Development of Protection Recommendations for Warehouse Storage of Li-ion Batteries

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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. The fire hazards inherent to Li-ion battery technology are well described in many overview documents [1, 2, 3, 4]. The unique potential for thermal runaway reactions to spread a fire differentiates Li-ion batteries from typical ordinary (endothermic) combustible materials found in warehouse storage. As a result, existing fire protection guidance for ordinary combustible products [5, 6] cannot be applied to validate the sprinkler system design without large-scale fire testing [7]. Given the inordinate cost and effort associated with testing Li-ion batteries, it is unlikely that extensive sprinklered fire testing is forthcoming. Thus, there is a need to establish a testing methodology that extends the application of the limited opportunities for large-scale testing.

2 Experimental Approach

A multi-phase study was undertaken to determine fire protection guidance for warehouse storage of cartoned Li-ion batteries [8, 9]. The study included of a comparison of the freeburn flammability characteristics of the select small- and large-format Li-ion batteries to standard commodities in a rack-storage configuration. 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. 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. It is important to note that this approach does not provide the same level of information regarding protection

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system performance gained through Commodity Classification [10] and was implemented due to the inordinate costs associated with testing large quantities of batteries.

3 Reduced-Commodity Hazard Assessment

The reduced-commodity test configuration was designed to capture the fire growth characteristics leading to sprinkler operation in a warehouse storage scenario. Figure 1 shows an example of the test setup of the 20 Ah polyer pouch battery. A similar setup was used for the other batteries. 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 standard 1.07 m × 1.07 m × 1.07 m (42 in. × 42 in. × 42 in.) commodity dimensions and representative air entrainment conditions around the commodity. The upper two tiers consisted of pallets loads of cartoned Li-ion batteries also stacked to maintain the standard pallet load dimensions.

30s 90s 180 s

Figure 1: Example photos from the reduced-commodity test of 20 Ah Li-ion polymer pouch batteries at multiple times after ignition.

The convective heat release rates, determined from the temperature rise of the gas flow in the Fire Products Collector (FPC) located above the test array, are shown in Figure 2. Data is presented for 2.6 Ah small-format polymer pouch and cylindrical batteries and 20 Ah large-format polymer pouch batteries. All batteries were at a nominal 50% state-of-charge (SOC) for consistency with standard warehouse storage conditions. It is assumed the battery chemistry will have minimal impact on the overall fire hazard in this test configuration. Standard cartoned commodities used to evaluate sprinkler protection in warehouse storage, i.e., Class 2 and cartoned unexpanded plastic (CUP) commodities [10] 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.

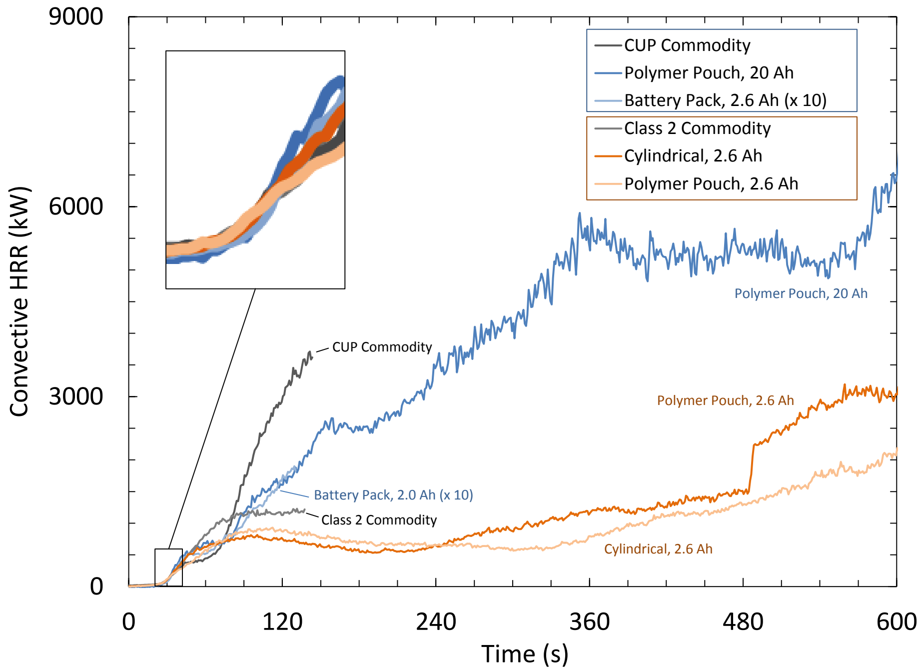

Figure 2: Convective heat release rates for small- and large-format Li-ion batteries and standard commodities. The time of each test has been slightly offset to align the initial fire growth period.

Qualitatively, all commodities shown in Figure 2 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 size and fire growth rate leading to predicted sprinkler operation are shown in Table 1. These data were determined following a theoretical method to calculate the response time of sprinkler links to rack storage fires developed by Kung, Spaulding, and You [11]. To summarize this approach, the thermal response of sprinkler links can be found from a simple balance between convective heat transfer to the link and heat stored in the link for cases when thermal radiation can be neglected. The governing equation can be expressed as [12, 13]

$$\frac{dT_s}{dt} = \frac{v^{1/2}(T - T_s)}{RTI} \tag{1}$$

where T_s is the temperature of the simulated link, T is the ceiling gas temperature, v is the gas velocity, and RTI is the response time index of the simulated link. To determine the link temperature, both the gas temperature and velocity under the ceiling are required. For testing under a FPC, where no ceiling is present, these values can be estimated using well-known plume laws for plume centerline excess gas temperature [14, 15].

From this data, the small- and large-format batteries exhibited similar flammability characteristics leading to sprinkler operation. When compared to standard commodities (both Class 2 and CUP), the 20 Ah batteries exhibited slightly higher flammability characteristics at the time of sprinkler operation. Though it should be noted that fire growth rates nominally within a factor of two and fire size values within 30% of the average are considered equivalent [10].

Table 1: Predicted operation times and corresponding fire growth characteristics for quick-response sprinklers with a link temperature rating of 74°C (165°F) assuming a 7.6 m (25 ft) ceiling height.

Cartoned Commodity	Sprinkler Operation	Fire Size*	Fire Growth*
	s	kW	(kW/s)
Li-ion, 20 Ah polymer pouch	37	335	33
Li-ion, 2.6 Ah polymer pouch	41	256	16
Li-ion, 2.6 Ah cylindrical	44	282	25
Li-ion, 26 Ah power tool packs†	51	270	20
Class 2	59	209	15
CUP	43	232	16

* Fire size and growth rate at the time of predicted sprinkler operation.
† Comprised of ten 2.6 Ah cylindrical cells in a hard plastic case.

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/paper 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. For each battery type, threshold values were determined that represent the earliest and latest time that batteries contributed to the overall fire severity. Detailed descriptions of the approach used to determine battery involvement can be found in reference [9] for large-format batteries and reference [8] for small-format Li-ion batteries.

Following this approach, large-format 20 Ah polymer pouch batteries became involved in the fire at an estimated 150 s after ignition. In comparison, the previously tested small-format Li-ion batteries became involved in the fire significantly later at an estimated 300 s after ignition. No estimate could be made for the power tool packs due to the added combustible load related to the plastic components dominated the fire development. Thus, the large-format battery represents the highest hazard among tested Li-ion battery commodities based on the flammability characteristics leading to first sprinkler operation and time of battery involvement in the fire.

3 Large-Scale Sprinklered Fire Test

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}) arranged in 3 m x 3 m (10 ft x 10 ft) spacing. 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. The test commodities were cartoned large-format 20 Ah polymer pouch batteries stacked 3-tiers high, with standard CUP commodity on each end. The flue space is 150 mm (60 in) throughout the array. Each pallet load of batteries consisted of 56 cartons, containing 20 batteries, arranged among seven levels of eight cartons each for a total of 1,120 batteries per pallet load. Ignition was achieved with two igniters, which are 76 mm x 76 mm (3 in. x 3 in.) cylinders of rolled cellu-cotton. Each igniter was soaked in 118 ml (4 oz.) of gasoline and sealed in a plastic bag. The igniters were offset 0.6 m (2 ft) within the center transverse flue, between the rack uprights, of test array.

From the fire test images shown in Figure 3 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 60 s flames extended approximately 1.5 m (5 ft) above the array. The sprinkler centered over the main array operated at 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 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 150 s. The test was conducted for 40 min and required only minimal manual firefighter intervention to extinguish a few lingering deep-seated flames.

90 s (Sprinkler operation) **East (aisle) face of main array**

Figure 3: Images of Large-scale fire test

4 Conclusions

Protection guidance for warehouse storage of cartoned Li-ion batteries have been developed through fire testing. A unique approach was developed that incorporated multiple fire test evaluations, 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 small- and large-format Li-ion batteries, as well as, standard warehouse commodities. The performance of ceiling-level sprinkler protection was then assessed with a large-scale sprinklered fire test of the large-format Li-ion batteries. Based on the experimental results, adequate protection can be achieved for storage of cartoned Li-ion batteries stored in racks up to 4.6 m (15 ft) under a ceiling up to 12.2 m (40 ft) high. Ceiling-level sprinkler protection options include K320 or K360 L/min/bar$^{1/2}$ sprinklers (K22.4 or K25.2 gpm/psi$^{1/2}$) at 2.4 bar (35 psi). Sprinklers should be quick-response, pendent, and have a 165^{o}F (74^{o}C) nominal temperature rating. This guidance applies to all small- and large-format batteries testing throughout this project.

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