DOT/FAA/TCTN-22/27

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

An Analysis of State of Charge in Lithium-ion Batteries

July 1, 2022

Technical Note

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No. DOT/FAA/TCTN-22/27	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle An Analysis of State of Charge in Lithium-ion Batteries		5. Report Date July 2022
		6. Performing Organization Code ANG-E21
7. Author(s) Daniel Keslar		8. Performing Organization Report No.
9. Performing Organization Name and Address US Department of Transportation William J. Hughes Technical Center Aviation Research Division Fire Safety Branch, ANG-E21 Atlantic City International Airport, NJ 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Aviation Administration Aircraft Certification Service Policy and Innovation Division (AIR-600) 800 Independence Avenue SW Washington, DC 20591		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code AIR-600
15. Supplementary Notes		

16. Abstract

In February 2022, a package containing 140 lithium-ion pouch cells caught fire on a conveyor belt in a sort facility of an all-cargo airline. One of the packages in the shipment was sent to the Federal Aviation Administration's (FAA) William J. Hughes Technical Center for hazard evaluation. Specialized cell analysis equipment was used to determine the state of charge (SOC) of the cells in the package. The measurements revealed that the cells were approximately at a 70% SOC, exceeding the maximum allowable shipping limit of a 30% SOC for the transport of cells and batteries classified as "UN3480, **Lithium-ion batteries** (including lithium-ion polymer batteries)".

It was hypothesized that the fire in this incident started when the terminals of two cells packaged together made contact, causing the cells to short circuit, overheat, and enter thermal runaway. Testing was conducted to validate this hypothesis and to evaluate the fire risk of these cells at various SOCs. Key findings include:

- The cells tested at a higher SOC present a much higher fire risk compared to cells tested at or below a 30% SOC. This was consistent with previous FAA studies.
- The as-delivered 70% SOC cells went into thermal runaway when short-circuiting the cell terminals. The resulting temperature was high enough to propagate to nearby cells despite the surrounding packaging. This suggests that the original cell fire may have started when cell terminals made contact in the original package.
- A spark igniter ignited the gases released from the tested cells during thermal runaway. This suggests that a spark created during thermal runaway could have helped ignite the original package fire, as the ignition of cell gases would have produced a significant flame

17. Key Words Thermal runway, state of charge, lithium-ion		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	19. Security Classif. (of this report) Unclassified

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Acronyms

Acronym	Definition
Ah	Ampere-hour
CC-CV	Constant Current – Constant Voltage Charging Method
FAA	Federal Aviation Administration
OEM	Original Equipment Manufacturer
SOC	State of Charge
Wh	Watt-hour

Executive summary

Lithium-ion batteries have become a common power source for many types of electronic devices. Due to their ability to undergo a phenomena known as thermal runaway, lithium-ion batteries present a unique fire threat when transported onboard aircraft. As a result of this threat, it is mandated that all lithium-ion batteries transported onboard aircraft but not packed with or contained within equipment (UN 3480) must be discharged to a level less than 30% of the total state of charge (SOC) of the cell or battery. Batteries that exceed this SOC percentage have an increased risk of going into thermal runaway, resulting in releasing flammable and toxic gases, high heat release rates, high temperatures, and propagating to nearby cells in the event of thermal runaway.

In February 2022, a package containing 140 lithium-ion pouch cells caught fire on a conveyor belt in a sort facility of an all-cargo airline. This package, one of five in a shipment, had been transported by air from its original destination and was being sorted at an airport prior to being sent to its final destination. One of the remaining packages in the shipment was sent to the Fire Safety Branch at the William J. Hughes Technical Center to conduct a hazard evaluation.

Using specialized cell/battery analysis equipment, it was determined that the cells in the package had a substantially higher SOC than the allowable 30%. The average SOC of all cells was approximately 70%. It was observed that two types of cells were packaged together in unsealed plastic sleeves. It was hypothesized that the cells slipped out of the sleeves during handling and the cell terminals made contact, causing the cells to short circuit and enter into thermal runaway.

Thermal runaway testing was conducted to analyze the fire threat of the cells at various SOCs. Testing results were consistent with previous FAA studies – high SOC cells experienced a more violent reaction during thermal runaway, resulting in considerable burn damage in the surrounding packaging and complete destruction of the cells. Of the five 70% SOC thermal runaway tests that were conducted, the cells experienced thermal runaway in four of the five tests. The 70% SOC cells that did undergo thermal runaway, propagated to other adjacent cells.

Additionally, a thermal runaway test was conducted with a spark igniter near the cell stack. The gases released during the test did ignite, suggesting that a potential spark or flame could have helped ignite the original package.

1 Introduction

1.1 Background

Lithium-ion batteries are commonly used as a power source in many different electronic devices such as phones, tablets, and laptops due to their low-cost, high-energy density and longevity. Despite these benefits, one major disadvantage of these batteries is the potential fire risk due to their ability to undergo a process known as thermal runaway, an uncontrolled and self-sustaining chemical process in which there is a sudden increase in temperature, often causing the battery to rupture, releasing flammable and toxic gases, and flames. As a result of this potential hazard, the transportation of lithium-ion batteries onboard aircraft is heavily regulated both domestically and internationally. The transport regulations[1] and industry standards[2] mandates that all lithium-ion cells and batteries transported onboard aircraft but not packed with or contained within equipment (UN 3480) must be shipped at a state of charge (SOC) less than or equal to 30% of their total capacity.

SOC is an electrical cell or battery's charge level compared to the total capacity of the cell or battery. Batteries at high SOCs have been shown to experience more violent reactions during thermal runaway. Previous testing has indicated that high SOC cells produce higher heat release rates, maximum temperatures, and concentrations of flammable and toxic gases during thermal runway events (Maloney, 2016; Maloney, 2022; Wang, et al., 2018). Additionally, high SOC cells and batteries are more likely to propagate to nearby cells and batteries. Conversely, batteries charged to less than 30% SOC are less likely to produce intense reactions and are less likely to propagate.

On February 3, 2022, a package containing 140 lithium-ion cells caught fire on a conveyor belt in a sort facility of an all-cargo airline. This package had been shipped via air transport from Hong Kong and was being transferred for air shipment to Montreal, Canada. This package was one out of five in a shipment, all of which contained lithium-ion batteries. Three of the packages within the shipment arrived at their ultimate destination, one was completely destroyed by the fire, and one was held from further transport due to safety concerns because of the fire. This stopped package was sent to the FAA Technical Center for further analysis on the possible cause of this incident.

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[1] Title 49 Code of Federal Regulations (CFR), Hazardous Materials Regulations (HMR), and the ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air (Doc 9284)

[2] IATA Dangerous Goods Regulations (DGR)

1.2 Objectives

The objective of this study was to provide analysis and insight into the cause of the package fire, as well as to investigate the fire risks posed by cells at differing SOCs. Specifically, this study had three main objectives:

1. Determine the as-shipped SOC of a randomized selection of twenty (20) cells from the package and compare to the 30% SOC mandated by the transport regulations.
2. Evaluate the thermal runaway hazard for three different states of charge – 30%, 70%, and 100%.
3. Determine if the gases released during thermal runaway are ignitable by a spark igniter.

2 State of Charge Analysis

A total of 140 pouch cells of five different types; 3.79V, 3.80V Cell #1, 3.80V Cell #2, 3.83V L-Shape, and 3.83V Square were shipped to the Federal Aviation Administration's (FAA) William J. Hughes Technical Center. Figure 1 shows pictures of each cell. The cells were used for replacements of various iPhone models including the iPhone 11 Max, iPhone XS Max, iPhone 11 Pro and iPhone 12 Pro ®. Due to the lack of information found during internet research, it was determined that the cells were not from the original equipment manufacturer (OEM).

Figure 1. Battery Cells from left to right; 3.79V, 3.80V Cell #1, 3.80V Cell #2, 3.83 L-Shaped, 3.83 Square

Cells were packed within unsealed hydrostatic sleeves, each contained within its own cardboard box. An exception to this was the 3.80V cells, in which two cells were packed within each cardboard container, as shown in Figure 2. It is hypothesized that the original package fire started when two 3.80V cells within the same cardboard container slipped out of the plastic sleeves and the terminals to the two batteries made contact, short circuiting the cells and causing thermal runaway. Subsequently, the fire was able to propagate to other nearby cells and the entire package caught fire.

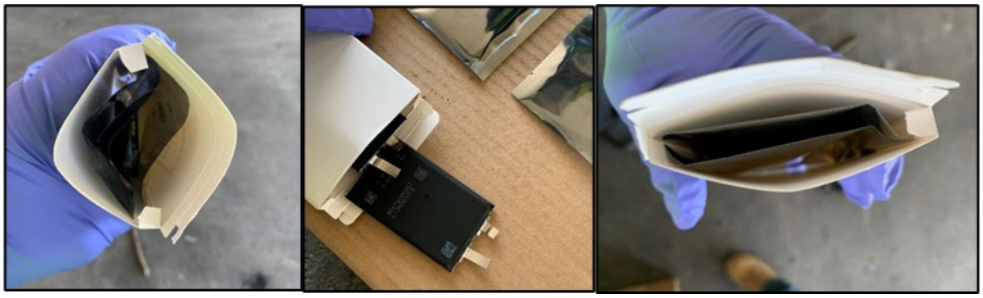

Figure 2. 3.80V Interior Packaging

The cells within the delivered package were tested using specialized cell/battery analysis equipment within the Fire Safety Branch labs to measure the SOC of the cells.

2.1 State of Charge Analysis Method

The SOC of the cells in this study was determined using the Fire Safety Branch's Arbin Instruments battery analyzer. The Arbin Instruments system operates with a measurement accuracy within 0.01% and a control accuracy within 0.02%. The instrument's full-scale voltage was 10 Volts. All cells were charged from the initial state of charge to maximum capacity, and then discharged completely. The Arbin Instruments analyzer calculated the total charge and discharge capacity during this process, which was then used to calculate initial SOC using the equation below.

$$SOC_{Initial} = \frac{Capacity_{Total} - Charge\ Capacity}{Capacity_{Total}} \quad (1)$$

A sample size of twenty cells were evaluated, in which four batteries of each type (3.79V, 3.80V Cell #1, 3.80V Cell #2, 3.83 Square, and 3.83 L-Shape) were charged using a Constant Current – Constant Voltage (CC-CV) charging method. In this method, constant current (CC) was used to charge the cell until the voltage reached the maximum charging voltage value, then the charging process shifted to constant voltage (CV) charging. In CV, the cell was charged at the maximum charging voltage value and the current decreased until it reached the minimum current termination value. A CC-CV charging method is standard for lithium-ion cells/batteries. An example of this charging method is shown in Figure 3 (Buchmann, 2017).

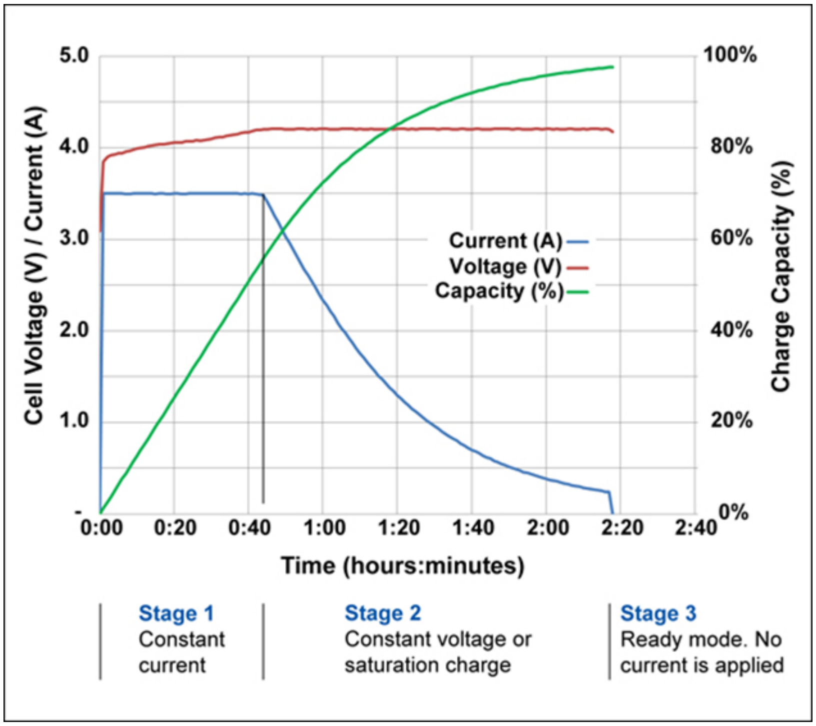

Figure 3. CC-CV Charging Method

The total capacity of cells/batteries can vary based on the charge/discharge rate, in which slower rates tend to provide higher battery capacities. For example, a battery that is charged/discharged at a rate of 1.0 Amps would appear to have a smaller capacity than the same battery that is charged/discharged at a rate of 0.2 Amps. It is generally recommended that lithium-ion batteries be charged/discharged at a rate of 0.2 – 1.0 of the total capacity (C). For example, a battery with a 3,000 mAh capacity should be charged at a rate ranging from 600 to 3,000 mA. Assuming the battery was at a 0% charge level, it would take five hours for the 0.2C rate (600 mA) and one hour for 1.0C (3000 mA) to charge to full capacity.

The amperage charge/discharge rate for these tests was selected to be 1/4 of the listed capacity (mAh) of the cell. This value was selected for both test accuracy and time consideration purposes, as this value would provide an accurate measurement of the capacity while allowing two tests to be performed within a day. The listed nominal voltage, listed cell capacity, maximum/minimum charging voltage and charging current of all cell types is shown in Table 1 below. No charging specifications were present for 3.80V Cell #2, so the same charging current was used as 3.80V Cell #1.

Table 1. Charging Values

Battery Type	Listed Capacity {C} [mAh]	Max Charge Voltage [V]	Min Charge Voltage [V]	Charging Current (1/4C) [mA]
3.79 L Shaped	3969	4.35	3.0	1000
3.80 V Square 1	3174	4.35	3.0	800
3.80 V Square 2	--	4.35	3.0	--
3.83 L Shaped	3046	4.4	3.0	750
3.83 Square	2815	4.45	3.0	700

2.2 SOC Evaluation Results

Using the methods described above, the average SOC of the twenty batteries tested was calculated to be 69.27%. Slight variations were observed based on the cell type tested, but the SOC of all batteries ranged from 64 to 74%. It is common for lithium-ion batteries to self-discharge at a rate of 1.5 – 2% per month, so the batteries may have been at a slightly higher SOC during the incident. The charge capacity (Ah), discharge capacity (Ah), total Watt-hour capacity, and SOC for all evaluated batteries is shown in Table 2.

All tested batteries exceeded the maximum 30% SOC per transport regulations for UN 3480 category batteries. This mandate requires all lithium-ion cells/batteries not packed with or contained within equipment to be below 30% SOC when transported on board aircraft.

Table 2. SOC Calculations

Battery Type	Iteration	Charge Capacity [Ah]	Discharge Capacity [Ah]	Total Energy [Wh]	State of Charge %
3.79 V L-Shaped	1	1.184	4.181	15.932	71.68%
3.79 V L-Shaped	2	1.162	4.177	15.886	72.19%
3.79 V L-Shaped	3	1.170	4.110	15.693	71.53%
3.79 V L-Shaped	4	1.153	4.132	15.767	72.09%
3.80 V Cell #1	1	0.474	1.827	6.809	74.07%

3.80 V Cell #1	2	0.533	1.865	6.969	71.42%
3.80 V Cell #1	3	0.564	1.814	6.790	68.93%
3.80 V Cell #1	4	0.491	1.807	6.738	72.83%
3.80 V Cell #2	1	0.530	1.520	5.647	65.12%
3.80 V Cell #2	2	0.412	1.522	5.658	72.90%
3.80 V Cell #2	3	0.417	1.515	5.650	72.46%
3.80 V Cell #2	4	0.418	1.507	5.603	72.29%
3.83 V L-Shaped	1	0.982	2.997	11.525	67.22%
3.83 V L-Shaped	2	0.943	2.947	11.310	67.98%
3.83 V L-Shaped	3	1.010	3.008	11.563	66.43%
3.83 V L-Shaped	4	0.977	2.889	11.067	66.18%
3.83 V Square Shaped	1	0.991	2.889	11.034	65.70%
3.83 V Square Shaped	2	1.008	2.913	11.137	65.38%
3.83 V Square Shaped	3	1.010	2.893	11.119	65.09%
3.83 V Square Shaped	4	1.046	2.902	11.121	63.95%

3 Thermal Runaway Testing

Prior to testing, it was hypothesized that the ignition of the fire was caused when two of the 3.80V cells, which were packaged together, had slipped out of their plastic sleeves and touched terminals of the opposite polarity, causing the batteries to short circuit, overheat and catch fire. Experimentation was conducted to test this hypothesis and to analyze the correlation between cells charged at varying SOCs and flammability risks.

3.1 SOC Comparison Testing

Testing was performed to analyze the flammability risks of cells at various SOC. In preparation for this test, lithium-ion pouch cells from the package were charged to three different states of charge (SOC) levels; 30%, 70%, and 100% and then separated into three stacks based on the SOC. These levels were chosen to simulate a thermal runaway event for three SOC scenarios; the maximum SOC level allowable in air transportation for UN 3480 cells/batteries (30%), the "as-delivered" cell SOC level (70%), and a worst-case scenario of 100% SOC.

Each stack consisted of two 3.80V cells within the bottom container and a 3.79V cell within the top container. Batteries were placed within their original packaging which included an unsealed plastic sleeve for each cell and the outer cardboard container. A picture of the setup is shown in Figure 4. The 3.80V cells within each stack were put into thermal runaway by cross-wiring the terminals, causing the cells to short circuit. All three stacks were cross-wired at the same time using a switch and the time needed for the batteries to experience thermal runaway was observed.

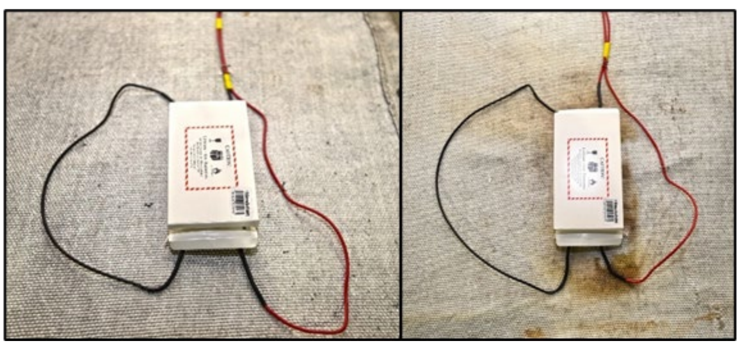

Figure 4. Test Setup and Battery Wiring

3.2 70% SOC Testing

Additional testing was conducted on four stacks of 70% SOC cells in order to analyze the burn damages and thermal propagation. For this iteration of testing, an additional cardboard container with a 3.83V square cell was added to the stack. It was observed during the initial tests that the bottom cell within the 3.80V container would often be the first to reach thermal runaway, so an additional cell was added underneath to see if the temperature would propagate downwards.

Type K stainless steel sheathed thermocouples were attached to each cell as shown in Figure 5. Thermocouples were attached to the side of the 3.80V cell to ensure that the thermocouple would not interfere with temperature propagation.

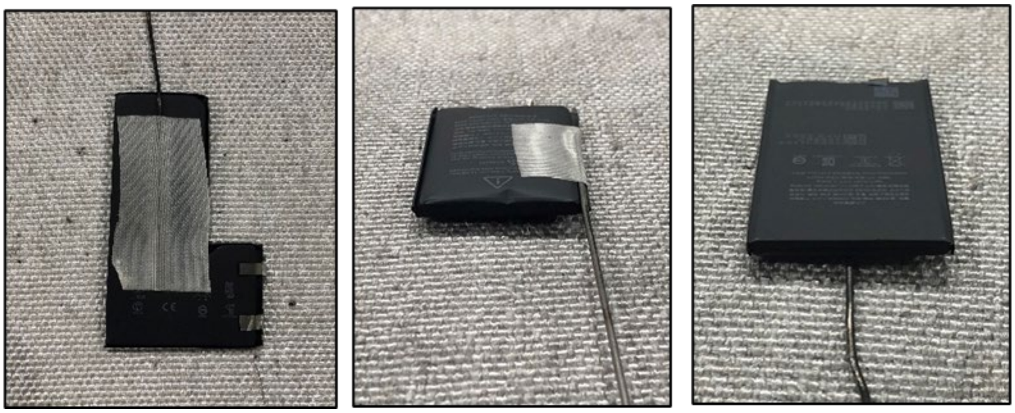

Figure 5. Thermocouple positioning of the 3.79V, 3.80V and 3.83V cells

For the last stack tested, a high-voltage spark igniter was added to determine if a spark could ignite the gases released during thermal runaway. The igniter was oriented three inches above the top front edge of the stack. A picture of the spark igniter's orientation is shown in Figure 6.

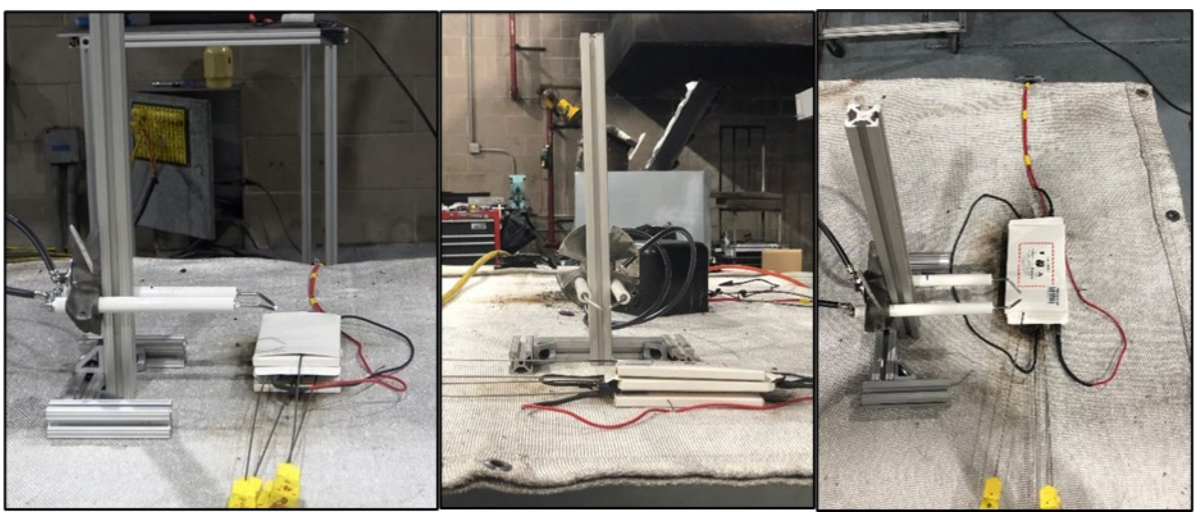

Figure 6. Spark Igniter Setup

4 Discussion of Results

4.1 SOC Comparison Discussion

The results of the SOC Comparison tests were consistent with previous studies conducted by the FAA (Webster, et al., 2016). Cells at higher SOCs experienced more violent reactions during thermal runaway than low level SOC cells.

The 30% cell stack released very little smoke and minimal damage was present in the post test analysis. Only the 3.80V cells showed signs of some damage presenting as slight swelling in the cells. It is common for damaged lithium-ion pouch cells to swell if damaged or overheated. There were no visible signs of damage to the 3.79V cell. No signs of flame or burn damage were present in this 30% SOC stack. Since only the 3.80V cells showed signs of damage and the 3.79 cells did not, this suggests that the heat was not able to propagate to the top cardboard container.

The 70% SOC stack went into thermal runaway and released a significant amount of smoke and gas. Additionally, there was a small amount of flame present within the interior of the packaging. There were signs of thermal propagation, as all cells within the stack experienced thermal runaway at different times during testing. Charring and burn damage were observed in both the cells and surrounding packaging during the post-test analysis.

The 100% SOC stack experienced thermal runaway and a significant amount of smoke, gas and flames were released. As the 3.79V cell underwent thermal runaway, the surrounding gas ignited and large flames were released. There was clear evidence of thermal propagation and the packaging and cells for all containers were completely destroyed.

Images of the peak reaction for each stack and the damages for each SOC stack is shown in Figure 7.

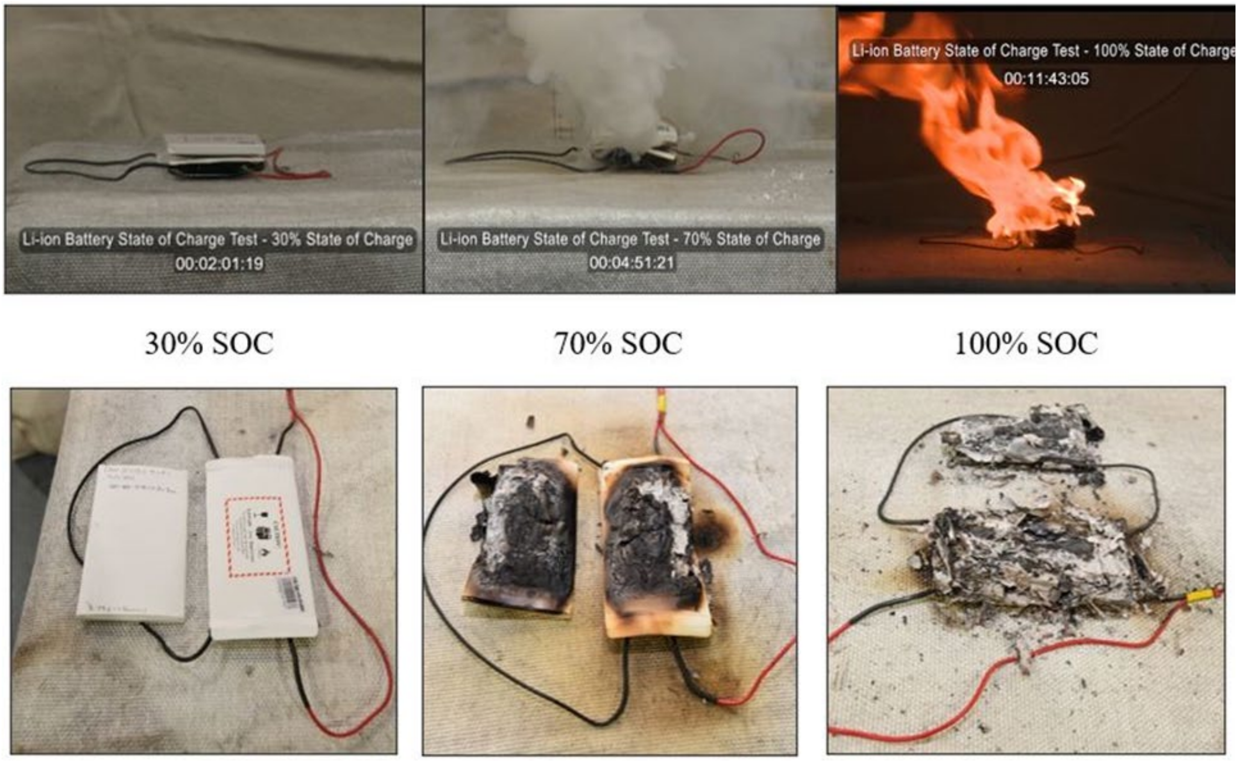

Figure 7. Peak reaction and post-test damages of each cell stack

4.2 70% SOC Testing Discussion

The ability of the cells to reach thermal runaway was inconsistent between tests. In three of the four tests, all cells underwent thermal runaway and reached temperatures ranging from 400 to 700°C. The 3.79V and 3.83V cells, which had the highest capacities, had the highest overall temperature peaks. Figure 8 shows the temperatures of all cells throughout testing. The sudden increase in temperature indicates that a cell has reached thermal runaway.

It was observed that the as-delivered 70% SOC cells experienced some temperature propagation between cardboard containers. Furthermore, it was evident during testing that the cell within the top container had reached thermal runaway shortly after the bottom cells went into thermal runaway. This suggests that the batteries were at a high enough SOC in the initial package fire incident that the temperature from one thermal runaway cell had enough energy to propagate to other cells within the container.

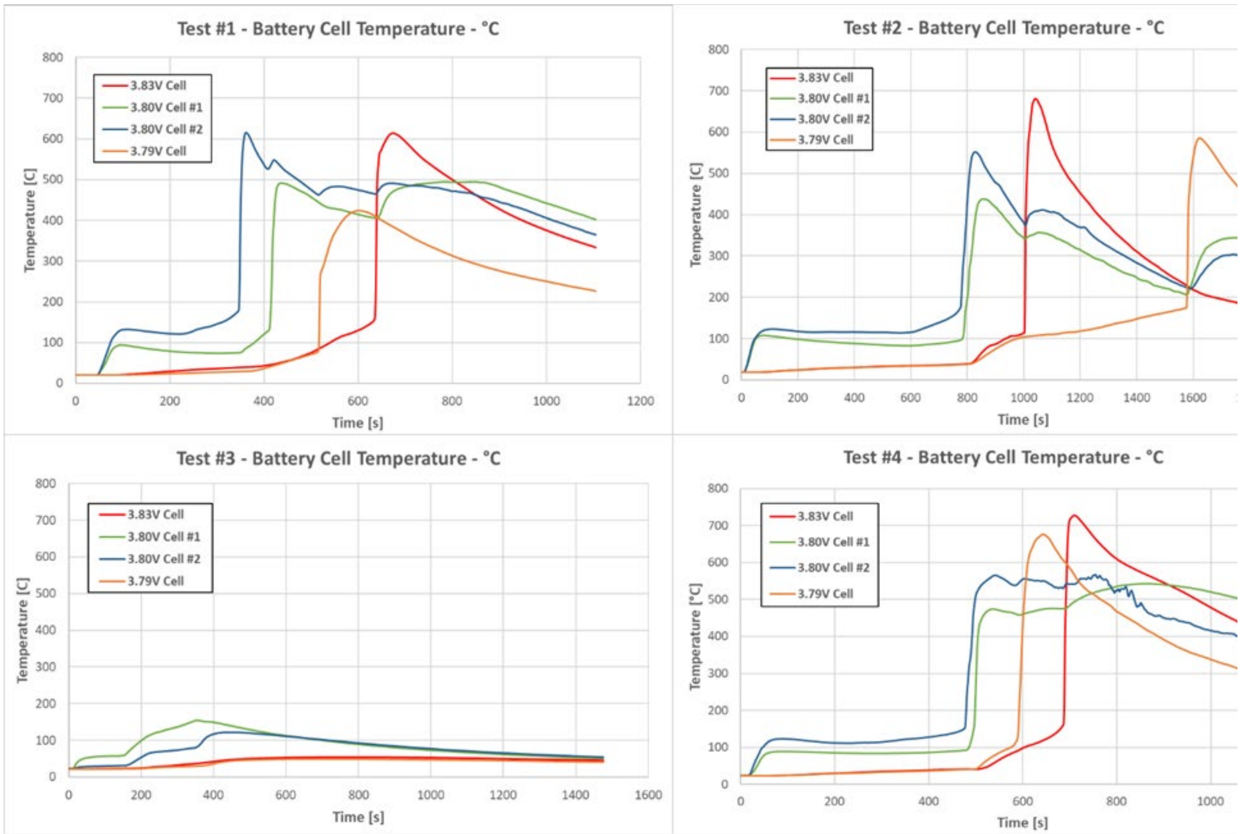

Figure 8. Cell Temperatures

The time needed for cells to reach thermal runaway was inconsistent throughout repeated testing. Throughout all four tests, the time from test to the initial thermal runaway event varied between six minutes to thirteen minutes. Once the initial cell achieved thermal runaway, however, the temperature was able to propagate to surrounding cells and cause them to enter thermal runaway within a few minutes.

In Test #1, the first cell was able to reach thermal runaway within the six minutes of testing and the temperature was able to propagate to all other cells in the stack within a five-minute period.

In Test #2, the first cell did not achieve thermal runaway until almost thirteen minutes into testing during which both 3.80V cells experienced thermal runaway. The temperature was able to propagate to both the top and bottom container, but it took an additional thirteen minutes for the 3.79V Cell to reach thermal runaway. This was a much longer time period compared to other tests, as it typically took less than five minutes for the temperature to propagate.

In Test #3, none of the cells experienced any thermal runaway events. Approximately five minutes into the test, 3.80V Cell 1 reached a max temperature of 150°C, but no other cells exceeded this temperature. No flame and very little smoke were visible for this particular test. A post-test analysis showed no signs of burn damage to the cells or surrounding container, however both 3.80V cells were bloated which indicated that the internal components of the cells were damaged from high temperatures experienced during testing.

In Test #4, the spark igniter ignited the gases released by the batteries during the thermal runaway event and a significant amount of flame was present. During thermal runaway events, lithium-ion and lithium metals batteries can sporadically create sparks that can ignite surrounding gases. This indicates that the gases released during thermal runaway may have ignited from a spark produced from the cell.

5 Conclusion

5.1 SOC Evaluation

The lithium-ion pouch cells were calculated to have an average as-shipped SOC of 70%. This value exceeded both domestic and international regulations for aircraft transport which require lithium-ion cells/batteries not shipped with or within equipment to be below 30% SOC.

5.2 SOC Comparison Testing

High SOC cells were more likely to have more violent reactions in the event of thermal runaway. The 70% and 100% SOC stacks consistently produced both flame and smoke, whereas the 30% SOC stack released very little smoke and no flame. Furthermore, cells charged to a higher percent were more likely to propagate to nearby cells. Burn damages were present for all cells and carboard packages for the 70% and 100% stacks, but only the 3.80V cells showed any signs of damage in the 30% stack. This was consistent with previous FAA testing (Webster, et al., 2016).

5.3 70% SOC Testing

A thermal runaway event occurred in all cells for three of the four 70% SOC stack tests conducted. In those three tests, all cells underwent thermal runaway and reached temperatures ranging from 400 to 700°C. Cells at 70% SOC produced enough heat to propagate to other cells within the container. The results of this testing indicates that it is likely the original fire started and spread when two of the 3.80V cell terminals made contact.

Furthermore, the gases released during thermal runaway were able to be ignited when a spark igniter was placed within close proximity. Lithium-ion cells can sporadically create sparks when undergoing a thermal runaway event. This indicates that a spark during the thermal runaway event could have ignited the gases released, causing a significant amount of flame.

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