Experimental Investigation of Cascading Failure in 18650 Lithium Ion Cell Arrays: Impact of Cathode Chemistry

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To investigate thermal runaway propagation in lithium ion cell arrays (referred to as cascading failure), a set of experiments was conducted under well-controlled conditions in a wind tunnel where 18650 form factor cells were arranged into a densely packed array. The cell arrays were constructed from 12 lithium ion cells arranged in a rectangular configuration (3 columns by 4 rows) with no inter-cell spacing (each cell was in a contact with the adjacent cells). Commercial cells of different cathode chemistry, lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), and lithium iron phosphate (LFP), were employed as test samples in this study. All studied cells were fully charged.

The experiments were conducted in both anaerobic (N_2) and air environments to demonstrate the impact of flaming combustion. In each experiment, thermal runaway was triggered into the middle cell of row 1 using an electric heater and was observed to propagate through the array via thermocouples attached to the cell bottom surfaces. The dynamics of cascading failure were quantified together with thermal energy release for each cathode chemistry. Furthermore, the yields of the ejected O_2, total hydrocarbons (THC), CO, CO_2, and H_2 were determined; corresponding fire hazards were assessed.

For LCO and NMC cell arrays tested in an N_2 or air environment, it was found that thermal runaway of the intentionally failed cell was sufficient to initiate cascading failure that fully propagated through the array. LFP cell arrays, however, underwent incomplete/partial cascading failure (maximum of six and eight cells out of twelve failed in N_2 and air, respectively). When LCO, NMC, LFP cell arrays were tested in air rather than N_2, the row-to-row thermal runaway propagation speed increased by factors of 9, 2, and 7, respectively, which was attributed to the influence flaming combustion of ejected materials.

On average, individual LCO, NMC, and LFP cells lost 38.4%, 54.7%, and 11.7% of their initial mass, respectively, when tested in N_2, and this percentage increased by 0.3-3.2% when tested in air. Measurements showed that failed LCO and NMC cells produced minor mass yields of O_2 and H_2 in addition to relatively large amounts of THC, CO, and CO_2. The yields of gases ejected from LFP cells were significantly less than the yields obtained for LCO and NMC cells. The lower flammability limit of the flammable portion (THC, CO, and H_2) of the ejected gases was found to be 5.79 ± 0.12, 5.92 ± 0.15, and 4.28 ± 0.15 vol.% in air for LCO, NMC, and LFP cells, respectively. The maximum volume of an enclosure where the gas ejection from a single cell creates a flammable mixture in an air environment was estimated to be 0.087 ± 0.017, 0.076 ± 0.0146, and 0.029 ± 0.019 m^3 for LCO, NMC, and LFP cells, respectively.

The sum of the chemical heat (associated with chemical reactions between battery materials inside and outside the cell casing during failure) and flaming combustion energy (associated with burning of ejected cell materials) was found to be 3.2, 1.9, or 2.5 times greater than the electrical energy stored for LCO, NMC, or LFP cell, respectively. Overall, the obtained results showed that LFP-based cell arrays are the least hazardous arrays. Therefore, they are recommended as a safe option, even though the nominal capacity of the LFP cells is relatively low.