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Effective Fire Extinguishing Systems for Lithium-ion Battery

Paola Russo[a]*, Cinzia Di Bari[b], Michele Mazzaro[c] , Armando De Rosa[c], Ilario Morriello[d]

[a] Dipartimento Ingegneria Chimica Materiali Ambiente, Sapienza Università di Roma, Roma, Italy
[b] Laboratorio Sistemi e Tecnologie per la Mobilità e l'Accumulo, ENEA DTE-PCU-STMA, CR Casaccia, Roma, Italy
[c] Direzione Centrale per la Prevenzione e la Sicurezza Tecnica, Nucleo Investigativo Antincendi, Roma, Italy
[d] Squadra di Pronto Intervento del CR Casaccia, ENEA ISER-CAS-SPI, CR Casaccia, Roma, Italy
paola.russo@uniroma1.it

Lithium-ion batteries are a popular choice of power source for a variety of energy and power demanding applications for both stationary applications and electromobility. Among electrochemical storage systems, Lithium-ion batteries were found to be promising candidate, due to their high power and high energy density.

In order to assemble high power batteries for plug-in hybrid electric vehicles and pure electric vehicles, several hundreds of large-format Lithium-ion cells will be required, and even more cells for power/energy demanding stationary applications. However, safety remains a significant concern, as battery failure leads to ejection of hazardous materials and rapid heat release. The failure of a single cell can generate a large amount of heat which can then initiate, in the worst case, the thermal runaway of neighbouring cells, leading to failure throughout the battery pack. The heat accumulation can also run into the venting of a cell, with the emission of flammable organic solvent inside the battery pack.

Battery failure can be initiated via a number of different abuse scenarios, such as overheating, overcharging, puncture/crushing, water immersion, or external short circuit. Development of effective mitigation strategies necessitates a study on battery failure events and a better understanding of important characteristics relating to safety, such as heat release, hazardous materials ejection, and thermal propagation. On the other hand, when a fire event is initiated, proper intervention strategies have to be defined in order to avoid it becoming catastrophic.

In this paper are reported the results of thermal abuse tests on single Lithium-ion cells and a battery pack. The tests were performed with the technical equipment and resources of National Fire Corps. Screening tests for battery fire extinguishing agents were also performed. The effectiveness of an agent was evaluated through experiments on the cooling effect of fire extinguishing agents. Among the various agents, water and foam were found to be the most effective.

1. Introduction

Rechargeable batteries are the most efficient and feasible solution for various types of storage applications, for small-scale as well as large-scale utilization. The main advantage of using Lithium is the low equivalent weight, the high specific and volumetric capacities (3860 mAh/g and 2047 mAh/cm^3, respectively) as well as the very low electrode potential of 3.05 V, which in turn allows cells to reach high voltages with appropriate cathodes (Nagaura, 1991; Nishi, 2001; Winter and Brodd, 2004; Armand and Tarascon, 2008). A further advantage of Lithium is its kinetic stability in various non-aqueous electrolytes. Currently, Li-ion batteries dominate the market for portable electronic devices (smart phones, electronic cigarettes, laptops, etc.), and have also been successfully implemented as the key technology for stationary energy storage as well as for automotives like hybrid, plug-in or fully electric vehicles (Blomgren, 2017; Andre et al, 2015). The development of Li-ion batteries is now dominated by the research for further improvement of their performances, in terms of the specific energy (gravimetric energy density (Wh/kg) and volumetric energy density (Wh/L)) (Scrosati et al., 2010, 2011; Wagner et al., 2013; Sarno et al., 2014; Crabtree et al., 2015; Larcher and Tarascon, 2015; Schipper and Aurbach, 2016; Cocchiara et al., 2016). This incremental performance growth of batteries has to match the increase of safety requirements of batteries in order to fulfill the various demands of consumers and

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society, such as rising application requirements as well as a growing trend for sustainability and lower costs. From a safety and fire protection point of view, the use of a flammable organic electrolyte in combination with a high energy density cell has created a number of new challenges with regard to the design of batteries, and with regard to their storage and handling. Significant incidents in airplanes and automotives have raised public awareness of potential problems associated with Li-ion batteries. The three major aircraft accidents where lithium battery cargo shipments were implicated, but not proven to be the source of the fire, are the following: Asiana Airlines 747 near South Korea on July 28, 2011 (400 kg Li batteries); UPS 747 in Dubai, UAE on September 3, 2010 (81,000 Li batteries); UPS DC-8 in Philadelphia, PA on February 7, 2006. Hazardous events are more and more frequently reported by the media, although incident numbers are likely to be highly correlated with the increased number of Li-ion batteries in use and their market shares, i.e. 195 separate incidents of explosion and fire involving an electronic cigarette were reported in the U.S. media in the period 2009-2016 (McKenna, 2017). Indeed, since early commercialization (1991) up to January 2018, the U.S. Federal Aviation Administration has recorded 191 incidents involving Li batteries carried as cargo or baggage (FAA, 2018).

Incidents can range from simple rupture of the cell case and leakage (more for pouch cells), to venting flammable and/or toxic gases and aerosols (hydrogen fluoride and other fluorine-containing toxics), up to fires and explosions. Battery thermal runaway is considered as the most potentially dramatic consequence in a battery system, following abnormal conditions of use, or in fewer cases resulting from manufacturing defaults. Thermal runaway occurs if the cell temperature exceeds a critical temperature, above which the increase in temperature is irreversible. In that case, the cell may emit a significant amount of gases from initial degradation reactions up to thermal runaway process, during which smoke is emitted, sometimes up to cell ignition and flaming combustion. Besides the related thermal hazard (fires, explosions), thermal runaway may also be responsible for mechanical effects (projection of fragments as well as toxic gases and vapors) (Wang et al, 2012). The most frequent triggering events are internal or external short-circuits, overcharge, overdischarge, or overheating.

In this study thermal abuse tests were performed on a single Li-ion cell and a battery pack. The tests were carried out exposing the cell to the flame of a LPG burner. EIG C020 Lithium-ion cells were utilized to examine the efficiency of carbon dioxide, foam, dry powder, pure water, and water mist in extinguishing lithium cell fires.

2. Experimental

2.1 Materials

EIG C020 cells were used for the tests. A picture of the pouch cell and its main characteristics are reported in Figure 1. The cells prior tests were charged to 50%. Tests were performed on single cells and on a battery pack made up of 48 cells (Figure 2).

		EIG C020 cell
Electric properties	Nominal Voltage	3.65 V
	Specific Energy	175 Wh/kg
	Voltage Limits	Charge: 4.15 V Discharge: 3.0 V
Geometric characteristics	Shape	Pouch
	Length	216 mm
	Width	130 mm
	Thickness	7.2 mm
	Volume	0.20218 L
Chemical composition	Anode	Graphite
	Cathode	Ni oxides
	Electrolyte	Mix of organic carbonates and LiPF6

Figura 1 - EIG C020 pouch cell and its main characteristics.

Figure 2 – Battery pack made up of 48 EIG C020 cells.

2.2 Test procedures

Thermal abuse tests were carried out on single cells and on the battery pack by exposure to the flame of a 7.5 kW LPG burner (Figure 2). During the tests a thermal imaging camera (FLIR) for monitoring the cell temperature and a video camera were used.
In fire extinguishing tests the single cell was heated up to a temperature of about 650°C and then the extinguishing agent was applied. Carbon dioxide, foam, dry powder, pure water, and water mist were used to extinguish the Li-ion cell fires. For the battery pack fire, water was used as extinguisher.

Figure 3 - Experimental setup for thermal abuse tests.

3. Results and Discussion

The maximum temperature of the cell during thermal abuse tests is reported in Figure 4. In these tests the cell exposed to the LPG flame reached a temperature of about 650°C in 2 min (Figure 5). When the burner was then switched off, the cell temperature decreased to about 400°C in 6 min. During the tests, the following aspects were observed: the leakage of gases from the cell and their subsequent ignition; the swelling of the cell and the leakage of great quantity of gases and flames; the extinguishment of the fire as the leakage of gases stopped (Figure 6).

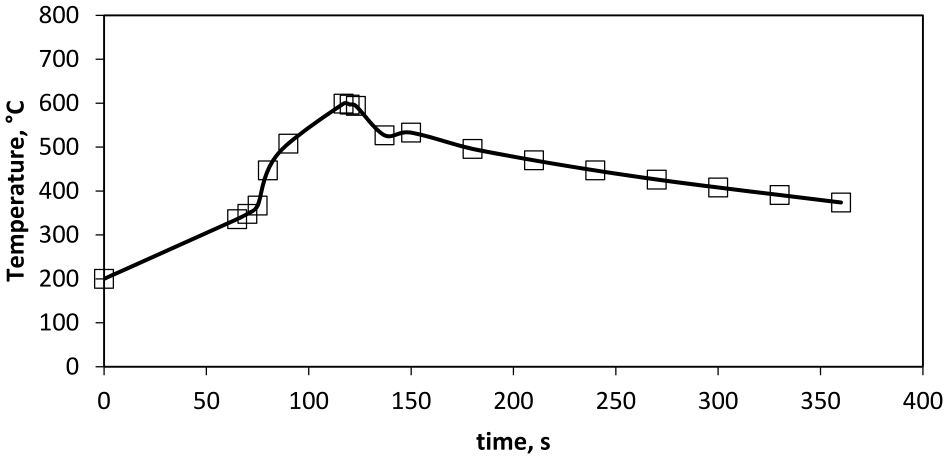

Figure 4 – Maximum temperature of single cell during thermal abuse tests.

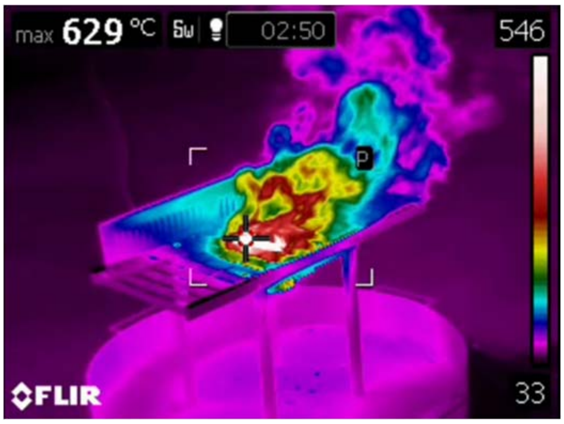

Figure 5 – Map of temperature at 2 min of thermal abuse test on single cell.

Figure 1 – A picture of the cell after thermal abuse test.

The multi-cell pack was arranged in order to reduce the likelihood of thermal runaway propagation by adjusting the cell spacing in order to minimize heat transfer between adjacent cells. In the case of battery pack, it was observed that cell thermal runaway causes thermal runaway in the adjacent cells by way of various mechanisms: direct case-to-case contact; impingement of hot vent gases; impingement of flaming vent gases (Figure 7). A maximum temperature of about 700°C was measured and a flame height up to 2 m was observed.

Figure 7 – A picture of the battery pack during thermal abuse test.

Results of exstinguishing tests on single cells are reported in Figure 8. The fire extinguishing agent includes water, water mist, foam, dry powder, and carbon dioxide. Among the various agents investigated, water and foam were the most effective by rapidly (<20 s) reducing the temperature of the cell and exstinguishing the fire. Water mist appeared less effective. Water mist fire extinguishing system has the following characteristics: low water consumption, cheap fire extinguishing agent, little damage to the object protected and green environmental protection. However, there are many problems in water mist fire extinguishing system: the uniformity of the water mist cannot be warranted; the liquid droplets reach the combustion surface with a certain amount of impulse and it is very difficult for water mist system to extinguish block fire. CO_2 and dry powder were the least effective; in particular, in the case of dry powder the high pressure jet caused the cell to fall on the floor.

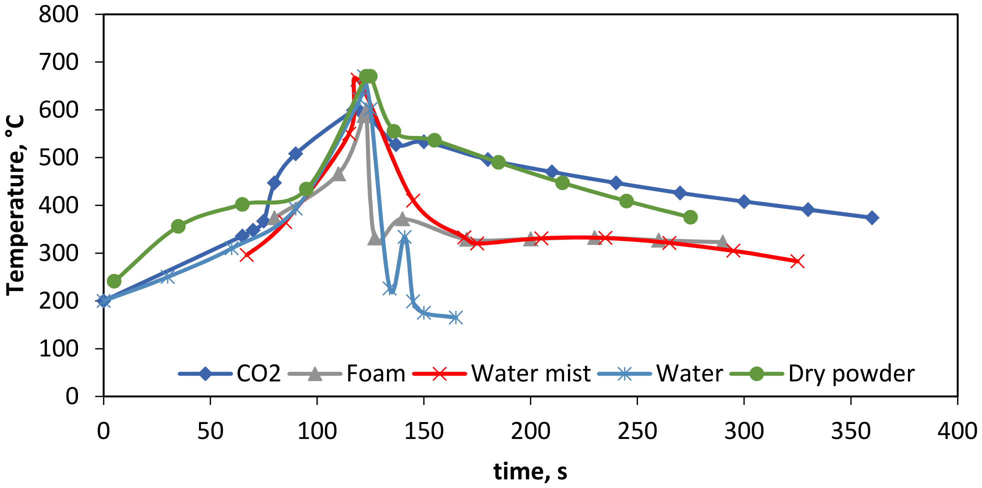

Figure 8 – Maximum temperature of single cell during exstinguishing tests.

4. Conclusions

The experimental studies have shown that Li-ion batteries have high fire risk. The oxidation of lithium metal generates a flash when the battery is heated up. The energy is the electrical energy and chemical energy contained in other toxic and harmful substances. These are the root of batteries combustion and reignition. In the case of the battery pack, it was observed that cell thermal runaway causes thermal runaway in the adjacent cells.The study on fire extinguishing agents and fire prevention technologies for lithium batteries has become an important part in the field of fire science. With reference to the fire extinguishing agents of lithium cells/batteries, currently they include mainly water, foam, dry powder, carbon dioxide and water mist. The results of tests have shown that the most effective are water and foam.

In view of the future widespread use of electric vehicles, fundamental research on fire fighting should be combined with emergency rescues.

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