Advances on High Safety and Longevity Lithium-ion Batteries

Trevor Grant, Elmira Memarzadeh, Raj DasGupta
Electrovaya Inc.
6688 Kitimat Road, Mississauga, ON L5N 1P8, Canada
tgrant@electrovaya.com

Abstract

The rollout of electric vehicles over the past five years has been hindered by recalls due to battery fire incidents and unreliable performance. While fire safety is a critical concern in passenger vehicles, the potential damage of fires is drastically compounded in vehicles which hold many passengers, carry out critical functions, or operate in the vicinity of large capital assets. This paper details Electrovaya's recent developments for its Infinity lithium-ion platform in achieving exceptional battery safety and reliability. Electrovaya's batteries currently leverage key safety technologies across the cell, pack, and battery management system designs. The resulting battery systems show remarkable stability for a high-capacity NMC battery when subject to extreme thermal fluctuation, mechanical shock, and electrical abuse. Infinity cells have also been shown to exhibit outstanding longevity for NMC chemistry, reaching beyond 9000 cycles under 1C cycling conditions. These results demonstrate how Electrovaya's Infinity technology gives superior performance over conventional lithium-ion battery solutions and is exceptionally well-suited for demanding applications where longevity and fire safety are critical metrics.

Keywords

Lithium ion battery; battery safety; ceramic; separator; cycle life

Introduction

Today, battery fires as a result of thermal runaway remain the most critical failure mode of lithium-ion packs in electric vehicle (EV) and stationary energy storage (BESS) applications. As the total number of battery systems in commercial use continue to grow and many applications have been in deployment for over 5 years, the importance of battery safety has become increasing apparent from cases where battery systems have catastrophically failed, or widespread battery replacements have been required. As the number of batteries in operation continues to grow and new types of vehicles are electrified, a greater priority to battery safety and longevity will be necessary to realize a successful electrification transition.

Thermal runaway in lithium-ion batteries can be broadly characterized as a feedback loop of heat-generating events within a battery causing a rapid rise in temperature. If the heat generation is not able to be stopped or dissipated, the thermal runaway process will culminate in a violent fire as the internal energy of the battery is uncontrollably released and components of the battery combust or thermally decompose.[1] In a battery pack made from many individual cells, a thermal runaway event in a single cell may propagate to quickly ignite the entire pack producing a self-sustaining fire that is exceptionally difficult to extinguish unless the system can be cooled and maintained at stable temperature to prevent re-initiation of the thermal runaway process.[2]

The heat required to accelerate a thermal runaway event may be generated by an internal short circuit within a battery cell as a result of direct electrical contact of anode and cathode. Maintaining integrity of the battery separator, responsible for providing electrical insulation between the anode and cathode, is critical to preventing short circuit events. Failure of the separator through mechanical abuse (crushing, bending, penetration), electrical abuse (over charge, over discharge), thermal abuse (rapid charge/discharge, elevated ambient temperature, thermal shock), and manufacturing defects (electrode misalignment, structural defects) may all lead to short circuit events subsequent thermal runaway of the cell.[3]

Conventional battery separators made from polyolefin (PO) materials (i.e. polyethylene and/or polypropylene) provide poor resistance to the propagation of localized internal short circuit events, which may easily produce enough heat to cause shrinkage of the separator resulting in an exponential increase in the severity of the short. PO-based separators begin to soften and lose structural stability above ∼100 °C and melt above 135 °C (polyethylene) or 160 °C (polypropylene). Separators formed from layered PO-based materials and ceramic coatings (e.g. alumina) may work to increase the separator's resistance to thermal runaway, however these techniques do not sufficiently mitigate the risk of thermal failure which can remain a limiting factor for instigating thermal runaway below 200 °C.[4] This paper will review results of Electrovaya's deployment and testing of full ceramic composite separators in commercial battery cells and packs, showing exceptional thermal stability while using high capacity Lithium-Nickel-Manganese-Cobalt-Oxide (NMC) cathode chemistry. Additionally, recently collected cycle life testing reveals industry-leading cycling performance for NMC-based cells.

Battery Safety

The building block of Electrovaya's infinity platform battery products is the 'EV-44' cell; an NMC-based lithium-ion cell incorporating a full ceramic composite separator. The ceramic composite separator is an integral cell-level safety to greatly reduce the likelihood and severity of a battery fire

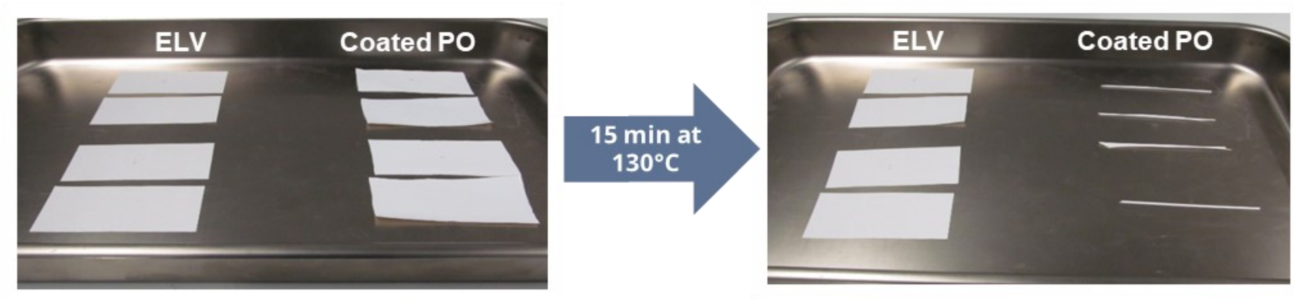

Figure 1. Thermal stability and shrinkage resistance of a full ceramic composite separator (ELV) vs a conventional ceramic coated PO separator (Coated PO).

due to superior thermal stability. Figure 1 demonstrates thermal stability of a full ceramic composite separator in comparison to a ceramic coated PO separator at 130 °C. It can be seen that the dimensional stability of the PO-based separator is critically lost as the base PO material undergoes a melting transition. In contrast, the structural integrity of a fully embedded ceramic composite separator is completely maintained with penetration of the ceramic material through the full depth of the separator film.

The significance of this improved thermal resistance on the cell safety is most appropriately demonstrated through a nail penetration test. In this test, an electrically conductive nail (O.D = 2.5 mm) is used to fully puncture a fully charged NMC-Graphite cell to simulate an internal short circuit. When employing a conventional PO-based polymer separator, the heat generated in the immediate vicinity of the short circuit event is sufficient to cause shrinkage of the separator and exponentially increase the shorted current pathway. In this case the cell fails catastrophically, characterized by rapid cell discharge, venting of the cell (excessive gas generation), and jet flames from ignition of the flammable liquid electrolyte (Figure 2A). Alternatively for a cell employing a full ceramic separator the short is not propagated and remains localized to the point of penetration (Figure 2B). Cell failure in this case is non-catastrophic, with no fire or significant loss of liquid electrolyte weight (< 10% weight loss), and no bulging of the cell pouch. This is an exceptional result for a cell containing NMC-based cathodes, which are known to be more susceptible to aggressive thermal runaway in comparison to other common cell chemistries (i.e. lithium-ion-phosphate, LFP) due to the lower onset temperature and more highly exothermic thermal decomposition reaction of NMC.[5] These tests exemplify the impact of component design on the overall safety of a lithium-ion cell.

Despite efforts at the cell level, the probability of thermal runaway can never be eliminated due to the inherently high potential energy stored within modern lithium-ion batteries. It is therefore critical to consider propagation risks of cell fire across a battery pack to mitigate the severity of an internal cell failure leading to thermal runaway. Electrovaya has recently completed third-party abuse testing of its commercial battery pack through Underwriters Laboratories (UL) safety certification. Among other tests as a part of UL2580 certification (testing standard for batteries for use in electric vehicles), Electrovaya's NMC-based packs successfully passed internal fire propagation abuse testing as a testament to the cell- and pack-level safety design. Figure 3 shows an Electrovaya battery after completing a fire propagation test wherein a single cell in a fully charged battery pack was forcibly ignited. During the test, the cell fire was fully contained within the sub-module holding the faulty cell and no flames exited the battery enclosure. The exterior batter connections and battery case remain intact and undamaged (Figure 3A). Additionally, the battery management system of the pack remained fully intact

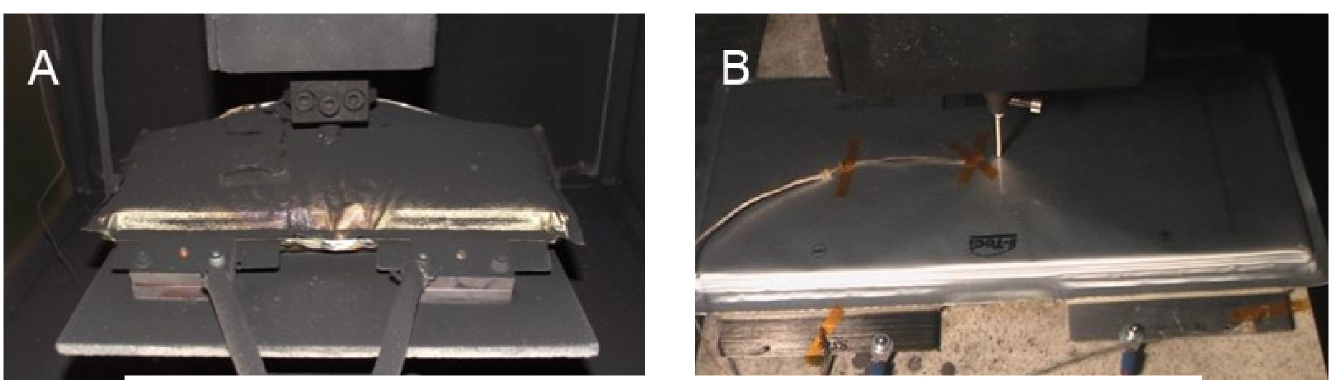

Figure 2. Nail penetration results form a fully charged NMC|Graphite cell having (A) a conventional PO separator, and (B) a full ceramic composite separator.

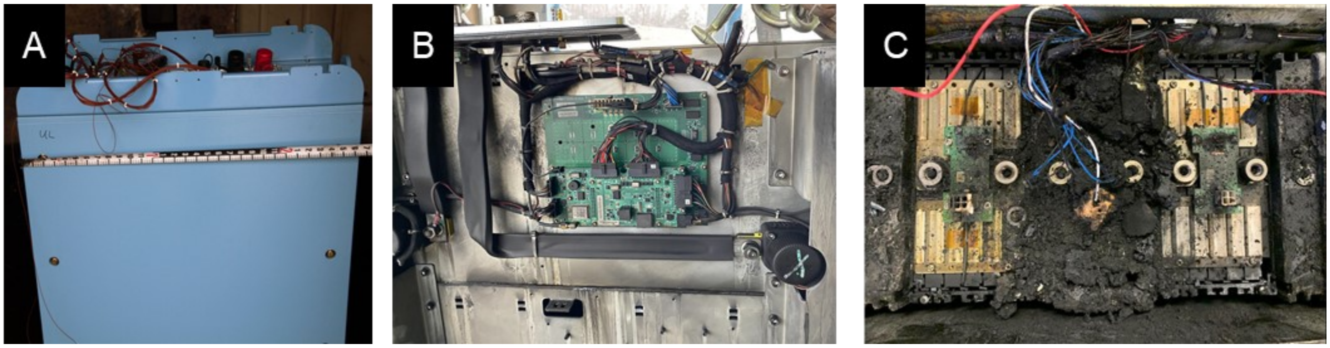

Figure 3. An Electrovaya 24V battery pack shown after fire propagating testing in which a single cell was forcibly ignited, depicting (A) unscathed battery enclosure and external connections, (B) intact battery management system, and (C) no fire propagation between adjacent modules.

(Figure 3B). Internal investigation of the faulted pack revealed that heat generated by the internal fire was not sufficient to induce separator shrinkage to cells in adjacent modules and no cells in adjacent sub-modules were ignited (Figure 3C).

Battery Longevity

Batteries for typical passenger EVs and other low-use applications may demand only one charge cycle per week under regular operation. In these cases, a battery cycle life of 1000 – 2000 cycles will allow for sufficient capacity retention through the lifetime of the vehicle or application. However, certain applications operating in demanding or continuous use conditions (i.e. busses, materials handling vehicles, autonomous vehicles, stationary energy storage systems, and others) may demand 1 or more full charge cycle per day in standard use. Conventional lithium-ion battery employed in these applications will almost certainly require a costly full battery system replacement through the vehicle or application lifetime as the battery performance becomes insufficient due to degradation.

Electrovaya has developed a commercial lithium-ion cell with industry-leading cycle life through nearly a decade of experience employing full ceramic separators in commercial lithium-ion batteries. Optimization of the cell assembly process, electrolyte composition, electrode chemistry, and other factors have enabled an NMC-based cell with exceptional longevity. Figure 2 shows ongoing long-term data of Electrovaya lithium-ion cells collected from over 2 years of cycle life testing at various state-of-charge (SOC) windows. Leveraging key cell chemistry and design elements along a full ceramic composite separator, Electrovaya cells have been proven to achieve remarkable cycle life beyond 9000 cycles for a relatively high energy density NMC cell, which is over twice the longevity observed from conventional off-the-shelf lithium-ion battery chemistries.[6]

For a given electric vehicle or stationary storage application, it is critical that the total cost of ownership over the battery lifetime is considered. Lithium-ion batteries designed to meet conventional applications (i.e. consumer electronics and passenger EVs) are not necessarily suited for many emerging battery use cases. Load cycle requirements (charge rates, discharge cycles per day) and operating conditions (ambient temperature, heat dissipation, potential mechanical abuse) need to be taken into when selecting a cell or module

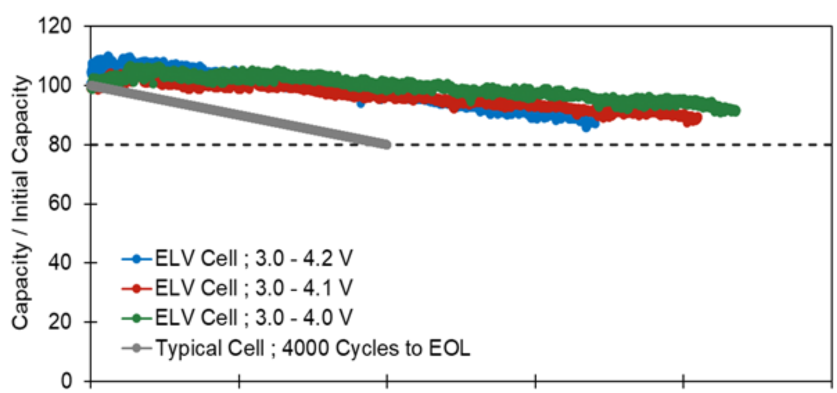

Figure 4. Long-term charge/discharge cycling results for Electrovaya cells at 100% SOC (blue), 90% SOC (red) and 80% SOC (green). Data collected at 25 ± 2°C, 1C current rate. A theoretical cell with a lifetime of 4000 cycles to 80% original capacity is shown for reference (grey)

to enable a successful long-term electrification solution. Electrovaya batteries are designed to excel through the entire lifetime of even the most demanding lithium-ion applications. Two decades of technology development and implementation gives superior performance over conventional lithium-ion battery solutions, and a lithium-ion battery which is exceptionally well-suited for critical use cases where longevity and fire safety are critical metrics.

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