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

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Federal Aviation Administration

#### Introduction

- Lithium-ion batteries are a common power source in many different electronic devices
  - Ex: Phones, tablets, laptops, EVs, etc.
- Lithium-ion batteries can undergo a process called "thermal runaway"
  - Thermal Runaway is an uncontrolled process which causes the temperature within the battery to increase exponentially, until it ruptures, releasing smoke or flame
  - Can occur when the cells are overheated, mishandled, or have a manufacturing defect
- Considered to be a hazardous material due to its significant fire risk
  - Past aircraft accidents have been caused from lithium-ion batteries



#### UN 3480

- Li-ion cells/batteries not packed with or contained within equipment must be classified as UN 3480
  - Does not include lithium-ion batteries which are transported within equipment (i.e within laptops, tablets etc.)
  - Includes lithium-ion polymer cells
- UN 3480 cells cannot exceed 30% state of charge (SOC) when transported onboard aircraft
- SOC is the electrical cell or battery's charge level compared to the total capacity of the cell or battery





Different types of Li-ion cells



### Why is SOC important?

- Batteries with a higher SOC are more likely to produce higher heat release rates, maximum temperatures and toxic gases during a thermal runaway event
- Cells are more likely to propagate to nearby cells/packaging at higher SOCs



30%70%100%Peak reactions of batteries at various SOCs from past FAA testing



### **SOC Testing**

- Lithium-ion cells of various sizes and chemistries were ordered from e-commerce platforms and sent for analysis to the FAA Technical Center
- Specialized battery analysis equipment was used to measure a cell's SOC
- A total of 72 lithium-ion cells of different types and chemistries were tested:
  - Types
    - Cylindrical Cells (32650s, 26650s, 18650s, 14500s, 10440s etc.)
    - Pouch Cells
  - Chemistries
    - Lithium Cobalt Oxide (LiCoO<sub>2</sub>) LCO
    - Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO<sub>2</sub>) NMC
    - Lithium Iron Phosphate (LiFePO<sub>4</sub>) LFP



#### Some of the evaluated cells







### **SOC Calculations**

- All cells were charged from the initial state of charge to full capacity, and then discharged completely
  - A Constant Current Constant Voltage (CC-CV) charging method was used
- It is generally recommended for batteries to be charged/discharged from 0.2 – 1 Capacity (C). For the purposes of these tests, a current of 0.2 C was used
  - Variations in charging current could affect a cell's calculated capacity, so a charge/discharge current of 0.2 C was held consistent throughout testing

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





### Categorization

- Challenges in determining mode of transportation for many packages
  - Many did not have a tracking # listed or identifiable business address
  - Batteries were categorized based on the suspected mode of transport
- A sample size of 4-5 cells were tested per package, or less than that if the package contained < 4</li>

<ul> <li>Confirmed Air Transport</li> <li>Tracking # on package</li> <li>Identifiable business</li></ul>	<ul> <li>Suspected Air Transport</li> <li>No package tracking #</li> <li>Identifiable business</li></ul>
address <li>Package shipped cross</li>	address <li>Package shipped cross</li>
country within two days	country within two days
<ul> <li>Unknown Transport</li> <li>No package tracking #</li> <li>Unidentifiable business</li></ul>	<ul> <li>Confirmed Land Transport</li> <li>Tracking # available</li> <li>Identifiable business</li></ul>
address	address



#### **Results**

- Of the 72 tested cells, 54% exceeded the 30% SOC limit
- 13% of tested cells exceeded 50% SOC
- A breakdown of the evaluated cells by mode of transportation is shown below:
  - Confirmed Air Transport 20 tested, 19 > 30%, 9 > 50%
  - Suspected Air Transport 19 tested, 7 > 50%
  - Unknown 23 tested, 13 > 30%, 2 > 50%
  - Confirmed Land Transport 10 tested





#### **Observations**

- SOC was not necessarily the same between the same battery manufacturers:
  - Three types of batteries were ordered from the same manufacturer, two types were found to be less than 30% SOC while the last set was ~ 55% SOC
  - For the 55% SOC batteries, two sets were ordered from different sellers one with a Canadian address and the other from Illinois. Canada shipment delivered through air and Illinois through land transport
- No significant differences in measured SOC was observed between different types of lithium-ion batteries



#### **Observations**

- Many manufacturers were found to have a much lower capacity than advertised
  - A few 18650 sellers had listed cell capacities over 9000 mAh, 3x greater than realistically possible
  - The measured capacity of these cells was approximately 1000 mAh, even though 18650s typically range from 2500 – 3500 mAh
  - This was observed in other sized cells as well (26650s), although not to this extent





### **Packaging Fire Threat**

- One package was ordered from an ecommerce platform and delivered via air
- Over 70 cells were scattered within the box without any protective packaging to prevent contact between cells
  - Cells could have made contact with terminals of the opposite polarity, leading to thermal runaway
- The voltages of the cells were evaluated
  - Many cells were found to be dead
  - Some cells were found to have high voltages and most likely would have exceeded the 30% limit



Interior of package and underneath plastic wrap



### **Packaging Fire Threat (Continued)**

- In addition to those observations, some cells within the package were found to be severely damaged
  - Several were swollen and showed signs of corrosion
- This indicates this the cells were damaged prior to or during transport







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- An analysis was done on lithium-ion cells that could be ordered online and delivered to everyday consumers
- A substantial amount of lithium-ion cells confirmed or suspected to be transported via aircraft were found to exceed the 30% SOC limit for UN 3480
  - 19 out of the 20 evaluated cells which were confirmed to be transported via aircraft exceeded 30%
  - 9 of those were found to be greater than 50%
- Some batteries shipped via air transport were found to be damaged/packed incorrectly
- These observations show that a fire threat is still present for some lithium-ion battery aircraft shipments despite regulations currently in place



#### **Additional Steps**

- Enforcement of these regulations are difficult
- There is no easy way to calculate the SOC in the field, as voltage is not a reliable way to get an estimate due to differences in battery types and chemistries
- Additional steps may be needed to ensure that SOC regulations are being followed



# **Questions?**

#### Contact:

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Confirmed Air Transport				
Battery Type	Amp-Hour [Ah]	Watt-Hour [Wh]	SOC	Pass/Fail?
18650	1.24	4.76	55.66%	Fail
18650	1.23	4.70	56.11%	Fail
18650	1.22	4.69	57.58%	Fail
18650	1.25	4.79	55.27%	Fail
14500	0.40	1.51	40.66%	Fail
14500	0.38	1.44	45.23%	Fail
14500	0.38	1.45	47.42%	Fail
14500	0.32	1.22	31.56%	Fail
14500	0.33	1.26	38.61%	Fail
18650	1.96	7.51	55.59%	Fail
18650	1.98	7.50	55.20%	Fail
18650	1.98	7.52	54.84%	Fail
18650	2.00	7.57	55.43%	Fail
26650	1.60	5.15	26.55%	Pass
26650	1.93	7.32	42.17%	Fail
26650	1.83	6.98	32.78%	Fail
14500	0.36	1.38	49.12%	Fail
14500	0.37	1.41	38.21%	Fail
14500	0.38	1.45	50.52%	Fail
14500	0.38	1.46	45.87%	Fail

#### Confirmed Air Transport





Suspected Air Transport				
Battery Type	Amp-Hour [Ah]	Watt-Hour [Wh]	SOC	Pass/Fail?
Pouch Cell	3.45	12.62	65.39%	Fail
Pouch Cell	1.86	6.86	68.07%	Fail
Pouch Cell	1.92	7.05	66.91%	Fail
10440	0.34	1.26	71.63%	Fail
10440	0.34	1.25	70.92%	Fail
10440	0.31	1.16	75.69%	Fail
10440	0.32	1.17	75.57%	Fail
18500	1.96	7.15	20.46%	Pass
18500	1.95	7.12	19.96%	Pass
18500	1.94	7.10	19.96%	Pass
18500	1.97	7.20	20.02%	Pass
18650	0.75	2.63	19.56%	Pass
18650	0.81	3.09	26.85%	Pass
18650	0.82	3.16	24.45%	Pass
18650	0.64	2.45	24.66%	Pass
18500	1.13	3.61	10.99%	Pass
18500	1.13	3.62	10.72%	Pass
18500	1.11	3.58	11.95%	Pass
18500	1.08	3.62	4.45%	Pass

#### Suspected Air Transport





Unknown Transport				
Battery Type	Amp-Hour [Ah]	Watt-Hour [Wh]	SOC	Pass/Fail?
18650	1.00	3.83	30.57%	Pass
18650	0.92	3.48	29.01%	Pass
18650	0.92	3.50	28.11%	Pass
18650	0.87	3.67	26.03%	Pass
18650	0.96	3.65	34.36%	Fail
18650	0.78	2.95	22.93%	Pass
18650	0.78	2.94	22.89%	Pass
18650	0.81	3.05	23.89%	Pass
18650	0.80	3.01	23.94%	Pass
16650	1.56	5.78	73.47%	Fail
16650	1.53	5.70	72.16%	Fail
18700	2.79	10.29	19.42%	Pass
18700	2.80	10.27	20.04%	Pass
18650	2.81	10.24	34.48%	Fail
18650	2.77	10.05	33.40%	Fail
18650	2.76	10.91	33.56%	Fail
18650	2.79	10.14	33.61%	Fail
18700	2.56	9.38	33.87%	Fail
18700	2.57	9.38	33.50%	Fail
18650	1.72	6.60	43.31%	Fail
18650	1.73	6.64	44.08%	Fail
18650	1.77	6.80	44.13%	Fail
18650	1.75	6.74	45.00%	Fail

#### Unknown Transport





Land Transport				
Battery Type	Amp-Hour [Ah]	Watt-Hour [Wh]	SOC	Pass/Fail?
18650	2.53	9.26	20.22%	Pass
18650	2.53	9.24	20.30%	Pass
18650	1.13	4.30	56.59%	Pass
18650	1.09	4.16	57.01%	Pass
18650	1.16	4.42	49.93%	Pass
18650	1.14	4.35	56.77%	Pass
18650	2.67	9.81	55.06%	Pass
18650	2.69	9.87	55.89%	Pass
32650	5.93	21.74	50.00%	Pass
32650	5.81	21.40	37.57%	Pass

#### Land Transport



■ < 30% ■ > 30 - 50% ■ > 50%

