Journal of Power Sources 329 (2016) 197–206

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Energy distributions exhibited during thermal runaway of commercial lithium ion batteries used for human spaceflight applications

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HIGHLIGHTS

- Modified ARC apparatus is developed to facilitate accurate thermal runaway energy calculations.
- Energy release during thermal runaway of commercial 18650 cells is characterized.
- Energy calculation based on cell body only is not sufficient for determining total energy release.
- Total energy release during thermal runaway is greater than the stored electrochemical energy.
- Experimentally grounded energy release approximation factors are developed.

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form
8 August 2016
Accepted 17 August 2016

Keywords:
Lithium ion battery
Thermal runaway
Battery safety
Accelerating rate calorimetry
Total energy release

ABSTRACT

Lithium ion (Li-ion) batteries provide low mass and energy dense solutions necessary for space exploration, but thermal related safety concerns impede the utilization of Li-ion technology for human applications. Experimental characterization of thermal runaway energy release with accelerated rate calorimetry supports safer thermal management systems. 'Standard' accelerated rate calorimetry setup provides means to measure the addition of energy exhibited through the body of a Li-ion cell. This study considers the total energy generated during thermal runaway as distributions between cell body and hot gases via inclusion of a unique secondary enclosure inside the calorimeter; this closed system not only contains the cell body and gaseous species, but also captures energy release associated with rapid heat transfer to the system unobserved by measurements taken on the cell body. Experiments include Boston Power Swing 5300, Samsung 18650-26F and MoliCel 18650-J Li-ion cells at varied states-of-charge. An inverse relationship between state-of-charge and onset temperature is observed. Energy contained in the cell body and gaseous species are successfully characterized; gaseous energy is minimal. Significant additional energy is measured with the heating of the secondary enclosure. Improved calorimeter apparatus including a secondary enclosure provides essential capability to measuring total energy release distributions during thermal runaway.

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1 Introduction

Lightweight and efficient energy and power management systems are essential components for space applications where relatively high costs are associated with the launch mass depending on the payload capability of the launch vehicle [1]. Lithium ion (Li-ion) batteries provide superior, lightweight and energy dense solutions necessary for space exploration vehicles, technology and satellites [2–6]. Safety concerns related to thermal runaway and subsequent cell-to-cell propagation impede the use of these cells for human spaceflight applications. Global interest in thermal runaway safety concerns was renewed following the Boeing 787 Dreamliner incident in which the aircraft's novel Li-ion battery used for auxiliary power experienced a short circuit induced thermal runaway failure. The event occurred on January 7th, 2013 while the vehicle was still on the tarmac, crew members and passengers were not on board, and no one on the cleaning and maintenance team was injured. One member of the emergency response team sustained minor injuries

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http://dx.doi.org/10.1016/j.jpowsour.2016.08.078
0378-7753/Published by Elsevier B.V.

[7].

The National Aeronautics and Space Administration (NASA) explores utilization of commercial Li-ion technology in a wide range of applications pertaining to human spaceflight. Examples include storage of energy collected via solar panels on the International Space Station (ISS), astronaut extravehicular mobility unit (EMU) power supply, tools utilized by astronauts during extravehicular activities (EVAs) such as the Li-ion pistol grip tool (LPGT), and for robotic applications such as humanoid robot Robonaut 2 (R2) [8,9]. Preventing and mitigating the disastrous effects of thermal runaway and cell-to-cell propagation are critical to ensuring astronaut safety for each of these applications. NASA updated battery certification requirements (20793 Rev-C) to include the evaluation of thermal runaway severity and the implementation of thermal management systems designed to prevent cell-to-cell propagation [8,9]. To satisfy these requirements, battery assembly developers must fully understand the total energy released to the system during thermal runaway. This study characterizes the total energy release of small format Li-ion cells considered by NASA for three different applications: (i) Robonaut 2 power supply, (ii) the Li-ion rechargeable EVA battery assembly and (iii) the EMU long life battery. Data here is used to ensure that these battery assemblies meet the new battery certification requirements listed in 20793 Rev-C.

Boston Power (BP) Swing 5300 cells are selected to power R2 in the form of a battery backpack in the near future. R2 is currently on board the ISS and receives power through a tether. R2 is a humanoid robot designed to demonstrate robotic activity in a microgravity environment and to assist astronauts by conducting routine maintenance activities [10]. The BP cells are slightly more than double the size, mass and power of the other 18650 cells considered in this study. The BP cells employ an aluminum can rather than the traditionally used stainless steel. The BP can is prismatic in shape with rounded edges. An open environment (non-ARC) thermal runaway event of a BP Swing 5300 cell, conducted at the NASA Johnson Space Center (JSC) Energy Systems Test Area (ESTA) facility is presented in Fig. 1. Thermal runaway is induced here by applying 163 W to the cell via patch heater. Points of interest include (i) the first visible appearance of smoke, (ii) the moment explosion occurs due to thermal instability and (iii) the short duration of self-heating following the explosion. The complete 4 K resolution video feed is provided with Supplementary Video 1. Understanding the total energy release distribution for the BP cell and instituting appropriate thermal design is necessary for R2 battery pack designers to prevent propagation of a single cell thermal runaway event.

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jpowsour.2016.08.078.

Astronauts are able to work in hostile space environments with the support of an EMU, which provides power, mobility, communication and life support systems. NASA works to update EMU power systems with new Li-ion battery assemblies designed to mitigate the effects of thermal runaway and to prevent cell-to-cell propagation, while also maintaining strict power requirements. The nickel metal hydride (NiMH) Rechargeable EVA Battery Assembly (REBA) will be replaced with the Li-ion Rechargeable EVA Battery Assembly (LREBA). The LREBA design incorporates 45 Samsung 18650-26F cells [8,9]. The EMU Li-ion Long Life Battery (LLB) replaced the silver-zinc (Ag-Zn) Increased Capacity Battery (ICB) in 2011 [11]. The LLB assembly consists of 80 MoliCel 18650-J cells [8,9]. Fig. 2 displays (a) an image of the EMU attached to an astronaut performing an EVA exterior to the ISS, (b) an image of a Samsung 18650-26F cell the moment thermal runaway occurs during non-ARC testing and (c) an image of a MoliCel 18650-J cell the moment thermal runaway occurs during non-ARC testing. Fig. 2a also indicates the installation locations for LREBA and LLB. The image of the EMU, credited to NASA, was taken from inside the Cupola Observational Module. Battery thermal management

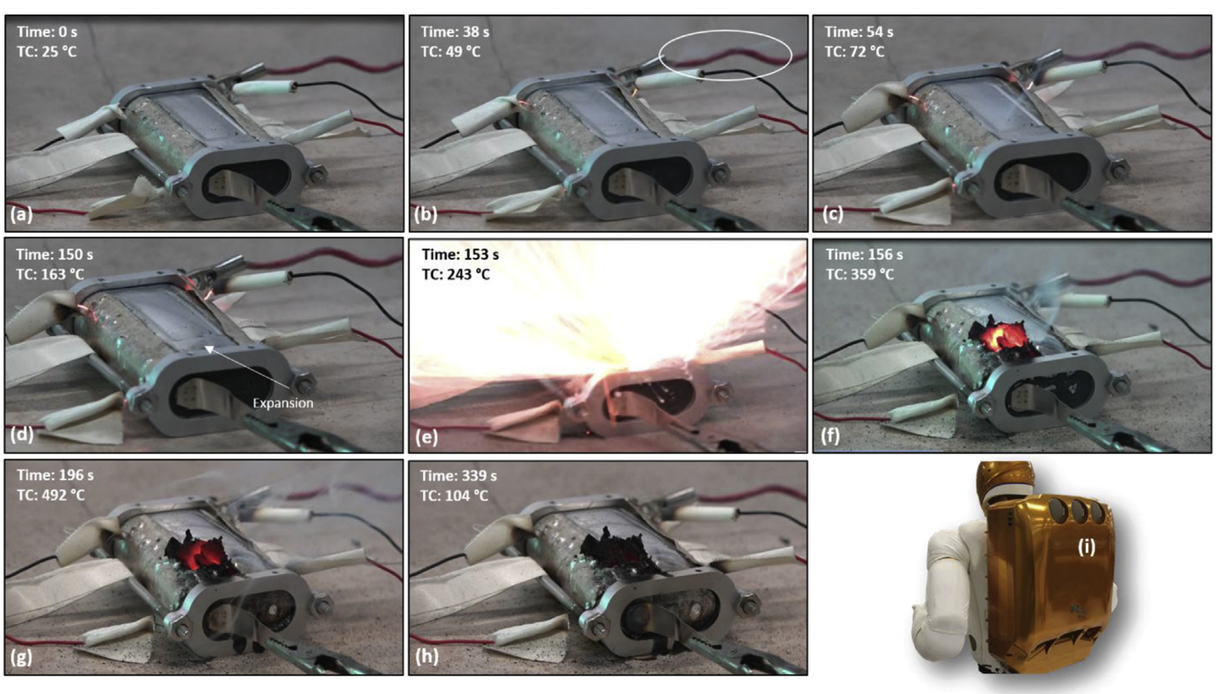

Fig. 1. Images of a Boston Power Swing 5300 Li-ion cell throughout an open atmosphere patch heater induced (non-ARC) thermal runaway event; 4 K resolution video is available with Supplementary Video 1. The figure displays the cell: (a) prior to heater instrumentation, (b) when smoke is first observed, (c) when smoke generation rates significantly increase, (d) moments before runaway occurs, (e) the instant that runaway occurs, (f) still heating from decomposition reactions following explosion, (g) when maximum temperature of 492 °C is achieved, (h) following a portion of the cool down period, (i) is an image of the R2 battery backpack that will contain 300 of the BP cells.