# National Transportation Safety Board

Washington, DC 20594

## Safety Recommendation

**Date:** May 22, 2014

**In reply refer to:** A-14-032 through -036

The Honorable Michael P. Huerta
Administrator
Federal Aviation Administration
Washington, DC 20591

We are providing the following information to urge the Federal Aviation Administration (FAA) to take action on the safety recommendations issued in this letter. These recommendations address certification testing of lithium-ion batteries to be used on commercial airplanes and the certification of new technology. The recommendations are derived from the National Transportation Safety Board's (NTSB) ongoing investigation of the January 7, 2013, battery event aboard a Boeing 787 in Boston, Massachusetts. As a result of this investigation, the NTSB has issued five recommendations, all of which are addressed to the FAA. Information supporting these recommendations is discussed below.

**Background**

On January 7, 2013, smoke was discovered by cleaning personnel in the aft cabin of a Japan Airlines Boeing 787-8, JA829J, which was parked at a gate at General Edward Lawrence Logan International Airport, Boston, Massachusetts. About the same time, a maintenance manager in the cockpit observed that the auxiliary power unit (APU)—the sole source of airplane power at the time—had automatically shut down. Shortly afterward, a mechanic opened the aft electronic equipment (E/E) bay and found "heavy smoke" and a "small flame" coming from the APU battery case.[1] No passengers or crewmembers were aboard the airplane at the time, and none of the maintenance or cleaning personnel aboard the airplane was injured.

Although this incident is still under investigation, the NTSB's preliminary findings indicated that one of the eight APU lithium-ion battery cells had experienced an uncontrollable increase in temperature and pressure (known as a thermal runaway) as a result of an internal

[1] The mechanic reported that he saw "heavy smoke in the [E/E] compartment" and a "small flame around APU batt[ery]." He estimated the flame size to be "about 3 inch[es]."

short circuit.[2] The single-cell failure propagated to adjacent cells, resulting in the cascading thermal runaway of several cells and the release of additional smoke and flammable electrolyte from the battery case.[3] This type of failure was not expected based on the testing and analysis of the APU battery system that Boeing performed as part of the 787 certification program.

The APU battery model is also used for the 787 main battery. On January 16, 2013, an incident involving the main battery occurred aboard a 787 airplane operated by All Nippon Airways during a flight from Yamaguchi to Tokyo, Japan. The airplane made an emergency landing in Takamatsu, Japan, shortly after takeoff. No injuries were reported. The Japan Transport Safety Board (JTSB) is investigating this incident with support from the NTSB. [4]

**Certification Requirements**

In September 2004, Boeing met with representatives of the FAA's aircraft certification office in Seattle, Washington, to indicate the company's intent to install lithium-ion technology for the main and APU batteries on the 787 airplane. In response, the FAA reviewed the adequacy of the existing regulations governing the installation of batteries in large transport-category airplanes and determined that the regulations did not sufficiently address several failure, operational, and maintenance characteristics of lithium-ion batteries that could affect the safety of the battery installations.[5] As a result, the FAA issued Special Conditions 25-359-SC, "Boeing Model 787-8 Airplane; Lithium-Ion Battery Installation," which detailed nine specific requirements regarding the use of these batteries on the 787.[6] The intent of these special conditions was to establish additional safety standards that the FAA considered necessary to provide a level of safety that was equivalent to the existing standards for aircraft batteries.

Special condition 2 of 25-359-SC stated, "design of the lithium-ion batteries must preclude the occurrence of self-sustaining, uncontrolled increases in temperature or pressure." During the NTSB's April 2013 investigative hearing on the Boston battery incident, Boeing and FAA representatives testified that only those failure conditions resulting in cell venting with smoke and fire were considered relevant to special condition 2. The Boeing and FAA representatives also testified that, at the time of the 787 certification, they believed that an uncontrolled increase in temperature or pressure could only occur if a cell or a battery were

[2] The APU battery consists of eight individual lithium-ion cells that are connected in series and assembled in two rows of four cells. The cells are based on a lithium cobalt-oxide compound technology and contain electrolyte liquid. The cause of the internal short circuit is currently under investigation.

[3] Evidence of the electrolyte fluid (in the form of residue and thermal damage) was seen within areas located about 20 inches from the APU battery installation. No primary structures (that is, those associated with airplane flight loads) were found damaged; secondary structures—specifically, the avionics rack and the floor panel—exhibited thermal damage near the location where the APU battery had been installed.

[4] The JTSB described this battery event as a "serious incident." For information about this investigation, see the JTSB's website, which can be accessed at http://www.mlit.go.jp/jtsb/english.html. The JTSB is also assisting the NTSB with its investigation of the Boston battery incident.

[5] The battery regulations that existed at the time were found in 14 *Code of Federal Regulations* (CFR) 25.1353, "Electrical Equipment and Installations," paragraphs (c)(1) through (4).

[6] The final special conditions for the 787 lithium-ion battery installation (72 *Federal Register* 57842, October 11, 2007) became effective on November 13, 2007.

overcharged. The NTSB's investigation has not found any evidence to date to indicate that the Boston incident battery was overcharged.

**Development Testing Results**

Boeing determined that an internal short circuit in a single cell that resulted in thermal runaway would not propagate to other cells within the battery. This determination was based in part on the results of development (noncertification) testing performed in November 2006 by GS Yuasa Corporation of Kyoto, Japan, which developed, designed, and manufactured the battery.[7] This testing involved driving a steel nail through a cell case to penetrate the electrodes of a fully charged single cell within a fully charged, nongrounded, preproduction battery to induce an internal short circuit within the cell.[8] The purpose of the test, which was conducted at a temperature representative of the E/E bay operating temperature during a typical flight, was to observe the behavior of the cells near the nail-penetrated cell, observe any release of smoke or initiation of fire, and document any damage to the battery case.[9]

The nail penetration test results showed that the surface temperature of the nail-penetrated cell increased, smoke vented from the cell and the battery case, and the surface temperature of the adjacent cells increased with no venting. On the basis of this development test and field reliability data of a similar cell designed and manufactured by GS Yuasa, Boeing determined that the effects of cell internal short circuiting would be limited to (1) the release of smoke from the battery, which could be effectively handled by the airplane's ventilation system, and (2) an increase in surface temperature of the short-circuited cell with no propagation of thermal runaway to adjacent cells, damage to the battery case, fire, or explosion. As a result, the 787 electrical power system (EPS) certification plan proposed by Boeing and approved by the FAA did not include a cell internal short circuit abuse test because it was not required for demonstrating compliance with special condition 2.[10]

**Accounting for Internal Short Circuits and Thermal Runaway in Certification Tests**

An FAA issue paper, dated March 2006, included Boeing's statement that the certification tests planned for the 787 main and APU batteries would substantiate that the battery

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[7] Boeing had collaborated with GS Yuasa and Thales Avionics Electrical Systems of France about the development tests to be performed on cells and batteries. (Thales designed the equipment for the 787 electrical power conversion subsystem, which includes the main and APU battery systems and is part of the 787 electrical power system.) Results from this testing helped Boeing determine what types of abuse (thermal, physical, and/or electrical) certification testing and/or safety analyses needed to be performed to show compliance with the applicable battery regulations, including the special conditions. The development tests were not required by the FAA.

[8] The test battery was considered to be in a "floating" ground state because its case was not electrically grounded. The battery case, when installed in the airplane, is grounded via the 787 common return network.

[9] APU battery temperature was not recorded on the incident flight recorder. However, after the incident, Boeing monitored E/E bay temperatures during several flights and reported average values of 10ºC to 15ºC (50ºF to 59ºF) during a typical flight.

[10] A cell internal short circuit abuse test simulates the most severe effects of internal short circuiting by triggering thermal runaway of a cell (or cells) within the battery to evaluate the potential for propagation to other cells and resulting hazardous effects, such as smoke, excessive heat, release of flammable electrolyte, fire, and/or explosion.

design would remove the possibility of internal short circuit failures.[11] In its design safety assessment for certification, Boeing considered the potential for smoke generation as a result of the internal short circuit failure mode. However, Boeing underestimated the more serious effects of an internal short circuit, that is, thermal runaway of other cells within the battery, excessive heat, flammable electrolyte release, and fire.[12] The 787 EPS certification plan proposed by Boeing, which, as previously stated, did not include a cell internal short circuit abuse test, was approved by the FAA in January 2007.

Lithium-ion batteries in service at that time in other applications (including cellular telephones and personal computers) were exhibiting susceptibility to internal short circuiting with effects such as excessive heating or an explosion.[13] Such failures were generally attributed to manufacturing or design deficiencies or exposure of the cell or battery to abuse conditions.[14] In addition, in December 2007, the NTSB issued safety recommendations addressing the hazards of transporting lithium batteries as a result of its investigation of an in-flight cargo fire aboard a United Parcel Service DC-8 airplane.[15]

Experts in lithium-ion technology have indicated that the conditions within a cell that lead to an internal short circuit can progress over time while the battery is in use and that these conditions are not readily detectable until an internal short circuit occurs.[16] Depending on its effects, an internal short circuit might not be detected and managed by a battery monitoring system in sufficient time to stop the thermal runaway of a cell and subsequent adjacent cells. For example, between the date that the Boston incident airplane was delivered new to the operator (December 20, 2012) and the date of the incident (January 7, 2013), there were no abnormal indications or maintenance messages related to issues with the incident battery.[17] As a result, it is important for manufacturers to demonstrate, as part of certification testing, that a battery's design can effectively mitigate the most severe effects of an internal short circuit because the failure conditions that lead to an internal short circuit may not be apparent.

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[11] Federal Aviation Administration Issue Paper SE-9, "Special Condition: Lithium-Ion Battery Installations," March 31, 2006.

[12] In April 2013, the NTSB held a forum on lithium-ion batteries in transportation. The forum included panelists from the US military, civilian government agencies, academia, and the transportation industry who discussed the safety risks of internal short circuits in lithium-ion batteries. The presentations from this forum can be found on the NTSB's website, which can be accessed at http://www.ntsb.gov. Information from two of the presenters is discussed in this section of the letter.

[13] S. Tobishima, "Secondary Batteries – Lithium Rechargeable Systems – Lithium-Ion: Thermal Runaway," *Encyclopedia of Electrochemical Power Sources*, Amsterdam: Elsevier, 2009, pages 409-417.

[14] For more information, see J. Lamb and C.J. Orendorff, "Evaluation of Mechanical Abuse Techniques in Lithium Ion Batteries," *Journal of Power Sources*, vol. 247, 2014, pages 189-196.

[15] For more information, see *Inflight Cargo Fire, United Parcel Service Company Flight 1307, McDonnell Douglas DC-8-71F, N748UP, Philadelphia, Pennsylvania, February 7, 2006*, Aircraft Accident Report NTSB/AAR-07/07 (Washington, DC: NTSB, 2007), which can be accessed at the NTSB's website.

[16] J. Lamb and C.J. Orendorff, "Evaluation of Mechanical Abuse Techniques in Lithium Ion Batteries." M. Keyser, D. Long, Y.S. Jung, A. Pesaran, E. Darcy, B. McCarthy, L. Patrick, and C. Kruger, "Development of a Novel Test Method for On-Demand Internal Short Circuit in a Li-Ion Cell," Presented at the Large Lithium Ion Battery Technology and Application Symposium, Advanced Automotive Battery Conference, Pasadena, California, January 2011. B. Barnett, D. Ofer, S. Sriramulu, and R. Stringfellow, "Lithium-Ion Batteries, Safety," *Encyclopedia of Sustainability Science and Technology,* New York: Springer, 2012, pages 6097-6122.

[17] During this time period, the airplane had logged 169 flight hours and 22 flight cycles.

It appears that the most severe effects of a cell internal short circuit were not demonstrated during GS Yuasa's 2006 lithium-ion battery development testing for a number of possible reasons, one of which is that the test setup did not include mechanical and electrical interfaces between the battery and the airplane system.[18] Thus, the test setup did not fully represent the battery installation on the airplane.

A postincident inspection of the Boston battery found evidence that electrical arcing between a cell case and the battery case had occurred at some point during the failure sequence.[19] There was also evidence of excessive current flow in the ground wire connecting the battery case to the airplane grounding point and in the shielded signal wires in the connector between the battery and the battery charger unit. This damage showed that a number of unintended electrical interactions occurred among the cells, the battery case, and the electrical interfaces between the battery and the airplane, likely after the initiation of thermal runaway in the first cell, which might have contributed to the propagation of thermal runaway to the other cells.

The NTSB conducted testing in March 2014 to understand the effects of temperature and installation configuration on the 787 battery's response to a simulated short circuit (via nail penetration) within a single cell.[20] In one test, the battery was electrically grounded using a single ground wire that was representative of the ground wire installed on the 787 airplane.[21] The battery temperature at the beginning of this test was between 11ºC and 14ºC (about 52ºF to 57ºF), which was consistent with measured temperatures in the E/E bay during a typical flight. In another test, the battery was not electrically grounded (similar to the test setup used by GS Yuasa in its 2006 battery development test), but the test was conducted at the battery's maximum operating temperature of 70ºC/158ºF.[22]

The test with the electrically grounded battery showed that when a short circuit was induced into a single cell inside the battery, thermal runaway occurred, resulting in cell swelling and venting of the nail-penetrated cell. None of the other cells in the battery underwent thermal runaway or vented. This test also showed that the initiating cell and other cells within the battery case began to electrically discharge at an uncontrolled rate, causing a high electrical current to

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[18] Integration of the battery into the 787 EPS involved connection of the battery to other system elements and airplane interfaces, including the battery charger unit, the electrical power bus, the electrical grounding point, and the physical mounting structure in the E/E bay. Design requirements were established for this integrated system and each system component, including the battery. Various development and certification tests were conducted by GS Yuasa, Thales, and Boeing to verify that the requirements could meet design, performance, and safety objectives. GS Yuasa's testing was conducted only at the battery level.

[19] The battery case exhibited a 0.25-inch-wide nodular protrusion that extended about 0.12 inch from the case. The protrusion was inspected using a scanning electron microscope and energy dispersive x-ray spectroscopy. The inspections determined that arc damage occurred from contact between the battery case and a cell case that was adjacent to the protrusion. For more information, see the March 2013 interim factual report for this incident on the NTSB's website.

[20] This testing was conducted at Underwriters Laboratories' facility in Northbrook, Illinois.

[21] The battery test setup did not include all electrical ground paths to the battery case as installed on the airplane (that is, the ground wire, shielded signal wires, and a physical connection between the battery case mounting rails and ground).

[22] A joint Thales and GS Yuasa document describing the thermal environment for the battery indicated that its operating temperature range was -18ºC to 70ºC (-0.4ºF to 158ºF).

discharge through the ground wire circuit.[23] Within 30 seconds of the initiation of cell venting of the nail-penetrated cell, the ground wire fused open, and the current flow through the grounding path ceased. The post-test inspection of the battery found signs of arcing between the nail-penetrated cell and the battery case, including welding of the cell case to the battery case.

The test with the ungrounded battery showed that thermal runaway of a single cell propagated to all other cells inside the battery case. This result (propagation to and venting of all cells) differed from the result of GS Yuasa's battery development test (venting of the nail-penetrated cell and no propagation to and venting of other cells), but the NTSB notes that GS Yuasa's battery test was performed at a temperature that did not reflect the battery's maximum operating temperature under normal conditions. The post-test inspection of the battery used for this NTSB test found no signs of arcing between the nail-penetrated cell (or other vented cells) and the battery case.

A presenter at the NTSB's forum on lithium-ion batteries in transportation stated that a cell internal short circuit is a critical safety concern and that the risk of propagation from a single-cell failure increases at higher temperatures.[24] Another presenter at the NTSB's forum stated that internal short circuits are one of the causes of catastrophic failures in lithium-ion batteries. She also stated that cell-level safety controls to mitigate the effects of lithium-ion battery failure modes do not necessarily translate to battery-level safety controls for this purpose. As a result, lithium-ion battery safety controls need to be verified by testing at the appropriate level and in the relevant environment.[25]

The Boston 787 battery incident demonstrated that thermal runaway of a single cell could propagate to other cells at a temperature consistent with that in the E/E bay during a typical flight, which is below the battery's maximum operating temperature. The incident battery also exhibited damage consistent with electrical arcing between a cell case and the battery case. Neither of the NTSB's tests nor GS Yuasa's battery development test had completely repeated the damage found in the Boston incident battery, but each NTSB test replicated one aspect of the documented battery damage. Specifically, the 70ºC/158ºF test repeated the propagation of thermal runaway to all cells within the battery, and the grounded battery test repeated electrical arcing damage sufficient to melt the battery case material. Thus, the NTSB's tests indicated that the damage to the battery that resulted when a single cell underwent thermal runaway varied and that design and environmental factors, such as installation interfaces and/or ambient temperature conditions to which the battery was exposed, could affect test results.

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[23] The incident battery ground wire was found intact with the wire insulation exhibiting an undamaged exterior surface but a slightly blackened interior surface, which was consistent with resistance heating associated with the flow of high levels of electrical current. The shielded signal wires also exhibited signs of internal heating that were consistent with resistance heating by high levels of electrical current. For more information, see the NTSB's interim factual report for this incident.

[24] Daniel H. Doughty, *Failure Mechanisms of Lithium-Ion Batteries*. Presented at the Lithium Ion Batteries in Transportation Forum, National Transportation Safety Board, April 2013. The presenter is the president of a battery safety consulting firm in Albuquerque, New Mexico.

[25] Judith Jeevarajan, *End-User Acceptance: Requirements or Specifications, Certification, & Testing*. Presented at the Lithium Ion Batteries in Transportation Forum, National Transportation Safety Board, April 2013. The presenter is the group lead for battery safety and advanced technology at the National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas.

Although the NTSB's tests were not exhaustive regarding all aspects of the battery design, use, and approved operating conditions, the test results indicated that, to fully understand the most severe effects that could occur when a single cell within a lithium-ion battery undergoes thermal runaway, various factors expected during normal operations need to be included in aircraft certification tests. In particular, it is important to ensure that installation, environmental, and usage factors are fully accounted for in abuse tests intended to demonstrate the most severe effects of an internal short circuit-induced thermal runaway. The current standard for lithium-ion battery design and safety certification in aviation applications, RTCA document DO-311, "Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems," includes abuse testing, but the document does not address all of the unique aspects of a battery's installation on an aircraft.[26] Thus, aircraft manufacturers need to evaluate whether additional requirements and testing are necessary to ensure aircraft-level safety.

The NTSB concludes that aircraft certification tests that induce thermal runaway of a cell in a lithium-ion battery configured as installed on the aircraft would better demonstrate to the FAA that the battery installation could effectively mitigate the potential safety effects of an internal short circuit. As a result, the NTSB recommends that the FAA develop abuse tests that subject a single cell within a permanently installed, rechargeable lithium-ion battery to thermal runaway and demonstrate that the battery installation mitigates all hazardous effects of propagation to other cells and the release of electrolyte, fire, or explosive debris outside the battery case. The tests should replicate the battery installation on the aircraft and be conducted under conditions that produce the most severe outcome. The NTSB also recommends that, after Safety Recommendation A-14-032 has been completed, the FAA require aircraft manufacturers to perform the tests and demonstrate acceptable performance as part of the certification of any new aircraft design that incorporates a permanently installed, rechargeable lithium-ion battery.

Although the NTSB believes that tests to induce thermal runaway of a cell are necessary to verify that a battery's design adequately mitigates the potential threats (to the aircraft and its occupants) of internal short circuiting, the NTSB is concerned about the reliability and repeatability of such tests. According to government and industry experts in lithium-ion battery technology, the test method used to induce thermal runaway (such as nail penetration or hot pad), the type of short induced, and the cell and battery design could all significantly impact test results such that the most severe effects of internal short circuiting would not be fully evaluated during certification.[27] According to a National Renewable Energy Laboratory report, "an internal short hazard is one of the most difficult to reproduce, yet it is the most important to solve to

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[26] In 2006 the FAA chartered a federal advisory committee, known as RTCA Special Committee SC-211, to develop a standard for the design, certification, production, and use of permanently installed, rechargeable lithium-ion battery systems. The committee included representatives from the FAA, US Air Force, US Navy, US Army, commercial air carriers, and battery and aircraft manufacturers. Boeing, Thales, and GS Yuasa were also members of the RTCA special committee. The resulting standard, DO-311, which was issued in 2008, is currently considered by the FAA to be an acceptable means of compliance to the special conditions for rechargeable lithium-ion batteries and battery systems.

[27] For more information, see David Howell, *U.S. DOE Perspective on Lithium-Ion Battery Safety*. Presented at Technical Symposium: Safety Considerations for EVs Powered by Li-Ion Batteries, National Highway Traffic Safety Administration, May 2011. Also see Premanand Ramadass, Weifeng Fang, and Zhengming (John) Zhang, "Study of Internal Short in a Li-ion Cell I. Test Method Development Using Infra-red Imaging Technique," *Journal of Power Sources*, vol. 248, 2014, pages 769-776.

improve safety."[28] Researchers have found that current test methods might not reliably produce failure effects as severe as those observed in actual field failures involving internal short circuiting and that, as a result, a consensus for how best to simulate this critical failure mode is needed.[29]

The NTSB conducted additional testing in March 2014 to understand and compare the energy level of a thermal runaway in response to three different methods of simulating an internal short circuit within a single cell from a 787 battery assembly. During the testing, thermal runaway of each cell was initiated using the indentation, nail penetration, or hot pad methods to simulate a short circuit, and temperatures were measured at various locations on the cell cases.[30] Preliminary test results indicated that, immediately after inducing the short circuit, (1) the maximum temperature at a common location on the cell cases ranged from about 240ºC to 375ºC (about 464ºF to 707ºF), (2) depending on the method used, the cell case temperature at various locations differed by as much as about 270ºC/518ºF, and (3) the hot pad method resulted in the highest temperatures measured.

Although various other factors, such as cell age, were not evaluated during this testing, the preliminary test results were consistent with the observations of industry experts who indicated that the method used to simulate a cell internal short circuit in a thermal runaway abuse test could have a significant impact on the resulting thermal energy released.[31] Thus, the method used to initiate thermal runaway as part of an internal short circuit abuse test could also influence how the thermal runaway condition could affect other cells within a battery.

Significant ongoing research about the causes and types of internal short circuiting in lithium-ion batteries and potential test evaluation methods to simulate worst-case effects is currently being conducted by experts within the US military, civilian federal agencies, US national laboratories, and test standards development organizations.[32] Maintaining awareness of this evolving body of knowledge could help the FAA determine the most reliable ways to simulate an internal short circuit in a lithium-ion battery and ensure that manufacturers have the guidance needed to address related aircraft-level safety hazards during certification.

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[28] Daniel H. Doughty, *Vehicle Battery Safety Roadmap Guidance*, Department of Energy, National Renewable Energy Laboratory, NREL Report No. SR-5400-54404 (Golden, Colorado: NREL, 2012). This report, which addressed lithium-ion battery safety in electric vehicles, noted that development of an internal short circuit test is an important objective that is being explored by several laboratories but that "no one test has gained acceptance by industry or test organizations."

[29] J. Lamb and C.J. Orendorff, "Evaluation of Mechanical Abuse Techniques in Lithium Ion Batteries." Daniel H. Doughty, *Vehicle Battery Safety Roadmap Guidance*. L. Florence, H.P. Jones, and A. Liang, *Safety Issues for Lithium-Ion Batteries*, Underwriters Laboratories, 2010.

[30] This testing was performed at Underwriters Laboratories' facility in Taipei, Taiwan.

[31] David Howell, *U.S. DOE Perspective on Lithium-Ion Battery Safety*. Premanand Ramadass, Weifeng Fang, and Zhengming (John) Zhang, "Study of Internal Short in a Li-ion Cell I. Test Method Development Using Infra-red Imaging Technique."

[32] J. Lamb and C.J. Orendorff, "Evaluation of Mechanical Abuse Techniques in Lithium Ion Batteries." M. Keyser et al., "Development of a Novel Test Method for On-Demand Internal Short Circuit in a Li-Ion Cell." Daniel H. Doughty, *Vehicle Battery Safety Roadmap Guidance*. Alvin Wu, Mahmood Tabaddor, and Carl Wang, *Test Methods for Simulating Internal Short Circuits in Lithium Ion Cells,* Presented at the Seventh Triennial International Fire and Cabin Safety Research Conference, December 2013.

The NTSB concludes that an evaluation of various methods to replicate internal short circuiting within a lithium-ion cell could help manufacturers determine whether they are using appropriate test methods to demonstrate the most severe effects that could result at the cell, battery, and aircraft levels given the battery's unique design and installation. Guidance on test protocols and methods that reliably simulate the most severe effects of internal short circuiting in lithium-ion batteries could help ensure that this failure mode is properly assessed as part of aircraft certification. As a result, the NTSB recommends that the FAA work with lithium-ion battery technology experts from government and test standards organizations, including US national laboratories, to develop guidance on acceptable methods to induce thermal runaway that most reliably simulate cell internal short-circuiting hazards at the cell, battery, and aircraft levels.

## In-Service Lithium-Ion Batteries

According to the FAA's March 2006 issue paper, the Boeing 787-8 airplane was the first large transport-category airplane to use permanently installed lithium-ion main and APU batteries.[33] The 787 also incorporated lithium-ion batteries in the airplane's flight control electronics, the emergency lighting system, and the recorder-independent power supply. Other airplane designs, including the Boeing 777-200/300/300ER and 737NG and the Airbus A380, have incorporated permanently installed lithium-ion batteries. Each of these airplane designs was required to comply with the same special conditions applied to the 787 certification. However, the methods used to show compliance with the special conditions in each of those programs were uniquely established with agreement between the applicant and the FAA to address the features, installation, and operating environment of each specific battery application.

Given the absence of a standardized certification test to evaluate a battery's response to a cell thermal runaway as installed on an aircraft, the NTSB concludes that the methods of compliance used to certify in-service lithium-ion batteries might not have adequately accounted for the hazards that could result from internal short circuiting. As a result, the NTSB recommends that the FAA review the methods of compliance used to certify permanently installed, rechargeable lithium-ion batteries on in-service aircraft and require additional testing, if needed, to ensure that the battery design and installation adequately protects against all adverse effects of a cell thermal runaway.

## Introduction of New Technology Into Aircraft

Although lithium-ion batteries have been used in non-aviation applications for more than a decade, the high-power nature of the 787 main and APU lithium-ion batteries represented new technology for use in commercial airplanes. New, first-of-a-kind technology can offer substantial improvements in operational efficiency, capabilities, and/or safety, and its safe introduction into the aviation system is a key objective of the aircraft certification process.

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[33] An article in an SAE International journal stated that the Cessna Citation J4, which was certified on March 10, 2010, was believed to be the first civil airplane certificated with a lithium-ion main battery. The 787-8 received transport-category approval on August 26, 2011. For more information about the SAE article, see Vernon W. Chang, Steven B. Waggoner, and John W. Gallman, "System Integration of a Safe, High Power, Lithium Ion Main Battery into a Civil Aviation Aircraft," *SAE International Journal of Aerospace*, vol. 3, no. 1, 2010, pages 149-158.

Although the 787 battery special conditions were developed with input from various FAA technical staff members and in consultation with members of the RTCA SC-211 committee, FAA certification staff members relied primarily on Boeing's expertise and knowledge to define the necessary tests and analyses for certification of the main and APU battery design. The NTSB recognizes that reliance on a manufacturer's expertise is a necessary part of the FAA's aircraft certification process and that this process has historically been an effective component for ensuring safety.[34] However, expertise outside the aviation industry during a certification program involving new technology could further strengthen the aircraft certification process by ensuring that both the FAA and the manufacturer are kept up to date about the most current research and information related to the technology, which could be rapidly expanding in other industries during the course of an aircraft certification program (which can typically last 5 or more years).[35]

As early as 2000, researchers supporting Department of Energy programs dedicated to the development of large-scale lithium-ion batteries for automotive applications had determined through testing that internal short circuiting could result in thermal runaway of a cell and the potential for propagation to other cells within the battery. The researchers had also determined that thermal runaway from internal short circuiting could result in venting with smoke and fire for a number of different cell and battery designs.[36] If the FAA had reached out to these or other experts working on large-scale lithium-ion batteries to tap into their knowledge, it is possible that the FAA could have recognized that the 787 methods of compliance were insufficient to appropriately evaluate the risks associated with cell internal short circuiting and that an internal short circuit test was needed as part of certification.

The nature of the aircraft certification process requires manufacturers to "lock down" designs early in the program because of the multiyear timeframe needed to complete the testing and evaluation required to demonstrate regulatory compliance. As a result, it is difficult for manufacturers to incorporate new information into the aircraft design as the certification program progresses. Incorporating new information becomes even more difficult once the aircraft design goes into service because design changes can require extensive recertification activity. As a result, the involvement of outside experts as early as possible in a certification program could be the most efficient way to help ensure the operational safety of a new technology.

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[34] In 2006, the NTSB found that the FAA's type certification process was sound and produced a high level of safety but that improvements were warranted because "existing policy, practices, and procedures for the ongoing assessment of risks…do not ensure that the underlying assumptions made during design and certification are adequately and continuously assessed in light of operational experience, lessons learned, and new knowledge." For more information, see *Safety Report on the Treatment of Safety-Critical Systems in Transport Airplanes*, Safety Report NTSB/SR-06/02 (Washington, DC: NTSB, 2006), which can be found on the NTSB's website.

[35] Title 14 CFR 21.17, "Designation of Applicable Regulations," states, "an application for type certification of a transport category aircraft is effective for 5 years…unless an applicant shows at the time of application that product requires a longer period of time for design, development, and testing, and the FAA approves a longer period."

[36] This work was performed as part of the Partnership for a New Generation of Vehicles (PNGV), a research collaboration involving the federal government and the US automotive industry. The PNGV partners, which included seven federal agencies, 19 federal laboratories, and a consortium representing three car manufacturers, researched different subject areas for building a hybrid electric car. For example, Sandia National Laboratories focused on energy storage (batteries and their safety).

The NTSB concludes that technical knowledge imparted by independent and neutral experts outside of the FAA and an aircraft manufacturer could provide the agency with valuable insights about best practices and test protocols for validating system and equipment safety performance during certification when new technology is incorporated. As a result, the NTSB recommends that the FAA develop a policy to establish, when practicable, a panel of independent technical experts to advise on methods of compliance and best practices for certifying the safety of new technology to be used on new or existing aircraft. The panel should be established as early as possible in the certification program to ensure that the most current research and information related to the technology could be incorporated during the program.

Therefore, the National Transportation Safety Board makes the following recommendations to the Federal Aviation Administration:

> Develop abuse tests that subject a single cell within a permanently installed, rechargeable lithium-ion battery to thermal runaway and demonstrate that the battery installation mitigates all hazardous effects of propagation to other cells and the release of electrolyte, fire, or explosive debris outside the battery case. The tests should replicate the battery installation on the aircraft and be conducted under conditions that produce the most severe outcome. (A-14-032)
>
> After Safety Recommendation A-14-032 has been completed, require aircraft manufacturers to perform the tests and demonstrate acceptable performance as part of the certification of any new aircraft design that incorporates a permanently installed, rechargeable lithium-ion battery. (A-14-033)
>
> Work with lithium-ion battery technology experts from government and test standards organizations, including US national laboratories, to develop guidance on acceptable methods to induce thermal runaway that most reliably simulate cell internal short-circuiting hazards at the cell, battery, and aircraft levels. (A-14-034)
>
> Review the methods of compliance used to certify permanently installed, rechargeable lithium-ion batteries on in-service aircraft and require additional testing, if needed, to ensure that the battery design and installation adequately protects against all adverse effects of a cell thermal runaway. (A-14-035)
>
> Develop a policy to establish, when practicable, a panel of independent technical experts to advise on methods of compliance and best practices for certifying the safety of new technology to be used on new or existing aircraft. The panel should be established as early as possible in the certification program to ensure that the most current research and information related to the technology could be incorporated during the program. (A-14-036)

Acting Chairman HART and Members SUMWALT, ROSEKIND, and WEENER concurred in these recommendations.

The NTSB is vitally interested in these recommendations because they are designed to prevent accidents and save lives. We would appreciate receiving a response from you within 90 days detailing the actions you have taken or intend to take to implement the recommendations. When replying, please refer to the safety recommendations by number. We encourage you to submit your response electronically to correspondence@ntsb.gov.

[Original Signed]

By: Christopher A. Hart,
Acting Chairman