The Investigation of a Lithium-Ion Battery Fire Onboard a Boeing 787 by the US National Transportation Safety Board

By Joseph M. Kolly, Joseph Panagiotou, and Barbara A. Czech of the National Transportation Safety Board

Joseph M. Kolly *is Director of the NTSB's Office of Research and Engineering, where he is responsible for oversight of the Board's three laboratory divisions—the Materials Laboratory, the Vehicle Recorders Laboratory, and the Vehicle Performance Laboratory—and the Board's Safety Research Division. He received his doctoral degree in mechanical engineering from the University at Buffalo, New York, USA, in 1996 and was a senior research scientist at Calspan/University at Buffalo Research Center (CUBRC) before joining the Board in 1998.*

Joseph Panagiotou *is an NTSB Fire and Explosion Investigator in the Materials Laboratory Division, Office of Research and Engineering. He performs fire and explosion investigations for all modes. Mr. Panagiotou worked as a laboratory research assistant at the University of Maryland from 2002 to 2004, designing and running fire tests for flammability and fire dynamics experiments. Mr. Panagiotou received his B.S. in Fire Protection Engineering (2002) and his M.S. in Fire Protection Engineering (2004) from the University of Maryland, College Park.*

Barbara A. Czech *is Associate Director for Program Management of the NTSB's Office of Research and Engineering, where she is responsible for managing engineering programs and engineering staff activities that provide technical and laboratory support to the NTSB's accident investigations. Ms. Czech received her B.S. in mechanical engineering from the University of Maryland in 1991.*

The US National Transportation Safety Board (NTSB) is an independent federal agency responsible for investigating all civil aviation accidents in the United States, as well as aviation incidents of significant safety impact. A fire in an auxiliary power unit (APU) lithium-ion battery onboard a Japan Airlines Boeing 787 Dreamliner at the General Edward Lawrence Logan International Airport, Boston, Massachusetts, in January 2013 prompted an NTSB incident investigation and ultimately, the Federal Aviation Administration's grounding of the aircraft. In this paper, we offer insight into the NTSB's investigation of the battery fire. The details of the Materials Laboratory examinations, including the methods and equipment used, will be discussed, as well as their significance in determining the cause and origin. The specific challenges of investigating "new and novel" technology will also be emphasized, such as the formation of multidisciplinary and internationally diverse teams of experts and facilities, and the use of unconventional testing techniques.

1. Introduction

Lithium-ion (Li-ion) battery technology is rapidly becoming a preferred choice for battery power across all segments of society. This relatively new technology offers significant improvements in energy and power density over conventional battery technologies, such as alkaline and NiCad. In transportation vehicle applications, Li-ion batteries deliver more energy and power with less weight and maintenance than conventional batteries, making them a desirable choice of manufacturers.

The Boeing 787 Dreamliner uses several types of Li-ion batteries to power different systems onboard the aircraft. The largest type of these batteries is used in two systems onboard the aircraft. One provides power to start the Dreamliner's APU and another (the main battery) provides power to selected electrical/electronic equipment during ground and flight operations. To date, the Dreamliner has experienced two failures of this type of battery in two separate incidents.

This paper describes the NTSB's laboratory examination procedures used to analyze the fire-damaged Li-ion battery from the Logan International Airport incident. The objectives of the examinations were to (1) Document the condition of, and damage to, the battery; (2) Determine the origin of the failure; and (3) Determine the cause of the failure.

1.1 Incident 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 airplane, which was parked at a gate at Logan International Airport. About the same time, a maintenance manager in the cockpit observed that the APU—the sole source of airplane power at the time—had automatically shut down. Shortly afterward, a mechanic opened the aft electronic equipment (E/E) bay and found heavy smoke and fire coming from the front of the APU battery case.(1) No passengers or crewmembers were aboard the airplane at the time, and none of the maintenance or cleaning personnel aboard were 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* Part 129.

Nine days later, 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. The airplane made an emergency landing in Takamatsu, Japan, shortly after takeoff. The Japanese Transportation Safety Board (JTSB) is investigating this incident with support from the NTSB. Since the main battery and APU battery on the Boeing 787 are of the same make and model. Therefore, both the NTSB and JTSB investigations have continuously shared investigative information and techniques.

1.2 Battery Design

Both the main and APU batteries consist of eight Li-ion cells that are connected in series and assembled in two rows of four cells. (See figure 1.) Table 1 shows the specifications for the APU battery and cells. The insulation sheets provide electrical insulation and physical separation between each cell and between the cells and the aluminum battery case, which is electrically grounded. Upper and lower fixation trays secure the position and orientation of the cells in the battery case.

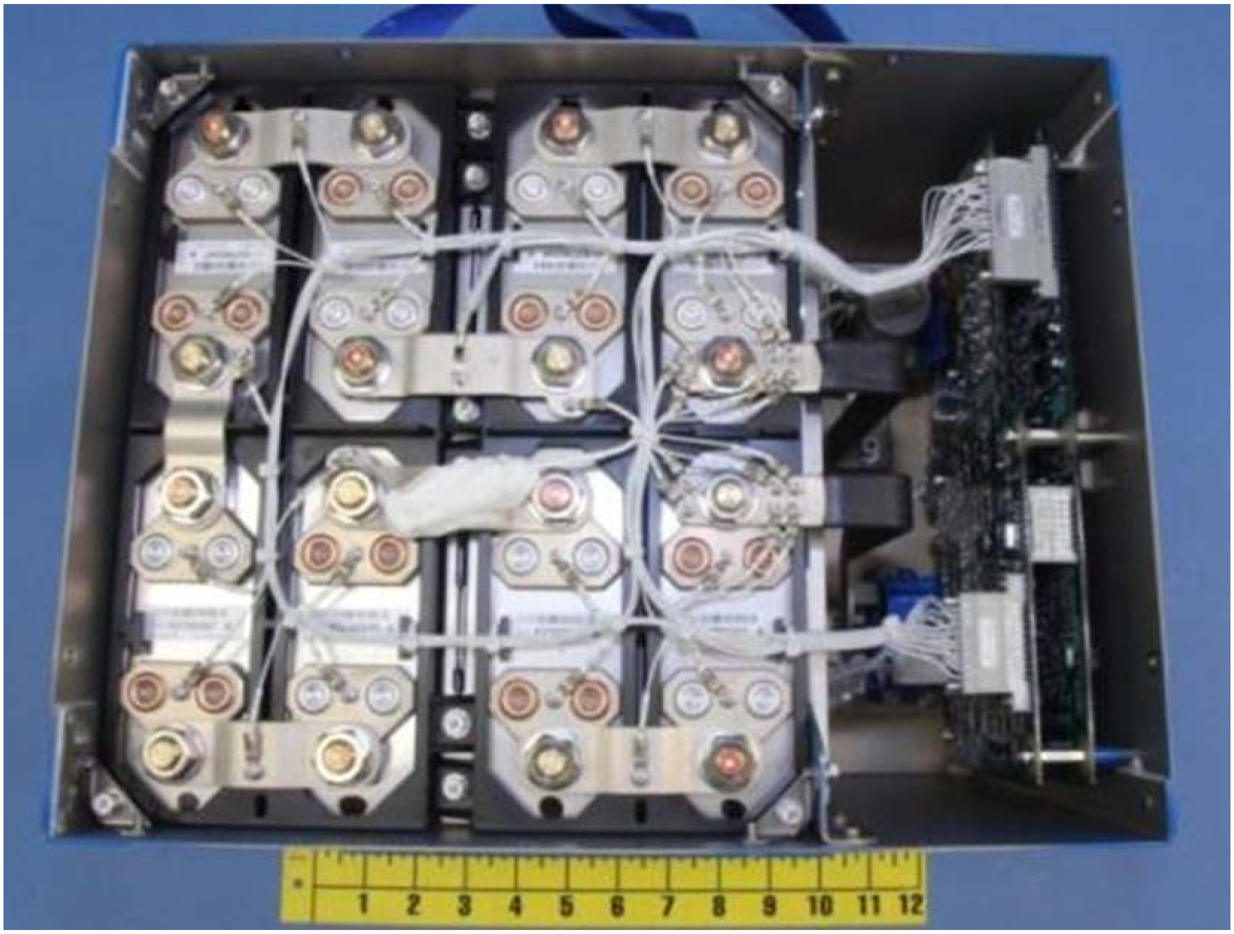

Figure 1. Exemplar for the 787 main and APU batteries.

Table 1. Battery and cell specifications.

Specification	**Battery**	**Cell**
Nominal capacity (ampere-hour)	75	75
Nominal voltage (volts)	29.6	3.7
Operational voltage range (volts)	20 to 32.2	2.5 to 4.025
Weight (pounds)	61.8	6
Dimensions (inches)		
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 Avionics Electrical Systems document. Cell specification information was provided by GS Yuasa.

In addition to the eight individual battery cells, the battery case contains two circuit boards that comprise the battery monitoring unit (BMU); a Hall effect current sensor for current monitoring; a contactor; bus bars(2) for the main current pathways between the cells and to the J3 connector, which leads outside the battery case; and sense wires leading to the BMU. By and large, these components are noncombustible, with the exceptions of the polymeric insulation and spacer materials. Figure 2 shows the battery components.

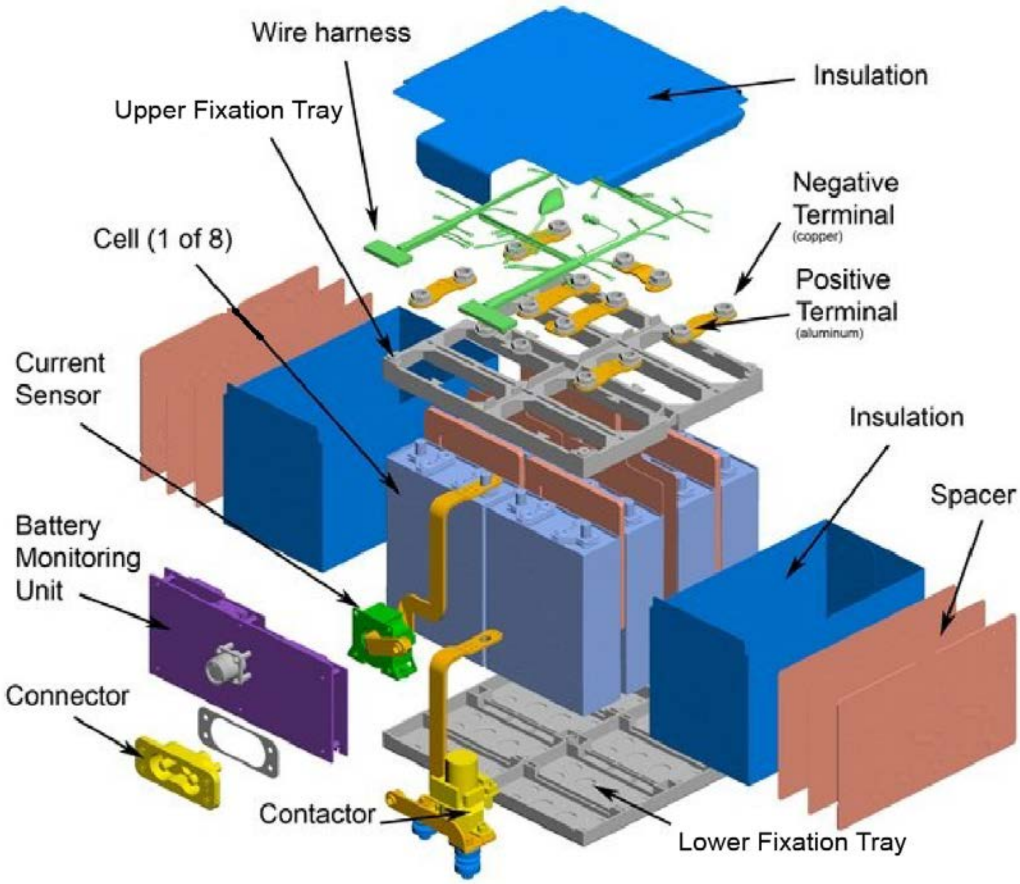

Figure 2. Components of the main or APU battery.

1.3 Cell Design

Each cell has three internal electrode winding assemblies, as shown in figure 3. Each winding assembly is about 33 feet long and is configured as a multi-layer continuous sheet of an electrode, followed by a separator, followed by another electrode, and then another separator. These windings are welded to current collectors, which then are affixed to the cell's electric terminals.

The electrochemistry is similar to that of other cobalt oxide Li-ion batteries. One electrode (the anode) is a copper foil coated in carbon; the other electrode (the cathode) is an aluminum foil coated in a lithium cobalt compound. The electrolyte is composed of lithium salt in an organic solvent. This cell has primarily nonflammable components, but the electrolyte is flammable.

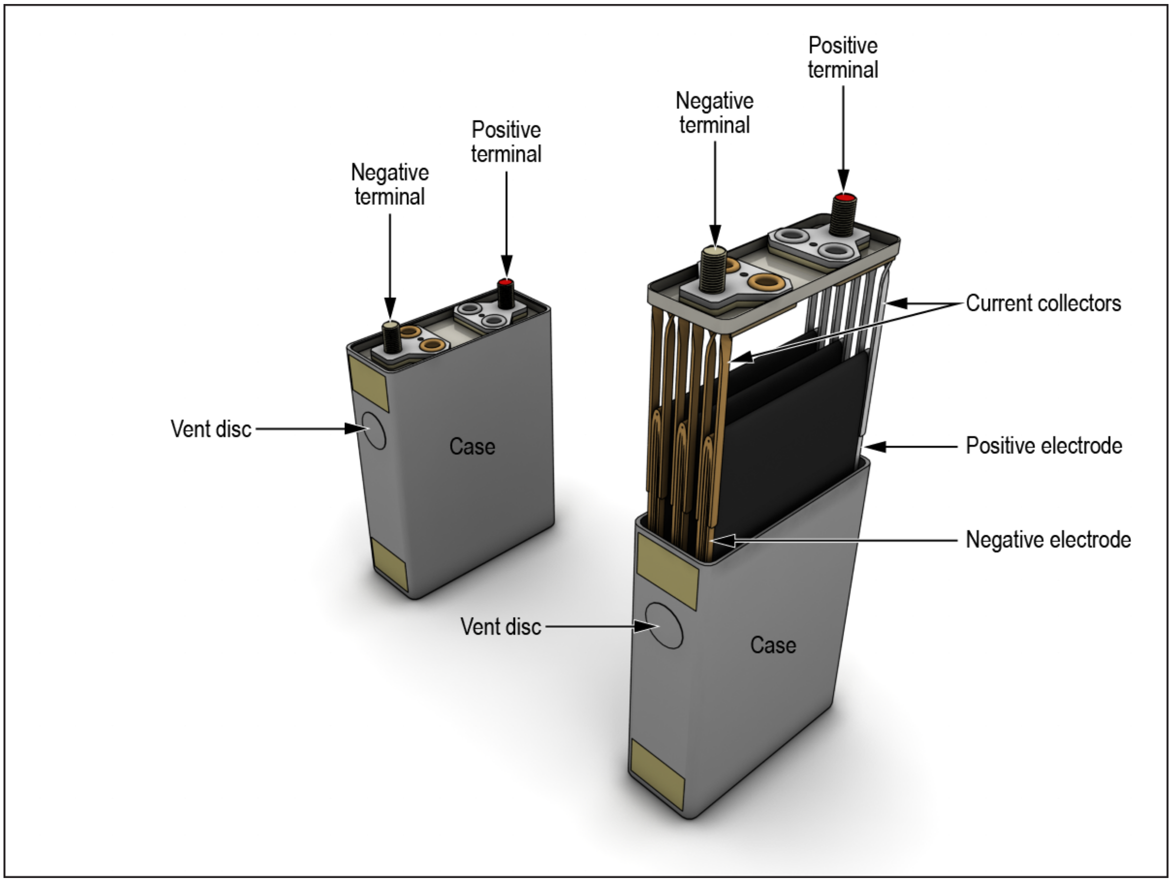

Figure 3. Cell design with three internal electrode winding assemblies.

2. Examination Methods and Procedures

The fire-damaged APU battery was removed from the aircraft by firefighters on scene; it was subsequently shipped to the NTSB Materials Laboratory in Washington, DC, for examination. An investigative group was formed consisting of NTSB Materials Laboratory staff, supported by technical expertise from the parties to the investigation.(3) In this instance, additional expertise was sought to augment the examination and analysis procedures. Technical consultants from other federal agencies(4) and private laboratories(5) with specific experience in Li-ion technology research and failure analysis were added to the investigative group.

A variety of destructive and non-destructive examination methods were employed at the NTSB's laboratories and other laboratory and testing facilities. These examinations included optical and scanning electron microscope (SEM) analysis with energy dispersive spectroscopy (EDS), radiographic analysis (digital radiographs and computed tomography [CT] scans), and microhardness testing.

2.1 Initial Examination of Battery Assembly

Initial visual examination indicated thermal and mechanical damage, including localized hot spots, on the external surface of the battery case. SEM/EDS analysis was conducted on these hot spots, and determined they originated in the inside of the battery case, therefore ruling out external sources such as electrical short circuiting and mechanical damage as an initiating event. The aluminum top (lid) of the case was bulged upward, exposing the internal components. The top was removed to reveal the upper surface of the battery assembly which exhibited severe thermal damage to the entirety of its internal components. Voltage measurements taken of each cell indicated the battery was completely discharged and electrical continuity measurements indicated each cell was shorted “open”.

The thermal damage to the battery components, such as charring of materials and distortions of the cells, indicated areas of higher interest and probability of identifying an origin of the thermal event. However, this obscured clear distinction of the components and prevented immediate disassembly of the battery; a more deliberate disassembly process was necessary to avoid destroying any potential evidence that might indicate the root cause of the failure. Figure 4 shows the condition of the battery as received in the laboratory (with the top of the case removed).

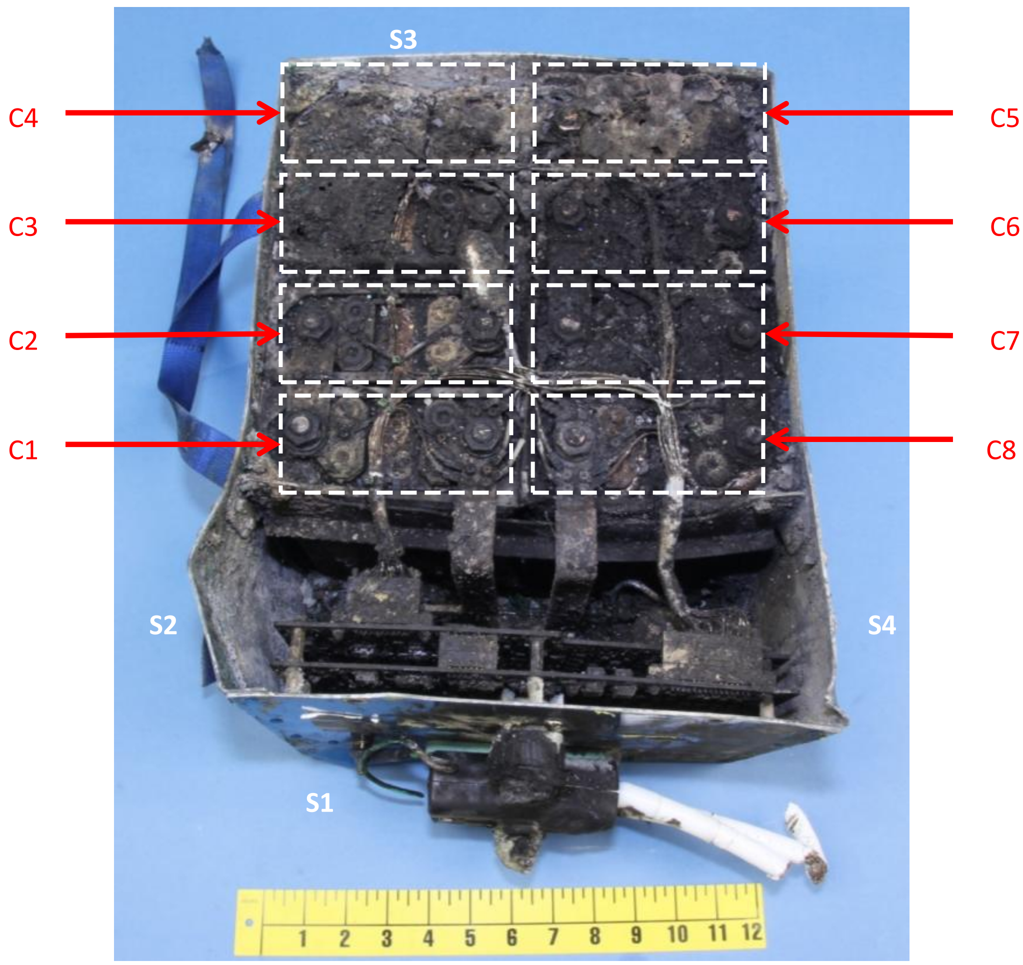

Figure 4. Opened battery case showing approximate cell locations.

Disassembly of the damaged battery was guided by the use of radiographic imaging of the intact assembly. This imaging method rendered a non-destructive view of the entire volume of the battery assembly. Once analyzed, the fire-damaged battery components could be carefully extracted from the case, with the prior knowledge of the internal structure that helped to identify and avoid destruction of any possible mechanical deformation or foreign debris that might be present.

Radiographic imaging of the damaged APU battery (and, for comparison purposes, of the undamaged main battery) was conducted at Chesapeake Testing in Belcamp, Maryland, under NTSB supervision. The batteries were documented using x-ray CT scans and digital radiography.

Because of the physical size of the battery, the imaging equipment must have sufficient energy to penetrate the battery, and sufficient volumetric and weight capacity to support and rotate the battery for imaging. In this instance, a Nikon Metrology 450 kV Microfocus scanner was used. The x-ray source in this equipment has an x-ray focal spot size of 80 µm.

To produce digital radiograph images, the battery was subjected to a process similar to a conventional x-ray. As such, the images contain elements throughout their volume superimposed on each other. The whole battery was imaged at least twice, and the separate images were obtained at positions rotated by up to 90 degrees.

For the CT scans, the battery was loaded into the imaging unit and placed on a turntable. The battery was then rotated in front of the x-ray source, and the x-rays were captured by a detector after they went through the battery. The x-ray source produced a cone of x-rays, and the portion of the battery imaged was adjusted slightly after each scan volume was completed until the entire assembly (or region of interest of the assembly) was scanned.

The scan volume created in the scanning process was approximately 1,600 pixels by 1,700 pixels by 2,000 pixels in volume for a whole battery scan and had resulting file sizes ranging between 5.8 gigabytes and 24 gigabytes.

Each CT volume was evaluated using the VGStudio Max software package. Post-processing using this software permits viewing individual two-dimensional planes or “slices” cut across the image in detail or can be used to create a three-dimensional reconstructed image of the component. During the CT scan evaluation, some sections of the components were digitally removed to allow closer observation of interior parts. This procedure was beneficial when searching the images for signs of foreign materials within the battery case, external to the cells.

The results of the radiographic imaging work indicated that, although several of the battery cells had permanently deformed (bulged), they remained mostly intact. In the radiographic image below (figure 5), one can clearly see the bulging of the cells and the electrode windings that remained within each cell. Also evident was both cell-to-cell and cell-to-battery-case contact. The imaging revealed an absence of foreign materials within the battery, external to the cells.

Following a complete review of the radiographic images, the battery was prepared for disassembly at the NTSB Materials Laboratory. The radiographic images provided critical benefits to this procedure. Investigators could view the internal volume of the battery to aid in disassembly and reduce damage during disassembly; they could also document the precise orientation of components that would be lost upon disassembly.

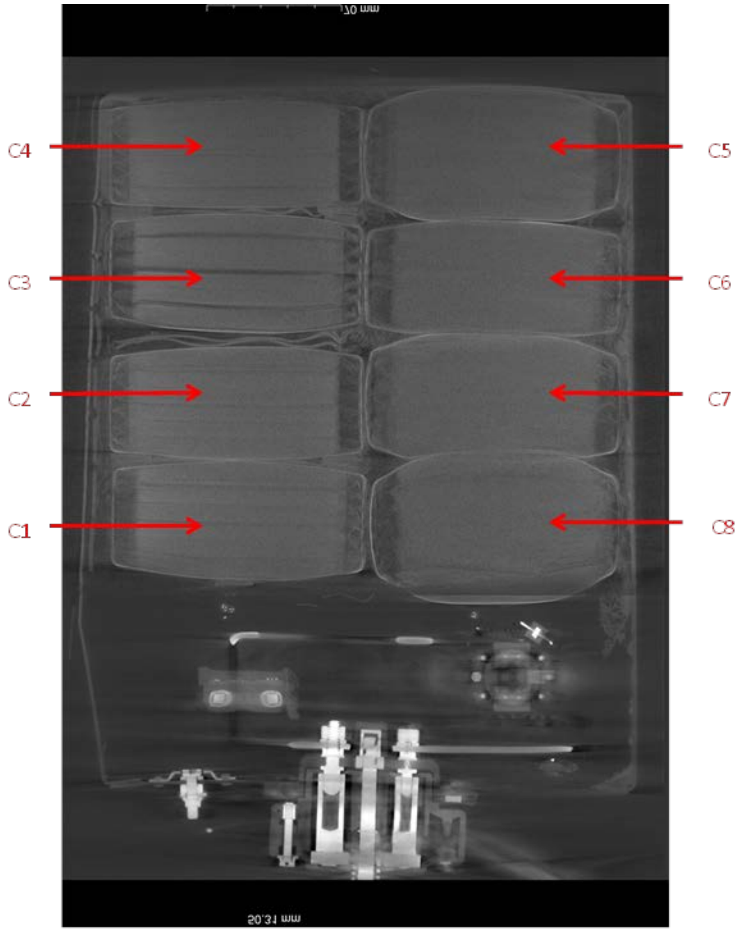

Figure 5. Radiographic image of JAL APU battery indicating cell locations.

From this image, it is apparent that the cells on the right side of the figure (cells 5–8) experienced greater mechanical damage, in the form of bulging, than those on the left side. This pattern also corresponded to more severe thermal damage to the polymeric materials on the right side of the battery.

Disassembly began by removing the rivets along the seams of the aluminum battery case and folding down the sides. (See figure 6.) Figure 6 shows the side of the battery that experienced the greatest thermal and mechanical damage. When the sides of the cells were exposed, it was apparent that cells 5–8 had relieved pressure through their vent discs. Cells 1–3 also vented but with less deformation of their vent discs.

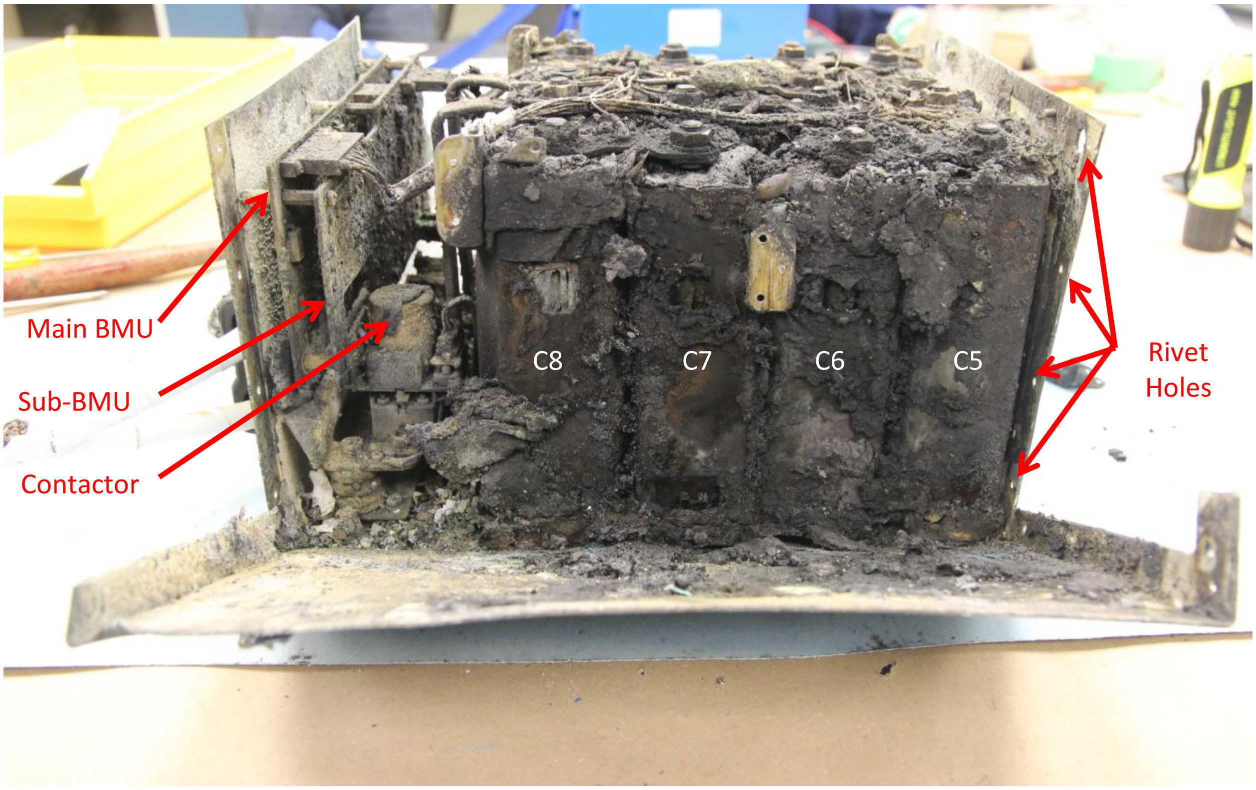

Figure 6. View of battery with battery case panel pulled back to reveal cells 5 through 8.

Next, the bus bars and wiring harness were removed, and then each of the eight cells was removed.

2.2 Bus Bar Examinations

Each bus bar was removed from each cell and examined. Photographs of both sides of the bus bars connecting the batteries are shown in figure 7.

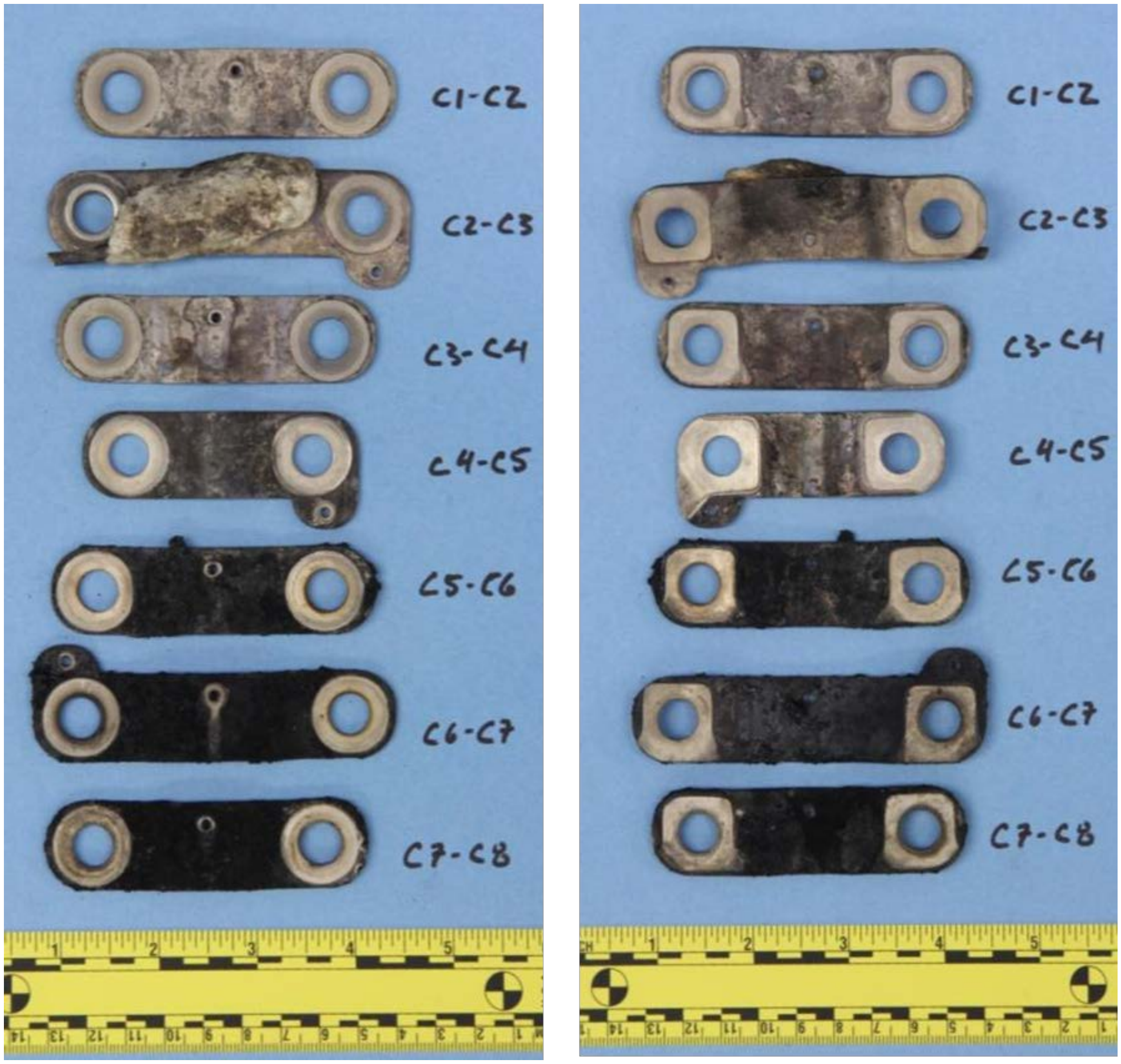

Figure 7. Views of bus bar contact surfaces. The photo on the left shows the contact surfaces facing the washer and the nut. The photo on the right shows the contact surfaces facing the battery terminal.

For each bolted connection, the condition of the faying contact surfaces was visually evaluated using a 5X to 50X zoom stereo microscope. No dark oxides or interference colors associated with high-temperature resistive heating were observed on the surfaces of the bus bars.

Metallurgical cross sections of some of the bus bars were prepared to facilitate microhardness testing and microstructural evaluation. Figure 8 shows the section of the bus bar connecting cells 4 and 5.

Figure 8. Section cut through the bus bar connecting cells 4 and 5.

The cross sections were mounted and polished, and their microhardness was tested in accordance with ASTM E384-11e1.(6) The locations of the microhardness indentations are displayed in figure 9. The mounted samples were then microetched in accordance with ASTM E407-07e1.(7) No microstructural changes, such as grain growth or hardness changes associated with localized heating, were observed.

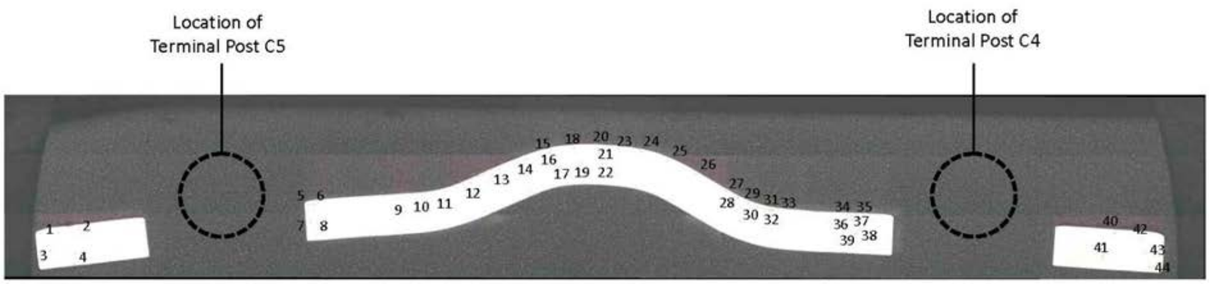

Figure 9. Microhardness indentation locations of C4–C5 bus bar.

2.3 Wiring Harness Examinations

When enough of the charred debris had been removed from the top portion of the battery to permit evaluation, the physical condition of the BMU's cell voltage-sensing wiring harness was evaluated. (See figure 10.)

Figure 10. Wiring harness, as removed. (View is from the bottom.)

The overall appearance of the wiring harness was consistent with exposure to a high-temperature environment with areas of varying severity. The insulation on the wires was mostly intact, but it exhibited varying degrees of thermal discoloration and staining from the expelled battery cell contents (carbonaceous, electrolyte, and cathode material). Evaluation of the thermal damage to the wiring harness suggested an area of higher temperatures or an area of longer exposure to elevated temperatures during the event. This also corresponded to areas of higher thermal damage to items such as the upper and lower fixation trays. The concentrated thermal damage suggested an area of higher interest for establishing an origin.

2.4 Detailed Cell Level Examinations

Following the disassembly of the battery, each cell was subjected to additional radiographic imaging. The resulting CT scans had a scan volume of approximately 1,300 pixels by 650 pixels by 1,850 pixels for each battery cell. As an example of the detail that can be obtained, the CT scan shown in figure 11 clearly shows a breach in the case of cell 5 less than 0.10 inch long.

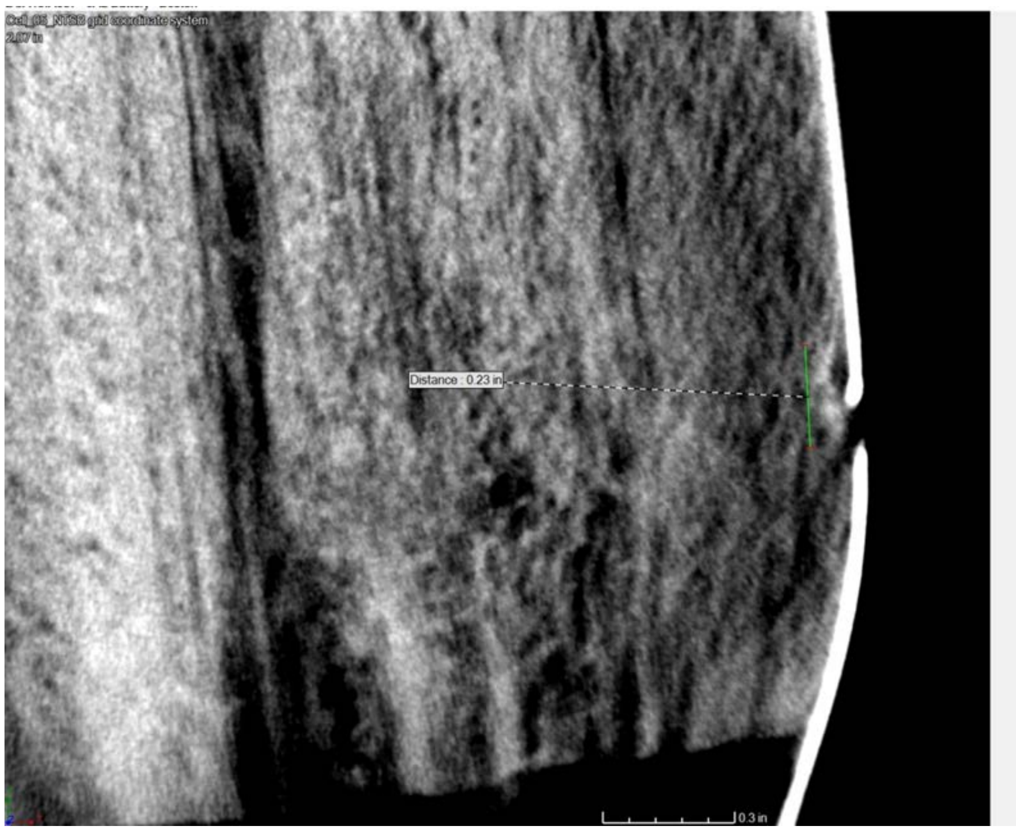

Figure 11. CT scan of cell 5 showing breach in case.

Prior to the extraction of the electrode windings from the cells, these scans were examined for any signs of damage, contamination, or other anomalies. Once these scans were reviewed, they were used to guide the disassembly process of the electrode windings from the cell case.

The disassembly procedure used a Dremel® abrasive disc cutoff tool to circumnavigate the top of each cell case, at the location of its weld seam. Cuts were also made down the longitudinal sides of one of the cell's faces to excise a panel of the cell case. This then allowed the header and windings to be removed from the remainder of the cell case. The current collectors attaching the windings to the cell header and terminals were then cut to liberate the individual electrode windings. Each of the three electrode windings was then carefully unwound on an examination table. Figure 12 shows one 33-foot-long length of the thermally damaged electrode from cell 6, unrolled on an examination table for visual inspection.

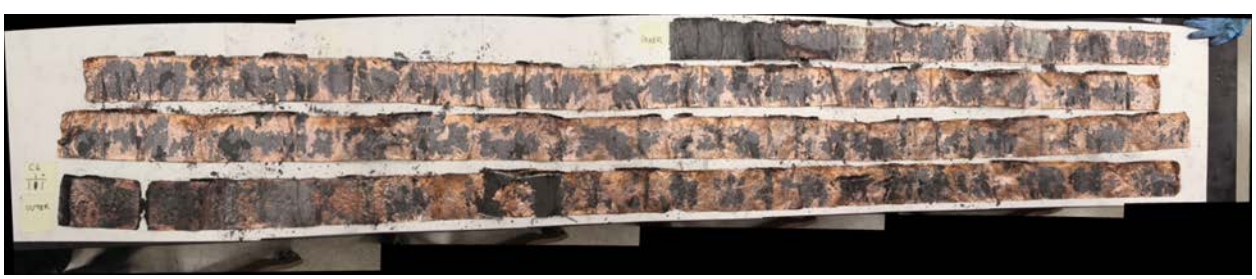

Figure 12. Cell 6 electrode unwound on table.

The entire surface of both sides of each electrode was then examined by the naked eye and digitally photographed. Any anomalous areas of interest were carefully sectioned and examined further with digital microscope and SEM. Areas of special interest included those showing unique thermal damage, such as burn-through spots and regions of discoloration. Figure 13 shows such anomalous areas on the electrode from cell 6. They are characterized by localized hot spots identified by purple hues in the copper foil. Additionally, these hot spots exhibit radiating patterns and repeat in the same relative position along the wraps of the winding. Small holes along the top edge of the copper foil indicate short circuiting between the electrodes of the winding.

Figure 13. Cell 6 electrode with anomalous areas of interest.

In these areas, SEM imaging was performed at magnifications of 100-1000X, and EDS was employed on anomalous features to examine their elemental constituents. The SEM/EDS examinations were conducted to identify any evidence of dendritic growth of lithium, copper plating, or foreign materials. These features are known to cause field failures of Li-ion batteries, and therefore are of high interest to the investigation. Examples of SEM images in the areas contained in the previous photograph are shown in figures 14–16. SEM/EDS proved very capable of characterizing these anomalies, but can be extremely time consuming. This is largely due to the limited field of view afforded by the SEM. This resulted in several hours of SEM analysis per anomalous region of interest.

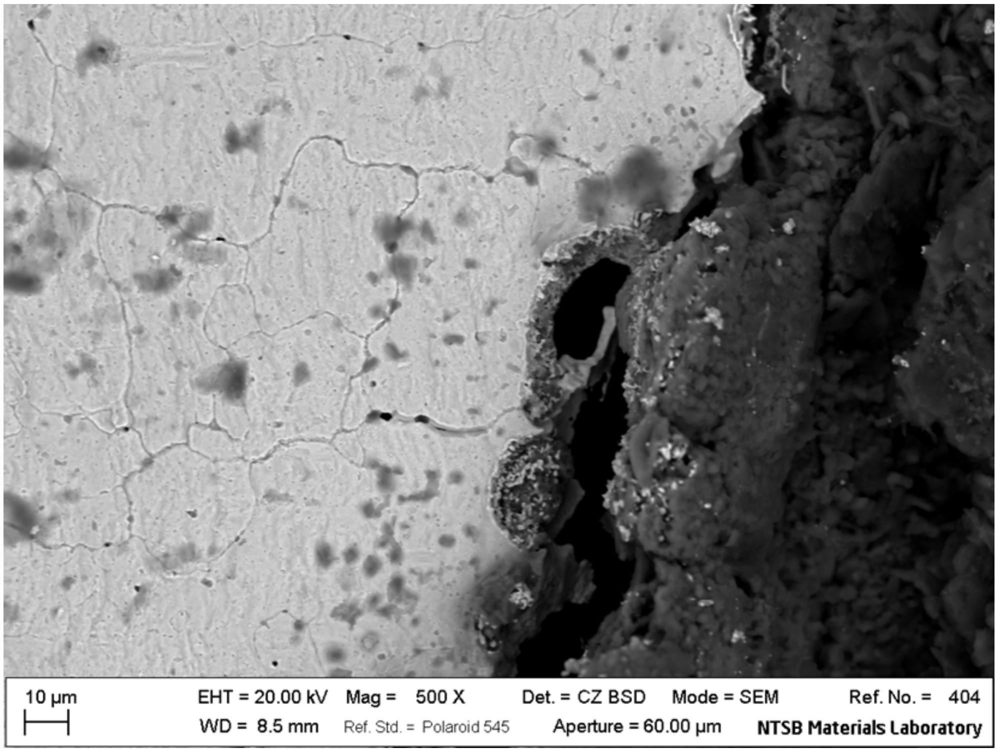

Figure 14. Grain boundary decohesion near a foil hole, cell 6.

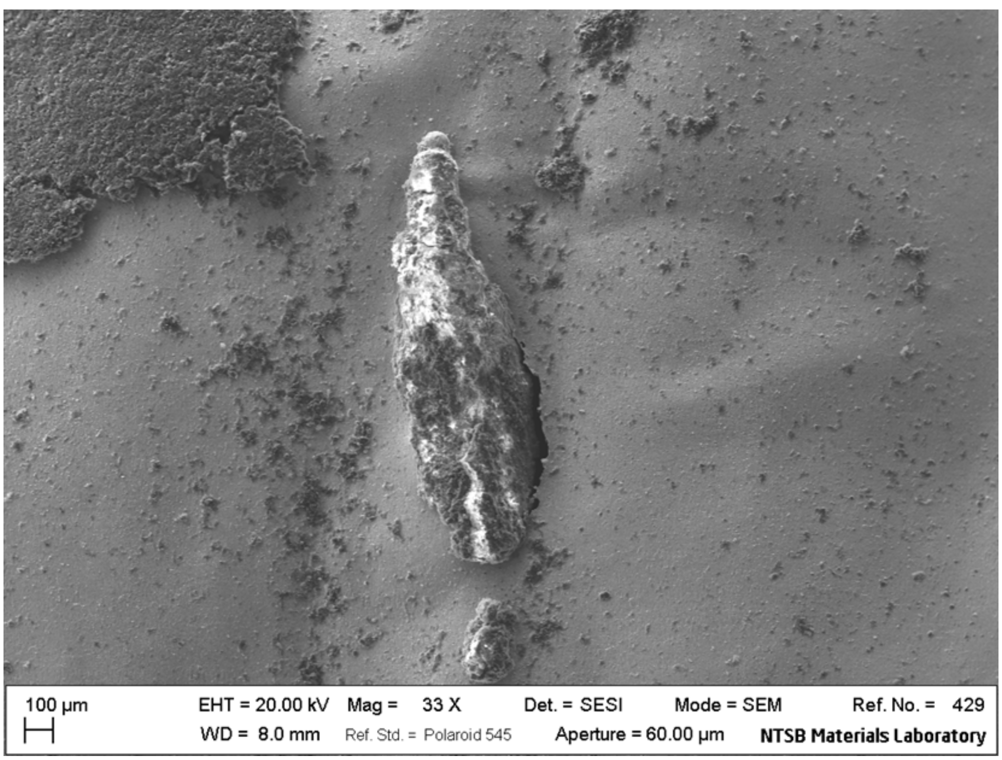

Figure 15. Aluminum lump projecting through the bottom of a copper foil wrap, cell 6.

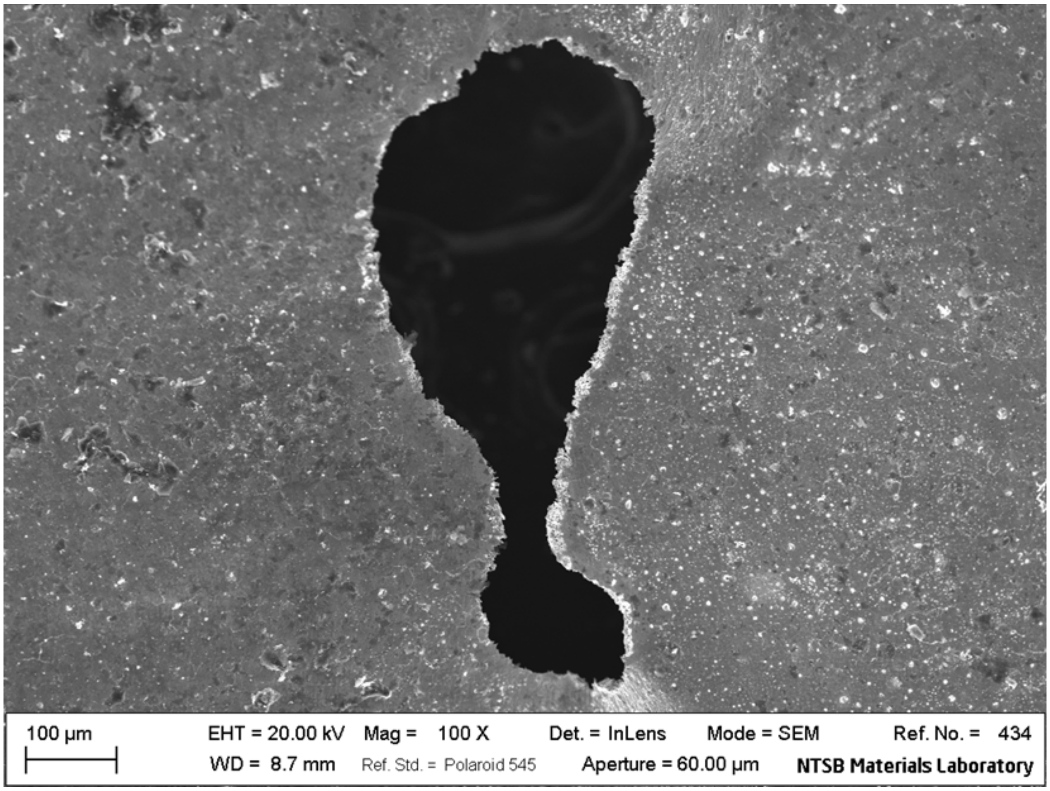

Figure 16. Hole in the bottom of the copper foil adjacent to the aluminum protrusion in figure 15, cell 6.

3. Initial Findings

The results of the examinations at the NTSB Materials Laboratory, with the results from radiographic examinations, enabled the NTSB to make public release of an initial set of findings earlier this year.(8) The examinations revealed multiple cell failures within the battery, as evidenced, in part, by mechanical deformation and bursting of the vent discs. This condition led the experts to conclude that the battery experienced a thermal runaway in which the failure of one battery cell cascaded to other neighboring cells within the battery assembly. The initial failure was determined to be an internal short circuit in cell 6. This finding was supported, in part, by observations that cell 6 was located in the area of greatest thermal and mechanical damage. Additionally, clear evidence of internal short circuits was found within the electrode windings of cell 6.

Work continues to determine the cause of the internal short circuit. As of this writing, mechanical damage and external electrical short circuits of the battery have been ruled out as factors in the battery failure. The NTSB is still considering manufacturing and design issues, as well as issues associated with the battery charging system.

4. Conclusions

The in-service failure of the Li-ion APU battery onboard the Boeing B-787 Dreamliner required a unique mix of technical expertise and analytic techniques to document the damage and condition of the battery, and determine the cause and origin of the failure. Investigators from the

NTSB Materials Laboratory were supported by experts from the parties to the investigation, and by additional expertise from other federal agencies and private consultants.

A combination of destructive and non-destructive analytic techniques was used to disassemble the battery into its components and examine each individually. Radiographic imaging successfully guided the disassembly and eliminated unnecessary destruction of evidence. Visual and microscopic examinations aided the radiographic imaging by identifying overall damage patterns and localized damage, which supported, in part, the finding of a thermal runaway condition that began with an internal short circuit in cell 6. Other methods (including microhardness testing and EDS) helped to rule out external short circuits and mechanical damage as factors in cause of the battery failure.

Notes

1 The mechanic provided a written statement to the 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 also reported that he "saw small flame around APU batt[ery]." He added that he "decided [to] discharge [the fire] extinguisher" but could not "discharge continuously" because he believed there was a "dangerous environment in the compartment." In addition, he stated that he "tried fire extinguishing, but smoke and flame (flame size about 3 inch[es]) did not stop." The maintenance manager also provided a written statement to the NTSB, which indicated that the mechanic had seen "flames around the APU battery."

2 A bus bar is a metallic copper strip that electrically connects the terminals of each cell in series.

3 These party participants included technical staff from the Federal Aviation Administration, Boeing Commercial Airplanes, Thales Avionics Electrical Systems, GS Yuasa (the manufacturer of the 787 main and APU batteries), and Japan Airlines.

4 Representatives from the Carderock Division of the Naval Surface Warfare Center, US Department of the Navy; and the US Department of Energy.

5 TIAX.

6 ASTM E384-11e1 "Standard Test Method for Knoop and Vickers Hardness of Materials," ASTM International, West Conshohocken, PA.

7 ASTM E407-07e1 "Standard Practice for Microetching Metals and Alloys," ASTM International, West Conshohocken, PA.

8 These findings were released during the NTSB press conference conducted on February 7, 2013, and in the NTSB Interim Factual Report on this investigation (Boston, Massachusetts, DCA13IA037, Boeing 787-8, JA829J, Japan Airlines) issued on March 7, 2013. For more information, see http://www.ntsb.gov/investigations/2013/boeing_787/interim_report_B787_3-7-13.pdf.