A Study of the State of Charge of Lithium-ion Batteries in Transportation

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Abstract

The transportation of lithium-ion batteries on aircraft is heavily regulated due to fire hazards associated with these power sources. Domestic and international regulations require lithium-ion cells not packed with or contained in equipment (Lithium-ion batteries, UN3480) to be no greater than 30% state of charge (SOC) when shipped within aircraft. Previous FAA studies have determined that cells that exceed this level are a serious hazard due to risk of thermal runaway and can lead to an unsafe condition on an aircraft.

However, despite these restrictions, isolated fire incidents involving lithium-ion cells have continued to occur at all-cargo sort facilities involving packages previously shipped by aircraft. FAA analyses of these thermal incidents have determined that the cells from these incidents exceeded the 30% SOC limit.

In order to understand the extent of this problem, an analysis was conducted on lithium-ion cells sold on different e-commerce platforms. The SOC of these cells was evaluated using battery analysis equipment. Results indicated that many cells continue to be shipped on aircraft at an unsafe SOC. Furthermore, some shipped packages containing lithium-ion cells were observed to have been inadequately stored and labeled.

Keywords

Lithium-ion; cells; batteries; battery transport; state of charge; SOC; UN3480; thermal runaway

Introduction

Due to the fire hazards associated with lithium-ion batteries, the transportation of lithium-ion cells and batteries on aircraft is heavily regulated. Lithium-ion cells are known to undergo a phenomenon known as thermal runaway, a self-sustaining chemical process in which a sudden uncontrollable increase in temperature occurs, often causing the battery to release toxic gases and flames. Thermal runaway may occur when cells are overheated, overcharged, mishandled or have a manufacturing defect leading to an internal short circuit.

The most well-known plane accident involving lithium-ion cells occurred in 2010 on UPS Airlines Flight 6, a cargo flight in which over 80,000 lithium-ion cells were stored within the aircraft's main cargo deck. A rapidly developing in-flight fire occurred within the cargo deck, which quickly damaged fire protection and critical systems, impeding the pilots' ability to make an emergency landing.

As a direct result of this and similar accidents, bulk cargo shipments of lithium-ion cells are prohibited on passenger aircraft. Shipment of lithium-ion cells are only permitted within cargo aircraft if certain criteria are met.

One of these requirements relates to a cell's SOC. The SOC is a cell's charge level compared to its total capacity.

Previous FAA studies have determined that the thermal energy released by a failure of a lithium-ion cell has a direct relationship between the total electrical cell capacity and SOC (Lyon, Richard, & Walters, 2016). Other studies have shown that cells at high SOCs are more likely to produce higher heat release rates, maximum temperatures, and concentrations of flammable and toxic gases during a thermal runaway event (Maloney, 2016; Wang, et al., 2018; Maloney, 2022). An example of cells undergoing thermal runaway at various SOCs is shown below in Figure 1.

As a consequence of these hazards, domestic and international regulations require that lithium-ion cells not packed with or contained within equipment (UN3480, Lithium-ion Batteries) must have a SOC no greater than 30% when transported on cargo aircraft. Additionally, packages must have specific labeling, signifying the specific UN hazardous material classification and/or forbidding the use in passenger aircraft, if required by regulation.

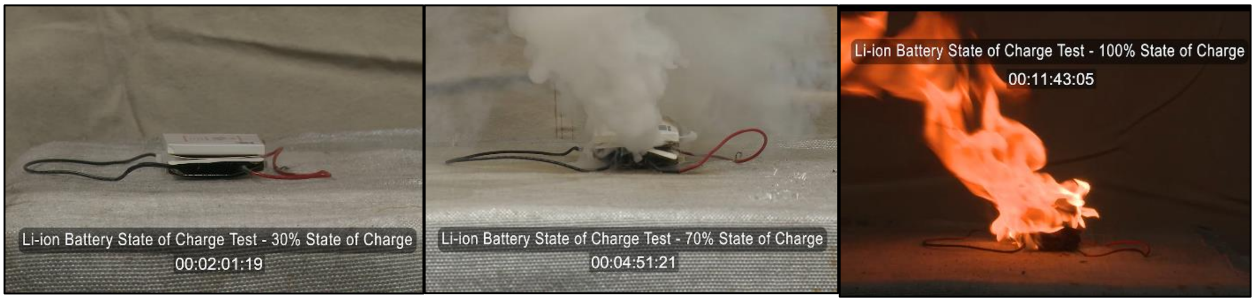

Figure 1. From left to right: Peak reactions of 6 Watt-hour lithium-ion pouch cells undergoing thermal runaway at 30%, 70% and 100% SOC, respectively

However, despite these restrictions, recent incidents at all-cargo sort facilities and on airport runways have continued to occur. Analyses of the cells from these incidents indicate that many of the cells continue to be shipped at a SOC greater than 30% (Keslar, 2022; Keslar, 2023). Although this data indicates that cells were shipped at high SOCs in isolated events, it is unknown if regulations were being adhered to on a wider scale.

Figure 2. Package containing li-ion cells undergoing thermal runaway in an all-cargo sort facility after previously being shipped on aircraft

In order to determine if air shipment regulations were being followed, an analysis was conducted by the FAA to determine if lithium-ion cells sold on various e-commerce platforms adhered to SOC requirements when shipped by aircraft. Cells were shipped to a non-FAA address and then brought to and tested at the FAA's William J. Hughes Technical Center.

Objective

The primary objective of this study was to measure the as-delivered state of charge of lithium-ion cells that were shipped via aircraft.

A secondary objective of this study was to examine the fire hazard of delivered packages, specifically examining the manner in which the cells were stored and the labeling on the exterior of the packaging.

Evaluated Cells

Lithium-ion cells of a variety of different sizes and chemistries were evaluated. Evaluated chemistries included lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), lithium manganese cobalt oxide ($LiMnCoO_2$) and unknown chemistries not specified during purchase.

Both cylindrical and lithium-ion polymer (pouch) cells were evaluated. Prismatic cells were not evaluated. Different sizes of the cylindrical cells include; 32650s, 26650s, 18700s, 18650s, 14500s, and 10440s. All evaluated cells ranged from 1 Watt-hour (Wh) to 22 Wh. A small sample of the cells evaluated within this study is shown below in Figure 3.

Figure 3. Collection of some of the pouch and cylindrical cells evaluated in this study

Cells that could be delivered within a short time period (1-3 days) from a cross-country business address were targeted. However, it was often noted that packages were delivered without a detailed shipping history. Therefore, cells were categorized based on their suspected mode of transport as follows:

1. Confirmed Air Transport

2. Suspected Air Transport

3. Unknown Transport

4. Land Transport

State of Charge Analysis

The state of charge was measured using an Arbin Instruments battery analyzer, which operates with a measurement accuracy within 0.01% and a control accuracy within 0.02%. Cells were charged to full capacity using a Constant Current – Constant Voltage (CC–CV) charging method and then completely discharged. The current throughout this process was recorded and the initial SOC was calculated using the equation below:

$$SOC_{Initial} = \frac{Capacity_{Total} - \ Charge\ Capacity}{Capacity_{Total}}$$

The C-rate and temperature are two variables that have been observed to impact SOC measurements. C-rate is the measure of the rate at which a cell is discharged relative to its maximum capacity. Throughout these tests, the ambient temperature was kept constant at room temperature (70°F). Furthermore, a C-rate was used according to manufacturer data sheets. However, if a manufacturer data sheet was unavailable, a 0.2 C-rate of the rated capacity of the cell was used.

Results

Initial test results indicate that many lithium-ion cells continue to be shipped at a SOC greater than the 30% limit. In total, over 100 cells from over 20 different shipments have been evaluated. Figure 4 shows a breakdown of the measured SOC for all cells based on their respective mode of transport.

For cells that were confirmed to have been transported on aircraft, more than 50% of the cells were found to have been shipped at an unsafe SOC. In total, 21 of the evaluated 36 cells were charged greater than the 30% limit.

Cells categorized as “Suspected Air Transport” and “Unknown Transport” had limited shipment information, which prevented confirmation of the shipment method. Overall, similar conclusions were observed for these categorized cells when compared to those shipped by air. The measured SOC for many cells within both of these categories exceeded the required 30% threshold with some observed to exceed 70% SOC.

Cells transported by land do not have to adhere to the 30% SOC requirement. However, data was still collected for the cells categorized in this transport

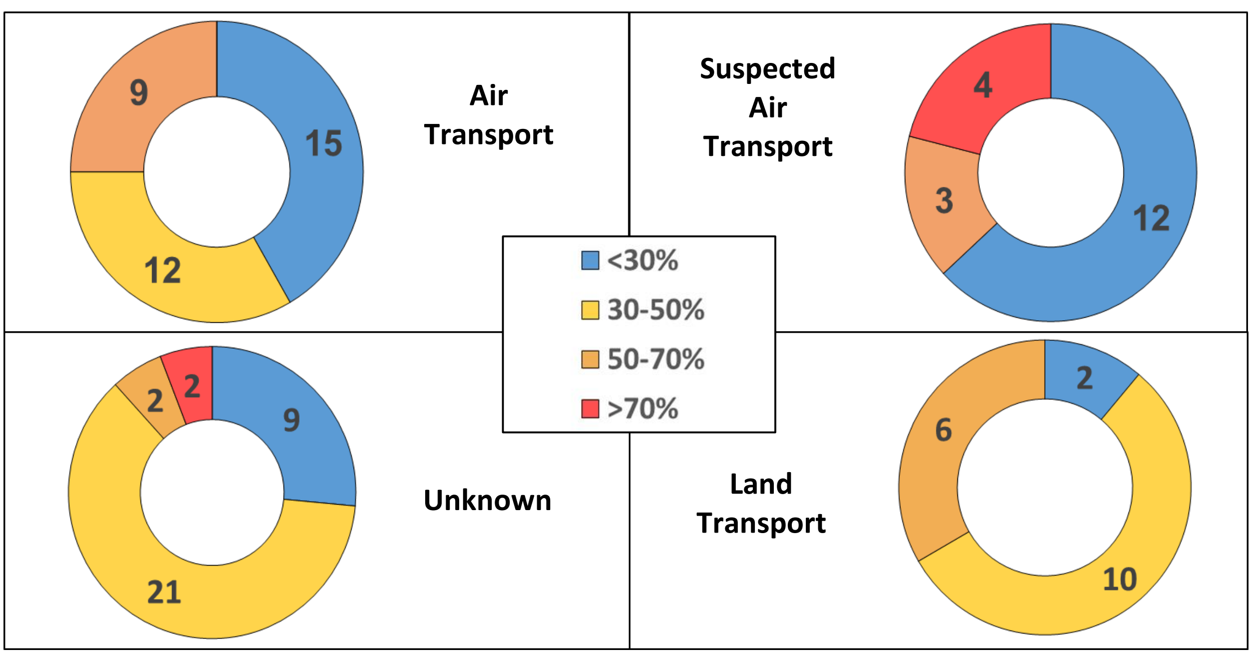

Figure 4. SOC Calculations for all four categorized shipment methods

method because it was noted that multiple sellers and shipment options were available during purchase. Therefore, it is possible that the selected cells could have been shipped via air depending on the selected options.

Packaging and Labeling

In addition to the SOC evaluations, the interior of packages was evaluated for proper storage and labeling. A majority of packages were observed to follow proper storage procedures (i.e., cells placed in non-metallic inner packaging that ensured cells did not make contact with electrically conductive materials or cells of the opposite polarity). However, it was noted that there were some exceptions to this, as shown in Figure 5. This image shows a package ordered from a secondhand seller from one of the evaluated e-commerce platforms.

Figure 5. Untampered package (left) and package with top plastic wrap removed (right)

Within this package, over 60 cells were sporadically stored with little to no protective packaging to prevent cell terminals from making contact with other cells/terminals of the opposite polarity. Furthermore, several of the cells within the package were observed to have significant signs of swelling and corrosion, indicating that a potential fire threat is present amongst secondhand lithium-ion sellers as well.

Besides proper storage, packages were evaluated for proper labeling. A significant number of packages analyzed in this study were found to have incorrect or missing labeling. Cells not packed with or contained in equipment must have UN ID number “3480” and a lithium battery mark on the exterior of the container signifying that lithium-ion cells are contained within. It was observed that a significant number of delivered packages within this analysis did not have this marking.

Conclusions

Regulations require lithium-ion cells not packed with or contained in equipment (UN3480, Lithium-ion Batteries) must have a SOC below 30% when shipped on aircraft. Many of the tested cells were observed to exceed this charge level. Furthermore, some packages confirmed as being shipped by air were determined to be a significant fire risk, as cells were damaged and improperly stored and labeled.

Test results suggest that additional measures may be needed to ensure safe shipment of lithium-ion cells on aircraft. Although regulations have been implemented on SOC to reduce the hazards of lithium-ion cells, enforcement of these regulations is difficult. Measuring the SOC is a difficult value to estimate within the field. Accurate SOC evaluations require expensive equipment and a considerable amount of time. It is not feasible for airlines to measure the SOC of all transported cells prior to air shipment. Therefore, additional safety measures may be needed to ensure safe shipment of lithium-ion batteries on cargo aircraft.

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