Underground Ventilation – Tukkaraja (Ed)

Evaluation of different suppression techniques for lithium-ion battery fires

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ABSTRACT: Lithium-ion (Li-ion) batteries are finding more use as power sources in the mining industry. However, they are known to pose significant fire and explosion hazards. When a Li-ion battery is exposed to excessive operating conditions, its internal temperature may exceed a normal operating range, allowing the active component materials to decompose or react with each other, eventually leading to thermal runaway. A Li-ion battery contains certain oxidizing agents making suppression of a battery fire very challenging. A series of Li-ion battery fire suppression tests were conducted by researchers at the National Institute for Occupational Safety and Health (NIOSH) to evaluate the effectiveness of different fire suppression test systems including dry chemical, water spray/mist, and Class D extinguisher powder. The batteries tested are commercial nickel manganese cobalt (NMC) and lithium iron phosphate (LFP) battery packs. The results indicated that dry chemical and Class D powder could extinguish the fire temporarily, but a reignition occurred. Water mist was able to extinguish the battery fire completely with continuous cooling of the battery to prevent the reignition. The suppression results for both NMC and LFP chemistries were also compared. These test results can be used to develop appropriate firefighting strategies for safe and effective suppression of battery fires in a mine.

1 INTRODUCTION

Li-ion batteries are known to pose significant fire and explosion hazards as the use of these batteries has become more widespread, ranging from consumer electronics, battery electric vehicles, to energy storage systems. The mining industry has also seen increased utilization of Li-ion batteries for powering equipment in both surface and underground mining operations. The safety issues related to Li-ion batteries pose a great challenge to their wider application of Li-ion batteries in large mining equipment which may consist of thousands of battery cells. Several battery fire incidents have occurred in underground mines in the early stages of battery electric vehicle deployment (Gillet, 2021). A battery fire is usually caused by thermal runaway that occurs when heat generated from exothermic reactions inside a battery outpaces heat dissipated from the battery. If unmitigated, thermal runaway will proceed to cell rupture and the venting of hot, toxic, and highly flammable gases, leading to a possible fire or explosion. These potential fire hazards need to be assessed and techniques developed to effectively suppress Li-ion battery fires.

Many laboratory-scale experiments have been conducted on the battery fire suppression techniques (Xu et al., 2021; Zhang et al., 2021; Cui et al., 2022; Said et al., 2022). Li et al. (2015) studied the fire-extinguishing efficiency of ABC powder, carbon dioxide, aqueous film-form foam (AFFF), and water mist on the 18650-type $LiCoO_2$ Li-ion battery pack. The ABC powder, carbon dioxide, and 3% aqueous film-form foam were able to extinguish the open flames of the Li-ion battery pack, but the reignition could not be avoided. The water mist

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system could not suppress the battery fire in the experiments because of low water flow rate. The laboratory experimental results of Xu et al. (2020) indicate that water mist/spray has a better suppression effect than CO_2 and HFC-227ea. The Federal Aviation Agency (FAA) conducted experiments to screen fire-extinguishing agents for battery fire involving consumer electronic products powered by Li-ion batteries (Maloney, 2014). The experimental results demonstrated that water-based extinguishing agents were the most effective, while nonaqueous extinguishing agents were the least effective. Russo et al. (2018) conducted experiments to evaluate the effectiveness of different fire extinguishing agents for single Li-ion cells and a battery pack. Out of the five fire-extinguishing agents including water, foam, dry powder, carbon dioxide, and water mist, water and foam were the most effective by rapidly reducing the temperature of the cell and extinguishing the fire.

There are few studies on the suppression of large Li-ion battery pack fires. Egelhaaf et al. (2014) carried out firefighting tests of Li-ion traction batteries, and the test results showed that the amount of water required to extinguish such a fire is a lot larger amount than that used for firefighting of conventionally driven vehicles. In National Transportation Safety Board (NTSB) investigations of battery fires in electric vehicles, the total amount of water used to suppress high-voltage Li-ion battery fires ranged from 300 to 20,000 gallons (NTSB, 2020). These studies indicated that water can be an effective suppression agent for fighting battery fires if a sufficient amount of water is available. For battery electric vehicles used in underground mines, water may not be readily available, or the amount of water may be limited. Therefore, research is needed to investigate the characteristics of different Li-ion battery fires in mines and effective fire suppression techniques. In this study, fire suppression experiments were conducted for both NMC and LFP battery packs using water mist, dry chemical, and Class D extinguishing powder, and the suppression results for these two battery chemistries were compared. Experiments were also conducted to study the effect of battery size on the suppression of NMC battery pack fires. The experimental results from this study may help develop appropriate firefighting strategies for safe and effective suppression of Li-ion battery fires in underground mines.

2 EXPERIMENTAL

Li-ion battery fire suppression experiments were conducted in a container with dimensions of 12-m long, 2.4-m wide, and 2.85-m high (40 ft × 8 ft × 9.5 ft) and using a data acquisition and test observation trailer located nearby the container. A fan is installed at one end of the container and the opposing end is open as shown in Figure 1. The ventilation velocity was set at 0.2 m/s (40 fpm) for all tests. The container is equipped with three fire suppression systems: dry chemical, water spray/mist, and Class D powder. The fire suppressant discharge nozzle direction is located above the battery. The suppression system is manually activated from outside the container. Thermocouple trees and gas sampling tubes were installed at the exit of the container to measure exit gas temperatures and collect gas samples. Two cameras were installed inside the container to monitor testing.

The batteries used for the suppression tests were a 12V 30Ah NMC battery pack consisting of 36 cylindrical cells and a 12V 35Ah LFP battery pack consisting of 24 cylindrical cells. Before each test, the battery pack was charged to the 100% state. During the tests, the battery pack was placed onto two heater strips for heating up with each of two 750-Watt heaters. In addition, 12 to 18 K-type thermocouples were attached to the surfaces of the battery cells of the battery pack to measure the battery temperature as shown in Figure 2. During the tests, when the battery reached thermal runaway, the heaters were turned off, and then, after a stable flame was established, the fire suppression system was activated. The suppression nozzle was placed 1.5 m above the battery pack. For the dry chemical and Class D powder suppression systems, the release time was between 30 and 50 seconds. For the water mist system, the flow rate was 3.6 gallon per minute and water was on for 2 to 5 minutes. Battery surface temperatures were measured by the data acquisition system. Air exiting the container was sampled using an infrared gas analyzer to determine concentrations of carbon monoxide

Figure 1. Battery fire suppression test setup.

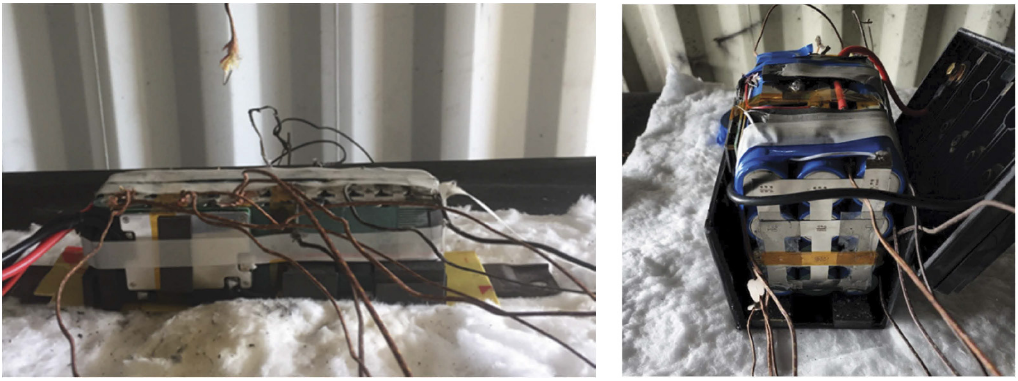

Figure 2. Battery packs and attached thermocouples. NMC (left), LFP (right).

(CO) and carbon dioxide (CO_2). Cameras were used to observe and record the fire and suppression behaviors. Observations were made on a monitor in the trailer to determine the times for the first appearance of smoke and flame and the final extinguishment of the fire if there was one.

3 RESULTS AND ANALYSIS

3.1 *Free burn tests*

Free burn tests were conducted to understand the fire characteristics for both 12V NMC and LFP battery packs. During the free burn, the battery pack was heated the same way as for the suppression tests, and the same ventilation airflow was used. As no fire suppressant was applied, the battery was left to burn all the way to self-extinguishment. For the NMC battery pack, flames appeared after the battery smoked for more than 6 minutes, and then the heaters were turned off. The first cell explosion occurred about 1.5 minutes after the first flame. Multiple cells exploded during the free burn, and the battery pack was disintegrated. The total burning time was 4.5 minutes with constantly violent explosions. For the LFP battery pack, flames appeared after the battery smoked for 5.5 minutes, then the heaters were turned off.

Compared to the NMC battery pack, significantly heavier smoke was generated before the first flame. The first cell explosion also occurred about 1.5 minutes after the first flame. However, very few cells exploded, and the battery pack was not disintegrated. The total burning time was over 19 minutes. The battery did not burn as violently as the NMC battery. Instead, the LFP battery only burned violently for 1-2 minutes, and then maintained a local small flame for 4-5 minutes, followed by another violent but short burn Figure 3 (a) shows the violent burn with cell explosion for the NMC battery pack, and Figure 3 (b) shows the flaming of the LFP battery.

The apparently different combustion behaviors of NMC and LFP batteries can be further examined in Figure 4. Figure 4 (a) shows the exit gas temperature increase above the ambient temperature, while Figure 4 (b) shows the measured CO_2 concentrations at the exit for the two batteries. The NMC battery had a slightly higher maximum gas temperature increase, but a lower maximum CO_2 concentration than the LFP battery. As observed, the NMC battery burned violently lasting for only 4.5 minutes. This can be seen clearly in the gas temperature increase and CO_2 concentration data. For the LFP battery, the gas temperature increase and CO_2 concentration data show clearly that there were a few peaks after the first peak indicating the existence of small flames and burning for more than 19 minutes. This is consistent with the observation on the camera monitor.

Figure 3. 12V battery pack free burn (a) NMC (left) and (b) LFP (right).

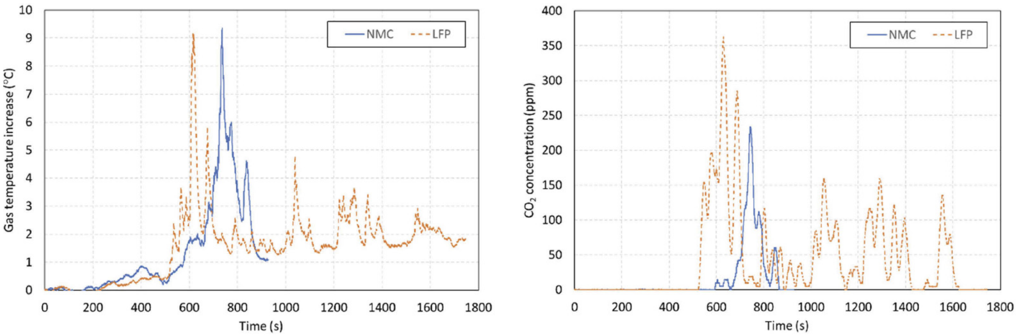

Figure 4. (a) Comparison of exit gas temperature increase (left) and (b) CO_2 concentrations (right).

3.2 *NMC and LFP battery pack fire suppression using dry chemical and Class D powder*

Dry chemical is a commonly used fire suppressant for mine equipment fires. In this study, a dry chemical suppression system was used to suppress fires from both 12V NMC and LFP battery packs under the same experimental conditions. For the NMC battery, the dry chemical suppression system was activated after the first cell explosion occurred, and the suppressant discharge lasted for 10 seconds. The flame was extinguished by the suppressant. Figure 5 (a) shows the burning of the NMC battery before the discharge of the suppressant, and Figure 5 (b) shows the NMC battery pack after the flame was extinguished. The battery pack was dislocated a little and broke into two sections by the cell explosion. After 2.5 minutes, the reignition occurred and the NMC battery exploded again as shown in Figure 5 (c). Eventually, the burning slowed down as shown in Figure 5 (d). The reignition lasted for about 8 minutes. Class D extinguishing powder was also tested for suppression of the battery pack fires. Similar to the dry chemical, the Class D powder was able to quench the flame quickly for the NMC battery pack; however, the flame came back in a few seconds after the discharge of the suppressant. The NMC battery continued to burn for about 5 minutes to self-extinguishment.

Figure 6 shows the LFP battery fire and suppression process with the dry chemical suppression system. Figure 6 (a) shows the flame before the discharge of the dry chemical. Figure 6 (b) shows the battery after the flame was extinguished by the suppressant with everything covered by the white chemical. After roughly 2 minutes, reignition occurred as shown in Figure 6 (c) because the dry chemical was not able to cool the LFP battery to stop the exothermic internal reactions. The LFP battery continued to burn all the way to self-extinguishment lasting for more than 10 minutes as shown in Figure 6 (d). During the reignition period, there was a cell explosion, and the flame went out for about half a minute and came back again. For the LFP battery pack, the Class D powder was not able to extinguish the flame, and the battery continued to burn for 10 minutes.

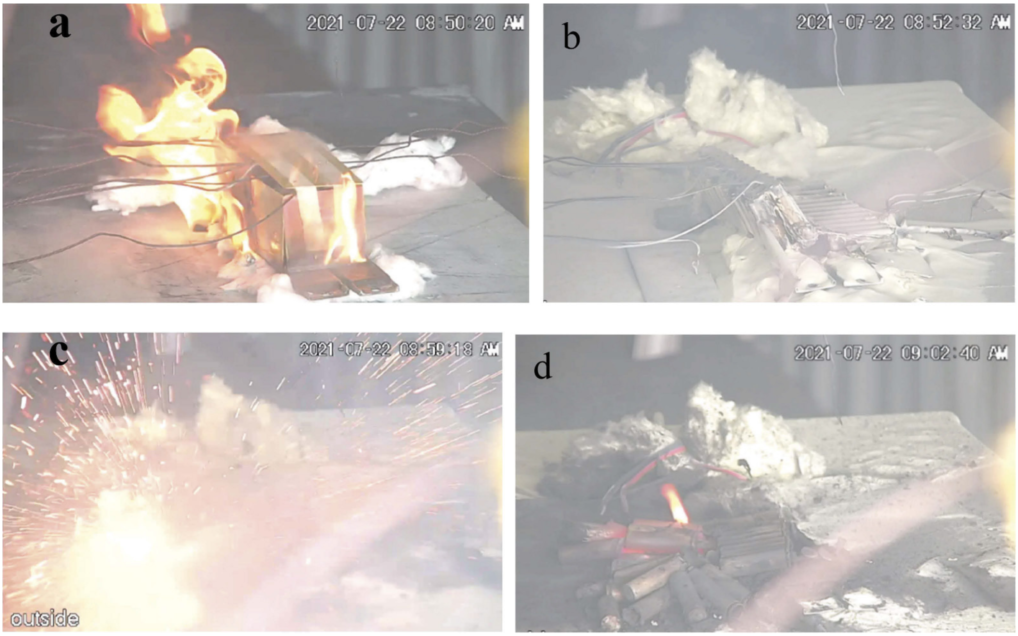

Figure 5. NMC battery fire suppression using dry chemical: (a) flame before suppression; (b) after suppressant discharge; (c) explosion following reignition; (d) flame near burnout.

3.3 *NMC and LFP battery pack fire suppression using water mist*

A water mist system was applied to suppress the battery fires from both the NMC and LFP battery packs. For the NMC battery fire, water mist was turned on one minute after the first flame, and the fire was extinguished in 65 seconds. There was one cell explosion during the suppression. Figure 7 (a) shows the burning of the NMC battery before water suppression

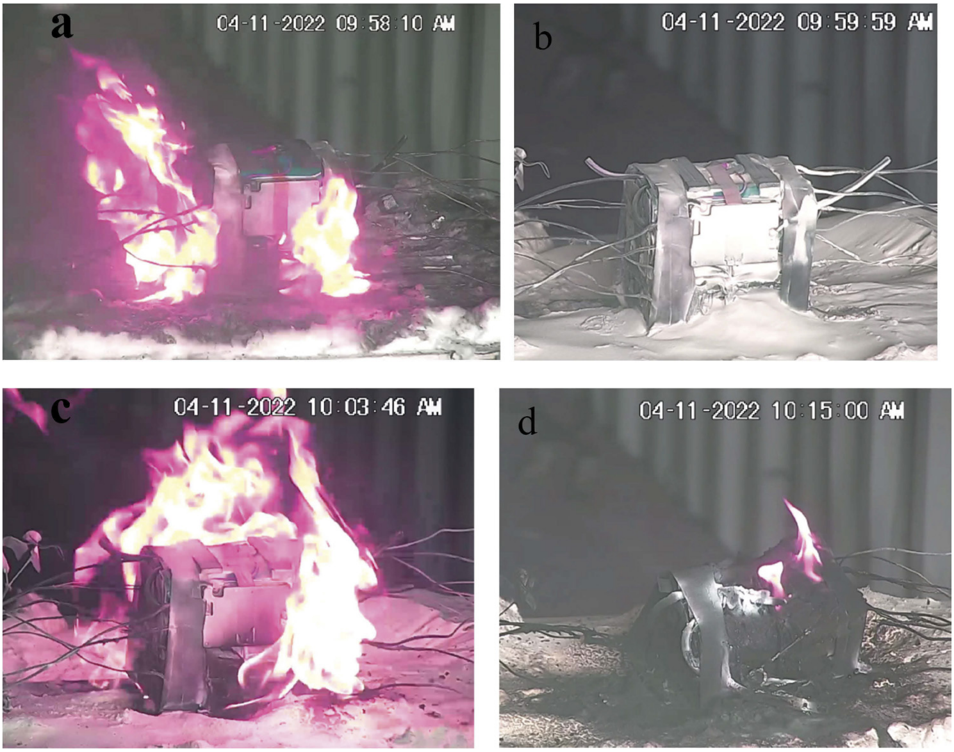

Figure 6. LFP battery fire suppression using dry chemical: (a) flame before suppression; (b) after suppressant discharge; (c) flame after reignition; (d) flame near burnout.

was turned on, while Figure 7 (b) shows the NMC battery after the fire was extinguished. Water was on for 2 minutes and there was no reignition. For the LFP battery fire, the water mist extinguished the flame in 43 seconds, but the flame occurred again in half a minute. As water was still on, the fire was extinguished in 14 seconds. The total extinguishing time was 86 seconds, and there was no reignition. Figure 8 (a) shows the burning of the LFP battery before the release of water mist, and Figure 8 (b) shows the LFP battery pack after the fire was extinguished. The results indicate that water mist was effective in extinguishing both the NMC and LFP battery pack fires as water could cool the battery continually to prevent the reignition of the battery.

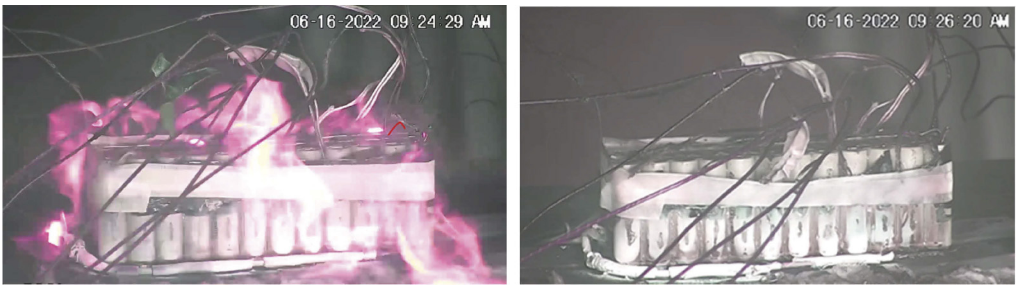

Figure 7. NMC battery fire suppression with water mist; (a) flame before suppression (left) and (b) flame out after water mist (right).

Figure 8. LFP battery fire suppression with water mist; (a) flame before suppression (left) and (b) flame out after water mist (right).

3.4 *Effect of battery size on suppression of NMC battery pack fires*

The effectiveness of a fire suppression system for a Li-ion battery can be affected significantly by the battery size. In this study, fire suppression tests were also conducted for a larger NMC battery pack. This larger NMC battery pack was 24V 40Ah consisting of 108 cylindrical cells in three rows. The test conditions and procedures were the same as for the 12V battery pack. With the water mist system, it took 172 seconds to completely extinguish the fire. During this process, the battery burnt violently with over 20 cell explosions. There was no reignition as water was on for 6 minutes to cool the battery. Compared to the 52-second extinguishing time for the 12V NMC battery pack, the larger size pack needed significantly longer extinguishing time with the water mist system.

With the dry chemical system, the flame was extinguished after the discharge of the suppressant. However, reignition occurred after 15 minutes, and the battery continued to burn for over 5 minutes. Compared to the 2.5 minutes before the reignition occurred for the 12V NMC battery pack with the dry chemical system, it took a significantly longer time for the reignition to occur for the larger NMC pack. With the Class D powder system, the flame was not completely extinguished, and a small flame persisted after the discharge of the powder. The battery continued to burn violently with multiple cell explosions for 12 minutes. For the 12V NMC battery pack fire suppression with the Class D powder system, the reignition occurred in a few seconds. These results demonstrate that Class D powder is ineffective for extinguishing the NMC battery pack fires.

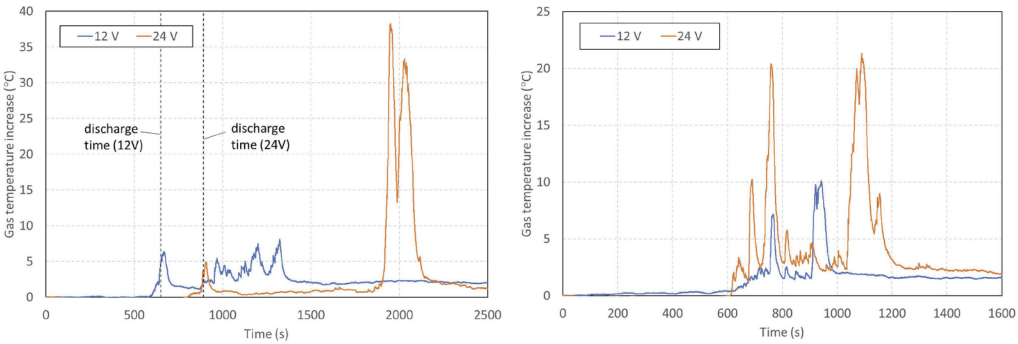

Figure 9. Comparison of exit gas temperature increases between different NMC battery pack sizes using (a) dry chemical (left) and (b) Class D powder (right).

Figure 10. Scattered NMC cells after flame was out with (a) dry chemical system (left) and (b) Class D powder system (right).

Figure 9 (a) and Figure (b) show exit gas temperature increases for both the 12V and 24V NMC battery packs during the fire suppression process using the dry chemical and Class D powder system, respectively. It can be seen that the dry chemical was able to extinguish the flame immediately after the discharge of the suppressant. But reignition occurred after 15 minutes as the dry chemical was not able to cool the battery. Dry chemical smothered the battery completely and stopped the radiative heat transfer from the flame to the battery as the flame was extinguished. The chemical reactions inside the battery were still ongoing, but there was no external heat transfer any longer. This may be the major reason that it took 15 minutes for the reignition to occur, and the battery burned very violently with many cell explosions. Using the dry chemical suppressant, 24V NMC battery pack was completely disintegrated, and cells were scattered as shown in Figure 10 (a). The maximum exit gas temperature increase was about 38° C for the 24V NMC battery pack fire while using the dry chemical suppressant, Figure 9 (a). On the other hand, the Class D powder was not able to extinguish the flame completely, but just reduced it to a small flame. The small flame continually radiated heat to the adjacent battery cells. The chemical reactions inside those cells were accelerated by the 24V NMC battery pack flame heat, and it took 70 seconds for those cells to explode producing a peak exit gas temperature increase of 20° C, Figure 9 (b). About 5 minutes later, there was another round of cell explosions with another peak exit gas temperature increase of 21° C. As shown in Figure 10, more of the 24V NMC battery pack cells exploded with the dry chemical system than with the Class D powder system.

4 CONCLUSIONS

Experiments were conducted to study the fire behaviors of 12V NMC and LFP Li-ion battery packs. Under the same conditions, the NMC battery pack burned more violently with more cell explosions than the LFP pack, while the LFP pack burned for a longer time and generated more CO_2. Fire suppression experiments were then conducted for both battery chemistries using dry chemical, Class D powder, and water mist systems. The experimental results demonstrate that water was more effective in extinguishing the battery pack fires than dry chemical and Class D powder because water was able to cool the battery continually. With dry chemical and Class D powder, the flame was extinguished temporarily, but reignition occurred after 2 to 2.5 minutes with the dry chemical, and a few seconds with the Class D powder.

The effect of battery size on the suppression of NMC battery pack fires was investigated through suppression tests using a larger 24V battery pack. The experimental results show that even though water was still able to extinguish the larger 24V battery pack fire, the extinguishing time increased significantly as compared to the smaller 12V battery pack, from 65 to 172 seconds indicating a large amount of water is needed to extinguish a large format Li-ion battery fire. With the larger 24V battery pack and the dry chemical, the flame was also extinguished temporarily, but it took a much longer time for the reignition to occur as compared to the smaller 12V battery pack, from 2.5 to 15 minutes, indicating the larger the battery size, the longer time for the reignition to occur. With the Class D powder system, the flame was not completely extinguished, and the battery continued to burn, indicating that the Class D powder is least effective for suppressing the Li-ion battery fires. The experimental results also demonstrate that the longer time before the reignition results in a more violent explosion, as more cells become involved.

5 DISCLAIMERS

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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