Auxiliary Power Unit Battery Fire
Japan Airlines Boeing 787-8, JA829J
Boston, Massachusetts
January 7, 2013

Incident Report

NTSB/AIR-14/01
PB2014-108867

National
Transportation
Safety Board

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490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2014. ***Auxiliary Power Unit Battery Fire, Japan Airlines Boeing 787-8, JA829J, Boston, Massachusetts, January 7, 2013*****. NTSB/AIR-14/01. Washington, DC.**

Abstract: This report discusses the January 7, 2013, incident involving a Japan Airlines Boeing 787-8, JA8297, which was parked at a gate at General Edward Lawrence Logan International Airport, Boston, Massachusetts, when maintenance personnel observed smoke coming from the lid of the auxiliary power unit battery case, as well as a fire with two distinct flames at the electrical connector on the front of the case. No passengers or crewmembers were aboard the airplane at the time, and none of the maintenance or cleaning personnel aboard the airplane was injured. Safety issues relate to cell internal short circuiting and the potential for thermal runaway of one or more battery cells, fire, explosion, and flammable electrolyte release; cell manufacturing defects and oversight of cell manufacturing processes; thermal management of large-format lithium-ion batteries; insufficient guidance for manufacturers to use in determining and justifying key assumptions in safety assessments; insufficient guidance for Federal Aviation Administration (FAA) certification engineers to use during the type certification process to ensure compliance with applicable requirements; and stale flight data and poor-quality audio recording of the 787 enhanced airborne flight recorder. Safety recommendations are addressed to the FAA, The Boeing Company, and GS Yuasa Corporation.

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Abbreviations

AC	advisory circular
ACO	aircraft certification office
AD	airworthiness directive
APSIF	UTC Aerospace Systems' Airplane Power Systems Integration Facility
APU	auxiliary power unit
ARAC	aviation rulemaking advisory committee
ARC	accelerating rate calorimetry
ARFF	aircraft rescue and firefighting
ARP	Aerospace Recommended Practice
ATP	acceptance test procedure
BCU	battery charger unit
BEA	Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile
BMU	battery monitoring unit
BOS	General Edward Lawrence Logan International Airport
CFR	*Code of Federal Regulations*
CT	computed tomography
CVR	cockpit voice recorder
DPA	destructive physical analysis
EAFR	enhanced airborne flight recorder
EASA	European Aviation Safety Agency
ECS	environmental control system
EDS	energy dispersive x-ray spectroscopy
E/E bay	electronic equipment bay

EICAS	engine indicating and crew alerting system
EPS	electrical power system
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FAI	first article inspection
FDR	flight data recorder
FHA	functional hazard assessment
FMEA	failure modes and effects analysis
FOD	foreign object debris
JAL	Japan Airlines
JTSB	Japan Transport Safety Board
KAI	Kanto Aircraft Instrument Company
NASA	National Aeronautics and Space Administration
NRT	Narita International Airport
NTSB	National Transportation Safety Board
ODA	organization designation authorization
SAE	Society of Automotive Engineers
SCD	specification control drawing
SEI	solid electrolyte interphase
SEM	scanning electron microscope
SPU	start power unit
TAK	Takamatsu Airport
TSO	technical standard order
UL	Underwriters Laboratories

Executive Summary

On January 7, 2013, about 1021 eastern standard time, smoke was discovered by cleaning personnel in the aft cabin of a Japan Airlines (JAL) Boeing 787-8, JA829J, which was parked at a gate at General Edward Lawrence Logan International Airport (BOS), Boston, Massachusetts. About the same time, a maintenance manager in the cockpit observed that the auxiliary power unit (APU) had automatically shut down. Shortly afterward, a mechanic opened the aft electronic equipment bay and found heavy smoke coming from the lid of the APU battery case and a fire with two distinct flames at the electrical connector on the front of the case. None of the 183 passengers and 11 crewmembers were aboard the airplane at the time, and none of the maintenance or cleaning personnel aboard the airplane was injured. Aircraft rescue and firefighting personnel responded, and one firefighter received minor injuries. The airplane had arrived from Narita International Airport, Narita, Japan, as a regularly scheduled passenger flight operated as JAL flight 008 and conducted under the provisions of 14 *Code of Federal Regulations* (CFR) Part 129.

The APU battery model is the same model 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 at Takamatsu Airport (TAK), Takamatsu, Japan, shortly after takeoff. The Japan Transport Safety Board investigated this incident with support from the National Transportation Safety Board (NTSB).

Boeing was responsible for the overall integration and certification of the equipment in the 787's electrical power conversion subsystem, which is part of the airplane's electrical power system (EPS). Boeing contracted with Thales Avionics Electrical Systems to design the 787 electrical power conversion subsystem, which includes the main and APU batteries. Thales then subcontracted with various manufacturers for the main and APU battery system components, including GS Yuasa Corporation, which developed, designed, and manufactured the main and APU batteries.

Boeing was required to demonstrate that the 787's design complied with the Federal Aviation Administration's (FAA) 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 airplane. As part of the compliance demonstration with these requirements and 14 CFR Part 25 airworthiness standards, Boeing performed a safety assessment to determine the potential hazards that various failure conditions of EPS components could introduce to the airplane and its occupants. Boeing determined that the rate of occurrence of cell venting for the 787 battery would be about 1 in 10 million flight hours. However, at the time of the BOS and TAK incidents (both of which involved cell venting), the in-service 787 fleet had accumulated less than 52,000 flight hours.

After the BOS and TAK events and the FAA's subsequent grounding of the US 787 fleet, Boeing modified the 787 main and APU battery design and its installation configuration to include, among other things, a stainless steel enclosure for the battery case and a duct that vents

from the interior of the enclosure to the exterior of the airplane to prevent smoke from entering the occupiable space of the airplane. In April 2013, the FAA issued an airworthiness directive mandating the installation of the modified battery aboard US 787 airplanes before they could return to service.

The 787 main and APU battery design was also modified to mitigate the most severe effects of an internal short circuit (that is, cascading, cell-to-cell thermal runaway of other cells within the battery; excessive heat; flammable electrolyte release; and fire). The recommendations resulting from the safety issues identified during this investigation could help prevent such effects from occurring in future battery designs.

The NTSB identified the following safety issues as a result of this incident investigation:

- **Cell internal short circuiting and the potential for thermal runaway of one or more battery cells, fire, explosion, and flammable electrolyte release.** This incident involved an uncontrollable increase in temperature and pressure (thermal runaway) of a single APU battery cell as a result of an internal short circuit and the cascading thermal runaway of the other seven cells within the battery. This type of failure was not expected based on the testing and analysis of the main and APU battery that Boeing performed as part of the 787 certification program. However, GS Yuasa did not test the battery under the most severe conditions possible in service, and the test battery was different than the final battery design certified for installation on the airplane. Also, Boeing's analysis of the main and APU battery did not consider the possibility that cascading thermal runaway of the battery could occur as a result of a cell internal short circuit.

- **Cell manufacturing defects and oversight of cell manufacturing processes.** After the incident, the NTSB visited GS Yuasa's production facility to observe the cell manufacturing process. During the visit, the NTSB identified several concerns, including foreign object debris (FOD) generation during cell welding operations and a postassembly inspection process that could not reliably detect manufacturing defects, such as FOD and perturbations (wrinkles) in the cell windings, which could lead to internal short circuiting. In addition, the FAA's oversight of Boeing, Boeing's oversight of Thales, and Thales' oversight of GS Yuasa did not ensure that the cell manufacturing process was consistent with established industry practices.

- **Thermal management of large-format lithium-ion batteries.** Testing performed during the investigation showed that localized heat generated inside a 787 main and APU battery during maximum current discharging exposed a cell to high-temperature conditions. Such conditions could lead to an internal short circuit and cell thermal runaway. As a result, thermal protections incorporated in large-format lithium-ion battery designs need to account for all sources of heating in the battery during the most extreme charge and discharge current conditions. Thermal protections include (1) recording and monitoring cell-level temperatures and voltages to ensure that exceedances resulting from localized or other sources of heating can be detected and addressed before cell damage occurs and (2) establishing thermal safety limits for cells to ensure that self-heating does not occur at a temperature that is less than the battery's maximum operating temperature.

- **Insufficient guidance for manufacturers to use in determining and justifying key assumptions in safety assessments.** Boeing's EPS safety assessment for the 787 main and APU battery included an underlying assumption that the effect of an internal short circuit within a cell would be limited to venting of only that cell without fire. However, the assessment did not explicitly discuss this key assumption or provide the engineering rationale and justifications to support the assumption. Also, as demonstrated by the circumstances of this incident, Boeing's assumption was incorrect, and Boeing's assessment did not consider the consequences if the assumption were incorrect or incorporate design mitigations to limit the safety effects that could result in such a case. Boeing indicated in certification documents that it used a version of FAA Advisory Circular (AC) 25.1309, "System Design and Analysis" (referred to as the Arsenal draft), as guidance during the 787 certification program. However, the analysis that Boeing presented in its EPS safety assessment did not appear to be consistent with the guidance in the AC. In addition, Boeing and FAA reviews of the EPS safety assessment did not reveal that the assessment had not (1) considered the most severe effects of a cell internal short circuit and (2) included requirements to mitigate related risks.

- **Insufficient guidance for FAA certification engineers to use during the type certification process to ensure compliance with applicable requirements.** During the 787 certification process, the FAA did not recognize that cascading thermal runaway of the battery could occur as a result of a cell internal short circuit. As a result, FAA certification engineers did not require a thermal runaway test as part of the compliance demonstration (with applicable airworthiness regulations and lithium-ion battery special conditions) for certification of the main and APU battery. Guidance to FAA certification staff at the time that Boeing submitted its application for the 787 type certificate, including FAA Order 8110.4, "Type Certification," did not clearly indicate how individual special conditions should be traced to compliance deliverables (such as test procedures, test reports, and safety assessments) in a certification plan.

- **Stale flight data and poor-quality audio recording of the 787 enhanced airborne flight recorder (EAFR).** The incident airplane was equipped with forward and aft EAFRs, which recorded cockpit audio data and flight parametric data. The EAFRs recorded stale flight data for some parameters (that is, data that appeared to be valid and continued to be recorded after a parameter source stopped providing valid data), which delayed the NTSB's complete understanding of the recorded data. In addition, the audio recordings from both EAFRs during the airborne portion of the flight were poor quality. The signal levels of the three radio/hot microphone channels were very low, and the recording from the cockpit area microphone channel was completely obscured by the ambient cockpit noise. These issues did not impact the NTSB's investigation because the conversations and sounds related to the circumstances of the incident occurred after the airplane arrived at the gate and the engines were shut down, at which point the quality of the audio recordings was excellent.

The NTSB determines that the probable cause of this incident was an internal short circuit within a cell of the APU lithium-ion battery, which led to thermal runaway that cascaded to adjacent cells, resulting in the release of smoke and fire. The incident resulted from Boeing's failure to incorporate design requirements to mitigate the most severe effects of an internal short circuit within an APU battery cell and the FAA's failure to identify this design deficiency during the type design certification process.

As a result of this investigation, the NTSB makes safety recommendations to the FAA, Boeing, and GS Yuasa. The NTSB previously issued safety recommendations to the FAA regarding (1) insufficient testing methods and guidance for addressing the safety risks of internal short circuits and thermal runaway and (2) the need for outside technical knowledge and expertise to help the FAA ensure the safe introduction of new technology into aircraft designs.

1. Factual Information

1.1 Event History

On January 7, 2013, about 1021 eastern standard time,[1] smoke was discovered by cleaning personnel in the aft cabin of a Japan Airlines (JAL) Boeing 787-8, JA829J, which was parked at a gate at General Edward Lawrence Logan International Airport (BOS), Boston, Massachusetts. About the same time, a maintenance manager in the cockpit observed that the auxiliary power unit (APU) had automatically shut down.[2] Shortly afterward, a mechanic opened the aft electronic equipment bay (E/E bay) and found heavy smoke coming from the lid of the APU battery case and a fire with two distinct flames at the electrical connector on the front of the case.[3] None of the 183 passengers and 11 crewmembers were aboard the airplane at the time, and none of the maintenance or cleaning personnel aboard the airplane was injured. Aircraft rescue and firefighting (ARFF) personnel responded, and one firefighter received minor injuries. The airplane had arrived from Narita International Airport (NRT), Narita, Japan, as a regularly scheduled passenger flight operated as JAL flight 008 and conducted under the provisions of 14 *Code of Federal Regulations* (CFR) Part 129.

The captain of JAL flight 008 reported that the APU was turned on about 30 to 40 min before the airplane left the gate at NRT (about 0247Z) and was shut down after the engines started.[4] He stated that the flight, which departed NRT about 0304Z, was uneventful except for occasional moderate turbulence about 6.5 to 7 hours into the flight. Flight data recorder (FDR) data showed that the airplane touched down at BOS at 1000:24 and that the APU was started at 1004:10 while the airplane was taxied to the gate. The captain indicated that the APU operated normally. FDR data also showed that the airplane was parked at the gate with the parking brake set and both engines shut down by 1006:54.

The maintenance manager (the JAL director of aircraft maintenance and engineering at BOS) reported that the passengers had deplaned by 1015 and that the flight and cabin crewmembers had deplaned by 1020, at which time he and the cabin cleaning crew had entered

1 All times in this report are eastern standard time unless otherwise noted.

2 The APU battery provides power to start the APU during ground and flight operations. The APU controller monitors the parameters that are needed to operate the APU. The APU controller is powered by the APU battery bus, which receives its power from the APU battery. If the APU battery were to fail, then the APU battery bus would no longer receive power, and the APU would shut down.

3 The mechanic provided a written statement to the National Transportation Safety Board (NTSB) describing his observations. The mechanic's statement indicated that, after he checked the aft E/E bay, he saw "heavy smoke in the compartment." He reported that he "saw [a] small flame around [the] APU batt[ery]." He added that he "decided [to] discharge [the hand-held dry chemical fire] extinguisher" but could not "discharge continuously" because he believed that there was a "dangerous environment in the compartment." Further, he stated that he "tried fire extinguishing, but [the] smoke and flame (flame size about 3 inch[es]) did not stop." In addition, the mechanic gave the NTSB a drawing that showed two 3-in flames at the electrical connector on the front of the battery case. (The front of the battery case is oriented toward the front of the airplane.) The maintenance manager also provided a written statement to the NTSB, which indicated that the mechanic had seen "flames around the APU battery."

4 Eastern standard time is 5 hours behind coordinated universal time (also referred to as UTC or Zulu time).

the airplane. Shortly afterward, a member of the cleaning crew told the maintenance manager, who was in the cockpit, about "an electrical burning smell and smoke in the aft cabin." The maintenance manager then observed a loss of power to systems powered by the APU and realized that the APU had automatically shut down. After confirming that the airplane's electrical power systems were off, the maintenance manager turned the main and APU battery switches to the "off" position. FDR data showed that the APU battery failed at 1021:15 and that the APU shut down at 1021:37, which was also when the APU controller lost power.

A JAL mechanic in the aft cabin at the time reported that, when the airplane lost power, he went to the cockpit and learned that the APU had shut down. The mechanic then went back to the aft cabin and saw and smelled smoke. A JAL station manager arrived at the airplane and reported that, when he went into the cabin (through the door where the passenger boarding bridge is attached), he saw "intense" smoke that was concentrated 10 ft aft of the door. The turnaround coordinator for JAL flights 008 and 007,[5] who had also entered the aft cabin and observed the smoke, described the smoke as "caustic smelling." The mechanic notified the maintenance manager about the smoke, and the maintenance manager asked the mechanic to check the aft E/E bay. The mechanic found heavy smoke and flames in the compartment coming from the lid of the APU battery case. The mechanic reported that he used a dry chemical fire extinguisher (located at the base of the passenger boarding bridge) to attempt to put out the fire but that the smoke and flames did not stop.

About 1037, ARFF personnel at BOS were notified about smoke in the cabin of a JAL airplane.[6] Review of a time-stamped airport security camera video showed that the first of five ARFF trucks arrived on scene within 1 min (at 1037:50).[7] The other four ARFF trucks arrived on scene about 2.5 min after initial notification. A ladder truck, a rescue truck, an airstair truck, a hazardous materials truck, and a fire command vehicle also responded to the incident.

The JAL mechanic advised ARFF personnel that the fire was in the aft E/E bay and led a firefighter to the aft E/E bay door.[8] The firefighter reported that, after entering the compartment, he could see "a white glow about the size of a softball" on a hand-held thermal imaging camera.[9] The firefighter also reported that he applied "a shot" of Halotron (a clean fire-extinguishing agent) to knock down the fire.[10] The thermal imaging camera showed that the white glow was

[5] JAL flight 007 had been scheduled to depart BOS later that morning using the incident airplane.

[6] The JAL station manager stated that he asked a gate agent to call ARFF. The gate agent then called her supervisor, who called ARFF from a telephone at the passenger check-in counter.

[7] The airplane was located at gate 8A in terminal E. The first ARFF truck to reach the scene (after incident notification) was already in terminal E for terminal familiarization training. The airport security camera recording times were correlated to the FDR times (within 3 seconds).

[8] The term "fire" is commonly used by ARFF personnel in reference to an ARFF response or event. Although the JAL mechanic reported that flames were coming from the front of the APU battery case, none of the ARFF personnel who responded to this incident reported seeing flames.

[9] The hand-held thermal imaging cameras that ARFF personnel at BOS used had a heat-density scale portrayed as brightness and/or coloring of an object (that is, the whiter and brighter the object, the higher the heat intensity).

[10] According to the Halotron website, "Halotron is a rapidly evaporating liquid…that leaves no residue, thereby minimizing or eliminating potential agent-related damage to…assets like electronic equipment, machinery, motors

still present but was less intense than before. The airport security camera video showed smoke coming out of the airplane, as shown in figure 1, at 1040:26.

Source: *Boston Herald*.

Figure 1. Photograph of smoke emanating from the incident airplane's aft E/E bay.

An ARFF captain went into the aft E/E bay with the thermal imaging camera, which showed a heat signature near the APU battery. After he exited the E/E bay, another firefighter entered it. This firefighter reported no visibility because of the smoke. He did not know where the battery was located within the E/E bay, but he knew of a "hot spot" about 6 to 8 in ahead of him, so he discharged a "quick burst" of Halotron for 10 to 20 seconds. The firefighter exited and reentered the E/E bay with the thermal imaging camera. He reported that the battery case was visible and that he saw "a white glow with radiant heat waves" but no flames. An ARFF lieutenant who entered the aft E/E bay reported that the battery appeared to be rekindling.

The ARFF captain reentered the E/E bay and saw heavy white smoke (which he had seen earlier billowing through the floor of the aft cabin) but no flames. The captain applied shots of Halotron to the fire for 5 min, which he believed had knocked down the fire. He reported that the battery was emitting white smoke, creating heavy smoke conditions. The ARFF captain also reported that the battery was hissing loudly and that liquid was flowing down the sides of the battery case. A firefighter (outside the airplane) reported that he heard a "pop" sound and saw

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and construction materials." Halotron is dispersed at a rate of 5 lbs per second. A "shot" of Halotron was estimated to last between 15 and 20 seconds, corresponding to between 75 and 100 lbs of the fire-extinguishing agent dispersed. ARFF personnel are trained to use a clean agent, such as Halotron, in electrical and avionics compartments because water would ruin electrical and avionics components.

smoke "pouring out of" the aft E/E bay. The ARFF captain received a minor burn on his neck when the battery, in his words, "exploded."

After additional firefighting efforts and the placement of a ventilation fan by the E/E bay door to clear smoke, the incident commander decided to remove the APU battery.[11] (The airport security camera video showed that, at 1105:58, smoke was no longer visible from the exterior of the airplane.) Firefighters reported that removing the battery was difficult because a metal kick shield installed in front of the battery prevented them from accessing the battery's quarter-turn quick disconnect knob. Also, the quick disconnect knob could not be turned because it was charred and had melted away. The airport security camera video showed that the battery was removed from the aft E/E bay at 1157:20, about 80 min after the initial notification of the event.[12] The ARFF incident report showed that the event was "controlled" about 1219 (about 1 hour 40 min after the initial notification).

1.2 Airplane Information

The Boeing 787 "Dreamliner" is a twin-engine, wide-body commercial airplane. The 787 program began in April 2004, with the 787's first flight in December 2009, certification in August 2011, and first delivery in September 2011. The incident airplane, JA829J, was delivered new to JAL on December 20, 2012. At the time of the incident, the airplane had logged 169 flight hours and 22 flight cycles. There were no abnormal indications or maintenance messages related to issues with the incident battery between the date of delivery and the date of the incident.

Boeing was responsible for the overall integration and certification of the equipment in the 787's electrical power conversion subsystem, which is part of the airplane's electrical power system. Boeing contracted with Thales Avionics Electrical Systems of Neuilly-sur-Seine, France, to design the 787 electrical power conversion subsystem, which includes the main and APU batteries. Thales subcontracted with various manufacturers for the main and APU battery system components.

1.2.1 Battery Information

The APU battery, part number LVP65-8-402, was developed, designed, and manufactured by GS Yuasa Corporation of Kyoto, Japan.[13] The battery had eight individual lithium-ion cells, all of which were from the same manufacturing lot that GS Yuasa produced in July 2012. The APU battery installed on the incident airplane, serial number 394, was manufactured in September 2012 and was delivered new to Boeing. The battery was installed in

[11] In addition, the incident commander asked a JAL mechanic and a firefighter to disconnect the main battery as a precaution in case it was feeding the APU battery fire.

[12] ARFF personnel had to cut the kick shield installed in front of the battery case to access the battery and then cut the connectors to the battery to remove it.

[13] GS Yuasa assigned this part number to the battery model at the time of the incident. Boeing's part number for the battery model at the time of the incident was B3856-901.

the incident airplane on October 15, 2012, and was initially charged by the airplane on or about October 19, 2012. Boeing records showed no installation issues associated with the APU battery. Boeing records also showed that, on December 6, 2012, the battery electrical connector was removed (to facilitate a routine inspection of a nearby power panel) and reinstalled the same day.

As previously stated, the APU battery (installed in the aft E/E bay) provides power to start the APU (installed in the tail of the airplane) during ground and flight operations. The aft E/E bay is an electrical equipment compartment located aft of the main landing gear and beneath approximately the third set of cabin doors (L3 and R3). The compartment is only accessible from the ground by a door in the aft cargo compartment and a set of doors in the airplane belly. The APU battery is located at floor level within the aft E/E bay.

Unique to the 787, the LVP65-8-402 battery model is also used for the 787 main battery, which is located in the forward E/E bay. The main battery, which also has eight individual lithium-ion cells, provides power to selected electrical/electronic equipment during ground and flight operations for normal and failure conditions. Table 1 shows the specifications for the LVP65-8-402 battery and LVP65 cells.

Table 1. Specifications for the main and APU battery and cells.

Specification	Battery	Cell
Nominal capacity (ampere-hours)	75	75
Nominal voltage (volts)	29.6	3.7
Operational voltage range (volts)	20 to 32.2	2.5 to 4.025
Weight (lbs)	61.8	6
Dimensions (in)		
Width	10.9	5.2
Depth	14.2	2.0
Height	8.5	7.7

Note: Battery specification information was based on information from a Thales document. Cell specification information was provided by GS Yuasa.

The 787 main and APU lithium-ion battery has primarily nonflammable components, but the electrolyte in the battery cells is flammable. The eight cells are connected in series and assembled in two rows of four cells, as shown in figure 2. Thermoplastic insulation sheets provide electrical isolation and physical separation between each cell and between the cells and the aluminum battery case, which is electrically grounded. Plastic upper and lower fixation trays secure the position and orientation of the cells in the battery case, and forward and center brace bars hold the fixation trays in place.

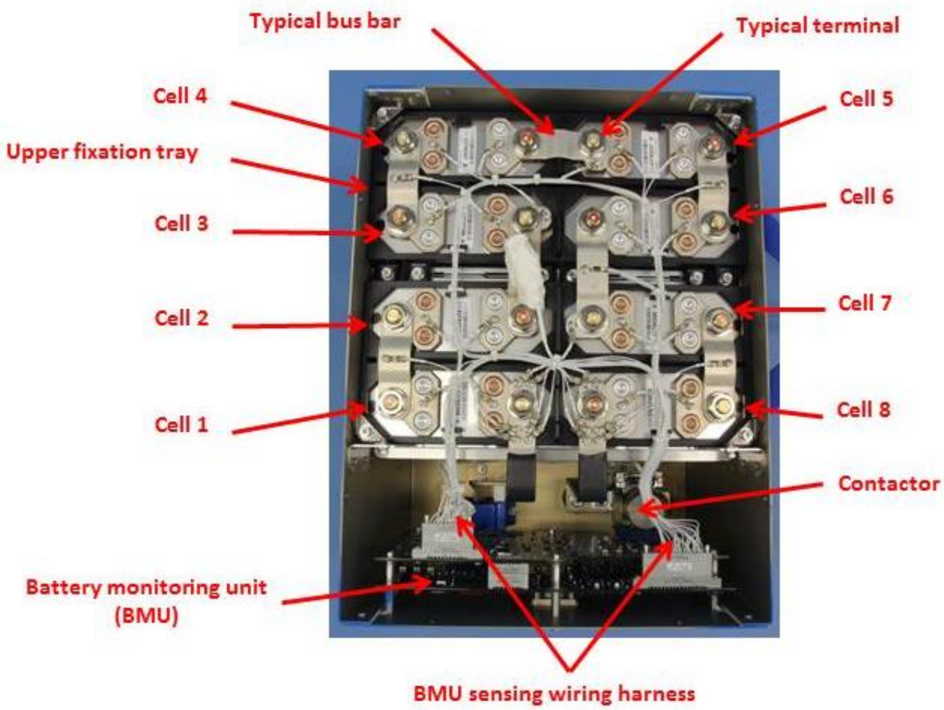

Figure 2. Main and APU exemplar battery.

In addition to the eight individual battery cells, the battery case includes two circuit boards that comprise the battery monitoring unit (BMU); cell voltage sensing wires between battery internal components and the BMU; a Hall effect current sensor for current monitoring; a contactor; bus bars for the main current pathways between the cells and to the J3 connector, which connects to the outside of the battery case; and the J1 connector, which leads outside of the battery case.[14]

Each cell has three internal electrode winding assemblies. Each winding assembly is about 30 ft long and is configured with an electrode, then a separator, then another electrode, and then another separator. One electrode—the anode—is a copper foil coated in a carbon active material; the other electrode—the cathode—is an aluminum foil coated in a lithium-cobalt-oxide compound active material. The separator material is made of polyolefin.

The three internal cell windings have been described as flattened “jelly rolls.” The innermost (last) wrap of the sandwiched electrode layers is the coated copper anode layer wrapped around a thermoplastic mandrel core. The coated aluminum cathode layer begins on the

[14] A Hall effect current sensor detects and measures electrical current in a wire and generates a signal proportional to the current measured. The plastic J3 connector provides battery power to the airplane, and the aluminum J1 connector provides signal information used by the BMU and the battery charger unit.

second-to-last wrap and ends on the second wrap. The outermost wrap, the first wrap, is an extra layer of anode and separator. The separator extends beyond the outermost wrap of anode and winds several more times around the exterior of the winding. Figure 3 shows the electrode winding layout. Two layers of thermoplastic electrical insulation surround the electrode winding assemblies. Sheets of thermoplastic insulation (held together with thermoplastic tape) electrically isolate the stainless steel cell cases (which are not grounded) from the windings.

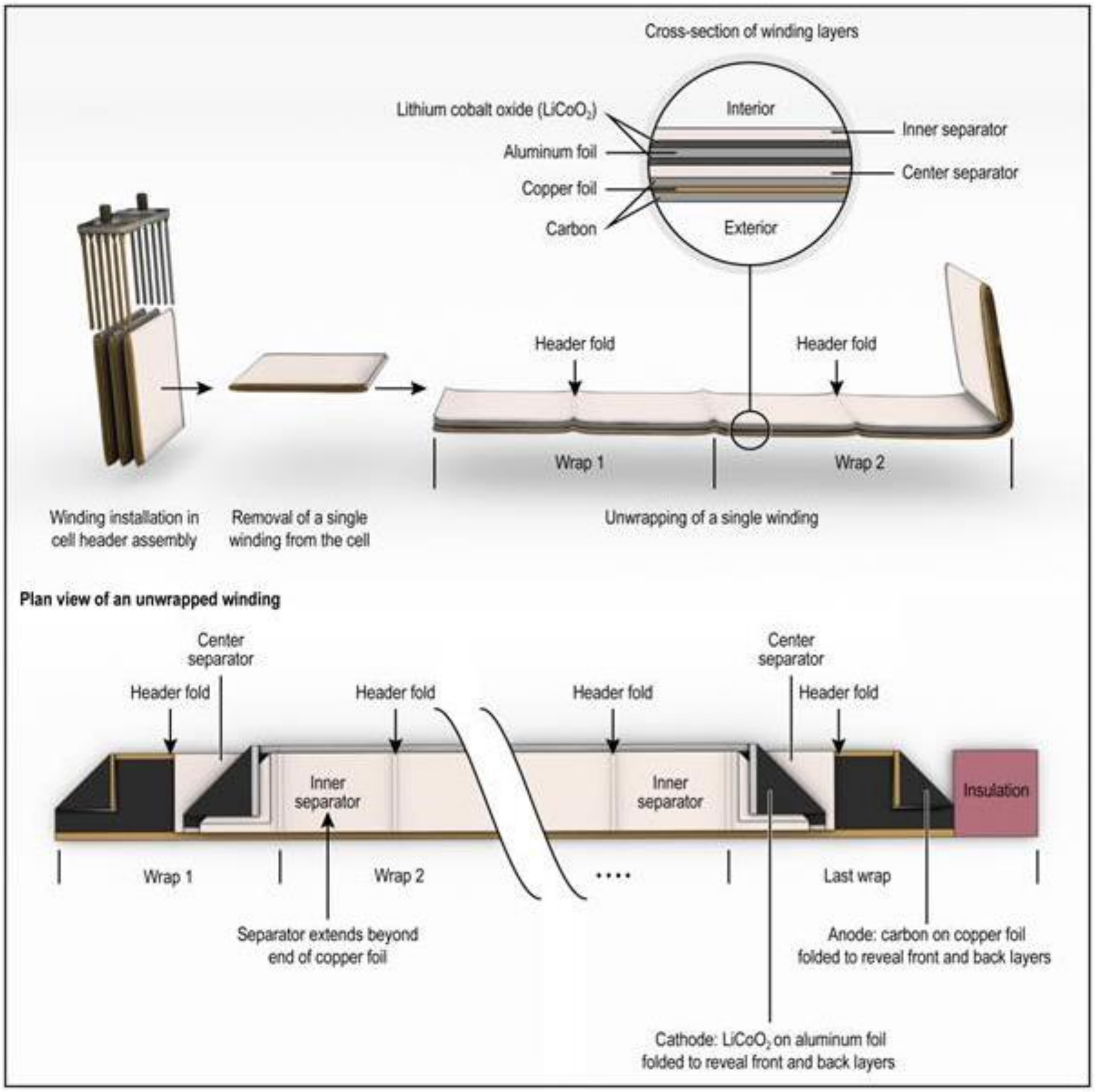

Figure 3. Electrode winding layout.

Two sets of current collectors—one set for the anode and one set for the cathode—are attached on their respective side of each winding assembly to conduct electrical current to and from the positive (cathode) and the negative (anode) terminal assemblies, which are connected to adjacent cells by bus bars. (The electrode edges, where the current collectors attach, are not coated with an active material.) Current collector "fingers" provide the electrical path between the windings and the terminal plates on the exterior of each cell. According to GS Yuasa, the aluminum current collector fingers were designed to melt open under high current conditions, thereby functioning as an electrical fuse. Three pairs of copper current collector fingers are used for the anode, and three pairs of aluminum current collector fingers are used for the cathode. The fingers extend about one-half of the way down the left (anode) and right (cathode) sides of the cell. At the top of the cell's interior, the current collector fingers connect together into either copper (anode) or aluminum (cathode) bars, which connect with their respective terminal plates on the cell's exterior. Thermoplastic electrical insulating material is used between the cell case and the current collector bars and terminal plates. Figure 4 shows a diagram of the cell construction. Section 1.4 discusses the postincident examination of the APU battery and cells involved in the BOS event.

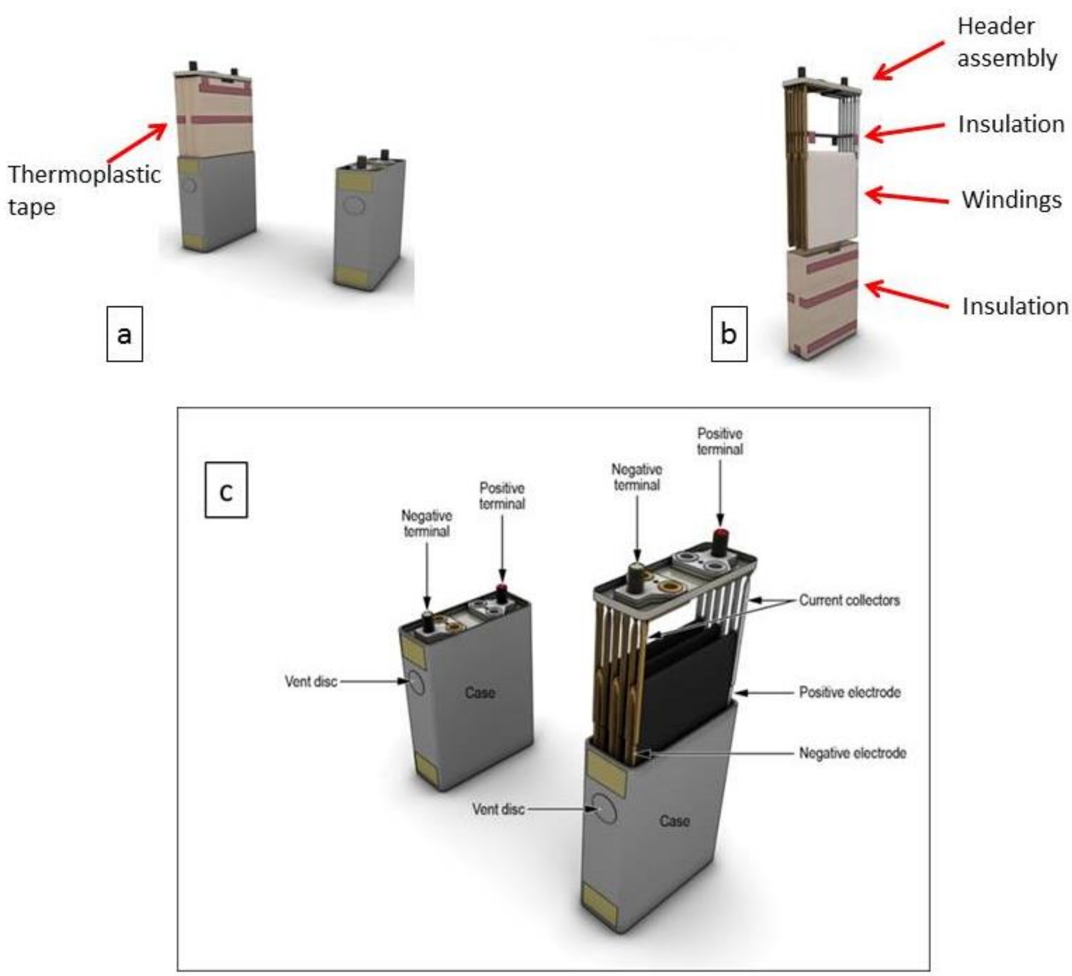

Figure 4. Exploded-view diagram of LVP65 lithium-ion cell construction.

Note: Figures 4a and 4b show the cell construction with the insulation (held together with thermoplastic tape) as installed in the cell. Figure 4c shows the cell construction without the insulation.

Each current collector attaches to two rivets that connect a collector plate with the respective terminal plate on a cell's exterior. Two aluminum rivets are installed at the positive terminal, and two copper rivets are installed at the negative terminal. The rivets provide electrical continuity between the cell's exterior and interior. Figure 5 shows a photograph of a riveted header assembly. Section 1.5.5 discusses the postincident examination of riveted assemblies.

Source: Underwriters Laboratories.

Figure 5. Riveted header assembly.

Boeing's requirements for the battery, as specified in a proprietary Thales/GS Yuasa report, included the following:

- a 5-year service life under any combination of operating conditions specified within the Thales/GS Yuasa report,
- an operating temperature range of -0.4ºF to 158ºF,
- a specific charge acceptance capability with an internal temperature between -0.4ºF to 32ºF,

- a specific current capacity from a fully discharged state within 75 min at an ambient temperature of 77ºF ± 18ºF for 30,000 flight hours, and
- a specific current end-of-life rated capacity or greater.[15]

1.2.2 Battery and Related Component Information

The BMU is mounted inside the battery case (see figure 2). The BMU includes a main circuit card and a subcircuit card, each of which contains two independent monitoring systems: BMU1 and BMU2 (main circuit card) and BMU3 and BMU4 (subcircuit card). Each of the four BMU systems has an initiated built-in test function. BMU1 monitors for cell overcharge, overdischarge, overheating, and imbalance; controls the cell balancing function when any cell reaches a predetermined threshold; and provides voltage measurement to the battery charger unit (BCU). BMU2 provides redundant monitoring for cell overcharge. BMU3 controls the contactor and provides additional monitoring for battery and cell overcharge. BMU4 monitors for cell overdischarge and high current charge. The BMU was designed to send a signal to the BCU to discontinue charging if any of the battery monitoring thresholds were exceeded. The incident main circuit card and subcircuit card were manufactured by Kanto Aircraft Instrument Company (KAI) Ltd. The main circuit card and subcircuit card do not contain nonvolatile memory, and none of the BMU data were recorded on the FDR. Examination and testing of the BMU components, which were thermally damaged, revealed no pre-failure anomalies.[16]

The contactor is a device that can electrically isolate the battery cells from the BCU and battery bus. The contactor, which is mounted in the bottom of the battery case near the BMU (see figure 2), is normally closed during battery operations. The contactor can only be commanded to open by BMU3 if a cell overvoltage or high battery voltage is detected. The incident contactor was manufactured by Zodiac Aerospace. The damage to the contactor precluded a full functional test from being performed. X-rays and disassembly of the contactor revealed no pre-failure anomalies.

The BCU includes an electric connector for communication (among the BCU, battery, and airplane), a ground wire stud, and power terminals for the two large battery cables. The BCU of the incident APU battery was manufactured by Securaplane Technologies. At Securaplane, the National Transportation Safety Board (NTSB) performed visual examinations, preliminary electrical tests, and acceptance test procedure (ATP) functional testing of the BCU. The ATP testing revealed a previously unknown electrical oscillation in the output charge voltage, which was later determined (through additional testing at Boeing and Underwriters Laboratories [UL]) not to be related to the circumstances of the incident, as discussed in section 1.5.8.[17]

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[15] The actual charge acceptance capability, current capacity, and current end-of-life rated capacity are proprietary.

[16] The damage to the BMU was too extensive to perform testing as a complete assembly; as a result, the testing was conducted at the component level.

[17] The NTSB contracted with UL to perform testing as part of this incident investigation. UL performed testing in its laboratories in Northbrook, Illinois; Melville, New York; and Taipei, Taiwan.

The APU controller operates the valves, motors, and sensors that control the operation of the APU and contains nonvolatile memory to record various APU parameters, including battery voltage. The APU controller in the 787 airplane is located near the bulk cargo door on the right side of the aft fuselage (where it is separated from the APU battery and the BCU). The incident APU controller was manufactured by Hamilton Sundstrand.[18] Examination and testing (as part of obtaining the nonvolatile memory) showed that the APU controller operated normally and that the APU's function did not affect the battery's operation at the time of the failure.

The start power unit (SPU) converts DC battery power to AC power for starting the APU and provides excitation power for the APU during startup. The SPU of the incident airplane was manufactured by Securaplane Technologies. ATP testing of the SPU found no anomalies, and the SPU's function did not affect the battery's operation at the time of the failure.

1.2.3 Postincident Airplane Examination

The aft E/E bay (the APU battery installation location) showed damage consistent with heat generated from the APU battery and smoke, hot gases, and electrolyte discharged from the battery. Evidence of material expelled from the battery (in the form of residue and thermal damage) was observed in an area that extended about 20 in from the battery installation. No primary structures (that is, those associated with airplane flight loads) exhibited damage; secondary structures—specifically, the avionics rack and the floor panel—exhibited thermal damage near the APU battery's installation location.[19]

The wires that connected to the battery case had been thermally damaged, and the front of the battery case showed thermal damage near the J1 and J3 connectors, where the mechanic's drawing indicated two small flames. The shielded bundle of signal wires, which were the circuits between the BMU and BCU, had burned away from the J1 connector. The copper conductors and shield braiding were melted, which was consistent with resistive heating due to high levels of electrical current (beyond the level that the wires were capable of carrying). The single wire designed to be the battery case ground wire (an intended electrical ground path) remained connected at each end, with the wire insulation partially melted and slightly blackened on the interior surface, which was also consistent with resistive heating due to high levels of electrical current.

The aft E/E bay contains electrical cabinets (referred to as panels) that house components used to distribute electrical power from each engine and the APU. The panel labeled P49 is the source of electrical power distribution for the APU battery bus. No physical damage was noted to the P49 panel. When the circuit breakers on the P49 panel were disengaged, continuity checks of the circuit breakers, contactors, and battery cables to the BCU and battery bus revealed no faults.

The environmental control system (ECS) on the incident airplane was designed to provide pressurized and heated or cooled air to the 787 passenger cabin and E/E bays. The ECS

[18] Hamilton Sundstrand later merged with Goodrich Corporation to form UTC Aerospace Systems.

[19] The avionics rack separated the APU battery from the BCU.

avionics cooling function was designed to remove smoke overboard through fans in the cooling ducts by changing supply valve positions (and using differential pressure when the airplane is in flight).[20] During this incident, the supply valves (which were electrically driven) lost electrical power after the APU shut down because the APU was the only source of electrical power being used at the time. As a result, smoke generated by the APU battery could not be effectively directed outside the cabin and aft E/E bay.

1.2.4 Additional Airplane-Related Information

According to the Japan Transport Safety Board (JTSB), on January 16, 2013, a "serious incident" involving the main battery occurred aboard a 787 airplane operated by All Nippon Airways during a flight from Yamaguchi to Tokyo, Japan.[21] The pilots received a smoke warning in the cockpit after the airplane climbed above an altitude of 32,000 ft. The airplane made an emergency landing at Takamatsu Airport (TAK), Takamatsu, Japan. Of the 137 airplane occupants, 4 passengers received minor injuries during evacuation via the emergency slides. The JTSB investigated this incident with the NTSB's support and issued its final report on the incident in September 2014 (JTSB 2014).[22]

Boeing reported that, as of the date of the TAK battery event (which occurred 9 days after the BOS battery event), the 787 fleet comprised 50 in-service airplanes that had accumulated 51,662 flight hours and 18,665 cycles.[23] After the BOS and TAK events, Boeing modified the 787 battery design and its installation configuration to include (1) additional insulation between the battery cells, (2) vents in the side of the battery case, (3) a stainless steel enclosure for the battery case, and (4) an ECS duct that vents from the interior of the stainless steel enclosure to the exterior of the airplane to prevent smoke from entering the occupiable space of the airplane. Section 1.8.1 discusses the Federal Aviation Administration (FAA) airworthiness directive (AD) mandating the installation of the new battery (part number LVP65-8-403) aboard US airplanes.[24]

[20] The aft E/E bay contains two smoke detectors.

[21] Chapter 1 of Annex 13, "Aircraft Accident and Incident Investigation," to the Convention on International Civil Aviation defines a serious incident as "an incident involving circumstances indicating that there was a high probability of an accident and associated with the operation of an aircraft which, in the case of a manned aircraft, takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked."

[22] The JTSB's report on the TAK incident stated that heat generation in a single cell "was probably caused by [an] internal short circuit" which developed into "thermal propagation to other cells, [which] consequently damaged the whole battery." The report also stated that possible contributing factors to the thermal propagation were that "the test conducted during the developmental phase did not appropriately simulate the on-board [battery] configuration, and the effects of internal short circuit were underestimated."

[23] One cycle comprises a complete engine startup and shutdown. The number of 787 flight hours indicated does not include about 6,000 flight test hours.

[24] GS Yuasa assigned this part number to the redesigned battery. The Boeing part number for the redesigned battery is B3856-902.

On January 14, 2014, an LVP65-8-403 main battery failed on a JAL 787 airplane that was parked at a gate at NRT. (The airplane was being prepared for scheduled flight.) The Japan Civil Aviation Bureau is investigating this incident with assistance from the JTSB and the NTSB. Maintenance personnel reported seeing smoke outside the cockpit window. Preliminary information indicated that one cell had overheated and vented electrolyte and that the enclosure for the battery case contained the vented electrolyte.

1.3 Flight Recorders

The BOS incident airplane was equipped with forward and aft General Electric model EAFR 2100 enhanced airborne flight recorders (EAFR), which recorded cockpit voice recorder (CVR) audio data and FDR parametric data.[25] The forward and aft recorders, which were powered by the left and right 28-volt DC buses, respectively, recorded the same set of flight data independently of each other. The forward recorder had an independent power supply to provide backup power to the recorder for about 10 min if the left 28-volt DC bus lost power.[26] (The aft recorder had no backup power supply.)

The CVR portion of the EAFR recorded 2 hours of audio data from the cockpit area microphone, the captain's audio selector panel/hot microphone, the first officer's audio selector panel/hot microphone, and the jumpseat/observer's position. The audio information from the forward recorder was used to produce a transcription summary for this incident. The summary began at 0828:21, when the airplane was level in cruise flight at 39,000 ft, and ended at 1031:35, when the forward EAFR stopped recording.

According to the transcription summary, at 1021:41, the CVR recorded sounds associated with the APU shutting down. Conversations among maintenance personnel and the turnaround coordinator about the APU shutdown began about 9 seconds later. At 1024:10, the turnaround coordinator reported smoke in the cabin. No voices were heard on the CVR from 1024:22 to the end of the recording (1031:35).

FDR data before 1021:01 showed no abnormal voltage or current indications. At 1021:01, the voltage of the APU battery decreased from 32 to 31 volts. Three seconds later, the data showed a change in current flow from 3 amperes out of the battery to between 44 and 45 amperes into the battery.[27] The current flow into the battery occurred for about 4 seconds; the remainder of the recording showed either no current flow or current flow out of the battery. Between 1021:07 and 1021:09, the battery voltage continued to decrease. At 1021:10, the battery voltage returned to 31 volts. At 1021:27, the battery voltage began decreasing again, reaching

[25] Specifically, the EAFR is a multifunction recorder that records flight (FDR) data; audio (CVR) data; and communication, navigation, and surveillance air traffic management messages. The EAFR is a new recording system with a new flight data recording format that allows multiple predefined frames of data that can vary in length and structure. This format provides more flexibility for storing data than older formats that use a single fixed-frame length and structure. The EAFR is currently installed only on 787 airplanes.

[26] A lithium-ion battery was used for the recorder independent power supply.

[27] This behavior was consistent with the BCU attempting to charge the battery.

28 volts at 1021:30, and the APU shut down 7 seconds later.[28] Table 2 shows selected events recorded before and after the APU shutdown. The FDR did not record any data indicating that the APU battery voltage had exceeded 32 volts.

Table 2. Events surrounding APU shutdown.

Time	Event
1000:24	Airplane touched down.
1004:10	APU started.
1006:15	Airplane completed turn into parking location.
1006:48	Parking brake set.
1006:52	Engine 1 shut down.
1006:54	Engine 2 shut down.
1021:01	APU battery bus voltage decreased from 32 to 31 volts.
1021:04	APU battery current increased from 3 amperes out of the battery to between 44 and 45 amperes into the battery.
1021:07	APU battery bus voltage decreased to 30 volts.
1021:08	APU battery current flow returned to 3 amperes out of the battery.
1021:09	APU battery bus voltage decreased to 29 volts.
1021:10	APU battery bus voltage increased to 31 volts.
1021:15	Engine indicating and crew alerting system (EICAS) message discrete indicated that the APU battery failed.
1021:27	APU battery bus voltage began decreasing 1 volt per second during the next 3 seconds.
1021:30	APU battery bus voltage reached 28 volts.
1021:37	APU battery bus voltage decreased to zero volts and returned to 28 volts three times, and APU battery current began to move between zero and 4 to 5 amperes out of the battery.
1021:37	APU controller went offline, and APU had shut down.
1021:37	Aft EAFR stopped recording. Forward EAFR continued recording for about 9 min 58 seconds.
1021:40	EICAS message discretes indicated that the left and right 1 and 2 AC buses became unpowered.
1021:41	EICAS message discrete showed that the APU battery failure was no longer indicated.
1022:00	EICAS message discrete indicated that the main battery was discharging.
1022:10	APU controller went back online.
1022:53	EICAS message discrete indicated that the main battery power switch was off.
1023:16	Airplane systems providing data to the EAFR had shut down.
1031:35	Forward EAFR stopped recording.

Note: The APU controller is the source of 32 recorded parameters, including APU shaft speed and APU battery bus voltage.

The EAFR has an integral flight data acquisition function, which receives data from various sources and then transmits those data to the FDR function according to a predetermined schedule for storage into crash-protected memory. If no new value has been received since the last time that a parameter's value was sent to the FDR function, the flight data acquisition function continues to transmit the last value received from the source. These data are referred to as "stale data."

For some parameters, the flight data acquisition function has multiple prioritized data sources from which it receives parameter values. For these parameters, a separate source index

[28] Key parameters that showed the APU battery failure and APU shutdown are presented in figure 2 of the FDR Group Chairman's Factual Report, which is available at www.ntsb.gov in the public docket for this incident (DCA13IA037). The EAFR records two parameters that indicate the APU battery voltage. Details about the sources of these parameters (APU_Batt_VDC_A and DCBus_APU_Battery_Volts) are included in addendum 1 of the FDR Group Chairman's Factual Report.

parameter that indicates the source being used is generated by the flight data acquisition function and then recorded.[29] For parameters with a source index, stale data are indicated by the source index being set to "no source available." Parameters that have only a single source do not have a source index parameter and thus do not have a recorded indication that the data could be stale.[30] This recording methodology can lead to cases in which apparently valid data continue to be recorded after a parameter source stops providing valid data. This problem delayed the NTSB's complete understanding of the recorded data during the initial stages of this investigation. Section 2.6.1 discusses issues associated with stale data in analyzing accidents, incidents, and maintenance events.

1.4 Incident Battery Examinations

1.4.1 External Observations

The APU battery was examined at the NTSB's materials laboratory in Washington, DC. Observations were documented using a numbering system designating the front of the battery (facing the external power connectors) as side 1, the left side as side 2, the back of the battery (facing the back wall of the aft E/E bay) as side 3, and the right side as side 4.[31]

Side 1 (forward face) of the battery case exhibited black residue and white powdery material on the exterior surface, which were consistent with thermal damage from the flames reported at the front of the case and the application of a dry chemical fire-extinguishing agent by the JAL mechanic, respectively. Side 2 (left side) of the battery case appeared to have the least visible damage of the four battery sides, with some soot residue and an area of buckling observed.

Side 3 (aft face) of the battery case appeared to be more damaged near side 4 than near side 2. Vertical black streaks, which were consistent with residue from dripping liquid, were observed toward side 4 in a location that corresponded to the right aft corner of the battery lid. A roughly oval deposit of black residue appeared on the side 3 upper portion near the side 4 edge. Side 3 had a mostly circular distortion near the lower corner adjoining sides 3 and 4. This distortion was a paint discoloration with about a 1-in diameter and a 0.25-in-wide nodular protrusion in the middle. The protrusion, which is discussed in more detail in section 1.4.4, was located about 1.5 in from the bottom and left edge of the battery case.

Side 4 (right side) of the battery case appeared to have the most extensive damage of the four battery sides. The exterior was heavily coated with black residue that was concentrated near side 3. Thicker black deposits were visible on the right side near the battery lid. Large, mostly

[29] In many cases, a source index parameter defines the source of a group of parameters that are transmitted to the EAFR from the same group of sources.

[30] Left and right radio altitude are among the mandatory parameters that do not have a recorded indication that the data could be stale.

[31] When facing aft in the airplane, the left and right sides of the battery correspond with the left and right sides of the airplane.

circular areas of thermal damage to the paint were located at the same elevation as the battery cell vent discs (as viewed from the exterior).[32] An area of thermal damage to the paint was adjacent to and opposite from the cell 6 vent disc. A distortion and an area of missing paint and soot were adjacent to and opposite from the cell 7 vent disc. Paint discolorations were visible at the cell 5 and 8 vent locations.

The lid on the battery case was bulged and creased. The right aft lid corner (as viewed from the front of the battery case) exhibited more soot, charring, and residue than the rest of the lid and the most damage to the lid fastening points.[33] Figure 6 shows the bulged battery case lid and side 4 of the battery case.

Figure 6. Right aft corner of the battery lid and side 4 of the battery case.

In addition, the NTSB's examination of the battery found no external fire or heat source that would have caused the battery to overheat (thermal abuse), no impact or other forces imposed on the battery from external sources (mechanical abuse), and no external shorting of wires (electrical abuse) associated with the battery system.

[32] A vent disc is a scored plate that ruptures when the internal pressure in a cell reaches a predetermined level. The battery was configured with the vent disc for each cell oriented toward the exterior of the battery.

[33] Eight mounting tabs were used to attach the battery lid to the battery case, and screws were used to fasten the mounting tabs. The two mounting tabs on side 1 remained engaged with the screws. The mounting tabs on sides 2 through 4 had torn from the screws by gross deformation and overstress. The torn mounting tabs and their fracture surfaces exhibited deposits consistent with breakage during the battery failure.

1.4.2 Radiographic Examinations of Incident Battery and Cells

The NTSB conducted radiographic examinations at Chesapeake Testing in Belcamp, Maryland, to examine and document the internal configuration of the incident airplane's main and APU batteries before disassembly and six of the eight APU battery cells after removal from the battery.[34] The batteries were documented using x-ray computed tomography (CT) scans and digital radiography, and the battery cells were documented using CT scans. The images of the components were examined for signs of missing or damaged parts, contamination, or other anomalies.

The CT scans of the main battery showed no anomalies outside the cells. (The main battery cells were subsequently examined for internal anomalies, as discussed in section 1.5.1.) The CT scans of the APU battery showed a breach of the battery case that corresponded with a breach of the cell 5 wall. The CT scans of the APU battery also showed that several cells were distorted with an expanded or a contracted profile, as shown in figure 7; several current collectors inside the cells had separated from their header assemblies; and some current collector fingers were out of their designed parallel alignment.

[34] Cells 2 and 8 were not included in the radiographic examinations because those cells were used to validate the cutting procedure that would be employed during the NTSB's internal examinations of all of the cells (see section 1.4.5). Cell 2 was chosen for the procedure because the cell exhibited relatively less thermal damage and cell case deformation than other cells in the battery. Cell 8 was also chosen for the procedure because, on the basis of available external cell evidence, that cell was the least likely of the more heavily damaged cells on the right side of the battery (cells 5 through 8) to have been the origination point for the event. In addition to the radiographic examinations of the batteries and cells, neutron computed tomography studies were conducted at the National Institute of Standards and Technology in Gaithersburg, Maryland, to examine and document the material distribution on the header assembly of each cell in the incident battery.

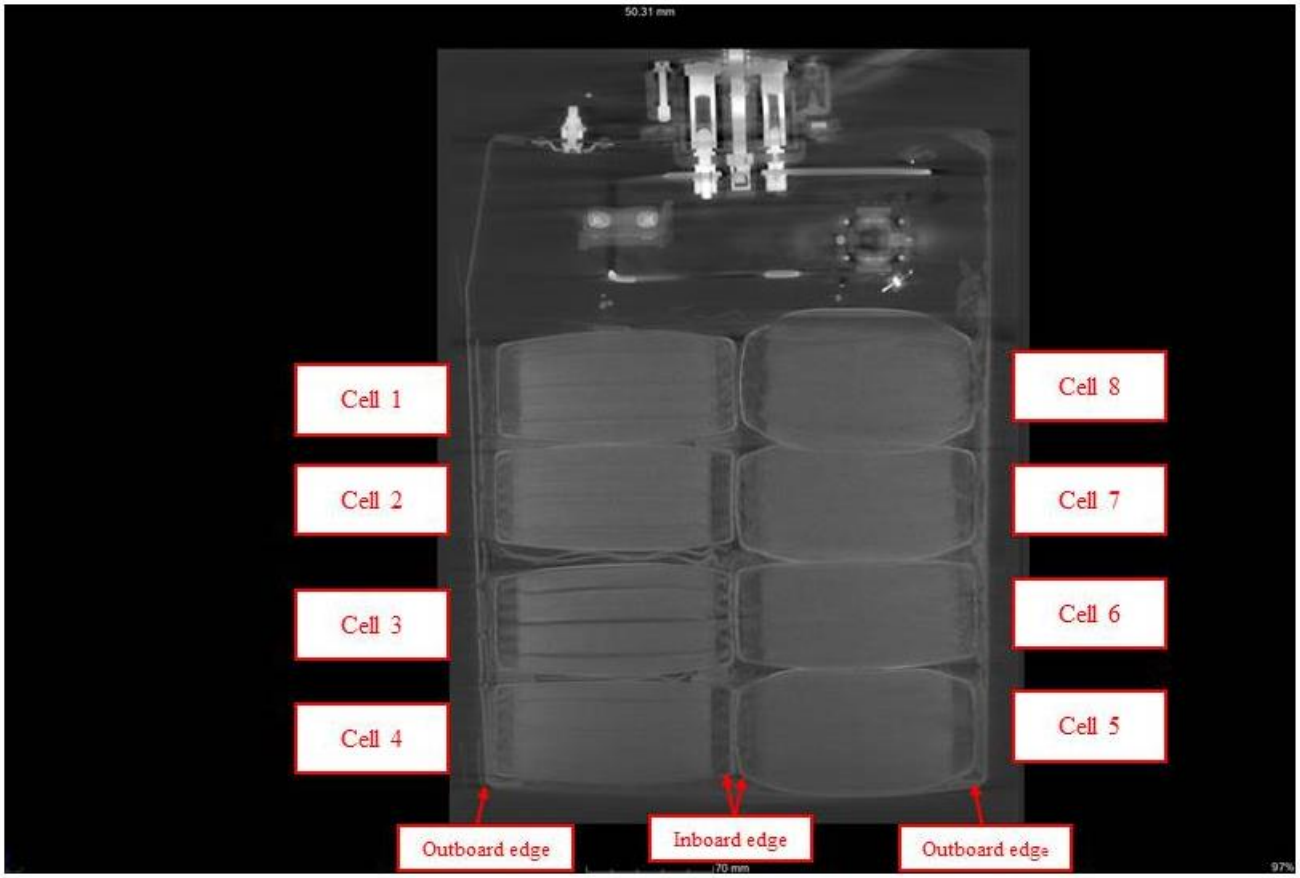

Figure 7. Cross-sectional view of the APU battery.

Note: This image was taken at the approximate midpoint of the cells. Due to the orientation of the incident APU battery during CT scanning, the resulting images appeared as mirror images of the battery. Thus, the orientation of the cells in this figure is different than the orientation of cells in other figures showing the APU battery.

The six individual APU battery cells that were examined were cells 1 and 3 through 7. The CT scans for cells 1 and 3 showed that the cells' current collectors were intact and that the windings were not uniform in some areas due to ripples and separations. The CT scans for cell 4 showed that the cell had no separations within the winding layers and that the current collectors were intact. Findings from the CT scans for cells 5, 6, and 7 included the following:

- Cell 5: Two cell wall breaches in separate locations were identified. The larger of the two breaches appeared to consist of separate smaller holes. The smaller breach appeared to consist of a single hole with some material missing from the outer cell wall around the hole. The areas inside the cell near the breaches differed from the general appearance of the cell. Also, two of the six aluminum (cathode) current collector fingers had breaks with rounded material on the ends. These breaks, as shown in figure 8, appeared as complete separations through the fingers. The current collector finger breaks occurred in the center winding. The other four aluminum current collectors and all of the copper (anode) current collectors were intact.

- Cell 6: Four of the six aluminum current collector fingers had breaks, as shown in figure 9, including one with breaks at multiple locations and another that was missing more material at the breakage location than the other current collector fingers with breaks. The current collector finger breaks occurred in the winding closest to cell 5 and the center winding. The other two aluminum current collectors and all of the copper current collectors were intact.

- Cell 7: Four of the six aluminum current collector fingers had breaks, including one with multiple breaks. All six current collector fingers appeared to be displaced from their original positions. The current collector finger breaks occurred in the winding closest to cell 6 and the center winding. The other two aluminum current collectors and all of the copper current collectors were intact.

Figure 8. Cross-sectional view of cell 5 aluminum current collectors.

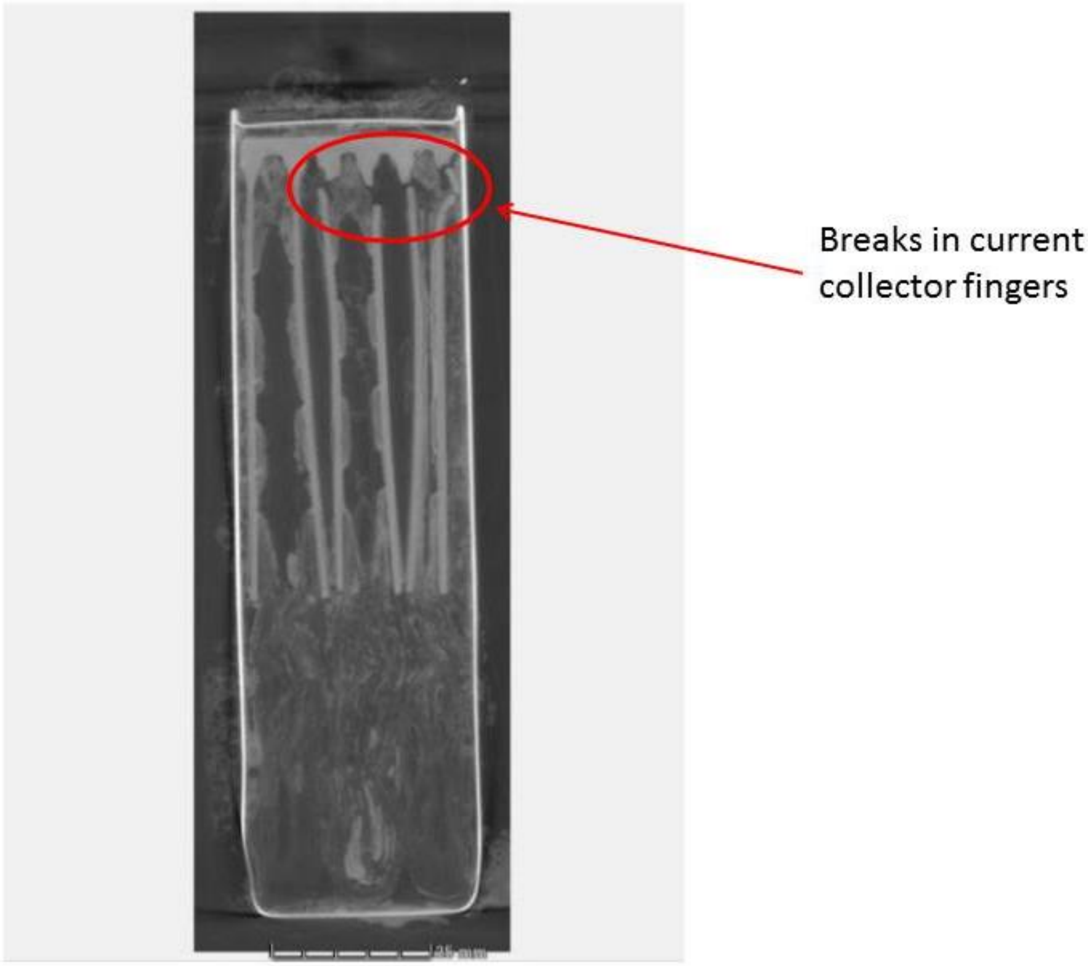

Figure 9. Cross-sectional view of cell 6 aluminum current collectors.

1.4.3 Disassembly of Incident Battery

After charred debris from the top of the battery case was removed, the physical condition of the BMU's sensing wiring harness was examined and was found to have damage consistent with exposure to a high-temperature environment. The damage to the wire insulation degraded progressively from the left side of the battery (cells 1 through 4), where the insulation was thermally discolored, to the right side of the battery (cells 5 through 8), where the insulation was missing for cells 5 and 6 (mostly in the position of cell 5), charred for cell 7, and thermally discolored for cell 8. Also, the wires above cells 5 and 6 were bare, indicating that the area of the most severe thermal damage to the wiring harness was located above cells 5 and 6.

Side 2 of the battery case was folded down to reveal cells 1 through 4. The insulation sheet adjacent to the battery cells remained in place. Behind this insulation sheet, a portion of the other insulation sheet was visible but was missing some sections. Although the insulation between cells 1 through 4 was damaged, the material could be distinguished from other thermally damaged material in the battery case. The interior surface of side 2 had a clean area with a similar outline to that of an insulation sheet. The rest of the interior surface of side 2 was coated with residue.

Battery case side 4 was folded down to reveal cells 5 through 8. The cells exhibited a darkened, charred appearance. The insulation sheets were completely charred and could not be distinguished from each other and other thermally damaged material in the battery case, and portions of the charred insulation adhered to the cells. The interior surface of side 4 had portions of the charred insulation adhering to areas where the insulation sheets contacted the interior surface. The rest of the interior surface of side 4 was coated with residue.

Side 3 of the battery case was folded down to reveal the sides of cells 4 and 5. The side of cell 4 had staining that resembled a flowing residue. The side of cell 5 had similar staining but also had a cleaner area on the cell case without staining, combustion products, and fire-extinguishing residue. The corresponding area on the interior surface of side 3 was similarly clean and had large portions of insulation that had adhered to the case. The insulation on side 3 was thermally degraded and fragmented, and the portions of the insulation adhering to the battery case directly behind cell 5 exhibited some thinning.

The battery case contained no foreign object debris (FOD). There was no evidence of cell-to-battery case shorting before the thermal event, bus bar shorting, or resistive heating of the bus bars (including those leading to the J1 connector through the contactor and Hall effect current sensor) within the battery case. There were no loose electrical connections at terminals or on BMU wires. There was also no visible evidence of water (resulting from condensation) within the battery case or external surfaces of the battery cells.

Cells 1 through 4 exhibited the least thermal and mechanical damage. Of these cells, cell 3 appeared to be the most thermally damaged. Cells 1 through 3 had vented (with their vent discs opened slightly), and the cell 4 vent disc remained intact.[35] Even though the cell 4 vent disc did not rupture, weight measurements for the cell were lower than specifications.

Cells 5 through 8 exhibited the most thermal and mechanical damage, as shown by the thermal decomposition and degradation of the materials in contact with these cells. These materials included bisphenol A thermoplastic polyester and crystalline thermoplastic; the lowest decomposition temperature of these materials is 550ºF. Thermal damage was the most severe near cells 5 and 6, as shown in figure 10. The vent discs on cells 5 through 8 had ruptured in a manner indicative of a rapid pressure release.[36] Cells 5 through 8 sustained gross mechanical plastic deformation with cells pressing into adjacent cells.

[35] The vent discs are scored with an “x” pattern, which enables preferential tearing when the disc ruptures, creating four independent petals. For the vent discs on cells 1 through 3, the four petals had parted slightly but remained in the same plane.

[36] For the vent discs on cells 5 through 8, the four petals were generally splayed out and positioned out of plane with each disc’s original position, which was indicative of a more forceful opening than that for the vent discs for cells 1 through 4. For cell 5, the petal closest to side 1 of the cell was completely missing.

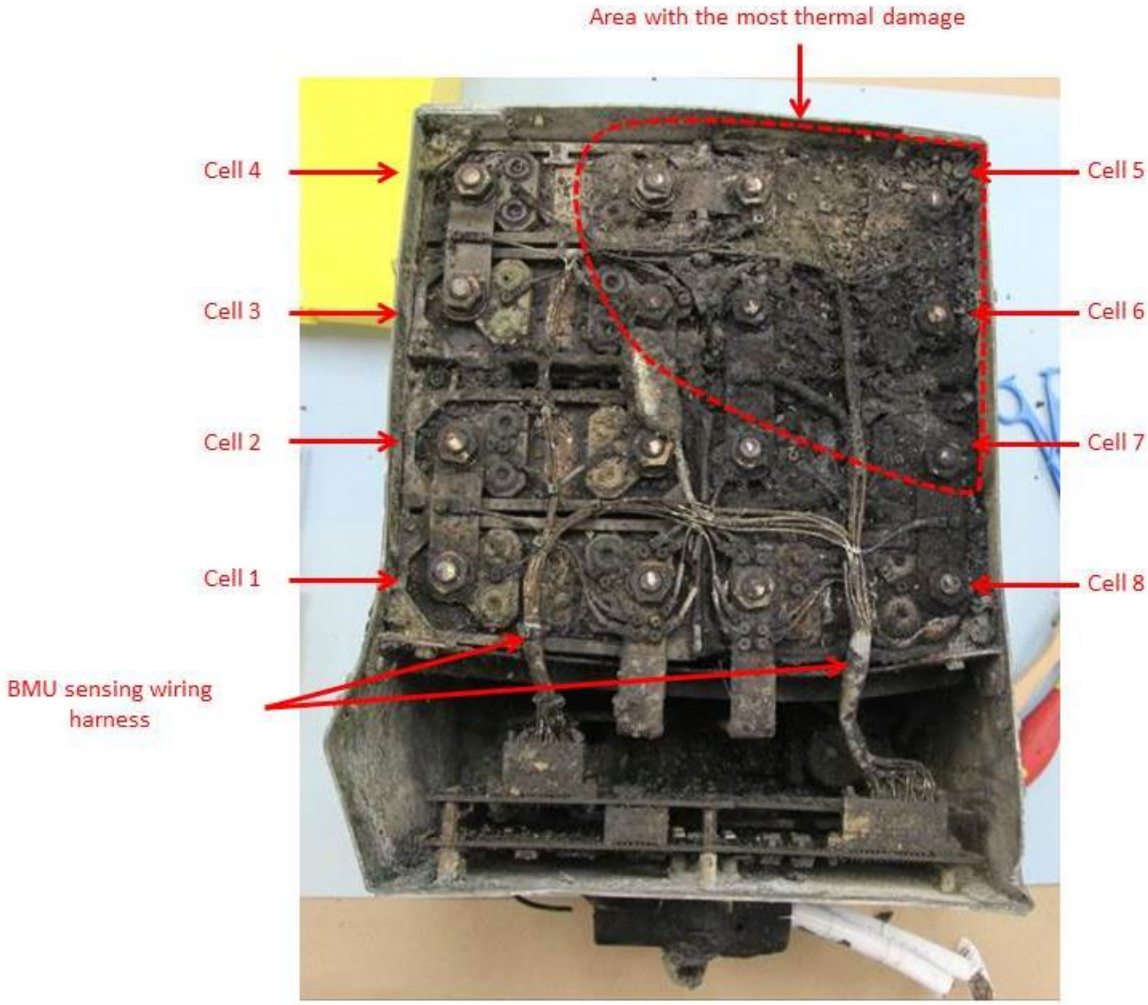

Figure 10. Thermal damage to battery.

The bus bars were removed from the cell terminal assemblies to allow extraction of the battery cells. The electrical contact surfaces of the bus bars showed no indications of localized resistive heating or arcing.

Debris and discoloration consistent with thermal damage were present on the cell 1 through 4 footprints on the lower fixation tray. The footprints of cells 5 through 8 were thermally decomposed, as shown in figure 11. Portions of the lower fixation tray under cells 5 and 6 could not be readily distinguished from other thermally damaged materials in the battery case. The portions of the upper fixation tray that contacted cells 1 through 4 sustained less damage than the portions that contacted cells 5 through 8. The cell 4 upper fixation tray imprint remained mostly intact, but the imprints for cells 1 through 3 showed progressively more damage. Minimal material remained from the portions of the upper fixation tray that contacted cells 5 through 8, which is also shown in figure 11.

Figure 11. Lower and upper fixation trays.

The J3 connector and receptacle were also examined. The J3 connector had dark deposits on one of the blades on the positive terminal. Analysis of the dark deposits revealed the presence of a hydrocarbon. The other blades on the positive terminal and the blades on the negative terminal of the connector appeared clean with no deposits, stains, or discoloration. The J3 receptacle had thermally induced deformation in one corner. The terminals on the receptacle showed no indications of deposits, stains, or discoloration.

1.4.4 Battery Case Protrusion and Corresponding Cell Case Damage

As stated in section 1.4.1, the battery case exhibited a 0.25-in-wide nodular protrusion on the lower left of side 3, as shown in figure 12. The protrusion extended about 0.12 in from the case. The protrusion appeared metallic and had no paint. Two concentric rings surrounding the protrusion corresponded with the discoloration of exterior paint. Deposits consistent with thermally degraded materials were observed on and near the protrusion. Three holes on the periphery of the protrusion were identified. The largest of these holes was elliptical in shape, with its longest dimension measuring 0.080 in. The two other holes, which were similar in size, measured about 0.004 in. Most of the interior side of the protrusion contained dull gray flaky material consistent with spatter, as well as shiny black material consistent with charred plastics and tars.

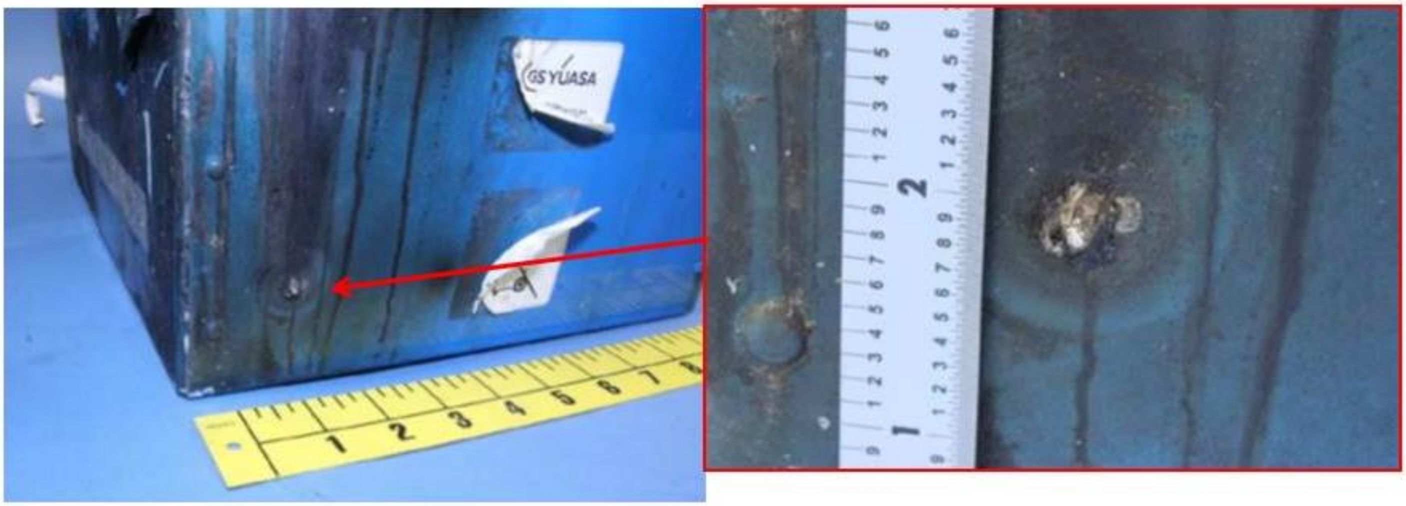

Figure 12. Protrusion on the lower left of battery case side 3.

The side of the cell 5 case that faced side 3 of the battery case had been heavily damaged, especially toward its edges and corners. Four holes were identified on the lower portions of this side of the cell case, all of which exhibited large amounts of dark, rough-appearing features consistent with decomposition products. The largest hole (in terms of size and amount of decomposition products) was about 0.2 in; this hole corresponded with the location of the protrusion on the battery case.

The battery case protrusion was examined using a scanning electron microscope (SEM) and energy dispersive x-ray spectroscopy (EDS). The examinations found that the observed damage was consistent with electrical arcing and contact between the cell 5 case and the battery case.[37] (Before contact, the cell 5 case was located about 0.2 in from the battery case with a plastic insulator in the space.) Specifically, evidence of material transfer between the cases was found on the interior surface of the battery case and the exterior surface of the cell case. Also, the battery case exhibited no inward deformation at the protrusion, but the cell case exhibited outward expansion. SEM and EDS examinations further showed that all the holes on the cell 5 case contained various compounds and alloys that were not consistent with the cell case material (a stainless steel) but were instead consistent with the battery case material (an aluminum alloy).

1.4.5 Disassembly of Incident Battery Cells

The NTSB conducted a teardown of each individual battery cell to determine whether the cells contained any anomalies.[38] The teardown, which was conducted in the NTSB's materials

[37] The other seven cells did not exhibit any evidence of electrical arcing on the exterior of the cell cases.

[38] Cell observations were documented using a numbering system that was similar to that for the battery. The front of the cell (facing the J1 and J3 power connectors) was designated as side 1, the left side was designated as side 2, the back of the cell (facing the back wall of the aft E/E bay) was designated as side 3, and the right side was designated as side 4.

laboratory, consisted of disassembling the cell cases, removing the electrode windings, separating the individual windings from the header assembly and current collectors, and unrolling the individual windings. Internal evaluations of each cell consisted of visual, chemical, electrical, and other observations about the overall condition of the internal cell components, the internal surface of the cell case, the current collectors, the header assembly, and the windings.

The windings had been heavily damaged as a result of the incident. The internal evaluations of the cells found no evidence of preexisting defects in, or internal damage to, the copper anode, aluminum cathode, or polyolefin separator. There was also no evidence of preexisting current collector separation, FOD of sufficient size within the cells to cause an internal failure that could lead to thermal runaway, and lithium deposits within the cell windings.

As stated in section 1.4.3, external observations of the cells showed that cells 5 through 8 were more thermally damaged than cells 1 through 4. In particular, the thermal damage to the materials near cells 5 through 8 and the opened vent discs of those cells (with the vent disc petals either missing or peeled outward from the cell cases) were consistent with a higher pressure, more energetic event in cells 5 through 8 compared with cells 1 through 4. The internal examination of the cells showed differences in the degradation of materials that were also consistent with higher temperature exposure in cells 5 through 8.

Cells 1 through 4, when opened, were generally wet and had a smell consistent with liquid electrolyte. The components of cells 1 through 4, including the anode, separator, and cathode, were found intact with most damage limited to a change in opacity in portions of the separator, which was consistent with the activation of the shutdown properties of the separator.[39] Damage patterns in cells 1 through 4 were consistent with greater external thermal exposure on battery side 4, which was closest to cells 5 through 8. The damage patterns were also consistent with less external thermal exposure on side 2, which faced the exterior of the battery case. In general, the windings for cells 1 through 4 exhibited damage consistent with greater thermal exposure on the exterior of the cells and the sides that were closer to other cells compared with the interior of the cells and the sides that were exposed to open areas within the battery case. There was no visual evidence of electrical short circuits found in the windings of cells 1 through 4.

Cells 5 through 8, when opened, were dry and did not have a smell consistent with liquid electrolyte. The components of cells 5 through 8 exhibited evidence of damage consistent with high heat exposure and localized high current, including several aluminum current collector fingers that had separated from their header assemblies. For each cell, the aluminum cathode was heavily damaged and was missing large sections of the foil. The copper anode was generally intact but contained pinholes and discolorations with areas of missing active coating material. The separator was missing, which was consistent with thermal exposure above the melting

[39] The separator is opaque but becomes more transparent as it thermally degrades. When this degradation occurs, the pores in the separator close, shutting down the lithium-ion transport between the anode and cathode. The shutdown properties of the separator activate just before melting begins.

temperature of the separator material. Sections 1.4.5.1 through 1.4.5.4 provide additional details about the teardown of cells 5 through 8, respectively.[40]

1.4.5.1 Cell 5

The cell 5 examination found evidence of arcing damage on the cell case interior and relatively minor damage to the winding adjacent to the protrusion in the battery case. The cell case was mostly intact. The lower half of the winding closest to battery case side 3 and adjacent to the protrusion in the battery case had adhered to the cell case. The appearance of the cell case and the adherence of the electrodes were consistent with localized heating, melting, separation, and solidification from electrical arcing. No visible portion of the thermoplastic insulation in the cell case remained. Black residue was present on the interior surfaces of the cell case and the exterior of the windings. SEM/EDS analysis found that the chemical composition of the residue was consistent with that of the thermoplastic insulation.

The condition of the aluminum cathode and the copper anode in each winding was consistent with high heat exposure. Most of the cathode material was present but was brittle. Most of the uncoated aluminum foil (at the edges of the windings) remained intact, but portions were missing. The coated aluminum foil was discolored and fractured with areas of the foil missing generally near the header (top) or footer (bottom) fold. Most of the missing aluminum foil had melted and solidified into oblong-shaped globules. The copper foil was intact but had discolorations and small pinholes that propagated through several wraps. The coating on the copper foil had mostly flaked off. The separator was not found during the examination.

For the winding that was closest to battery case side 3, the copper foil was discolored at the header fold with small ripples. The copper foil also exhibited a band of darker color adjacent to the nodular protrusion, which was consistent with high heat exposure. This band of color propagated from the exterior to interior wraps of the winding. The center winding copper foil had ripples along the header fold. This winding appeared to have more overall damage than the other two windings. The winding closest to cell 6 showed the most fragmentation of the aluminum foil and the coated material. The first and second wraps of the winding had thermally adhered to the interior of the cell case, and portions of the first wrap had also thermally adhered to subsequent wraps of the winding. One of the innermost wraps showed folds in the copper foil on the side facing cell 6, which were present through several layers of the winding, as shown in figure 13. Other notable features found during the winding examination were the lack of any sizeable repeating rifts in the windings and the greater amount of damage to the exterior wraps of the windings compared with the interior wraps.

[40] For additional information about the teardown of cells 1 through 4, see Materials Laboratory Factual Report 13-060, which is available at www.ntsb.gov in the public docket for this incident. Also, during the teardown of the eight cells, numerous specimens were excised to examine, using SEM and EDS, the physical and chemical characteristics of various internal components. Materials Laboratory Factual Report 13-060 also includes information from these examinations.

Figure 13. Cell 5 winding closest to cell 6.

The pair of aluminum current collectors for the center winding (which in this cell were adjacent to the vent disc) were no longer connected to the header assembly. The detachment of the current collectors occurred at the top of the current collector fingers where the collectors were designed to act as a fusible link. SEM examinations found that the breaks were consistent with thermal fracture associated with high current, as shown by the CT scans of the rounded features at the fracture surfaces (see figure 8). The two other pairs of aluminum current collectors and the three pairs of copper current collectors were intact.

1.4.5.2 Cell 6

The interior of the cell 6 case exhibited a blackened appearance. Portions of the windings and other charred materials were stuck to the bottom of the case on sides 1 and 3. There was no evidence of electrical arcing or short circuits between the windings and the cell case.

The windings exhibited varying degrees of thermal damage based on the amount of aluminum cathode material remaining and the thermal discoloration of the copper anode foil. The winding closest to cell 5 had the least cathode material remaining, and the winding closest to cell 7 had the most cathode material remaining, which was consistent with higher temperatures on side 3 of the cell that tapered off toward side 1. The separator material had melted and could not be identified in all three windings.

For the winding closest to cell 5 and the center winding, the aluminum foil was mostly missing, with the active material coating remaining. Remnants of the aluminum foil were visible as specks or small blobs of solidified aluminum. For the winding closest to cell 7, the aluminum foil was intact but was brittle. The second wrap included an area where the aluminum foil had fused to the copper foil.

For all three windings, large portions of the active material coating for the copper foil had delaminated, exposing large areas of the foil. Pinholes and localized areas of thermal discoloration, which were consistent with localized hot spots, were observed near the edges of the copper foil. The winding closest to cell 5 showed areas of concentrated thermal discoloration that appeared in a repeating pattern on the copper foil, as shown in figure 14. One area of thermal discoloration began on multiple exterior wraps and became lighter toward the interior wraps. Another area of thermal discoloration began about midway through the wraps and continued all of the way to the interior wraps. This pattern of thermal discoloration, which was concentrated on the side of the foil closest to the copper current collectors, exhibited a radiating pattern of wrinkles. The center winding showed an area of thermal discoloration that began at one of the outermost wraps and continued into the winding. The winding closest to cell 7 showed a repeating area of thermal discoloration at one of the outermost wraps.

Figure 14. Cell 6 winding closest to cell 5.

The current collector sides of the winding assemblies (cell sides 2 and 4) appeared blackened and charred and had no remaining insulation material. The copper current collectors were intact and attached to the windings. The aluminum current collectors exhibited fractures with areas of missing material, and two of the three pairs of aluminum current collectors (those in the winding closest to cell 5 and the center winding) had fused and were disconnected from the header assembly. The other pair of aluminum current collectors were intact.

1.4.5.3 Cell 7

The condition of the cell 7 electrodes was consistent with high heat exposure. The three windings had varying amounts of the aluminum cathode foil remaining. The winding closest to cell 8 had more aluminum foil and active material remaining than the two windings that were closer to cell 6. In each of the windings, the coated aluminum was discolored and fractured with areas of aluminum missing generally near the header or footer fold.

The copper anode foil in the winding closest to cell 6 was discolored at the header fold and had small ripples. The copper foil in the center winding was missing a section adjacent to the vent disc, which was consistent with high thermal exposure. The missing section propagated through the winding, with the most material missing from the exterior of an outermost wrap. The copper foil in the winding closest to cell 8 was discolored at the header fold and contained small ripples in a radiating pattern. The separator was not found.

The pair of aluminum current collectors for the center winding and the pair for the winding closest to cell 6 were no longer connected to the header assembly. The separation in these current collectors occurred at the top of the current collector fingers where the collectors were designed to act as a fusible link. The center winding current collector fingers were separated in one location, and the current collector fingers closest to cell 6 were separated in several locations. The other pair of aluminum current collectors and the three pairs of copper current collectors were intact.

1.4.5.4 Cell 8

For cell 8, there was no discernible difference in the amount of thermal damage between the cathode and anode sides of the winding assemblies. All of the current collectors were intact and showed no readily identifiable abnormalities.

Portions of copper anode windings adhered to the side 1 and side 3 surfaces of the cell case and exhibited hues of purple and blue, consistent with exposure to high temperatures in an oxidizing environment. The cell case surfaces did not reveal any evidence of electrical arcing. The side 2 and side 4 surfaces exhibited a blackened appearance, and charred thermoplastic insulation had adhered to the surfaces. The bottom of the cell case also exhibited a blackened appearance with pieces of charred material adhering to the bottom surface.

The aluminum cathode foil in all three windings was found melted and discontinuous, but the winding closest to cell 7 appeared to be exposed to the highest temperatures because the aluminum foil in the center winding and the winding closest to the BMU had more intact aluminum remaining. (More aluminum remained on the winding closest to the BMU than on the center winding.) For each winding, the copper anode foil could be seen in the areas where the aluminum foil was missing. Small globules of solidified aluminum were interspersed throughout the remaining carbon active material. The separator material had completely melted and could not be identified.

For the winding closest to cell 7, most of the copper foil exhibited discoloration consistent with severe thermal exposure, particularly along the edge where the electrode attached to the current collector near the header fold of the winding. This discoloration continued throughout the winding. The center winding and the winding closest to the BMU showed concentrated thermal discoloration along the edge of the copper foils where they had been attached to the current collector near the header fold of the windings. This discoloration also continued throughout the windings. Areas speckled with small holes appeared throughout the copper foils, some of which continued through several wraps of the windings.

1.4.5.5 TIAX Examination of Cell Teardown Samples

The NTSB contracted with TIAX LLC of Lexington, Massachusetts, to independently examine and analyze cell 6 samples (which included remnants from all three cell windings) to determine if any internal short circuit indicators were present. TIAX's examination of the cell 6 evidence confirmed the findings of the NTSB's cell 6 examination (TIAX *Review* 2013). For example, TIAX determined that the winding closest to cell 5 was more thermally and physically damaged than the other two windings, with almost no aluminum cathode foil remaining; the winding closest to cell 7 had the least damage. TIAX found that most of the aluminum current collectors and all of the separators had melted and that a major portion of the copper (anode) current collectors remained.[41] TIAX also found that most of the copper current collectors had small holes, especially near wrinkled and folded areas of the copper foil. TIAX found no evidence of foreign metal.

TIAX's examination of the winding closest to cell 5 showed regions of thermal discoloration on the copper current collector. TIAX indicated that such areas could be consistent with the presence of an internal short but that it was not possible to determine whether a short could have occurred locally or developed from an external source.

TIAX's examination of the remaining copper current collectors showed that, in the winding closest to cell 7 and the center winding (which, as previously stated, were less damaged than the winding closest to cell 5), the windings' outer regions appeared more damaged thermally than the inner regions. TIAX indicated that this observation was consistent with "an origin of thermal stress" outside these windings with elevated temperatures that decreased toward the windings' inner regions.

Some abnormalities were observed in multiple regions of the windings. For example, a significant amount of beaded metal was observed around the edge of an irregularly shaped hole in a copper current collector in the winding closest to cell 5. TIAX noted that this type of formation could indicate the highest temperatures reached during the incident. The NTSB analyzed the ridges using EDS and found that the beads at the edge of the irregularly shaped hole were copper, which indicated that the hole had resulted from the melting of copper.

1.5 Exemplar Battery Examinations and Testing

1.5.1 Radiographic Examinations of Exemplar Battery Cells

Additional radiographic studies were conducted to examine and document the internal configuration of individual battery cells from five batteries. One of the batteries was the main battery installed on the incident airplane (referred to as battery 412); the other four batteries (referred to as batteries 149, 305, 344, and 376) were provided by Boeing.[42] These batteries had been installed on 787 airplanes being assembled at Boeing but were removed before any flight

[41] TIAX referred to the current collector fingers and the foils of the electrode winding assemblies as current collectors.

[42] The battery numbers reflect the battery serial numbers.

time because the batteries overdischarged and latched.[43] The CT scans of these cells were examined for indications of missing or damaged parts, contamination, or other anomalies.[44]

The CT scans showed that all of the cells from all five batteries contained areas of wrinkled and/or separated windings. Three batteries (149, 376, and 412) showed an anomaly (specifically, a small protrusion from the insulator) in the aluminum terminal plate for one cell; one battery (305) showed this anomaly for two cells. Battery 305 showed a measureable angle between the aluminum current collectors and the cell header in one cell; battery 149 showed this condition for two cells. (The measured angles ranged from about 1.0º to 1.7º.) Battery 149 also showed a localized bulge in one cell's wall. In addition, battery 305 showed copper current collectors that had out-of-alignment clips in two cells.

1.5.2 Cell Soft-Short Tests

A soft short can occur when the electrical isolation between the positive and negative electrodes of a cell is compromised. TIAX indicated that features creating soft shorts could reside undetected within a cell and develop slowly over time. TIAX further indicated that some soft shorts could dissipate over time, whereas others could become severe enough to result in the early failure of a battery (a loss of capacity and failure to hold a charge) or progress to "a more serious, higher-magnitude short" that could cause "catastrophic failure of the cell" (TIAX *Report* 2013).

The Naval Surface Warfare Center, Carderock Division, and TIAX performed two different types of nondestructive soft-short testing. A total of 40 cells from the incident airplane main battery and the four batteries that Boeing provided were used for the soft-short testing. The test results were used along with the radiographic examination results (discussed in section 1.5.1) to identify possible cells for TIAX's destructive physical analysis (DPA) of an exemplar battery cell, as discussed in section 1.5.3.

The Carderock soft-short testing involved a procedure that monitored cell self-discharge rate decays, which, for lithium-ion cells, occur from current leakage across the separator.[45] The test procedure discharged cells to a low state of charge, removed the discharge load, and observed the cells during a 1- to 2-week period to determine whether any anomalous decays in cell voltage occurred.[46] (Voltage decay is an indicator of a potential soft-short formation within

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[43] Overdischarging of the battery occurs when the battery or any cell is below a predetermined voltage. If a cell's voltage drops below the predetermined level, the BMU latches a fault and prevents the battery from recharging.

[44] Before CT scanning began, the five exemplar batteries were disassembled at the Naval Surface Warfare Center, Carderock Division, US Department of the Navy. During disassembly, the batteries were evaluated for construction consistency and the presence of FOD. No anomalies were found.

[45] The Carderock soft-short testing was based on the Darcy test method, which was developed by the battery group lead for projects and integration at the National Aeronautics and Space Administration's (NASA) Johnson Space Center in Houston, Texas.

[46] State of charge is the percent of electrical potential between the designed minimum and maximum voltage potentials.

the cell.) None of the eight cells from the five batteries exhibited anomalous decays in cell voltage during the observation period.

The TIAX soft-short testing involved (1) charging each cell individually to the nominal voltage of 3.7 volts, (2) placing each cell test group in a pre-test configuration for 12 hours to equalize any variations in the state of charge, and (3) connecting each cell group to soft-short test instrumentation and monitoring the response of each cell for 24 hours to measure the level of self-discharge of each battery cell.[47] (According to TIAX, an internal short could have "an anomalously higher level of self-discharge" compared with other cells in the test group.) TIAX's report on the testing indicated that "all [40] cells showed normal (short-free) response characteristics."

UL conducted additional soft-short-related tests, referred to as aging sorting tests. UL conducted these tests to identify cells with possible internal anomalies because, according to UL, cells with such anomalies could exhibit higher self-discharging rates than cells without internal anomalies (Tabaddor and others 2014). The testing, which was conducted at temperatures of 77ºF, 32ºF, and -0.4ºF, produced generally consistent results among the cells in each battery. The testing found all but one cell to be within acceptable limits. (At -0.4ºF, a cell in one battery displayed a performance change in the discharge rate that differed from the other cells; this characteristic had not been displayed at other temperatures, and the specific cause of the difference was not determined.)

1.5.3 Examinations of Cells From the Incident Airplane Main Battery

TIAX and UL performed separate DPAs of cells from battery 412 to note any abnormalities in the cells. The laboratories used different methods to conduct the DPAs, but both laboratories' DPAs found areas in the cell windings that were susceptible to lithium deposits.

TIAX conducted coin cell tests before its DPA to determine the anode-to-cathode ratio in the cells and the tolerance of the electrodes to the specific charging conditions likely to lead to lithium deposits.[48] The coin cells were built from samples of electrodes and electrolyte harvested from cell 4 in battery 344. According to TIAX, the tests showed that (1) the anode-to-cathode ratio had "a large anode capacity excess," which would be consistent with a cell designed to avoid lithium deposits on the anode, and (2) voltage, charging current, and temperature extremes (within allowed operational ranges for the cell) did not produce visual evidence of lithium deposits (TIAX 2014).[49] Thus, according to the results of the coin cell tests, the LVP65 cell chemistry was not susceptible to lithium deposits under high-current or low-temperature conditions.

[47] The TIAX soft-short testing, which was based on a proprietary test method, was quicker and more sensitive than the Carderock soft-short testing.

[48] Coin cells are small specimens extracted from battery cells that are used to examine the electrochemical properties of the anode and cathode, excluding cell- and battery-level effects.

[49] According to GS Yuasa, the 787 battery cells were designed so that the capacity of the anode was greater than that in previous cell designs.

Before TIAX's DPA, cell 1 in battery 412 was charged to the maximum voltage allowed by the BMU (4.2 volts) at the maximum normal charging current (46 amperes) at 32ºF to simulate the worst-case conditions for potential lithium deposits (within the airplane's specified operating envelope).[50] A fully charged cell, in which the anode appears bright gold in color, facilitated the identification of potential abnormalities. This process was repeated 20 times (with rest periods in between each charging cycle) before the DPA was performed. According to TIAX's report, the following abnormalities were observed during the DPA:

- More than 100 areas of "ingressed under-lithiation" of the anode (that is, areas of the anode that were incompletely charged) were found in each winding.

- More than 90 full creases spanning the width of the electrodes and several hundred partial creases (that is, those that did not run from one side of an electrode to its other side) were found in all three windings.[51] The full creases in the anodes were located generally where the connection to the current collectors (along the edges) ended. Many of the full and partial creases showed features consistent with underlithiation of the anode.

- A total of 61 clusters of silver-colored deposits were located in the outer two windings, with fewer clusters located in the center winding.[52] These deposits were generally adjacent to underlithiated areas on the anode. According to TIAX, these areas indicated that mechanical abnormalities in the windings resulted in uneven charging of the anode, which might have caused lithium to deposit adjacent to underlithiated areas.

Samples of the silver-colored deposits observed during TIAX's DPA were analyzed at the Naval Surface Warfare Center, Carderock Division, using x-ray photoelectron spectroscopy. The analysis showed that the deposits contained lithium along with the constituents of the electrolyte (Mansour and others 2014). No metallic elements besides lithium were found.

The DPAs that UL performed were conducted as part of testing to determine whether potential risks of cell degradation, failure, or loss of performance under specific applications, such as low temperature, existed for LVP65 cells. The DPAs involved three cells from battery 412 (cells 3, 5, and 6). All of the test cells were at 100% state of charge (4.025 volts). Cell 3 was subjected to pulse charging at -0.4ºF, cell 5 was subjected to normal constant-current constant-voltage charging at 32ºF, and cell 6 was subjected to pulse charging at 77ºF.[53] The pulse

[50] The DPA could not be performed at the battery's minimum operating temperature (-0.4ºF) because, upon charging at this temperature, the voltage reached 4.025 volts rapidly, causing the current to spike and drop. Thus, high current could not be sustained long enough to produce lithium deposits.

[51] The normal folds at the top and bottom of the windings were not considered to be creases.

[52] Each cluster represented an entire feature area and not the number of individual deposits.

[53] Pulse charging involves applying current in rapid short repetitive intervals. During the UL tests, the intervals ranged from about 0.25 to 0.50 second.

charging tests revealed no lithium deposits in the cell tested at 77ºF and a progressive decrease in charge transfer (cell capacity) as the temperature decreased to -0.4ºF.[54]

Visual examinations of the windings from cells 5 and 6 revealed features consistent with lithium deposits. (UL referred to these deposits as lithium dendrites).[55] No features consistent with lithium deposits were observed in the cell 3 windings. All observed features were found adjacent to wrinkled regions of the windings. According to UL, wrinkles can form dendrites by creating "non-uniform current density distributions" within the windings due to the "uneven contact between the electrodes and separator in a wrinkled region" (Tabaddor and others 2014).

A normal electrode assembly with consistent uniform spacing between the anode and cathode allows uniform lithium-ion transport via the shortest pathway. Thus, an assembly with wrinkled or creased regions could result in non-uniform lithium-ion transport. According to UL, non-uniform lithium-ion transport could also occur from following causes:

- localized deformations of the windings during manufacturing, such as those that occur when flattening the assemblies to the "jelly roll" shape or by stresses resulting from welding the current collectors to the electrodes;
- poor quality control of the coating and winding processes during manufacturing; and
- cell swelling during charge and contracting during discharge, which creates movement of the current collector fingers attached to the windings.

1.5.4 Cell-Level Abuse Tests

UL conducted testing 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 exemplar battery assemblies.[56] The internal short circuits were initiated in a single cell winding using the indentation, nail penetration, or hot pad methods.[57] The tests were conducted at temperatures of 77ºF and 158ºF. Cell temperatures were measured by thermocouples at

[54] In its submission to the NTSB for this investigation, GS Yuasa stated that, after the incident, it conducted more than 100 cold charge cycle tests, all of which revealed a loss of capacity when charging repeatedly at -9.4ºF.

[55] A lithium dendrite is a lithium metal deposit that can form on a coated anode surface. Lithium dendrites can grow over time and cause internal short circuiting. The lithium metal can react exothermically with electrolyte. In addition, lithium dendrites can cause the electrodes to become unstable and thus result in an exothermic reaction. Such reactions at both the anode and cathode, as well internal short circuits from lithium dendrite formation, can result in a thermal runaway (Belov and Yang 2008, 885-894).

[56] Cells 1 through 8 from batteries 149 and 241 were used for the indentation, nail penetration, and hot pad tests; cell 8 from battery 171 was also used for a hot pad test. (Boeing provided batteries 241 and 171, in addition to the previously provided battery 149, for the cell-level abuse tests). A total of 17 cells were tested.

[57] The indentation method, which UL developed, creates a localized, small-scale internal short circuit condition by stressing the electrodes without breaching the cell case. The nail penetration method involves inserting a nail through a cell case to penetrate the electrodes and induce an internal short circuit condition within the cell. The hot pad method involves placing a small electric heating pad on a cell to heat the cell to a desired temperature to induce an internal short circuit condition.

various locations on the cell cases, and cell voltage responses were measured by probes attached to the cell terminals.

During all tests, when the internal short circuit was induced in a single winding of a cell, the cell voltage decreased immediately.[58] The cell voltage then recovered but, within 30 seconds, decreased again and remained at a level consistent with the failure of all three windings (Wang and Wu 2014). The most significant effects observed from the tests included the temperature increase and venting as the cell entered thermal runaway, the decrease and recovery in cell voltage that occurred immediately after the induced internal short circuit, and the fused aluminum current collectors in response to the internal short circuit.[59]

Figure 15 shows the cell voltage output measured during an internal short circuit test. The test was conducted at 77ºF, and the internal short circuit was induced using the indentation method. Region A in the figure shows the fully charged cell before the introduction of the simulated internal short circuit in a single winding of the cell. Region B shows the cell voltage output immediately after the initiation of the internal short circuit but before the failed winding’s current collector fused open. The cell’s temperature reached about 150ºF at this point in the test (about 5 seconds after the initiation of the internal short circuit). Region C shows the voltage output after the failed winding’s current collector fused open and the subsequent recovery of the cell with the voltage output from the two remaining windings. Region D shows the decreasing cell voltage output as the remaining two windings fail due to the heat generated by the first failed winding.[60] The cell’s temperature reached about 500ºF at that point in the test (about 27 seconds after the initiation of the internal short circuit). The cell’s maximum temperature, about 610ºF, occurred about 90 seconds after the initiation of the internal short circuit.

[58] For the 158ºF tests, the voltage drop was between 0.50 to 0.75 VDC; for the 77ºF tests, the voltage drop was between 1.00 and 1.25 VDC.

[59] Excessive current flow through the current collector finger causes the fuse portion of the finger to heat to the point of melting and open the electrical circuit between the winding and the other windings in a cell. Postincident discussions with GS Yuasa revealed that the current collector fingers were sized to allow for required power loads that the cell would encounter in service without fusing open.

[60] The three electrode windings in the 787 main and APU battery cell design are electrically connected in parallel. When the voltage of a single winding arranged in parallel with other windings drops below that of the adjacent windings, the remaining windings will attempt to charge the lower voltage winding to equalize the voltage across the parallel circuit. The charging currents that result could discharge the remaining windings, causing an overall drop in cell voltage or a rupture of the cell assembly. (Reddy and Linden, 2011).

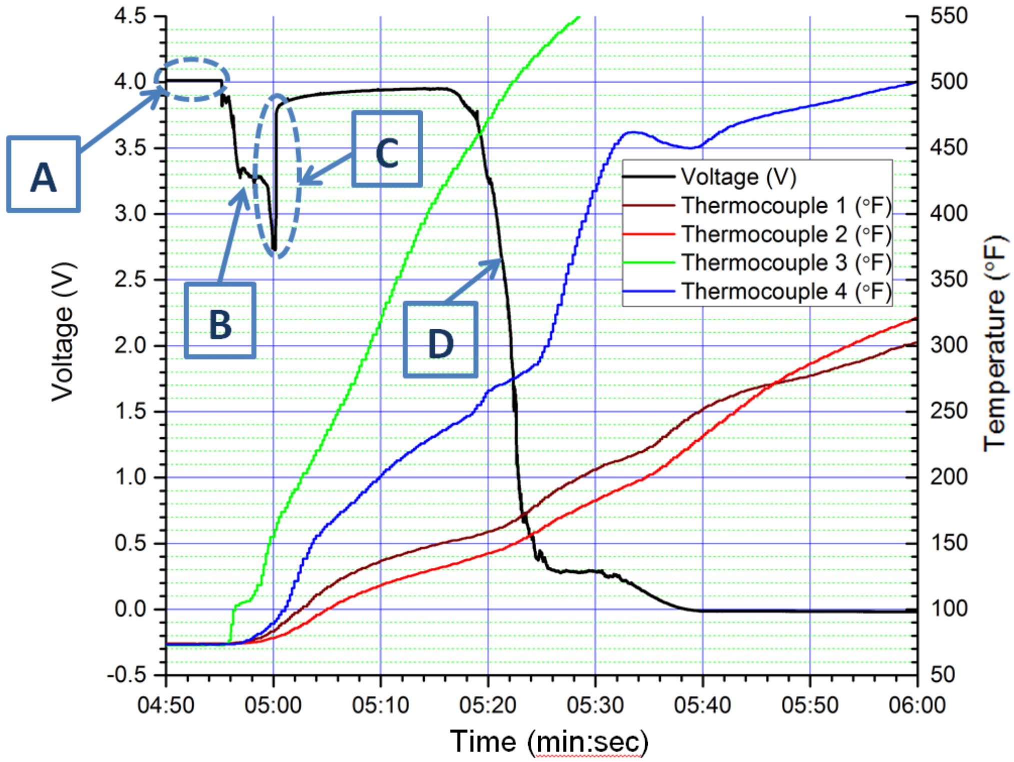

Figure 15. Results of cell-level internal short circuit abuse test.

Note: The preceding paragraph describes each region depicted in this figure. The thermocouples used to measure cell temperature were typically placed at the cell's copper (negative) rivet (thermocouple 1), the aluminum (positive) rivet (thermocouple 2), 0.2 in from the internal short circuit initiation point (thermocouple 3), and 0.1 in from the vent disc (thermocouple 4).

During all indentation and nail penetration tests conducted at 77ºF and 158ºF, the current collector fingers in the initiating outer winding fused open. During some of the indentation and nail penetration testing at 158ºF, the current collector fingers in the center winding also fused open. During all hot pad testing conducted at 77ºF and 158ºF, only the current collector fingers in the initiating outer winding directly adjacent to the hot pad fused open. None of the center or far outer windings had fused current collectors.

When nail penetration testing was conducted at 158ºF on two separate cells with a nail that entered the top of the cells (rather than the side of the cells) and shorted only the center winding, the center winding current collector fingers fused open, and the current collector fingers in the outer windings remained intact.[61] Data recorded during these tests showed that, after the internal short circuit was induced, the cell voltage dropped immediately, abruptly recovered, and then dropped to zero volts. For the tests in which the current collector fingers fused open in the

[61] A similar behavior involving only the center current collector fingers fusing open in the initiating cell was observed during the 158ºF full-scale battery nail penetration test described in section 1.5.7. Also, as stated in section 1.4.2, CT scans of the incident battery showed that, for cell 5, the current collector fingers in only the center winding fused open as a result of the battery thermal event.

outer winding and the center winding, the recorded data showed two separate voltage decreases with two recoveries.

UL's testing showed that, with a significant internal short circuit, the current flow through a winding could reach a level sufficient to open the winding's fusible link. In addition, the testing showed that conduction of the heat generated by an internal short circuit in one winding of a parallel arrangement to adjacent windings could cause thermal damage in those windings and lead to thermal runaway of the entire cell.

Thermal abuse testing performed using accelerating rate calorimetry (ARC) showed that the cells, at zero and 100% state of charge, started to generate internal heat at temperatures as low as 144ºF, which is below the maximum operational temperature of the battery (158ºF).[62] When the ambient condition of a fully charged cell was increased beyond 176ºF, the self-heating rate exceeded 0.04ºF per minute. When the temperature of the cell was raised to about 266ºF, the separator melted, and the cell entered thermal runaway and vented. None of the current collectors fused during the abuse testing using ARC.

1.5.5 Rivet Observations During Cell- and Battery-Level Testing

The aluminum and copper rivets on 787 main and APU battery cells clamp together the electrical components at the top of each cell, including a copper top plate, external and internal thermoplastic seals, and a current collector, to conduct current flow into and out of the cells.[63] The rivets also provide a hermetic seal intended to prevent leakage of electrolyte from the cell case and protect the electrolyte from external moisture. Evidence of rivet seal leakage was found in cell 4 of the incident APU battery, which had melted seals and weighed less than specifications despite the vent disc remaining intact.

During tests to determine the effects of simulated APU starts on individual cells and a complete battery assembly, UL made observations about the aluminum rivets (Wang, Chiang, and Wu 2014).[64] The APU start simulations on a full battery were performed using battery 459 at temperatures of 77ºF and 32ºF after the individual battery cells underwent the same levels of charge and discharge.[65] After a normal battery-level first charge/discharge cycle at 77ºF, the

[62] The cells were slowly heated in an ARC chamber so that an adiabatic condition existed (that is, no heat was transferred between the cells and the surrounding environment) until the cells began to self-heat to the point that they eventually failed.

[63] The aluminum rivets conduct energy from the aluminum current collector, and the copper rivets conduct energy from the copper current collector.

[64] UL disassembled the battery before the battery-level tests to examine and test the individual cells and reassembled the battery afterward using GS Yuasa documentation provided to UL by the NTSB. (The battery could be disassembled and reassembled outside of GS Yuasa.)

[65] The APU start profile is similar to two failed starts followed by a successful start during a short time period using the APU battery as the only starting power source. An APU start discharge attempt at -0.4ºF was not completed because the battery voltage dropped and the test was stopped to prevent battery damage. As shown in UL's test plan (which was distributed to the parties to the investigation before testing began), the discharge rate used during UL's testing was based on the design requirement at the time of certification, and a post-test review found that this discharge rate was not exceeded.

temperature of the aluminum rivets on the positive terminal of cell 5 increased progressively through 14 cycles to a maximum temperature of 315ºF, which exceeded the melting temperature of the separator and the temperature at which the thermoplastic seals begin to soften.[66]

An infrared thermal image taken at 32ºF during the last of the 14 battery-level test cycles showed that the aluminum rivets on cell 5 were sources of heat in addition to heat from the electrode windings. The image also showed that heat was conducted from the cell 5 aluminum rivets through the copper bus bar to the copper rivets on cell 6. Further, strain gauges placed on the sides and tops of the cell cases showed that the stresses in the cells increased during discharge, with cell 5 exhibiting the highest strain during a test at 32ºF. In addition, the efficiency of the cells decreased as temperatures decreased such that 30% of the discharge energy heated the cell when the temperature was reduced to 0ºF.

UL performed subsequent examinations and testing on cell 5 from battery 459, including CT scans; DC resistance measurements; cell leakage tests; and a cell DPA, which included visual inspection of the separator and compositional analysis of the electrolyte. The testing showed that the aluminum rivet seals leaked and that the DC resistance between the aluminum current collectors and the riveted joint was significantly higher (three orders of magnitude) than that of the same joint in other cells. The CT scans revealed visible gaps between the rivet and the current collector (internally) and the rivet and the copper top plate (externally). During the DPA examination, plastic seals were found deformed, and the separator material showed localized melting between the anode and cathode adjacent to the aluminum center winding current collector finger. Separator melting was not observed elsewhere in the windings.

The 787 battery was designed to measure temperature only on two cell bus bars and not at or within each cell. Infrared thermal images and thermocouple data from the UL battery-level testing showed that (1) temperatures were not even across the surfaces of individual cells, (2) the cell temperatures differed from each other, and (3) the bus bar temperatures were lower than the cell temperatures and substantially lower than the temperature at the rivets, and (4) the changes in bus bar temperatures lagged behind the changes in cell temperatures. As a result, UL conducted heat flow tests on a header assembly that had been removed from a cell to determine the internal temperatures of a cell. The interior portion of one of the aluminum rivets was heated until the exterior of the rivet reached the 315ºF maximum temperature measured during the APU start simulations. At that temperature, the interior portion of the rivet measured 332ºF, and the top of the internal aluminum current collector measured 277ºF, which was higher than the melting temperature of the separator.[67]

The NTSB's CT scans of the rivet assemblies in cells from the main battery on the incident airplane (battery 412) revealed gaps and voids between the rivets and assembly components. After the rivet assembly in cell 5 was cross-sectioned, rinsed, and dried, water

[66] During the testing, the temperature of both aluminum rivets was measured using an infrared camera. A thermocouple was also placed on one of the rivets to further measure temperature.

[67] The interior portion of the rivet and the current collector had been within the cell before it was disassembled for the heat flow test.

seeped out of gaps at the edges of the plastic seals in the assembly. The water revealed gaps that were not initially seen under magnification.

Further examination of cell 5 in battery 412 revealed brown deposits that were consistent with dried electrolyte. These deposits were found around a rivet hole of the internal current collector, which had been in contact with an aluminum rivet. Closer examination of the current collector's surface showed evidence of material consistent with oxidation products under the rivet head. The current collector was bent and skewed out from the rivets, and the exterior plastic seal was deformed, diminishing the sealing surface. The deformation caused the plastic sealing surfaces to separate from the top of the stainless steel cell case. Multiple gaps between the contact surfaces were found between the rivet and copper top plate and between the rivet and current collector. The copper plate had a nickel finish, and the shoulder of the rivet had an impressed circular pattern (consistent with machining ridges) that had not been transferred into the nickel plating, which was consistent with a lack of compressive force in this area. The rest of the plating around the rivet hole showed no indications of contact with the rivet.

1.5.6 Cold Temperature Cell- and Battery-Level Testing

The airplanes involved in the BOS, TAK, and NRT events were based in Tokyo and were exposed to below-freezing temperatures during the winter months. At the time of the NRT event, the 787s based in Japan represented less than one-third of the worldwide 787 fleet. Even though other 787 airplanes had occasionally been exposed to below-freezing temperatures while at their base location, the winter temperatures in Tokyo were the coldest of the cities where 787 airplanes were based. The NTSB was concerned that cold weather exposure could be a significant risk factor for the 787 main and APU lithium-ion battery.[68] As a result, UL conducted cold temperature testing at the cell and battery levels to determine the effect that cold temperature charging could have on the battery's performance. During the cell-level testing, the cells heated significantly more when discharged at temperatures between 0ºF and 32ºF than at temperatures above 32ºF.

As previously stated, during battery-level testing at 32ºF, the aluminum rivets on a cell increased in temperature to a maximum of 315ºF, which exceeded the melting temperature of the separator material. Cell disassembly found melting at the edges of the separator layers that had been adjacent to the aluminum current collector fingers. (Such melting was not found during the cell-level tests.) Measurement of the electrical resistance across rivet-to-collector joints after cell disassembly showed that the resistance in a cell that heated (cell 5 of battery 459) was 74.5 milliohms; the resistance of other cells was typically 0.03 milliohm. In its submission for this investigation, Boeing stated that it was revising the low temperature charging limit for the main and APU battery and BCU to "reduce the likelihood of an internal short circuit and improve cell and battery reliability."

[68] In its report on the TAK incident, the JTSB noted the cold temperatures that existed at the time of the three battery events and indicated that cold temperature could be related to the cause of the failures.

1.5.7 Battery-Level Nail Penetration Tests

UL conducted nail penetration tests on LVP65-8-402 batteries to determine the effects of a simulated short circuit within a single cell. The nail penetration tests were conducted with battery numbers 436 and 445, which Boeing provided in addition to the other 787 exemplar batteries.[69] A specially designed nail with an embedded thermocouple (which provided a single temperature within the nail-penetrated cell) was used during the tests.

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 (Chapin and others, *NTSB Battery Tests [Asset 445]*, 2014).[70] The battery temperature at the start of this test was between 52ºF and 57ºF, which was consistent with temperatures in the E/E bay during a typical flight, as measured by Boeing.[71] In another test, the battery was not electrically grounded (similar to the test setup used by GS Yuasa in a 2006 battery development test, as described in section 1.7.3), and the test was conducted at the battery's maximum operating temperature of 158ºF (Chapin and others, *NTSB Battery Tests [Asset 436]*, 2014).[72]

The test with the electrically grounded battery showed that thermal runaway occurred when a short circuit was induced into a single cell inside the battery, 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 discharge through the ground wire circuit.[73] 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 examination of the battery found evidence of arcing between the nail-penetrated cell (cell 6) and the battery case, including welding of the cell case and the center brace bar of 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 results of GS Yuasa's battery development test (venting of the

[69] Before the testing, the batteries were disassembled so that nondestructive tests could be performed. Cells 1 and 2 from battery 445 were damaged during disassembly, so they were replaced with identical cells from battery 271, which Boeing also provided.

[70] The battery case, when installed in the airplane, is grounded via the 787 common return network. 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).

[71] APU battery temperature was not recorded on the incident EAFR. After the incident, Boeing monitored E/E bay temperatures during several flights and reported average values of 50ºF to 59ºF during a typical flight.

[72] UL's reports on these tests included detailed information about the test facility, test fixture, instrumentation, data acquisition, test procedures, and results.

[73] As previously stated, 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 resistive heating associated with the flow of high levels of electrical current. Also, the shielded signal wires exhibited signs of internal heating that were consistent with resistive heating by high levels of electrical current.

nail-penetrated cell and no propagation to and venting of other cells), but the NTSB notes that GS Yuasa performed its battery test at a temperature that did not represent the battery's maximum operating temperature under normal conditions (158ºF). The post-test examination of the ungrounded battery used for the UL test found no evidence of arcing between the nail-penetrated cell (or other vented cells) and the battery case.

The findings of these tests were part of the basis for Safety Recommendations A-14-32 through -36, which were issued in May 2014 (see section 1.8.2).

1.5.8 Additional Testing

Early in the investigation of the BOS incident, the NTSB performed ATP functional testing of the BCU of the incident airplane's APU battery at Securaplane's facility. At the request of the JTSB, the NTSB also performed ATP testing on both BCUs from the airplane involved in the TAK incident. As stated in section 1.2.2, the ATP testing revealed a previously unknown electrical oscillation in the output charge voltage of each BCU. Boeing and UL conducted separate detailed examinations of the BCU from the APU battery that had been installed on the BOS airplane and integrated system testing of a battery, the BCU, and battery-related components. The testing at Boeing and UL found that the oscillation could slightly diminish the battery's life but was unrelated to thermal runaway.[74] As a result of its testing, Boeing changed the BCU design to minimize the oscillation. GS Yuasa conducted testing as part of the JTSB's investigation of the TAK incident and similarly found that the BCU oscillation could shorten a cell's life.

During the investigation of the BOS and TAK incidents, Boeing developed and conducted (along with its contractors) more than 40 different laboratory and airplane tests to understand various battery failure modes. Boeing also performed tests to learn information that would support the redesign of the main and APU battery systems.[75]

Boeing performed a laboratory test to understand the effects of moisture condensing on the battery. This test subjected the battery case and internal battery components to simulated flight cycles in an environmental chamber with varying temperature, pressure, and humidity conditions.[76] After the testing was completed, small amounts of condensation were noted on the top of the cells. The condensation created an electrical short path between the cell case and the battery case. Boeing performed a subsequent laboratory test in which a single cell was placed in a container with saline solution and voltage was provided to represent the other cells of a battery.

[74] One of the reports that UL developed as part of this investigation refers to the BCU oscillation testing as part of the "Noisy Test Procedure" (Tabaddor and others 2014). "Noisy" electrical power refers to the lack of continuous voltage; current; and, if AC power, frequency. UL's report includes specific details about the frequency and current characteristics used for the testing.

[75] For additional information about the testing that Boeing performed, see the testing addendum to the Airworthiness Group Chairman's Factual Report, which is available at www.ntsb.gov in the public docket for this incident.

[76] The battery assembly used during this test did not use actual cells; thermally equivalent representative cells were instead used for the testing.

The single cell vented, and post-test examination revealed damage internal to the cell header, including evidence of arcing, shorting, and heat damage.

Another laboratory test examined the vibration environment of the battery. This test subjected the battery to vibration levels in the pitch, roll, and yaw axes in excess of the levels occurring during in-service operations. The battery's performance was monitored, and the battery was examined, before and after each vibration series. Slight changes in cell case voltages were noted, but no changes in the battery's performance were observed. Post-test examinations of the battery revealed areas of slight abrasions to battery components and one failed BMU sensing wire.[77]

In addition to the previously mentioned integrated battery/BCU system component testing, Boeing conducted flight and ground tests with an instrumented 787 airplane to determine the atmospheric and electrical environment of the system installation. During the flight and ground tests, the battery and charger performed with no anomalies, and no thermal or vibration data exceeded the design requirements. Temperatures for the main and APU battery and the forward and aft E/E bays during the flight tests were comparable with in-service temperatures. Examination of the flight test data showed oscillations during the constant-voltage charging cycle at low-current loading, which were similar to the oscillations observed during the BCU testing at Securaplane. No other abnormal electrical transients were observed in the flight and ground test data.

1.6 Battery Manufacturing Information

1.6.1 Main and Auxiliary Power Unit Battery Development

In 2003, Boeing created a statement of work to outsource the design and manufacture of the 787 power conversion subsystem and awarded this contract to Thales in May 2004. Thales then subcontracted (with concurrence from Boeing) the design and manufacture of the 787 main and APU battery to GS Yuasa and the design and manufacture of the 787 battery charging system to Securaplane Technologies.[78]

Boeing, with participation from Thales, created the specification control drawing (SCD) and interface control drawing to be used during the development and manufacture of the 787 battery and battery charging system.[79] Thales was responsible for providing these specifications to GS Yuasa and Securaplane, managing these subtier suppliers, and meeting all of the

[77] The LVP65-8-403 battery design incorporated improvements to the BMU sensing wiring installation.

[78] Outsourcing is an industry practice that can be practical and effective when all aspects of the design, manufacture, and certification of a component or system have been verified to ensure an airplane's safety of flight. Postincident interviews revealed that all of the companies involved with the design and manufacture of the 787 power conversion subsystem agreed that each would retain ownership of their associated intellectual properties.

[79] According to Boeing, the SCD depicts the performance and design requirements, functional and physical interfaces, and quality assurance requirements for the development, procurement, and configuration control of an item or assembly. The interface control drawing is a formal engineering document that defines, among other things, the interface between mating parts, connections, and signals.

specification requirements for the battery and battery charger system. Thales, along with its subtier suppliers, was also responsible for providing Boeing with required testing and analysis results.

The basic design of the battery began in 2005. As part of the design, GS Yuasa contracted with KAI to design and manufacture the BMU. As the battery design matured, preliminary design reviews and critical design reviews were conducted by Boeing along with Thales and GS Yuasa. Qualification testing was witnessed by delegated representatives from Boeing.[80]

In early 2007, GS Yuasa and Thales redesigned the battery (with Boeing's approval) after a November 2006 fire at Securaplane during the development of the BCU.[81] The redesigned battery included a contactor and a BMU subcircuit card to interrupt charging in an abnormal situation. Qualification testing of this redesigned battery was completed in June 2007. In October 2009, GS Yuasa and Thales redesigned the battery again (with Boeing's approval) after a July 2009 cell venting event at UTC Aerospace Systems' Airplane Power Systems Integration Facility (APSIF), where 787 power conversion subsystem components were tested as an integrated electrical system.[82] The redesigned battery included a modified BMU4 subcircuit card to avoid the subsequent recharging of the battery after overdischarge and a battery diode module (added to the electrical system) so that the main battery could be charged only by the dedicated charger and not be inadvertently charged by the airplane's electrical system. The critical design review for this battery redesign was completed in January 2010, and qualification testing was completed in June 2010.[83] (The FAA was aware of both battery events.)

Boeing required its suppliers and subtier suppliers to perform first article inspections (FAI), according to industry standards, on first production runs of any component. The FAI was the primary method for inspecting and testing vendor components and was considered to be an essential step in approving an order or a contract. The intent of the FAI was to determine if a vendor's product met acceptance and quality control requirements to ensure that all engineering, design, and specification requirements were correctly understood, accounted for, verified, and

[80] Qualification tests are performed to demonstrate that a design conforms to a set of requirements, such as the requirements defined in Boeing's main and APU battery SCD.

[81] On November 6, 2006, a fire occurred at the main Securaplane building when a 787 development battery was being charged for a test. The battery had been in use for about 14 months. Investigation of the incident found that thermal runaway of the battery occurred and that the BMU was not connected directly to the BCU. The cause of battery failure was unknown but was surmised to be a cell internal short circuit followed by overcharge of at least one other cell.

[82] On July 7, 2009, an APU battery experienced a loss of voltage and vented electrolyte during integrated system testing at UTC Aerospace Systems' APSIF. An investigation of the incident by Boeing, Thales, and GS Yuasa determined that the failure of the battery most likely resulted from thermal runaway of a single cell due to an internal short circuit created by repetitive overdischarge and subsequent high-rate charging operations. During the NTSB's April 2013 investigative hearing on the BOS incident, Boeing representatives testified that integrated system testing was conducted on the entire electrical system, including the APU and its grounding system, and that a number of protective (non-abuse) tests were conducted to ensure that the APU system would meet its design requirements.

[83] The changes to the battery that were made after the BOS and TAK incidents are discussed in sections 1.2.4 and 1.8.1.

recorded. GS Yuasa accomplished the FAI for the main and APU battery in November 2008, and Thales approved the FAI results in January 2009. GS Yuasa performed another FAI of the battery after its redesign resulting from the APSIF event. Further, in November 2010, Boeing performed an FAI on an LVP65-8-402 battery at GS Yuasa and found that the battery complied with acceptance and quality control requirements.

Boeing's surveillance of Thales was conducted in accordance with contractual specifications and requirements. Boeing also relied on the Bureau Veritas Certification to perform surveillance assessments of Thales twice a year.[84]

Thales conducted two audits of GS Yuasa between the time that battery production began and the incident. These audits, which were conducted in June 2011 and September 2012, found 11 discrepancies, all of which were subsequently closed. None of the discrepancies were directly related to battery or cell manufacturing. Thales reported the results of these audits to Boeing.

Boeing did not conduct any audits of GS Yuasa before the incident and relied on Thales to audit its subtier suppliers.[85] After the incident, Boeing sent an audit team to Thales and GS Yuasa (and KAI) to review the management of subtier suppliers, quality of manufacturing and business processes, and adherence to Boeing standards. The audit found 17 items of noncompliance with Boeing requirements. Most of the noncompliance items at GS Yuasa involved adherence to written procedures and communication with Thales and Boeing regarding authorization for proposed procedural and testing changes for the battery. The noncompliance items at Thales involved adherence to contractual requirements for Boeing's approval on drawing or procedural changes. Corrective actions for all of the noncompliance items have been completed by Thales and verified by Boeing.

The FAA did not conduct any audits of GS Yuasa before the incident.[86] In late January 2013, the FAA conducted an audit of GS Yuasa (and KAI) and found several items of noncompliance, including (1) noncompliance with component/assembly part markings and no traceability to assembly drawings and instructions and (2) noncompliance with assembly and installation instructions of battery components.[87] Corrective actions for these and other items of noncompliance have been completed by GS Yuasa and verified by the FAA.

[84] The Bureau Veritas Certification is an international certification organization that Boeing used to help ensure that its suppliers had an accredited quality management system in place.

[85] Boeing had a source inspector at GS Yuasa, but the inspector was contractually limited to determining whether specific inspection and checklist items, as detailed in agreements among Boeing, Thales, and GS Yuasa, met minimum quality standards. Any issues that the inspector found had to be routed to a US Boeing representative to coordinate through Thales.

[86] The FAA did not consider the 787 battery to be a critical component because the Seattle Aircraft Certification Office (which was responsible for the airplane's certification) regarded the battery as a redundant system. As a result, the FAA's automated supplier selection process, which identifies suppliers for evaluation, did not select GS Yuasa.

[87] Other items of noncompliance involved storage procedures for returned batteries and the root cause and analysis for returned batteries.

1.6.2 Cell Manufacturing Process

After the BOS incident, the NTSB visited GS Yuasa's production facility for the 787 main and APU battery to observe the LVP65 cell manufacturing process, including the electrode coating, winding, flattening, assembly, and postassembly inspection stages.[88] The coating process involved placing a foil roll on a reel in an enclosed case, unrolling the foil, and coating the foil (except its edges) with anode or cathode active material.[89] The machine operator checked the thickness of the coating periodically using a hand-held micrometer. The uncoated area on the edge of the foil material was monitored visually and measured periodically by the operator.[90] During operations in which the foils were unwound, the machine operator also monitored the foil roll for defects such as wrinkles.[91] After one side of the foil roll was coated, dried, and rewound, the roll was inverted, unwound, coated on the opposite side, dried, and rewound. Winding sensors in the machinery were in place to prevent misalignment of the foil roll. The machine operator visually inspected the winding edges for burrs. If defects were found during the coating process, an engineering-level review board would be convened to determine the disposition of the foil material.

Another machine used a cylindrical winding mandrel to wind the cathode and anode foils together with the separator sheets to create the cell windings. Afterward, the machine operator measured the alignment and weight of each winding. The machine operator then partially flattened each winding by hand compression, as shown in figure 16a, and positioned the three windings for final flattening. The final flattening process was accomplished using a compression jig with two flat plates facing the three windings. After final flattening, the machine operator attached heat-resistant plastic tape to the ends of the cell where the curves of the windings were located, as shown in figure 16b. Figures 16a and 16b also show perturbations of the electrode foil that were created during the flattening process.[92]

[88] At the time of the NTSB's visit, GS Yuasa was manufacturing LVP65-8-403 batteries.

[89] As previously stated, the current collectors are attached to the uncoated edges of the electrode winding assembly.

[90] At the time of the NTSB's visit, operators involved with cell manufacturing were working either 0800 to 2000 or 2000 to 0800 (local time) Monday through Friday unless production demands required more work hours. Operators involved in the postassembly CT inspection process received two 15-min breaks and one 45-min meal break during each shift.

[91] GS Yuasa defined "wrinkles" as visible longitudinal or diagonal surface creases in the electrode coating on the foil that occur before the winding and flattening processes.

[92] In this report, a perturbation is defined as a change in the electrode foil nominal form due to compressive buckling.

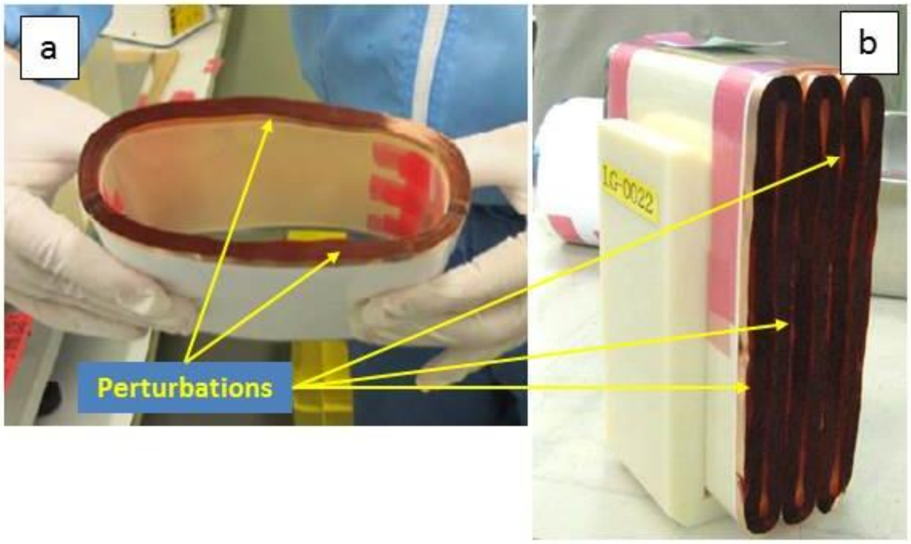

Figure 16. Winding flattening process.

Note: Figure 16a shows an electrode being hand flattened after winding and removal from the mandrel, and figure 16b shows the three-electrode assembly after final flattening and taping.

The flattened three-winding assembly was then manually attached to a prefabricated cell header assembly, which consisted of the cell header cover, two sets of current collectors attached to the cover with insulators in between, and two threaded terminals. Metallic tweezers were used to align the windings with the cell header assembly before manual ultrasonic welding.[93] A vacuum and vacuum brush on the ultrasonic welding machine (operated by a foot pedal) were in place to remove FOD generated from welding. Afterward, the cell was wrapped with an insulating polymer film and heat-resistant tape and placed inside a prismatic (rectangular-shaped) stainless steel cell case.

The next process involved manual tungsten inert gas welding of the header cover to the cell case. During this process, the welded cell was examined visually by an inspector using a magnifying glass to identify potential weld deposit defects. If a defect was identified, the cell case header cover would be welded again. The cell was also inspected for potential damage to the insulating film, excessive heat, and other defects. If such damage was found, an engineering-level review board would determine the disposition of the cell. A prefabricated small hole in the side of the cell case was used to manually fill the battery cell with liquid electrolyte. The electrolyte filling process was performed using three separate steps to prevent overflow, and the cell was precharged to low voltages in between each filling step.[94]

The postassembly inspection process involved examining a cell's interior using CT scans. An inspector viewed the CT image to identify any potential ultrasonic weld defects on the current collectors and any enclosed FOD. (The CT resolution settings were unknown because

[93] Metallic tweezers were used for processes in which precision was needed to assemble parts.

[94] The NTSB did not observe the electrolyte filling process during its visit to GS Yuasa.

they were not supplied to the NTSB.) If a defect was identified, the cell would be subject to further assessment.[95] GS Yuasa stated that less than 1% of manufactured cells were rejected.

1.7 System Safety and Certification

As part of its investigation of this incident, the NTSB reviewed the *Federal Aviation Regulations* and special conditions applicable to the 787 main and APU battery and battery charger system. The NTSB also reviewed the corresponding certification plan, which Boeing developed and the FAA approved. The plan defined the agreed-upon methods to be used to demonstrate that the battery and its charger system met applicable FAA and European Aviation Safety Agency (EASA) requirements.[96] In addition, the NTSB reviewed sections of Boeing's 787-8 electrical power system (EPS) safety assessment that pertained to the main and APU battery, which Boeing developed to evaluate the EPS design for compliance with safety requirements defined by the FAA and EASA.

1.7.1 Type Certification Overview and Battery Special Conditions

On March 28, 2003, Boeing applied for a type certificate for the 787-8 airplane. The FAA's aircraft certification office (ACO) in Seattle, Washington, conducted the certification oversight process. In September 2004, Boeing met with representatives from the ACO to indicate the company's intent to use lithium-ion technology for the main and APU battery on the 787 airplane.[97] At that time, the 787 was expected to be the first transport-category airplane to have permanently installed, rechargeable lithium-ion batteries.[98] 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.[99]

Title 14 CFR 21.16, "Special Conditions," states that, if the FAA finds that airworthiness regulations do not contain adequate or appropriate safety standards for an aircraft because of a "novel" or an "unusual" design feature, special conditions should be issued to prescribe safety standards that establish a level of safety equivalent to that established in the regulations. Special conditions are developed by the appropriate ACO with the applicant's full participation. The ACOs use issue papers to review the adequacy of existing regulations; determine the special

[95] Information about other steps in the cell assembly process (and information about the battery assembly process) is detailed in the Manufacturing Data and Manufacturing Cell Group Factual Report, which is available at www.ntsb.gov in the public docket for this incident.

[96] The 787-8 FAA certification was also validated by EASA.

[97] Boeing also intended to use lithium-ion batteries in the 787's flight control electronics, emergency lighting system, and recorder independent power supply.

[98] After the incident, the FAA stated that the Cessna Citation CJ4 was the first civil airplane certificated with a lithium-ion main battery. The Citation CJ4 is not a transport-category airplane.

[99] The battery regulations that existed at the time were in 14 CFR 25.1353, "Electrical Equipment and Installations," paragraphs (c)(1) through (4).

conditions that would be proposed to address any inadequacies; and track the relevant technical, regulatory, and administrative issues that could arise in certifying the new technology.

In a March 31, 2006, issue paper, "Special Condition: Lithium-Ion Battery Installations" (referred to as Issue Paper SE-9), the FAA stated that, despite limited experience with the use of lithium-ion batteries in commercial aviation applications, other users of lithium-ion batteries, including wireless telephone manufacturers and electric vehicle manufacturers, had experienced safety problems with this technology. These problems included overcharging; overdischarging; and flammability of cell components as a result of the liquid electrolyte, which could serve as a source of fuel for an external fire if the battery case were breached. The FAA also noted that, in general, lithium-ion batteries are "significantly more susceptible to internal failures that can result in self-sustaining increases in temperature and pressure (thermal runaway)" than nickel-cadmium or lead-acid batteries.

On April 23, 2007, the FAA issued a notice of proposed special conditions (*Federal Register* 2007, 21162), which proposed nine safety requirements regarding the use of lithium-ion batteries for the 787 to ensure that these battery installations would not be "hazardous or unreliable." On September 28, 2007, the FAA issued Final Special Conditions 25-359-SC, "Boeing Model 787-8 Airplane; Lithium-Ion Battery Installation" (*Federal Register* 2007, 57842), which became effective on November 13, 2007. The intent of the final special conditions, which are shown in appendix B, was to establish additional safety standards that the FAA considered necessary to provide a level of safety equivalent to the existing standards for aircraft batteries.

According to the 787-8 type certificate data sheet, the airplane received transport-category approval on August 26, 2011. The type certification basis included the 14 CFR Part 25 airworthiness standards and the special conditions for the lithium-ion battery installation.[100]

1.7.2 Certification Plan

FAA Order 8110.4, "Type Certification," described the responsibilities and procedures for the FAA and the type certificate applicant to follow when evaluating and approving design data for new civil aircraft, such as the 787-8.[101] In accordance with paragraph 2-11d(1)(d) of the order, Boeing's 787 EPS certification plan presented a high-level system description of the EPS, which included the main and APU battery and battery charger system; defined the methods (for example, tests and analyses) to show compliance with applicable FAA and EASA requirements;

[100] The applicable regulations were 14 CFR Part 25 through amendment 25-119 and amendments 25-120, 25-124, 25-125, and 25-128 (with exceptions). Other applicable regulations were 14 CFR Part 26, "Continued Airworthiness and Safety Improvements for Transport Category Airplanes"; 14 CFR Part 34, "Fuel Venting and Exhaust Emission Requirements for Turbine Engine Powered Airplanes"; 14 CFR Part 36, "Noise Standards: Aircraft Type and Airworthiness Certification"; equivalent level of safety references; and special conditions for 13 other subjects.

[101] When Boeing submitted its application for the 787-8 type certificate, revision B of FAA Order 8110.4, dated April 24, 2000, was in effect. Revision C of the order was issued on October 12, 2005.

and defined the compliance submittals (that is, certification deliverables) to be provided to the agencies. The FAA approved the initial certification plan on December 22, 2005. Boeing was required to ensure that the certification plan was kept current throughout the 787's design, development, and certification phases, and any revisions to the certification plan were required to be approved by the FAA.

According to Boeing, on January 8, 2007, the FAA approved revision C of the certification plan and indicated that Boeing could proceed with the implementation of the proposed certification activities. Boeing conducted tests and analyses to demonstrate, among other things, that the main and APU battery and battery charger system complied with relevant 14 CFR Part 25 requirements, including sections 25.863, "Flammable Fluid Fire Protection," paragraphs (a) and (b)(3); 25.1309, "Equipment, Systems, and Installations," paragraphs (a), (b)(1), (b)(2), and (c) through (g); and Special Conditions 25-359-SC.

1.7.3 System Safety Assessment

Safety assessments are a primary means of compliance for systems that are critical to safe flight and operation. These assessments are performed by the manufacturer and its suppliers and are reviewed and accepted by the FAA. Safety assessments proceed in a stepwise, data-driven manner to ensure that all significant single-failure conditions have been identified and all combinations of failures that could lead to hazardous or catastrophic airplane-level effects have been considered and appropriately mitigated. The safety assessment process, which is outlined in FAA Advisory Circular (AC) 25.1309-1A, "System Design and Analysis," is not mandatory, but manufacturers that do not conduct safety assessments must demonstrate compliance in another manner, such as ground or flight tests. Boeing indicated in certification documents that it used a version of AC 25.1309 (referred to as the Arsenal draft) as guidance during the 787 type design certification program.[102]

Overall compliance with the applicable 787-8 main and APU lithium-ion battery safety requirements was shown through formal analyses and qualification tests. Thales and GS Yuasa performed these analyses and tests, and Boeing reviewed and approved the results.

Boeing's 787-8 EPS safety assessment, dated September 16, 2009, presented the overall safety analysis of the EPS. This analysis evaluated the design of the EPS for compliance with safety requirements derived from 14 CFR Part 25, EASA certification specifications, Special Conditions 25-359-SC, and accompanying advisory material. For the main and APU lithium-ion battery and battery charger systems, the safety assessment included a failure modes and effects analysis (FMEA) to provide a bottom-up qualitative and quantitative way to identify the effects

[102] In 1996, an FAA aviation rulemaking advisory committee (ARAC) was chartered to harmonize the FAA's practices related to 14 CFR 25.1309 with those of Europe and Canada. The committee released its final report to the FAA in August 2002, but the revised AC 25.1309, referred to as the Arsenal draft, has not yet been issued. On April 29, 2003, the FAA published a notice of availability of the ARAC-recommended proposed changes to the airworthiness standards for transport-category airplanes regarding equipment, systems, and installations as well as the current AC 25.1309 (version 1A). This notice of availability indicated that the ARAC-recommended proposed changes could be used for airplane certification programs through a request for an equivalent level of safety finding.

of a failure at the next (higher) level of a system; a functional hazard assessment (FHA) to determine the potential hazards that various failures of electrical system components could introduce to the airplane and its occupants; and a fault tree analysis for the hazards identified in the FHA.[103]

The FHA identified and classified two hazards associated with the main and APU lithium-ion battery: "battery vents smoke/fire," which was classified as catastrophic, and "battery vent and/or smoke (without fire)," which was classified as hazardous.[104] On the basis of the FHA's results, Boeing defined failure detection and mitigation requirements for the main and APU battery, including the following three requirements related to smoke, gas, and electrolyte release:

- The battery shall have a probability of less than 1 x 10^{-7} for gas emission.
- The battery shall have a probability of less than 1 x 10^{-7} for smoke emission.
- The battery shall be designed to prevent spilling flammable fluid, a hazardous event with a probability of less than 1 x 10^{-9}.

This analysis determined that overcharging was the only known failure mode that could result in cell venting with smoke and fire. As a result, Boeing established additional design requirements to ensure that the likelihood of occurrence of an overcharge event would be extremely improbable (one in 1 billion flight hours or a probability of 1 x 10^{-9}).[105] Boeing further determined that cell venting without fire could be initiated by several different failure modes, including external overheating, external short circuiting, internal short circuiting, recharging a battery that has been overdischarged, a high rate of charging, or charging at cold temperatures.

[103] A FMEA is an analytical process that postulates all known and reasonable failure modes. The FMEA assesses the effects of those failures and documents the effects that the failures could have at the airplane level. The FMEA also supports the development of fault tree basic events. An FHA examines a system's functions and purpose, identifies failure conditions that could occur with a loss or malfunction of the system, and classifies those conditions by severity (at the airplane and system levels). After the hazard classification for a system is established, the manufacturer conducts system-specific safety analyses to identify ways to mitigate the adverse effects of a failure condition. A fault tree analysis is a structured, deductive, top-down qualitative and quantitative analysis that depicts the relationship(s) between each failure condition and its primary cause(s).

[104] The harmonized requirements for 14 CFR 25.1309 define a catastrophic event as one that normally involves a hull loss with multiple fatalities. This event is assigned an allowable qualitative probability of being extremely improbable and an average quantitative probability of less than 1 x 10^{-9} per flight hour. The harmonized requirements for section 25.1309 define a hazardous event as one that normally involves a large reduction in functional capability or safety margins of the airplane with serious or fatal injury to a small number of passengers or cabin crew along with physical distress or excessive workload impairing the flight crew's ability. This event is assigned an allowable qualitative probability of being extremely remote and an average quantitative probability of less than 1 x 10^{-7} per flight hour.

[105] The risk of fire was addressed through overcharge protections. For example, Boeing required that "the battery monitoring unit when combined with the overall battery protection subsystem shall prevent undetected over-charge (over-voltage)."

One of the objectives of a FMEA is to support safety analyses by documenting that there are no known single-point failures that would result in catastrophic failure conditions. Boeing's 787 EPS safety assessment identified no single-point-failure catastrophic effects for the main and APU lithium-ion battery.

Boeing's FMEA was based on information contained within GS Yuasa's FMEA, which GS Yuasa developed with assistance from Boeing and Thales. GS Yuasa's FMEA included a calculation of a representative failure rate for the LVP65 cell. This calculation was based on in-service data from about 14,000 existing large-scale industrial lithium-ion cells manufactured by GS Yuasa, which had a similar design and manufacturing process as the LVP65 cell.[106] GS Yuasa's FMEA indicated that none of the industrial cells had experienced any failures, including venting, electrolyte release, or rupture of a vent disc. (GS Yuasa's FMEA did not include an analysis of usage and environmental similarities between the industrial cells and the LVP65 cells or a discussion of the hazardous effects of a lithium-ion cell failure, including overheating or venting.) On the basis of this information, Boeing determined that the rate of occurrence of cell venting for the 787 battery would be about 1 in 10 million flight hours.

Boeing's 787 EPS safety assessment also included Boeing's analysis of the results of a single development (noncertification) nail penetration test that GS Yuasa performed in November 2006.[107] This test 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. 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.[108]

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.[109] On the basis of this development test and the in-service data of the industrial cell that GS Yuasa designed and manufactured, Boeing determined that the effects of a cell internal short circuit would be limited to (1) the

[106] According to GS Yuasa, failure rate data from industrial cells were used because, at that time, there were no available in-service failure history data for the LVP65 cells. According to GS Yuasa, a cell's failure rate was related more to the cell's manufacturing process and mechanical design rather than the materials used in the construction of the cell. GS Yuasa noted that some variation in chemistry existed between the LVP65 cell and the industrial cell but indicated that the difference in chemistry could impact the effect of the failure and not the probability of occurrence.

[107] Boeing collaborated with GS Yuasa and Thales about the development tests to be performed on cells and batteries. 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.

[108] As previously stated, Boeing reported that E/E bay temperatures during a typical flight ranged from 50ºF to 59ºF.

[109] Tests and analyses that GS Yuasa performed were reviewed by Boeing project engineers, safety reliability and maintainability engineers, and authorized representatives (who acted on behalf of the FAA during certification tasks).

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.

At the conclusion of the 787 testing and safety assessment process, Boeing prepared documentation for the FAA showing Boeing's proposed methods for demonstrating compliance with 14 CFR 25.1309 and each of the nine special conditions in 25-359-SC. The FAA used this information to make findings of compliance. Title 49 CFR 44702(d) allows the FAA to delegate to a qualified individual a matter related to issuing a certificate or a matter related to the examination, testing, and inspection necessary to issue a certificate. In October 2005, the FAA established the organization designation authorization (ODA) program to address delegations to organizations and standardize its oversight of organizational designees.[110] With an ODA, FAA-approved engineering designees in various technical areas act on behalf of the FAA during certification tasks. Boeing, which received ODA approval in August 2009, refers to its engineering designees as authorized representatives. They can make findings, as authorized by the FAA, for certain reports or tests in support of type certification programs, but only the FAA can issue a type certificate. Boeing's and the FAA's roles in the certification of the 787 main and APU battery are further discussed in section 2.5.

1.8 Additional Information

1.8.1 Federal Aviation Administration Actions After Battery Incidents

On January 11, 2013, 4 days after the BOS incident, the FAA announced that it would undertake a comprehensive review of the 787's critical systems with the possibility of further action pending new data and information. The FAA stated that, in addition to a review of the 787's design, manufacture, and assembly, it would verify that the 787 battery system complied with the special conditions that were part of the 787's certification (as discussed in section 1.7 and appendix B).

On January 16, 2013, after the TAK incident, the FAA issued emergency AD 2013-02-51 to address a potential battery fire risk in the 787.[111] The emergency AD "was prompted by recent incidents involving lithium-ion battery failures that resulted in release of flammable electrolytes, heat damage, and smoke on two Model 787-8 airplanes." The emergency AD indicated that these conditions "could result in damage to critical systems and structures, and the potential for fire in the electrical compartment." The emergency AD instructed owners and operators of Boeing 787-8 airplanes to, "before further flight, modify the battery system, or take other

[110] Before that time, designated engineering representatives performed certification activities that the FAA delegated.

[111] Earlier that day, JAL and All Nippon Airways had voluntarily decided to stop 787 operations as a result of the TAK battery event. On January 17, 2013, the Japan Civil Aviation Bureau issued a directive with the same content as FAA emergency AD 2013-02-51. Civil aviation authorities in other countries also required operators of 787 airplanes to temporarily cease operations.

actions, in accordance with a method approved by the Manager, Seattle Aircraft Certification Office."[112]

On March 12, 2013, the FAA announced that it had approved Boeing's certification plan for a redesigned 787 battery system. The FAA stated that the certification plan required Boeing to conduct "extensive testing and analysis" to demonstrate compliance with the applicable safety regulations and special conditions. Also, the FAA stated that the improvements to the battery system included "a redesign of the internal battery components to minimize initiation of a short circuit within the battery, better insulation of the cells and the addition of a new containment and venting system."

On April 19, 2013, the FAA announced that it had approved Boeing's modifications to the 787 battery system, which were designed "to address risks at the battery cell level, the battery level and the aircraft level." The FAA stated that a team of agency certification specialists observed "rigorous tests" that Boeing was required to perform and reviewed a "detailed analysis" of the design changes. The FAA also stated that it would monitor the modifications of the affected airplanes in the US fleet to ensure proper installation of the new design.

On April 22, 2013, the FAA superseded AD 2013-02-51 with AD 2013-08-12, which became effective on April 26, 2013 (*Federal Register* 2013, 24673). AD 2013-08-12 required 787 operators to (1) install main and APU battery enclosures and ECS ducts; (2) replace the main battery, the APU battery, and their respective battery chargers; and (3) revise the maintenance program to include a requirement for replacement of the main and APU battery enclosure vent burst discs.[113] The AD was intended to "allow the aircraft to return to service as soon as possible by mandating a modification that will address the unsafe condition." The AD noted that, for all future 787 airplanes, the replacement batteries, their respective chargers and enclosures, and duct installations would be incorporated before delivery.

AD-2013-08-12 detailed Boeing's measures to improve the reliability of the battery and prevent any hazardous effects on the airplane from a battery failure. According to the AD, those measures are as follows:

- Minimize the Probability of a Single Battery Cell Failure–Each main and APU battery consists of a set of individual cells within a battery case. Each battery cell will be encapsulated to isolate the cell electrically. Locking nuts with specific torque values will be used on every cell terminal to prevent overheating of the terminal due to a loose electrical connection. Drainage within the battery case will be improved to remove any condensation within the battery. The battery monitoring and charging unit will be changed to

[112] One US operator had six 787s in service when the emergency AD was issued. On February 1, 2013, the FAA issued AD 2013-02-51, which stated that emergency AD 2013-02-51 had previously been sent to all known US owners and operators of 787-8 airplanes but that "this AD is effective February 22, 2013 to all persons except those persons to whom it was made immediately effective by Emergency AD 2013-02-51" (*Federal Register* 2013, 12231).

[113] The vent burst discs are frangible discs on the battery enclosures.

reduce the operational voltage range to lessen electrical stress on the battery cell and to enhance overdischarge protection. Boeing has also made mandatory changes to the battery manufacturing and acceptance testing processes to improve the overall quality of the battery.

- Minimize the Probability of Multiple Cell Failure Propagation–Additional insulation will be provided between each battery cell and between each cell and the battery case to thermally and electrically isolate the individual battery cells. High temperature sleeving will also be added to the battery internal wiring harness to protect against short circuits. In addition, cell venting will be added to the battery case to allow any cell [gases], including electrolytes, to escape into the battery enclosure to minimize heat build-up within the battery case.

- Preclude Hazardous Airplane-Level Safety Effects of a Battery Failure That Might Occur–As stated previously, each main and APU battery consists of a set of individual cells within a battery case. The case containing the cells will be secured within a stainless steel, sealed enclosure. This enclosure will be connected to a titanium ECS duct that vents to the outside of the airplane. Should a battery failure occur, and generate significant heat, pressure, and [gases], a metallic frangible disc (also referred to as a vent burst disc) at the interface of the enclosure and vent duct will open and allow the heat, pressure, and [gases] to safely vent overboard through the ECS duct. This will prevent the introduction of any heat, pressure, or [gases] in the electronics equipment bays or any occupied area of the airplane.

On March 19, 2014, the FAA announced the findings of a joint FAA-Boeing team that was formed in January 2013 to review the Boeing 787's design, manufacture, and assembly processes. The team found that the 787 "was soundly designed" and "met its intended safety level" and that Boeing and the FAA had "effective processes in place to identify and correct issues that emerged before and after certification."

In the team's report on its findings, the team made recommendations to further improve Boeing processes and FAA oversight (FAA 2014). The team recommended that Boeing (1) continue to implement gated design and production processes, (2) ensure that suppliers are fully aware of their responsibilities, (3) ensure that suppliers identify realistic program risks, and (4) require suppliers to follow industry standards for personnel performing Boeing-required inspections. The team recommended that the FAA revise its orders on (1) certificate management of manufacturers to recognize new aircraft manufacturing business models; (2) production approval procedures to better address complex, large-scale manufacturers with extended supply chains; and (3) engineering conformity inspections to ensure that they are based on risk. The FAA indicated that it was taking actions to address these three recommendations.

1.8.2 Previously Issued Safety Recommendations

In response to the circumstances leading to this incident, on May 22, 2014, the NTSB issued Safety Recommendations A-14-32 through -36 to the FAA. In its letter to the FAA, the

NTSB stated that the type of failure that occurred during this incident—thermal runaway of a single cell as a result of an internal short circuit and the cascading thermal runaway of other cells within the battery—was not expected based on the testing and analysis of the APU battery system that Boeing performed as part of the 787 certification program (see section 1.7.3). The recommendations asked the FAA to take the following actions to (1) account for internal short circuits and thermal runaway during lithium-ion battery certification tests and (2) ensure the safe introduction of new technology into aircraft designs:

> 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-14-32)
>
> After Safety Recommendation A-14-32 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-14-33)
>
> 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-14-34)
>
> 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-14-35)
>
> 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-14-36)

Boeing's description of the certification testing performed on the redesigned battery model (LVP-8-403) before the 787 returned to service was consistent with the NTSB's certification recommendations. On August 19, 2014, the FAA responded to Safety Recommendations A-14-32 through -36. Section 2.5.3 discusses the FAA's response and the NTSB's classifications of the recommendations.

2. Analysis

2.1 Failure Sequence

According to the available evidence from this incident investigation, the NTSB concludes that the battery failure did not result from overcharging, overdischarging, external short circuiting, external heating, installation factors, or environmental conditions of the airplane. Specifically, EAFR data before the event did not show any evidence of the battery being charged to a level above the designed operating voltage, the battery being discharged to a level below the overdischarge threshold, or any high-current discharges that could be associated with an external short circuit. The EAFR data showed no preexisting battery failure messages indicating that the overdischarge protection circuit had activated. In addition, examination of the aft E/E bay (where the APU battery was installed) showed no evidence of external short circuits, such as chafing on the battery cables, or external sources of heat, mechanical damage, or electrical abuse that could have initiated the battery failure.

Individual component tests (including those for the BCU, SPU, and APU controller) and integrated system tests, which included a BCU and other battery-related components, found no evidence indicating that external components were related to the battery failure. Vibration testing was performed at levels that exceeded in-service levels without damage that could lead to battery failure. A battery-level test showed that condensation could occur within the battery and result in a shorting path between the cell and battery cases, and a cell-level test with moisture showed that a cell failure could occur and result in arcing, shorting, and heat damage internal to the cell header. However, the damage observed during the cell-level test was not found in the cell header from the incident APU battery. In addition, airplane flight test data did not show any abnormal electrical transients that could lead to battery failure.

External observations of the battery case showed more thermal damage on the right side of the case than the left side. The right aft corner of the battery case showed the most thermal damage and the most damage to the case lid and its fastening points. The right aft area corresponded to the positions of cells 5 and 6.

The inside of the battery case, the BMU sensing wiring harness, and the lower and upper fixation trays showed the most thermal damage in the areas near cells 5, 6, and 7. The insulating material between the cells was the most damaged in the areas adjacent to cells 5 through 8. Further, cells 5 through 8 vented, and the petals of their vent discs were splayed out, indicating that the cells vented under high pressure. Cells 1 through 3 also had ruptured vent discs, but they remained mostly in the same plane as the vent opening, indicating that the venting occurred with less force than the venting for cells 5 through 8. This evidence showed that the initiating thermal event and subsequent thermal runaway of additional cells began on the right side of the battery where cells 5 through 8 were located.

CT scans of the battery showed that the aft side of cell 8 had expanded into cell 7 and that cell 7 appeared to have expanded into cell 6, indicating that cell 8 vented after cell 7 and that cell 7 vented after cell 6. CT scans and examinations showed that side 3 of cell 6 (which was closest to cell 5) was slightly convex with a flat area in the middle of the cell. CT scans and examinations also showed that side 1 of cell 5 (which was closest to cell 6) was convex with a concave-to-flat area in approximately the middle of the cell. Although the sequence of whether cell 5 or cell 6 expanded first could not be determined due to the complexity of these features, the NTSB was able to determine that the thermal event initiated in a single cell.

Cells 5 and 6 exhibited comparable internal thermal damage, including the melting of the aluminum cathode, no remaining separator or other insulating materials, and fused current collector fingers. Cells 5 and 6 also showed evidence of internal short circuiting, including pinholes, radiating patterns, and thermal discoloration. The lower and upper fixation trays were more thermally damaged in the position of cell 6, and cell 3 (across from cell 6) exhibited the most thermal damage of the cells on the left side of the battery. Cell 7 also sustained internal thermal damage similar to cells 5 and 6, including two pairs of fused current collector fingers. This thermal damage pattern, centered about the position of cell 6 and extending to cells 5, 7, and 3, is consistent with the battery thermal event originating in cell 6.

The NTSB and UL's postincident testing on individual cells showed that an internal short circuit could cause current collector fingers to fuse open and lead to failure of a cell.[114] Data recorded during these tests showed a distinctive trace in which the cell voltage initially decreased, abruptly recovered, and then decreased to zero volts. The incident EAFR recorded a decrease in battery voltage followed by a single recovery in voltage and then a drop in voltage to a level consistent with one failed cell in the battery. Visual examinations and CT scans showed that one set of cell 5 aluminum current collector fingers (in the center winding) had fused open and that two sets of cell 6 aluminum current collector fingers (in the winding closest to cell 5 and the center winding) had also fused open.

During the individual cell tests in which two sets of aluminum current collector fingers fused open as a result of an internal short circuit, the recorded data showed two separate voltage decreases with two recoveries, which were not seen in the incident EAFR data. In addition, a full battery test that simulated an internal short circuit (via nail penetration) in cell 6 showed arcing between cell 6 and the center brace bar, which was not found in the incident battery. The similarity between the voltage drop behavior observed during testing for a single pair of fused current collector fingers and the EAFR data from the incident and the lack of welding between cell 6 and the center brace bar are consistent with an internal short circuit originating in cell 5.

The NTSB concludes that the battery failure resulted from an internal short circuit that occurred in cell 5 or cell 6 and led to thermal runaway that propagated to adjacent cells. The thermal damage to the battery cells precluded a determination of the cause of the internal short circuit, and postincident laboratory testing and subsequent engineering analysis of potential failure modes were unable to determine the precise cause of the internal short circuit. Possible causes for cell internal short circuits are discussed in sections 2.3 and 2.4.

[114] The NTSB and UL's testing showed that, when current collector fingers fused open only in the center winding, that winding had to be the initiation point of the internal short circuit rather than initiation due to heat from an adjacent cell or winding.

2.2 Emergency Response

The response to the incident was timely. According to airport security camera video, the five BOS ARFF vehicles that responded to the incident did not experience any delay from initial notification to arrival at the scene. The ARFF truck that was positioned near the incident airplane responded to the event within 1 min of initial notification, and the four other ARFF vehicles arrived on scene within 2.5 min of initial notification. The firefighting procedures used during the incident, including the use of Halotron, were appropriate and consistent with guidance in effect at the time.[115]

The incident commander decided to have the APU battery removed from the airplane once the intensity of the battery fire diminished. ARFF personnel encountered difficulties in removing the battery from its installation location, especially given that they could not readily access the battery's quick disconnect knob. One of Boeing's postincident changes to the battery and its installation involved placing the redesigned battery into a sealed stainless steel enclosure connected to a duct that was intended to allow heat, pressure, and gases resulting from a battery failure to vent outside of the airplane. As a result of this change, Boeing created and distributed firefighting procedures for events involving the main and APU lithium-ion battery. These procedures advise ARFF personnel to allow a battery undergoing thermal runaway to vent overboard and then stand by to monitor for additional fire. Thus, during active venting of the 787 main or APU battery, it is no longer necessary for ARFF personnel to enter the E/E bay.[116]

2.3 Cell Manufacturing Concerns

GS Yuasa stated that it manufactured the incident battery according to drawing specifications provided by Thales and Boeing, and GS Yuasa's and Boeing's FAI processes showed that the battery complied with Boeing's acceptance and quality control requirements. However, the NTSB's observations of GS Yuasa's cell manufacturing process identified several concerns.

First, the manual cell winding flattening process can create perturbations (that is, electrode foil buckling) in the windings. Such perturbations (see figure 16) were visually consistent with the wrinkles found in the CT scans of LVP65-8-402 exemplar batteries and those

[115] On June 12, 1995, the FAA issued CertAlert 95-03, which described the approved use of Halotron in airport firefighting operations. Also, Safety Alert for Operators 09013, "Fighting Fires Caused By Lithium Type Batteries in Portable Electronic Devices," which was issued on June 23, 2009, stated that a Halon replacement (Halotron) could be used to prevent the spread of such fires to other flammable materials. At commercial airports, Halotron has been effectively used to fight fires in areas with sensitive electrical equipment, such as that in the aft E/E bay. In January 2014, the FAA issued a report indicating that, for consumer electronic devices, water was "the most effective" in suppressing lithium-ion battery fires and preventing thermal runaway propagation (FAA 2014). The report did not address the use of water for suppressing fires involving large, permanently installed, rechargeable lithium-ion batteries, such as the 787 main and APU battery.

[116] According to Boeing, if the battery is not venting or when active venting is complete, firefighters should enter the E/E bay to ensure that no visible fire source exists. If a visible flame is present, Halon (or Halotron) is the recommended agent for suppressing the fire. Boeing procedures indicated that the battery pack should not be disconnected from the airplane's electrical system by using the quick disconnect knob or cutting the battery cables.

observed during DPAs of the main battery on the incident airplane (as discussed later in this section). The windings are predisposed to such defects because flattening a round cylindrical object into an oval cylindrical object can cause uneven deformation and distortion due to the non-uniform distribution of stress, which results in buckling in areas of compressive stress. Also, subsequent swelling and contracting of the electrodes during charging and discharging can further exacerbate perturbations within the winding layers.

Second, two of the welding operations—ultrasonic welding of the current collectors to the winding and tungsten inert gas welding of the cell header to the cell case—occur in an area where internal cell components are also assembled. Welding can generate FOD in the form of weld spatter and small metallic particles that become airborne. No physical shielding was used at the tungsten inert gas weld station to isolate this FOD-generating process from adjacent FOD-sensitive processes, such as those involving internal components of nearby open cells. Even though the ultrasonic welding machine incorporated a vacuum system to mitigate the amount of FOD generated, this process was observed generating airborne FOD.

Third, some of the cell manufacturing processes were not consistent with industry practices.[117] For example, production of wound prismatic (rectangular-shaped) battery cells is typically performed on a flattened elliptical or rectangular mandrel, which reduces the chance for perturbations and folds during winding, but GS Yuasa used a cylindrical mandrel during the winding process.

The cell electrolyte filling process was also inconsistent with industry practices. The electrolyte was filled in three iterative steps to prevent overflow followed by a precharge to low voltages after each step. GS Yuasa stated that the cell's solid electrolyte interphase (SEI) layer does not form during the precharging process because the final precharge brings the battery to 20% state of charge.[118] Industry practices for electrolyte filling include one-step filling followed by a full charging sequence to develop the SEI layer. Developing the SEI layer is important because it allows safe cell operation during normal charging and discharging, and disruption of the SEI layer could lead to internal short circuiting. It is unknown whether GS Yuasa's precharging process affects the development of the SEI layer or the chemical properties or performance aspects of the cell. GS Yuasa representatives stated that the company has not studied the effect of its iterative electrolyte filling process on battery safety. Thus, the safety effect of GS Yuasa's precharging process during the electrolyte filling process is unknown.[119]

Last, GS Yuasa used CT equipment during the postassembly inspection process to ensure that the current collectors were properly welded to the winding edges and that FOD was not

[117] The industry practices discussed in this section were based on information from (1) discussions with industry personnel, including those from the Naval Surface Warfare Center, Carderock Division; the US Department of Energy; and TIAX; and (2) site visits to other battery manufacturer plants.

[118] During the full initial charge and discharge of a cell, the surface of the anode forms the SEI layer.

[119] Although the NTSB did not observe the electrolyte filling process during its visit to GS Yuasa, the NTSB did observe dried material consistent with solid electrolyte residue on the electrolyte filling container and tube, which was not consistent with industry practices because superfluous solid material introduced into a battery cell could interfere with the battery charging and discharging processes.

enclosed in a cell. However, the resolution settings of GS Yuasa's CT equipment was such that many internal cell features, including individual winding layers, could not be identified during the NTSB's visit to GS Yuasa's facility. As a result, perturbations in the windings and small-sized FOD and burrs might not be recognized with the CT equipment used at the time of the NTSB's visit. GS Yuasa stated that it was not aware that FOD might not be visible on the company's CT scans.

GS Yuasa's CT scans also did not detect features that the NTSB, TIAX, and UL identified during this investigation. For example, TIAX's and UL's DPAs of cells from the main battery on the incident airplane found cell windings with numerous wrinkles, folds, and creases.[120] Also, the NTSB's CT scans of the eight cells in each of the five exemplar batteries (including the main battery from the incident airplane) revealed wrinkled windings, cell-to-cell inconsistencies in the clearances between the current collector fingers and the cell case sides, and variances between the rivet heads of the terminals and the top of the cell windings. GS Yuasa indicated that it did not know whether such features could result from its LVP65 cell manufacturing process and that it did not have a process to inspect for the features.

Manufacturing defects, including FOD, burrs on component edges, and perturbations in windings (which were visually consistent with the wrinkles found in postincident CT scans and cell teardowns), are known to lead to local lithium deposits, perforation of the separator layer, or shorting between electrodes (Mikolajczak and others 2011). During the UL and TIAX DPAs of battery cells from the main battery on the incident airplane, silver-colored deposits consistent with lithium metal were observed adjacent to wrinkles (that is, those features that were visually consistent with perturbations). According to GS Yuasa representatives, the company has not studied the effects of folds and wrinkles on battery safety, performance, and reliability.

GS Yuasa monitors for "wrinkles" (that is, visible longitudinal or diagonal surface creases) in the anode and cathode foils before the winding process but does not monitor for features such as perturbations formed during the winding, flattening, and assembly processes. Further, although GS Yuasa stated that it had a formal process for actively monitoring for and controlling burrs, GS Yuasa's process for monitoring for FOD was not a formal standardized quality control process for locating, reducing, and preventing FOD generation during the cell assembly process.

GS Yuasa performed most of its quality control inspections after a cell was fully manufactured and indicated that less than 1 percent of manufactured cells were rejected. This low rejection rate could be the result of few defects to detect; however, most of the evidence (that is, poor internal manufacturing steps along with the lack of a formal inspection for manufactured defects) indicated that GS Yuasa's inspection process did not adequately screen for defects that developed during the manufacturing process. GS Yuasa's checks during the manufacturing process relied on visual inspection rather than formal sampling processes that included rejection or acceptance criteria.

[120] The wrinkles and folds can modify the anode-to-cathode ratio locally, resulting in lithium deposits on the anode surface.

Vigilance decrements might also have played a role in the inadequate inspection process. GS Yuasa indicated that personnel involved with cell manufacturing for LVP-8-402 batteries worked 8-hour shifts. The visual inspection tasks performed by these personnel were vigilance tasks.[121] Human factors research on inspection indicates that, as time on task increases, defects are more likely to be missed, especially if they seem to rarely occur (Fisher and others 2006, 997-1024).[122]

Industry research on lithium-ion battery hazards showed that, about the time that the LVP65 cells were being manufactured, cell failures in various industries had been caused by, among other things, internal faults resulting from manufacturing defects (Mikolajczak and others 2011). However, GS Yuasa did not establish its cell manufacturing process to minimize the potential for manufacturing defects or develop formal inspection criteria of the cells that would reliably identify any defects that were introduced during the process.

Although GS Yuasa was responsible for manufacturing the 787 main and APU battery and cells, Thales was responsible for providing Boeing with consistent and safe power conversion subsystems (which included the main and APU battery systems) for 787 airplanes. Thales audited GS Yuasa in June 2011 and September 2012, and all of the discrepancies noted in the audits were subsequently addressed. However, none of the discrepancies were related to cell features, such as perturbations created and FOD generated, from GS Yuasa's cell manufacturing process. Postincident interviews revealed that Thales did not recognize that such features could result from the cell manufacturing process or that GS Yuasa's quality controls were not established to detect these features.

Boeing and FAA personnel did not conduct any audits of GS Yuasa before the incident. (Boeing stated that it relied on Thales to audit its subtier suppliers.) Boeing, as the production approval holder (that is, the holder of a production certificate), provided oversight to ensure that its contracted suppliers of the 787 power conversion subsystem adhered to their approved quality control system for the manufacturing of subsystem components. The FAA provided oversight of Boeing to ensure that (1) its contracted suppliers followed approved procedures for the production of products, articles, and parts that conformed to Boeing's approved type design and (2) such products, articles, and parts were airworthy and safe for operations. However, given the observations discussed above about GS Yuasa's cell manufacturing process, Boeing's and the FAA's oversight of suppliers manufacturing the 787 power conversion subsystem components could have been more effective.

The NTSB concludes that GS Yuasa's cell manufacturing process allowed defects that could lead to internal short circuiting, including wrinkles and FOD, to be introduced into the

[121] The NTSB notes that visual inspection tasks performed during 8-hour workdays can lead to vigilance decrements. At the time of the NTSB's visit to GS Yuasa, personnel involved with cell manufacturing were working 12-hour shifts because of the demand for new LVP65-8-403 batteries after the 787 returned to flight.

[122] The greatest performance decrements are expected within the first 30 minutes of time on task; during that time, performance can be reduced as much as 30% but is typically reduced no more than 10% (Teichner 1974, 339-353). A 30% performance decrement is more likely for a highly detectable signal (defect) during a 3-hour period.

Boeing 787 main and APU battery. Therefore, the NTSB recommends that GS Yuasa (1) review its cell manufacturing processes to minimize or prevent defects that could affect cell safety and (2) ensure that its employees are properly trained to identify and eliminate these defects. The NTSB also recommends that Boeing develop or revise processes to establish more effective oversight of its suppliers (including subtier suppliers) to ensure that the product being manufactured adheres to established industry standards. Further, the NTSB recommends that the FAA develop or revise processes to establish more effective oversight of production approval holders and their suppliers (including subtier suppliers) to ensure that they adhere to established manufacturing industry standards.

2.4 Thermal Management of Large-Format Lithium-Ion Batteries

Testing performed during the investigation showed that a cell in a 787 battery assembly generated localized high-temperature conditions during maximum current discharge. This measured high temperature was above the allowable design maximum temperature, which could lead to an internal short circuit and cell thermal runaway. This section describes those test results and discusses the importance of ensuring that large-format lithium-ion battery and cells are sufficiently designed and monitored to prevent degradation that can lead to cell thermal runaway.

2.4.1 Battery Internal Heating During High-Current Discharge

The NTSB and UL performed testing on an exemplar 787 battery to evaluate the battery's performance during discharge under the highest currents that the battery was rated to carry. The testing included simulated APU starts at 77ºF and 32ºF with a high-current load. The battery cell design used riveted joints (part of the terminal assembly in the cell headers) as part of the current conduction path into and out of the cells. The simulated APU start tests revealed significant localized heating near the aluminum rivets of one of the test battery's cells. The temperature change was the greatest during the discharge phase of repeated battery charge and discharge cycles at lower temperatures.[123] The affected cell, located in position 5 of the test battery, began to exhibit a more substantial temperature rise in the area of the aluminum riveted joint compared with the temperature rise in other cells in the battery after the first full charge/discharge cycle of the test. During the subsequent test cycles, the affected cell's temperature increased progressively to a maximum temperature of 315ºF near this joint.

Post-test measurement of the riveted joint of the affected cell showed a significant increase in contact resistance (three orders of magnitude) between the aluminum rivet and the current collector compared with the contact resistance of cells from another 787 battery.[124] Because the heating occurred during periods of maximum current draw on the

[123] In this context, a cycle comprises three high-current discharges followed by one charge. The battery was allowed to stabilize after each cycle.

[124] The affected cell's post-test contact resistance measured between the aluminum rivet and the current collector was 74.5 milliohms, whereas the resistance in the same location for a cell from another battery was 0.030 milliohm. The Boeing battery SCD required contact resistance for new components to be less than 0.025 milliohm.

battery and was localized to the area of the riveted joint, the NTSB and UL determined that the source was resistive heating resulting from current through the area of high contact resistance.[125] The cell's windings were also a source of resistive heating during the simulated APU start testing, with the most significant heating occurring at 32ºF.[126] Although all of the battery cells would have been affected by this heating, only cell 5 showed excessive localized heating near the cell's aluminum riveted joint.

This testing also showed that the heat generated inside the battery during the heaviest current loading condition of a full APU start could expose a cell to temperatures exceeding the maximum approved operating temperature of the battery (158ºF) without detection by the battery's monitoring system. Post-test disassembly and examination of the affected cell showed thermal degradation (melting) along the edges of the cell's separator in the location where the aluminum current collectors attached to the cell windings, indicating that the cell's maximum temperature (at the aluminum riveted joint) exceeded the melting temperature of the separator.[127] The post-test examination of the affected cell also showed that the excessive temperature of the cell caused (1) softening and deformation of the plastic insulator material positioned between the aluminum rivet, the aluminum current collector, and the cell case to provide a hermetic seal at each rivet and (2) electrolyte leakage through the riveted joint.[128] Moisture entering the cell and electrolyte exiting the cell due to the softening and deformation of the seal could degrade internal cell chemistry and lead to cell failure, including thermal runaway.

The NTSB reviewed the design of the 787 main and APU battery cells to determine potential causes of the resistive heating observed near the aluminum rivets. The Boeing SCD for the battery stated that "connector contacts shall be designed to carry the same or better electrical current as the equivalent wire size." However, the aluminum rivet used in the 787 main and APU battery cell had a smaller cross-sectional area than would be required, according to the American Wire Gauge standard, for a wire rated to carry an equivalent current. Further, the Boeing SCD for the battery required terminal attachments to have "a complete metal-to-metal compression system." Examination of the rivet assemblies showed that the riveted joint had no springs or

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[125] The electrical contact resistance between mated components (such as an aluminum rivet and a current collector) is a function of the real contact surface area between interfacing parts of a joint, contact pressure between mating surfaces, surface topography, and the presence of an oxide on mating surfaces, among other factors. The smaller the contact area between interfacing parts of the joint, the higher the resistance to current flow, and the more heat generated. The heat generated when a current is passing through a conduction path is directly proportional to the square of the current multiplied by the resistance of the conduction path.

[126] Testing performed by the NTSB and UL showed that, as the 787 main and APU battery approached temperatures below 32ºF, the battery's efficiency decreased such that 30% of the discharge energy was released as heat instead of usable electrical energy at 0ºF. This heat loss was the result of both electrochemical and resistive heating losses in the cell windings, which increased at colder temperatures. (Lithium-ion cells normally heat during discharge as a result of the electrochemical reaction that occurs within the battery cells. Heat is also produced as a result of resistance in electrical current conduction paths within the battery and cells.)

[127] Boeing's EPS safety assessment indicated that heat-induced shrinkage of a cell separator, such as that observed after the NTSB and UL's testing, is a potential cause of cell internal short circuiting and could lead to thermal runaway.

[128] According to UL, the thermoplastic seals used between the rivets, the cell case, and the current collector can permanently deform when exposed to temperatures between about 176ºF and 230ºF under load.

other compression devices.[129] Thus, the aluminum riveted joint assembly could be a significant source of resistive heating during maximum current discharge conditions for the 787 main and APU battery. Proper sizing of electrical components and positive retention of pressure in a joint are essential in preventing resistive heating, particularly during the most severe discharge current levels for the battery (that is, those that occur during a full APU start).

Another potential cause of the resistive heating was the poor electrical connection between the rivet and current collector components in the riveted joint. During the APU start tests, the excessive heating in the joint became evident only after the affected cell had successfully completed earlier cell- and battery-level simulated APU starts, indicating that the electrical connection between the rivet and current collector components degraded with continued usage. Proper design, manufacture, and damage tolerance of electrical connections among the components of a joint intended to transmit current through the cells is critical to minimize resistive heating inside the battery under the most severe operating conditions during repeated charge and discharge cycles. Testing of large-format lithium-ion batteries designed to carry large currents (similar to the 787 main and APU battery) for other applications showed that heat generated by poorly formed joints can flow toward the internal battery and cell structure, resulting in a considerable temperature increase that can lead to thermal runaway (Taheri and others 2011, 6525-6533).

After the BOS and TAK battery incidents, Boeing modified and recertified the 787 main and APU battery design to prevent a full battery thermal runaway resulting from a cell internal short circuit. The redesign also included a stainless steel enclosure designed to mitigate the effects of a full battery thermal runaway if it were to occur, even though FAA Special Conditions 25-359-SC did not require this enhanced level of mitigation.[130] Preventing cell thermal runaway by minimizing sources of heating is critical to the safety of future lithium-ion battery designs. However, current industry standards for the design and qualification of permanently installed, large-format, rechargeable lithium-ion batteries used on civil aircraft do not include guidance on industry best practices to minimize internally generated sources of heating, such as resistive and electrochemical heating, in the design and manufacture of these batteries.

Identifying and minimizing all sources of heating generated within a large-format lithium-ion battery during operation (particularly heating that can be localized to a cell as a result of electrical current flow through components, connections, and cell windings at lower temperatures) are important parts of the battery's design and manufacturing processes. These

[129] Without such devices, additional causes of joint degradation could include thermal shock, torque applied to the terminal during assembly, bending of the current collectors during the manufacturing of the cell header assembly, manufacturing errors, or the stress created within various cells when the battery is subjected to temperature extremes. A NASA technical standard requires that clamping pressure across semipermanent joints (such as those containing rivets) be consistent with applicable mechanical engineering assembly and installation requirements (NASA 2013).

[130] According to Boeing, the redesigned battery system included changes to prevent and isolate a fault if one were to occur. The redesign incorporated multiple layers of protection, including the new enclosure, to ensure that there would be no impact to the airplane and no possibility of fire if a battery failed. The enclosure was designed to keep any amount of battery overheating from affecting the airplane.

actions are necessary to account for the cumulative effects of electrochemical and resistive heating within a cell or in other locations within the battery to minimize the possibility that a cell (or cells) could be exposed to temperatures above allowed operational limits during high-current, low-temperature discharging that could cause permanent damage to a cell and lead to thermal runaway.

The NTSB concludes that the thermal protections incorporated in large-format lithium-ion battery designs need to account for all sources of heating in the battery during the most extreme charge and discharge current conditions and protect cells from damage that could lead to thermal runaway. Therefore, the NTSB recommends that the FAA work with aviation industry experts to develop or modify design safety standards for large-format lithium-ion batteries to require that sources of excessive heating, including electrical contact resistance from components and connections, be identified, minimized, and documented as part of the design. The standards should include measures for identifying and minimizing potential sources of heating that consider the range of operating temperatures and the most extreme electrical currents that the battery could be expected to experience during repeated charge and discharge cycles.

2.4.2 Cell-Level Temperature and Voltage Monitoring

FAA special condition 1 (see appendix B) required the 787 main and APU battery to maintain safe cell temperatures during any foreseeable charging or discharging condition and any failure of the charging or battery monitoring system not shown to be extremely remote. Maintaining safe cell temperature is critical because, once a cell heats to the point that the SEI layer degrades or the separator becomes thermally damaged, an internal short circuit and thermal runaway can occur. Further, as shown by the affected cell in the NTSB and UL's simulated APU start tests, localized heating of the cell to excessive temperatures occurred rapidly and went undetected by the BMU when the battery was discharged at its maximum current rating. Thus, the thermal management protections incorporated into the battery did not detect the developing temperature exceedance and prevent the cell from reaching an unsafe temperature.

The 787 main and APU battery was designed to measure temperature only on two cell bus bars and not at each cell. The NTSB and UL's simulated APU start tests showed that the temperature sensors on the bus bars recorded a peak value that was less than the cell temperature at the aluminum riveted joint. Thus, the temperature measured on the bus bars did not accurately reflect actual cell temperatures. In addition, the temperatures measured on the bus bars are not recorded by the BMU or at another location in the airplane. Accurate temperature data at the cell level, when monitored and recorded, could allow the battery monitoring system to (1) detect a rise in cell temperature and take actions before the temperature exceeded safe limits and caused damage and (2) provide timely notification to the flight crew or maintenance personnel if required.

Special condition 7 addressed voltage monitoring to prevent overcharging that could lead to thermal runaway. During the NTSB and UL's simulated APU start testing on individual cells, cell voltages (in millivolts) were found to be an important indicator of battery health and could thus be used to mitigate failures. Also, during cell abuse testing, a drop in voltage of an individual cell preceded thermal runaway and venting.[131] The 787 main and APU battery design incorporated provisions to monitor each cell's voltage and inhibit discharging of the battery below a specified voltage to protect the cells against overdischarge. Comparing the voltage drops of various cells during discharge could allow the BMU to inhibit subsequent charging or electrically isolate the cell to minimize further damage to the battery. The voltages measured by the sensors on the 787 cell bus bars were not recorded, and design standards do not require voltage data to be recorded. These data, if recorded, could provide maintenance or engineering personnel with trend data or other important information that could be used to determine the cause of a cell failure.

The NTSB concludes that more accurate cell temperature measurements and enhanced temperature and voltage monitoring and recording could help ensure that excessive cell temperatures resulting from localized or other sources of heating could be detected and addressed in a timely manner to minimize cell damage. Therefore, the NTSB recommends that the FAA work with aviation industry experts to develop or modify existing safety standards related to the design of permanently installed lithium-ion batteries to require monitoring of individual cell temperature and voltage and recording of exceedances to prevent internal cell damage during operations under the most extreme operating temperatures and currents. The NTSB also recommends that, once the guidance requested in Safety Recommendation A-14-115 has been issued, the FAA require type certification applicants to demonstrate that the battery monitoring system maintains each individual cell within safe temperature limits at the most extreme battery operating temperatures and the heaviest electrical current loads approved for operation**.** In addition, the NTSB recommends that the FAA work with lithium-ion industry experts to (1) conduct research into battery monitoring system technologies that could improve the recognition of conditions leading to thermal runaway, (2) develop active mitigation of such conditions to minimize damage, and (3) update design and safety standards accordingly.

2.4.3 Thermal Safety Limits for Cells

Boeing established the 787 main and APU battery's maximum operating temperature (158ºF) at the same maximum operating temperature as that for nickel-cadmium batteries installed in other airplane models. The NTSB and UL's ARC testing on 787 main and APU lithium-ion battery cells determined that the cell began to self-heat at 144ºF.[132] Maintaining cell temperature at or just above a cell's self-heating threshold for an extended period of time could

[131] For example, the testing found that about 0.8 second elapsed between the time that an initial failure in a cell (as indicated by a 20-millivolt voltage drop) was detected and the time when the cell went into thermal runaway and vented.

[132] Different types of cell-level testing are available to determine the onset of cell damage and objectively establish limits for the battery monitoring system to provide a margin of safety. The ARC test is a well-documented technique that slowly heats cells in adiabatic conditions to document the heat absorbed or generated by the cells.

result in thermal runaway.[133] Thus, the upper temperature limit of the 787 battery was inappropriate for the cell materials.

GS Yuasa did not use the self-heating threshold to determine the safe temperature limit for the 787 battery. Instead, GS Yuasa determined the safe cell temperature by conducting a test in which cell temperatures were elevated until cell venting occurred; in another set of tests, the cells were exposed to reduced temperatures for varying durations, and no cell venting occurred. These test methods were inadequate because the cells might not have been at elevated temperatures long enough to go into thermal runaway from the breakdown of cell materials. The temperature at which cell self-heating begins can be an objective measure for establishing a battery's margin of safety.

Thermal runaway due to overheating can occur either rapidly when a cell is exposed to temperatures that are high enough to melt the separator or slowly as the cell's SEI layer degrades when above the self-heating temperature. Research showed that SEI layer damage is cumulative and that the thermal degradation of some commercial cells, when maintained at their self-heating temperature, continued for 2 days before thermal runaway occurred (Mikolajczak and others 2011).

As previously stated, FAA special condition 1 required the 787 main and APU battery to maintain safe cell temperatures during any foreseeable charging or discharging condition and any failure of the charging or battery monitoring system not shown to be extremely remote. However, current aviation industry standards do not define methods to determine safe cell temperature limits. Such standards exist for non-aviation-related applications.[134]

The NTSB concludes that determining the initial point of self-heating in a lithium-ion cell is important in establishing thermal safety limits. Therefore, the NTSB recommends that the FAA work with industry experts to develop appropriate test methods for determining the initial point of self-heating in a lithium-ion cell to establish objective margins of thermal safety for future battery designs.

2.5 Certification Process

Type certification is a regulatory process that the FAA uses to ensure that aircraft product designs comply with applicable *Federal Aviation Regulations* and, as in this case, applicable special conditions. The 787 main and APU lithium-ion battery design was evaluated and approved as part of the Boeing 787 type design certification program. Although the investigation of this incident found that thermal runaway of a cell (due to an internal short circuit within a

[133] According to a NASA technical memorandum, "above a threshold temperature, a 'self-heating' condition could occur due to exothermic reactions occurring internally within the cell. Such reactions may include reactions between lithium and electrolyte and the thermal decomposition of internal cell components. If the internal heat generation is allowed to continue, a catastrophic cell 'thermal runaway' condition could occur, which would be a serious safety concern for a manned application"(Baldwin and others, 2010).

[134] For example, see Sandia National Laboratories' electrical energy storage system abuse test manual for electric and hybrid electric vehicles (Doughty and Crafts, 2006).

single cell of the APU battery) propagated to other cells and resulted in thermal runaway of the battery and fire, this design vulnerability was not identified during the certification of the 787 battery installation.

The NTSB's investigation of this incident found that more effective implementation of the certification process for designs incorporating new technology could be achieved through improvements in several focused areas. These areas include validation of the assumptions made and the data used in preliminary and final safety assessments developed during certification programs and the manner in which the FAA evaluates methods of compliance with special conditions during the certification process, as discussed in sections 2.5.1 and 2.5.2, respectively. Improvements in these areas could help foster better interactions between type design applicants and the FAA to ensure the completeness of data used by the applicant to demonstrate compliance with FAA requirements.

2.5.1 Validation of Assumptions and Data Used in Safety Assessments Involving New Technology

To effectively show compliance with FAA requirements during the certification process, Boeing needed to identify all foreseeable ways that 787 main and APU battery failures could cause the identified airplane-level hazards of venting with smoke and fire (classified by Boeing as a catastrophic event) or venting with or without smoke (classified by Boeing as a hazardous event). Boeing recognized that the propagation of cell-to-cell thermal runaway was a failure condition that could result from an internal short circuit in a single battery cell and evaluated this failure condition using the results of GS Yuasa's November 2006 development nail penetration test.[135] As stated in section 1.7.3, 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. As a result of this test, Boeing, Thales, and GS Yuasa determined that an internal short circuit in a single cell that resulted in thermal runaway would not propagate to other cells within the battery case or generate a fire.

Boeing and Thales performed preliminary and final EPS safety assessments, which included fault tree analyses, FMEAs, and failure rate data provided by GS Yuasa. These assessments considered internal short circuit failures but were developed with the underlying assumption that the most severe effect of an internal short circuit within a cell would be limited to venting of only that cell without fire and propagation to other cells. Thus, the potential for an internal short circuit to lead to multiple-cell or battery thermal runaway with venting, electrolyte leakage, excessive heat, and fire was not analyzed in the safety assessment.

As shown by the circumstances of the BOS incident, the assumption that thermal runaway of a cell would not propagate to other cells within the battery case was incorrect.

[135] Boeing, Thales, and GS Yuasa indicated that other battery-level development nail penetration tests were performed, but no documentation of those tests and their results was available for the NTSB's review. For information about these tests, see the addendum to the System Safety and Certification Group Chairman's Factual Report, which is available at www.ntsb.gov in the public docket for this incident.

Validation of assumptions related to failure conditions that can impact safety is a critical step in the development and certification of an aircraft. The validation process must employ a level of rigor that is consistent with the potential hazard to the aircraft in case an assumption is incorrect. Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 4754 provides a structured process for managing and validating assumptions with steps that include ensuring that assumptions are explicitly stated, appropriately disseminated, and justified by supporting data (SAE 2010).[136] The ARP notes that validating assumptions can be accomplished using reviews, analyses, and tests.

Development testing is often necessary to validate important design assumptions, but the nail penetration test performed by GS Yuasa did not adequately account for a number of factors that were relevant to propagation risk. For example, the test was not conducted at the battery's maximum operating temperature of 158ºF, and the test setup did not fully represent the battery installation on the 787 airplane.[137] Also, the test did not include repeated trials of inducing thermal runaway of a cell in multiple batteries to understand how the repeatability of these tests could impact the validity of the test results. Further, the test was performed using a development unit that did not incorporate the final battery design certified as part the 787 type design.[138]

Other development tests were performed to evaluate various aspects of the 787 battery's performance, including the July 2009 integrated system test at UTC Aerospace Systems' APSIF. This test was not designed to evaluate internal short circuiting effects or the cell-to-cell propagation risk. During the test, the battery was unintentionally charged at an excessive rate, which resulted in the venting of a single cell. Although the thermal runaway of that cell did not propagate to other cells within the battery case, the results of this test should not have been considered to be confirmation of the results of GS Yuasa's 2006 nail penetration test because the APSIF test was not designed to examine engineering factors that could likely influence whether

[136] SAE ARP 4754 is an industry guideline that addresses design development for civil aircraft systems with failure modes that could affect the safety of aircraft on which the systems are installed. SAE ARP 4754 defines validation as "the determination that the requirements for a product are correct and complete." The original version of the ARP, "Certification Considerations for Highly-Integrated or Complex Aircraft Systems," was issued in November 1996 and was in use at the time of the 787 certification program. The current version of the ARP, revision A, was issued in December 2010 and was retitled, "Guidelines for Development of Civil Aircraft and Systems." The revised guideline was expanded to include all types of aircraft certification programs and not just those incorporating highly integrated or complex systems.

[137] The NTSB and UL's postincident nail penetration testing with an ungrounded battery at the battery's maximum operating temperature showed that thermal runaway of a single cell propagated to all other cells inside the battery case. Also, the JTSB conducted a heat propagation test on three 787 main and APU batteries. During all three tests, an internal short circuit was initiated in a single cell of each test battery using the nail penetration method. According to the JTSB's final report on the TAK incident, propagation of thermal runaway to multiple cells within the battery occurred during two of the three tests. For both of these tests, the battery was connected to the BCU, and the battery case was grounded, simulating the actual configuration as installed on the airplane. One of these tests was conducted at 158ºF, and the other test was conducted at 86ºF. The test involving the ungrounded battery case (during which no propagation occurred) was conducted at 86ºF.

[138] According to Boeing, Thales, and GS Yuasa, electrolyte leakage was observed during two engineering (noncertification) cell vent tests in September 2009; as a result, the battery case design was modified to incorporate additional sealing to prevent electrolyte leakage. Also, the preproduction battery design used during GS Yuasa's testing had a different vent disc arrangement than the arrangement in the final battery design.

an internal short circuit would lead to propagation. As a result, the repeatability of the test result under all operating environments and usage conditions was not ensured.

Further, GS Yuasa's qualification abuse tests, which were intended to demonstrate that the battery design met the criteria established in the 787 main and APU battery SCD, did not provide adequate evidence to discount the possibility of propagation in the event of cell thermal runaway resulting from an internal short circuit.[139] Specifically, none of these tests drove a cell into thermal runaway to demonstrate that propagation would not occur or that the battery case could contain the effects of multiple-cell venting. Also, the batteries used during the tests were not grounded as installed on the airplane. Thus, the results of these tests were not relevant or sufficient for making assumptions about propagation with a grounded battery and for the full range of operating conditions.[140]

In addition to underestimating the most severe effects of a cell internal short circuit, Boeing, Thales, and GS Yuasa also underestimated the rate of occurrence for this failure mode. Boeing indicated in its EPS safety assessment that the rate of occurrence of cell venting would be about one in 10 million flight hours. However, this predicted failure rate was significantly lower than the actual failure rate observed for the 787's first 52,000 hours of service, during which time both the BOS and TAK incidents occurred.

Boeing used data from GS Yuasa to determine the rate of occurrence of cell venting. These data were based on GS Yuasa's experience with a lithium-ion battery with a similar mechanical design, which GS Yuasa manufactured for use in an industrial application. Of the more than 14,000 similarly designed lithium-ion battery cells in service at the time, GS Yuasa found that none had experienced thermal runaway or venting. Because no failures had occurred, GS Yuasa used probabilistic methods to estimate a failure rate for the industrial battery cells.[141] After accounting for capacity differences between the two battery applications and establishing that the environmental and usage conditions and the manufacturing processes for the 787 and industrial applications would be similar, GS Yuasa determined that the 787 main and APU battery cells would have a failure rate similar to that of the industrial cells.

The method that GS Yuasa used in estimating the failure rate for 787 main and APU battery cells was consistent with industry practices for components manufactured with controlled processes and subjected to similar stress conditions during normal use over time. However, the NTSB found no documented analysis comparing the duty cycle and environment expected in the

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[139] The qualification abuse testing included two external short circuit tests (low and high impedance shorts at battery terminals), one overcharge test (charge battery to 36 volts for 25 hours), and one overdischarge test (discharge battery to zero volts). These qualification tests were conducted at the battery's maximum operating temperature of 158ºF, and no thermal runaway occurred. A qualification test involving high-temperature storage (185ºF for 18 hours) also resulted in no thermal runaway.

[140] During the NTSB's April 2013 investigative hearing on the BOS incident, a Boeing representative testified that Boeing used "state of the art in testing" and that no propagation of cells occurred during qualification abuse testing, nail penetration testing, and the venting event at APSIF.

[141] Probabilistic methods model and describe the random variations in systems. Probabilistic methods demonstrate compliance in the certification process using probabilistic risk analysis techniques.

787 application with that experienced in the industrial application. If the 787 application had higher mechanical and/or electrical stress levels than the industrial application due to differences in duty cycle and environment, the onset of certain failure modes could be accelerated, or failure modes not previously exhibited in the industrial cells, such as internal short circuiting and cell venting, could be manifested in the 787 battery cells.[142] Given the potential safety consequences of cell venting and the lack of historical data on cell and battery performance in an airplane application, Boeing, Thales, and GS Yuasa should have performed a structured engineering analysis, supplemented by testing, to compare the differences in duty cycle and environment between the two applications and measure the impact on battery and cell features that drive safety-related failure modes, effects, and rates. This level of rigor was needed to determine whether the use of the industrial cell failure rate was appropriate for the 787 application.

Boeing indicated in certification documents that it used a version of AC 25.1309 (referred to as the Arsenal draft) as guidance in preparing the EPS safety assessment for the 787 type design certification program. The draft AC addressed the treatment of assumptions and data, stating that the underlying assumptions, data sources, and analytical techniques used in safety analyses should be identified and justified to ensure the validity of the conclusions made in safety assessments. However, the analysis that Boeing presented in its EPS safety assessment did not appear to be consistent with the guidance provided in the draft AC. Specifically, the analysis did not (1) identify Boeing's assumption that thermal runaway of a cell would not propagate to other cells and (2) provide the engineering rationale needed to justify broad use of this assumption under all operating conditions. Also, the analysis did not sufficiently evaluate and justify the use of the industrial battery failure rate data in predicting the risk of a cell venting occurrence for the 787 battery. Further, even if this information had been included in the EPS safety assessment, the validity of the supporting safety analyses would have been difficult to justify given the limited data available. For example, the assumption that propagation would not occur was based on the result of GS Yuasa's single 2006 nail penetration test, and the failure rate prediction for cell venting was developed without a rigorous comparison of the most severe environmental and usage conditions between the industrial and 787 battery applications.

AC 25.1309 (Arsenal draft) also stated, "where it is not possible to fully justify the adequacy of the safety analysis and where data or assumptions are critical to the acceptability of the failure condition, extra conservatism should be built into either the analysis or the design." The assumption that the design of the main and APU battery prevented thermal runaway of a single cell from propagating to other cells inside the battery case was critical to accepting the risk of an internal short circuit in a cell because, if the assumption were incorrect, thermal runaway of the battery could occur. As a result, Boeing should have taken a more conservative approach in its safety analyses by including the possibility that propagation of thermal runaway from cell to cell could result from an internal short circuit and considering the potential effects if this failure condition were to occur. If such an approach had been taken, Boeing authorized representatives

[142] For example, stresses on the cells introduced by altitude changes would only be present in the 787 application, and these stresses applied over time in service could change the failure modes, the severity of failure effects, and increase the rates of failure for the cells and the entire battery installation. Deterministic methods that involve accelerated stress testing are commonly used to evaluate the influence of engineering factors, such as stress, design, and environment, on item reliability (Condra 1993).

and/or FAA certification engineers independently reviewing the EPS safety assessment would likely have required Boeing, Thales, and GS Yuasa design engineers to (1) perform more exhaustive test and analysis to properly validate claims about propagation and cell failure rate or (2) incorporate design features to safely accommodate cascading thermal runaway of all cells inside the battery case.[143]

Critical assumptions and conclusions made in GS Yuasa's and Thales' safety analyses and used in Boeing's EPS safety assessment were not fully delineated and justified with appropriate data and engineering rationale. However, multiple independent reviews of the EPS safety assessment by Boeing authorized representatives and FAA certification engineers did not reveal these deficiencies. The review process for safety assessments should be designed to closely examine the data used to support conclusions and challenge assumptions, particularly those that could result in significant safety consequences if incorrect. Also, the review process should be designed to ensure a conservative approach when available engineering data and experience are limited.

The NTSB concludes that Boeing's EPS safety assessment did not consider the most severe effects of a cell internal short circuit and include requirements to mitigate related risks and that the review of the assessment by Boeing authorized representatives and FAA certification engineers did not reveal this deficiency. Therefore, the NTSB recommends that Boeing modify its process for developing safety assessments for designs incorporating new technology to ensure that the conclusions made are validated and that any identified deficiencies are corrected. The NTSB also recommends that the FAA provide its certification engineers with written guidance and training to ensure that (1) assumptions, data sources, and analytical techniques are fully identified and justified in applicants' safety assessments for designs incorporating new technology and (2) an appropriate level of conservatism is included in the analysis or design, consistent with the intent of AC 25.1309 (Arsenal draft). Further, the NTSB recommends that, during annual recurrent training for engineering designees, the FAA discuss the need for applicants to identify, validate, and justify key assumptions and supporting engineering rationale used in safety assessments addressing new technology.

2.5.2 Validating Methods of Compliance for Designs Involving New Technology

The FAA was responsible for approving Boeing's methods of compliance and the data produced from various analyses and tests. The FAA approved Boeing's qualification test program (which was outlined in Boeing's EPS certification plan) and Boeing's EPS safety assessment as methods of demonstrating that the battery complied with the FAA's special conditions. Boeing's safety assessment was an important method of compliance because it identified the battery failure modes that could produce conditions prohibited by the FAA's special conditions and defined the safety requirements needed to mitigate the potential risks to a

[143] Regarding the process for validating assumptions, ARP 4754 stated, "where the consequences of an erroneous assumption appear to have significant potential to reduce safety, one possible validation strategy consists of showing how the system design, in fact, limits or bounds the achievable consequences of an assumption error."

level deemed acceptable by the FAA.[144] However, because Boeing's safety assessment did not consider the potential for cell-to-cell propagation with fire as a result of an internal short circuit, Boeing did not identify, in the 787 main and APU battery SCD or elsewhere, safety requirements directly addressing battery performance with a single cell in thermal runaway. Also, because the battery SCD did not contain a specific requirement for battery performance with a cell in thermal runaway, the need for a thermal runaway qualification test or other related verification activity as part of the battery's certification would have been less visible to Boeing authorized representatives and FAA certification engineers.[145]

Although GS Yuasa's battery design included features intended to prevent cell-to-cell propagation, such as cell spacing and thermal insulation materials between cells, these provisions were insufficient, as demonstrated by the BOS and the TAK incidents. These battery design features were not fully linked to defined, measurable performance criteria in Boeing's battery SCD, so the effectiveness of the design features in preventing propagation was not verified during battery qualification testing. The NTSB concludes that Boeing failed to incorporate design requirements in the 787 main and APU battery SCD to mitigate the most severe effects of a cell internal short circuit and that the FAA failed to uncover this design vulnerability as part of its review and approval of Boeing's EPS certification plan and proposed methods of compliance.

AC 25.1309 (Arsenal draft) noted that a safety assessment should trace the work leading to conclusions (including the basis for classification of the severity of hazards, the assumptions made, and supporting rationale for assumptions) as part of certification. However, none of the certification deliverables to which the FAA and Boeing agreed established the relationships among each individual special condition, related hazards and assumptions from the EPS safety assessment, safety requirements in the main and APU battery SCD, and the resulting data used to show compliance.[146] Thus, the FAA could not effectively use traceability principles to evaluate the completeness of Boeing's proposed methods of compliance, particularly for special condition 2, which addressed battery thermal runaway.[147] As a result, the FAA approved Boeing's proposed EPS certification plan, including qualification tests, for the 787 main and APU battery without the details necessary to demonstrate compliance with the individual special conditions.

If these relationships had been fully discussed in certification documentation or through other communications between Boeing and the FAA as part of the certification process, Boeing authorized representatives and FAA certification engineers would have had a better understanding of how the assumption regarding the propagation of thermal runaway as a result of

[144] AC 25.1309 (Arsenal draft) provided guidance on the acceptable failure probability per flight hour of equipment and systems installed on an airplane as a function of the severity of the resulting failure condition.

[145] ARP 4754 defines verification as "the evaluation of an implementation of requirements to determine that they have been met."

[146] Traceability is defined in revision A of ARP 4754 as "the recorded relationship established between two or more elements of the development process."

[147] Special condition 2 indicated that the "design of the lithium-ion batteries must preclude the occurrence of self-sustaining, uncontrolled increases in temperature or pressure."

a cell internal short circuit related to special condition 2.[148] In addition, traceability would likely have revealed the absence of safety requirements addressing cell thermal runaway and propagation in the battery SCD and the need for a thermal runaway test as part of planned qualification tests to demonstrate that the design met the requirements of special condition 2 for the internal short circuit failure condition. However, guidance used by FAA certification staff at the time of Boeing's application for the 787-8 type certificate, including FAA Order 8110.4, "Type Certification," revision B, did not include the use of traceability principles that relate each special condition to design data and compliance deliverables (such as test procedures, test reports, and safety assessments) as part of certification planning to ensure that the methods of compliance were correct and complete.

The NTSB concludes that unclear traceability among the individual special conditions, safety assessment assumptions and rationale, requirements, and proposed methods of compliance for the 787 main and APU battery likely contributed to the FAA's failure to identify the need for a thermal runaway certification test. Therefore, the NTSB recommends that the FAA develop written guidance for its certification engineers and engineering designees about the use of traceability principles to verify that the methods of compliance proposed by type certification applicants for special conditions involving new technology are correct and complete. The NTSB also recommends that, once the guidance requested in Safety Recommendation A-14-121 has been issued, the FAA provide training to its certification engineers and engineering designees on the subjects discussed in the guidance. The NTSB further recommends that the FAA require applicants to discuss key assumptions related to safety-significant failure conditions, their validation, and their traceability to requirements and proposed methods of compliance during certification planning meetings for type designs involving special conditions.

2.5.3 Certification of Lithium-ion Batteries and Certification of New Technology

As stated in section 1.8.2, the NTSB issued Safety Recommendations A-14-32 through -36 to the FAA regarding (1) insufficient testing methods and guidance for addressing the safety risks of internal short circuits and thermal runaway and (2) the need for outside technical knowledge and expertise to help the FAA ensure the safe introduction of new technology into aircraft designs. On August 19, 2014, the FAA responded to these recommendations.

In its response letter, the FAA stated that it has been working with RTCA Special Committee SC-211 to revise RTCA document DO-311, "Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems," to "capture all the enhancements and lessons learned" from the BOS incident, including the need for a test that subject a single cell

[148] A review of available minutes from monthly meetings between the FAA and Boeing during the planning and implementation phases of the 787 certification program did not reveal any communications related to Boeing's assumption or proposed qualification test plan for the main and APU battery as it related to the thermal runaway propagation failure condition due to cell internal short circuiting.

within a lithium-ion battery to thermal runaway as a result of an internal short circuit.[149] The FAA also stated that, until these revisions are completed, it would use the issue paper process to provide new design applicants with acceptable methods of compliance for conducting tests and analyses to address the potential failure effects of permanently installed, rechargeable lithium-ion batteries. The FAA further stated that it was surveying previous approvals of rechargeable lithium battery systems to determine those existing approved designs that require additional testing and/or analysis to ensure that they can mitigate all adverse effects of a cell thermal runaway. In addition, the FAA stated that it was setting up meetings with internal stakeholders to determine how best to implement Safety Recommendation A-14-36.

The NTSB is encouraged that the FAA is taking steps to enhance RTCA document DO-311 but is concerned that aircraft installation factors might not be addressed in the document given that DO-311 is a battery-level standard. On the basis of the FAA's actions, the NTSB classifies Safety Recommendations A-14-32 through -36 "Open—Acceptable Response" pending review of future updates regarding the FAA's progress in completing the recommended actions.

2.6 Flight Recorder Issues

2.6.1 Stale Flight Data

The EAFR is a new recording system with a new flight data recording format, and the 787 is currently the only airplane that uses the EAFR to record CVR, FDR, and other data. The investigation of this incident found that the EAFR recorded stale data for some parameters (see section 1.3). The recording of stale data impacted the early stages of this investigation because significant additional effort was required to identify stale data when possible as well as those parameters for which it was not possible to determine whether the data samples were stale. This process delayed the NTSB's complete understanding of the recorded data.

Stale EAFR data could impact future investigations as well. The recording of stale data could lead to cases in which apparently valid data continued to be recorded after a parameter source stopped providing valid data, which could result in latent faults in the recording system for mandatory parameters.[150] These mandatory parameters would thus be unavailable because an EAFR's source would no longer be providing the data. In addition, the safe operation of an aircraft could be impacted if stale EAFR data were unintentionally used by an operator to assess and resolve maintenance issues.

[149] 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.

[150] Title 14 CFR 121.344, "Digital Flight Data Recorders for Transport Category Airplanes," details mandatory parameter requirements. Title 14 CFR Part 121 Appendix M provides supplemental information to 14 CFR 121.344.

The NTSB concludes that stale EAFR data could impede future accident and incident investigations by delaying the full understanding of the recorded data; stale data could also impact aircraft safety if an operator's maintenance activities were based on these data. At this time, the NTSB is concerned with the EAFR stale data recording issue on 787 airplanes because future EAFR installations might take greater advantage of the flexibility of the new recording format, which could mitigate the stale data issue. Therefore, the NTSB recommends that the FAA require Boeing 787 operators to incorporate guidance about the EAFR stale data issue in their maintenance manuals to prevent stale data from being used for maintenance activities or flight recorder maintenance. In addition, the NTSB recommends that the FAA (1) evaluate whether the recording of stale data by the Boeing 787 EAFR, including whether the data are specifically identified as stale, impacts the certification of the recording system regarding the ranges, accuracies, and sampling intervals specified in 14 CFR Part 121 Appendix M and (2) take appropriate measures to correct any problems found.

2.6.2 Poor-Quality Cockpit Voice Recording

The investigation of this incident found that the audio recording obtained from both EAFRs was poor quality. The signal levels of the three radio/hot microphone channels of the audio recording (the captain's audio selector panel, the first officer's audio selector panel, and the jumpseat/observer's position) were very low and used only about 25% of the available total dynamic range of the recorder. Further, throughout the recording, random full-deflection noise spikes could be heard. These random noise spikes were very short in duration but used the full dynamic range of the radio/hot microphone channel recording.

The recording from the cockpit area microphone channel of the EAFR was also poor quality. During the airborne portion of the flight that was captured on the recording, almost all of the individual crew conversations were completely obscured by the ambient cockpit noise. After the airplane landed, the cockpit noise was reduced, so the crew conversations became clearer. Once the airplane arrived at the gate and the engines were shut down, the crew conversations could easily be heard, and the overall quality of the recording was excellent. Thus, the issues with the EAFR audio recording did not impact this investigation because the conversations and sounds related to the circumstances of the incident occurred during the portion of the recording that was excellent quality.

The EAFR was certified under FAA Technical Standard Order (TSO) C123B, "Cockpit Voice Recorder Equipment," which was based on the European Organization for Civil Aviation Equipment (EUROCAE) ED-112A document, "Minimum Operational Performance Specification for Crash Protected Airborne Recording Systems." The installation and performance requirements in chapter I-6 of the EUROCAE document also include guidance to determine if a CVR installation would be acceptable. This guidance stated that the CVR should use all available dynamic ranges of the recorder and mitigate cockpit area background noise. The FAA took exception to this chapter of the EUROCAE ED-112A document and removed the chapter's requirements from the final TSO C123B language. As a result, the CVR certifier and installer can determine what constitutes an acceptable recording without the use of any industry-approved standard regarding specific installation guidance.

The NTSB concludes that the poor audio recording quality of the EAFR could impede future aircraft investigations because the recorded conversations and other cockpit sounds might be obscured. Therefore, the NTSB recommends that the FAA require Boeing to improve the quality of (1) the EAFR radio/hot microphone channels by using the maximum available dynamic range of the individual channels and (2) the cockpit area microphone airborne recordings by increasing the crew conversation signals over the ambient background noise. In addition, the NTSB recommends that the FAA either remove the current exception to ED-112A chapter I-6 in TSO 123B or provide installers and certifiers with specific guidance to determine whether a CVR installation would be acceptable.

3. Conclusions

3.1 Findings

1. The battery failure did not result from overcharging, overdischarging, external short circuiting, external heating, installation factors, or environmental conditions of the airplane.

2. The battery failure resulted from an internal short circuit that occurred in cell 5 or cell 6 and led to thermal runaway that propagated to adjacent cells.

3. GS Yuasa's cell manufacturing process allowed defects that could lead to internal short circuiting, including wrinkles and foreign object debris, to be introduced into the Boeing 787 main and auxiliary power unit battery.

4. The thermal protections incorporated in large-format lithium-ion battery designs need to account for all sources of heating in the battery during the most extreme charge and discharge current conditions and protect cells from damage that could lead to thermal runaway.

5. More accurate cell temperature measurements and enhanced temperature and voltage monitoring and recording could help ensure that excessive cell temperatures resulting from localized or other sources of heating could be detected and addressed in a timely manner to minimize cell damage.

6. Determining the initial point of self-heating in a lithium-ion cell is important in establishing thermal safety limits.

7. Boeing's electrical power system safety assessment did not consider the most severe effects of a cell internal short circuit and include requirements to mitigate related risks, and the review of the assessment by Boeing authorized representatives and Federal Aviation Administration certification engineers did not reveal this deficiency.

8. Boeing failed to incorporate design requirements in the 787 main and auxiliary power unit battery specification control drawing to mitigate the most severe effects of a cell internal short circuit, and the Federal Aviation Administration failed to uncover this design vulnerability as part of its review and approval of Boeing's electrical power system certification plan and proposed methods of compliance.

9. Unclear traceability among the individual special conditions, safety assessment assumptions and rationale, requirements, and proposed methods of compliance for the 787 main and auxiliary power unit battery likely contributed to the Federal Aviation Administration's failure to identify the need for a thermal runaway certification test.

10. Stale enhanced airborne flight recorder data could impede future accident and incident investigations by delaying the full understanding of the recorded data; stale data could

also impact aircraft safety if an operator's maintenance activities were based on these data.

11. The poor audio recording quality of the enhanced airborne flight recorder could impede future aircraft investigations because the recorded conversations and other cockpit sounds might be obscured.

3.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of this incident was an internal short circuit within a cell of the auxiliary power unit (APU) lithium-ion battery, which led to thermal runaway that cascaded to adjacent cells, resulting in the release of smoke and fire. The incident resulted from Boeing's failure to incorporate design requirements to mitigate the most severe effects of an internal short circuit within an APU battery cell and the Federal Aviation Administration's failure to identify this design deficiency during the type design certification process.

4. Recommendations

4.1 New Recommendations

As a result of this investigation, the National Transportation Safety Board makes the following new safety recommendations:

To the Federal Aviation Administration:

> Develop or revise processes to establish more effective oversight of production approval holders and their suppliers (including subtier suppliers) to ensure that they adhere to established manufacturing industry standards. (A-14-113)
>
> Work with aviation industry experts to develop or modify design safety standards for large-format lithium-ion batteries to require that sources of excessive heating, including electrical contact resistance from components and connections, be identified, minimized, and documented as part of the design. The standards should include measures for identifying and minimizing potential sources of heating that consider the range of operating temperatures and the most extreme electrical currents that the battery could be expected to experience during repeated charge and discharge cycles. (A-14-114)
>
> Work with aviation industry experts to develop or modify existing safety standards related to the design of permanently installed lithium-ion batteries to require monitoring of individual cell temperature and voltage and recording of exceedances to prevent internal cell damage during operations under the most extreme operating temperatures and currents. (A-14-115)
>
> Once the guidance requested in Safety Recommendation A-14-115 has been issued, require type certification applicants to demonstrate that the battery monitoring system maintains each individual cell within safe temperature limits at the most extreme battery operating temperatures and the heaviest electrical current loads approved for operation. (A-14-116)
>
> Work with lithium-ion industry experts to (1) conduct research into battery monitoring system technologies that could improve the recognition of conditions leading to thermal runaway, (2) develop active mitigation of such conditions to minimize damage, and (3) update design and safety standards accordingly. (A-14-117)
>
> Work with industry experts to develop appropriate test methods for determining the initial point of self-heating in a lithium-ion cell to establish objective margins of thermal safety for future battery designs. (A-14-118)
>
> Provide your certification engineers with written guidance and training to ensure that (1) assumptions, data sources, and analytical techniques are fully identified

and justified in applicants' safety assessments for designs incorporating new technology and (2) an appropriate level of conservatism is included in the analysis or design, consistent with the intent of Advisory Circular 25.1309 (Arsenal draft). (A-14-119)

During annual recurrent training for engineering designees, discuss the need for applicants to identify, validate, and justify key assumptions and supporting engineering rationale used in safety assessments addressing new technology. (A-14-120)

Develop written guidance for your certification engineers and engineering designees about the use of traceability principles to verify that the methods of compliance proposed by type certification applicants for special conditions involving new technology are correct and complete. (A-14-121)

Once the guidance requested in Safety Recommendation A-14-121 has been issued, provide training to your certification engineers and engineering designees on the subjects discussed in the guidance. (A-14-122)

Require applicants to discuss key assumptions related to safety-significant failure conditions, their validation, and their traceability to requirements and proposed methods of compliance during certification planning meetings for type designs involving special conditions. (A-14-123)

Require Boeing 787 operators to incorporate guidance about the enhanced airborne flight recorder stale data issue in their maintenance manuals to prevent stale data from being used for maintenance activities or flight recorder maintenance. (A-14-124)

Evaluate whether the recording of stale data by the Boeing 787 enhanced airborne flight recorder, including whether the data are specifically identified as stale, impacts the certification of the recording system regarding the ranges, accuracies, and sampling intervals specified in 14 *Code of Federal Regulations* Part 121 Appendix M, and take appropriate measures to correct any problems found. (A-14-125)

Require Boeing to improve the quality of (1) the enhanced airborne flight recorder radio/hot microphone channels by using the maximum available dynamic range of the individual channels and (2) the cockpit area microphone airborne recordings by increasing the crew conversation signals over the ambient background noise. (A-14-126)

Either remove the current exception to European Organization for Civil Aviation Equipment ED-112A, "Minimum Operational Performance Specification for Crash Protected Airborne Recording Systems," chapter I-6 in Technical Standard Order 123B, "Cockpit Voice Recorder Equipment," or provide installers and certifiers with specific guidance to determine whether a cockpit voice recorder installation would be acceptable. (A-14-127)

To the Boeing Company:

> Develop or revise processes to establish more effective oversight of your suppliers (including subtier suppliers) to ensure that the product being manufactured adheres to established industry standards. (A-14-128)
>
> Modify your process for developing safety assessments for designs incorporating new technology to ensure that the conclusions made are validated and that any identified deficiencies are corrected. (A-14-129)

To GS Yuasa Corporation:

> Review your cell manufacturing processes to minimize or prevent defects that could affect cell safety, and ensure that your employees are properly trained to identify and eliminate these defects. (A-14-130)

4.2 Previously Issued Safety Recommendations Classified in This Report

Safety Recommendations A-14-32 through -36 are classified "Open—Acceptable Response" in section 2.5.3 of this report.

> 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-14-32)
>
> After Safety Recommendation A-14-32 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-14-33)
>
> 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-14-34)
>
> 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-14-35)
>
> 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 14-36)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

CHRISTOPHER A. HART
Acting Chairman

ROBERT L. SUMWALT
Member

MARK R. ROSEKIND
Member

EARL F. WEENER
Member

Adopted: November 21, 2014

5. Appendixes

Appendix A: Investigation and Hearing

The National Transportation Safety Board (NTSB) was notified of this incident on January 7, 2013, and sent an investigator to the scene the same day and two investigators to the scene the next day. The following investigative groups were formed: airworthiness, airport emergency response, battery and fire, manufacturing, and systems safety and certification. Also, specialists were assigned to conduct the readout of the flight data recorder and transcribe the cockpit voice recorder at the NTSB's laboratory in Washington, DC. In addition, a specialist was assigned to conduct radiographic studies of 787 batteries and cells.

The following organizations provided technical assistance to the NTSB during this investigation:

- Naval Surface Warfare Center, Carderock Division, US Department of the Navy, West Bethesda, Maryland;
- TIAX LLC, Lexington, Massachusetts;
- Underwriters Laboratories LLC, Northbrook, Illinois; Melville, New York; and Taipei, Taiwan
- US Department of Energy, Washington, DC;
- Chesapeake Testing, Belcamp, Maryland;
- National Institute of Standards and Technology, Gaithersburg, Maryland; and
- Naval Research Laboratory, Washington, DC.

Parties to the investigation were the Federal Aviation Administration (FAA) and Boeing Commercial Airplanes. In accordance with the provisions of Annex 13 to the Convention on International Civil Aviation, the Japan Transport Safety Board (JTSB) and the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) participated in this investigation. Japan Airlines and GS Yuasa Corporation participated in the investigation as technical advisors to the JTSB, and Thales Avionics Electrical Systems and the European Aviation Safety Agency participated in the investigation as technical advisors to the BEA, as provided for in Annex 13.

On April 23 and 24, 2013, the NTSB held an investigative hearing regarding the Boeing 787 battery's design and certification. The safety issues discussed were the battery system's (1) selection and certification requirements, (2) design and development, (3) design verification and validation, and (4) certification and the FAA's findings of compliance. Parties to the investigative hearing were the FAA, Boeing, Thales, and GS Yuasa.

Between the date of the incident and the investigative hearing, the NTSB issued an interim factual report on this incident (March 7, 2013) and held a forum on lithium-ion batteries in transportation (April 11 and 12, 2013). The interim factual report and presentations from the forum are available at www.ntsb.gov.

Appendix B: Boeing 787 Type Certification Special Conditions 25-359-SC

The FAA issued the following nine special conditions, in place of the electrical equipment and installation requirements of 14 *Code of Federal Regulations* (CFR) 25.1353(c)(1) through (c)(4), for the design and installation of lithium-ion batteries as part of the type certification basis for the Boeing 787-8:

> (1) Safe cell temperatures and pressures must be maintained during any foreseeable charging or discharging condition and during any failure of the charging or battery monitoring system not shown to be extremely remote. The lithium-ion battery installation must preclude explosion in the event of those failures.
>
> (2) Design of the lithium-ion batteries must preclude the occurrence of self-sustaining, uncontrolled increases in temperature or pressure.
>
> (3) No explosive or toxic gases emitted by any lithium-ion battery in normal operation, or as the result of any failure of the battery charging system, monitoring system, or battery installation not shown to be extremely remote, may accumulate in hazardous quantities within the airplane.
>
> (4) Installations of lithium-ion batteries must meet the requirements of 14 CFR 25.863(a) through (d).
>
> (5) No corrosive fluids or gases that may escape from any lithium-ion battery may damage surrounding structure or any adjacent systems, equipment, or electrical wiring of the airplane in such a way as to cause a major or more severe failure condition, in accordance with 14 CFR 25.1309(b) and applicable regulatory guidance.
>
> (6) Each lithium-ion battery installation must have provisions to prevent any hazardous effect on structure or essential systems caused by the maximum amount of heat the battery can generate during a short circuit of the battery or of its individual cells.
>
> (7) Lithium-ion battery installations must have a system to control the charging rate of the battery automatically, so as to prevent battery overheating or overcharging, and,
>
> (i) A battery temperature sensing and over-temperature warning system with a means for automatically disconnecting the battery from its charging source in the event of an over-temperature condition, or,

(ii) A battery failure sensing and warning system with a means for automatically disconnecting the battery from its charging source in the event of battery failure.

(8) Any lithium-ion battery installation whose function is required for safe operation of the airplane must incorporate a monitoring and warning feature that will provide an indication to the appropriate flight crewmembers whenever the state-of-charge of the batteries has fallen below levels considered acceptable for dispatch of the airplane.

(9) The Instructions for Continued Airworthiness required by 14 CFR 25.1529 must contain maintenance requirements for measurements of battery capacity at appropriate intervals to ensure that batteries whose function is required for safe operation of the airplane will perform their intended function as long as the battery is installed in the airplane. The Instructions for Continued Airworthiness must also contain procedures for the maintenance of lithium-ion batteries in spares storage to prevent the replacement of batteries whose function is required for safe operation of the airplane with batteries that have experienced degraded charge retention ability or other damage due to prolonged storage at a low state of charge.

The FAA noted that these special conditions were “not intended to replace 14 CFR 25.1353(c) in the certification basis of the Boeing 787-8 airplane” and that the special conditions applied “only to lithium-ion batteries and their installations.” The FAA also noted that the requirements of 14 CFR 25.1353(c) remained in effect “for batteries and battery installations of the Boeing 787-8 airplane that do not use lithium-ion batteries.”

Appendix C: Comments From the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile

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Ministère de l'Ecologie,
du Développement durable
et de l'Energie

BEA
Bureau d'Enquêtes et d'Analyses
pour la sécurité de l'aviation civile

Le Bourget, le 28 octobre 2014

To : David Helson
NTSB investigator

<u>Subject</u> : BEA comments to append to the NTSB draft report for the serious incident to the Boeing 787-8 registered JA829J

Dear David,

Thank you for having associated the BEA (Bureau d'Enquêtes et d'Analyses pour la sécurité de l'Aviation Civile) with the investigation into the serious incident to B 787-8, registered JA 829J, and for giving us the opportunity to make comments on the Draft Final Report.
We hereby present you with the comments that we would like to be appended to the final report in accordance with the provisions of Annex 13.

We are also proposing safety actions to be taken in the light of the investigation done.

The BEA remains at your disposal for any further information that you may wish to obtain.

Yours sincerely.

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BEA proposed comments to append to the report.

The BEA agrees that an internal short circuit within a cell of the APU battery led to thermal runaway that cascaded to thermo-mechanical propagation to surrounding cells.

However, the initiating phenomenon of the internal short circuit has not been identified during the investigation and it was impossible to conclusively determine the origin of the internal short circuit. Indeed, the internal short circuit is not a root cause by itself but a “way point” in the chain of events. The reason of the development of the short circuit inside the first cell could not be determined from post incident laboratory testing and subsequent engineering analysis of potential failure modes.

The fact that the root cause couldn’t be determined should also be included in the section 3.1 Findings and also in the section 3.2 Probable Causes.

In addition, the NTSB report also lists some concerns that have been observed during the investigation (refer to sections 2.3 and 2.4), namely:

- The **presence of wrinkles** generated by the manufacturing process or influenced by the manufacturing process and developed during charge and discharge due to swelling/deswelling. The report considers that “wrinkles and folds can modify anode-to-cathode ratio locally, resulting in lithium deposits at the anode surface”. The BEA states that although wrinkles were observed during DPA of the incident batteries, their effect on lithium deposition hasn’t been proved (no Li-metal was found by XPS analysis). The various tests performed by GSY, on LVP 65 cells didn’t reveal neither Li metal dendrites nor internal short with heat generation and venting.

- The **presence of FOD** related to the manufacturing process : no FOD was identified during the teardown of the incident battery and during post incident investigation on exemplar batteries.

- The **propensity of cells to generate self-heating** below the upper operational specified temperature (70°C) (section 2.4.3): Lab in charge assessed self-heating rate in cell at 100%SOC and stated that cells self-heat at temperature as low as 60°C with a self-heating rate near 0.01°C.min-1. However the sensitivity threshold of this equipment is as high as at 0.02°C.min-1. Values below the sensitivity threshold are not relevant. The sensitivity threshold is reached at 85°C for 100%SOC cell1 which is consistent with the current state of the art on lithium-ion battery.

- The **seal assembly and rivets integrity**. Thales testing shows that when the battery is used within its specified power and temperature ranges then no anomaly occurs[2].

Proposed safety actions to be taken

The BEA suggests to take into account of the various reports and the Thales testings and to consider the following safety actions to be taken :

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[1] UL report entitled “Multi-Level Forensic and Functional Analysis of the 787 Main/APU Lithium Ion Battery” Doc. ref. NTSBC130004 2014, p 120-123.

[2] THALES Submission to the National Transportation Safety Board For the DCA13IA037 page 17 & 18

- “As the investigation could not identify the mechanism of the internal short circuit, the aircraft manufacturer and the equipment manufacturers should :

  - continue studies of internal short circuit mechanism considering the effects of internal and external phenomenon that potentially impacts the Li-ion batteries in operational conditions, such as the aircraft electrical environment and particularly the risk associated to potential transient current and voltage ;

  - continue studies on the impact of other environmental parameters such as humidity and vibrations ;

  - continue efforts to improve Li-ion batteries quality and its reliability.

BEA detailed comments on the NTSB draft report on the serious incident to the Boeing 787-8 registered JA829J.

Page/Section:	Sentence/Comment:
	§ 1.4.3 Disassembly of the incident Battery **Existing sentence:** “There was no evidence of cell-to-battery case shorting before the thermal event, bus bar shorting or resistive heating of bus bar …”.
Comment:	APU battery has demonstrate the presence of a protrusion on side 3 facing Cell 5. At the place of the protrusion the cell 5 exhibits a small hole. The Cell 5 windings also demonstrate holes that are consistent with materials that had penetrated into the cell 5 and its windings. The material found in the cell 5 and its winding were chemically analyzed and confirmed to be Battery aluminum alloy. This was interpreted by the investigation team as resulted from an arcing phenomenon between the cell 5 casing and Battery case. At this stage there is no evidence to say that arcing occurs before or during the thermal event. **Modification proposal** **“There was evidence of cell 5-to-battery case shorting during the JAL event. The exact time, at which the shorting between cell 5 and battery case occurs, is not determined. In addition there is no evidence of bus bar shorting or resistive heating of bus bar ….”**

Page/Section:	Sentence/Comment:
	§ 1.4.3 Disassembly of the incident Battery **Existing sentence:** There was also no visible evidence of water (resulting from condensation) within the battery case or external surfaces of the battery cells.
Comment:	APU battery has undergone a very significant heating during the thermal runaway. Therefore, if water, for instance from condensation, had been present, it has been vaporized during thermal runaway. Consequently, it was impossible to find any evidence of water inside the battery after the event. In order not to rule out this parameter, the following wording is proposed.

	Modification proposal **“Due to high heat exposure of the APU battery during the incident event, it was obviously not possible to conclude on water presence resulting from condensation within the battery before or during the incident event.”**

Page/Section:	Sentence/Comment:
	§ 1.5.3 Examinations of main battery cells from incident airplane **Existing sentence:** “More than 100 areas of “ingressed underlithiation” of the anode (that is, areas of the anode than are incompletely charged) were found”
Comment:	Color variations in full charge carbon anode are known to be due to underlithiation. However, color is only a semi-quantitative and subjective measure of Li state of charge [1], [2]. Additionally XPS analysis from Carderock don’t show any obvious difference in lithium concentration between “blue or purple areas”, called “underlithiated” and gold areas, called “ fully lithiated” **Modification proposal** **More than 100 areas of “ingressed” underlithiation of the anode were found (that is, areas of the anode than are incompletely charged. However Carderock XPS analysis doesn’t show any significant concentration difference of lithium element between blue/purple area, called underlithiated area, and gold area, called fully lithiated area**) [1] Direct in situ measurements of Li transport in Li-ion battery negative electrodes, Harris et al, Chemical Physics Letters 485 (**2010**) 265–274 [2] Revisited structures of dense and dilute stage II lithium-graphite intercalation compounds, D. Billaud et al, J. Phys. Chem. Solids 57 (1996) 775.

Page/Section:	Sentence/Comment:
	§ 1.5.3 Examinations of main battery cells from incident airplane **Existing sentence:** “According to TIAX, these areas indicate that mechanical abnormalities in the windings results in uneven charging of the anode and might have caused lithium to deposit adjacent to underlithiated area.”
Comment:	This explanation, representing TIAX’ interpretation, is only based on a phenomenal description and is not supported by any technical and scientific demonstration, simulation, calculation and complete testing. **Modification proposal** **“According to TIAX, these areas indicate that, in theory, mechanical abnormalities in the windings might result in uneven charging of the anode and might have caused lithium to depose adjacent to underlithiated area. However TIAX didn’t perform**

	chemical analysis, simulation, calculation and appropriate testing to validate this scenario. At the opposite, Carderock showed through deep chemical analysis (XPS) that the observed silver colored deposits didn't contain any lithium metal, invalidating the explanation proposed by TIAX"

Page/Section:	Sentence/Comment:
	§ 1.5.3 Examinations of main battery cells from incident airplane **Existing sentence:** "In its submission to the NTSB for this incident, GS YUASA stated that, after the incident, it conducted more than 100 cold charge cycle tests, and all of the tests revealed a loss of capacity when charging repeatedly at -9.4°F."
Comment:	The reader would surely be interested not only by the loss of capacity during charge/discharge cycles which is normal behavior of this battery technology in these specific test conditions, but it would be of greater interest to learn there from those tests that no dendrite was created during those cold charge cycles. For information, the 105 cycles of tests widely cover the time period that the incident battery was exposed onboard airplane. Such important and relevant information needs to be provided to the reader in order to have better understanding of potential dendrite presence or not according to the operating conditions specified on this airplane. **Modification proposal** **"In its submission to the NTSB for this incident, GS YUASA stated that, after the incident, it conducted more than 100 cold charge cycle tests, and all of the tests revealed a loss of capacity when charging repeatedly at -9.4°F and no lithium plating was observed**".

Page/ Section:	Sentence/Comment:
	§1.5.4 Cell-level abuse tests **Existing sentence:** "… cells started to generate internal heat at temperatures as low as 144°F, which is below the allowable operational temperature of the battery"
comment	As written by BEA/Thales comments on the airworthiness group report, UL used an ARC equipment to assess self-heating rate in cell at 100%SOC and 0%SOC. The sensitivity threshold of this equipment is given at 0.02°C.min^{-1} by the equipment manufacturer (cf UL report p121 and 122). However UL states that cells self-heat at temperature as low as 60°C (self-heating rate near 0.01°C.min^{-1}, but the self-heating rate at this temperature is below the sensitivity threshold of

	the equipment. Values below the sensitivity threshold are not relevant. The sensitivity threshold is reached at 110 °C for 0%SOC cell (cf p 121, UL report) and 85°C for 100%SOC cell (cf UL report 122). **Modification proposal** "…**cells started to generate internal heat at temperatures as low as 85°C (100%SOC) and 110°C (0%SOC)** (and remove the last part of the sentence as the battery is qualified for temperatures comprised between -18°C and 70°C).

Page/Section:	Sentence/Comment:
	§ 1.5.5 Rivet observations during cell- and battery-level testing **Existing sentence:** *"*the aluminum rivets on the positive terminal of cell 5 increased progressively through 14 cycles to a maximum of 157°C/315°F*"*
Comment:	Some precision need to be added: - In some case, the UL tests were performed with an average current of 940A. - The worst case with a battery voltage at 20Vdc corresponds to a power of 18.8KW during the simulation of APU start. - With a battery fully charged before the APU start simulation, the battery voltage is between 25 and 26Vdc the power was comprise between 23.5KW and 24.4KW. - Thales tests have demonstrated that the rivets are designed to withstand APU start with a maximum power of 18KW in all the temperature range in compliance with Boeing SCD. - In the case of APU start out of Boeing SCD (> 18KW) the rivets are damaged and this damage are irreversible. **Modification proposal** **Taking into account of Thales testing and submission, this paragraph should be amended by adding that in the operating range this phenomenon does not occur.**

Page/Section:	Sentence/Comment:
	§ 1.5.5 Rivet observations during cell- and battery-level testing **Existing sentence:** *""The cell leakage test showed that the seal of the cell was damaged"*
Comment:	Note that all the tests performed by UL and reported in the section refer to battery that was tested outside of the power specified domain over 18 kW as mentioned in the previous comment. Thales tests exactly showed the same results after abnormal APU start (>18KW) **BEA suggests taking into account the THALES results in this chapter or clearly indicates that tests were performed out of power specified domain.**

Page/Section:	Sentence/Comment:
	§ 2.1 Failure sequence **Existing sentence:** *“A battery-level test showed that condensation could occur within the battery and result in shorting path between the cell and the battery cases, and cell-level test with moisture showed that a cell failure could occur and result in arcing, shorting, and heat damage internal to cell header. However the damage observed during the cell-level test was not found in the cell header from the incident APU battery. In addition, airplane flight test data did not show any abnormal electrical transients that could lead to battery failure ”*
Comment:	*During the investigation, it was not possible to show that the JAL Boston Cells, and specifically cell 5 and cell 6, had experienced or not shortings as described in the Thales submission. In addition based on information provided by NTSB, the flight test recording system was capable of recording signals that had frequency up to hundreds of Khz. The Transient phenomena that are seen as a potential contributing factor by BEA and Thales are in a range of 2 to 4 Mhz. That means that such phenomenon couldn’t be captured by the aircraft flight test installation.* **The BEA suggests taking into account the THALES results in this chapter and to modify it as follows :** ***The information collected during the investigation does not allow to determine if the damages observed during the cell-level test on the cell headers were similar to the incident APU battery. In addition, during the airplane flight test, the system used to collect the electrical data had limited electrical transients recording capabilities (in the range of hundreds Kilo Hertz) and did not make it possible to capture electrical transient phenomenon that occurs with High Frequency range (Mhz).***

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