National Transportation Safety Board

Hazardous Materials Accident Brief

Lithium-Ion Battery Truck Fire Following Aerial Transport

Brampton, Ontario, Canada

June 3, 2016

The Accident

On June 3, 2016, about 4:05 p.m. local time, a FedEx W900 local delivery truck and all of its cargo were destroyed by a fire while the driver was delivering packages to a business in Brampton, Ontario, Canada; no injuries were reported.[1] The fire began among a shipment of four large-format lithium-ion batteries, each of which was individually packaged in a fiberboard box.[2] No other dangerous goods were on board.[3] The international shipment of the four lithium-ion batteries originated from Braille Battery, Inc. (Braille), a battery manufacturer located in Sarasota, Florida, and were destined for Brampton, Ontario, Canada. The batteries were initially transported by FedEx on two separate US-registered cargo airplanes before being transferred to the delivery truck. The fire occurred about 10 hours after the batteries were offloaded from the cargo airplane at the Toronto, Canada, International Airport. Figure 1 shows both the interior and exterior damage to the FedEx truck. Estimated damages were over $71,000. The Federal Aviation Administration (FAA) notified the National Transportation Safety Board (NTSB) of the accident over concerns that the fire could also occur during air transport.[4]

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[1] Although this accident occurred in Canada, the National Transportation Safety Board (NTSB) investigated this incident because the shipment originated from an air carrier that is from the United States (US) and it involved lithium-ion batteries that were shipped in a configuration that was presumed compliant with US regulations. This was a limited investigation.

[2] (a) Lithium batteries fall into two main categories: lithium-metal (primary) batteries that are nonrechargeable batteries used in devices such as watches, calculators, and cameras, and lithium-ion (secondary) batteries are rechargeable. Both types of lithium batteries may be transported via cargo aircraft but are prohibited from being transported as cargo on a passenger aircraft. (b) Some large-format batteries are made by connecting smaller battery cells into series and parallel combinations. A "large" battery is defined under the United Nations (UN) *Manual of Tests and Criteria*, Section 38.3 (UN 38.3), as having "a gross mass of more than 12 kg."

[3] *Dangerous goods* is the phrase used internationally to describe hazardous materials.

[4] For more information, see the safety recommendation report associated with this investigation, *Standards for Lithium-Ion Battery Shipments by Air* HZMSR-20/01. Additional information about this accident investigation can be found in the public docket for this accident (NTSB DCA16SH001) by accessing the Accident Dockets link for the Docket Management System at www.ntsb.gov. For more information on our safety recommendations, see the Safety Recommendation Database at www.ntsb.gov.

Figure 1. The fire damage to the FedEx truck and its contents. The contents of the truck were removed by firefighters following the fire. (Courtesy of FedEx.)

Shipping Information

In early 2016, Braille received an order for 16 custom-made, large-format, United Nations (UN) 3480 lithium-ion batteries from SpaceMaker Systems Inc. (SpaceMaker), a material handling company that manufactured devices for automating warehouses and factories. SpaceMaker requested that four of those batteries be shipped by air from Sarasota, Florida, to a warehouse in Brampton, Ontario, Canada.[5]

FedEx received the battery shipment and subjected the packages to its dangerous goods acceptance process before loading them onto the airplane. A checklist was used to assess the shipment's compliance with the US Department of Transportation (DOT) Hazardous Materials Regulations (HMR), as well as the International Civil Aviation Organization (ICAO) standards.[6] Once the checklist was completed, it was scanned, along with the shipper's declaration and other associated documentation, into an electronic repository.

On June 2, 2016, FedEx loaded the batteries into a unit load device, then onto a FedEx Airbus A300 cargo flight from Tampa (Florida) International Airport to Indianapolis (Indiana) International Airport. The batteries were offloaded and sorted at a FedEx station in Indianapolis, and then loaded onto a FedEx Boeing MD10-30 cargo airplane, which departed Indianapolis on

[5] The other 12 batteries were shipped by ground to other US-based warehouses.

[6] Title 49 *Code of Federal Regulations* (*CFR*) Parts 100-185; International Civil Aviation Organization, *Technical Instructions for the Safe Transport of Dangerous Goods by Air*, 2015-2016 edition. (Montreal, Quebec, Canada: 2015).

June 3, 2016, about 4:15 a.m., and arrived at Toronto (Ontario, Canada) Pearson International Airport on June 3, 2016, about 5:36 a.m.

At Toronto, FedEx personnel offloaded the four lithium-ion batteries from the airplane and again conducted the FedEx dangerous goods acceptance process, where no damage was noted. Personnel then loaded the four batteries onto a FedEx local delivery truck for transport to a storage warehouse in Brampton.

About 3:30 p.m., the driver of the FedEx truck returned to the truck after completing an unrelated package delivery. He opened the bulkhead door and noticed smoke coming from the upper-right corner of the rear of the truck, where he had placed the lithium-ion battery packages. He then drove the truck away from the customer's building to the end of an empty parking lot. The driver evacuated the truck without injury and called emergency response at 3:54 p.m., reporting that the truck was on fire and "exploding." The fire spread rapidly, eventually destroying the truck and its contents. The Brampton Fire Department arrived on scene at 3:59 p.m., evacuated everyone within the area, and contained the fire by 4:24 p.m. Brampton firefighters opened one of the fiberboard boxes and determined that a lithium-ion battery was the origin of the fire. According to the FedEx inventory list, there were no other dangerous goods on board the truck.

Braille Battery Design

The batteries that were to be delivered to SpaceMaker were Braille Intensity iM3124D batteries; Braille's specifications for each battery was 24 volts (V), 100 ampere hours (Ah).[7] The design was unique to the specifications provided by SpaceMaker. Each battery consisted of two modules mounted directionally parallel inside a battery case.

Each module consisted of cylindrical cells that were encased in a stainless steel case with a blue polyethylene terephthalate (PET) outer wrap.[8] Braille assembled each module by electrically connecting the cells by spot welded metal tabbing in a configuration of seven cells-in-series, 10 cells-in-parallel. The edges of each module were wrapped with black polyvinylchloride electrical-isolation tape and 2-inch fiber-reinforced clear polypropylene tape. Then, yellow polyamide-imide (heat-reflective) tape was used to cover the sides of the module (edges and positive bus).[9] An exemplar battery module is shown in figure 2.

[7] NTSB investigators performed independent calculations that indicated that the battery was rated 25.2 V, 90 Ah, 2.3 watt hour.

[8] These were 3.6 V, 4.5 Ah, 16.2 watt hour batteries, 26650 Batteries are often characterized by their diameter and length. A 26650 battery cell is about 26 millimeters in diameter and 65 millimeters long.

[9] A *bus* is a metallic strip or bar, typically made of copper, brass, or aluminum, that conducts electricity within an electrical device.

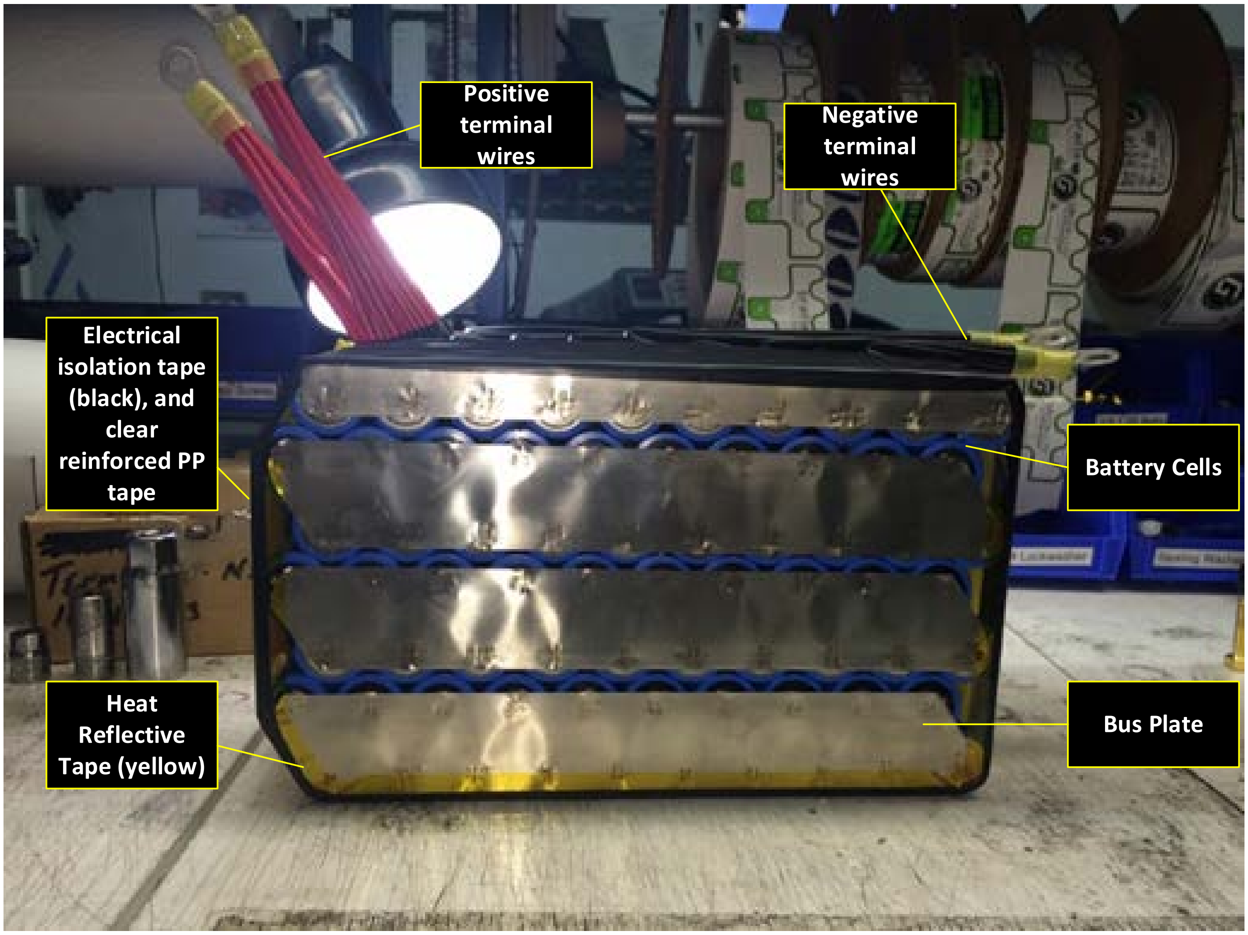

Figure 2. Battery module identical to the one involved in the accident. (Courtesy of FAA.)

The two modules in each battery were placed inside a Battery Council International Group 31 car battery case made of polypropylene, fitted with positive and negative terminal wires connected to the battery modules.[10] The modules were placed within the case with the terminal wires facing the top of the case as shown in figure 3.

[10] *Group 31* designates the specific dimensions and post configuations of a battery, as defined by the Battery Council International.

Figure 3. Exemplar battery modules configuration inside the battery case. (Photograph courtesy of FAA.)

The lid of the case was modified for its intended use. The internal terminal post was located in a premolded opening in the lid. The internal terminal consisted of a 9/16-inch diameter bolt that went through one end of a conductive crossbar with the opposite end of the crossbar connected to the external terminal post located in a modified opening in the lid. (See figures 4 and 5.)

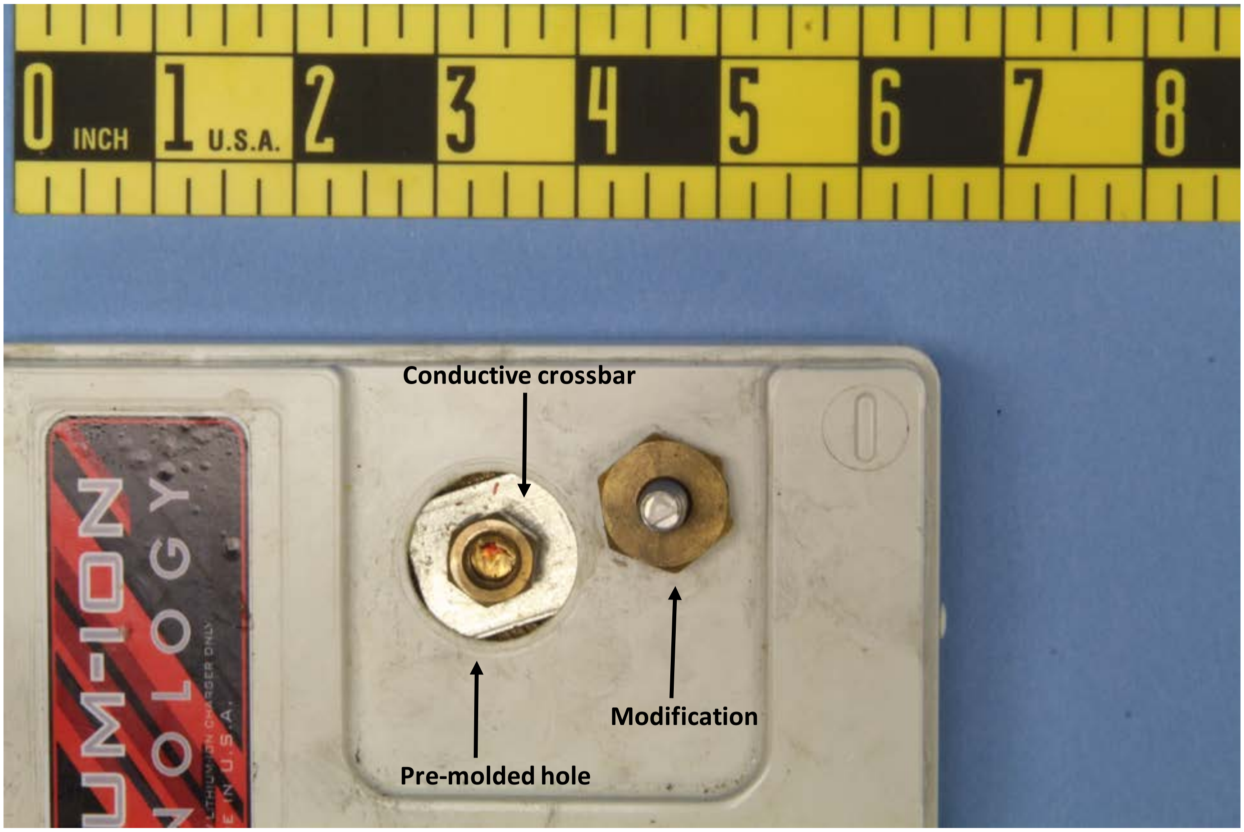

Figure 4. Photograph of modified terminal placement in case lid.

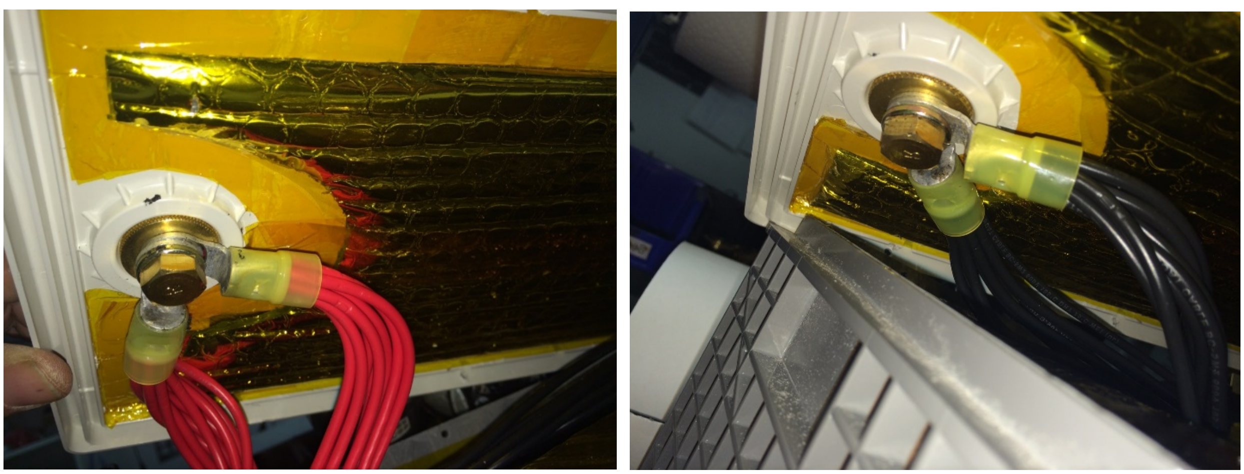

Figure 5. Exemplar positive and negative terminals on Braille battery lid. (Courtesy of FAA.)

Postaccident Examination and Testing

Following the accident, the damage to the batteries was documented and the batteries were labeled sequentially with the battery with the most damage labeled #1. (See figure 6.) The Brampton Fire Department determined battery #1 started the fire; its battery case and lid were destroyed, and the modules and associated hardware separated into individual cells and partial strings of cells. The individual cells and string fragments that were recovered from this battery had heavy-to-moderate sooting on their surfaces and had heavy-to-moderate bulging at the top vents. One of the cell cases exhibited melting consistent with electrical contact. Electrolyte salt residue was present on the surface of several of the cells, suggesting electrolyte vented from these cells. The top vent bulging and presence of electrolyte salt residue was consistent with the cells overheating and going into thermal runaway.[11]

Figure 6. Four Braille batteries involved in the fire.

The outer case for battery #2 separated from the rest of the battery and only the case lid and two battery modules with associated wiring were recovered from the scene. Batteries #3 and #4 were intact; however, their battery case lids exhibited charring and melting. When opened, the modules for batteries #3 and #4 were found loosely packed in the battery cases. After removing the modules from the cases, module #2 showed evidence of electrical arcing from one cell on top of the module, as seen in figure 7. Similar damage was found on the adjacent terminal bolt.

[11] *Thermal runaway* in lithium-ion batteries is a failure mechanism where exothermic decomposition of constituents within the battery cell lead to an uncontrollable rise in temperature and catastrophic failure of the cell possibly resulting in electrolyte release and fire.

Figure 7. Burn patterns observed on the top string showing electrical arcing on one of the modules of battery #2.

Investigators noted deformed and discolored tape layers and missing material from the bus plates on the corners of the intact modules, revealing evidence of rubbing and scraping between the modules and the terminal bolts. The cells within the modules displayed visible evidence of contact between the blue PET cell wrap and the battery terminal bolt on the inside lid of the battery case. Electrolyte salt residues, consistent with electrolyte venting, were present on the top surface of several of the cells.

NTSB determined from its examination and testing that the modules were not secured and could move within the case. Furthermore, the modification made to the lid for the terminal posts did not provide enough clearance between the bolts and the modules. During transport, the shifting modules rubbed against the terminal bolt causing the bolt to tear through the tape layers and the cell wrap, damaging the cell casing, eventually resulting in a localized short circuit.[12] The short circuit caused the damaged cell to go into thermal runaway, producing excessive heat that caused surrounding cells to go into thermal runaway, resulting in a cascading failure of the battery.

[12] A *short circuit* is an electrical circuit that allows current to travel along an unintended path with little or no electrical impedance. A localized short circuit of this type can occur if the exterior conductive case of one or more cells is penetrated by a foreign conductive objective and bridges the positive and negative terminals.

Shipping Regulations

Lithium-ion batteries are classified as Class 9 miscellaneous hazardous materials, one of nine hazard classes that present a hazard during transportation.[13] Title 49 *Code of Federal Regulations* (*CFR*) 173.185 describes the packaging requirements that the batteries must meet for transport.[14] This shipment did not have noncombustible interior packaging. The combustible packaging facilitated the spread of the fire from the box and involved other boxes in the shipment. When shipped internationally by air, US hazardous materials transportation regulations also require lithium-ion batteries to comply with ICAO standards.[15]

ICAO Annex 18 contains standards for transporting dangerous goods (hazardous materials) by air. One of the standards requires hazardous materials be shipped according with ICAO's *Technical Instructions for the Safe Transport of Dangerous Goods by Air* (Technical Instructions).[16] This standard includes provisions for the classification of dangerous goods, circumstances when dangerous goods are forbidden on passenger or cargo aircraft, and hazard communication and packing instructions (PI). Within the Technical Instructions are specific PIs, such as PI 965, which is required for UN 3480 lithium-ion batteries that meet the quantity and capacity limits under the HMR. Braille certified in the shipping declaration that it was packaged in accordance with PI 965.[17] However, the packaging consisted of three foam modules made of polyurethane foam encased in a polyethylene film bag, which is a combustible material that does not comply with PI 965.

PI 965 requires that before transport, lithium-ion batteries be able to pass each test stipulated in the UN *Manual of Tests and Criteria*, Part III, Section 38.3 (UN 38.3).[18] These tests subject the battery or cell to different pressures, vibrations, temperatures, shock, external short circuiting, overcharge or forced discharge, and either impact or crushing force that would lead to internal short circuiting. If a lithium-ion cell or battery assembly fails the tests, the standards require that the battery or cell manufacturer correct the failure before the battery or cell is tested again.

Braille was unable to produce records showing that the battery design was tested in accordance with UN 38.3. The short circuits observed in the batteries following the accident

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[13] Title 49 *CFR* 172.101 lists lithium-ion batteries as a Class 9 hazardous material. The hazard class of a hazardous material is indicated either by its class (or division) number. There are nine different classifications of hazardous materials that are defined in 49 *CFR* 173.140.

[14] Title 49 *CFR* 173.185 (e)(1) also requires cushioning material that is noncombustible for low-production runs and prototype lithium-ion cells and batteries.

[15] Title 49 *CFR* 171.22.

[16] International Civil Aviation Organization, *Technical Instructions for the Safe Transport of Dangerous Goods by Air*, 2015-2016 edition. (Montreal, Quebec, Canada: 2015).

[17] In accordance with 49 *CFR* 172.200, the FAA requires that hazardous materials shipments include a form certifying that the cargo has been packed, labeled, and declared according to international regulations.

[18] UN Economic and Social Council's Subcommittee of Experts on the Transport of Dangerous Goods, *UN Manual of Tests and Criteria*, Fifth revised edition. (New York and Geneva, Switzerland: United Nations, 2009). *UN Manual of Tests and Criteria* is a developed by the United Nations' Economic and Social Council's Subcommittee of Experts on the Transport of Dangerous Goods, of which ICAO is a specialized agency. At the time of the accident, the fifth edition was in effect. A sixth edition has been published and manufacturers and distributors of lithium-ion batteries and cells were required to be in compliance with the revisions by January 2020.

suggested that had an iM3124D-100 battery been subject to the vibration or shock tests stipulated in UN 38.3 tests, it would likely have failed.[19] The vibration test involved firmly securing a battery on a platform of a vibration machine and was repeated multiple times over a span of a few hours. The shock test also involved securing the battery to a test machine and subjecting the battery to a timed frequency of pulse durations through a number of cycles. These tests would likely have created the conditions that caused the battery failure in this accident.

In February 2016, the ICAO Technical Instructions were amended to include a new standard that lithium-ion batteries may only be transported by cargo aircraft at a state of charge (SOC) not exceeding 30 percent of their rated design capacity unless there is an exemption approved by a competent authority.[20] Lithium-ion batteries transported at a reduced SOC pose a lower fire risk, should a cell go into a thermal runaway during transport. These changes went into effect in April 2016, 2 months prior to the accident shipment.

As required by ICAO, Braille tested a random sample of battery modules for all shipments prior to fabrication of the modules and reported an average SOC of 29 percent, which was within the threshold set by the new ICAO Technical Instruction standard.[21] Braille did not retest the SOC of the modules after the large format batteries were fabricated. When the NTSB sent battery #2, module #1 for SOC testing following the accident, testing had to be halted because the module experienced elevated temperatures and anomalous voltage.[22] Though testing results were inconclusive for the overall rated capacity of the module, the measurement of capacity from the discharge cycle found that one of the accident modules had a minimum SOC of 47.7 percent, which exceeded the ICAO threshold.

Testing also revealed that the individual cells within the module distributed electrical charge in such a manner that some of the strings of cells in the module were overcharged, and others had no charge, showing an imbalance of voltage. If one cell short circuited, a cascading effect would occur where the rest of the cells in the string would accept current to maintain overall battery voltage. The healthy cells within a string would accept more current, and charge/discharge faster than the cells' other parallel strings, causing a disparity in cell string voltages. This would lead to eventual overcharge or discharge of the whole battery, which would then overheat, resulting

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[19] (a) Short circuit and voltage disparities were observed during postaccident testing. Discussion on these observations can be found in the safety recommendation report associated with this investigation, *Standards for Lithium-Ion Battery Shipments by Air* HZMSR-20/01.

[20] (a) *State of charge measurement* is most commonly performed by one of three methods: open circuit voltage method; electrochemical impedance spectroscopy method; and charge/discharge cycling with coulomb counting method. There are no industry-standard protocols for measuring SOC, nor are testing variations, reproducibility, and repeatability aspects established. (b) International Civil Aviation Organization, *Supplement to the Technical Instructions for the Safe Transport of Dangerous Goods by Air*, 2015-2016 edition. (Montreal, Quebec, Canada: 2016). (c) According to 49 *CFR* 107.1, a *competent authority* is a national agency that is responsible, under its national law, for the control or regulation of some aspect of hazardous materials (dangerous goods) transportation. (d) The competent authority can grant an exemption but did not in this case.

[21] Braille's SOC evaluation data listed a test sample of 600 Shandong Goldencell lithium-ion cells that were charged to 4.15 V (1.5A, C/3 rate) and discharged to 2.75V (1.5A, C/3 rate).

[22] These tests were performed at the Carderock Division of the Navel Surface Warfare Center in Montgomery County, Maryland, at the request of the NTSB.

in a thermal runaway event. The battery was not outfitted with a battery management system which could have prevented an imbalance in cell voltages between parallel strings.

Special Provisions for Lithium-Ion Battery Shipments by Air

The batteries manufactured by Braille may have qualified under a special provision in the ICAO standards that would have allowed the company to ship the batteries without UN 38.3 testing because they met the criteria as low-production and prototype batteries.[23] To qualify for this special provision, a shipper must seek an approval under a competent authority of the state of origin. Braille did not apply for this approval. During this investigation, the NTSB examined the special provision to shipping standards for prototype or low-production lithium-ion batteries. This resulted in two safety recommendations being issued to the Pipeline and Hazardous Materials Safety Administration to remove special provisions.[24]

Postaccident Actions

On December 8, 2017, the FAA proposed a $1.1 million civil penalty against Braille for the shipment of the lithium-ion batteries involved in the June 3, 2016, accident, as well as other illegal shipments of lithium-ion batteries by air.[25] The company was cited for the following violations:

- not meeting the testing standards under the UN *Manual of Tests and Criteria* Part III, Section 38.3 or the DOT's Hazardous Materials Regulations (49 *CFR* 173.185(a)(1));
- not equipping its batteries with a means to prevent dangerous reverse current flow (49 *CFR* 173.185(a)(3)(iii));
- not packaging the batteries for shipment to prevent sparks or generate heat (49 *CFR* 173.21(c));[26]
- not providing its employees with required hazardous materials transportation training (49 *CFR* 172.702 (a));

[23] According to ICAO *Technical Instructions*, A3-1-28, US Variation 3, when shipping prototype lithium batteries and cells in accordance with Special Provision A88 to the United States, the shipper must also seek approval from the appropriate US authority.

[24] Safety Recommendations A-20-31 and -32.

[25] (a) The penalty amount was later reduced to $235,000, which Braille is required to pay by September 2021. (b) Federal Aviation Administration, "FAA Proposes $1.1 Million Civil Penalty Against Braille Battery Inc. For Alleged HazMat Violations," news release, December 8, 2017. https://www.faa.gov/news/press_releases/news_story.cfm?newsId=22374&omniRss=press_releasesAoc&cid=102_P_R, accessed January 6, 2020.

[26] The FAA citation refers to Braille's failure to secure the battery to prevent it from generating sparks and heat. The module was not secure, which allowed contact between the bolt and the cell, which led to the short circuit. There is no packaging that would have stopped or slowed down this fire. For more information on this regulation, see the interpretation letter on this regulation that was issued in 2003 by the Research and Special Programs Administration, the predecessor to the Pipeline and Hazardous Materials Safety Administration.

- not following the DOT's Hazardous Materials Regulations or acquiring the necessary exemption under an approval or special permit (49 *CFR* 171.2(b)).[27]

In addition, the FAA prohibited Braille from shipping lithium batteries by air for 2 years, issuing an Emergency Prohibition/Restriction Order in September 2016.[28] The FAA rescinded the order in July 2018 after the agency determined Braille was complying with DOT regulations. Braille posted the UN testing documentation for its lithium-ion batteries on its website.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the fire on a FedEx delivery truck in Brampton, Ontario, Canada, on June 3, 2016, was an electrical short circuit between the battery terminal bolt and the upper cells of the lithium-ion battery module, causing a thermal runaway within the battery, igniting the battery and its packaging. Contributing to the electrical short circuit was Braille Battery, Inc.'s design that did not protect against short circuiting. Also contributing to the consequences of the accident was Braille Battery, Inc.'s use of combustible packing materials.

For more details about this accident, visit www.ntsb.gov/investigations/dms.html and search for NTSB accident identification number DCA16SH001.

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[27] *Federal Register* 81, no. 188 (September 28, 2016): 66713.

[28] For more information, see the FAA announcement on the issuance of the 2016 Emergency Prohibition/Restriction Order.

The NTSB has authority to investigate and establish the facts, circumstances, and cause or probable cause of a pipeline accident in which there is a fatality or substantial property damage, or significant injury to the environment. (49 U.S. Code, Section 1131 - *General authority*)

The NTSB does not assign fault or blame for an accident or incident: rather, as specified by NTSB regulation, “accident/incident investigations are fact-finding proceedings with no formal issues and no adverse parties…and are not conducted for the purpose of determining the rights or liabilities of any person.” Title 49 *Code of Federal Regulations*, Section 831.4. Assignment of fault or legal liability is not relevant to the NTSB’s statutory mission to improve transportation safety by investigating accidents and incidents and issuing safety recommendations. In addition, statutory language prohibits the admission into evidence or use of any part of an NTSB report related to an accident in a civil action for damages resulting from a matter mentioned in the report. 49 U.S. Code, Section 1154(b).