition flue, which does not change with additional commodity. Comparisons of peak heat release rate between tests should be avoided due to the discrepancy in quantity.

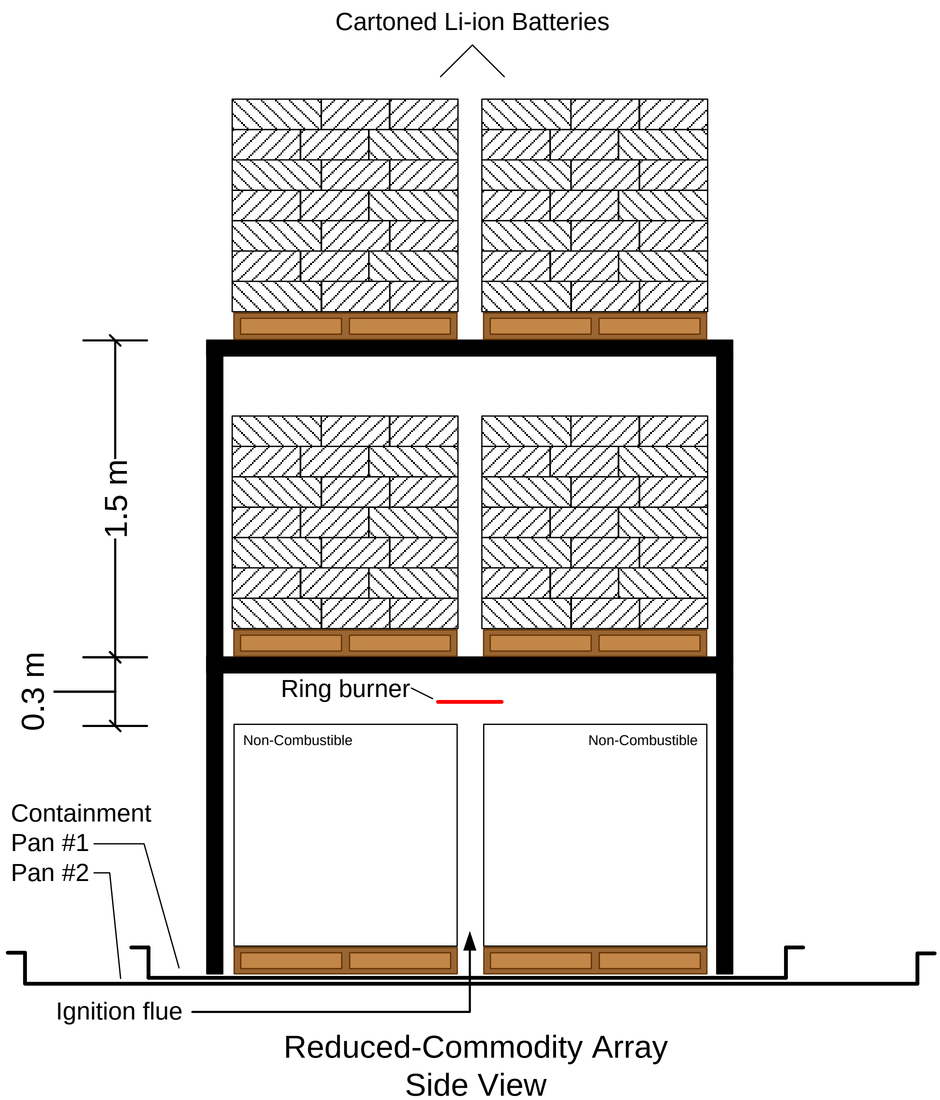


Figure 3-1: Elevation view of reduced-commodity test rack.

3.1.2 Ignition

Ignition was achieved with a 0.33 m (13 in.) diameter propane ring burner centered in the transverse flue 0.15 m (6 in.) below the second-tier test commodity, Figure 3-2. Propane was supplied at a rate of 30 L/min (1.06 ft^3/min), resulting in a nominal 45 kW (chemical) heat release rate, calculated as

$$\dot{q}_{C3H8} = \dot{v} \times \rho \times \Delta H_c.$$

Here $\dot{v}$ is the volume flow in m^3/s, ρ is the density of propane at 20°C (68°F) and 101.3 kPa (1 atm) with a value of 1.88 kg/m^3 (0.12 lb/ft^3), and ΔH_c is the net heat of complete combustion of propane with a value of 46.0 kJ/g.

All fire size estimates in this report include the contribution from the propane ring burner ignition source, which was constant for the test duration. The minimum measurable burner contribution was estimated as 20 kW (convective).

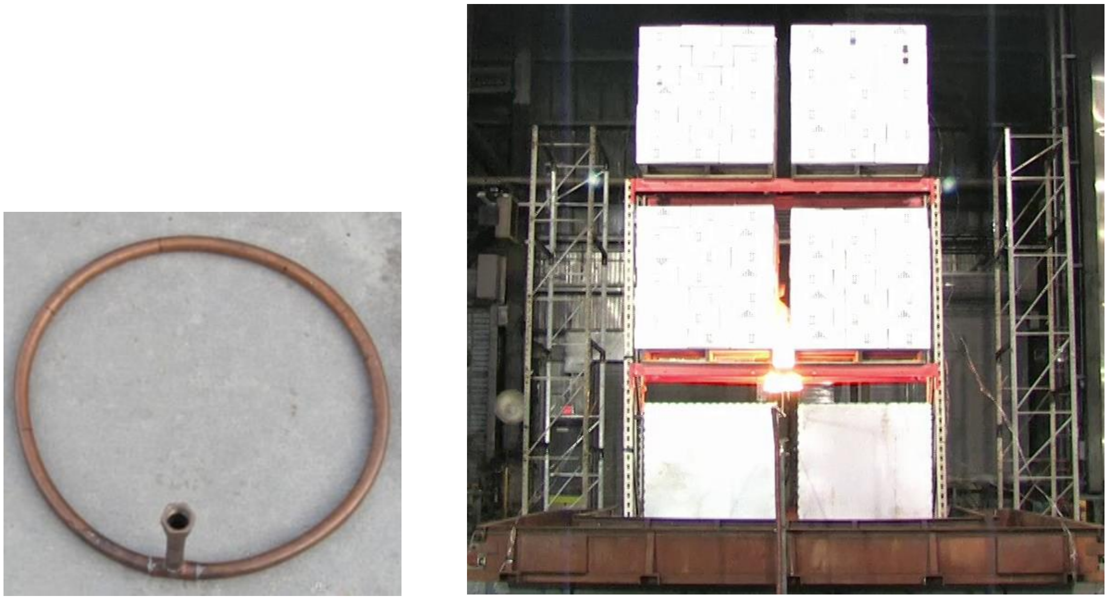


Figure 3-2: Propane ring burner (left) within the rack and fire size within rack (right).

3.2 Documentation and Instrumentation

Documentation for each test included video, still photography, and pertinent measurements necessary to evaluate product performance. All instrumentation was calibrated in accordance with ISO 17025 [23]. The following instrumentation was installed within the laboratory space and the exhaust duct for the 20-MW FPC:

- Environmental conditions, including relative humidity, dry-bulb temperature, and wet-bulb temperature of the air inside and outside of the lab, were measured just prior to each test as well as continually during each test with Vaisala HMT337 humidity and temperature transmitters. Units are located within the laboratory space at four points surrounding the test array and at one outdoor location near the air inlet to the laboratory.
- Convective flow within the FPC duct was measured with a Type K, bare-bead, 6.4 mm (0.252 in.) sheathed, chromel-alumel thermocouple and an impact tube averaging ring.
- Combustion gases within the FPC duct were measured with non-dispersive infrared (NDIR) CO and CO_2 gas analyzers to calculate the generation of carbon monoxide and carbon dioxide; a paramagnetic O_2 analyzer to measure depletion of oxygen; a flame ionization detector (FID) total hydrocarbon (THC) analyzer to measure the release of volatile organic compounds (VOC) as equivalent methane.
- A flow meter and metering valves monitored and controlled the propane flow to the ring burner.
- Twelve thermocouples were used to monitor internal heating of the commodity during the fire test. Each thermocouple was a Type K, grounded junction, 1.6 mm (0.625 in.) diameter, sheathed, chromel-alumel thermocouple. As shown in Figure 3-3, the thermocouples were located 150 mm (6 in.) in from the ignition flue between the third and fourth level of cartons on

both the second- and third-tier commodity. Horizontally, thermocouples were located at the midpoint of the pallet load and 150 mm (6 in.) from the outer edges.

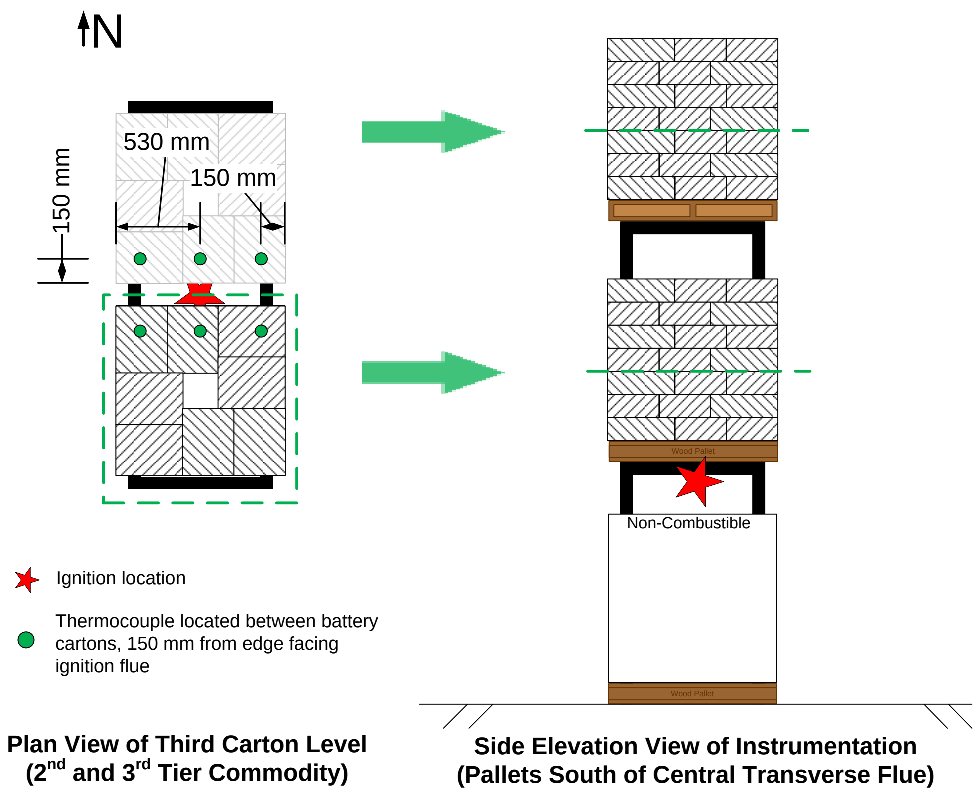


Figure 3-3: Thermocouple locations used during the reduced-commodity test.

The video data included two high-definition video cameras set at floor level, one high-definition camera elevated above the floor, and two infrared cameras (FLIR® T650sc long-wave IR (LWIR) and Bullard® T4MAX) for observation of the fire. A schematic of camera locations is shown in Figure 3-4.

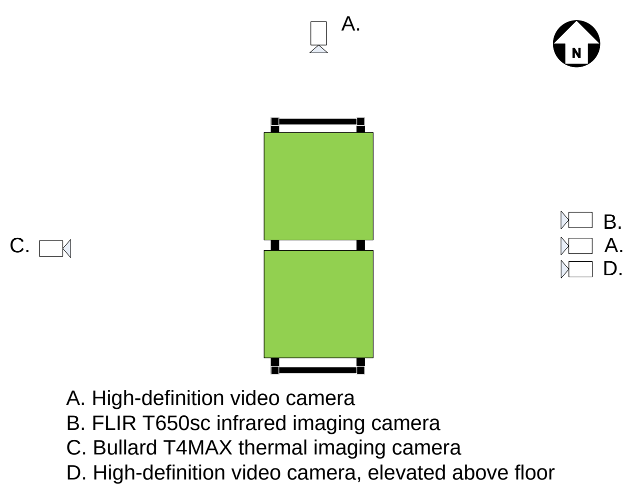


Figure 3-4: Plan view schematic of camera locations (not to scale).

3.3 Test Results

3.3.1 Heat Release Rate

The convective heat release rates, determined from the temperature rise of the gas flow in the FPC, is shown in Figure 3-5. Previous data from small-format Li-ion batteries and FM Global standard cartoned commodities are included as reference. To simplify the comparison, the time of each test has been slightly offset to align with the initial fire growth period of the 20 Ah polymer pouch battery. The data series for CUP and Class 2 commodities, and Li-ion battery packs, are truncated when the test material was largely consumed.

A close-up of the convective heat release rates is provided in Figure 3-6 to highlight the change in fire development that occurs once the cartons are breached and the contents become involved. The commodities are grouped based on their fire development, where materials that exhibit a fire development similar to CUP commodity are shown in the left figure and those similar to Class 2 commodity are shown in the right figure.

The 20 Ah polymer pouch battery exhibited a steady increase in the initial growth until a nominal peak value of 700 kW (convective) was achieved at 1 min (60 s). A delay in the fire growth was then observed as a temporary plateau in the heat release curve until 1 min 15 s (75 s). The fire intensity steadily increased to a value of 2,500 kW at 2 min 30 s (150 s) before exhibiting another temporary plateau until 3 min 10 s (190 s). The fire then increased to a value of 5,300 kW by 5 min 40 s (340 s) before a prolonged plateau until 9 min 30 s (570 s). Though not shown on Figure 3-5, the heat release rate increased to a maximum of 8,750 kW at 10 min 4 s (604 s), followed by a dip in the heat release until 13 min (780 s), before steadily declining as the combustible material was consumed. An estimated 10,300 ± 1,030 MJ (9,800 ± 980 BTU$\times 10^3$) of convective energy was released during the data collection portion (7,200 s total) of this test.

It should be noted that the convective heat release rate was used for this evaluation because it is relevant to determine sprinkler activation and the chemical heat release of a Li-ion battery cannot be accurately measured. The vent gases and combustion products of a Li-ion battery contain significant percentages of CO_2 and O_2 formed from the thermal degradation processes (pyrolysis rather than combustion) of the organic carbonates in the electrolyte. This form of CO_2 and O_2 production does not involve the same energy release of typical combustion processes and may lead to an over-prediction of the chemical heat release rate from carbon dioxide and oxygen consumption calorimetry [15].

Qualitatively, all commodities shown in Figure 3-5 exhibited a similar initial fire development as the flames spread vertically along the corrugated board cartons that lined the fuel space above ignition. After the initial fire development, the 20 Ah polymer pouch batteries exhibit an increased fire hazard compared to the small-format cylindrical and polymer Li-ion batteries, in terms of fire growth rate. The fire growth trend, however, is consistent with that of the power tool packs until the limited quantity of battery packs was consumed. Quantified values of fire growth rate leading to sprinkler operation can be found in Table 3-1.

Note: In Figure 3-5, “cylindrical” refers to the 18650 form factor batteries with a capacity of 2.6 Ah at 3.7 V; battery packs contained ten 18650 cylindrical batteries in a robust plastic casing. All small-format batteries were at a nominal 50% state-of-charge, consistent with their normal storage condition [15].

As highlighted in Figure 3-6, the 20 Ah polymer pouch batteries exhibit a fire growth similar to CUP commodity. It was previously established that the plateau in the heat release rate for CUP commodity occurred as the flames penetrated the cartons and the plastic cups stored within became involved in the fire [15]. For the 20 Ah polymer pouch batteries the subsequent increase in the heat release rate indicates involvement of the batteries and is further discussed in Section 3-5. In the case of the power tool packs, the heavy plastic cases of the battery pack dominated the fire hazard and there was no observable contribution from the batteries before the product was consumed.

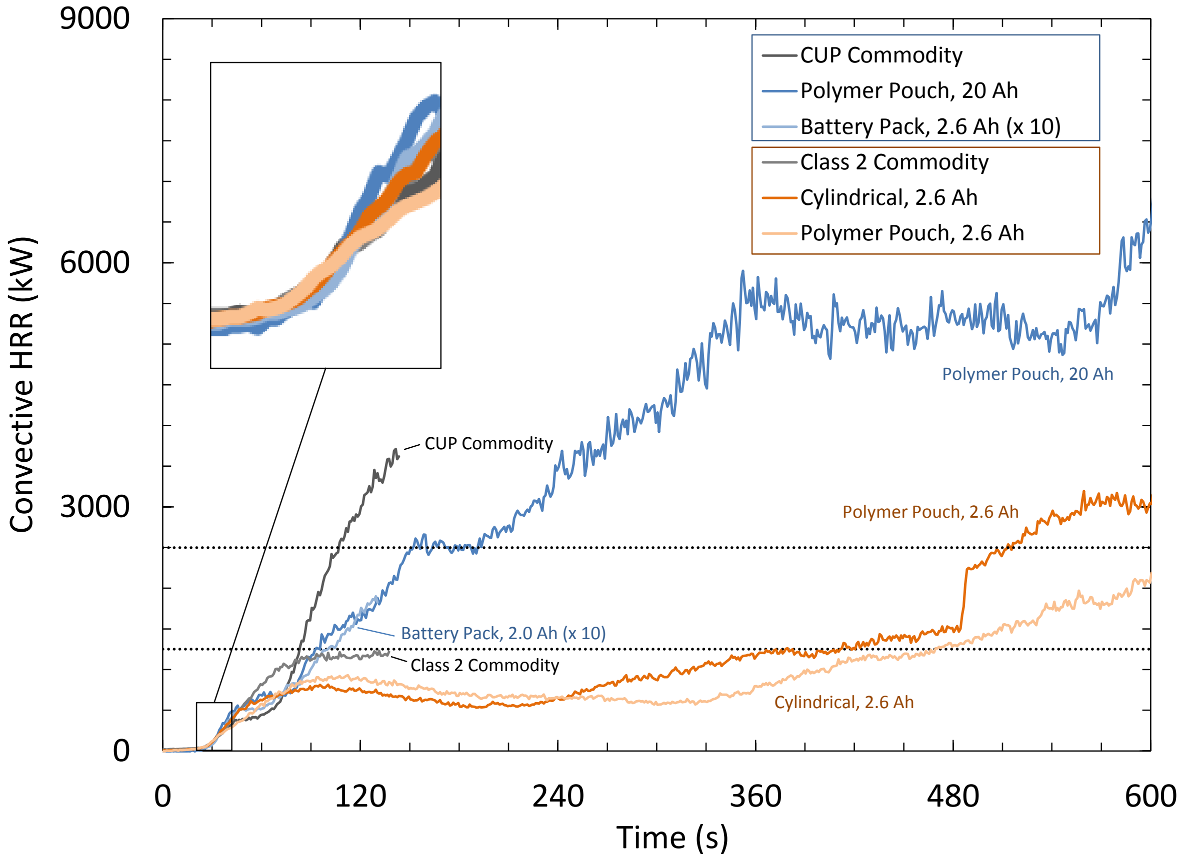


Figure 3-5: Convective heat release rates for 20 Ah polymer pouch battery and small-format Li-ion batteries and FM Global standard commodities. The time of each test has been slightly offset to align the initial fire growth period.

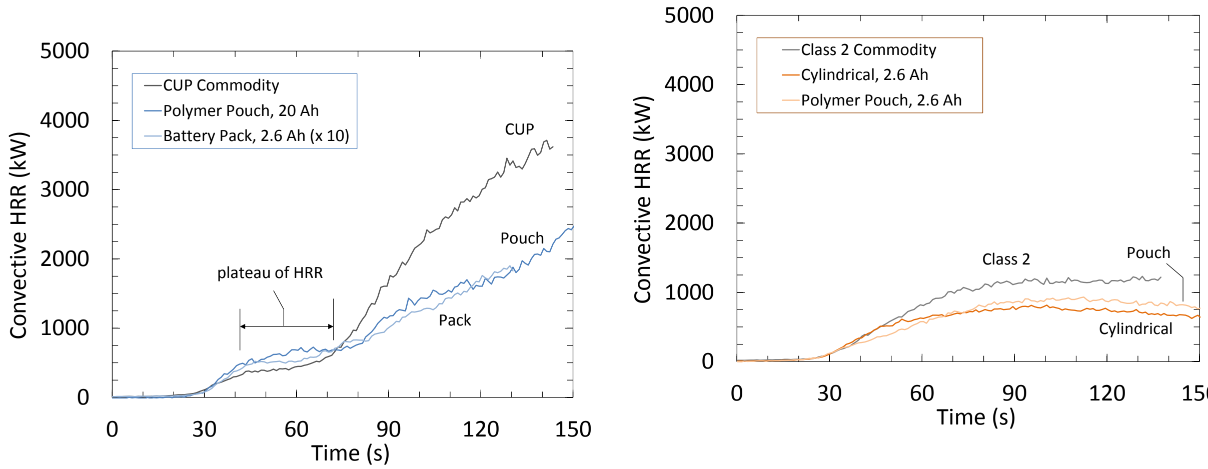


Figure 3-6: Close-up of convective heat release rates for FM Global standard commodities and Li-ion battery commodities; grouping based on similarity in growth curve.

3.3.2 Period of Flammability Characterization to Predict Sprinkler Response

Prediction of sprinkler operations resulting from the fire test should only occur during the period where fire damage was contained within the commodity of interest. For the purpose of this project, once the fire reached the extent of the combustible commodity the results could no longer be used to evaluate sprinkler response, since further fire propagation would not be possible.

It is important to note that additional information regarding the overall fire hazard of each commodity can be obtained after the period of flammability characterization. Evaluation of the time of significant battery involvement in the fire and the overall fire hazard from the quantity of commodity in each test are discussed in Section 3.3.4.

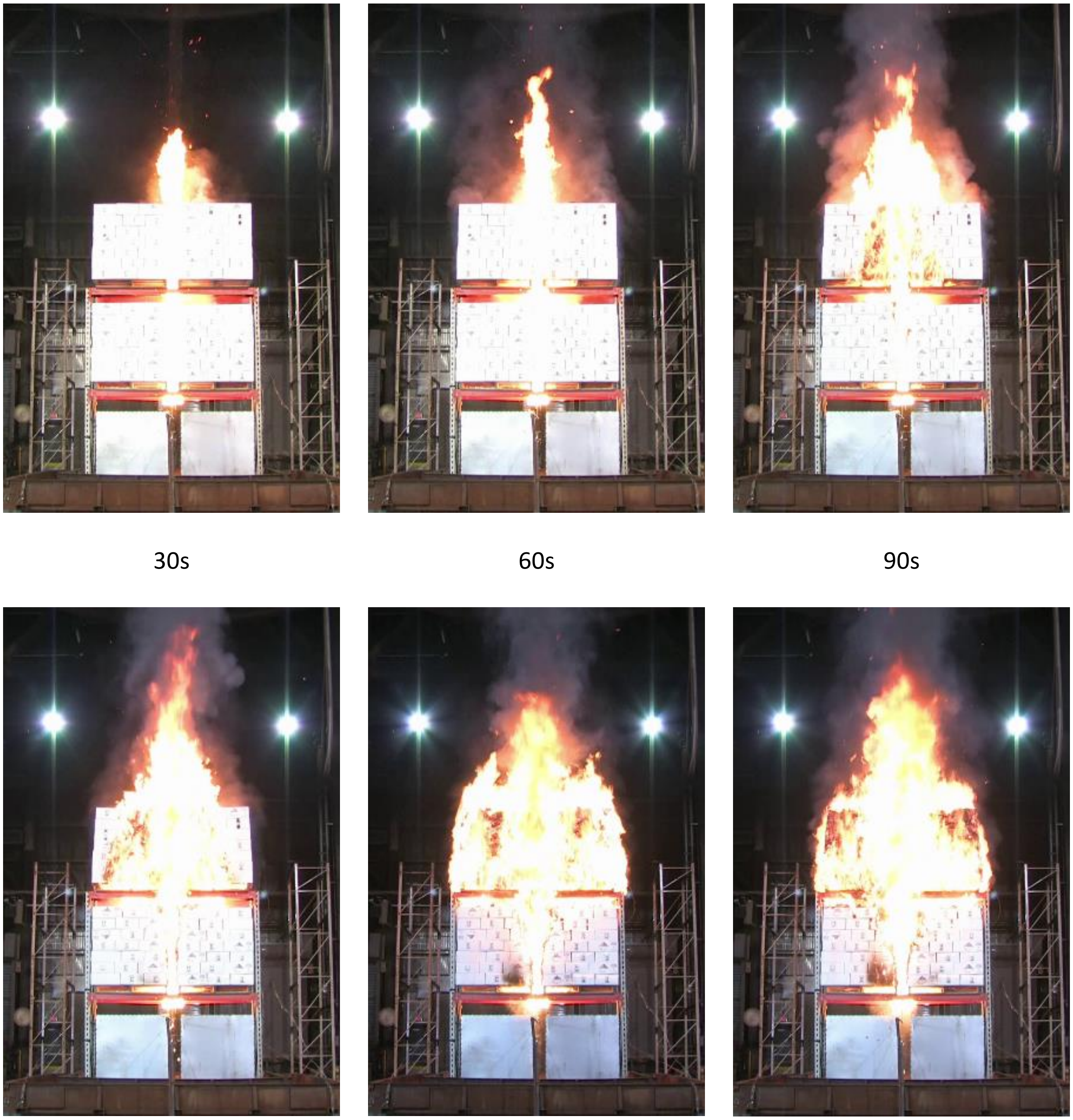
The three monitoring techniques for fire propagation are:

- Standard video cameras to monitor the location of flame attachment (Section 3.3.2.1)
- Thermocouples to monitor internal heating of the commodity (Section 3.3.2.2)
- Product collapse due to fire damage (Section 3.3.2.3)

Based on the combined techniques (*i.e.*, visual observation, internal heating, and commodity collapse), the period of flammability characterization to predict sprinkler operation times can extend to 2 min 30 s ± 5 s (150 ± 5 s) after ignition. This period extends beyond the 1 min 15 s ± 5 s (75 ± 5 s) established for previous results for FM Global standard cartoned commodities and small-format Li-ion batteries because of the additional quantity of test commodity used in the large-format battery test.

3.3.2.1 Flame Attachment (Standard Video Recording)

Figure 3-7 shows a photographic time evolution of the fire in 30 s increments after ignition of the propane burner. In can be seen that the fire was contained within the ignition flue at 30 s, with flames extending approximately 0.3 m (1 ft) above the array. At 1 min (60 s), flames had spread about one-third of the pallet width on the third tier. The fire then began to spread laterally on the third tier, reaching the extents of the commodity by 2 min 20 s (150 s). Lateral spread along the second-tier commodity began at 3 min (180 s) after ignition.



30s 60s 90s

120 s 150 s 180 s

Figure 3-7: Test images shown in 30 s increments from ignition for the large-format polymer pouch batteries.

3.3.2.2 Internal Heat of Commodity (Thermocouples)

Internal heating of the commodity was measured with thermocouples located between battery cartons 150 mm (6 in.) in from the ignition flue. As detailed in Section 3.2, the thermocouples were located between the third and fourth level of cartons on both the second- and third-tier commodity. Horizontally, thermocouples were located at the midpoint of the pallet load and 150 mm (6 in.) from the outer edges.

Figure 3-8 presents the thermocouple measurements acquired during the fire test. The convective heat release rate is included for reference to the time evolvement of the fire. The threshold temperature of 180^{o}C (356^{o}F) was added based on the oxidation temperature of electrolyte that results in a high-rate runaway reaction (peak rates > 100^{o}C/min) [9]. A legend is provided to describe the thermocouple location within the test array. Notable data series are additionally labeled using the following convention: tier 2 or tier 3 (T2/3), north or south pallet load (N/S), and horizontal position of West, center, or East (W/C/E). For example, T3-S-C references the thermocouple located at the center of the third-tier pallet load on the south side of the rack.

For this test, the threshold temperature was first exceeded by the thermocouple on tier 3, South pallet load, center location (T3-S-C) at 2 min 53 s (173 s) after ignition. Exceedance of the threshold temperature is only one measure of the potential for battery involvement. Since the thermocouples are located between the cartons, not directly connected to the batteries, high temperatures could also occur due to involvement of the cartons or plastic dividers.

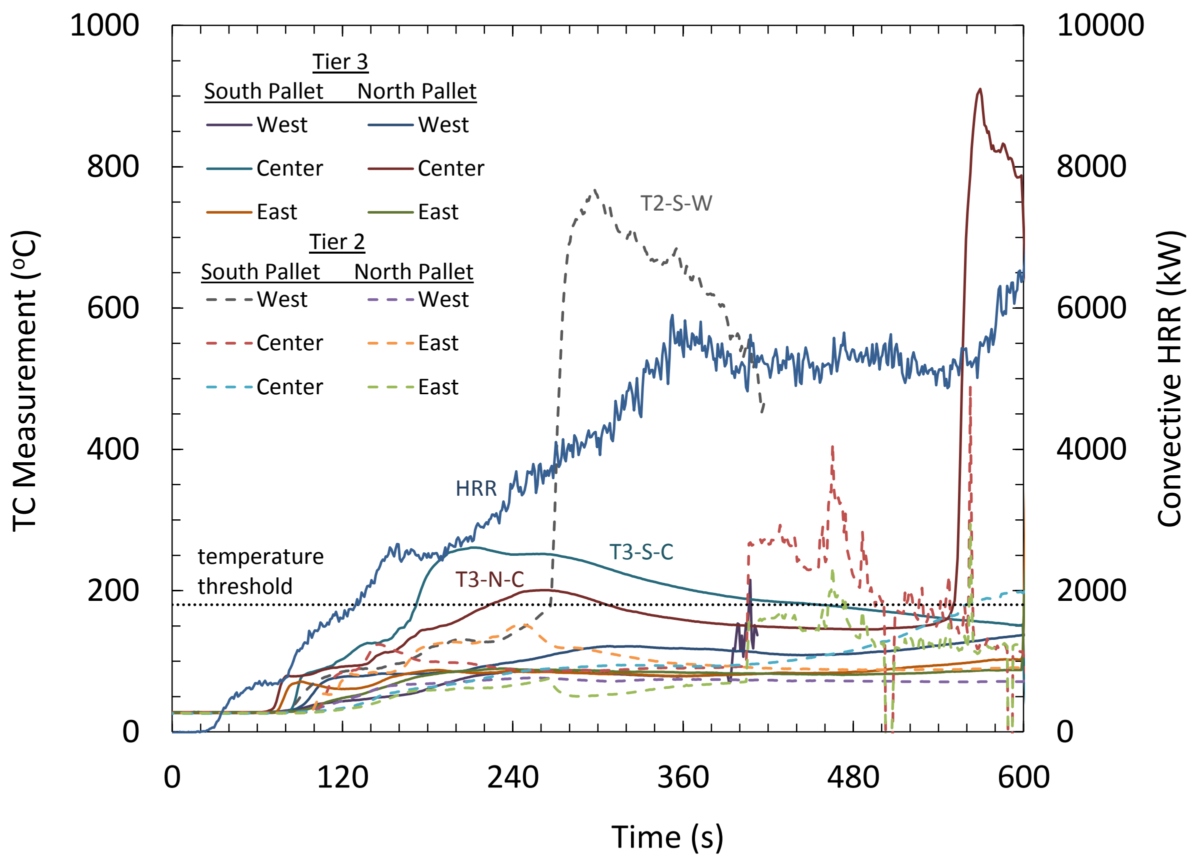


Figure 3-8: Internal heating of commodity using TCs located within the test commodity.

3.3.2.3 Commodity Collapse

Collapse of commodity due to fire damage is common in all rack storage tests and does not impact the validity of the test. In the previous reduced-commodity tests with small-format Li-ion batteries, collapse could significantly impact the fire development because the non-combustible portion of the pallet load might be exposed [15]. This concern does not exist in the present study, where the entire pallet load was comprised of Li-ion batteries. However, for comparison to the previous battery tests, collapse should not occur during the period where sprinkler predictions are made. It was assumed that major collapse, visually estimated as greater than 10% of the overall quantity of Li-ion batteries, was sufficient to impact the fire development. All other commodity collapse was considered minor.

During the 20 Ah polymer pouch battery test, individual batteries began falling from the third tier of the array sporadically at 3 min 48 s (228 s). A major collapse of commodity occurred at 7 min 15 s (435 s) after ignition, followed by sporadic minor collapses. A catastrophic failure of the rack beam supporting the third tier commodity occurred at 9 min 56 s (596 s), resulting in complete collapse of the commodity. Based on these observations, collapse impacting the fire development (*i.e.*, greater than 10% of available batteries) occurred at 9 min 56 s (596 s) after ignition.

3.3.3 Predicted Sprinkler Response

All sprinkler responses were calculated using the method described in Reference [15] and are based on the convective heat release rates from ignition, which are illustrated in Figure 3-5. Figure 3-9 provides the results of the predicted response of a quick-response sprinkler where the ceiling height was set to 9.1 m (30 ft) above the floor (*i.e.,* 4.9 m (16 ft) above the array). The fire growth rate was calculated as a 10 s linear trend of the convective fire size leading up to link operation.

Table 3-1 contains complete sprinkler response calculations for quick-response sprinklers, having an RTI of 27.6 $(m\text{-}s)^{1/2}$ (50 $(ft\text{-}s)^{1/2}$), with ceiling heights between 7.6 m and 12.2 m (25 ft and 40 ft) where the storage array was nominally 4.6 m (15 ft) high. Corresponding values for small-format Li-ion batteries and FM Global standard commodities are provided from Reference [15]. It should be noted that fire growth rates nominally within a factor of two and $\dot{Q}_{be}$ values nominally within 30% of the average are considered equivalent.

For a ceiling height of 7.6 m (25 ft), the predetermined sprinkler operation temperature of 74^{o}C (165^{o}F) was reached at 37 s after ignition for the 20 Ah polymer pouch test. The corresponding convective fire size at link operation, $\dot{Q}_{be}$, was 335 kW and the fire growth rate was 33 kW/s. Increasing the ceiling height to 9.1 m (30 ft) resulted in a predicted link operation time of 41 s, $\dot{Q}_{be}$ value of 480 kW, and a fire growth rate of 34 kW/s.

In comparison to previously tested small-format Li-ion batteries, the 20 Ah polymer pouch batteries exhibited similar flammability characteristics ($\dot{Q}_{be}$ and fire growth rate) at the time of sprinkler operation. When compared to FM Global standard commodities (both Class 2 and CUP), the 20 Ah polymer pouch batteries tended to display slightly higher flammability characteristics at the time of sprinkler operation.

Using full-pallet loads of batteries allowed for the prediction of sprinkler operations under greater ceiling heights than the previous testing, as discussed in Section 3.1. As a result, Table 3-1 includes sprinkler response calculations for 10.7 m and 12.2 m (35 ft and 40 ft) ceilings. The predicted link operation times were 48 s for a 10.7 m (35 ft) ceiling and 58 s for a 12.2 m (40 ft) ceiling. The corresponding $\dot{Q}_{be}$ values were 549 kW and 688 kW, and fire growth rates were 15 kW/s and 11 kW/s, respectively. The notable decrease in the fire growth rate (at sprinkler operation) compared to calculations at 7.6 m and 9.1 m (25 ft and 30 ft) ceilings is a result of the predicted sprinkler operation during the plateau portion of the heat release rate, which can be seen in Figure 3-9 around 1 min (60 s).

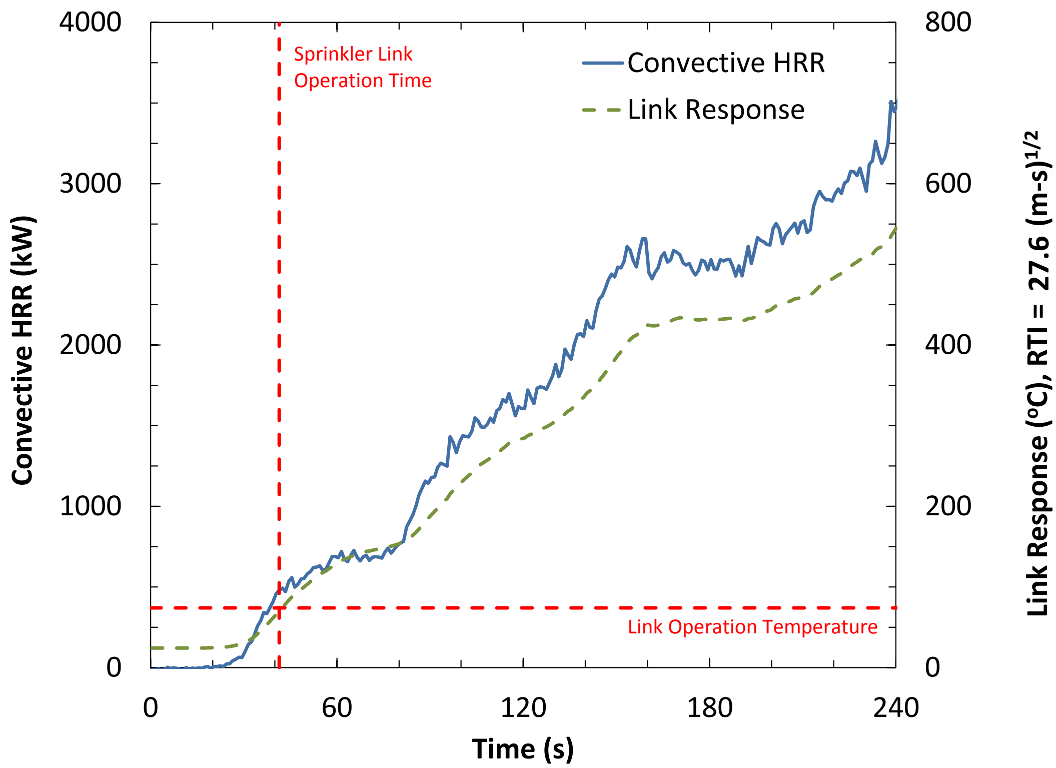


Figure 3-9: Example of sprinkler link response during 20 Ah polymer pouch test; quick-response sprinkler with a 74°C (165°F) temperature rating below a 9.1 m (30 ft) ceiling.

Table 3-1: Predicted operation times for quick-response sprinklers with a link temperature rating of 74°C (165°F) at multiple ceiling heights.

Predicted Sprinkler Response	**Ceiling Height = 7.6 m (25 ft)**		
	Link Operation (s)	**Q_{be} kW**	**Fire Growth (kW/s)**
Li-ion, 20 Ah Polymer Pouch	37	335	33
Li-ion, small-format†	43	270	20
Class 2	59	209	15
CUP	43	232	16
Ceiling Height = 9.1 (30 ft)			
Li-ion, 20 Ah Polymer Pouch	41	480	34
Li-ion, small-format†	77	388	18
Class 2	65	367	24
CUP	52	321	11
Ceiling Height = 10.7 m (35 ft)			
Li-ion, 20 Ah Polymer Pouch	48	549	15
Ceiling Height = 12.2 (40 ft)			
Li-ion, 20 Ah Polymer Pouch	58	688	11

† Represented as the average of the values from the small-format 2.6 Ah cylindrical and polymer battery tests found in Reference [15].

3.3.4 Time of Battery Involvement

For the purpose of this study, battery involvement references the time during the fire development when the batteries are observed to contribute significantly to the fire severity. In a warehouse storage fire scenario, the determination of battery involvement is complicated by the large quantities of combustible packaging components that comprise the test commodities, *i.e.*, wood pallets, plastic dividers, and cartons. By accounting for the contribution of the packaging, it is reasonable to attribute any excess energy release to the combustion of Li-ion batteries.

Figures 3-10 presents the convective heat release rate measured during the early growth portion of the fire. The convective heat release rates for FM Global standard Class 2 and CUP commodities are included for reference. Following the approach used for testing of small-format Li-ion batteries [15], lower and upper threshold values represent the range of time when the batteries became significantly involved in the fire.

The lower threshold value represents the steady-state heat release of FM Global standard Class 2 commodity of 1,250 kW. Exceedance of this threshold value provides a conservative estimate of the contribution to the overall fire severity from the contents stored within the cartons. Before this time, the heat release rate can be attributed solely to the combustion of carton material. As shown in Figure 3-10, the convective HRR for the Li-ion batteries exceeded the lower threshold value at approximately 1 min 30 s (90 s) after ignition.

The time of battery involvement can also be estimated at a later stage in the fire development. As discussed in Section 3-10, suppression tests have shown that the plastic dividers contribute to the fire before the batteries become involved. Thus the increase of the convective HRR that occurs before the plateau at approximately 2 min 30 s (150 s) can be (at least partially) attributed to the plastic dividers. Subsequent exceedance of the upper threshold value at 3 min (180 s) corresponds to the latest time after ignition that the Li-ion batteries are not significantly contributing to the fire severity.

Using the lower and upper threshold values, the time of significant involvement of the 20 Ah polymer pouch battery is estimated to occur between ~ 1 min 30 s (90 s) and ~ 3 min 15 s (195 s) after ignition. Taking the average of these values and rounding to the nearest 30 s increment results in a nominal time of battery involvement of 2 min 30 s (150 s), under free-burn conditions. Before this time, the heat release rate can be attributed to the combustion of packaging components. In comparison, the previously tested small-format Li-ion batteries became involved in the fire significantly later at an estimated 5 min (300 s) after ignition. Thus, the current battery represents a higher hazard commodity based on the flammability characteristics leading to first sprinkler operation and time of battery involvement in the fire.

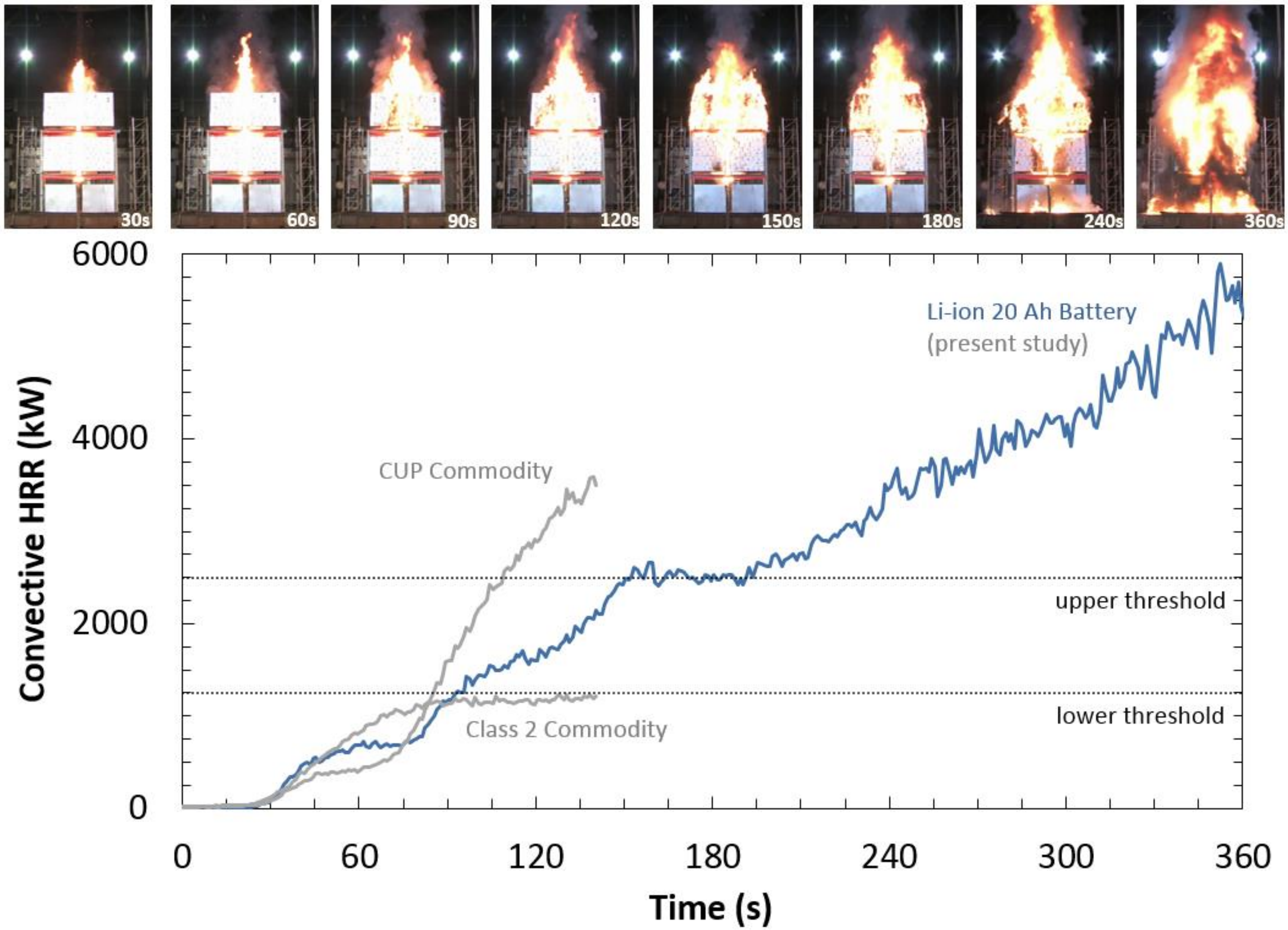


Figure 3-10: Determination of the time of battery involvement.

4. **Large-Scale Fire Test**

This section describes the large-scale sprinklered fire test conducted to determine automatic sprinkler fire protection guidance for warehouse storage of cartoned Li-ion batteries. As discussed in Section 3, the large-format 20 Ah Li-ion polymer pouch battery used in the present study represents a greater hazard than previously tested small-format Li-ion batteries in cartoned warehouse storage [15]. As a result, protection guidance established from the large-scale test can be applied to the small-format cylindrical and polymer Li-ion batteries evaluated during this multi-phase project.

4.1 Test Overview

Figure 4-1 presents a photo of the large-scale test array and Figure 4-2 presents an overview schematic of the array and sprinkler layout. The main fuel array consisted of a three-pallet-load-high open-frame, double-row steel rack under a 12.2 m (40 ft) ceiling. This array size represents rack storage up to 4.6 m (15 ft). The main array measured approximately 7.3 m long × 2.3 m (24 ft × 7.5 ft) wide in a 6 × 2 pallet load arrangement, and included 24 pallet loads of Li-ion battery commodity. The end pallet of each row consisted of FM Global standard cartoned unexpanded plastic (CUP) commodity [24]. A single-row target array containing four pallet loads of the CUP commodity was located across a 1.2 m (4 ft) aisle on either side of the main array. Overall, the target arrays measured approximately 4.9 m × 3.0 m (16 ft × 3 ft). Using the pallet load design, described in Section 2.2, this test included 26,880 batteries packaged in 1,344 cartons.

Figure 4-1: Photo of large-scale test main array, before constructing the target array.

Note that the 24 pallet loads of batteries available for this project were less than the 72 pallet loads of commodity used in a standard three-tier-high large-scale test. In a standard test, the main and target arrays consist of an 8 × 2 and 6 × 2 pallet load arrangement, respectively [25, 26]. As a result, the allowable extent of fire spread for the battery test is less than a standard test because the fire must be contained within the extent of the test commodity. Further details on the evaluation criteria can be found in Section 4.5.

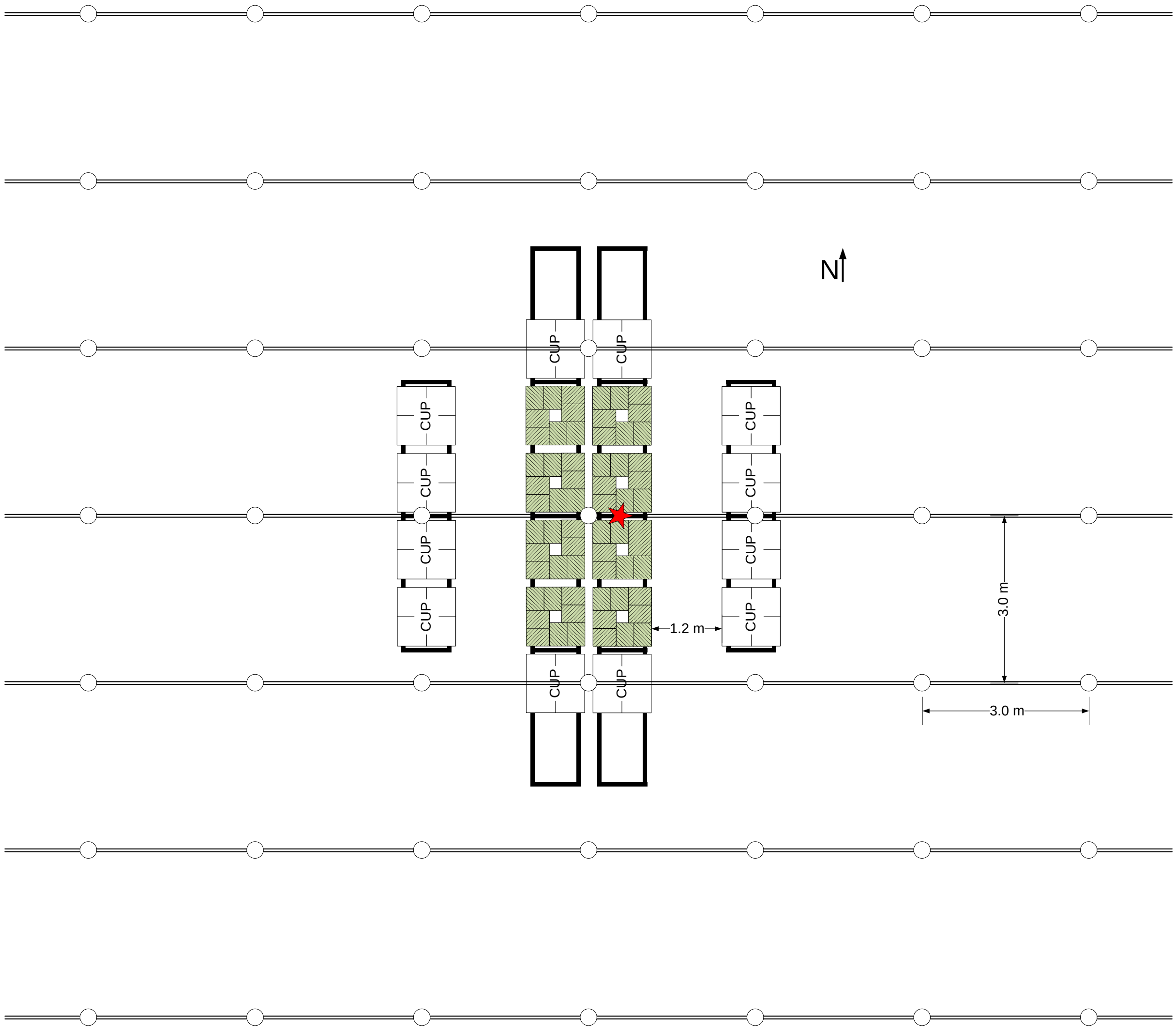


Figure 4-2: Plan view of large-scale test array. Li-ion battery commodity is shown as green cartons. Open circles represent the location of ceiling-level sprinklers. Ignition location at the base of the array is shown as a red star.

4.2 Automatic Sprinkler Protection

Ceiling-level sprinkler protection was provided by an FM Approved sprinkler with a K-factor of 320 L/min/bar^{½} (22.4 gpm/psi^{½}). The sprinkler was of pendent type, with a 74°C (165°F) temperature rating and a nominal RTI of 27.6 m^{½}s^{½} (50 ft^{½}s^{½}). A nominal operating pressure of 2.4 bar (35 psig) provided a discharge of 500 L/min (133 gpm) per sprinkler, resulting in a 53 mm/min (1.3 gpm/ft^2) water density.

Sprinklers were located on 3.0 m × 3.0 m (10 ft × 10 ft) spacing. In accordance with FM Global Property Loss Prevention Data Sheet 2-0, *Installation Guidelines for Automatic Sprinklers* [27], each sprinkler was installed with the heat-sensing link 0.43 m (17 in.) below the ceiling and was oriented with the sprinkler frame arms parallel to the sprinkler pipe. Consistent with FM Global standard procedures for a large-scale fire test, each the sprinkler's heat-sensing link was facing towards the north.

4.3 Ignition

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

Figure 4-3: Igniter locations within the rack, located at the rack uprights. (representative image shown)

4.4 Documentation and Instrumentation

Documentation for each test included video, still photography, and pertinent measurements necessary to evaluate sprinkler performance. All instrumentation was calibrated in accordance with ISO 17025 [23].

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

- Sprinkler protection was provided at 49 locations at the ceiling. Each sprinkler had its operating mechanism included in an electric circuit to determine operation times.
- Bare-bead, 0.8 mm (20-gage), chromel-alumel thermocouples, placed 165 mm (6-1/2 in.) below the ceiling at 125 locations. These thermocouples have been shown to have a response time index (RTI) of 8 ± 1 $m^{1/2}s^{1/2}$ (14.5 ± 1.8 $ft^{1/2}s^{1/2}$).

- Bi-directional probes to measure ceiling jet velocity immediately below the ceiling. Probes were located at four orthogonal locations with radial distances from the ceiling center of 2.1 m and 4.0 m (7 ft and 13 ft) [at 0.12 m (0.4 ft) below the ceiling], and 10.4 m (34 ft) [at 0.46 m (1.5 ft) below the ceiling]. These measurements are available for future analysis but are not discussed in this report.
- Thermocouples imbedded in a cross-shaped steel angle, made from two 51 mm wide x 610 mm long x 6 mm thick (2 in. x 24 in. x 0.25 in.) angle iron segments, attached to the center of the ceiling. Measurements from these thermocouples are referred to as steel temperatures.
- Flow meters and pressure controllers to monitor and control the sprinkler system.
- Combustion gases within the FPC duct were measured with non-dispersive infrared (NDIR) CO and CO_2 gas analyzers to measure the generation of carbon monoxide and carbon dioxide; a paramagnetic O_2 analyzer to measure depletion of oxygen; a flame ionization detector (FID) total hydrocarbon (THC) analyzer to measure the release of volatile organic compounds (VOC) as equivalent methane. THC measurements are available for future analysis but are not discussed in this report.

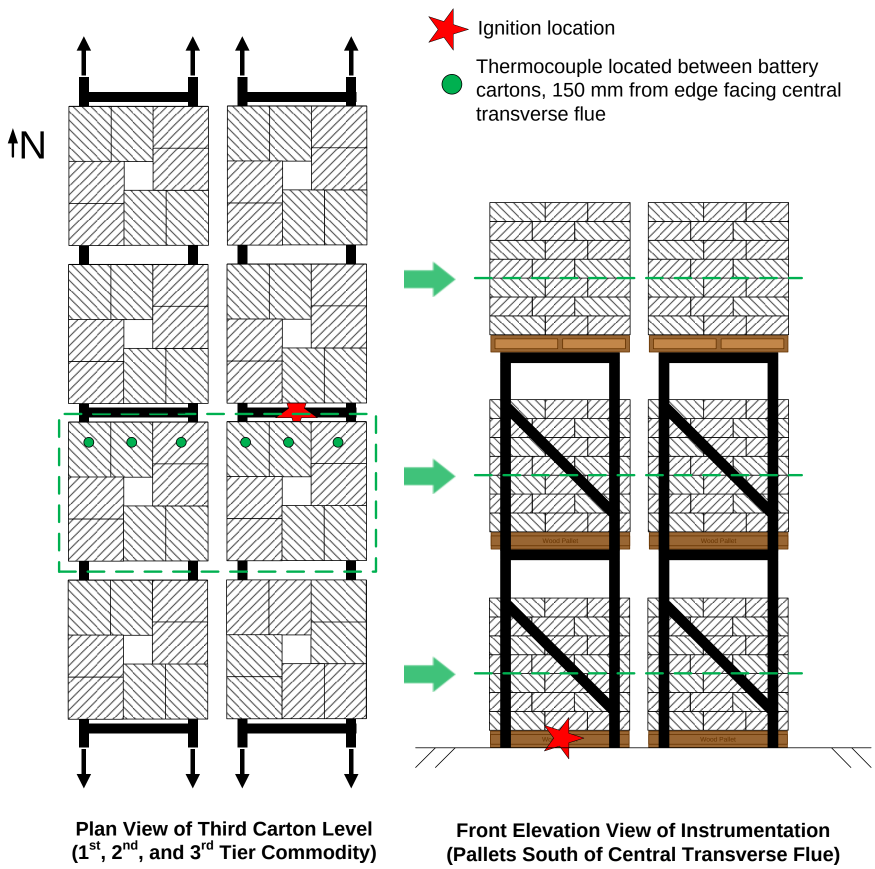


Figure 4-4: Thermocouple locations used during the large-scale test.

- Eighteen thermocouples were used to monitor internal heating of the commodity during the fire test. Each thermocouple was a Type K, grounded junction, 1.6 mm (0.625 in.) diameter, sheathed, chromel-alumel thermocouple. The thermocouples were located 150 mm (6 in.) in from the ignition flue between the third and fourth level of cartons on all three tiers of the commodity. Horizontally, thermocouples were located at the midpoint of the pallet load and 150 mm (6 in.) from the outer edges. An illustration of the thermocouple placement can be found in Figure 4-4.

The video data included two high-definition video cameras located at the floor level, one high-definition camera elevated above the floor, and two infrared cameras (FLIR® T655 long-wave IR (LWIR) and Bullard® T4MAX) for observation of the fire. A schematic of each camera location is shown in Figure 4-5.

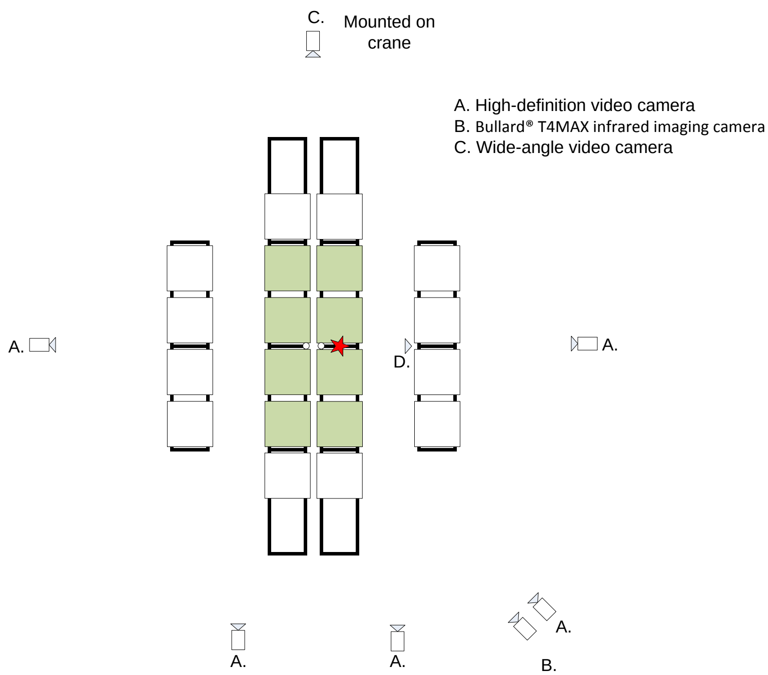


Figure 4-5: Plan view schematic of camera locations (not to scale).

4.5 Evaluation Criteria

Assessment of the sprinkler protection performance was based on its ability to efficiently suppress the test fire. The primary judgment criteria are the number of sprinkler operations, the extent of fire damage, and the magnitude and duration of ceiling steel temperatures.

1) Sprinkler operations. Since this is a unique test configuration, there is no specified number of acceptable sprinkler operations. However, excessive sprinklers along the perimeter of the test ceiling would constitute a failure. Sprinklers operating at the ceiling perimeter would indicate the presence of high-temperature gases at the edge of the ceiling that could have traveled further along the ceiling, operating additional sprinklers, had they been present.

2) Extent of fire spread. Fire damage should be largely confined to the commodity surrounding the central transverse flue (*i.e.*, ignition flue), the fire should not propagate into the CUP commodity capping the array, and there should be no fire spread across the aisle to the target array.

3) Steel TC measurements. The maximum allowable ceiling steel temperature measurement is 538°C (1,000°F). This criterion is based on the assessment that structural steel loses 50-60

percent of its load-bearing strength upon reaching the 538°C (1,000°F) threshold [28, 29]. The loss of strength could cause failure of the ceiling structure resulting in collapse of the roof. Values in excess of these thresholds during a test are taken as an indication of ineffective fire protection.

4.6 Test Results and Data Analysis

A summary of the test conditions and results is shown in Table 4-1. A single sprinkler operated at 1 min 30 s (90 s) after ignition and suppressed the fire. Fire damage remained within the confines of the array and there was no jump to the target commodity. The results in terms of fire damage, steel temperatures, and number of sprinkler operations were within levels specified in Section 4.5 indicating that the sprinkler system provided adequate protection.

Table 4-1: Large-scale fire test setup summary

Test Configuration and Results	Value
Test Configuration	
Commodity	Cartoned 20 Ah Li-ion batteries
Main array dimensions [pallet loads]	6 x 2 x 3
Target array dimensions [pallet loads]	4 x 1 x 3
Flue width, nominal [m (ft)]	0.15 (0.5)
Aisle width [m (ft)]	1.2 (4)
Storage height [m (ft)]	4.6 (15)
Ceiling height [m (ft)]	12.2 (40)
Main array located below - number of sprinklers	1
Ignition location relative to rack	offset
Sprinkler response, nominal [RTI, $m^{1/2}s^{1/2}$ ($ft^{1/2}s^{1/2}$)]	27.6 (50)
Sprinkler rating [°C (°F)]	74 (165)
Sprinkler K-factor [L/min/bar$^{1/2}$ (gpm/psi$^{1/2}$)]	53 (22.4)
Sprinkler discharge pressure [bar (psi)]	2.4 (35)
Sprinkler spacing [m × m (ft × ft)]	3 × 3 (10 × 10)
Test Results	
Sprinkler Operations	1
Total Chemical Energy Released [MJ (BTU x 10^3)]	100 ± 5 (90 ± 5)
Consumed Commodity [pallet load equivalent]	< 1
Target Jump (west only) @ Time [min:s]	No
Maximum Steel Temperature [°C (°F)] @ Time [min:s]	32°C (90°F) @ 1 min 30 s
Test Termination [min:s]	40:00

4.6.1 Test Images

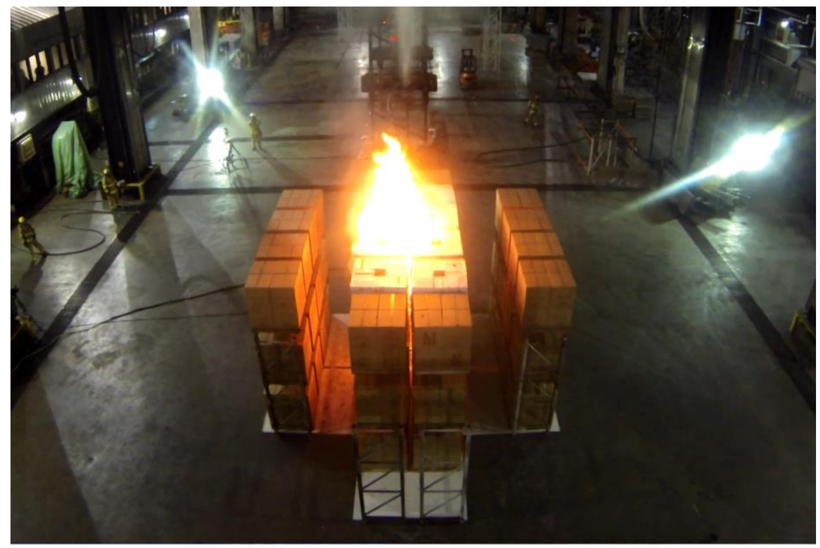
From the fire test images shown in Figures 4-6 and 4-7 it can be seen that the fire within the central transverse flue reached the top of the array by 30 s after ignition. The fire continued to grow and at 1 min (60 s) flames extended approximately 1.5 m (5 ft) above the array. The sprinkler centered over the main array operated at 1 min 30 s (90 s) as flames were spreading across the aisle face of the commodity on the second and third tier, as well as across the longitudinal flue. By 2 min (120 s) the fire was contained within the array, though involvement of the commodity on either side of the central transverse flue on the first and second tiers persisted until approximately 2 min 30 s (150 s). The test was conducted for 40 min (2,400 s) and required only minimal manual firefighter intervention to extinguish a few lingering deep-seated flames.

The extent of damage to the test array is shown in Figure 4-8. All three tiers of commodity surrounding ignition in the central transverse flues were heavily damaged. The top left image shows the damage sustained to the east (aisle) face of the main array. The top right image shows the corresponding damage to the commodity across the longitudinal flue after the east commodity was removed. In both images, a portion of the cartons was charred or consumed allowing involvement of the internal plastic dividers and batteries in the fire. Examples of the damage sustained by the commodity on either side of the central transverse flue, adjacent to ignition, are shown in the bottom right image for the first tier and bottom left image for the second tier.

0 min 30 s (30 s)

1 min 0 s (60 s)

1 min 30 s (90 s)



1 min 30 s (90 s)

Figure 4-6: Images of large-scale fire test.

~ 2 min (120 s)

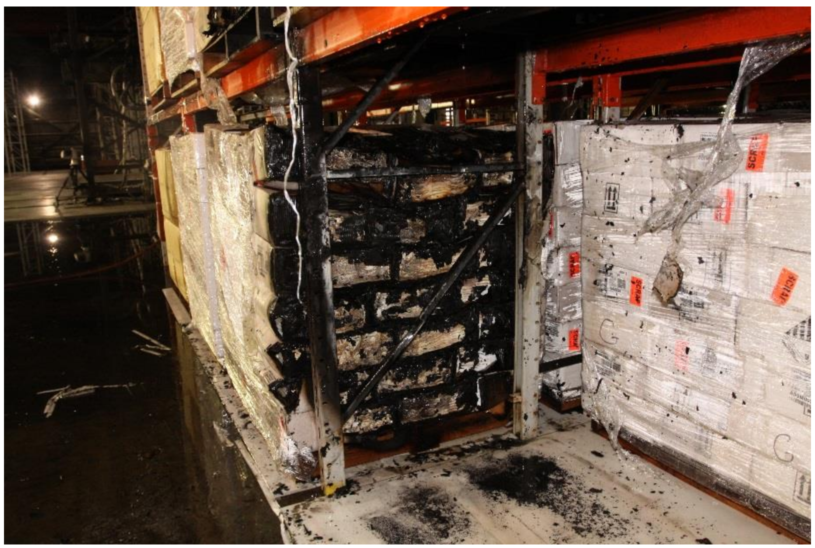
~ 2 min 30 s (150 s)

> 6 min (360 s)

Figure 4-7: Images of large-scale fire test (continued).

East (aisle) face of main array

Commodity across longitudinal flue



First tier ignition flue

Pallet load from second tier ignition flue

Figure 4-8: Post-test images showing extent of damage to test commodity.

4.6.2 Sprinkler Operations and Area of Commodity Damage

A plan view of the sprinkler operation pattern is presented in Figure 4-9. A single sprinkler, centered over the main array, operated at 1 min 30 s (90 s) and suppressed the fire. The approximate extent of commodity damage is shown in the figure by the shaded areas. Damage was primarily limited to the ignition flue with some lateral fire spread along the sides of the pallet loads facing the longitudinal flue and the aisle space. Charring of the cartons facing the open inner core of the pallet loads on the second and third tiers was also observed.

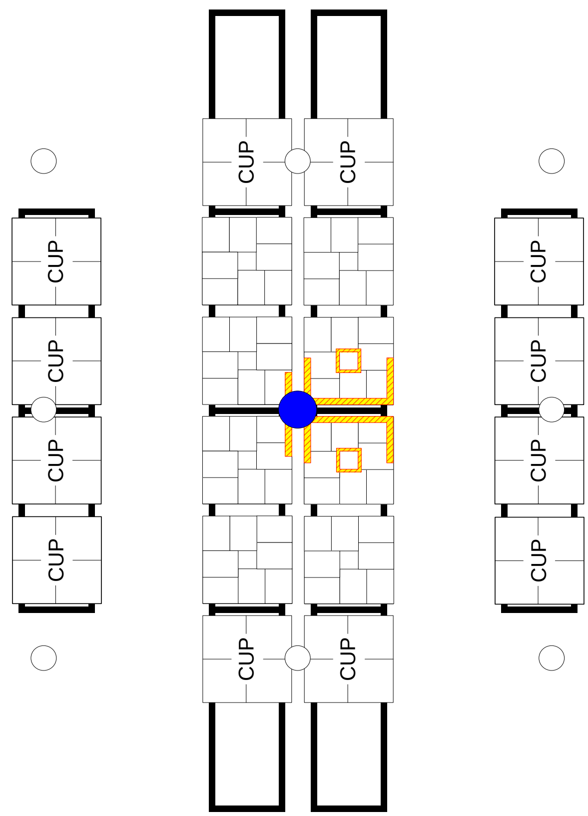


Figure 4-9: Sprinkler operation pattern and commodity damage.

4.6.3 Energy Release

Figure 4-10 presents the convective heat release rate and total integrated chemical energy produced during the large-scale test. The convective heat release rate was estimated by applying the ceiling gas temperature measurements made immediately below the fire test ceiling to fire plume and ceiling layer correlations [30]. While not as accurate as the measurements made with the FPC for the Reduced-Commodity test (Section 3.3.1), the estimated convective HRR provides a reasonable approximation of the real-time fire development up to sprinkler operation. Convective measurements can be significantly impacted by cooling from a sprinkler discharge and therefore may not reflect the heating condition within the test array. For example, cooling of the fire plume gases above the test array or wetting of thermocouples used to measure ceiling gas temperatures can occur even though the fire is still present within the array. Total energy was calculated from the generation rates of carbon dioxide and carbon monoxide[12] during the test and the measurement was therefore not affected by sprinkler operation. Also, since the majority of consumed materials in this test were ordinary combustibles, the errors associated with burning Li-ion batteries in Section 3.3.1 are not a significant factor in this case. It should be noted that chemical energy was measured within the exhaust duct located well above the movable fire test ceiling and is therefore significantly delayed and smeared compared to the actual fire development. For error analysis, it was assumed that the total energy up to test termination has ± 10% error. The estimated total energy released was 100 ± 5 MJ (90 ± 5 BTU x 10^3) or the equivalent of less than one pallet load of batteries, as listed in Section 2.2 Data were acquired for the 40-minute duration of the test.

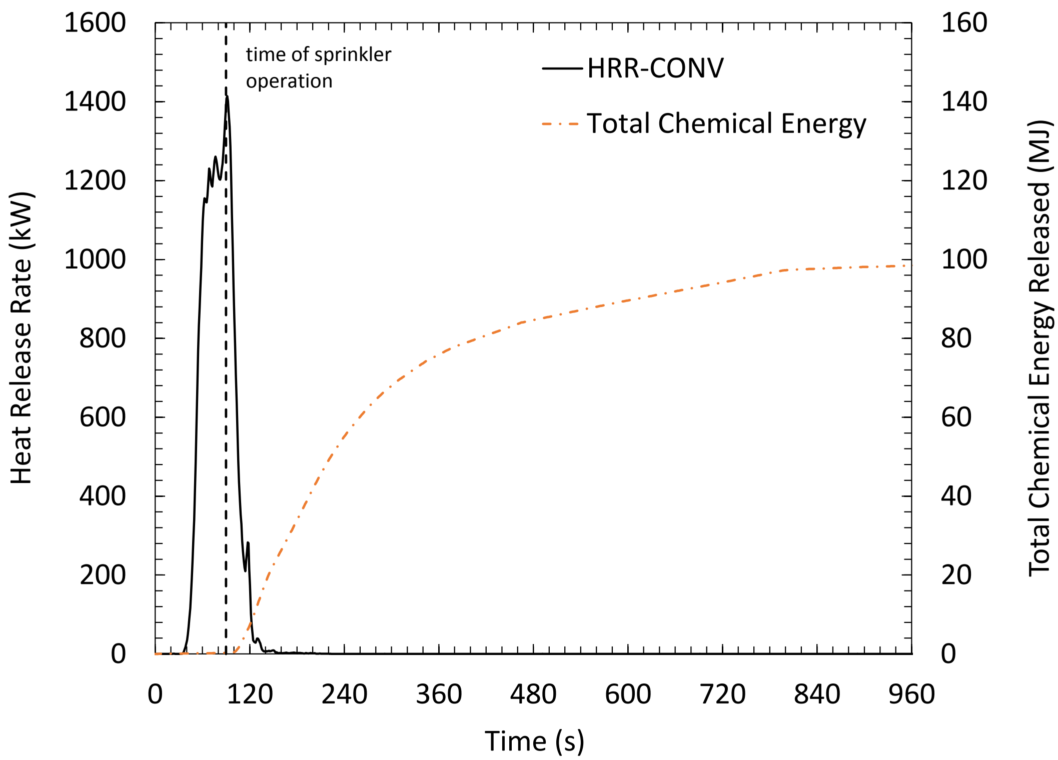


Figure 4-10: Total integrated energy.

4.6.4 Ceiling Thermocouple (TC) Measurements

Figure 4-11 presents the steel TC measurements for the large-scale test. The maximum steel TC measurement was 32°C (90°F) at 1 min 30 s (90 s). This value represents the average of all nine thermocouples extending out to 0.3 m (12 in.) in all four directions from the center of the ceiling. The adjacent ceiling TC measurement, located above ignition, was 109°C (228°F).

[12] Energy calculations use the following average values for the net heat for complete combustion per unit mass of fuel: ΔH_{CO2} = 11.4 kJ/g (4,900 BTU/lb) and ΔH_{CO} = 7.9 kJ/g (3,400 BTU/lb).

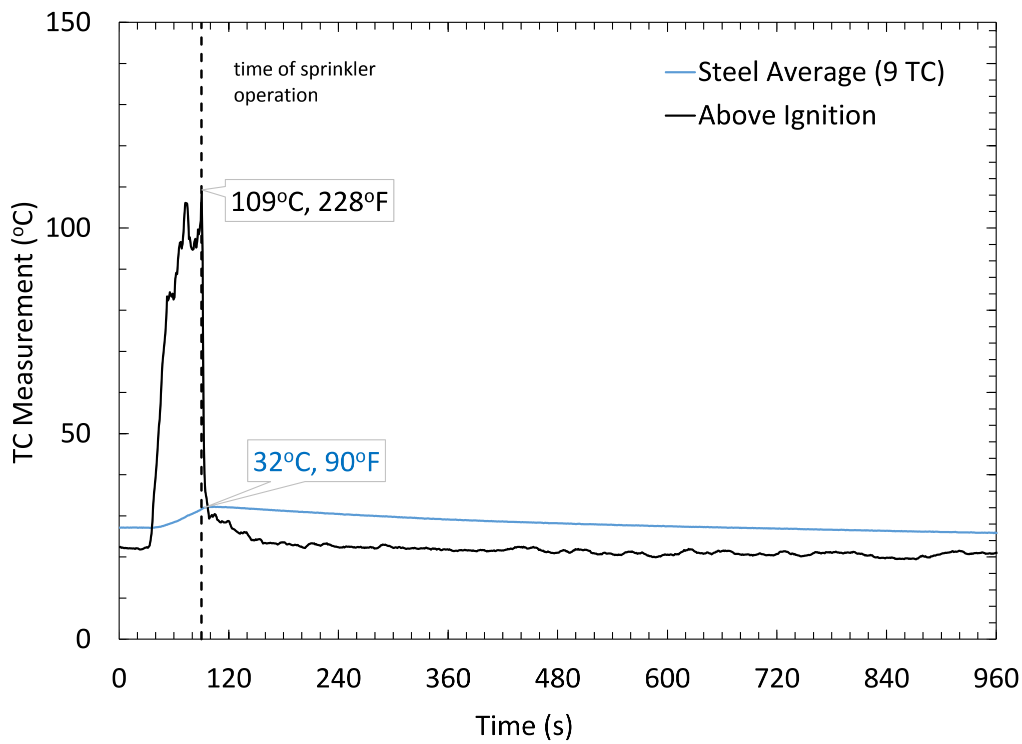
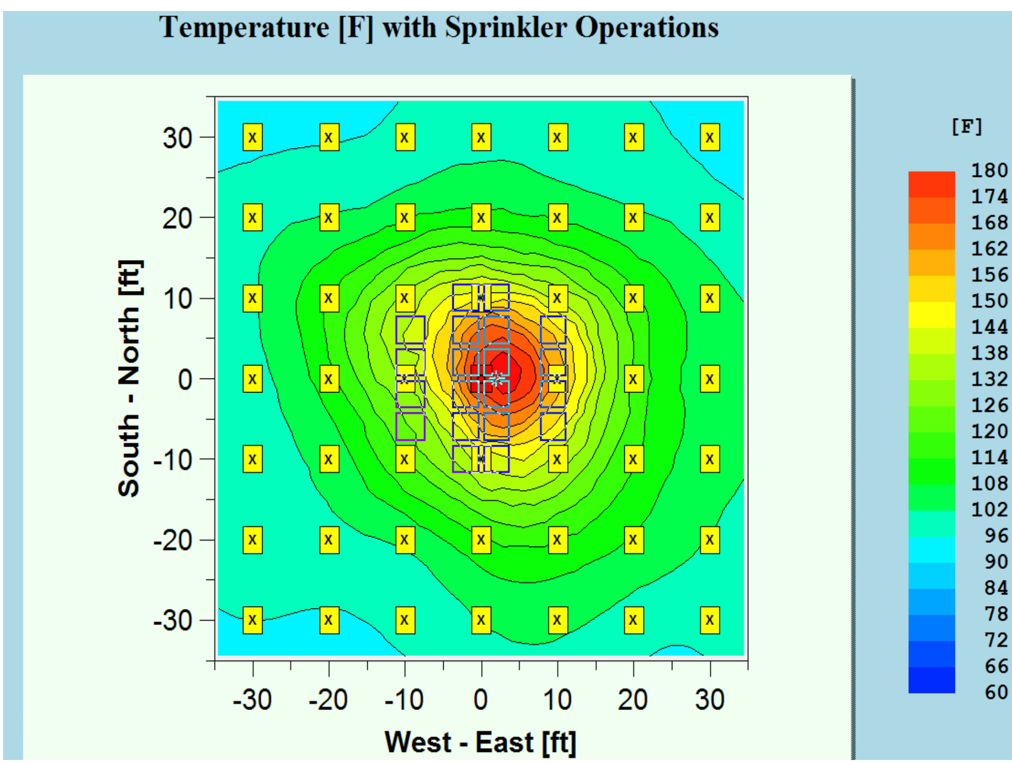


Figure 4-11: Ceiling level TC measurements.



[centroid coordinates: 0.8 m (2.7 ft) east × 0.3 m (0.9 ft) north]

Figure 4-12: Contour plot of ceiling TC measurements at first sprinkler operation 90 s after ignition.

Figure 4-12 presents the ceiling TC measurement contours at first sprinkler operation. The corresponding location of the ceiling gas centroid was 0.8 m (2.7 ft) east × 0.3 m (0.9 ft) north, which coincides with the ignition location. The alignment of the centroid with the ignition location indicates the fire plume was centered over ignition.

4.6.5 Evaluation of Internal Heating

Internal heating of the commodity was measured on all three tiers. As illustrated in Figure 4-4, thermocouples were located in the pallet loads on the south side of the central transverse flue on both the east and west side of the longitudinal flue.

Figure 4-13 presents the thermocouple measurements acquired during the large-scale fire test. A legend is provided to describe the thermocouple locations within the test array. Notable data series are additionally labeled using the following convention: tier number (T#), east or west pallet load (EP/WP), and horizontal position of west, center, or east (W/C/E). For example, T1-EP-W references the first tier, east row, west horizontal thermocouple location.

Unlike the Reduced-Commodity test, which was a free-burn fire, the convective heat release rate is not included in Figure 4-13 for reference to the time evolvement of the fire. In a sprinklered test, convective measurements can be significantly impacted by cooling from the discharged water and therefore may not reflect the heating condition within the test array.

The peak TC measurement of 83^{o}C (180^{o}F) was recorded on tier 1, east pallet load, center location (T1-EP-C) at 2 min 40 s (160 s) after ignition. This location was adjacent to ignition and shows the prolonged heating of the commodity due to the sustained fire within the ignition flue after the sprinkler operated at 1 min 30 s (90 s). Elevated measurements were also observed in the commodity in the east row surrounding ignition at T2-EP-W, T2-EP-C, and T1-EP-W.

It is notable that wetting of the TCs can be observed from the reduction of the measurement from a nominal ambient value of 25^{o}C (77^{o}F) to 19^{o}C (66^{o}F). Wetting was more prevalent on the upper two tiers, which is consistent with post-test observations where significant water infiltration into the cartons was noted during test cleanup.

No TC measurements were observed to exceed the threshold temperature of 180^{o}C (356^{o}F), which was used for the Reduced-Commodity test to represent the oxidation temperature of electrolyte that results in a high-rate runaway reaction (peak rates > 100^{o}C/min) [9]. However, since these thermocouples are located between cartons, not directly attached to the batteries, the actual temperature of the batteries could have been significantly higher. Visual observations of batteries damaged during the test were made during cleanup suggesting that the carton packaging was insulating the thermocouples from the heat released by the batteries.

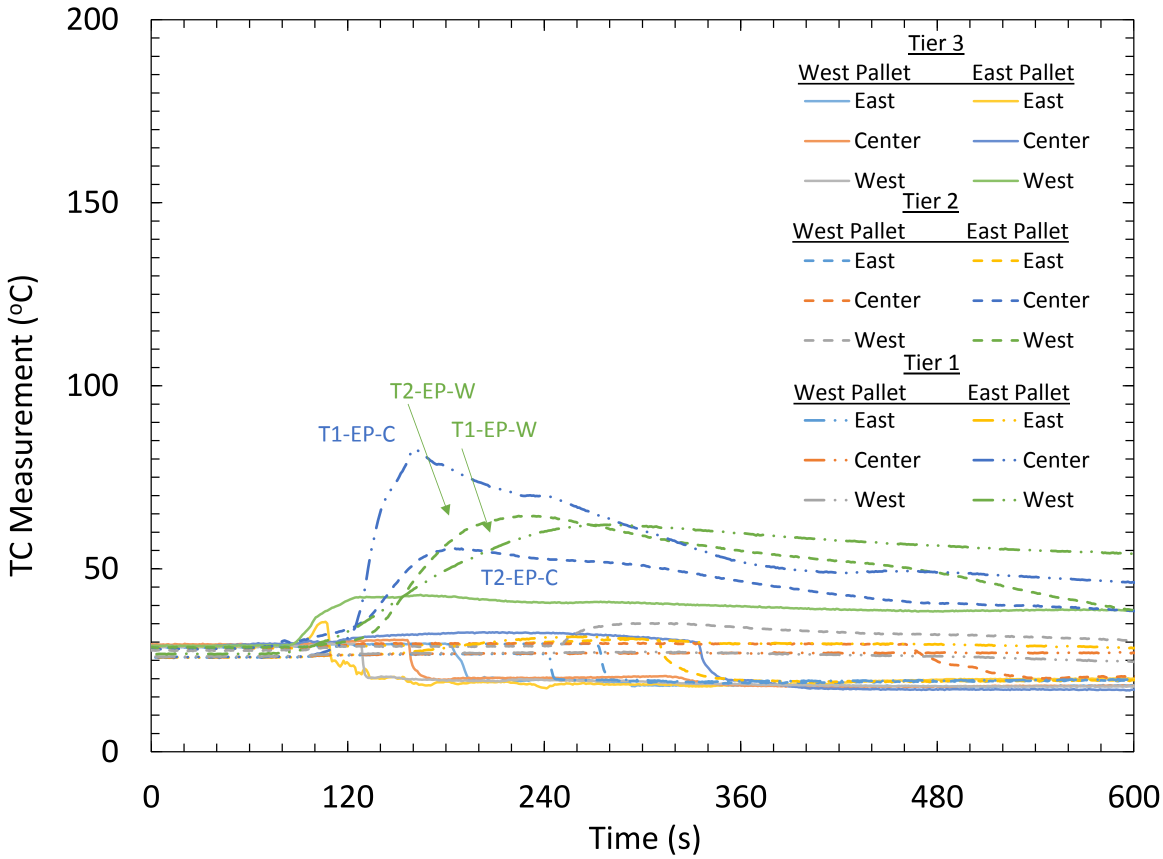


Figure 4-13: Internal heating of commodity using TCs located within the test commodity.

5. **Supplemental Experimental Evaluations**

Two supplemental experimental evaluations were conducted to address the potential for battery-to-battery fire spread. Section 5.1 considers an internal ignition scenario, where thermal runaway of a battery propagates to adjacent batteries. Section 5.2 evaluates the effectiveness of the sprinkler protection at suppressing a fire at a later stage of battery involvement than was achieved in the large-scale test.

5.1 Internal Ignition

Four fire tests have been conducted to establish a reliable and consistent method for assessing the potential to induce internal ignition of a pallet load of batteries. For this purpose, internal ignition refers to a cascading effect where thermal runaway of one or more batteries propagates to the batteries within adjacent cartons, without causing an external fire. Images of each test are shown in Figure 5-1 and descriptions of each test are as follows:

- For the first test, a single battery was placed on top of a metal surface that was heated from below with a propane burner. Thermal runaway of the battery was observed as an expansion of the pouch battery due to conductive heating. The severity of the heating resulted in rupture of the seams along the edges of the battery and an errant propane flame (from the heating source) ignited the escaped electrolyte.
- The second test consisted of a single battery heated to 343°C (650°F) via a foil heater affixed to both sides of the battery. Thermal runaway began within five minutes of exposure. The battery pouch expanded; however, the seams did not rupture and no fire occurred.
- For the third test, foil heaters were again used to overheat one battery within a carton (which contained 20 batteries). Limiting the space for the battery pouch to expand resulted in breach of the seams and leaked electrolyte was observed as a discoloration of the carton. At the completion of a 2-hour heating period, thermal runaway occurred in only three batteries: the battery with the heaters was heavily damaged, while the adjacent batteries above and below were partially expanded. The polystyrene plastic dividers were softened but not charred.
- The fourth test was a repeat of the third test, except ignition of the flammable gases outside of the carton was achieved with a propane pilot flame after a 1-hour heating period. The carton of batteries burned to completion with a peak heat convective HRR of ~ 30 kW.

From these tests it can be concluded that thermal runaway of the polymer pouch battery used in this project does not result in battery-to-battery propagation within a carton. It is therefore reasonable to assume that thermal runaway of one or more batteries within a single carton will not propagate to batteries within an adjacent carton. Thus an external fire, possibly initiated by ignition of escaping electrolyte, is necessary to spread the fire beyond the carton where a thermal runaway occurs. Once an external fire is present, flame propagation along the carton results in a similar fire development to the external ignition scenario.

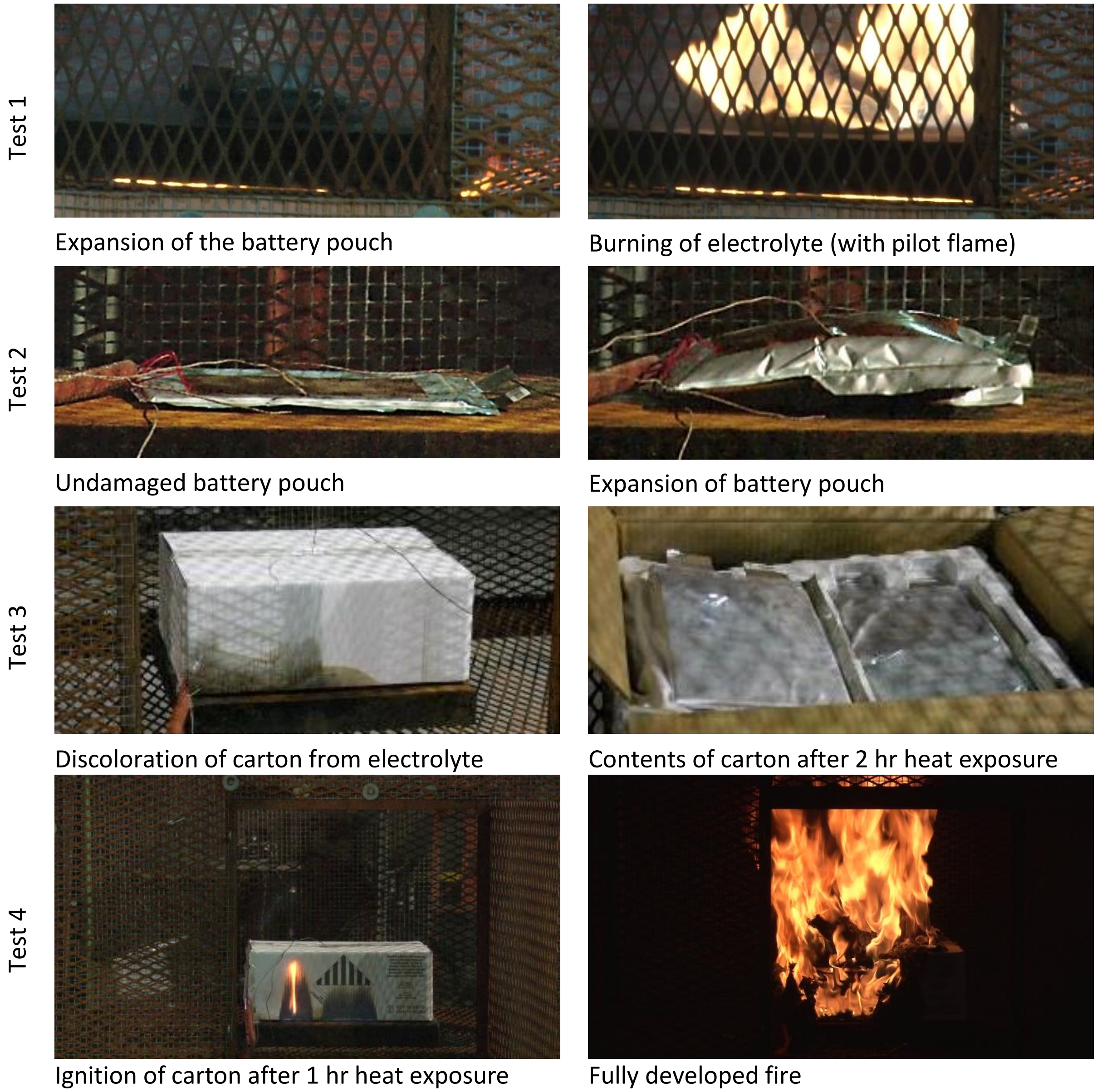


Figure 5-1: Photos of internal ignition evaluation tests.

It is also worth noting that there is not enough air within a carton to burn a single battery. Each battery (used in this project) contains 34 g (0.07 lb) of electrolyte. Using diethyl carbonate as a representative electrolyte component, the stoichiometric equation and air-to-fuel ratio can be quantified as shown in Eqs. 1 and 2. Assuming an air density of 1.2 kg/m^3 (0.075 lb/ft^3) combustion of each battery requires 0.2 m^3 (7.1 ft^3) of air. Each carton has dimensions of 0.43 m × 0.33 m × 0.15 m (16.75 in. × 12.8 in. × 5.75 in.), or an empty volume of 0.02 m^3 (0.7 ft^3), which provides an order of magnitude less air than needed to burn a single battery.

$$C_5H_{10}O_3 + 6\,(O_2 + 3.76\,N_2) \rightarrow 5\,CO_2 + 5\,H_2O + 22.6\,N_2 \qquad \text{Eq. 1}$$

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{6\ mol\ (32\ g/mol + 3.76 \times 28\ g/mol)}{1\ mol \times 118\ g/mol} = 7\ \frac{g}{g} \qquad \text{Eq. 2}$$

The conclusion that an external fire is necessary to propagate battery involvement to adjacent cartons can also be reasonably applied to hard-cased Li-ion batteries, where rupture can be accompanied by spattered molten aluminum and other ignition sources. In 2010, Webster studied the process of battery-to-battery propagation in a carton containing one hundred 18650 cylindrical Li-ion batteries [31]. A single battery was removed from the carton and replaced with an electric cartridge heater. During that test, it was noted that the carton caught fire before the batteries adjacent to the heater experienced thermal runaway. Webster conducted a larger version of this test in 2012, involving 50 cartons (5,000 batteries) stacked in a 2 × 4 × 6 arrangement [32]. Overheating of the adjacent batteries resulted in thermal runaway and ignition of the released flammable gas outside of the carton. Subsequent spread of the fire to adjacent cartons occurred due to the external fire.

5.2 Later Stage Suppression Test

An intermediate-scale suppression evaluation using the water application apparatus was conducted to determine the effectiveness of applied water at suppressing a battery fire. Since this test does not rely on sprinkler response, water application can be delayed to a later stage of battery involvement than can be achieved during the large-scale fire test. The combination of the intermediate- and large-scale tests confirms that sprinklers can protect a growing rack storage fire, as well as a developed battery fire.

Test Design and Method

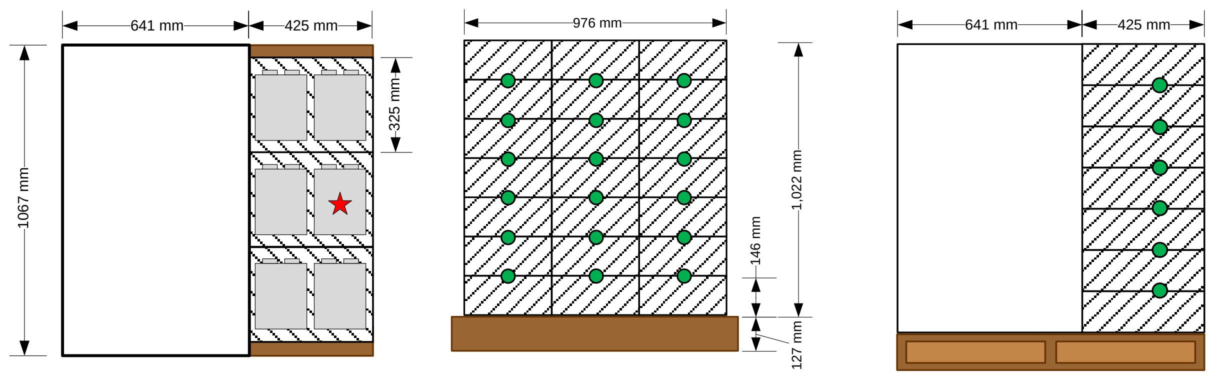
The pallet design for the intermediate-scale suppression test is shown in Figure 5-2. The design consists of 21 cartons, arranged 3 wide x 1 deep x 7 high, resulting in dimensions of 0.97 m × 0.43 m. × 1.0 m (38.3 in. × 16.75 in. × 40.25 in.). A metal liner was fabricated to fill the remaining portion of the pallet, with dimensions of 1.1 m × 0.64 m × 1.0 m (42 in. × 25.25 in. × 40.25 in.).

The later stage suppression evaluation consisted of two tests, as shown in Figure 5-3. Test 1 involved a single pallet load to represent thermal runaway of a carton facing the aisle of a rack storage arrangement. Test 2 involved two pallet loads to represent thermal runaway of a carton facing the flue of a rack storage arrangement. In both cases, thermal runaway was induced in a battery centrally located within a carton using foil heaters as shown in Figure 5-4. The 'ignition carton' was located at the middle of the bottom stack of the pallet load. A propane pilot flame was offset ~25.4 mm (1 in.) from the face of the carton to ignite flammable gas that escaped from the carton.

Water application began after carton surfaces on the ignition side of the pallet were consumed. This approach improved the potential that the batteries are contributing to the overall severity of the fire. Water was applied using the water application apparatus (WAA), which provides a uniform water flux to the top surface of an object [33], at a density[13] of 12 mm/min (0.3 gpm/ft^2). While water applied from

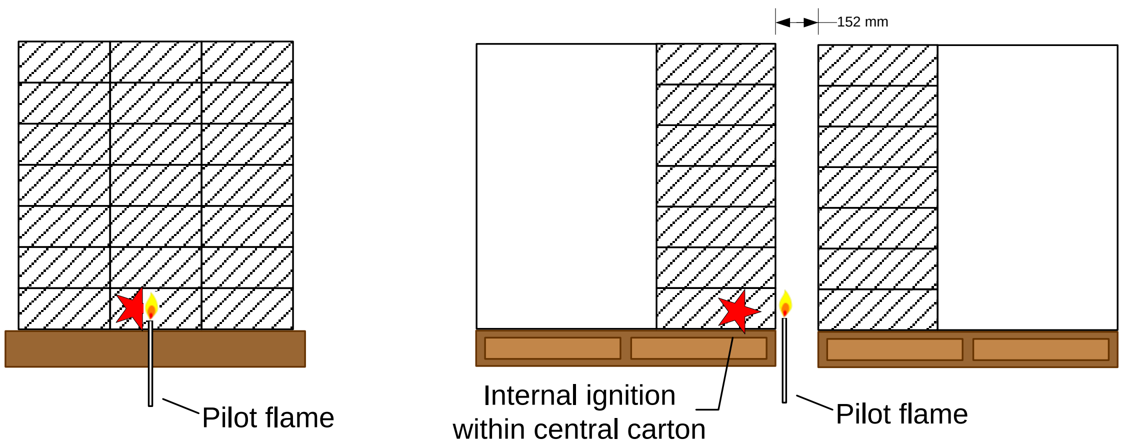
[13] Note that the critical delivered flux to 3.0 m (10 ft) high rack storage of cartoned commodities ranges from 7.3 mm/min (0.18 gpm/ft^2) for CUP to 11 mm/min (0.26 gpm/ft^2) for CEP.

the WAA is not equivalent to sprinkler density, it should be noted that the 52 mm/min (1.3 gpm/ft^2) discharge density used in the sprinklered test was a factor of four higher. The actual quantity of sprinkler water reaching the test commodity is impacted by the non-uniformity of the spray pattern, as well as evaporation and displacement due to the fire plume gases. As a result, suppression in the intermediate-scale test suggests a safety factor in the sprinklered test, in terms of discharge density needed to protect the battery portion of the fire.



Plan view (illustrating battery location with the cartons) | Front elevation view | Side elevation view

Figure 5-2: Intermediate-scale suppression test pallet design. The location of the ignition battery is identified with a red star and TC locations are shown with green circles.



Test 1: Aisle face ignition | Test 2: Flue ignition.

Figure 5-3: Intermediate-scale suppression test ignition location. The location of the carton containing the ignition battery is identified with a red star.

Figure 5-4: Photos of heater placement within ignition carton. Left photo shows a foil heater affixed to a battery on the fifth level (of ten levels) within the carton. Right photo shows the heater wiring exiting the carton.

5.2.1 Suppression Test 1: Aisle Face Ignition

The first suppression test was conducted using a single pallet load to represent ignition of an aisle-facing carton. Photos of the test are shown in Figure 5-5. The foil heaters were set to 340°C (650°F) and the pilot flame was ignited at 0 min. Thermal runaway, observed as wetting of the ignition carton due to leaked electrolyte, occurred by 10 min 30 s (630 s). No ignition of the flammable contents within the carton occurred and at 31 min 37 s (1,897 s) the pilot ignition flame was pushed against the cartons. The cartons ignited and by 34 min (2,040 s) flames had traveled along a narrow vertical path to the top of the pallet load. Since the base of the pilot flame was located at the vertical midpoint of the carton, the lower portion of the carton saturated with electrolyte did not ignite. At 46 min (2,760), a propane torch was used to ignite the lower portion of the carton. Fire spread across the entire face of the pallet load leading to collapse of the center stack of cartons at 49 min (2,940 s). Water application, at a rate of 12 mm/min (0.3 gpm/ft^2) began at 50 min 27 s (3,027 s) and the fire was suppressed within 5 min (300 s). The test was terminated at 60 min (3,600 s) using a garden hose to extinguish a few lingering flames shielded by the collapsed cartons.

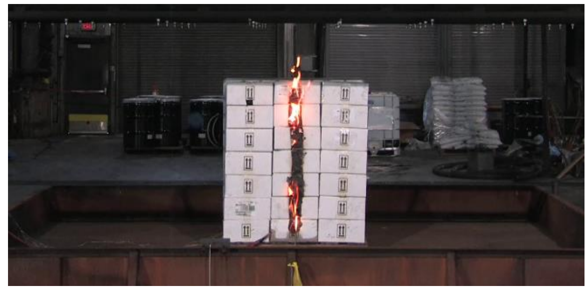
During post-test inspection, it was estimated that 30% of the batteries showed signs of damage. The majority of damaged batteries was located in the area adjacent to ignition, *i.e.*, bottom of the center stack of cartons. Minimal damage was observed on the batteries located in the outer stacks of cartons. In addition, the fire was generally contained to the outside portion of the cartons (towards ignition), including all the carton surfaces on the ignition side of the pallet load, with minimal penetration to the inside portion of the cartons (towards the metal liner).

Figure 5-6 shows the convective heat release rate as well as the predicted response of a quick-response sprinkler located 3.0 m (10 ft) above the array (following the method described in Section 3.3.3). Water was applied to the fire 25 s after the predicted operation time of a quick-response sprinkler, 50 min 27 s (3,027 s) versus 50 min 2 s (3,002 s). Additional delay in the time of water application was not possible due to collapse of the commodity. The convective HRR peaked at ~300 kW, before water application, and a total of 25.5 MJ of convective energy was released during the test. The carton surfaces on the ignition side of the pallet load account for 65%, *i.e.*, 16.5 MJ, of the total energy released[14]. Since the

[14] Using the carton dimensions and heat of combustion listed in Section 2.2 and 2.3, respectively.

wood pallet was not involved in the fire, the remaining energy was contributed from the plastic dividers and batteries.

31 min 37 s – pilot flame pushed against cartons



34 min 0 s – flame spread

46 min 0 s – secondary ignition

49 min 0 s – collapse of center stack

50 min 27 s – start of water application

55 min 27 s – suppressed fire

1 hr – test termination
(before fire fighter intervention)

Figure 5-5: Photos of suppression Test 1.

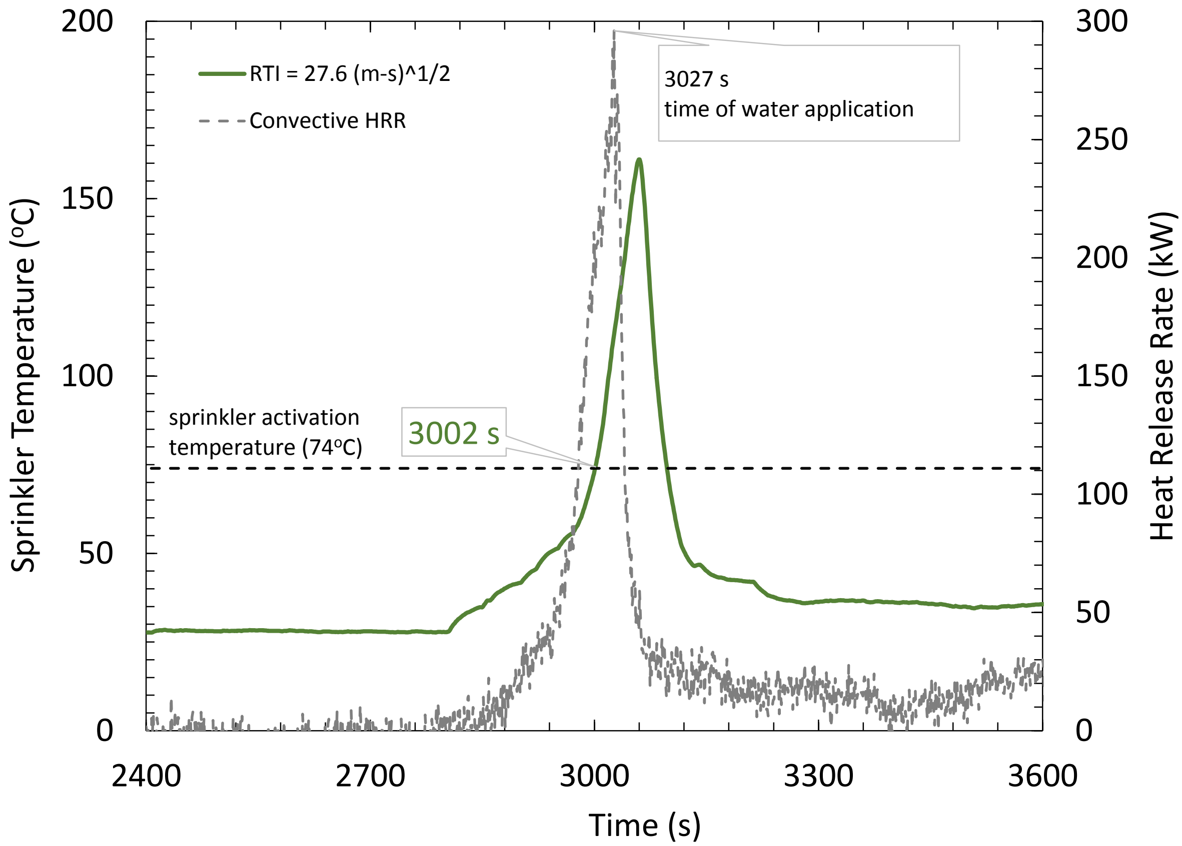


Figure 5-6: Suppression Test 1 convective heat release rate and predicted sprinkler response.

5.2.2 Suppression Test 2: Flue Face Ignition

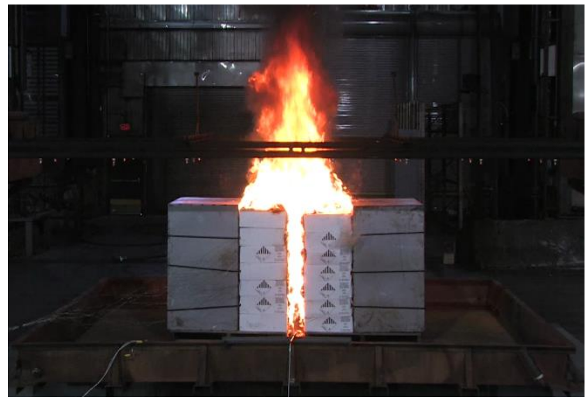
The second suppression test was conducted using two pallet loads separated by 150 mm (6 in.) to represent ignition of a flue-facing carton. Photos of the test are shown in Figure 5-7. The foil heaters were set to 340°C (650°F) and the pilot flame was ignited at 0 min. Smoke was observed exiting the carton at the penetration for the heater cables at 10 min (600 s). Thermal runaway, observed as wetting of the ignition carton due to leaked electrolyte, occurred by 19 min (1,140 s). There was no ignition of the flammable contents within the carton and at approximately 32 min (1,920 s) the pilot ignition flame was pushed against the cartons. The cartons ignited and by 38 min (2,280 s) the entire flue area was involved in the fire and flames had traveled across the tops of the cartons. Water application, at a rate of 12 mm/min (0.3 gpm/ft^2) began at 41 min 10 s (2,470 s) and the fire was largely suppressed within 5 min (300 s). The combination of fire damage and wetting of the cartons caused the stacks to lean towards each other, which impeded the water flow to the remaining burning surfaces and resulted in a small deep-seated fire that was not extinguished.

At 60 min (3,600 s) the water flow was turned off to evaluate the potential for reignition. As shown in Figure 5-8, the fire slowly redeveloped and began to spread along exposed combustible material. The test was terminated at 75 min (4,500 s) with a fire hose stream.

32 min - pilot flame pushed against cartons

36 min 20 s – fire spread across ignition flue

37 min 30 s – fire spread across of cartons



38 min – full involvement of ignition flue

41 min 10 s – start of water application

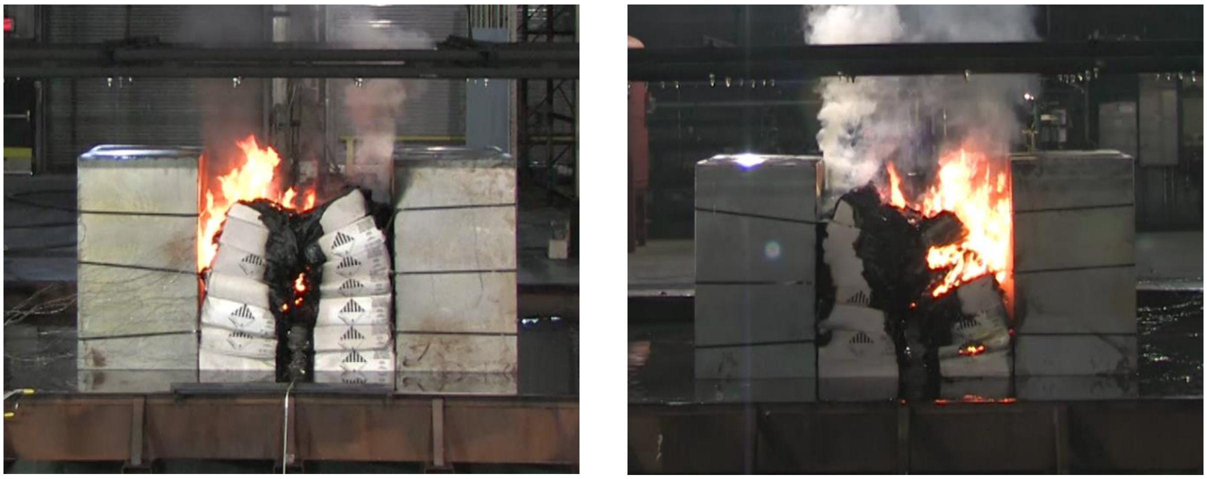
44 min 10 s – suppressed fire

60 min – water off

Figure 5-7: Photos of suppression Test 2.

During post-test inspection, it was estimated that at least 70% of the batteries showed signs of damage. The most heavily damaged batteries were located in the area facing the ignition flue, though damaged batteries were also observed on the backside of the cartons facing the non-combustible liners.

Figure 5-9 shows an example of a battery rupture that occurred well after the local fire was extinguished. The fire had been suppressed for over 10 min before thermal runaway of a battery resulting in a fire within the flue. The fire could not ignite the combustible material wetted by the water discharge and the fire extinguished when the battery was consumed.



Front of array　　Back of array

Figure 5-8: Photos of Test 2 reignition after shutdown of water application.

54 min 30 s – suppressed fire　　56 min 10 s – battery rupture

Figure 5-9: Example photos of thermal runaway leading to battery rupture.

Figure 5-10 shows the convective heat release rate as well as the predicted response of a quick-response sprinkler (following the method described in Section 3.3.3). Water was applied to the fire 2 min 48 s (168 s) after the predicted operation time of a quick-response sprinkler, 41 min 10 s (2,470 s) versus 38 min 22 s (2,302 s). The convective HRR peaked at ~ 675 kW, before water application, and a total of

110 MJ convective energy was released during the test. The carton surfaces on the ignition side of the pallet load account for 45%, *i.e.*, 49 MJ, of the total energy released. Since the wood pallet was not involved in the fire, the remaining energy was the contribution of the plastic dividers and batteries.

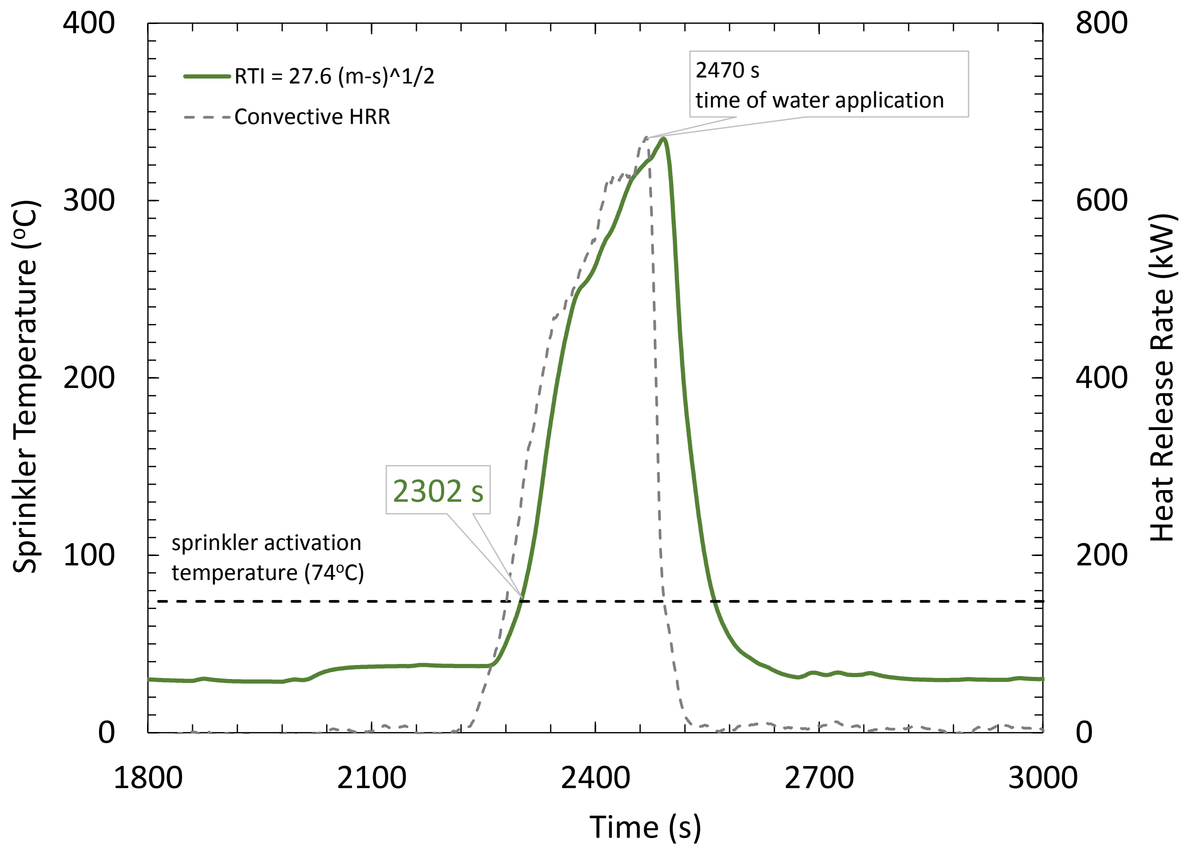
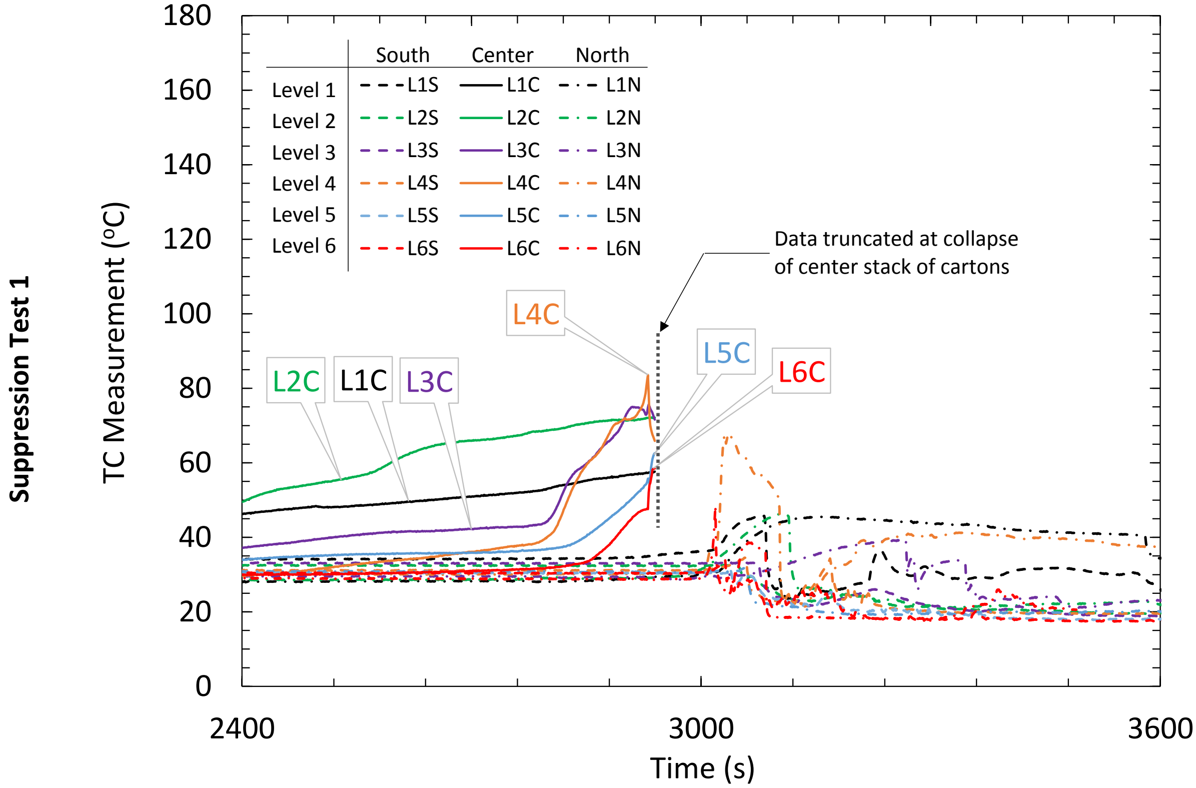


Figure 5-10: Suppression Test 2 convective heat release rate and predicted sprinkler responses.

5.2.3 Comparison of Internal Heating

Internal heating of the commodity was measured with thermocouples located between each level of battery cartons in the pallet load containing the internal ignition heater. As shown in Figure 5-2, 18 thermocouples were located 150 mm (6 in.) in from the ignition face of the pallet load. Horizontally, thermocouples were located at the midpoint of the pallet load and 150 mm (6 in.) from the outer edges. Additional description of the thermocouple type can be found in Section 3.2.

Figure 5-11 presents the thermocouple measurements acquired during Suppression Tests 1 and 2. A legend is provided to describe the thermocouple location within the test array. Notable data series are additionally labeled using the following convention: Level (1 through 6) and horizontal position of west, center, or east (W/C/E). For example, L6C references the thermocouple located between the sixth and seventh carton of center of the pallet load.



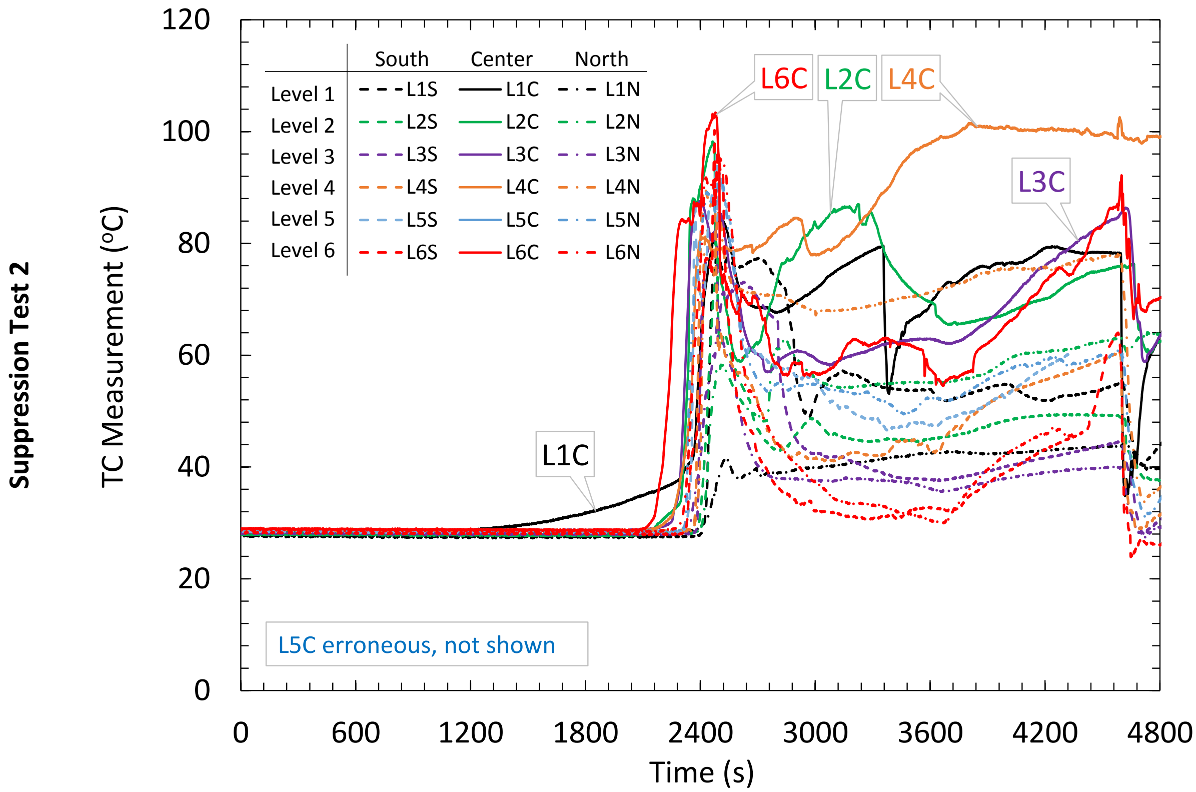


Figure 5-11: Internal heating of commodity using thermocouples located between the cartons of the test commodity.

For Suppression Test 1, a maximum temperature of 756°C (1,390°F) was recorded by L4C at 50 min 25 s (3,025 s) after ignition. A similar response was seen for other thermocouples located within the center stack of cartons. This spike in temperature coincided with collapse of the center stack, which exposed the thermocouple to combustion gases, and was likely not related to widespread thermal runaway of the batteries within the cartons. Since these measurements no longer represent the heating condition within the cartons, the data series for the thermocouples within the center stack have been truncated at the time of collapse, *i.e.*, 49 min (2,940 s). The remainder of thermocouples located at the outer stack of cartons recorded peak temperature that were nominally consistent with ambient temperature.

For Suppression Test 2, a maximum temperature of 103°C (217°F) was recorded by L6C at 41 min 04 s (2,464 s) after ignition. In general, higher temperatures were recorded at center stack of cartons compared to the outer stacks. However, all thermocouples measured peak temperatures that were elevated above ambient temperature. The reduced peak temperatures measured in Suppression Test 2 compared to Suppression Test 1, 103°C (217°F) versus 756°C (1,390°F), is due to the increased stability of the cartons. Without collapse of the cartons, the thermocouples were not directly exposed to combustion gases.

The combined results of Suppression Test 1 and 2 indicate that heat transfer between cartons is slow, even in the presence of a large fire. The insulating properties of the cartons and the plastic dividers effectively inhibit the fire development and delay battery involvement in the fire.

6. **Discussion**

6.1 Pre-wetting of Adjacent Combustibles

Automatic sprinkler protection can prevent fire spread by pre-wetting adjacent combustibles. This mechanism is particularly important for deep-seated fires where sprinkler water may not able to reach burning materials. In the case of cartoned Li-ion batteries, battery-to-battery thermal propagation can occur inside a carton even after the fire has been extinguished. The obvious questions is then, how much pre-wetting is needed to prevent fire spread after the fire has been initially suppressed? The discussion below addresses this question.

Thumuluru and Xin studied the effect of pre-wetting on fire propagation along corrugated board surfaces [34]. Experiments were conducted using a 2.4 m (8 ft) tall parallel panel apparatus to represent conditions of a rack storage fire, Figure 6-1 (left). The fuel load consisted of three layers of double-wall corrugated board attached to non-combustible panel walls that were located on either side of a 0.3 m (12 in.) wide propane sand burner.

Using a range of ignition sizes and water flow rates, a critical water flow rate beyond which the fire would no longer spread along the corrugated board was identified. Figure 6-1 (right) shows the total heat released over a 450 s period for ignition fire sizes of 48, 66, and 99 kW. It was found that a critical water flow rate of 12 g/m/s (0.005 gpm/in.) was sufficient to prevent flame spread for all fire sizes tested.

While not a parameter of the study, the critical water flow rate applied to the top of the fuel array is also a function of the wall height exposed to the ignition fire. As the wall height increases, the quantity of water reaching the base of the ignition fire will decrease due to evaporation. In the context of pre-wetting, the height of the exposed wall used by Thumuluru and Xin [34] is greater than the height of a single carton, or pallet load, of batteries. Thus the critical water flow rates of their work can be reasonably applied to the battery reignition scenario.

Pre-wetting water flow rates expressed as mass flow rate per lateral width (g/m/s [gpm/in.]) can be roughly compared to volumetric flow rate per unit area (mm/min [gpm/ft^2]), *i.e.*, sprinkler density, by assuming that water applied to the top of a pallet load does not accumulate and flows uniformly to the sides of the pallet load [35]. Using the dimensions of an FM Global standard pallet load, 1 g/m/s (4.05 x 10^{-4} gpm/in.) converts to 0.2 mm/min (0.005 gpm/ft^2). As noted in Section 5.2, direct comparison between sprinkler density and flow rate per unit area is not possible due to the non-uniformity of a typical sprinkler discharge pattern, evaporation and displacement of discharged water due to the fire plume gases, and evaporation of water flow along the commodity surfaces.

Following the commodity classification protocol, Xin and Tamanini [33] reported critical delivered water flux (CDF) values for 3.0 m (10 ft) high rack storage of cartoned commodities ranging from 7.3 mm/min (0.18 gpm/ft^2) for cartoned unexpanded plastic (CUP) to 11 mm/min (0.26 gpm/ft^2) for cartoned expanded plastic (CEP) [33]. Discounting differences in the test configurations, the critical pre-wetting flow rate of 12 g/m/s (0.005 gpm/in.) noted above, *i.e.*, 2.4 mm/min (0.06 gpm/ft^2), is on the order of one third of the CDF values. This result is consistent with the conclusions of Thumuluru and Xin [34] who argued that less water is needed to prevent fire spread than to control or suppress a growing fire.

With respect to the present project, adequate protection of a large-scale battery fire was accomplished with a 53 mm/min (1.3 gpm/ft^2) sprinkler density. Reducing the water density delivered to the top of the commodity by half to account for the non-uniformity of the sprinkler discharge pattern, the corresponding pre-wetting flow rate of 130 g/m/s (0.05 gpm/in) is a factor of 10 larger than the critical pre-wetting flow rate determined by Thumuluru and Xin [34]. While there is no direct comparison between pre-wetting flow and sprinkler density, it is reasonable to assume that reignition of the batteries within a carton will not lead to fire spread over adjacent cartons once sprinklers are discharging water.

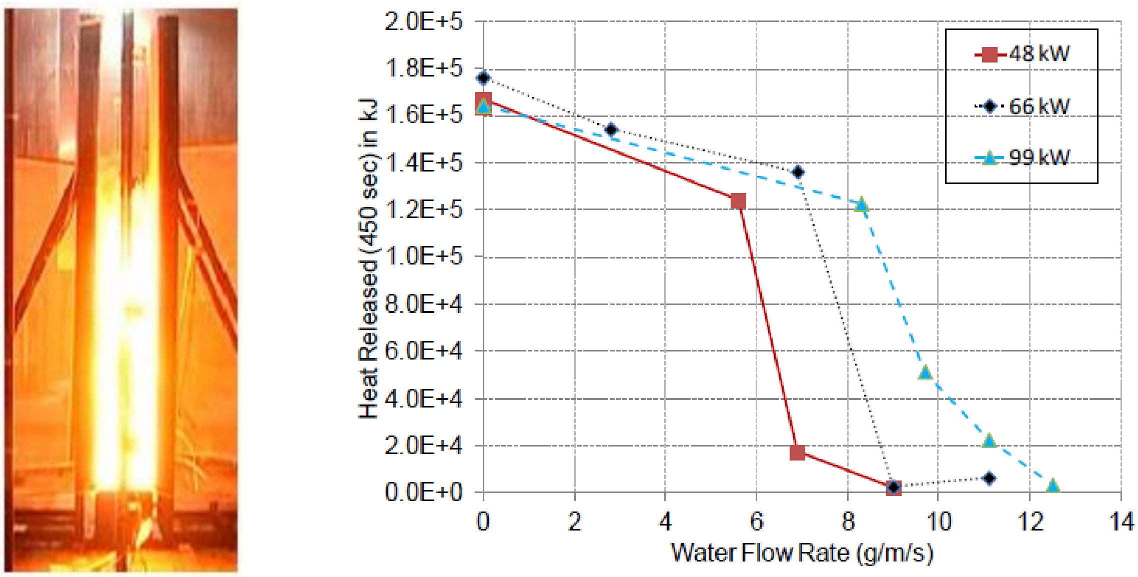


Figure 6-1: Photo demonstrating the fire spread in a parallel panel configuration (left) and plot of overall heat released as a function of the water flow rate for various ignition sizes (right). *Courtesy of Thumuluru and Xin.*

6.2 Application of Test Results to Protection Recommendations

Protection recommendations for warehouse storage of cartoned Li-ion batteries have been developed through fire testing and comparison to commodities with similar hazard characteristics. In consultation with the FM Global Engineering Standards group, which is responsible for the *FM Global Property Loss Prevention Data Sheets,* protection recommendations have been established based on current knowledge and may be amended if additional research specific to the hazard of Li-ion batteries is conducted. The bases for the protection recommendations, which can be found in Section 8, are described below and are specific to warehouse storage of cartoned Li-ion batteries and should not be generally applied to other commodities or storage configurations.

Based on the results of the testing presented in this report, and building upon Reference [15], cartoned Li-ion batteries exhibit a fire hazard similar to CUP commodity (Section 3.3). For limited storage heights, this conclusion aligns with Hazard Class HC-3 of FM Global Property Loss Prevention Data Sheet 3-26, *Fire Protection Water Demand for Nonstorage Sprinklered Properties* [36], which defines protection for nonstorage facilities where the fire hazard could approach the equivalent of nominal 1.5 m (5 ft) high in-process storage of CUP commodity. In addition, power tool packs exhibited no observable energy contribution from the Li-ion batteries when stored up to 4.6 m (15 ft) high [15]. Therefore, for the storage configuration tested in this project, *i.e*., 4.6 m (15 ft) high, power tool packs can be protected as CUP commodity per FM Global Property Loss Prevention Data Sheet 8-9, *Storage of Class 1, 2, 3, 4 and Plastic Commodities* [37] for ceiling heights up to 12.2 m (40 ft).

Storage beyond those included in this project or listed above, including battery characteristics (e.g., SOC, quantity of electrolyte, and format) and packaging components (e.g., cartons and dividers) requires a more robust protection scheme to account for several unknowns that can negatively affect protection effectiveness. Fire Protection Scheme A combines in-rack automatic sprinklers (IRAS) and horizontal barriers for protection of high-hazard commodities, such as rack storage of ignitable liquids or level 3 aerosols. Complete specifications and drawings can be found in Section D.2.2.1 of DS 7-29, *Ignitable Liquid Storage in Portable Containers*, July 2014 [38]. Similar specifications can be found in Section E.2 of FM Global Property Loss Prevention Data Sheet 7-31, *Storage of Aerosol Products*, January 2012 [39]. This system design is expected to provide the highest level of protection required for storage of the Li-ion batteries tested in this project and can be applied to array configurations beyond the scope of this project.

The previous phase of this project discussed how the low-flash point hydrocarbons commonly used within the electrolyte for Li-ion batteries are prone to reignition [15]. While that discussion related to testing with small-format batteries, a similar result has been observed for large-format batteries (Section 5.2). Reignition is a concern for any battery chemistry using low-flash point hydrocarbons and has been observed for multiple Li-ion battery chemistries. The impact of burning projectiles is expected to be minimal where commodity is segregated away from other combustibles or where Scheme A protection utilizing quick-response sprinklers is provided. The segregation distance recommendation should reflect the propensity for projectiles based on the Li-ion battery design. For instance, hard-cased cylindrical batteries are more prone to be ejected far distances than soft-cased polymer batteries and therefore require a greater segregation distance.

7. **Conclusions**

A project was conducted to determine fire protection guidance for warehouse storage of cartoned Li-ion batteries. Testing was conducted at multiple scales with the intent of expanding the application of a large-scale sprinklered fire test to other Li-ion battery types. All evaluations were conducted at the FM Global Research Campus in West Glocester, R.I., USA.

This project represents a unique approach to determining protection guidance due to the inordinate cost and limitations of availability associated with testing of Li-ion batteries. The combined effects of different storage height, ceiling height, protection system design, commodity type and composition are yet to be well understood and should not be inferred from these test results alone. Additionally, significant changes in the Li-ion battery design and chemistry may require additional research.

The applicable storage conditions are:

- Rack storage heights up to 4.6 m (15 ft).
- Ceiling heights up to 12.2 m (40 ft).
- Bulk-packaged 20 Ah polymer pouch batteries in corrugated board cartons with heavy plastic dividers at nominally 50% state-of-charge (SOC).

The methodology for this project consisted of bench-scale through large-scale evaluations using a 20 Ah polymer pouch Li-ion battery, comprised of iron phosphate chemistry, at a nominal 50% SOC. The first test evaluated the flammability characteristics of the selected Li-ion battery compared to FM Global's standard commodities and previously tested small-format Li-ion batteries. This was an intermediate-scale free-burn fire test focused on measurement of the heat release rate and the time of significant battery involvement. Subsequent predictions established the fire hazard present in a sprinklered fire scenario and provided the basis for protection system guidance. Based on the result of the intermediate-scale test, and building upon Reference [15], the following conclusions can be made:

- The cartoned 20 Ah large-format battery used in the present study represent a higher hazard than the previously tested 2.6 Ah small-format batteries (cylindrical and polymer pouch). This conclusion is based on the following test results, which indicate that the large-format battery contributed to the overall fire severity closer to the predicted time of sprinkler operation than the small-format batteries:
    - The predicted time of sprinkler operation was similar for all cartoned Li-ion batteries and FM Global standard commodities included in this project. This result supports the assumption that, for three-tier-high, open-frame racks, the carton packaging dominates the fire development leading to first sprinkler operation.
    - Under free-burn conditions, the 20 Ah Li-ion polymer pouch battery used in this project contributed to the overall severity of the rack storage fire 2 min 30 s (150 s) after igntion, versus 5 minutes (300 s) for the 2.6 Ah cylindrical and polymer pouch batteries previously tested in Phase 2 [15].

- The product packaging, e.g., corrugated board containers and dividers, was identified as a key factor driving the hazard in Li-ion batteries in storage. While the corrugated board cartons were shown to dominate the initial fire growth, the plastic content within the cartons was shown to be a driving factor in the overall commodity hazard, in particular:
    - Cartoned batteries containing significant quantities of plastics exhibited a similar rapid increase in the released energy due to plastics involvement early in the fire development.
        - For the large-format 20 Ah Li-ion polymer pouch batteries used in this project, the heavy plastic dividers contributed to the overall severity of the fire before involvement of the batteries.
        - For the power tool packs, tested in Phase 2 [15], the heavy plastic case of the battery pack dominated the fire hazard and there was no observable contribution from the batteries.
    - Cartoned batteries containing minimal plastics (*e.g.,* the small-format Li-ion cylindrical and polymer batteries tested in Phase 2 [15]) exhibited a slower increase in energy release and a delay in the battery involvement due to heating of the batteries. In this case the plastic dividers represented a lesser combustible load than the heavy plastic dividers used for the 20 Ah polymer pouch battery.

Caution should be taken when extending the results of the testing presented in this report beyond the specific combination of packaging and battery listed. Changes in the components of the packaging can significantly impact the flammability characteristics of cartoned Li-ion batteries. One key aspect of the packaging driving the fire hazard is the divider used to separate the batteries within the cartons. Potential divider materials represent a wide range of fire properties and include liner board, fiber board, thin or heavy plastic, and expanded foam. Even for the same battery, changing the liner material can significantly impact the fire hazard. Changes in the Li-ion battery can also have a similar effect on the overall hazard of the cartoned product. For instance, high SOC has been shown to increase the likelihood and severity of thermal runaway. The quantity of electrolyte, which is the main combustible source, is a function of the battery capacity and can also vary with the battery format (e.g., cylindrical or polymer pouch). Thus, even for the same packaging, changes in the battery can impact the fire hazard. A new flammability assessment should be conducted when potentially significant changes to the cartoned product are encountered.

The performance of ceiling-level sprinkler protection was then assessed with a large-scale sprinklered fire test of the cartoned large-format 20 Ah polymer pouch batteries. The test was conducted using a three-tier-high rack-storage array, which represents storage up to 4.6 m (15 ft) high. Protection was provided by quick-response, pendent sprinklers, having a 74°C (165°F) rated link with a K-factor of 320 L/min/bar$^{1/2}$ (22.4 gpm/psi$^{1/2}$) under a 12.2 m (40 ft) ceiling. In accordance with the evaluation criteria established in Section 4.5, and building upon Reference [15], the following conclusions can be made:

- Storage up to 4.6 m (15 ft) under ceiling heights up to 12.2 m (40 ft) is adequately protected by a fire protection system comprised of pendent sprinklers having a K-factor of 320 L/min/bar^{½} (22.4 gpm/psi^{½}), with a nominal 74°C (165°F) temperature rating and a nominal RTI of 27.6 m^{½}s^{½} (50 ft^{½}s^{½}), installed on 3.0 m × 3.0 m (10 ft × 10 ft) spacing at an operating pressure of 2.4 bar (35 psig). This conclusion is based on one sprinkler operation extinguishing a large-scale test fire without manual intervention.

- Protection guidance established from the large-scale fire test can be reasonably applied to the small-format Li-ion batteries previously tested for this project. This conclusion is based on the results of the reduced-commodity test indicating that the cartoned large-format battery used in this project represented a higher hazard than the previously tested small-format batteries.

Three supplemental evaluations were then carried out to reinforce the sprinkler protection guidance resulting from the successful large-scale fire test. The first evaluation assessed the likelihood and impact of ignition resulting from thermal runaway of one or more batteries within a carton. The effectiveness of sprinkler water at suppressing a fire at a later stage of battery involvement than was achieved in the large-scale test was then assessed. Finally, literature data were reviewed to compare the minimum water application rate needed to prevent flame spread along the carton packaging versus the sprinkler protection used in the large-scale test. Based on the results of these supplemental tests the following conclusions can be made:

- For all small- and large-format Li-ion batteries used in this project, the development of a rack storage fire leading to sprinkler operation should be similar for both ignition scenarios where the fire initiates inside or outside of the carton. This conclusion is based on the following test results:
    - Thermal runaway of the 20 Ah polymer pouch battery used in this project did not result in battery-to-battery propagation within the carton. Experimental data have shown that thermal runaway of up to three batteries simultaneously within a single carton did not propagate to the adjacent batteries within the same carton.
    - There is not sufficient air within a carton to support combustion of a single 20 Ah polymer pouch battery. Thus, fire propagation primarily occurs outside of the carton. In addition, review of literature data has shown that battery-to-battery propagation following thermal runaway of small-format cylindrical batteries occurs only after the carton has breached [32].
    - Once an external fire is present, flame propagation along the carton material will dominate the fire development leading to sprinkler operation and will occur before the batteries contribute to the overall fire severity.

- The sprinkler system used in the large-scale fire test is sufficient to protect against a fire where the Li-ion batteries are contributing more to the overall fire severity than occurred in the large-scale test. This conclusion is based on the following analysis:

- Intermediate-scale testing, designed to delay the application of protection water until the batteries were contributing to the overall fire, confirmed the adequacy of sprinkler protection guidance resulting from the successful large-scale fire test.
- In addition, review of literature data provided in Reference [34] has shown that a lower sprinkler discharge rate than used in the large-scale fire test can also control or suppress fire development along corrugated board cartons.

An experimental methodology to develop sprinkler protection guidance for warehouse storage of Li-ion batteries using a reduced quantity of commodity has been established. This methodology provides a unique means of extending the application of a successful large-scale fire test to other Li-ion batteries by a combination of small- to intermediate-scale fire tests. However, lacking complete large-scale sprinklered fire test experience for each Li-ion battery, a conservative approach to establishing sprinkler protection guidance should be taken.

8. **Recommendations**

Protection recommendations for warehouse storage of cartoned Li-ion batteries have been developed through fire testing and comparison to commodities with similar hazard characteristics. In consultation with the FM Global Engineering Standards group, which is responsible for the *FM Global Property Loss Prevention Data Sheets,* protection recommendations have been established based on current knowledge and may be amended if additional research specific to the hazard of Li-ion batteries is conducted.

The best protection recommendations based on current knowledge, for each Li-ion battery included in this project and Reference [15], are summarized below:

- Li-ion polymer pouch batteries (capacity up to 20 Ah at ≤ 50% SOC) and Li-ion cylindrical batteries (capacity up to 2.6 Ah at ≤ 50% SOC):
    - For a single unconfined pallet load of batteries stored on the floor to a maximum of 1.5 m (5 ft) high, protect as an HC-3 occupancy per FM Global Property Loss Prevention Data Sheet 3-26, *Fire Protection Water Demand for Nonstorage Sprinklered Properties*, July 2011. Additionally, maintain a minimum of 3.0 m (10 ft) separation between adjacent combustibles.
    - For batteries stored solid pile, palletized, or in racks up to 4.6 m (15 ft) under a ceiling up to 12.2 m (40 ft) high, protect with quick-response, pendent, sprinklers with a 165°F (74°C) nominal temperature rating. Protection options include:
        - K320 L/min/bar$^{1/2}$ sprinklers @ 2.4 bar (K22.4 @ 35 psi). The water flow demand should allow for 12 sprinkler operations.
        - K360 L/min/bar$^{1/2}$ sprinklers @ 2.4 bar (K25.2 @ 35 psi). The water flow demand should allow for 12 sprinkler operations.
    - For batteries stored higher than 4.6 m (15 ft) or ceiling heights greater than 12.2 m (40 ft), store batteries in racks and protect with Scheme A per Section D.2.2.1 of FM Global Property Loss Prevention Data Sheet 7-29, *Ignitable Liquid Storage in Portable Containers*, April 2012 (DS 7-29)
- Li-ion power tool packs (*i.e.,* comprised of 18650-format cylindrical batteries with a total pack capacity up to 26 Ah at ≤ 50% SOC):
    - Protect in-process storage of power tool packs as an HC-3 occupancy per FM Global Property Loss Prevention Data Sheet 3-26, *Fire Protection Water Demand for Nonstorage Sprinklered Properties*, July 2011. Limit in-process storage area to 19 m^2 (200 ft^2) and one pallet high. Additionally, maintain a minimum of 2.4 m (8 ft) separation between adjacent combustibles.
    - For power tool packs stored up to 4.6 m (15 ft) high under a ceiling up to 12.2 m (40 ft), protect as FM Global standard cartoned unexpanded plastic (CUP) commodity per

FM Global Property Loss Prevention Data Sheet 8-9, *Storage of Class 1, 2, 3, 4 and Plastic Commodities*, FM Global, July 2011.

- For power tool packs stored higher than 4.6 m (15 ft) or ceiling heights greater than 12.2 m (40 ft), store batteries in racks and protect with Scheme A per Section D.2.2.1 of DS 7-29.

All ceiling sprinklers should be installed in accordance with FM Global Property Loss Prevention Data Sheet 2-0, *Installation Guidelines for Automatic Sprinklers*, January 2014.

Storage beyond the above listed conditions, including battery characteristics (*e.g.*, SOC, quantity of electrolyte, and format) and packaging components (e.g., cartons and dividers), requires a more robust protection scheme to account for several unknowns that can negatively affect protection effectiveness. Fire Protection Scheme A combines in-rack automatic sprinklers (IRAS) and horizontal barriers for protection of high-hazard commodities, such as rack storage of ignitable liquids or level 3 aerosols. Complete specifications and drawings can be found in Section D.2.2.1 of DS 7-29. Similar specifications can be found in Section E.2 of FM Global Property Loss Prevention Data Sheet 7-31, *Storage of Aerosol Products*, January 2012. This system design is expected to provide the highest level of protection required for storage of the Li-ion batteries tested in this project and can be applied to array configurations beyond the scope of this project.

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