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A State of Charge Analysis of Lithium-ion Cells Shipped via Air

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16. Abstract

A thermal event involving a package containing lithium-ion pouch cells occurred within a sorting facility of an all-cargo airline in December 2022. This package had been previously shipped via air and was being handled for delivery to its next destination. Following the incident, the package was sent to the William J. Hughes Technical Center for further evaluation using battery analysis equipment to determine the as-delivered state of charge (SOC) of the cells.

Lithium-ion cells not packed with or contained in equipment (Lithium ion batteries, UN3480) that are transported via aircraft are mandated by Federal regulations to be at a SOC no greater than 30%. Previous FAA studies have determined that lithium-ion cells exceeding this level are a serious hazard due to risk of thermal runaway and can lead to an unsafe condition on an aircraft.

Upon inspection, many of the cells in the package were observed to have significant signs of damage, including swelling and corrosion. However, it could not be determined if this damage occurred prior to or after the incident. SOC testing was performed on cells that did not show significant signs of damage. Testing determined that 14 of the 25 tested cells exceeded the maximum 30% SOC requirement. Of these 14 cells, 7 exceeded 70% SOC, with the highest evaluated cell recording a SOC of over 90%.

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

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Acronyms

Acronym	Definition
CC-CV	Constant Current – Constant Voltage
FAA	Federal Aviation Administration
mA	milliampere
mAh	milliampere hour
SOC	State of Charge
V	Volts
Wh	Watt-hour

Executive summary

The transport of lithium-ion cells on aircraft is heavily regulated due to the significant risk of fire and toxic gas hazards that these power sources pose. Lithium-ion cells are prone to a phenomenon known as thermal runaway, a self-sustaining reaction in which the internal temperature of the cell increases uncontrollably. This reaction can cause the cell to rupture and release toxic gases and flames. Past FAA studies have determined that the state of charge (SOC) of a lithium-ion cell affects the severity of a thermal runaway event and the likelihood that the heat would propagate to adjacent cells or cargo. As a result of this risk, transport regulations and industry standards require lithium-ion cells not packed with or contained in equipment (Lithium ion batteries, UN3480) to be shipped at a SOC less than or equal to 30% of their total capacity when transported on aircraft.

In December 2022, a package containing lithium-ion pouch cells experienced a thermal event in a commercial sorting facility of an all-cargo airline. This package had been shipped from overseas via air prior to arrival at the facility and was being prepared for shipment to its next location. Workers within the facility reported that the package felt warm to the touch and they smelled a burning odor. After further inspection, charring of the surrounding packaging and many of the cells was observed, and evidence was noted that a thermal event had occurred.

Following the incident, the package with the cells was sent to the William J. Hughes Technical Center for further analysis. Tests using specialized battery analysis equipment were conducted to determine the SOC of these cells. Analysis concluded that a significant number of tested cells exceeded the 30% SOC limit. Of the 25 total evaluated cells, 14 exceeded the 30% SOC limit, and 7 were determined to be at a SOC greater than 70%, with the highest cell measured in excess of 90%.

From the test results, it can be concluded that the package contained cells that exceeded the 30% SOC limit and therefore posed a significant fire risk. Although the direct cause of the thermal runaway event could not be determined, the high charge level of these cells was a likely factor in the severity of the thermal event and the ability for heat to spread to other cells in the container

1 Introduction

Lithium-ion batteries are a type of rechargeable battery commonly used within electronic devices due to their high energy density, low self-discharge rate, and long lasting performance. These batteries are frequently used as the main power source within electronics such as laptops, phones, and tablets. Despite these advantages, however, lithium-ion cells can pose a significant fire risk due to their propensity to undergo a phenomenon known as thermal runaway.

Thermal runaway is an uncontrollable and self-sustaining chemical reaction in which the temperature of the cell suddenly increases, often exceeding temperatures of 1,000° F (Keslar, 2022). During the peak of this reaction, it is common for the cell to expel toxic and flammable gases, and emit flames to the surrounding area. A thermal runaway event may occur if cells are overheated, overcharged, mishandled, or have a manufacturing defect leading toward an internal short circuit.

The state of charge (SOC) of a cell or battery has been found to be an important determinant in predicting a cell's fire hazard. The SOC is an electrical cell or battery's charge level compared to its total capacity. Past FAA studies have determined that the thermal energy released upon failure of a lithium-ion cell is directly correlated with the total electrical capacity of the cell and the state of charge (Lyon, Richard, & Walters, 2016). Furthermore, previous testing has concluded that cells charged at higher SOCs are more likely to produce higher heat release rates, maximum temperatures, and concentrations of toxic and flammable gases during a thermal runaway event (Maloney, 2016; Wang, et al., 2018; Maloney, 2022)

As a result of this risk, the transport of lithium-ion cells onboard aircraft is heavily regulated. Industry standards[1] and transport regulations[2] mandate a maximum SOC of 30% for all cells not packed with or contained in equipment (Lithium ion batteries, UN3480). This does not include lithium-ion batteries transported by passengers in the cabin.

In December 2022, an incident involving a package containing lithium-ion pouch cells occurred within a commercial sorting facility of an all-cargo airline. Workers within the facility reported a burning odor and the package was found to be warm to the touch. After further investigation, signs of black charring were observed throughout the interior of the package. The cells and package were sent to the William J. Hughes Technical Center for further evaluation.

[1] IATA Dangerous Goods Regulations (DGR)
[2] 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 Battery analysis

Forty-eight pouch cells of nine different types were contained in the package and evaluated at the William J. Hughes Technical Center. These cells were originally intended to be used as replacements for various types of smartphone models. Cells were individually packaged in clamshell type sealed plastic. Images of the nine cell types evaluated are shown in Figure 1, with their associated model numbers.

35H00261 (10.66Wh)

35H00263 (13.28Wh)

GMSB3 (17.46Wh)

KS40 (10.7Wh)

NT40 (14.5Wh)

JG30 (10.7Wh)

G013A-B (11.2Wh)

MK50 (18.2Wh)

NG50 (18.2Wh)

Figure 1: Nine types of cells within the package

Evidence of damage was observed at initial package inspection. Significant char damage was discovered in the clamshell plastic packaging of the JG30 model cells, and evidence of burn damage was observed on the exterior cardboard material of the package.

In addition to the signs of charring on the surrounding packaging, evidence of damage was observed on the cells themselves. An unknown liquid-like residue was observed on the exterior casing of several of the GMSB3 model cells. This residue liquid evaporated approximately thirty minutes after package opening, leaving small solid remnants on the cell casings. The residue had a chemical-like odor, so it is believed that this was a result of leakage of the internal contents of the cells.

Furthermore, signs of corrosion were found on the outer casing of some of the JG30 and GMSB3 model cells. All NG50 model cells were observed to have a significant amount of swelling, which indicated that the internal components of the cell had sustained damage. It cannot be confirmed if this swelling occurred prior to the incident or if it was a direct result of the heat from thermal runaway. Images of some of the damage observed on the packaging and the exterior of the cells is shown in Figure 2.

Prior to SOC testing, the as-delivered voltage of all cells in the package were measured using a multimeter. A significant number of cells were found to be either completely discharged (no voltage reading) or to have a very low voltage (lower than 2.75V). Cells that are discharged below a minimum threshold (usually between 2.75V – 3.0V for many lithium-ion chemistries) can experience unwanted chemical reactions, potentially causing a short circuit if recharged. Therefore, SOC testing was not conducted on cells that showed significant damage to the exterior cell or if the measured voltage was below 3.0V.

Figure 2: Thermal event charring / cell damage

3 State of charge testing

Testing was performed using an Arbin Instruments battery analyzer. This instrument operates with a measurement accuracy within 0.01% and a control accuracy within 0.02%. The battery analyzer's full-scale voltage was 10 Volts.

To determine SOC, cells were charged from the unknown initial charge state to maximum capacity and then discharged completely. Cells were charged using a constant current – constant voltage (CC-CV) charging method, which is typical for rechargeable lithium-ion batteries. With this charging method, the cell is charged at a constant current until a maximum voltage is reached. Subsequently, the maximum voltage is kept constant and then the current is slowly decreased until the termination current value is reached.

The Arbin Instruments battery analyzer recorded the charge and discharge capacity during this process. The initial SOC of the cell was then calculated using Equation 1 below. Within this method, the recorded discharge capacity is equal to the total capacity of the cell.

$$SOC_{Initial} = \frac{Capacity_{Total} - \ Charge\ Capacity}{Capacity_{Total}} \tag{1}$$

Two variables relevant in calculating the SOC of a cell are the C-rate and ambient temperature. C-rate is "a measure of the rate at which a battery is discharged relative to its maximum capacity" (MIT, 2008, p. 1). For example, a 2500 mAh cell discharged at a rate of 1.0C would equate to a discharge current of 2500 mA. A 0.5C rate would equate to a discharge current of 1250 mA. Variations in C-rate and temperature can affect the calculated capacity of a cell. Cells that are discharged at faster rates often record slightly lower capacities compared to slower rates. More energy is turned into heat at higher C-rates, which can result in loss of measured cell capacity (Ma, et al., 2018). An example of this is shown in Figure 3, which shows a discharge curve of a typical lithium-ion cell (Sanyo Energy (U.S.A.) Corporation, 2012).

Furthermore, temperature is a known factor to affect the discharge capacity of a cell. Cold temperatures can increase the internal resistance of a cell and lower the capacity (Cadex Elecronics, 2021). Figure 4 displays a discharge curve of a typical lithium-ion cell at various temperatures (Sanyo Energy (U.S.A.) Corporation, 2012).

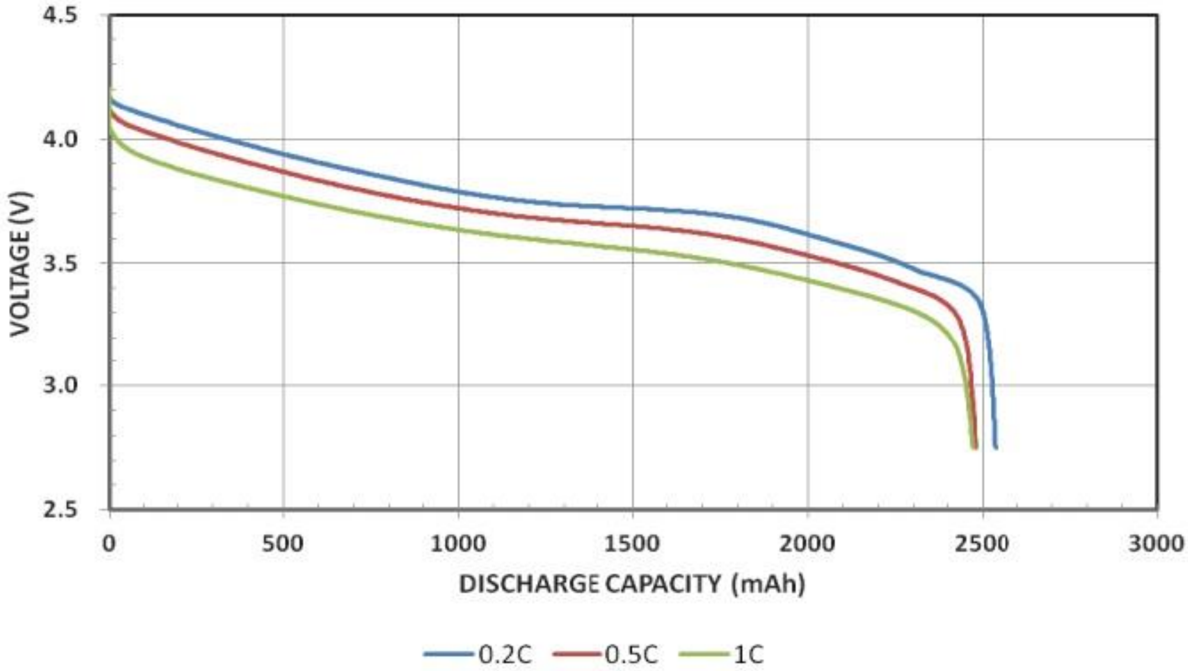

Figure 3: C-rate discharge capacity comparisons

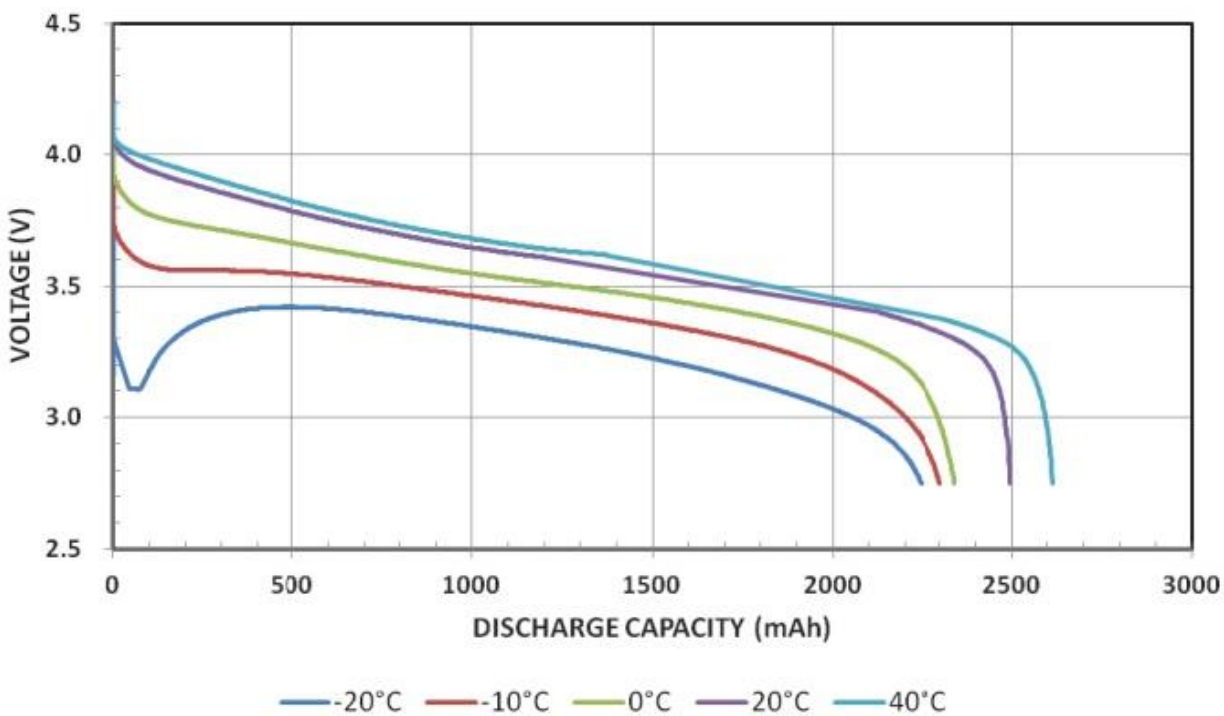

Figure 4: Temperature discharge capacity comparisons

In order to minimize variance in recorded capacity data, the C-rate and temperature throughout testing were kept constant. Cells were charged and discharged at room temperature (70°F). Additionally, the C-rate was kept constant at a selected rate of 0.2C of the typical capacity of the cell.

Online research was conducted to find manufacturer data sheets for each cell type involved in the incident; however, specifications were unavailable. Some charging specifications such as the maximum charge voltage, nominal voltage, and rated capacity were listed on the outer casing of the cells. However, other information such as the minimum charge voltage and termination current could not be found. Therefore, these values were assumed based on specifications from similar types of cells.

Table 1 shows the charging specifications for each cell type that was evaluated because of the incident. The values not explicitly stated on the cell itself are highlighted in orange.

Table 1: Charging specifications for each cell type evaluated

Cell	**Nominal Voltage**	**Rated Capacity**	**Typical Capacity**	**Max Voltage**	**Min Voltage**	**Termination Current**	**CC Charge Current**
	[V]	**[mAh]**	**[mAh]**	**[V]**	**[V]**	**[mA]**	**[mA]**
NG50	3.87	4700	5000	4.45	3.0	100	1000
35H00261	3.85	2770	---	4.40	3.0	100	600
JG30	3.80	2820	3000	4.40	3.0	100	600
NT40	3.85	3760	4000	4.40	3.0	100	800
MK50	3.87	4700	5000	4.45	3.0	100	1000
KS40	3.80	2820	3000	4.4	3.0	100	600
G013A-B	3.85	2815	---	4.4	3.0	100	600
35H00263	3.85	3450	---	4.4	3.0	100	700
GMSB3	3.86	4524	4614	4.4	3.0	100	900

A minimum voltage of 3.0V was selected for all evaluated cells, a conservative assumption since data sheets could not be obtained for these cells. Lithium-ion cells typically have a cut-off voltage ranging from 2.5V to 3.0V depending on the cell type and chemistry. Cells discharged to a voltage below these values can be permanently damaged. A termination current of 100 mA was selected for all cells.

The calculated state of charge data for each cell type tested is shown below in Table 2.

Table 2: Measured SOC data

Cell Type	Test #	Initial Voltage	Charge Capacity	Discharge Capacity	State of Charge
		[V]	[Ah]	[Ah]	[%]
35H00261	1	4.12	0.47	2.24	79.00%
	2	4.15	0.41	2.22	81.64%
	3	4.11	0.50	2.27	77.76%
	4	4.10	0.48	2.22	78.15%
JG30	1	3.71	2.59	2.95	12.25%
MK50	1	3.76	4.05	4.94	18.05%
	2	3.71	4.37	4.94	11.50%
	3	3.76	4.05	4.94	17.99%
	4	3.75	4.05	4.91	17.42%
	5	3.75	4.08	4.95	17.60%
	6	3.76	4.02	4.94	18.64%
	7	3.76	4.03	4.92	18.00%
	8	3.75	4.06	4.93	17.56%
	9	3.75	4.06	4.91	17.34%
	10	3.75	4.10	4.95	17.13%
KS40	1	3.71	1.30	2.64	50.67%
	2	3.69	1.34	2.63	48.96%
	3	3.67	1.47	2.61	43.62%
35H00263	1	4.08	0.74	2.72	72.90%
GMSB3	1	3.86	2.18	4.19	48.02%
	2	4.27	0.40	4.39	90.86%
	3	3.85	2.32	4.41	47.52%
	4	3.86	2.42	4.44	45.48%
	6	4.15	0.86	4.40	80.50%
	7	3.80	2.94	4.45	33.86%

4 Discussion of results

A considerable number of cells in the damaged package were found to be completely discharged and/or severely damaged upon arrival to the William J. Hughes Technical Center, so as such could not be included in the SOC test. It is unknown what the SOC of those cells were as a result of the thermal runaway event. Conclusions could only be based on evaluation of cells in good enough condition to undergo a full charge/discharge cycle test.

The average SOC of all tested cells was determined to be approximately 40%. Data could only be collected for 6 of the 9 cell types within the package. Measured SOC was observed to vary depending on the cell type. Cells were mostly observed to be within 10% SOC of other cells of the same type. However, the GMSB3 cell models were an exception, demonstrating a much larger disparity in measured SOC. The lowest charged cell of this type recorded a SOC of 33.86%, whereas the highest recorded SOC was 90.86%. Measurements for the NG50, NT40, and G013 cell models could not be collected as all these cells were either damaged or had a very low voltage.

Of the 25 tested cells, 14 were determined to exceed the maximum allowable limit of 30%. Furthermore, 7 of the cells were found to have calculated SOCs exceeding 70%. The 14 cells that were observed to exceed 30% SOC were from four types of cell models; GMSB3, KS40, 35H00261, and 3500263.

5 Conclusions

Numerous FAA studies have determined that lithium-ion cells shipped at high states of charge present a more significant threat of thermal runaway, with a greater threat of fire. Results of these studies have determined that the SOC of a lithium-ion cell directly affects the severity of a thermal runaway event and the likelihood that the heat is able to propagate to adjacent cells or cargo.

It can be concluded that many cells shipped within this package were not packed in accordance with the current Federal requirements for hazardous material packaging for air transport (Shippers - General requirements..., 2023). Over half of the tested cells were determined to exceed the 30% limit required by industry standards and transport regulations. Additionally, some cells had measured states of charge exceeding 80%. Therefore, it is evident that the high SOC of cells within this package likely contributed to the propagation of heat during the thermal incident.

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