AI2014-4

AIRCRAFT SERIOUS INCIDENT
INVESTIGATION REPORT

ALL NIPPON AIRWAYS CO., LTD.
JA804A

September 25, 2014

Japan Transport Safety Board

The objective of the investigation conducted by the Japan Transport Safety Board in accordance with the Act for Establishment of the Japan Transport Safety Board (and with Annex 13 to the Convention on International Civil Aviation) is to prevent future accidents and incidents. It is not the purpose of the investigation to apportion blame or liability.

Norihiro Goto
Chairman,
Japan Transport Safety Board

Note:

This report is a translation of the Japanese original investigation report. The text in Japanese shall prevail in the interpretation of the report.

AIRCRAFT SERIOUS INCIDENT INVESTIGATION REPORT

EMERGENCY EVACUATION USING SLIDES
ALL NIPPON AIRWAYS CO., LTD.
BOEING 787-8, JA804A
TAKAMATSU AIRPORT
AT 08:49 JST, JANUARY 16, 2013

September 19, 2014
Adopted by the Japan Transport Safety Board
Chairman Norihiro Goto
Member Shinsuke Endo
Member Toshiyuki Ishikawa
Member Sadao Tamura
Member Yuki Shuto
Member Keiji Tanaka

SYNOPSIS

Summary of the Serious Incident

On January 16 (Wednesday), 2013, a Boeing 787-8, operated by All Nippon Airways Co., LTD., registered JA804A, took off from Yamaguchi Ube Airport for Tokyo international Airport at 08:11 local time as its scheduled flight 692. When it was climbing through 32,000 ft over Shikoku Island, an EICAS message of battery failure came on at 08:27 accompanied by unusual smell in the cockpit. The airplane diverted to Takamatsu Airport and landed there at 08:47. An emergency evacuation was executed using slides on T4 taxiway at 08:49.

Four passengers out of 137 occupants (the Captain, seven crewmembers and 129 passengers) suffered minor injuries during the evacuation.

Although the main battery was damaged, it did not lead to a fire.

Incidentally, a similar incident had occurred prior to Takamatsu event by nine days in the United States, on January 7, 2013 (Eastern Standard Time) at Logan International Airport, Boston, Massachusetts.

About one year after the serious incident, another similar main battery incident occurred at Narita International Airport on January 14, 2014.

Probable Causes

The emergency evacuation was executed on Takamatsu Airport taxiway in the serious incident, which was a consequence of emergency landing deriving from the main battery thermal runaway during the airplane's takeoff climb.

Internal heat generation in cell 6 very likely developed into venting, making it the initiating cell, resulting in cell-to-cell propagation and subsequent failure of the main battery. It is very likely that cell 6 internal heat generation and increased internal pressure caused it to swell, melt the surrounding insulation material and contact the brace bar creating a grounding path that allowed high currents to flow through the battery box. The currents generated arcing internal to the battery that contributed to cell-to-cell propagation consequently destroying the battery.

Cell 6 heat generation was probably caused by internal short circuit; however, the conclusive mechanism thereof was not identified.

In the serious incident, the internal short circuit of a cell developed into cell heat generation, thermal propagation to other cells, and consequently damaged the whole battery. The possible contributing factors to the thermal propagation are that the test conducted during the developmental phase did not appropriately simulate the on-board configuration, and the effects of internal short circuit were underestimated.

Safety Recommendations

1. Actions to be taken by the Federal Aviation Administration

The internal short circuit test by nail penetration method under the simulated on-board configuration with the battery ground wire demonstrated a thermal runaway, while the test without the ground wire did not.

Given the facts and analyses of other tests combined, in the serious incident the very likely sequence of scenario for the main battery thermal runaway is as follows:

- Cell 6 was the initiator of the thermal propagation;
- Cell 6 and the brace bar contacted with each other allowing high currents to flow through the battery box to cause arcing; and
- Arcing bolstered the thermal propagation leading to the thermal runaway.

It is very likely that the engineering test conducted during the developmental phase did not develop into thermal runaway because the battery box was not grounded with the ground wire. This demonstrates that it was inappropriate to exclude the internal short circuit test from the safety assessment based on the test result which was not conducted simulating the actual airplane configuration.

There is a possibility that present standards for airplane lithium ion battery do not appropriately address the electric environment although they stipulate environmental conditions such as temperature, humidity, inertia, and so on. In addition, the fault tree analysis in the safety assessment provided to the Japan Transport Safety Board lacks the assessment of the thermal propagation risk.

The probability of lithium ion battery thermal event with venting was estimated to be less than 1 out of ten million flight hours in the type certification; however, in reality three events of cell heat generation have occurred in less than 250,000 flight hours, resulting in the rate far exceeding the estimate. The calculation of failure rate in the type certification, which was done based on the failure records of similar LIB, was probably inappropriate.

In addition, contactor opening not expected in the design is very likely associated with cell venting; therefore, the necessity for risk reassessment on the loss of all electric power should be examined.

The Japan Transport Safety Board, in light of the serious incident investigation, makes the following safety recommendations that the Federal Aviation Administration of the United States of America should take the following mitigation actions.

The FAA should:

a. Provide instruction to airplane manufactures and equipment manufactures to perform equipment tests simulating actual flight operations.
b. Review the technical standards for lithium ion battery to ensure that the electric environment is appropriately simulated, and if necessary, amend the standards.
c. Review the lithium ion battery failure rate estimated during the 787 type certification, and if necessary, based on its result, review the lithium ion battery safety assessment.
d. Review the type certificate for its appropriateness on heat propagation risk.
e. Assess the impact of contactor opening after the cell vent on the flight operation and take appropriate actions, if necessary.

2. Measures to Be Taken to Instruct The Boeing Company as a Designer and Manufacturer of the 787

Although this investigation could not conclusively identify the mechanism of the internal short circuit, low temperature during overnight stay possibly contributed to the internal short circuit as the three battery incidents (this serious incident inclusive) occurred in the midst of cold January and low temperature is said to be favorable for lithium metal deposition. In addition, there are reports of cell contamination deriving from manufacturing, which may be related to the cause of the battery event. Furthermore, this investigation found the unexpected battery charger unit operation and contactor opening which are outside the design envelope in relation to the charging control.

In light of these facts, the Federal Aviation Administration should supervise Boeing to:

a. Continue the study of internal short circuit mechanism considering the effects of non-uniform winding formation and other factors deriving from manufacturing process; and continue efforts to improve lithium ion battery quality and its reliability, reviewing the LIB operational conditions, such as temperature.

b. Improve BCU and contactor operations which are outside the design envelop.

The following abbreviations and unit conversions are used in this report.

Abbreviations

AC: Advisory Circular
AD: Airworthiness Directive
Ah: Amp hour
ANA: All Nippon Airways
AOM: Airplane Operations Manual
APSIF: Airplane Power Systems Integration Facility
APU: Auxiliary Power Unit
ASG: APU Starter Generator
ATC: Air Traffic Control
ATP: Acceptance Test Procedure
ATCC: Air Traffic Control Center
BCU: Battery Charger Unit
BDM: Battery Diode Module
BIT: Built-in Test
BMU: Battery Monitoring Unit
BPCU: Bus Power Control Unit
CA: Cabin Attendant
CC: Constant Current
CFR: Code of Federal Regulations
CG: Center of Gravity
CP: Certification Plan
CP: Chief Purser
CRN: Current Return Network
CT: Computed Tomography
CV: Constant Voltage
CVR: Cockpit Voice Recorder
DC: Direct Current
DME: Distance Measuring Equipment
DPA: Destructive Physical Analysis
EAFR: Enhanced Airborne Flight Recorder
EE: Electronic Equipment
EICAS: Engine Indicating and Crew Alerting System
EPS: Electrical Power System
FAA: Federal Aviation Administration
FCE: Flight Control Electronics
FDR: Flight Data Recorder
FHA: Functional Hazard Assessment
FL: Flight Level
FMEA: Failure Modes and Effects Analysis
FO: First Officer
FOD: Foreign Object Damage
fpm: feet per minute

FTA: Fault Tree Analysis
GCU: Generator Control Unit
HBB: Hot Battery Bus
HECS: Hall Effect Current Sensor
ILS: Instrument Landing System
IP: Issue Paper
JAXA: Japan Aerospace Exploration Agency
JCAB: Civil Aviation Bureau of Japan
JTSB: Japan Transport Safety Board
JIS: Japanese Industrial Standards
LIB: Lithium Ion Battery
MAC: Mean Aerodynamic Chord
MFD: Multi-Function Display
MLG: Main Landing Gear
MOPS: Minimum Operational Performance Standard
MTBF: Mean Time Between Failure(s)
NLG: Nose Landing Gear
NTSB: National Transportation Safety Board
OCV: Open Circuit Voltage
ODA: Organization Designation Authorization
PF: Pilot Flying
PM: Pilot Monitoring
RAT: Ram Air Turbine
RCCA: Root Cause Corrective Actions
RIPS: Recorder Independent Power Supply
RNAV: Area Navigation
RTCA: Radio Technical Commission for Aeronautics
SC: Special Condition
SEI: Solid Electrolyte Interface
SEM: Scanning Electron Microscopy
S/N: Serial Number
SOC: State Of Charge
TC: Type Certificate
TIG: Tungsten Inert Gas
TSO: Technical Standard Order
TWR: Tower
UTC: Universal Time Coordinated
V_{DC}: Volt DC
VHF: Very High Frequency
VOR: VHF Omni-directional Ranging
VSGS: Variable Frequency Starter Generator

Unit Conversion

1 foot (ft): 0.3048 meters
1 knot (kt): 0.5144 meters per second (1.852 kilometers per hour)
1 nautical mile (nm): 1,852 meters

1 pound (lb):	0.4536 kilograms

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1. PROCESS AND PROGRESS OF THE SERIOUS INCIDENT INVESTIGATION

1.1 Summary of the Serious Incident

On January 16 (Wednesday), 2013, a Boeing 787-8, operated by All Nippon Airways Co., LTD., registered JA804A, took off from Yamaguchi-Ube Airport for Tokyo international Airport at 08:11 local time (Japan Standard Time, UTC+9 hr) as its scheduled flight 692. When it was climbing through 32,000 ft over Shikoku Island, an EICAS message of battery failure came on at 08:27 accompanied by unusual smell in the cockpit. The airplane diverted to Takamatsu Airport and landed there at 08:47. An emergency evacuation was executed using slides on T4 taxiway at 08:49.

Four passengers out of 137 occupants (Captain, seven crewmembers and 129 passengers) suffered minor injuries during the evacuation.

Although the main battery was damaged, it did not lead to a fire.

1.2 Outline of the Serious Incident Investigation

This event falls under the category of “A case where emergency evacuation was conducted with the use for emergency evacuation slide,” as stipulated in Item (iv), Article 166-4 of the Ordinance for Enforcement of the Civil Aeronautics Act, and is classified as a serious incident.

1.2.1 Investigation Organization

On January 16, 2013, the Japan Transport Safety Board (JTSB) designated an investigator-in-charge and four investigators to investigate this serious incident. On January 28, it designated two additional investigators for the investigation.

On February 6, the JTSB also designated an expert advisor for detailed investigation of lithium-ion battery:

Dr. Hitoshi Naito
Space Power System Group
Aerospace Research and Development Directorate
Japan Aerospace Exploration Agency (JAXA)

1.2.2 Representatives from Relevant States

Two accredited representatives from two States participated in this investigation: one from the United States of America, as the State of design and manufacture of the airplane, and the other from France, as the State of Design and Manufacture of the electrical subsystem of the airplane.

1.2.3 Implementation of the Investigation

January 16-19, 2013:	On-site investigation, airplane investigation, and interviews at Takamatsu Airport
January 22-23:	Battery computer tomography (CT) scanning at JAXA
January 24-March 5:	Battery examination at the manufacturer

January 26-27:	Battery monitoring unit (BMU) examination
February 2-6:	Battery charger unit (BCU) and bus power control unit (BPCU) examination
February 16-17:	Battery-BCU test
March 11-12:	Progress meeting at the National Transportation Safety Board (NTSB)
March 18-19:	Airplane examination at Takamatsu Airport
April 8:	Airplane examination at Takamatsu Airport
April 21-27:	NTSB investigative hearing and progress meeting
May 14-17:	Battery examination
May 29-31:	Examination of battery manufacturing
June 2-8:	Progress meeting at Boeing
June 11-13:	Battery examination
June 18-19	Battery examination
June 20:	BMU examination and airplane examination
June 24-September 17:	Battery test
November 1-28:	Cell heat propagation test

1.2.4 Comments from the Parties Relevant to the Cause of the Serious Incident

Comments were invited from the parties relevant to the cause of the serious incident.

1.2.5 Comments from the Relevant States

Comments were invited from the relevant States.

2. FACTUAL INFORMATION

2.1 History of the Flight

On January 16, 2013, a Boeing 787-8, operated by All Nippon Airways Co., LTD. (hereinafter referred to as "ANA"), registered JA804A, took off from Yamaguchi-Ube Airport for Tokyo International Airport at 08:11 as its scheduled flight 692. When it was climbing through 32,000 ft around FIATO (waypoint, over Imabari City) an instrument indication of battery failure came on at 08:27 accompanied by unusual smell in the cockpit. The airplane diverted to Takamatsu Airport and landed there at 08:47. At 08:49 an emergency evacuation was executed on T4 taxiway.

The flight plan of the airplane was summarized as follows:

Flight rules: Instrument flight rules
Departure aerodrome: Yamaguchi-Ube Airport
Estimated off-block time: 08:00
Cruising speed: 493 kt
Cruising altitude: FL 410
Route: FIATO (waypoint) to Y16 (RNAV route) to KTE (Kagawa VOR/DME) to (further waypoints omitted)
Destination aerodrome: Tokyo International Airport
Estimated elapsed time: 1 hr 04 min
Alternate aerodrome: Narita International Airport
Fuel load expressed in endurance: 2 hr 39 min

Two pilots occupied the cockpit: the Captain in the left seat as the pilot flying (PF, the pilot mainly in charge of flying), the first officer (FO) in the right seat as the pilot monitor (PM, the pilot mainly in charge of duties other than flying).

The event developed as follows according to the enhanced airborne flight recorder (EAFR[1]) data, air traffic control (ATC) communications data, and statements of flight and cabin crew.

2.1.1 History of Fight Based on Flight Recorder Data and ATC Communication Data

08:10:49 The airplane took off from runway 07, Yamaguchi-Ube Airport.
08:17:22 Fukuoka Air Traffic Control Center (ATCC) directed the airplane to fly directly to Kagawa VOR/DME climbing to FL 410. The FO repeated the direction.
08:26:31 The airplane was climbing through 32,000 ft at 1,500 fpm.
08:26:43 The FDR data shows that the main battery voltage began to drop from 31 V (Main_Battery_voltage).
08:26:44 Main battery failure was detected (ELEC_MAIN_BATTERY).
08:26:51 Main battery voltage dropped to 11 V and leveled off.
08:26:54 The FO became aware of the indication of EMER LIGHTS[2]

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[1] EAFR has flight data recorder (FDR) function, cockpit voice recorder (CVR) function and data-link recorder function. See section 2.9 for the details.

[2] EMER LT is a lighting system to be turned on in case of loss of all electricity of the airplane. The system

(Illumination of emergency lights) on the engine indicating and crew alerting system (EICAS[3]) screen.

08:27:09 He notified the Captain of the burning smell.

08:27:24 The FO voiced “ELEC MAIN BATTERY” and the Captain started to select the nearest airport.

08:27:25 Detection of failed main battery was canceled.

08:27:31 Smoke detector downstream of forward electronic equipment (EE) bay detected smoke and the master caution was illuminated (SMOKE_EQUIP_CLG_FWD, Master_Caut_Act).

08:27:43 Main battery failure was detected again. Detection and cancelling cycles repeated several times.

08:27:44 The Captain decided to divert to Takamatsu Airport.

08:27:52 Main battery discharge and abnormal voltage of the main battery bus were detected. (MAIN_BATTERY_DISCH, ELEC_HOT_BATTERY_BUS)

08:27:57 The airplane declared a state of emergency due to smoke requesting a radar vector to Takamatsu Airport and emergency descent.

08:28:06 After reaching 33,600 ft the airplane began to descent.

08:28:25 The main battery voltage fluctuated between 11 V and 26 V. (The fluctuation continued until 08:35:29.)

08:28:28 Fukuoka ATCC directed the airplane to descend to FL 210. The FO read back the direction.

08:29:03 Fukuoka ATCC directed the airplane to divert to Takamatsu Airport via Kagawa VOR/DME. The FO read back the direction.

08:30:24 Smoke was again detected in the forward EE bay and the master caution illuminated.

08:30:48 The FO notified a cabin attendant of the intended emergency landing.

08:30:49 The airplane’s rate of descent reached 7,000 fpm when it was descending through 23,000 ft.

08:31:56 Fukuoka ATCC directed the airplane to establish a radio contact with Kansai Departure.

08:32:03 The airplane established a radio contact and informed of the emergency and requested continued descent and a vector to Takamatsu runway. Kansai Departure directed it to descend to FL 150, followed by further descent to FL 130 for a radar vector to the runway.

08:33:40 Kansai Departure directed the airplane to establish a radio contact with Kansai Approach.

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illuminates general area, aisles and doors to indicate their location. It is powered by the battery stored in Wireless Control Unit. It is designed for the loss of a hot battery bus to activate the emergency lighting system.

[3] EICAS is an integrated system to provide flight crew with information on engine and other systems using visual and aural methods.

08:33:53	The airplane established the radio contact with Kansai Approach and reported on its emergency situation. It requested vector to BRUTE (waypoint). Kansai Approach directed the airplane to descend to 9,000 ft.
08:34:47	Kansai Approach directed the airplane to make a left turn to BRUTE. Then it directed it to establish a radio contact with Kansai Radar.
08:35:23	The airplane established the radio contact and reported on the emergency situation. It requested the vectoring to runway 26 of Takamatsu Airport and further descent. Kansai Radar started the vectoring to the final approach course.
08:36:59	The FO made a public announcement saying that the airplane would make an emergency landing at Takamatsu Airport.
08:37:50	The FO responded to the inquiry from Kansai Radar saying that: the cockpit situation remained the same with thin smoke possibly by an electric fire; the main battery had failed; there was a possibility of erroneous instrument indications; they need to land as soon as practicable.
08:40:50	Kansai Radar cleared the airplane to perform a visual approach to Takamatsu Airport.
08:42:13	At pressure altitude 2,800 ft the auxiliary power unit (APU) was started.
08:42:17	The airplane requested Takamatsu Airport Traffic Control Tower for an emergency landing with a visual approach to runway 26. The Tower directed the airplane to continue approach.
08:43:17	The Tower directed ANA 531 to execute a go-around, which was approaching to runway 26.
08:43:51	The gear lever moved to DOWN position. Recorded main battery voltage temporarily dropped to 3 V from 11 V and returned to 11 V.
08:43:53	The Tower cleared the airplane to land on runway 26 with the wind information of 150 ° 4 kt.
08:45:21	The third smoke detection in the forward EE bay and the illumination of the master caution light.
08:45:35	The autopilot was disengaged and this illuminated the master warning light.
08:46:56	The airplane landed on runway 26.
08:47:06	The Tower, using the crash horn, informed the stations concerned of its landing and the runway closure.
08:47:14	The airplane requested to vacate the runway into T4 taxiway to stop there. The Tower approved the request.
08:47:45	The FO inquired the Tower whether it observed the smoke coming from the airplane.
08:47:57	The Tower reported no smoke was visible.
08:48:03	The airplane taxied into T4 taxiway. The fourth EE bay smoke

was detected and the master caution light illuminated. The condition of detection continued until the end of the recording.

08:48:07	The Tower visually recognized the smoke and directed the airplane to stop there.
08:48:24	It stopped and parking brakes were set.
08:48:37	The Captain decided to execute an emergency evacuation and made a public announcement to the passengers.
08:48:40	He executed the evacuation command.
08:49:00	Fuel flow to both engines was cut off.
08:49:09	Fire switch for #1 engine was pulled, followed by that of #2 engine.

The FDR records show that the temperature in the forward EE cooling system duct remained around 25°C with small temperature fluctuation when the smoke was detected during the period from the takeoff from Yamaguchi-Ube Airport to the landing at Takamatsu Airport.

(See Figure 1: Estimated Flight Route, Figure 2: FDR Records)

2.1.2 Statements of Crewmembers

a. Flight Crew

The Captain reported to the operations room at Yamaguchi-Ube Airport and started his pre-flight check. No anomalies were logged in the maintenance log book.

The airplane was pushed back at 08:00 and took off at 08:10. When it was climbing through 30,000 ft the FO and the Captain sensed a burning smell of an electrical short circuit, followed by the EMER LT message on the EICAS screen. When the FO opened the status page, he found several messages. Next came the MAIN BATTERY DISCHARGE message.

Sometime later, SMOKE EQUIP COOLING FORWARD message appeared. In case of on-board fire/smoke, the regulation requires diversion to the nearest airport. The Captain reduced the climb rate to divert to the suitable airport. When he looked forward he spotted Takamatsu Airport just ahead. He decided to divert there. After some radio transmissions with the air control authorities he received a radar vector to the airport. The airplane received a clearance of an ILS runway 26 approach. With good airport weather conditions flight crew were able to visually confirm the airport.

Approximately 5 nm ahead of the airplane flew ANA flight 531 from Tokyo. The airplane was supposed to land after flight 531 by visual approach. When it aligned itself on the final approach course to runway 26, Takamatsu Tower directed flight 531 to go around to give the first priority of landing to the emergency airplane.

The Captain disengaged the autopilot sooner than usual as a precaution based on the electrical system EICAS messages. Based on the FO’s suggestion, the auxiliary power unit (APU) that is normally started after the landing was started before the landing in order to secure the electrical power. The landing was uneventful with normal instrument readouts and breaking on the runway was done as usual.

There was no visible smoke in the cockpit during the flight. The fumes lingered without increasing intensity. Cabin attendant's (CA) report to the Captain on the cabin situation indicated the same.

The Captain was ready to execute an emergency evacuation after the landing. When he halted the airplane on T4 taxiway he asked the Tower whether it could see the smoke coming out of the airplane. The Tower initially reported no smoke was visible but later recognized the smoke. The Captain also saw white smoke wafting beyond the right window near the FO. He suspected an on-board fire and initiated the evacuation.

The evacuation started without delay in the passenger cabin. Both flight crew run the evacuation check list and later moved to the passenger cabin. The Captain helped the evacuation at cabin mid-section while the FO the forward cabin. The Captain confirmed no remaining passengers in the cabin, let the CAs evacuate and evacuated himself as the last person

Just after the evacuation large amount of smoke was observed, but it became thinner as the time went by.

b. CAs

Fasten Seatbelt sign went off at 08:17 and each CA started to prepare their service.

Around 08:25 the chief purser (CP) at 1L[4] station received a Captain's interphone call about a burning smell in the cabin. As she was not able to give a quick answer, she hung up the phone and went to 2R station for 2R CA's awareness. 2R CA sensed no smell in the forward-most galley, but when she finished serving beverage in the forward cabin she sensed a burning smell on the left aisle near the seat rows 1 and 2. She stated that it was a faint smell which could be easily masked by the scent of coffee or miso soup, both of which were being served then.

Four CAs in the aft cabin had the same awareness that they sensed the weird smell. The 2L CA, who was directed by the CP to report the situation to the Captain, reported the presence of unusual smell in the cabin.

At 08:37 an abrupt public announcement from the cockpit was made without prior consultations with the CP, saying that the airplane would divert to Takamatsu Airport due to the smoke detected on the airplane.

The CP questioned whether the Captain intended to launch an emergency evacuation using slides at the airport, and he wanted passengers to adopt brace position. He answered that he intended to make a normal landing and in case of changed plan he would give instructions. The CP disseminated his intention to all CAs over the intercom's all-call mode and directed them to prepare for the landing. Just after the direction,

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[4] The 787 has eight cabin doors with four doors on either side. Left doors are referred to as 1L-4L, while right doors 1R-4R. 1L is the most forward cabin door on the left. Each CA is assigned to a door for emergency evacuation.

4-chime sounded. (4-chime denotes that it is all right to walk around the assigned area for landing preparation.) CAs started before-landing safety check while 4R CA did the normal before-landing announcement. The airplane landed at Takamatsu Airport at 08:47. After the landing the CP gave a public announcement, "We have landed at Takamatsu Airport. Please remain seated until the Captain turns off seat belt signs. I'll give you updates when they're ready."

The airplane stopped taxing. Approximately 30 sec later, evacuation orders and signal sounded almost at the same time. The CP saw something white outside of 1R door. She checked the outside situation and started the emergency door opening. The CP was the first person who did the emergency door opening. Although some CAs were not sure about the validity of the evacuation orders and signal, they started door opening after hearing the CP's direction to do so. 4L door was not opened because there were few passengers in its vicinity and the judgment to use other doors for quick evacuation. The slides on the seven doors opened for the evacuation operated normally.

No passengers were panicked. The first person standing at the top of the slide didn't jump. After the first one slid down, the remaining passengers followed suit. Some passengers scared to slide down were directed to sit on the door sill and CAs pushed them on the back. Some passengers tried to bring their personal belongings, but CAs persuaded them to abandon them. Female passengers putting on high-heeled shoes slid after putting them off. Some male passengers supported the evacuation at the bottom of the slide. The evacuation went on in an orderly manner.

Some CAs confirmed no remaining passengers in the restrooms or passenger seats, and then jumped the slide with necessary gears.

Passengers were calm until the completion of the evacuation. On the ground they started to shoot pictures roaming around the airplane. CAs huddled them up near the airplane nose facing the airplane, made them in 10-person groups for head count. After being counted they were asked to sit on the ground. All passengers were confirmed to have evacuated and so were crew.

The Captain stood in front of the huddled passengers and explained the situation. Passengers in the rear were explained later when he walked to them. There were no passengers who requested English interpretation.

One CA stated that the airplane landed at 08:47; the Captain explained the situation to the passengers at 08:58; evacuation itself seemed to have done in 3 to 4 min followed by long head count.

The serious incident occurred on T4 taxiway in Takamatsu Airport at 08:49, on January 16, 2013.

(See Figure 1: Estimated Flight Route)

2.2 Injuries to Persons

Four passengers suffered minor injuries when they landed after sliding down the emergency evacuation slides.

2.3 Damage to the Airplane

2.3.1 Extent of Damage

Minor damage.

2.3.2 Damage to the Airplane Components

Main battery: Severe heat damage
Main battery ground wire: Fused open

2.4 Personnel Information

a. Captain Male, Age 53
Airline transport pilot certificate : March 12, 1997
Type rating for Boeing 787 November 30, 2012
Class 1 aviation medical certificate
Validity: Until August 4, 2013
Total flight time: 13,642 hr 46 min
Flight time in the last 30 days: 48 hr 22 min
Total flight time on the type: 55 hr 24 min
Flight time on the type in the last 30 days: 48 hr 22 min

b. FO Male, Age 46
Airline transport pilot certificate : March 15, 1999
Type rating for Boeing 787 August 31, 2011
Class 1 aviation medical certificate
Validity: Until August 5, 2013
Total flight time: 10,946 hr 04 min
Flight time in the last 30 days: 23 hr 29 min
Total flight time on the type: 475 hr 55 min
Flight time on the type in the last 30 days: 23 hr 29 min

2.5 Airplane Information

2.5.1 Airplane

a. Airplane type and others
Type: Boeing 787-8
Serial number: 34486
Date of manufacture: December 1, 2011
Certificate of airworthiness: No. 2012 – 004
Validity: From January 16, 2012 to the day when the application of ANA's maintenance regulations expires
Category of airworthiness: Airplane, Transport Category T
Total flight time: 2,150 hr 45 min
Flight time since the last periodical check
(A02 inspections, October 29, 2012): 398 hr 40 min

b. Airplane history

The airplane was the ninth 787 built and was delivered to ANA as JA804A on 14 January, 2012.

The incident battery (S/N 270) was manufactured and passed the acceptance test procedures (ATP) on November 24, 2011 and was delivered to ANA on February 3, 2012. It was in stock until October 16, 2012 as a reserve part receiving maintenance care.

The original main battery delivered with the airplane on-board (S/N 240) was removed on October 17, 2012 following the malfunction in which cockpit displays went black after the power-up. It had a total flight time of 1,694 hr and 12 min and 1,300 cycles. On the same day, main battery (S/N 270) was installed on the airplane. It had flight time of 456 hr 33 min and 371 cycles.

2.5.2 Weight and Balance

The weight of the airplane at the time of the serious incident was estimated to be approximately 303,600 lb with the center of gravity (CG) at 22.1 % MAC, being within the allowable limits. (Maximum certified weight is 370,000 lb. Allowable CG range corresponding to this weight is between 6.0% and 36.9% MAC in longitudinal axis.)

2.6 Boeing 787

2.6.1 General

The Boeing 787-8 (hereinafter referred to as "the 787") is a twin-engine commercial wide-body airplane. The 787 program started in April 2004, with its maiden flight in December 2009. The type certificate was granted in August 2011. The first delivery occurred in September 2011. According to Boeing the total number of in-service 787 global fleet as of January 16, 2013 was 50 with combined flight time of approximately 50,000 hr.

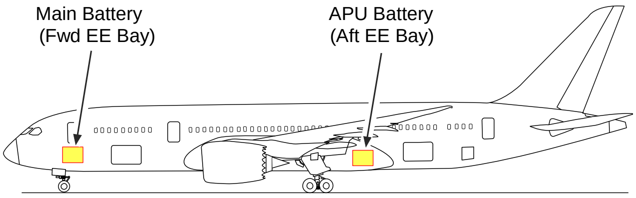

Fig. 2.6.1: Battery Location

One of the characteristics of the airplane is its reduced total weight to increase fuel efficiency. Composite materials, limited hydraulic systems account for the reduced weight. Pneumatic system was abandoned and replaced by electric systems. As the fuselage is made up of composite material, cabin pressure and humidity is set higher than conventional airplanes: approximately 0.8 atmospheric pressure and approximately 20%, respectively.

Grounding to the fuselage is available any place for conventional aluminum-based airplanes; however, 787's composite fuselage makes it impossible so that they use current return networks (CRN) for grounding terminal.

Transport category airplanes traditionally have used Ni-cd batteries as the main battery and for starting an APU; 787s use light weight, high capacity lithium ion batteries (LIBs). The main battery is identical to the APU battery. The main battery is installed in the forward EE bay, while the APU battery is in the aft EE bay.

The 787uses LIBs of significantly different design and capacity for applications such as flight control electronics (FCE), recorder independent power supply (RIPS) and emergency lights.

Boeing selected Thales Avionics Systems of France (hereinafter referred to as "Thales") as a supplier of the 787 power conversion subsystem, a part of the airplane's electrical power system in May, 2004. The use of LIBs was decided in September the same year. Thales selected GS Yuasa Technology Ltd. (hereinafter referred to as "GYT") and Securaplane Technologies Inc. (hereinafter referred to as "STI") as LIB and BCU suppliers, respectively in January, 2005. Boeing participated in the selection process and did not object to Thales's decision to select these suppliers.

The incident battery was the third-generation battery (first generation, mass production model) counted from the developmental phase. The first-generation battery passed the critical design review in November, 2005. Next year an incident occurred at STI. The battery was overcharged and resulted in fire because a signal wire between the battery and the BCU was not connected and the battery was charged resulting in overcharging and fire. The second-generation developmental battery was developed through design change with addition of a contactor and sub-BMU (BMU 3).

However, in 2009, an incident occurred at UTC Aerospace Systems Airplane Power Systems Integration Facility (APSIF) in the United States of America, in which a battery cell vented[5] with leaked electrolyte and smoke. The investigation revealed that repeated over-discharging followed by high current recharge may have resulted in copper-dissolving into electrolyte which led to internal short circuits. After the incident, following corrective design changes were made: BDM was inserted to block charging currents from the hot battery bus (HBB); a circuit to monitor the BDM was added to the BMU; the latch mechanism was added to the BMU to avoid recharging after over-discharging; and battery box sealing was added. With these modifications the battery evolved into the third generation.

2.6.2 Forward Equipment Cooling System

Air sucked in from cheek area by supply fans goes into each panel in the forward EE bay. After cooling elements in each panel, warmed air is released into the bay. The cooling vent fan sucks the warmed

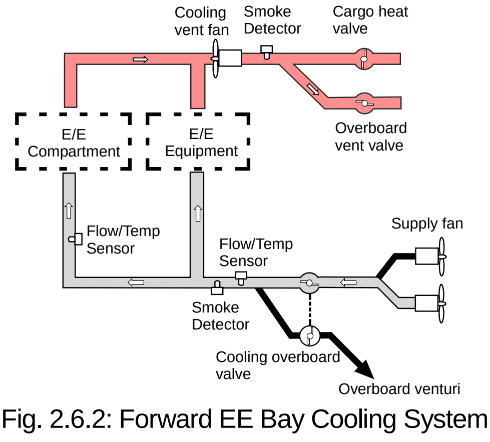

Fig. 2.6.2: Forward EE Bay Cooling System

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[5] To "vent" means that the cell safety valve opens due to excessive internal pressure.

air and pushes it to forward to outflow valve and forward cargo bay.

The air sucked in passes through a smoke detector before going into the forward EE bay. The warmed air sucked from the bay goes through the smoke detector downstream of the exhaust fan.

In case of smoke detection in the bay, normally closed override valve opens and some of the warm air is sucked overboard through the forward override valve by Venturi effect and the rest by the cooling vent fan.

2.6.3 Electrical Power Systems

The Electrical Power Generation and Start System (EPGSS) consists of unique electrical components that generate, control and protect airplane power, and supply power to start the main and APU engines. The EPGSS includes the following components:

- Four (4) Variable Frequency Starter Generators (VFSGs),
- Two (2) APU Starter Generators (ASGs),
- Six (6) Generator Control Units (GCUs),

In the extremely improbable event that all four VFSGs fail and main AC power is temporarily lost, the ASGs provide backup power. If the ASGs fail for any reason, including if the APU battery is unavailable to start them, the airplane is equipped with a hybrid 10kVA Ram Air Turbine (RAT) generator/hydraulic pump that can provide the airplane with power. The main battery's only role in a power failure is to support standby operations, including main engine igniters. The Main and APU battery ratings are 50 amp-hours at end-of-life.

Main battery discharging currents during normal flight operation is several Amps with temporary peak of approximately 100 A.

An APU start using the APU battery scenario consists of two failed APU start attempts which can be followed by another attempt after having a 5-minute rest. The APU battery draws approximately 600 A of currents.

2.6.4 DC/Stand-by Power System

DC/stand-by power system consists of a main battery and its dedicated BCU, a BDM, an APU battery and its dedicated BCU, start power unit and other components.

The main battery is connected to the HBB and the BCU with a 32 Vdc J3 cable. A J1 cable is a control cable which connects the main battery and the BCU.

Fig. 2.6.4 illustrates the wiring around the main battery. The main battery voltage recorded on the FDR is sensed at the HBB.

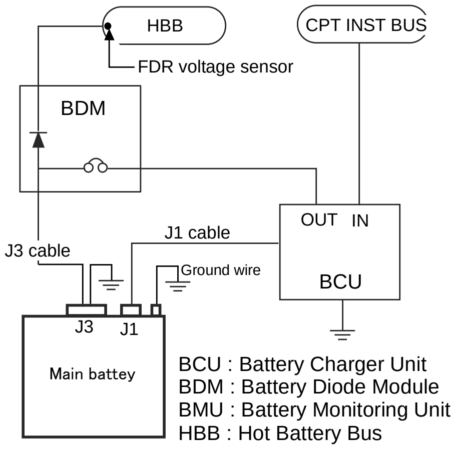

Fig. 2.6.4: Wiring Around Main Battery

2.6.5 Battery

2.6.5.1 LIB for the 787

a. Specification

- Nominal DC voltage: 29.6 V
- Nominal capacity: 75 Ah
- Weight: 28.5 kg
- Operational temperature: -18 °C through +70 °C

b. Battery components

It consists of eight lithium-ion cells which are connected in series with busbars and assembled in two rows of four cells. Each cell is electrically insulated with resin plates (melting point at approximately 250 °C). Other battery components are as follows:

- A BMU
- A contactor
- A Hall-effect current censor (HECS)
- Two temperature sensors and wiring
- Busbars
- Battery case (aluminum)
- Brace bar
- Ground stud (a terminal for ground wire)

As electrolyte is in contact with the cell case, it has electric potential as shown in Fig. 2.6.5.1-2.

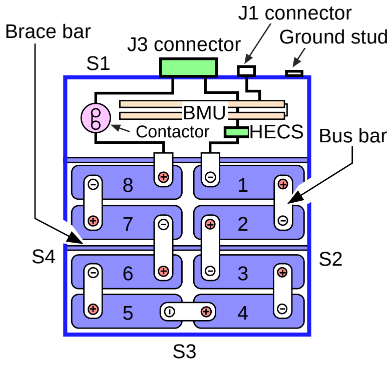

Fig. 2.6.5.1-1: Battery Components

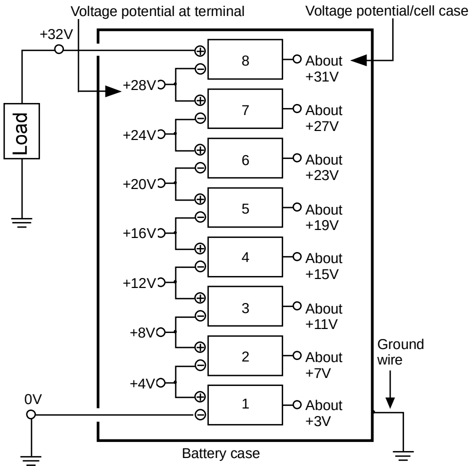

Fig. 2.6.5.1-2: Voltage Potential

Sides of the battery and cell are labeled as follows: the side with J1 connector is S1 (front) followed clockwise by S2, S3, and S4.

2.6.5.2 Cell

The cell case is made of stainless steel. Its top case (header) is welded to the lower case and gaskets are inserted between the current collector and terminal plate to ensure tightness. The case has a safety valve designed to break under excessive internal pressure. There are two types of cell configurations, type A and B, to orient the safety valve of each cell towards the inside wall of the battery case. Their sole difference in cell configuration is the safety valve location.

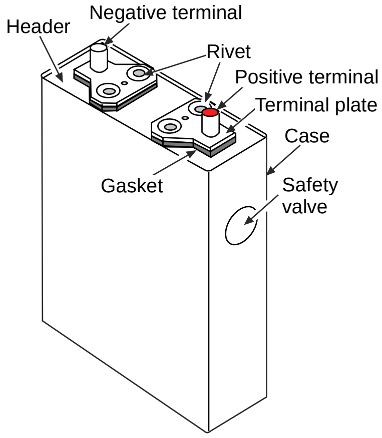

Fig. 2.6.5.2-1: Cell Exterior

Each cell contains three internal electrode element windings, each of which is shrouded in an outer resin insulating sheet. Four layers of films are placed on top of the other: a separator, a negative electrode (anode), a separator, and positive electrode (cathode). Then they are rolled and almost flattened to fit in the case. The anode is a copper foil coated with carbon compound (negative active material); the cathode is an aluminum foil coated with lithium cobalt oxide ($LiCoO_2$) compound (positive active material). The separator is a porous plastic film. A positive current collector is clipped to the aluminum foil; a negative current collector to the copper foil. Positive (Negative) current collector is riveted to the terminal plate with a resin gasket in-between, which serves as a electric and physical insulator. The rivet is the same material with the corresponding terminal. A brass nut fixes a busbar to positive/negative terminal.

Each cell material's melting point is as follows:

- Copper: Approx. 1,085°C
- Aluminum: Approx. 660°C
- Separator: Approx. 130°C
- Resin sheet: Approx. 280°C
- Resin plate: Approx. 250°C

A winding which is on the inside of S1 is referred to as W1, a winding on the inside of S3 W3, and the winding in-between is W2.

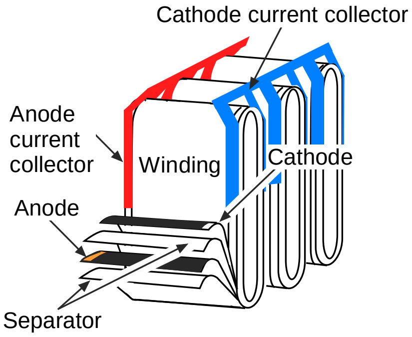

Fig. 2.6.5.2-2: Windings

2.6.5.3 BMU

The BMU consists of two circuit boards: main BMU and Sub-BMU. The former has BMU1 and BMU2 functions while the latter BMU 3 and BMU4 functions. The BMU has multiple protective functions against overcharging and over-discharging. Its main functions are as follows:

a. It sends battery condition signals to the BCU.

b. It is designed to provide overcharging detection/protection and over-discharging detection/protection even when the airplane power is off or the battery is in storage.

c. It maintains cell voltage balance. If one cell exceeds threshold voltage when the battery total voltage is near full charge and charging current is less than a threshold, the BMU reduces charging current for the cell by a set value to equalize each cell voltage.

d. It provides latch function against charging after over-discharging.

e. It detects imbalanced cell. If one cell voltage is less than a threshold with the battery total voltage of more than a set value, the BMU prohibits charging.

f. It conducts built-in test (BIT) for itself and sends fail signals in case of failed BIT. A BIT includes contactor operational test. The BIT other than the contactor test runs moments after the BMU start-up.

Contactor function test is programmed to start the sequence after the first start-up and end approximately 1 sec after the following conditions are met:

- The BCU is in a charging mode.
- The battery total voltage has reached a threshold near full charge.
- The charging current is less than a set threshold.

The BCU interface control document explains that the contactor opens less than a set low current value during the last phase of the charging to avoid possible high voltage transient phenomenon at high current.

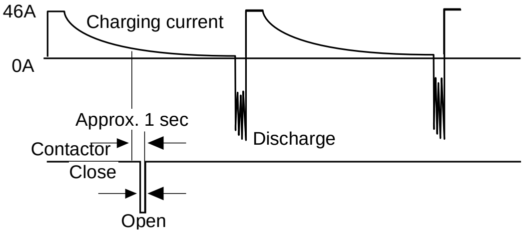

Fig. 2.6.5.3: Designed Timing of Contactor Opening

2.6.5.4 Contactor and HECS

The contactor disconnects the main battery from the BCU and HBB under overcharging conditions (cell voltage is more than 4.55 V or battery voltage is more than 36.5 V). It opens when its coil drive is energized under non-normal conditions. It is normally closed.

HECS measures magnetic flux which is in proportion to the magnitude current, convert it to current value and send it to the BMU and the BCU.

2.6.5.5 Ground Wire

The battery box is electrically insulated from its contents and is grounded to the CRN to prevent accumulation of static charges.

2.6.5.6 Brace Bar

The brace bar is made of stainless steel and it bridges battery box S2 and S4 to maintain box geometry and to fix cells in place. It extends between cells 2 and 3, and cells 6 and 7. Plastic cell fixation plates are bolted to the bar.

2.6.6 BCU

The BCU connected to the main battery is identical to that to the APU battery. The BCU charges the battery. A BCU provides:

a. Input voltage: 22.0 V-32.0 V
b. Output voltage/current: 16.0 V-32.2 V/ 0.0 A-46.0 A
c. Charging mode: Constant current mode and constant voltage mode.
d. Control method: Pulse-width modulation switching method

The BCU uses constant current (CC)-constant voltage (CV) mode which is widely used for LIB charging. Sensed output voltage and current information is fed back to the BCU to control

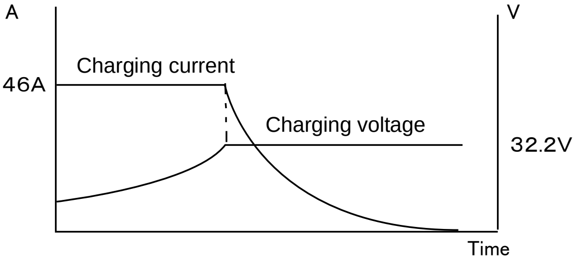

Fig. 2.6.6: CC-CV Charging

the duration of current release.

Under CC charging mode, the BCU keeps charging currents at 46 A until the battery voltage reaches 32.2 V. When it reaches the value, it reduces the charging current to maintain 32.2 V.

e. Protective function

The BCU terminates battery charging upon receiving the BMU signal indicating the abnormal condition of the battery.

2.6.7 Battery Diode Module

The battery diode module (BDM) is inserted between the main battery and the HBB to stop the charging current influx from other sauces than the BCU.

The BDM consumes approximately 1 V of voltage potential.

2.7 LIB

2.7.1 LIB Mechanism

The LIB is a rechargeable battery in which lithium ions move between the cathode and anode through the electrolyte.

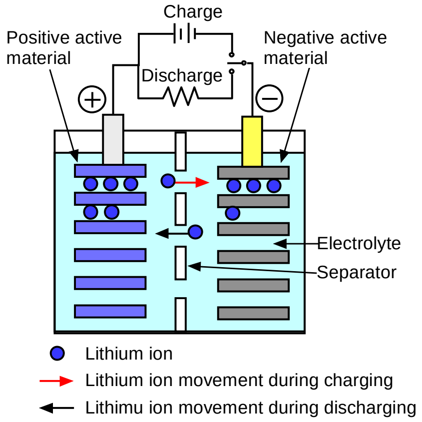

Fig. 2.7.1: How a Li-ion Battery Works

The LIB's cathode active material's main ingredient is $LiCoO_2$. Charging makes active material on both electrodes swell slightly while discharging makes it shrink slightly. Charge-discharge cycle leads to gradual degradation in the structural integrity of active material causing reduced lithium ion movement. Lithium ions are also consumed in forming the solid electrolyte interface (SEI[6]). The SEI degrades over the life of the LIB, reducing its charging capacity. Gradual degradation of the electrolyte throughout its service generates very small amounts of gas increasing the internal pressure of a cell.

LIBs are designed to meet a specific purpose and use, accordingly the performance of LIBs may be tailored by changing active material ingredients, charging capacity and charging method.

The LIB has the following characteristics:

- High voltage and energy density per cell and cell can be miniaturized and lighter.
- Short-time recharging
- Small memory effect[7]

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[6] SEI is a film formed on anode at very early stage of usage. It has conductivity to lithium-ions, but it lacks electron conductivity so that it does not hamper charging/discharging. It inhibits reductive decomposition of electrolyte on anode.

[7] Memory effect denotes the phenomenon of apparent reduction of usable battery capacity when it is repeatedly charged before its capacity is fully consumed.

2.7.2 LIB Hazard Sources

The LIB has five hazard sources as explained below, which accompany thermal phenomenon and cell venting.

a. Overcharging

Charging done beyond 100% state of charge (SOC) results in overcharge. Detecting the overcharging is possible by monitoring cell voltage as it surpasses the voltage which corresponds to 100% SOC.

b. Over-discharging

Discharging beyond 0% SOC results in over-discharging. Under over-discharging state, copper dissolves into electrolyte from anode. Overcharging is detectable by monitoring the voltage of each cell in the battery.

c. External short circuit

External short circuit occurs outside of a battery. When it occurs, cell internal resistance and high currents generate Joule heat.

d. Cell case short circuit

The 787 main and APU battery cells are designed such that the metal cell case has an electrical potential approximately midway between positive and negative terminals. Contact between the cell case and the battery box (which is grounded to match the potential of cell 1's negative terminal) alters the cell chemistry which can lead to re-deposition of conductive material and subsequent internal short circuits.

e. Internal short circuit

An internal short occurs between cathode and anode within a battery cell. When it occurs, electrolyte evaporates at the point of shorting due to heat generation caused by high currents. Some internal short circuit occurs as a result of a soft short, some occurs with other reasons. Major reasons of internal short circuit are as follows:

- Foreign metal particles in the cell interior
- Damaged separator
- Re-deposition of conductive materials within the cell (e.g. copper, lithium, etc.)

2.7.3 Soft Short

Soft short denotes an elevated self-discharge rate caused by very small currents between the anode and cathode through electrical path generated between the two. In soft short test, open circuit voltage (OCV) is monitored for certain period of time.

2.7.4 Lithium Metal Deposition

Some used cells may have lithium metal deposition on anode.

Major causes for lithium metal deposition are: exceeded intercalation speed at anode due to overcharging, reduced intercalation speed due to degraded anode active material across ages, concentrated charging currents due to uneven electrode distance, and reduced speed of lithium ions due to low temperature.

Charging speed below the lithium-ion intercalation speed into anode is ideal and under such conditions lithium metal deposition does not occur. Under certain conditions, high charging rate caused by high current density exceeds the rate of lithium intercalation. Ionic lithium refused from intercalation into anode is reduced to lithium metal on anode. Deposited lithium metal forms two morphologies: a flat one is called plating, and spiky tree-branch like one is described as “Lithium Dendrite” or simply “Dendrite. (LIBs for the 787 are lithium ion battery and have different anode material.) As a reference lithium dendrite on lithium metal anode is shown in Fig. 2.7.4 [8]. Lithium metal’s melting point, as a reference, is 180 °C.

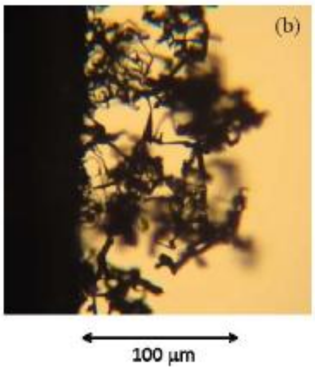

Fig. 2.7.4: Lithium Dendrite (b)

In general, degraded LIBs sometimes exhibit lithium metal deposition and dendrite; however, they do not always lead to internal short circuit. Controlled charging not to overwhelm the cell capacity could minimize the rate of internal short circuit.

2.8 Serious Incident Site and Damage Information

2.8.1 Serious Incident Site

The serious incident occurred on T4 taxiway, Takamatsu Airport.

After the occupants were led to the airport building, the airplane was towed to an aircraft stand after releasing the wheel brakes. Wing tip lights and fuselage rear-end light remained illuminated until the J3 cable connector was disconnected from the APU battery.

2.8.2 Damage Information

The main battery received severe heat damage.

2.8.3 Detailed Damage Information

Dark green/black deposits coated inside wall of air ducts downstream of forward EE bay and fuselage skin downstream of the Override Valve and Outflow Valve. There was no trace of fire

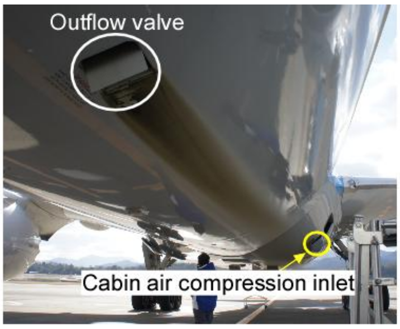

Fig. 2.8.3-1: Conditions Downstream of Outflow Valve

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[8] “Morphological Variation of Electrodeposited Li in Ionic Liquid”
ECS Trans., 41 (41) 3-10 (2012)
Authored by Kei Nishikawa, Hitoshi Naito, Makoto Kawase and Tetsuo Nishida.
The dendrite images (b) was captured when cathode and lithium metal anode were soaked in electrolyte to observe the morphology.

damage near the main battery; however, molten material was found on the battery tray while soot-like material was on the BCU case and nearby battery rack side walls and upper wall.

The battery case lid bulged upwards by approximately 2 cm with black molten material on the lid interior. Molten material also seeped out of the battery case through gap created between the case and the lid, running down on the case walls and deposited on the battery tray.

The molten material covered the top of the battery cells. Each cell was heat-damaged.

The power cable (J3 cable) which connects the battery and the BDM, and the cable that connects the battery and the BCU (J1 cable) were intact. The battery case had no discoloration or puncture caused by arcing; however, the battery case ground wire was fused open.

Fig. 2.8.3-2: J3 Cable Connector

Each cell was deformed as Fig. 2.8.3-3: CT Scan Image shows.

a. Cell 1

S1 and S3 were convex and two cathode current collector fingers on W3 were fused open. Each winding was heat-damaged. Separators and both electrodes exhibited high temperature heat damage. Metal foils clipped by current collectors were also damaged.

The cell was vented.

b. Cell 2

S1 was concave while S3 was convex. Two cathode current collector fingers on W3 were fused open. Each winding was heat-damaged. Separators and both electrodes exhibited high temperature heat damage. Metal foils clipped by current collectors were also damaged. The cell was vented.

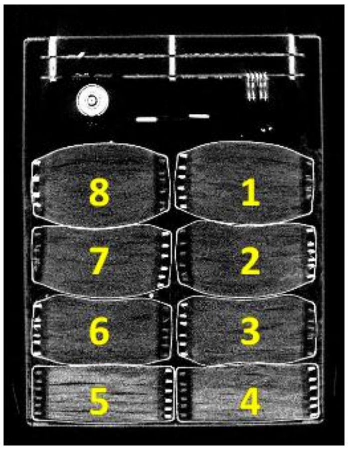


Fig. 2.8.3-3: Battery CT Scan Image

c. Cell 3

S1 and S3 were concave. Arc damage was found on the shoulders of anode current collectors and corresponding position of the brace bar. Each winding was heat-damaged. Separators and both electrodes exhibited high temperature heat damage. Metal foils clipped by current collectors were also damaged.

All six cathode current collector fingers were fused open and they had traces of arcing. Header around it was melted leaving a big hole. The part of the busbar that connects to cell 4 negative terminal was olso melted over this hole. The nut and washer used to bolt the busbar to the positive terminal remained. Busbar side of the washer exhibited traces of arcing.

Cell 3 S4 and Cell 6 S2 were fused together. The corner of Cell 3 header where S1 and S4 meet was perforated.

The cell was vented

d. Cell 4

S1 and S3 were slightly convex. Cathode current collector fingers were intact. Each winding was heat-damaged. Separators were melted but not charred. On the case edge just beneath the busbar, there were perforations.

The cell was not vented.

e. Cell 5

S1 and S3 were slightly convex. Cathode current collector fingers were intact. Each winding was heat-damaged. Separators were melted but not charred.

There was a hole of approximately 1 mm diameter on S1, which is located approximately 80 mm from the bottom and 15 mm from the edge of S2. A scanning electron microscope (SEM) analysis confirmed that this hole was perforated from outside to inside. A semicircular discoloration which corresponds to the location of the hole was observed on the W1.

The cell was not vented.

f. Cell 6

S1 and S3 were concave. All six cathode current collector fingers were fused open. Each winding was heat-damaged: separators and coated electrode compounds were charred.

Cell 6 S2 and Cell 3 S4 were fused together. S1 had a big oblong hole at the portion corresponding to the brace bar, and part of the brace bar was welded to the portion near the hole.

There were two small pits on S3, whose position correspond to the hole on Cell 5.

The cell was vented.

g. Cell 7

S1 was concave and S3 was convex. Two cathode terminal current collector fingers on W3 were fused open. Each winding and its separators and coated electrode compounds were heat-damaged.

The cell was vented.

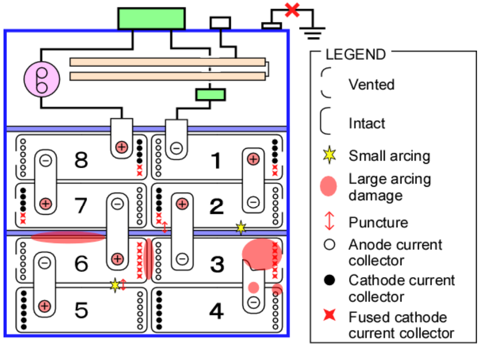
h. Cell 8

S1 and S3 were convex. Two cathode terminal current collector fingers on W3 were fused open. Each winding and its separators and coated electrode compounds were heat-damaged.

The cell was vented.

i. Summary of the battery damage

Fig. 2.8.3-4 illustrates the summary of battery damage. Cathode current collectors were fused except cells 4 and 5. All cell windings were heat-damaged and this denied to identify the



Note: The busbar between cell 4 and 5 and cell windings are not shown.

Fig. 2.8.3-4: Battery Damage

initiating point of heat generation or metal deposition.

(See Figures 5 through 15 (page 77 through page 84) for the visual presentation of the damage.)

j. Other battery components

(1) BMU

Two circuit boards were heat-damaged. Some semiconductors were displaced due to melted fixing solder. Electrical part of the ATP was unavailable due to the heat damage. The solder melts at 180°C.

(2) Contactor

Exterior was discolored black due to heat damage. Interior contact points exhibited no damage caused by big currents except for the traces of arcing usually observed after ordinary use.

(3) HECS

The exterior was heat-damaged with cracks.

(4) Wiring to cell terminals

Insulator of the wiring was charred by heat and parts of the wiring were separated.

k. Other components

(1) BCU

On February 2 and 3, 2013, two BCUs (one for the main battery, the other for the APU battery) were put to the ATP at the manufacture in Tucson, Arizona. They passed the ATP.

(2) Bus power control unit and generator control unit

On February 5 and 6, bus power control unit (BPCU) (left and right) and generator control unit (GCU) (R1 and R2) were put to the ATP and memory dump was done at United Technologies Aerospace Systems in Phoenix, Arizona, to analyze the stored data. No anomalies were found.

2.9 Flight Data Recorder

The airplane has two EAFRs (Collins, P/N 182690-002), each installed in the forward and aft fuselage. Its FDR recorded about 58 hr of flight data while CVR 2 hr of audio data. Both EAFRs retained records at the time of the serious incident.

The FDR data include main battery voltage, and APU battery voltage and current at every two seconds—no main battery current. (See Figure 2 (on page 74) and Figure 3 (on page 75))

The time recorded in the recorder was corrected by synchronizing the VHF communication keying signal to the speaking-clock time signal (by Nippon Telegraph and Telephone Corporation) recorded in the ATC communication records.

2.10 Rescue and Fire Fighting

The airport fire engines were in position on the taxiways before the airplane touched down on the runway. One of the four slightly injured persons walked to the terminal building and ambulanced to a local hospital.

No trace of fire spared the firefighting personnel the fire extinguishing activities. The chronicled events after the reception of the emergency landing are detailed in the Appendix 1 “Response on the Ground”which was compiled by Takamatsu Airport Office, Osaka Regional Civil Aviation Bureau.

2.11 Tests and Studies

2.11.1 Reason of Navigation Light Illumination and FDR Battery Voltage Drop

After the airplane was delivered to ANA, Boeing identified a potential discrepancy in the Window Heat/Towing Power control panel. Consequently, Boeing sent a request to the airline on September 10, 2012 to check the presence of a discrepant circuit card assembly in the Window Heat/Towing Power Control Panel and requested a response by January 11, 2013. The airplane had the circuit card and its presence became apparent after the serious incident.

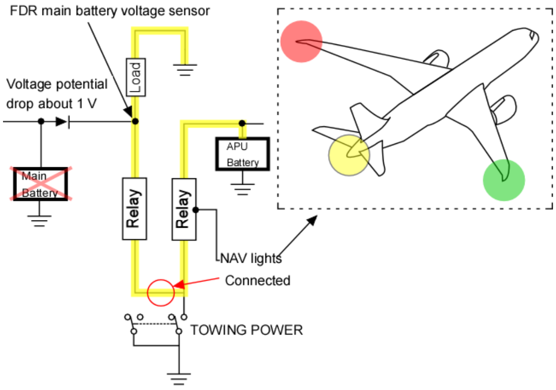


Fig. 2.11.1-1: Wiring Which Caused Navigation Light Illumination

With this circuit card installed, under voltage equilibrium between the APU battery and main battery, electric currents do not flow. However, with the absence of the main battery or lower voltage than that of the APU battery, the card circuitry allows the currents to flow from the APU battery to the main battery circuit even if the TOWING POWER switch is in OFF position and wingtip lights and fuselage-end light are illuminated.

In order to confirm this phenomenon on the airplane, the card was reinstalled and the main battery was removed. We confirmed the illumination of wingtip lights and fuselage end light, and the multi-function display (MFD) screen in the cockpit showed the main battery voltage of 12 V as shown in Fig. 2.11.1-2.

	FWD EXT PWR			AFT EXT PWR	RAT GEN
	L	R	SOURCE		
AC-V	114	114	ACTIVE LVL	0	0
FREQ	400	400	180 KVA	0	0
LOAD	0.36	0.42	0.39	0.00	--

	ATRU				L ATU	R ATU
	L1	L2	R1	R2		
(+) DC-V	277	278	276	281	--	--
(-) DC-V	276	277	279	280	--	--
AC-V	--	--	--	--	114	110
LOAD	0.00	0.00	0.00	0.00	0.28	0.29

	MAIN BAT	L TRU	C1 TRU	C2 TRU	R TRU	APU BAT
DC-V	12	30	30	30	28	32
DC-A	1 DIS	58	51	49	65	1 CHG

Fig. 2.11.1-2: APU Battery Sneak Voltage

2.11.2 Inspection of Other Batteries

Test subjects were removed batteries from the 787 due to maintenance reasons.

a. The test subject was the battery S/N 189 which was installed on a 787 as an APU battery. This battery was selected because the OCV of cell 2 was lower than other cells, suggesting the presence of a soft short. In order to compare cell 2 with other cells, cells 4 and 6 were also selected as subject cells.

   After CC-CV discharging the cells voltage were reduced to 2.70 V. Their self-discharging behavior was monitored for two weeks, but cell voltage remained the same.

b. The battery S/N 269 which was installed on a 787 as a main battery was manufactured in November, 2011 and shipped out in May, 2012. Since then it was stored in stock receiving maintenance care and it was installed on a 787 in October, 2012. Next month it was removed due to the BATTERY FAIL advisory message. Confirmed OCV at the Company was: 3.73 V for cell 3 and 3.98 V for other cells.

   As it passed one year since its shipment back to GYT with its OCV 0V, no soft short test was available.

   As healthy cell OCV does not go down to 0 V in one year, we performed a destructive physical analysis (DPA) of the cell 3 being suspected of interior defects. The examination found a small round burn mark on a separator indicating possible soft short. Other cells were also dismantled for comparison; however, no short circuit trace was found.

   It is noted that wrinkles were found in the anode of dismantled cells, but not on the cathode.

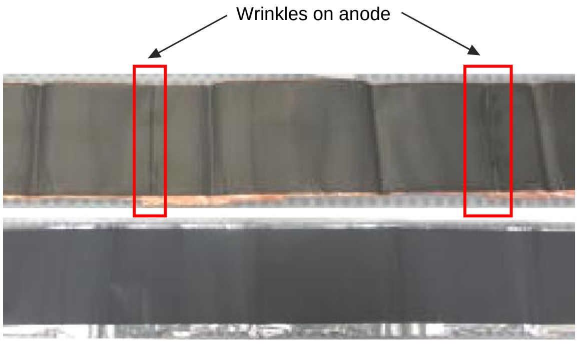


Fig. 2.11.2: Anode (top) and Cathode (bottom) from a Dismantled Cell

2.11.3 Cell Balancing Test

In order to confirm cell balancing function, the removed main battery BCU from the airplane was connected to a battery. Voltage of cells 1, 3, 5 and 7 was lowered to test the function. The voltage curves showed that the voltage of each cell converged within the range of 4.00 V-4.07 V as shown in Fig. 2.11.3-1.

We performed the tests in two configurations: one with the main battery BCU, the other with the BCU for APU battery. In both cases the phenomenon of small charging/discharging in short cycle at the last portion of CV charging was observed as Fig. 2.11.3-2 illustrates when the CC charging shifted to CV charging.

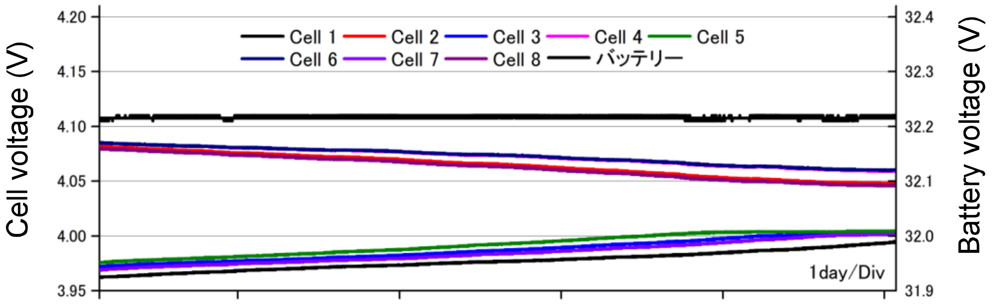


Fig. 2.11.3-1: Cell Balancing Test

Thales interpreted this phenomenon that it is out of design scope, but has nothing to do with cell heat generation. It only shortens the cell life.

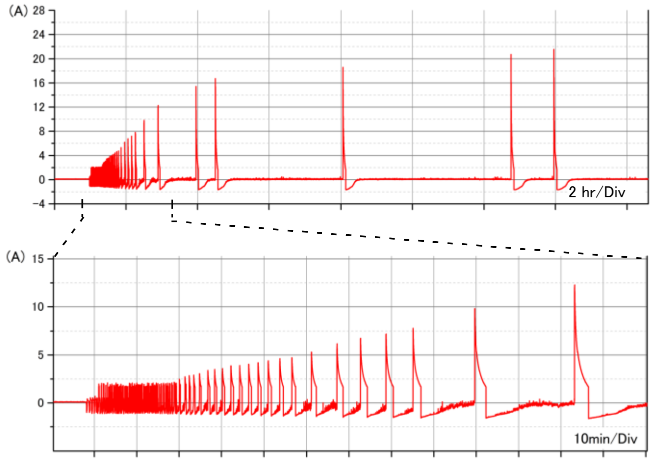


Fig. 2.11.3-2: Charging/Discharging at Short Cycle

Boeing and GYT interpreted the phenomenon likewise that it has nothing to do with cell's thermal generation ant it only shorten the cell life.

In order to confirm the cell voltage imbalance detection function, we connected a resistor to cell 2 and discharged the battery and waited for the function to activate. Fig. 2.11.3-3 shows that when the cell 2 voltage went bellow 3.89 V, charging inhibit signal became activated.

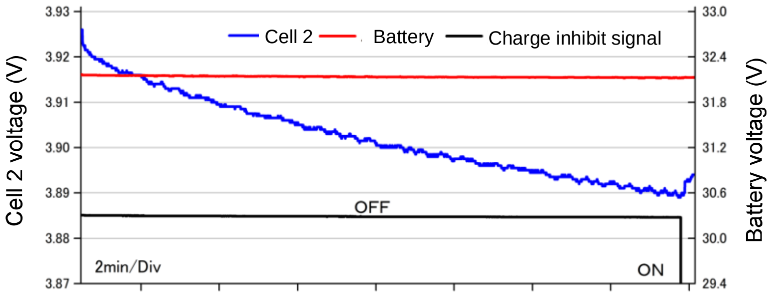


Fig. 2.11.3-3: Detection of Cell Voltage Imbalance

2.11.4 On-board Test

In order to confirm the designed functionality of on-board components connected to the main battery, we conducted on-board test using the serious incident airplane in April, 2013 at Takamatsu Airport. We measured voltage and current at blue dots and red dots, respectively. A specially prepared branch cable was inserted between J1 cable and BCU. The battery voltage between the contactor and the BCU, and current measured by the HECS were logged through the branch cable. The results were as follows:

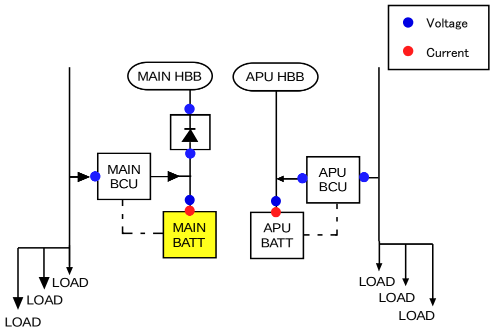


Fig. 2.11.4-1: Measuring Points, On-board Test

a. Oscillating phenomenon of charging currents fluctuating from +3 A to -2 A was observed at the end of battery charging. This was identical to what observed during the battery-BCU integration test (see section 2.11.6.1).

b. During battery charging, charging current fluctuated between 23 A and 68 A. Voltage spike as high as approximately 45 V was observed in the main battery voltage. The spike was observed approximately 1 sec after the charging currents went less than approximately 8A, accompanied by a current interruption of approximately 25 msec as shown in Fig. 2.11.4-2.

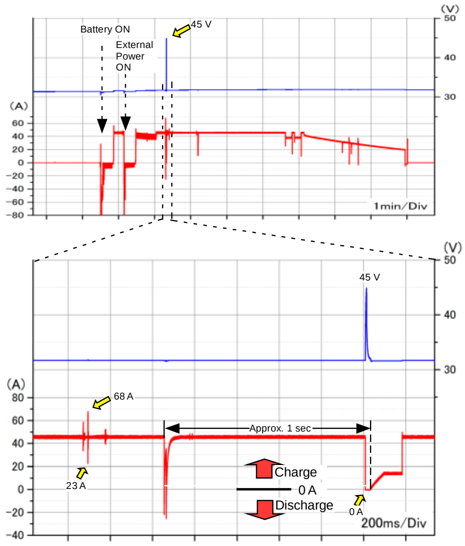


Fig. 2.11.4-2: Voltage Spike

c. During a discharge (approximately -60 A) a momentary voltage drop to 0 V was observed. This phenomenon was observed approximately 1 sec after the charging current went less than approximately 8 A, accompanied by a current interruption of approximately 23 msec as shown in Fig.2.11.4-3.

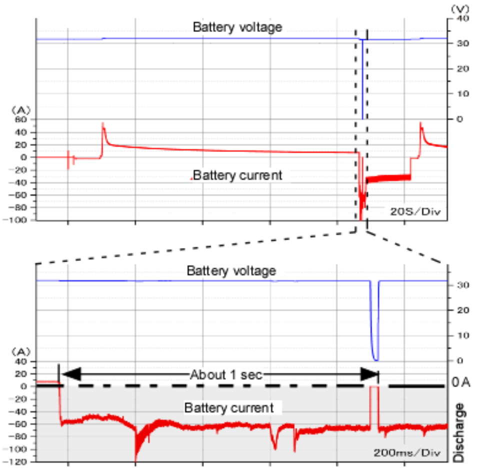


Fig. 2.11.4-3: Instantaneous Voltage Drop

It is noted that the instantaneous voltage drop/spike and charging current oscillation did not accompany heat generation or other anomalies.

2.11.5 Battery Heat Propagation Test

Table 2.11.5: Test Configuration

Configuration	Battery Temp.	BCU	Battery Box
1	70℃	Connected	Grounded
2	30℃	Connected	Grounded
3	30℃	Not connected	Not grounded

We performed battery testing at JAXA Kakuda Space Center (hereinafter referred to as “Kakuda Test”) in November, 2013 in order to observe heat propagation at full battery level. Three test configurations are shown in Table 2.11.5. The tests were videotaped and recorded using data loggers at 10 Hz interval. Recorded parameters are temperature, cell voltage, battery incoming voltage (between cell 1 negative terminal and cell 8 positive terminal), battery outgoing voltage (at J3 connector), ground wire currents (HECS output) and J1 signal. (See Figure 2: Thermo-Couple Location in Appendix 2)

We used nail penetration method against cell 6 which was considered to be the initiating cell as the Boeing test analysis suggested in the description in section 2.11.6.7. The nail was equipped with an internal thermo-couple to record the interior temperature of the target cell.

Fig. 2.11.5-1 shows the wiring diagram simulating the on-board

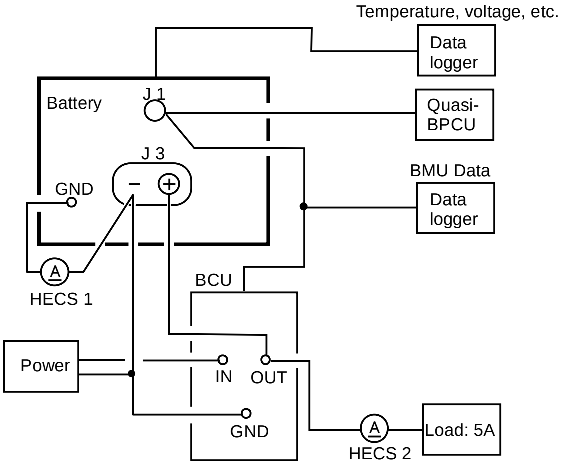


Fig. 2.11.5-1: Test Set-up

installation with a BCU, BMU and quasi-BPCU and ground wire: J3 connector was hooked up to the BCU and the load; J1 connector was hooked up to the BCU and the quasi-BPCU; ground stud was hooked up to the ground wire. The ground wire was not the identical one with that of the actual airplane in terms of material configuration and length.

a. Configuration 1

Flames broke out approximately 15 seconds after the nail penetrated cell 6. Approximately 5 min later cell 5 vented. The flames damaged sensing wiring and gaining data became unavailable. We terminated the test 8 min after the venting of cell 6 confirming four cells vented. A moment after the nail penetration, the outgoing battery voltage repeatedly dropped down to 0 V. As the incoming voltage remained the same, it was concluded that the contactor opening caused the phenomenon.

Battery DPA revealed venting of cells 5, 7 and 8 caused by thermal runaway[9]. The ground wire registered 200 A-600 A of currents and the brace bar was welded to cell 6 S1 at two points. Video image analysis revealed that the spewing gas was ignited by the sparking between the test frame and the nail.

b. Configuration 2

All cells vented within 46 min after the nail penetration and thermal propagation from cell to cell lead to a thermal runaway. The ground wire was fused open. The highest current value registered was 1,630 A. A portion of the brace bar was fused to cell 6 S1 as shown in Fig. 2.11.5-2 and an arcing hole was created next to the welded area.

A moment after the nail penetration, the outgoing battery voltage repeatedly dropped down to 0 V. As the incoming voltage remained the same, it was concluded that the contactor opening caused the phenomenon. The contactor tear-down exhibited traces of arcing on contactor points.

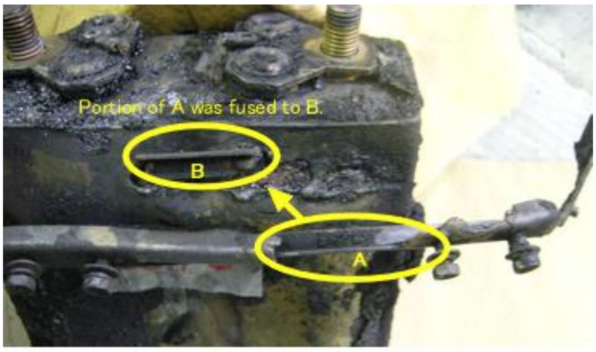


Fig. 2.11.5-2: Cell 6 and Brace Bar

Cell venting order was determined based on cell voltage data: cell 6 followed by cell 7, cell 5, and cell 8. Reliable venting order afterward was not available due to damaged sensing wiring.

The video footage confirmed that the timing of the erupting flames coincided with cell 7 venting and 1,010 A current that ran through the

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[9] Thermal runaway in this report denotes "uncontrollable battery conditions of self-sustaining increase in temperature and pressure." The 787 special conditions include a passage "self-sustaining increases in temperature and pressure (thermal runaway)."

ground wire, which was approximately three seconds after the ground wire experienced maximum currents of 1,630 A.

Cell 6 behaved as follows when it was nail-penetrated.

No sooner had the nail penetrated the cell than it vented with white smoke while cell internal temperature shot up to 400 °C. 34 sec after the nail penetration, approximately 940 A of currents ran through the ground wire and concurrently the nail's internal thermo-couple and sensor on cell 6 S1 sensed increased temperature rise. The temperature continued to rise, as indicated by the nail's internal thermo-couple sensor and reached approximately 950 °C in 45 sec. (See Appendix 2: Thermal Propagation Testing at Kakuda Space Center)

The voltage of cell 6 drooped by approximately 1 V then recovered to approximately 4 V, and finally dropped to 0 V. When cell voltage dropped to 0 V from 4 V, more white smoke was observed. The same was true to venting of cell 7 and cell 5.

c. Configuration 3

Cell 6 vented and cell temperature rose in approximately 66 min, but it failed to develop into thermal propagation. Right after the nail penetration, the outgoing battery voltage repeatedly dropped down to 0 V. As the incoming voltage remained the same, it was concluded that the contactor opening caused the phenomenon.

Cell 6, brace bar, other cells, or battery box showed no trace of arcing.

(See Figure 3: Test Results in Appendix 2)

2.11.6 Tests Done by Boeing after the Serious Incident

2.11.6.1 Battery-BCU Integration Test

In order to clarify the battery characteristics when the battery was connected to various loads, a battery-BCU integration test was conducted at Hazardous Test Facility in Seattle, Washington in February, 2013. Used BCU's were ones withdrawn from JA804A (the BCU for the main battery and the one for APU battery), and the BCU for APU battery from the Boston event (See section 2.13.2 a) airplane, and the BCU owned by Boeing.

Fig. 2.11.6.1-1: Fluctuation of Charging Current

The tests were done to gauge each cell voltage, temperature and battery voltage, current, and temperature, simulating a nominal takeoff, nominal APU start, battery-only APU start, and input voltage interruption.

In the test simulating an input voltage interruption into the BCU (load 0 A, power interruption 20 msec), small current oscillation was observed in charging currents of both main battery BCU and APU battery BCU. (See Fig. 2.11.6.1-1)

A current interruption of approximately 22 msec approximately 1 sec after the fulfillment of the contactor BIT criteria (see 2.6.5.3) was observed during a nominal APU start with engine-run conditions using the Boston event APU BCU.

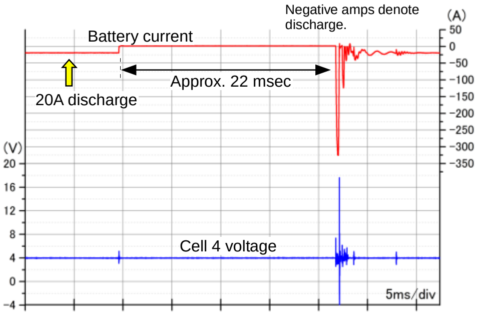


Fig. 2.11.6.1-2: High Transient Voltage

Boeing comment on the phenomenon was: "The contactor opened as part of BIT operation resulting in a transient. As this test simulated an APU start under engine-run conditions and the battery BIT on actual airplane is conducted upon airplane powered up. Therefore, an actual airplane does not experience this phenomenon."

2.11.6.2 Wet Cell Case Test

In order to confirm that water condensation in the battery box could cause a short circuit, a cell was placed in the grounded aluminum case filled with saline solution. 28 V was applied to the cell negative terminal to simulate cell 8. The test demonstrated that shorting a cell case to the ground via saline solution can lead to a cell venting.

During cell DPA following the tests, conductive deposits were found around the negative terminal along with signs of shorting, arcing, and heat damage.

2.11.6.3 Cell Case Grounding Test

Following the test above, this test was done to prove the theory that a short circuit from the case to the ground can cause a short circuit. 20 V was applied to cell 6 negative terminal and its case was grounded. The cell vented 40 hr later. The cell voltage data showed that the voltage dropped by 0.5 V from 4.2 V, recovered to approximately 4.0 V, then dropped to 0 V.

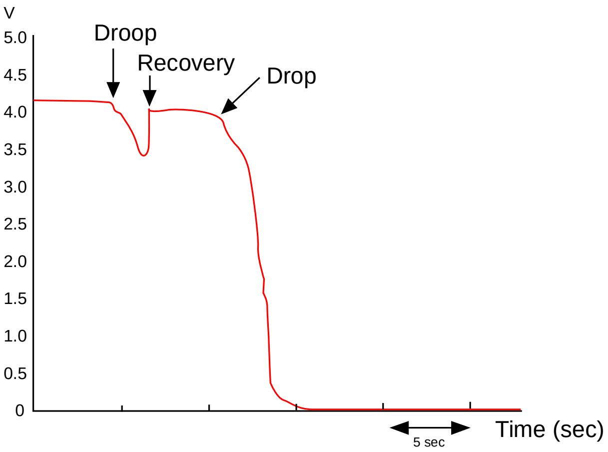


Fig. 2.11.6.3: Voltage Drop When a Cell Vented

The voltage drop and subsequent recovery was later understood to be caused by an internal short circuit within one of the three windings within the cell, followed by fusing of the cathode current collectors on the affected winding. The final voltage drop to 0V was interpreted to be internal short circuit of the remaining windings.

2.11.6.4 Full Battery Vent Test

The test purpose was to demonstrate multiple cell failure propagation. In the test cell case of cell 7 was grounded to the battery box.

The ground wire fused open. Heat generated from cell 7 damaged the plastic upper insulation cover cell 7 header. Cell 7 DPA found traces of arcing on anode current collectors and cell case.

2.11.6.5 Full battery Vent with Enclosure Duct

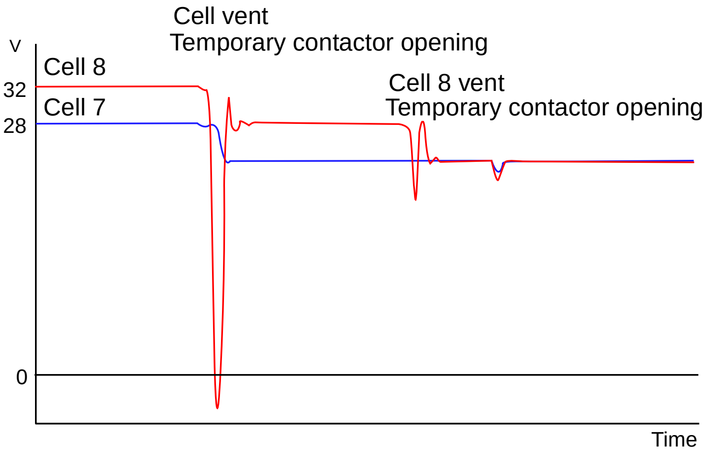


Fig. 2.11.6.5: Battery Voltage Fluctuation (First test)

The purpose of the test was to observe battery behavior under thermal propagation and to confirm the functionality of a battery box enclosure box (see section 5.1.1 c (1)). Two tests were done using model 901 batteries (batteries in use at the time of the serious incident).

In the first test, cell 7 was heated with a heater blanket for forced venting. After the venting of the cell 7, temporal opening and closing of the contactor which was observed in the serious incident was also observed. When cell 8 vented, the contactor behaved the same way. When cell 8 physically contacted the battery box, J3 negative current exceeded 1,000 A, and the battery voltage dropped from 24 V to 5 V in approximately 4 sec.

In the second test, the temporal opening and closing of the contactor was observed after cell 7 venting.

2.11.6.6 Ground Wire High Current Test

In order to observe ground wire behavior, a ground wire was connected between the battery positive and negative terminals. This resulted in a ground wire fusing in 0.1 sec with approximately 6,000 A of currents.

The fused ground wire exhibited no smoldering insulation cover and melted wire spewed out from the insulation. Boeing's interpretation is "Judging from the damage, the current experienced in Takamatsu event would have been less than 6,000 A."

2.11.6.7 Thermal Propagation Scenario for Takamatsu Event

Boeing's thermal propagation scenario is explained as follows using the FDR voltage fluctuation labeling A-H at specific events as shown in Fig. 2.11.6.7.

a. Event A

Judging from cell deformation, initiator cell is either cell 3 or cell 6. Cell 3 arced from its negative current collector through case (the corner of S1 and S4) to brace bar. Arcing requires melted plastic fixation frame. For this to happen, another cell should have vented before cell 3, and cell 6 was the first cell to vent.

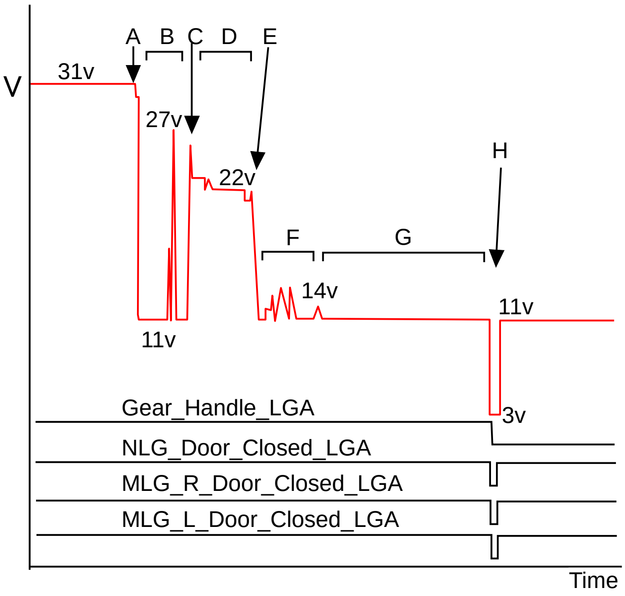


Fig. 2.11.6.7: Battery Voltage Fluctuation, Takamatsu Event

Cell 6 vented and battery voltage dropped from 31 V to 29 V then suddenly dropped to 11 V (Battery output voltage is approximately 1 V higher than the voltage recorded on the FDR. The difference is due to the voltage drop across the BDM between the battery and the location of FDR voltage sensor.) Event G explains why 11 V was recorded. The actual battery voltage is less than 11 V, possibly 0 V as the contactor was very likely open.

Section 2.11.6.5 explains the mechanism of contactor opening when a cell vents.

b. Event B

Voltage instantly rose to 20 V and then to 27 V. This was caused by contactor closing. The ground wire fused open. Swollen cell 6 due to internal short circuit contacted with the brace bar creating short circuit path to the battery case, allowing high currents to run through them. After the ground wire was fused open, current dropped significantly due to the higher resistance of the battery mount bolts to the tray.

c. Event C

The contactor closed and voltage rose to 26 V, and dropped to 23 V. Most likely cell 3 vented.

d. Event D

Fluctuating voltage indicates cell-to-cell and cell-to-battery case short circuits due to previously spewed electrolyte and mechanical contact from swelling cells and melted insulation. At this moment cell 6 and battery case had shorted and cell 6 and cell 3 cases had shorted to each other. These short circuits created closed path from cell 3 to cell 4 to cell 5 to cell 6, consuming the energy of cells 4 and 5. High currents and arcing melted cell 3 positive terminal.

e. Event E

As the busbar connecting cells 3 and 4 was separated, recorded main battery voltage dropped to 11 V. (Note: Event G explains why 11 V was recorded.)

f. Event F

Short circuit continued for the remaining cells. Varying resistance levels caused erratic voltage changes. Some of the fluctuation may have been due to the battery contactor opening and closing.

g. Event G

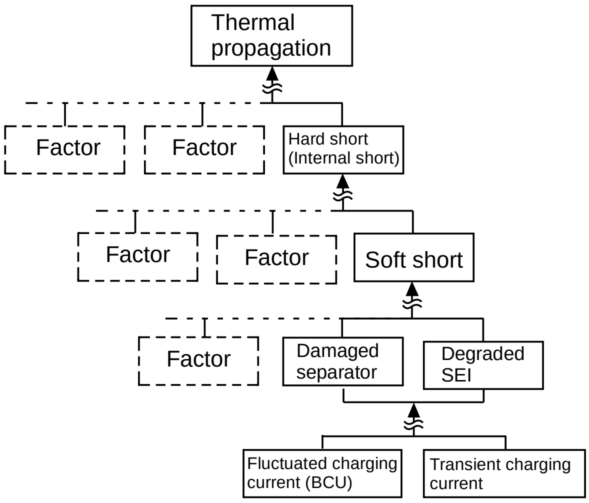
The discrepant circuit card assembly caused sneak voltage from the APU battery being registered as 11 V. Actual main battery voltage is unknown due to the masking of the sneak voltage.

h. Event H

Voltage drop to 3 V coincides with landing gear extension. Wheel well door opening illuminates “Door Unsafe lights” in the wheel wells resulting in the voltage drop.

2.11.6.8 Boeing’s Cause-Effect Diagram

After the battery fire in Boston and the serious incident, Boeing set up a task force to troubleshoot and establish corrective actions. This activity is called “Root Cause and Corrective Action (RCCA)” and the task force formulated a cause and effect diagram which explains possible root causes for events in Boston and Takamatsu.



(Based on Boeing material)

Fig. 2.11.6.8: Cause-Effect Diagram (partial)

The diagram illustrates overcharging, over-discharging as well as external and internal short circuit. One scenario for a short circuit is that “fluctuation of BCU charging current” and/or “transient charging current” leads to “degraded SEI” and/or “separator damage.” And as Fig 2.11.6.8 illustrates with other contributing factors, “Soft short”, to “Hard short (internal short)” occurs resulting in a thermal propagation. But the cause and effect diagram did not include the effects of cold temperatures.

2.11.6.9 Additional Testing by an Outside Firm

In addition to testing conducted at Boeing during 2013, after coordination with the NTSB, Boeing contracted an outside firm to perform additional testing to help understand what might have caused the Boston and Takamatsu events and the report was presented to the company (hereinafter referred to as "EX Report"). The following are the excerpts of the report based on test conducted and inspection of new cells and teardown of cells from batteries that were removed by operators in-service. (The JTSB added titles.)

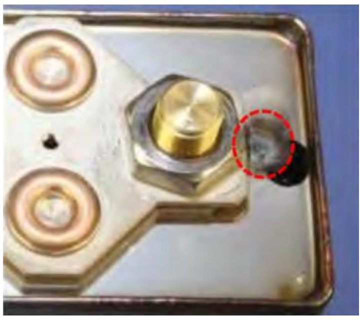


Fig. 2.11.6.9-1: Distinctive Hole

a. Short circuit between cell case and battery box

Tests with a low impedance connection between a cell can (case) and the battery box, and with a bias between the terminals and the can, have shown that the fault current through the formed conductive pathways always results in signature holes in the cell can near the negative electrode; a signature that was not observed in the documented incident evidence.

b. Foreign metal piece in a winding

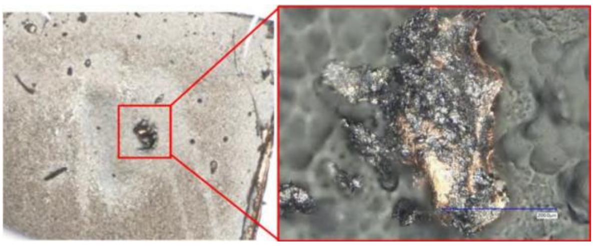


Fig. 2.11.6.9-2: Copper Particle Discovered on Separator

The copper current collector had a small copper piece penetrating through some layers of the separator. This feature was likely introduced during cell manufacturing and did not have an immediate effect on cell characteristics or performance. Over time, this feature could have penetrated additional layers of separators and created an internal short.

c. Carbon black and particles of $LiCoO_2$

Carbon black is added to the positive electrode to increase the electronic conductivity of the coating. The presence of the agglomerates indicates that the conductivity of the electrode may not be uniform, resulting in non-uniform current density.

Large particulates of $LiCoO_2$ were also found in the positive electrode.

Analysis of the cross-sections of the LVP65 cell found numerous occurrences of particles which is approximately two times thicker than the separator and as thick as positive active material.

d. Copper dissolution

Evidence of copper dissolution was found throughout a cell. Copper-rich deposits were found on the interface between the negative electrode and the separator, coating graphite particles and within the pore structure of the separator. Copper dissolution can occur in the cell if it is over-discharged during use or if the cell is allowed to rest for an extended period of time with electrolyte prior to formation during the manufacturing process.

e. Gaps and folds in the electrodes

One swollen cell which had been on-board an airplane was analyzed by Computed Tomography (CT) and optical microscopy. The analysis found some gaps in some parts of the winding.

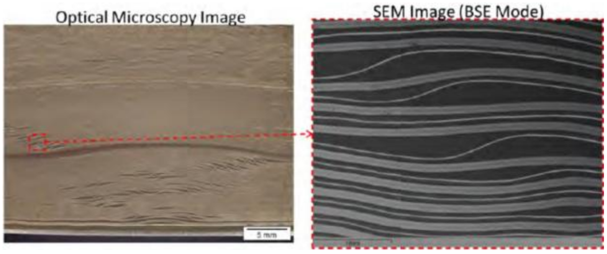


Fig. 2.11.6.9-3: Gaps in Electrodes

These gaps (an irregularity in the windings) were possibly the result of a manufacturing flaw.

2.11.7 Tests Done by the NTSB for the Boston Event Investigation

The tests done by the NTSB for Boston event investigation found the following.

2.11.7.1 Simulated APU Start Test

The simulated APU start tests were done at a contracted laboratory using the same type of battery which has a known service history.

The test scenario was the most rigorous one within Boeing specification. Three consecutive APU start comprised one cycle. When one cycle was done, certain interval was inserted before the next cycle for the cell temperature to return to ambient temperature. 14 cycles were done in total. The recorded highest currents were about 600 A.

A thermal infrared image showed the increased temperature around cell 5 positive terminal after some cycles of APU start. Thermal couples attached to the rivet (aluminum) next to cell 5 positive terminal recorded temperatures more than 100 °C. Cell 5's measured DC resistance exceeded that of normal cell by far greater value.

The laboratory expressed possibilities of internal short circuit as a result of partial melting of the separator close to the rivet by the heat generated at the rivet. CT scanning and physical examination of the rivet cross section revealed gaps at the conjunction between the rivet and current collector. The laboratory suspects that the existence of gap leads to high DC resistance between the rivet and positive terminal. It points out that the defect comes from manufacturing process or battery use. It expresses a concern to use aluminum rivet to unite current collectors and the header.

2.11.7.2 Cell DPA

A cell DPA under 100 % SOC condition found wrinkles and discolorations on anode. Presence of crystallized branching compounds was observed near the wrinkles. The composition of the compounds was not definitively verified by analysis. The laboratory says that compared with the morphology of the lithium dendrites published in literatures, these observed protrusions are suspected to be metallic lithium dendrites electro-deposited on the carbon anode during cycling.

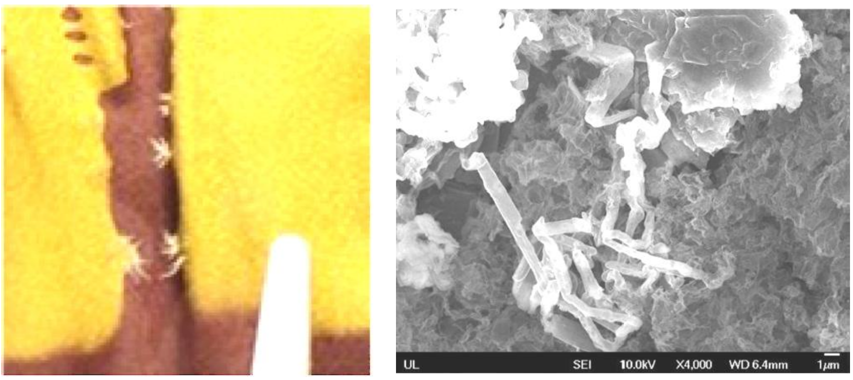


Fig. 2.11.7.2: Branching Crystals and Dendrites
(white conical object is pointer)

2.11.8 Tests Done by GYT after the Serious Incident

GYT conducted its own test to confirm deposition of lithium metal. It stated that the repeated low temperature charging/discharging cycles under 100% SOC conditions did not lead to the conclusive confirmation of lithium metal deposition.

2.12 Type Certificate

2.12.1 Type Certification in the United States of America

The Federal Aviation Administration (FAA) is responsible for prescribing minimum standards required in the interest of safety for the design, material, construction, quality of work, and performance of aircraft. (Hereinafter the minimum standards are referred to as “the airworthiness standard.” The airworthiness standards are stipulated in the Code of Federal Regulations (CFRs).

It is 14 CFR Part 25 which applies to the large-sized wide body airplane such as the 787 whose airworthiness category falls under “Transport.”

The airplane manufacturer must demonstrate to the FAA that the airplane or product being submitted for approval complies with all applicable CFRs. Successful completion of the certification process enables the FAA to issue a type certificate (TC).

Certification Basis and method of compliance are stated in the FAA approved certification plan.

2.12.2 TC Applied to 787s

Boeing applied for an FAA TC for its new Boeing Model 787-8 passenger airplane on March 28, 2003. The applicable certification basis includes the 14 CFR Part 25 Airworthiness Standards, amendments 25-119, 25-120, 25-124, 25-125 and 25-128 with some exceptions and special conditions (SCs) as noted in the 787-8 TC data sheet including 25-359-SC for the LIB installation. The methods to comply the FAA approved certification plan are stated in "787 electrical power system (EPS) certification plan." According to the 787 TC datasheet, the 787 airplane was granted transport category approval on August 26, 2011.

2.12.3 Delegation of FAA's Certification Activities

For several decades, the FAA has delegated non-safety-related certification activities to individual Designated Engineering Representatives in the private sector. In 2005, The FAA issued a rule that established the Organization Designation Authorization (ODA) program to allow for more comprehensive delegation to appropriately structured and monitored organizations. Boeing's delegated compliance organization received ODA approval from the FAA on August 18, 2009. Since then certification activities, including 787 certification activities, were delegated to Boeing's Delegated Compliance Organization in accordance with FAA approved Boeing Procedures Manual.

2.12.4 Special Conditions

If, during the conceptual design phase, the FAA determines that existing regulations or safety standards applicable to the design feature being certified are inadequate or inappropriate, it can determine that special conditions are necessary. The special conditions include additional airworthiness standards to maintain equivalent level of safety with the existing airworthiness standards. (14 CFR 21.16)

Special conditions begin with an issue paper and its developments are recorded in the issue paper.

The proposed use of lithium ion batteries on 787s was judged to be a novel or unusual design feature and the FAA developed an Issue Paper, SE-9, "Special Condition: Lithium Ion Battery Installations."

a. Issue paper

At the time of the FAA's review of the proposed 787 design, there was limited experience with the use of rechargeable LIBs in applications involving commercial aviation. The FAA noted that other users of this technology, ranging from wireless telephone manufacturing to the electric vehicle industry, have noted safety problems with LIBs, which included overcharging, over-discharging, and flammability of cell components. The FAA cited the following issues in its Issue Paper:

(1) Overcharging

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 their nickel-cadmium or lead-acid counterparts. This is especially true for overcharging, which causes heating and destabilization of the components of the cell leading to formation (by plating) of *highly unstable metallic lithium. The metallic lithium can ignite, resulting in a self-sustaining fire or explosion. Finally, the severity of thermal runaway from overcharging increases with increasing battery capacity, because of the higher amount of electrolytes in large batteries.*

(2) Over-Discharging

Discharge of some types of lithium ion batteries beyond a certain voltage (typically 2.4 volts) can cause corrosion of the electrodes of the cell, resulting in loss of battery capacity that cannot be reversed by recharging. This loss of capacity may not be detected by the simple voltage measurements commonly available to flight crews as a means of checking battery status. This is a problem shared with nickel-cadmium batteries.

(3) Flammability of Cell Components

Unlike nickel-cadmium and lead-acid batteries, some types of lithium ion batteries use liquid electrolytes that are flammable. The electrolytes can serve as a source of fuel for an external fire, if there is a breach of the battery container.

b. Special conditions (25-359-SC)

After the review of the issue paper, the FAA issued nine special conditions for the 787 LIB installation (25-359-SC) to mitigate safety problems caused by overcharging, over-discharging, and flammability of cell components on September 28, 2007. The special condition became effective on November 13, 2007 as part of the type certification basis for the Boeing Model 787-8 airplane.

The special conditions for the 787 LIB were the same as the ones for LIBs for emergency lights installed on Airbus A380, which were issued and became effective on November 30, 2006. The special conditions for the Airbus A380 and 787 LIB were the same even though the battery configuration and capacity on each aircraft are different.

25-359-SC states:

In lieu of the requirements of 14 CFR 25.1353(c) (1) through (c) (4), the following special conditions apply. Lithium ion batteries on the Boeing Model 787-8 airplane must be designed and installed as follows:

(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.

Note: These special conditions are not intended to replace 14 CFR 25.1353(c) in the certification basis of the Boeing 787-8 airplane. These special conditions apply only to lithium ion batteries and their installations. The requirements of 14 CFR 25.1353(c) remain in effect for batteries and battery installations of the Boeing 787-8 airplane that do not use lithium ion batteries.

2.12.5 Boeing Certification Plan

Boeing developed the 787 electrical power system certification plan and obtained FAA approval of the original plan on December 22, 2005. The certification plan presented a high-level system description of the electrical power systems, which included the battery and battery charger system, and defined the methods to be used to show compliance to applicable FAA requirements. The FAA approved the certification plan, reviewed the qualification test procedures, approved the type inspection authorization, and granted final approval to the test reports.

2.12.6 Safety Assessment

2.12.6.1 System Safety Assessment Criteria

Airworthiness standards applied to passenger airplanes are stipulated in 14 CFR Part 25 and EASA CS-25, and their safety standards are in Part 25-1309/ CS 25 Chapter F: Equipment, systems and installation.

Table 2.12.6.1-1: Relationship between Probability and Severity of Failure Condition

Classification of Failure Conditions	No safety effect	Minor	Major	Hazardous	Catastrophic
Allowable qualitative probability	No probability requirement	Probable	Remote	Extremely Remote	Extremely Improbable
Allowable quantitative probability: average probability per flight hour on the order of	No probability requirement	$<10^{-3}$	$<10^{-5}$	$<10^{-7}$	$<10^{-9}$
Effect on aeroplane	No effects on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on occupants excluding flight crew	Inconceivable	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injuries to a small number of passengers or cabin crew	Multiple fatalities
Effect on flight crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation

(CS-25AMC25.1309)

The advisory circular (AC) 25. 1309-1a which provides interpretation is now being reviewed and its draft version (AC 25, 1309-1b/Arsenal Version) provides the same contents as CS-25 AMC 25. 1309. The 787 TC safety assessments were done in accordance with the arsenal version.

The interpretation of safety assessment stipulated in the draft version and CS-25 AMC 25. 1309 is: allowable quantitative probability for a major failure must be extremely remote; however, that for minor failure to be fairly high (allowable quantitative probability varies inversely with the gravity of failure). For instance, the allowable quantitative probability for a failure classified as catastrophic, in which the situation is extremely grave with hull loss and multiple fatalities, should be less than 1 x 10^{-9} per flight hour (extremely improbable), while minor failure where airplane functions and safety are hardly affected is allowed to occur with a relatively high probability.

Table 2.12.6.1-2: Explanation of Quantitative Probability Terms

Qualitative failure terms	Description
Probable	Anticipated to occur one or more times during the entire operational life of each aeroplane
Remote	Unlikely to occur to each aeroplane during its total life, but which may occur several times when considering the total operational life of a number of aeroplanes of the type.
Extremely Remote	Not anticipated to occur to each aeroplane during its total life but which may occur a few times when considering the total operational life of all aeroplanes of the type.
Extremely Improbable	So unlikely that they are not anticipated to occur during the entire operational life of all aeroplanes of one type.

(CS-25AMC25.1309)

2.12.6.2 Safety Assessment for 787 Lithium-Ion Battery

The safety assessment of 787 LIB was conducted to identify potential hazards to crew and passengers in accordance with the arsenal version of AC25-1309-1a, SAE ARP4761 “Safety analysis guidance” and SAE ARP4754 “Assured Development Guidance,” of which the latter two were referred by AMC 25. 1309. A functional hazard assessment identified hazards associated with the cell vents. The hazards were classified in accordance with arsenal version of AC25-1309-1a and AMC 25. 1309. Identified probability of occurrence for “vent, smoke and fire of the battery,”

Table 2.12.6.2: Feared Events Described in Safety Assessment

Specific hazard	Severity	Probability of occurrence	Event source
Vent, smoke, fire	Catastrophic	10^{-9}	BCU failure Contactor failure Cell imbalance BMU failure
Vent, smoke	Hazardous	10^{-7}	Crush, Impailing Overheat
Vent, electrolyte leakage/fume, no smoke and no explosion of the battery	Hazardous	10^{-7}	Heat generation Gas generation Electrochemical corrosion of cell
Vent, no smoke and no fire of the battery	Major	10^{-5}	BCU failure BMU failure Heat

was less than 1 x 10^{-9} per flight hour, while that for "vent and smoke of the battery" was less than 1 x 10^{-7} per flight hour.

2.12.6.3 787 LIB Failure Mode Assessment

As shown in Fig. 2.12.6.2, 787 EPS safety assessment identified the following failure modes for the catastrophic hazard—vent, smoke and fire of the battery. They are: BCU failure, contactor failure, BMU failure and cell imbalance. The fault tree analysis (FTA) done by Thales concluded that combined failure of BCU, contactor, BMU and cell imbalance generate a vent with smoke. The FTA included an analysis of a vent with fire deriving solely from overcharging.

The FTA included an analysis for the cause of a vent with smoke/without fire deriving from severe internal short circuit or battery heating.

In order to assess the effect of venting, GYT performed a battery level test triggering an internal short circuit by nail penetration (See the details in section 2.12.7.1). The test resulted in a vent with smoke without generating fire.

It is noted that the FTA included in Thales' safety assessment did not include the risk assessment of the thermal propagation.

2.12.6.4 Probability of Battery Failure

The document on failure modes and effects analysis (FMEA) approved by Thales states that Thales and GYT established 787 LIB failure rates based on the cell failure records of large industrial LIB, which has similar in cell structure with the 787 battery. At the time of failure rate estimation, no failure had been reported to GYT so that it set the failure number as zero. It calculated a mean time between failures (MTBF) employing Poisson distribution with the number of failure cases and total operational duration. The MTBF was then used to calculate the failure rate. Cell size was adjusted with a coefficient.

The shapes of two types of cells are similar, but compound ingredients are not identical. The confidence level used for the failure rate estimation was 60%. This was how the failure rate for the 787 main battery was calculated.

2.12.7 Tests Done during Developmental Phase

2.12.7.1 Internal Short Circuit Test by Nail Penetration

In 2006, with consultations with Thales and Boeing, GYT conducted one of several battery nail penetration tests to assess the impact of an internal short circuit. The test configuration was: nail penetration to cell 2, without connecting wire to the BCU for charging/discharging, and without battery box ground wire, under non-controlled ambient temperature. The penetrated cell vented with smoke without generating smoke. No other cells vented.

Fig. 2.12.7.1: Observed Smoke

This test was a part of engineering tests and the test result was presented to the FAA at a briefing when Boeing was finalizing the LIB technical requirements. As a result, the internal short circuit test was not included in the TC engineering test.

2.12.7.2 Climatic Tests

In 2010 GYT conducted climatic tests as part of TC engineering tests. The tests were conducted in accordance with the procedures approved by Thales and Boeing.

a. Low temperature test

In the test, a battery temperature was varied from in-flight outside temperature to battery operational lower limit and BMU function was checked accompanied by discharging at tens of amps and charging.

The test revealed no anomalies to battery voltage, electric insulation resistance, temperature sensor, contactor, or impedance. No leakage of electrolyte was observed.

b. Tests at Varied Temperature

In the test, couples of cycles of tests were conducted. In each cycle a subject battery was exposed to operational temperature range. The battery discharging/charging behaviors, and BMU functions across this temperature range were monitored.

The test revealed no anomalies.

2.12.7.3 External Short Circuit Test

In 2010, GYT conducted external short circuit test (low and high resistance). The tests were conducted in accordance with the procedures approved by Thales and Boeing.

a. Low resistance external short circuit test

A fully charged battery was warmed to its upper limit of operational temperature. The external short circuit path was created using low resistance. Power cables used were elongated actual power cables.

The test revealed that the short circuit allowed several thousand amps of currents to run for an extremely short time after the shorting and the current dropped to 0 A. The contactor was expected to open, but the data analysis concluded that the contactor remained shut and the current dropped to 0 A as the current collectors fused open. The post-test battery temperature was within safety range. No electrolyte leakage, smoke or fire was observed.

b. High resistance external short circuit test

A fully charged battery was warmed to its upper limit of operational temperature. The external short circuit path was created using high resistance. Power cables used were elongated actual power cables.

Fig. 2.12.7.3: Damage on J3 Cable Connector

The test revealed that the short circuit allowed several thousand amps of currents to run and the current dropped to 0 A. The average current value exceeded 1,000 A. The shorting starts concurrently with the start of the test, and 2 min after the shorting, smoke or fumed electrolyte was observed, reaching the maximum level 5 min after the shorting. The J3 cable connector exhibited distinctive damage associated with external short circuit.

2.12.7.4 Overcharging Tests

a. Overcharging test (Battery voltage at 36 V and contactor operation)

In 2010, GYT performed an overcharge test in which battery voltage was increased up to an overcharging threshold. The tests were conducted in accordance with the procedures approved by Thales and Boeing.

In the test, charging continued for more than a day to maintain battery voltage at overcharged level. Then the voltage was increased more to observe contactor operation.

The test revealed that battery temperature remained within safety range, and no electrolyte leakage, smoke or fire was observed until the battery voltage reaches the upper threshold. BMU overcharge detection and contactor operation proved operational at battery voltage design threshold.

b. Overcharging test (One cell venting)

With consultation with Thales and Boeing, GYT performed an overcharging test. In order to test battery behavior, one cell was overcharged exceeding SOC 100% until it vented.

The test resulted in a blowtorch-like fire from the overcharged cell vent hole, which fused open the battery box. The fire also fused metal protection shield placed next to the battery box.

2.12.8 Minimum Operational Performance Standard for LIB System

Radio Technical Commission for Aeronautics (RTCA) is a non-profit organization consisted of representatives from industries and other fields, and was established in 1935. It has special committees to formulate aeronautics standards for on-board systems. “DO-311 Minimum Operational Performance Standard (MOPS) for Rechargeable Lithium Ion Battery” was drafted by the special committee 211 and finalized in 2008. Some of the committee members are from Boeing, Thales, GYT and FAA.

Although RTCA standards are industry standards, if FAA considers it appropriate to refer RTCA standards from technical standard orders (TSO), many of the incorporated standards are used as MOPS when airplane equipment design approvals are granted in accordance with TSO. When 787 LIB special conditions were established in 2007, the applicable standard was TSO-179 (issued in 2006). The FAA did not incorporate DO-311 into 787 LIB airworthiness standards, because it was established after the special conditions 25-359-SC became effective and the FAA did not intend to grant LIB TSO as single airplane equipment. The LIB for the 787 was approved as part of the TC.

The TSO was amended into TSO-179a in 2011. The new TSO refers to DO-311, DO-178B, DO-254, and DO-160F as certification standards. TSO-179a includes MOPS and it refers the Table 4-1, TO-311.

DO-311 includes a test named "Induced Destructive Overcharge Test with Protections Disabled" to clarify the effects of thermal runaway. The test procedure includes a test in which short circuits of single or multiple cells and a battery charger is disconnected. DO-311 also includes a required test intended to contain explosion. These tests are required to be performed under overcharging conditions; however, DO-311 does not include specific test procedures to simulate internal short circuits.

2.13 Other Information

2.13.1 Battery Manufacturing

2.13.1.1 Cell

Cell manufacturing is divided into three processes: mixing of active materials into paste for the positive and negative electrodes; formation of windings; and insertion of windings into a cell case. All the process is done in environmentally controlled rooms.

In the same manufacturing facility of the 787 batteries, other large-sized multi-purpose batteries are manufactured using the same cell ingredients and manufacturing methods including the winding machine for the anode and cathode rolls. GYT maintains that it has received no anomaly reports for the large LIBs.

a. Making of active material pastes

$LiCoO_2$ is one of the main ingredients for the paste for positive electrode, while carbon compounds are for the paste for negative electrode. Each batch of paste has its use-by date, and it is scrapped in case of exceeding the limit.

b. Winding formation

The manufacturing procedure for the positive electrode is identical to the negative electrode. The active material paste is coated on copper or aluminum foil, baked, pressed and wound. During this process, thickness, bubbles, wrinkles and winding alignment are checked. Thickness is measured with a manual thickness gauge, and other inspections are conducted visually.

Next electrodes foils are installed in a winding machine which merges the foils with a separator in between to create a cell winding roll. Each individual winding is hand flattened, and three rolls are pressed flat by a hand-operated compressing jig. A flattened cell winding exhibited flexural deformation. GYT maintains that the deformation at this stage have no effects on battery cell as it is known that the both electrodes swell and shrink during charging and discharging, respectively.

c. Cell assembly

Current collectors are hand assembled and clipped to the copper and aluminum foil on each side of a compressed roll. This assembly is then ultrasonically-welded to each corresponding electrode. The welded bundle is then wrapped with insulating film and heat-resistant tape, and inserted into a cell case. The header and the case is tungsten-inert-gas (TIG)-welded and be subjected to air leak test.

The cell is then fed with electrolyte through a small hole. The hole is plugged with a spherical metal ball and resistance-welded. The cell goes through a number of inspections: weight, leak, AC/DC resistance, capacity, internal soft short, CT scanning.

2.13.1.2 Battery Assembly

Fig. 2.13.1.2 illustrates internal parts used for a battery construction. All assembly is done manually. Lower fixation frames are placed on the battery box floor. Cells are placed on them facing each safety valve oriented to the box side wall. Spacers are inserted between the cells. Top fixation frames are placed on the cells and bolted to the brace bar. Busbars, thermo-sensors are connected to the cells. The BMU, contactor, and HECS are installed in the box to finalize the battery construction. The battery goes through AC/DC resistance check and ATP.

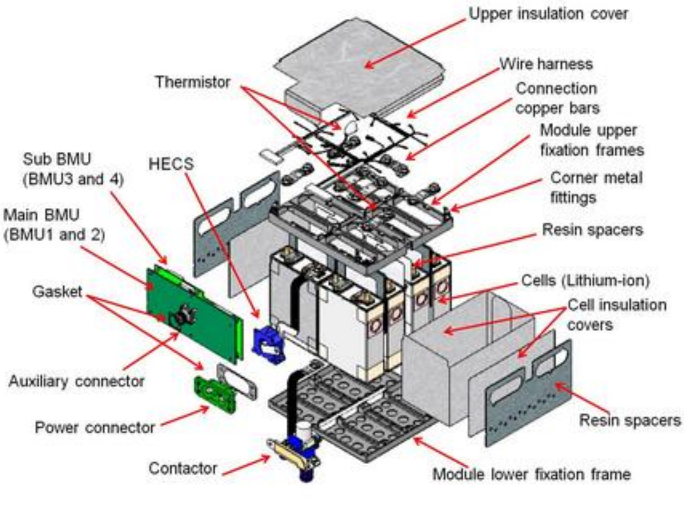


Fig. 2.13.1.2: Battery Assembly

2.13.1.3 Foreign Object Damage Prevention Measures

The following foreign object damage (FOD) prevention measures are taken by GYT and it maintains no possibility of contamination during manufacturing.

a. Manufacturing process

The cell manufacturing facility is an environmentally controlled clean room. It is mandatory to wear head cover, electro static dissipative shoes and other garments to maintain the cleanness. When a person goes into the facility, he/she has to go through double doors and air curtain to be dusted off. At the entrance floor, one steps on sticky sheet to remove dust from the soles. The facility's interior air pressure is higher than outside to push back small particles suspended in the air. The air filters installed in the intake air fans are replaced periodically.

Cell manufacturing facility is divided into active material mixing room and cell assembly room. Both rooms have almost the same level of FOD prevention measures. Cell assembly personnel are required to wear gloves and surgical masc.

The powdery cell active materials are weighed after reception and put into the mixer to produce paste. There is no specific procedure to filter out foreign objects.

There is no possibility of foreign object contamination deriving from cutting dust as no cutting procedure is involved in the cell manufacturing process.

Possible foreign object contamination can occur when active materials are coated on foils and current collectors are ultrasonically-welded to windings. Magnetic filters are used to catch foreign ferrous metallic objects during the coating process. A vacuum cleaner is attached next to the welding machine to remove debris generated during the ultrasonic welding.

b. Inspection during and after the manufacturing

Before a cell is fed with electrolyte, voltage is applied between the positive and negative terminals to check for internal short circuit.

After the cell manufacturing, it is subjected to soft short test and CT scanning.

2.13.2 Similar Battery Events

a. Boston event

At 10:21 on January 7, 2013 (US. Eastern Standard Time), an APU battery of a 787 parked at a gate at General Edward Lawrence Logan International Airport, Boston generated smoke. A mechanic on board the airplane saw two small vertical flames on the connector when he opened the aft EE bay.

The event is now under investigation by the NTSB[10].

b. Narita event

On January 14, 2014, a mechanic on board a 787 parked at Narita International Airport for preparation for the next flight saw smoke flowing outboard and confirmed a message of failed main battery and BCU on the EICAS screen. The investigation found that cell 5 had vented and the remaining seven cells were still producing a normal voltage (approximately 4 volts). In 2013, all 787 airplanes were modified to house the main and APU batteries in metal enclosures ducted to the outside of the airplane. In this event, the enclosure box prevented any electrolyte from escaping into the cabin and expelled it overboard.

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[10] For the detail of the investigation, visit the NTSB website at http://www.ntsb.gov.

At that time global 787 fleet accumulated total flight time of 250,000 hr.

Fig. 2.13.2-1: Wrinkles of Anode Graphite during Narita Event Investigation

In the investigation lead by the Civil Aviation Bureau of Japan (JCAB), remaining cells were dismantled under 100% SOC condition. The examination revealed wrinkles on anode graphite.

The examination also found a metallic particle in a separator. Ingredient analysis of the particle found that it was stainless steel. GSY has a theory that the small particles during DPA migrated into the cell interior.

Initial products of lithium compounds were found on the dismantled electrodes and they are now under analysis.

CT-scanning of cells except cell 6 revealed that the amount of cell electrolyte differed from cell to cell.

During the investigation process, there was a report about the surface temperature of the battery enclosure box which went down to almost 0°C during flight operation. According to Boeing, batteries before Takamatsu event probably experienced the same temperature drop during flights.

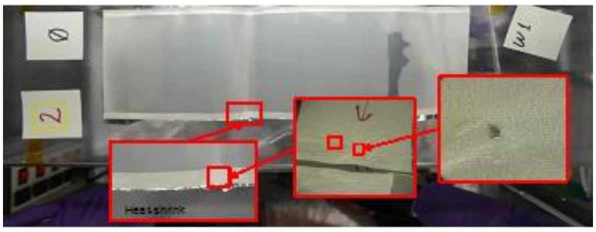


Fig. 2.13.2-2: Metallic Particles Discovered during Narita Event Investigation

2.13.3 Procedures for Emergency Landing

JA804A's airplane operations manual (AOM) includes the following passage:

2.0 AOM, Chapter CI Checklist Instructions
2.0.0 Section 2 Non-Normal Checklists
General

(Snip)

The Non-Normal Procedures stated in this chapter are prepared for *some of the typical situations. Under the unconceivable situations which these procedures cannot cope with, good judgment of flight crew should be employed.*

(Snip)

(12) Emergency Landing

The captain considers an emergency landing at the nearest suitable airport if the following situations develop or other ones which require so.

(Snip)

- *Smoke/fumes and/or fire in the cabin and/or crew rest compartment and flight crew cannot confirm the smoke ventilation or extinguished fire.*

  (Snip)
- *any other situation determined by the flight crew to have a significant adverse effect on safety if the flight is continued.*

(Snip)

Cabin or Cockpit Smoke/Fume/Fire

In case of smoke/fumes or fire in the cabin (overhead crew rest compartment inclusive), one cabin attendant should be assigned as a contact person for flight crew for situation update on fire fighting activities.

Turn on Seat Belt Signs Selector to maintain cabin order, if necessary, use PA announcements.

In case of cabin/cockpit air pollution with smoke/fumes, other toxic gases, or noxious fumes, or imminent threat of pollution, consider immediate use of oxygen masks/smoke hoods. They are protective against smoke/fumes, CO_2*, and other noxious gases.*

(Omitted)

2.13.4 Evacuation Procedures

The airplane evacuation procedures are as follows:

1. PARKING BRAKE ······ SET
2. OUTFLOW VALVE switches (both) ······ MAN
3. OUTFLOW VALVE MANUAL switches (both) ······ Hold in OPEN until the outflow valve indications show full open to depressurize the airplane
4. FUEL CONTROL switches (both) ······ CUTOFF
5. Evacuation ······ Initiate (PIC)
6. Advise the tower
7. Engine fire switches (both) ······ Pull

8. APU fire switch ·· Override and pull
9. If an engine or APU fire warning light is illuminated:
Illuminated fire switch ································ Rotate to the stop and hold for 1 second.

2.13.5 History of Overnight Stay before the Serious Incident

The history of airplane's overnight stay up until the serious incident (December 1, 2012 through January 15, 2013) revealed that the lowest outside temperature was -2.6°C on 23 December, 2012. (See Figure 5: Lowest Temperature at Overnight Stay Airports (Dec. 1, 2012-Jan. 15, 2013)

3 ANALYSIS

3.1 Airman Competence Certificate

The Captain and the FO held valid airman competence certificates and valid aviation medical certificates.

3.2 Aircraft Airworthiness Certificate

The airplane had a valid airworthiness certificate and had been maintained and inspected as prescribed.

3.3 Relations to the Meteorological Conditions

The similar incidents in Boston, Takamatsu and Narita all occurred in January, during the cold season. Although statistical samples are insufficient, the fact that they all occurred in winter is non-negligible, suggesting that low temperature is a possible contributing factor.

3.4 Developments from Battery Failure to the Landing

a. Judging from the airplane's location and altitude at the time of the annunciation of battery malfunction in the cockpit, flight crew's statements, chronicled radio transmissions between the airplane and the air traffic control facilities, the airplane landed uneventfully at Takamatsu Airport, wasting least amount of time. The air traffic controller's handling of the other airplane that was supposed to land before the airplane to go around very likely expedited the landing of the serious incident airplane.

   The CVR and FDR records demonstrate that the flight crew calmly handled the situation in accordance with the procedure. The APU start-up, usually a post-landing procedure, was done before the landing to secure redundancy of auxiliary electric power. Electric power generation after the APU start-up could have helped flight crew obtain emergency power for public announcement in power loss conditions after engine shut-down with failed main battery.

b. The very likely reason for burning smell

   As shown in Figure 2: FDR records, the smoke ventilation system started to function after the main battery voltage dropped. It is highly probable that the system operated as designed. The smoke was extracted overboard through the override valve and forward outflow valve, but part of it was sucked in from the cabin air compression inlet, forwarded to the cockpit and cabin to be sensed.

c. The emergency lights are designed to be automatically illuminated in case of loss of airplane electric power (zero HBB power). It is very likely that the loss of HBB power as a result of the main battery failure triggered the first indication of the EMER LIGHTS on the EICAS screen as designed.

3.5 Evacuation

Judging from the Captain's statement and CVR records, it is very likely that he decided to execute the evacuation when he received the positive response of the air traffic controller on the smoke from the airplane. Judging from the CAs' statements, some passengers brought their belongings, but most of them slid the emergency evacuation slides leaving their belongings on the plane as per the CAs' instruction. It is very likely that the evacuation went smoothly although four passengers suffered minor injuries.

The fire fighting vehicles from the airport rescue and fire fighting service were already in position by the runway prior to the landing of the airplane.

3.6 FDR Battery Voltage Record

As described in section 2.11.1, as the discrepant circuit card assembly was installed on the airplane, it allowed the currents to flow from the APU battery to the main battery circuit when main battery voltage was lower than that of the APU. As Fig. 2.11.1 illustrates, the main battery sensor for the FDR picks up the APU battery voltage. Therefore, it is highly probable that at the time of the main battery failure, FDR main battery voltage recorded 11 V that was the sneak voltage from the APU battery, and the actual main battery voltage was less than 11 V.

The presence of the discrepant circuit card assembly indicates that the airplane was delivered to ANA as a result of imperfect final delivery check.

3.7 Analysis of Kakuda Testing

3.7.1 Cell Behavior upon Internal Short Circuit

As described in section 2.11.5.b, and the records in Figure 11-1: Detailed cell voltage drop (Configuration 2), Appendix 2 illustrates, cell internal pressure increased and it vented right after the internal short circuit occurred. The cell voltage temporally dropped by approximately 1 V, recovered to 4 V and finally dropped to 0 V.

The internal short circuit of a winding very likely caused positive and negative electrodes to contact, generating high currents resulting in decomposition of electrolyte and cell venting.

The shorted winding possibly consumed electrical energy to become a carbonized conductor, and currents from the two parallel windings flowed in the conductor resulting in voltage drop due to internal resistance, leading to the voltage drop.

The possible reason for the recovery of cell voltage is that the cathode current collectors of the shorted winding fused open and shut the current flow. As the cathode terminal current collectors are made of aluminum while that of anode current collector is copper, the difference of their melting point very likely explains the reason of fused current collectors.

Cell internal heat very likely melted the separators of the remaining windings resulting in short circuit and the cell voltage dropped to 0 V.

3.7.2 Irregular Contactor Opening upon Cell Venting

As described in section 2.11.5, the tests conducted in configurations 2 and 3 at Kakuda exhibited contactor openings when cells vented. As described in section 2.6.5.4, the contactor is designed to open when cell voltage reach overcharge threshold. When the contactor opened in the tests, no voltage data for each cell and battery suggested the overcharging. Probable reasons for irregular contactor opening under non-overcharging conditions are effects of spewed cell material or heat generated by the failed cells on the BMU; however, the cause remained undetermined. As the same phenomenon was observed in the battery vent test conducted by Boeing, it is very likely that the cell venting is accompanied by irregular contactor opening in the case of the LIB.

Irregular contactor opening occurs sometime within a few seconds or several tens of seconds after the cell venting. When the contactor opens, battery voltage instantaneously drops to 0 V.

The main battery is the primary backup power in case of multiple failures of power sources on the airplane. Although the probabilities of cell venting under the condition of multiple failures of power sources are very remote, it would be a grave situation if that actually happened. In light of three similar battery events, consideration should be given to the risk assessment of this issue.

3.7.3 Post-vent Short Circuit between Cell Case and Battery Box

As described in the section 2.11.5 b. and the Figure 11-1: "Fluctuations of Cell Voltage and Ground Wire Current" in Appendix 2, approximately 1,000 A of ground wire currents were recorded approximately 30 sec after the cell 6 venting. This indicates that the concurrent physical contact between the swollen cell 6 and the brace bar. At this stage, it is very likely that the failed cell itself was transformed into a combined conductor which contains all the shorted windings and melted resin sheets wrapping each winding, as described in section 3.7.1. The short circuit with the battery box very likely caused both terminals of cell 6 to have equal electric potential with the ground; however, no battery voltage drop is recorded in the test. As described in the section 2.11.6.5, the battery voltage drop during ground wire high currents was observed in the battery vent test performed by Boeing. It was very likely caused by the mechanism in which shorted point to the battery box became the ground voltage potential.

As the short circuits between the cell case and battery box occur erratically, the corresponding voltage values probably fluctuate accordingly.

3.7.4 Arcing

The tests conducted in configurations 1 and 2 at Kakuda demonstrated fused spots between cell 6 case and the brace bar, which was caused by arcing. Given the currents as high as 1,000 A that ran through the ground wire, it is very likely that the phenomenon similar to arc-welding occurred when shorted points detached from the brace bar due to erratic short circuits between cell 6 case and brace bar. The timing when cell 6 case was welded to the brace bar very likely corresponds to the timing when the last high currents ran through the ground wire and cell 7 vented.

When two live contact points repeatedly continue to open and close, arc-welding-like arcing occurs increasing the ambient temperature.

In the test configuration 3 at Kakuda, no trace of arcing was confirmed. This was very likely that establishing a short circuit path between the cell case and the ground through the battery box was unable as the ground wire of the battery box was not connected.

3.7.5 Fused Ground Wire

As described in the section 2.11.5 b. and the Figure 11-1: Fluctuations of Cell Voltage and Ground Wire Current" in the Appendix 2, it is very likely that around the time when cell 7 vented, internal short circuit in the cell, caused by heat propagation from cell 6, increased its internal pressure causing the case to swell. Swollen cell 7 very likely pushed the brace bar towards cell 6, reestablishing short circuit path allowing high currents to run through the ground wire. The timing of the contact coincided with 1,630 A of currents through the wire just after cell 7 venting. The next high current jump to 1,010 A coincided with bursts of flames preceded by sputtering sound. This demonstrates that the ground wire fused at the timing of the second current jump.

As the ground wire used in the test was not identical with the airplane ground wire in terms of length and material—different electric resistance. Because the current value at which the wire was fused is an acceptable value considering the wire resistance, the test probably simulated the high currents which fuse the wire in the serious incident.

3.7.6 Differed Results between Test Configurations 2 and 3

The Kakuda test demonstrated clear difference in heat propagation between configurations 2 and 3.

The tests in configurations 1 and 2 resulted in arcing while that in configuration 3 did not.

Erratic cell case-to-brace bar contacts or cell case-to-battery box result in arcing generating arc welding-like phenomenon. Erratic arcing radiates heat and the cell temperature probably becomes higher than that of cell heat generation. The possible major reasons why configurations 1 and 2 demonstrated heat propagation while the configuration 3 did not are as follows:

- With the ground wire connected, it allows high currents to run through in case of short circuit between the cell case and brace bar (battery box) resulting in arcing;
- Without the ground wire, high currents result in no arcing.

3.8 Main Battery Thermal Runaway Scenario

3.8.1 Sequence of Venting

a. The order of venting based on the CT scan image

Prior to the opening of the safety valve, pressure within a venting cell causes it to swell and sides of neighboring cells are pushed in. As described in the section 2.6.5.2, venting occurs when internal cell pressure reaches certain threshold. Once the safety valve has been opened, the internal pressure is released and the cell case loses the stiffness that resulted from the internal pressure. When a neighboring cell swells, it pushes into the first cell deforming its side. Judging from the deformation observed in the CT scan image in Fig. 2.8.3-3: CT scan Image, the cell that vented first was either cell 3 or cell 6, and the order of venting for other cells are as follows:

Cell 3 venting was followed by cell 2 and then cell 1

Cell 6 venting was followed by cell 7 and then cell 8

b. Initiating cell

As described in the section above, either cell 3 or cell 6 was very likely the venting initiator.

The FDR battery voltage fluctuation depicted in Figure 3 illustrates that the voltage dropped from 29 V to 14 V in 2 sec, followed by another drop to 11 V in 2 sec. The actual main battery voltage at the time when FDR recorded main battery voltage as 11 V was very likely less than 11 V as described in section 3.6. The possible causes for voltage drop are as follows:

(1) Contactor behavior after venting

As described in section 3.7.2, irregular contactor opening was observed after venting. Contactor opening disrupts physical and electric connection so that voltage instantaneously drops to 0 V.

Irregular contactor opening occurs sometime within a few seconds or several tens of seconds after the cell venting.

(2) Short circuit between cell case and battery box

As described in section 3.7.3, the short circuit with the brace bar (battery box) may have caused the vented cell's potential to drop to the ground potential resulting in a battery voltage drop.

In the case of short circuit between the cell case and brace bar, if the vent initiator were cell 3, recorded battery voltage would be 20 V (total voltage of cell 4 through cell 8); if the initiator were cell 6, battery voltage be 8 V (total voltage of cell 7 and 8). Judging from the description in section 3.6, the actual main battery voltage was less than 11 V, the initiator cell was very likely cell 6.

Another reasoning for cell 6 as the initiator. As the welded brace bar to cell 6 in configurations 2 and 3, Kakuda testing shows if cell 6 vents first, swollen cell 6 makes contacts with the brace bar leading to short circuits. As the contacts are erratic, arcing between cell 6 S1 and the brace bar was big and this does not contradict the cell 6 damage. Furthermore, cell 6-to-brace-bar welding at Kakuda testing very closely resembles that of the serious incident. This fact also supports the theory that the initiating cell was cell 6.

3.8.2 Contactor Opening

The assumption that the cell-case-to-battery-box short circuit had continued during the period of FDR voltage of 11 V as stated in section 3.8.1, contradicts the continued short circuit as the ground wire fuses instantly.

As cell venting is accompanied by irregular contactor opening with high probability as described in section 3.7.2, it is very likely that the main battery experienced similar contactor opening.

3.8.3 Scenario of Main Battery Failure

The JTSB's battery failure scenario with the help of Boeing's event scenario described in section 2.11.6.7 (Battery voltage in this section derives from FDR records.) is as follows:

a. Event A

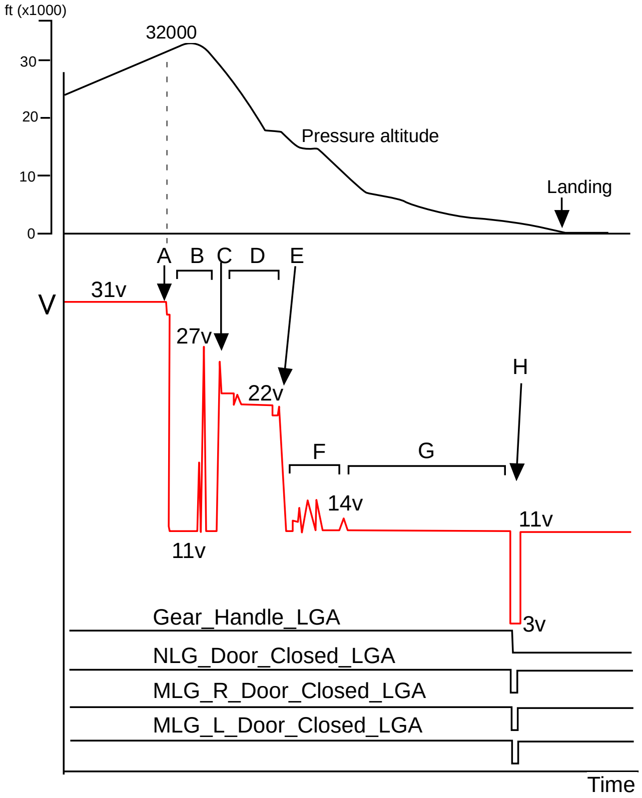


Fig. 3.8.3-1: Battery Voltage Fluctuation during Takamatsu Event

Main battery voltage dropped from 31 V to 30 V. It is very likely that a cell experienced an internal short circuit (see section 3.10) which resulted in rapid cell heating and case swelling and subsequent venting during this drop. As described in section 3.8.1 b., cell 6 was the very likely cell as the initiator. Plastic insertions around cell 6 melted due to cell heat generation.

Then, the main battery voltage dropped to 14 V after being recorded as 29 V. This voltage drop was the result of possible contactor opening or probable cell-case-to-battery-box short circuit as stated in section 3.8.1 b.

b. Event B

During the period while the main battery voltage was 11 V, contactor opening and/or cell 6-to-battery-box short circuit was probably in progress as described in section 3.8.2.

Battery voltage jump to 20 V was probably caused by the temporary cell case separation from the brace bar. The following voltage jump to 27 V suggests that cell 6 was the sole vented cell then. Another voltage drop to 11 V was probably caused by the contactor opening or recurrence of short circuit between cell 6 and the brace bar.

c. Event C

Recorded 26 V implies possibility of contactor closing and a short circuit of the second cell. The voltage drop to 23 V suggests the possibility of the venting of the second cell. Cell 5 was not vented as described in section 2.8.3 e and Kakuda testing demonstrated that the second venting cell was the cell located next to the S1 or S3 of the venting cell. In light of these facts, the second vented cell was probably cell 7.

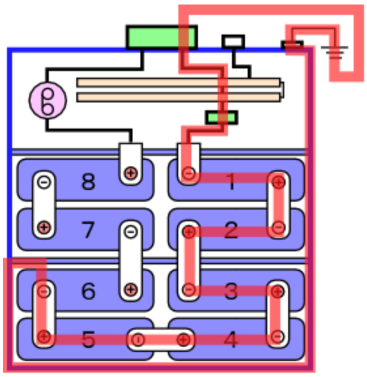


Fig. 3.8.3-2: Short Circuit Path

d. Event D

Voltage drop from 23 V to 21 V was probably caused by draining of charged energy of cell 1 through cell 5 for arcing when cell-to-cell or cell-to -battery box short circuit occurred.

Cell 3 venting and short circuit between the cases of cell 3 and cell 6 thereafter probably resulted in arcing and their welding (see section 3.8.3.1). Welded cell 3 and cell 6 probably generated a closed circuit path through cells 3, 4, 5, and 6, draining more energy from cell 4 and cell 5.

Melted gasket at positive terminal of cell 3 allowed arcing between the cell 3-to-cell 4 busbar and cell 3 positive terminal, draining all the energy of the two cells.

It is probable that cells 4 and 5 did not vent because their energy was all drained.

e. Event E

Voltage dropped from 22 V to 11 V. This was probably caused by another contactor opening or short circuit between cell 6 and the brace bar.

f. Event F

Voltage fluctuation was probably caused by short circuit among cells or associated arcing.

g. Event G

Battery voltage remained at 11 V. As described in section 3.6 and as Boeing explains, the discrepant circuit card assembly on the airplane was responsible for the sneak voltage of 11 V.

h. Event H

As Boeing explains, battery voltage very likely dropped to 3 V as wheel well door lights illuminated.

3.8.3.1 Scenario for Welding of Cells 3 and 6

Heat radiation from arcing associated with cell 6 to brace bar probably melted separators within cell 7 and cell 3 eventually leading to internal short and venting. It is probable that swollen cell 3 touched cell 6 S2, induced arcing and consequently welded them together.

Welded cell 3 and cell 6 allowed a closed short circuit path to form with cell 4 and 5. It is probable that the resin gasket below cell 3 positive terminal melted due to radiated heat creating a gap between the positive terminal plate and busbar, causing opening and closing of live terminals which lead to arc-welding-like arcing and consequently melted cell 3 positive terminal, cell header around the positive terminal, fixing bolt and the busbar itself.

3.9 Phenomena Observed during Charging/Discharging

3.9.1 Fluctuation of Charging Currents

As described in sections 2.11.3, 2.11.4 and 2.11.6.1, cell balancing test, on-board test and battery-BCU test exhibited small oscillation of charging currents. Although the amplitude of fluctuations is fairly small compared to the battery capacity, it is desirable that their negative characteristics—repeated shallow charging and discharging, unnecessary fluctuation, possible negative impact on battery life—should be improved.

3.9.2 Phenomenon of High Transient Voltage during Discharging

As described in section 2.11.6.1, in the test simulating a nominal APU start with engines running (battery output current 20 A), each cell and battery registered a high transient voltage. Approx. 1 sec after the contactor BIT criteria was met, current interruption occurred for 22 msec instantaneously followed by the high transient voltage. Judging from the occurrence, BIT function of the BMU is probably responsible for the phenomenon described in section 2.6.5.3. f.

During the on-board test, a momentary voltage drop to 0 V was observed during a discharge of approximately 60 A. As this phenomenon was observed approximately 1 sec after the charging current dropped below a set threshold, accompanied by a current interruption of approximately 23 msec, contactor BIT function of the BMU is probably responsible for the phenomenon.

Given the fact that contactor BIT runs during the discharging phase, actual airplanes possibly experience high transient voltage applied to each cell.

3.9.3 Phenomenon of Voltage Spike during Charging

As described in section 2.11.4.b, during the on-board test, a voltage spike up to approximately 45 V was observed during 46 A charging. As the spike was observed approximately 1 sec after the charging currents went below the set threshold and the charging currents were interrupted for approximately 25 msec. BMU’s contactor BIT function is probably responsible for the phenomenon.

BMU’s contactor BIT operation is not intended in the original design philosophy—the BIT should not run while the charging current is high, but at the last phase of charging operation where charging current is less than the set threshold to avoid high voltage transient which is associated with the contactor opening. Therefore, it is desirable that the phenomenon should be improved.

3.10 Cause of Heat Generation

As described in section 2.7.2, conceivable major causes for battery heat generation are overcharging, over-discharging, external short circuit, cell case short circuit, and internal short circuit. Possibility of each cause is analyzed as follows:

a. Overcharging

Overcharging accompanies voltage increase; however, the FDR records showed no increase of the main battery voltage. This fact demonstrates the absence of overcharging at battery level.

Overcharging derived from imbalanced cells would leave traces of fire damage around the battery box as described in the section 2.12.7.4 b.; however, there was no trace of fire damage around the main battery as described in section 2.8.3, it is very likely that cell-level overcharging deriving from cell imbalance is very unlikely.

b. Over-discharging

Over-discharging accompanies voltage decrease; however, the FDR records in Figure 2 showed no main battery voltage decrease. This fact demonstrates the absence of over-discharging at battery level.

c. External short circuit

As described in section 2.12.7.3 a., when exterior circuit resistance of the battery is very small, a short circuit allows several thousand amps of current to run through the circuit fusing aluminum cell current collectors, leaving no battery exterior damage. When the exterior circuit resistance is high as described in section 2.12.7.3 b, the J3 cable connector suffers damage. But none of the airplane J3 connector, J1 cable, or J3 cable exhibited damage as described in section 2.8.3. These facts demonstrate small possibility of external short circuit.

d. Short circuit of cell case

As described in 2.11.6. 2 and 2.11.6.9 a., cell-case-to-ground direct shorting or that via saline solution can lead to a cell venting. According to the EX Report, short circuit between cell case and battery box is associated with distinctive damage; however, the incident battery did not have such damage. This fact indicates that the possibility of cell case short is low.

e. Internal short circuit

As possibilities of above mentioned causes for heat generation are low, it is possible that the cause of battery heat generation was internal short circuit.

3.11 Causes for Internal Short Circuit

As concluded in section 3.10, internal short circuit is a likely cause for cell heat generation. The JTSB analyzed possibilities for major causes stated in section 2.7.2 e.

3.11.1 Foreign Object in a Cell

As stated in sections 2.11.6.9 b, and 2.13.2.b, small copper pieces were found in two cells.

Against these facts, GYT maintains that the possibility of foreign object's cell contamination during manufacturing, which contributes to internal short circuit is low, because:

- Cells are manufactured in environmentally controlled clean rooms (Section 2.13.1.3 a.);
- Cells are subjected to internal short circuit test (Section 2.13.1.3.b.);
- Cells are subjected to soft short test and CT scanning (Section 2.13.1.3 b.); and
- Safety records proved by other-than-aviation purpose cells which share the identical cell ingredients and manufacturing processes (Section 2.13.1.1).
- Metal particles migrated in a cell during DPA (2.13.2.b)

However, metal pieces were found not from a single cell but from two cells. As stated in section 2.11.6.9 b, Ex Report states that the possible cause of metal FOD derives from cell manufacturing. Given these facts, it may be impossible to deny the possibility of metal FOD.

3.11.2 Separator Damage

Possible separator damage is caused by crack, melting and shrinking. Cracks can be caused from tensile stress during winding rolling and generated during charging and discharging.

a. Crack during manufacturing

This type of crack would be probably detected by inspection during and after manufacturing. In addition, as described in section 2.13.1.1, GYT maintains that it has received no reports of anomalies for the large-sized multi-purpose batteries manufactured using the same cell ingredients and manufacturing methods. These facts suggest the low possibility of separator damage during manufacturing.

b. Crack during charging and discharging

As described in 2.11.6.9 c, there was a case where agglomerates were discovered, whose diameter was larger than that of normal positive material. This may not be an ideal condition for active material; however, the possibility of separator damage triggered by an agglomerate whose size is less than thickness of active material layer is probably low.

c. Melting and shrinking by heat

One possible factor is external heat transferred to cell interior causing separator shrinkage. As described in 2.11.7.1, the simulated APU start test done by the NTSB confirmed the phenomenon of increased rivet temperature. It is possible that increased resistance at cell terminals cause increased Joule heat ($=I^2 \times R$) which is transferred via current collectors, and the heat subsequently causes separator shrinkage leading to an internal short circuit.

However, the battery involved in the serious incident was the main battery. As stated in section 2.6.3, its maximum discharging currents are around one sixth of that of the APU battery. Given this fact, it is unlikely that serious incident main battery experienced increased rivet temperature.

3.11.3 Lithium Metal Deposition

a. Effects of low-temperature environment

In the serious incident, the battery suffered severe heat damage making it impossible to analyze microscopic structure of the cells. In light of the fact that all similar incidents occurred in cold season, it is probably difficult to deny the effects of cold conditions on internal short circuit.

Airplane interior temperature during overnight stay varies depending on outside temperatures. Therefore, the LIBs were very likely exposed to low temperatures during winter overnight stay. Upon the airplane power-up, EE bay temperature rises in short time, but cell core temperature does not reach EE bay temperature in short time. There is also a possibility that battery surface temperature was near zero during flight operations as described in section 2.13.2 b. Given these two facts, it is possible that repeated irregular charging and discharging were conducted with low cell core temperatures during the cold season, which derived from service destinations and accompanying routes.

b. Flexural deformation and wrinkles on anode

A flattened anode roll exhibited flexural deformations (see section 2.13.1.1 b), while another battery withdrawn from another 787 exhibited the same deformations (see sections 2.11.2.b and 2.13.2 b). EX Report includes a discovery of gaps in the electrodes.

As described in section 2.7.4, non-uniform winding formation such as flexural deformation and wrinkles may produce non-uniform distance between the electrodes and localized charging currents concentration leads to accelerated lithium metal deposition.

Battery charging and discharging or cell manufacturing process is possible contributing factor for wrinkle formation.

c. Degradation of cell interior

As the serious incident battery was on board the airplane for about three months as described in section 2.5.1, the possibility of cell interior degradation associated with service duration was probably remote.

However, as described in section 3.9.1, the BCU exhibited small oscillation of charging currents which deemed to pose negative effects on battery life. This suggests that the current fluctuation degrades cell interior causing anode active materials to become non-uniform eventually affecting the cell performance.

d. Lithium metal deposition in the serious incident main battery

As described in sections 2.11.7.2 and 2.11.8.1, the NTSB and GYT performed testing to identify lithium metal deposition.

The NTSB testing observed the deposition which has lithium metal features; however, deposit ingredients were not definitively verified and lithium metal was not identified. This is because of lithium's high reactive character which evades its detection and possible detection methods have limitations.

GYT maintains that its testing did not identify the presence of lithium metal.

e. Lithium metal deposition in the serious incident main battery

Lithium metal was not identified in the testing. But as the following findings are confirmed as described in above a., b., and c., lithium metal had probably deposited in the serious incident main battery.

- Effects of low temperature environment on charging.
- Wrinkles discovered on anode in the same type LIB.
- Possibility of non-uniform anode active material due to degraded anode active material.

f. Possibility of internal short circuit caused by lithium metal deposition

The serious incident main battery had possible lithium meal deposition as described in above sub-section e. However, if the main battery was used under proper conditions, internal short circuit deriving solely from lithium metal deposition is very unlikely (see section 2.7.4).

However, as stated in sections 3.9.1 and 3.9.2, fluctuating charging currents and transient peak voltage are observed on 787 battery system, it is possible that these electric transient or other factors combined may have affected the lithium metal deposition leading to an internal short circuit.

3.11.4 Summary of Internal Short Circuit Cause

From the analyses of internal short circuit stated in sections 3.11.1 through 3.11.3, we have three possible candidates for interior short circuit: lithium metal deposition in the cell, metal piece contamination, and damaged separator. Given the fact that all similar battery incidents occurred in January, during cold season, among three candidates, lithium metal deposition deriving from charging under cold conditions could have existed. However, it is unlikely that lithium metal deposition was the sole causal factor of the internal short circuit leading to venting. It is possible that these electric transient or other factors combined may have affected the lithium metal deposition leading to an internal short circuit.

Note that analyses in sections 3.11.1 through 3.11.3 only provide possible causes of internal short circuit, and as no mechanism of internal short circuit was conclusively identified, we cannot exclude the possible involvement of other factors associated with design and manufacturing.

3.12 Type Certificate

3.12.1 Applicability of Type Certificate

3.12.1.1 Issue Paper

As described in the section 2.12.4 a., the FAA noted safety problems with lithium-ion batteries, which included overcharging, over-discharging, and flammability of cell components. Among them failure mode includes overcharging and over-discharging. As described in section 2.11.6.8, the cause-effect diagram prepared by Boeing help renew failure modes which include external short circuit and internal short circuit other than overcharging and over-discharging. As described in section 2.11.5, Kakuda testing demonstrated a thermal runaway derived from internal short circuit. The FAA probably underestimated the risk of internal short circuit during special condition study. In light of this, it should have studied all the failure modes including external and internal short circuit.

3.12.1.2 Special Conditions 25-359-SC

The special conditions consist of nine conditions (see section 2.12.4.b). The second condition states "Design of the lithium-ion batteries must preclude the occurrence of self-sustaining, uncontrolled increases in temperature or pressure." Based on this condition and its interpretation, as described in section 2.12.6.2, the TC safety assessment allowed "battery vents smoke/fire," to have quantitative probability of less than 1 x 10^{-9} per flight hour, and "Battery vent and/or smoke (without fire)" quantitative probability of less than 1 x 10^{-7} per flight hour.

The Boston event preceded the serious incident by nine days. At the time of the serious incident, the global 787 fleet accumulated flight time of approximately 50,000 hr. This means the actual statistical probability for the event "Battery vent and/or smoke (without fire)" to become 4 x 10^{-5} per flight hour, well above the expected 1 x 10^{-7} per flight hour.

3.12.1.3 Probability of Cell Failure

As described in 2.12.6.4, according to the failure modes and effects analysis conducted for type certification, GYT established 787 LIB failure rate based on the industrial LIB cell failure record, which is similar in cell structure. However, at the time of the analysis, failure reports of the industrial LIB did not reach GYT, so that it established probability of cell failure based on zero failure counts and total operational duration, calculating MTBF using Poisson distribution.

The volume difference between the industrial battery cell and that of 787 battery was corrected using coefficient. For the calculation, confidence level of 60% was used. For general statistical analysis, confidence level of 95% or 99% is used; however, it is possible that the confidence level of 60% stated in Japanese Industrial Standards (JIS) C 5003 was used. It should be noted that the JIS standard applies to electronic parts which are continually manufactured based on substantially identical design under established quality control, and which ensure reasonable deduction of the probability of failure.

As described in section 2.12.6.4, GYT states that the active material ingredients for the large industrial battery cell and that of 787 battery are not identical. It is possible that calculation of probability of failure, based on performance records of the large industrial LIB whose occurrence conditions for overcharging, over-discharging, and internal short circuit are not proven to be equal to those for the 787 batteries, was inappropriate as a method for TC safety assessment.

On the other hand, JIS C 5003 stipulates the method of estimation for probability of failure using confidence level of 90%. The estimation using JIS method should have been calculated using widely used confidence level of 95% or JIS confidence level of 90%.

3.12.2 Handling of Internal Short Circuit Test

As described in section 2.12.7.1, GYT performed the internal short circuit test (by nail penetration) as part of the engineering tests during the battery developmental phase. The internal short circuit did not develop into a thermal runaway. Based on the test result and reliability analysis of cell that has similar design, Boeing concluded that internal short circuit would not lead to a thermal runaway and proposed the FAA that the internal short circuit test (by nail penetration) was unnecessary to be included for type certificate. The FAA accepted the proposal and the internal short circuit test was not included in the certification plan.

The nail penetration test was performed without connecting following cables and wire to the battery: J3 cable which connects the battery and loads, J1 cable which transmits signals from BMU, BCU or BPCU, and a battery box ground wire. The test did not simulate the actual on-board configuration as the ground wire was not connected.

Kakuda tests conducted in configurations 1 and 2, which simulated actual on-board configuration, replicated thermal runaways. In the test of configuration 1, the battery burst into flames moments after the nail penetration. Video analysis confirmed that the insufficient electrical insulation between the nail and the test platform was responsible for sparking which lead to flames. In the test of configuration 2, the battery burst into flames right after the second cell vented presumably due to sparks caused by overheat and fusing of the ground wire. In both tests, the ignition source was related to test setup which included equipment that was not installed on an actual airplane.

However, thermal propagation from the nail-penetrated cell to the next cell was observed before flames started to blow. In general a battery with high temperature has larger thermal energy. In terms of a total energy stored in a battery, a high temperature battery has larger energy if stored capacity is the same. Therefore, even if the test of configuration 1 had been conducted without bursting flames, thermal propagation could have occurred.

The test of configuration 3, in terms of the test configuration, was the same as the engineering test done by GYT during developmental phase, which did not develop into a thermal propagation.

Battery DPA for test configurations 1 and 2 confirmed that both S1s of nail-penetrated cell 6s were welded to the brace bar. Arcing was very likely responsible for the welding, and the test of configuration 3 demonstrated that a battery without a ground wire did not produce this type of damage.

As the engineering test during the developmental phase was performed without connecting the ground wire to the battery box, it is very likely that no arcing occurred resulting in thermal propagation.

These facts show that it is inappropriate to exclude the internal short circuit from the safety assessment based on the test result which was done not simulating the actual airplane configuration.

It is very likely that, in retrospect, the general rule, that testing of airplane systems must be conducted simulating actual operations, was not applied to the certification test.

3.12.3 Latest LIB Airworthiness Standards (TSO-179a/RTCA DO-311)

As described in section 2.12.8, the latest version of LIB airworthiness standards is TSO-179a, and its minimum operational performance standards refer to RTCA DO-311 as specific standards.

However, RTCA DO-311 does not stipulate test procedures to properly simulate internal short circuit. Even if TSO-179a/ RTCA DO-311 had been applied to 787 LIB certification standards, it would not be certain whether internal short circuit tests could have been conducted properly simulating the internal short circuit under on-board environment. RTCA DO-311 should be amended to mandate internal short circuit tests simulating proper on-board environment.

4 CONCLUSIONS

4.1 Findings

The analysis on the main battery failure is summarized as follows. (For the details, see the section enclosed in parentheses at the end of each section.)

a. Influence of meteorological conditions

We cannot disregard the fact that all battery incidents (the serious incident inclusive) occurred in winter. Therefore, at present low temperature environment was the possible contributing factor to the battery failure.

(Section 3.3)

b. Analysis of Kakuda testing

(1) Irregular contactor opening upon venting

Tests exhibited contactor openings under non-overcharging conditions. (Section 3.7.2)

(2) Post-vent short circuit between cell case and battery box

In the test of configuration 2, approximately 1,000 A of ground wire currents were recorded approximately 30 seconds after the cell 6 venting. This indicates that the concurrent physical contact between the swollen cell 6 and the brace bar occurred at the cell vent timing. The short circuit with the battery box very likely caused both terminals of cell 6 to have equated electric potential with the ground. (Section 3.7.3)

(3) Arcing

The test of configuration 2 demonstrated fused spots between cell 6 case and the brace bar, which was caused by arcing. Given the fact that large currents run through the ground wire, it is very likely that erratic arcing between cell 6 and the brace bar was similar to arc-welding.

(Section 3.7.4)

(4) Fused ground wire

The ground wire very likely fused open when high currents of 1,010 A ran after cell 7 vented. (Section 3.7.5)

(5) Differed results between Kakuda test configurations 2 and 3

The possible major reason why the test of configuration 2 demonstrated heat propagation while that of configuration 3 did not is as follows: With the ground wire connected, it allows high currents to run through in case of short circuit between the cell case and brace bar (battery box) resulting in arcing; without the ground wire, high currents result in no arcing.

(Section 3.7.6)

c. Scenario of main battery failure

(1) Judging from the deformation observed in the CT scan image, the cell vented first was very likely either cell 3 or cell6. Judging from FDR main battery voltage value, Kakuda test results, and the battery damage, the initiating cell was very likely cell 6.

(Section3.8.1)

(2) As it is confirmed that high probability of contactor opening is associated with a cell venting, it is very likely that the main battery experienced similar contactor opening. (Section 3.8.2)

d. Phenomenon observed during charging/discharging

(1) Fluctuated charging currents

Although the amplitude of fluctuated charging current identified in the on-board test is fairly small in light of battery capacity, it is desirable that their negative characteristics—repeated shallow charging and discharging, unnecessary fluctuation, and possible negative impact on battery life—should be improved. (Section 3.9.1)

(2) Phenomenon of high transient voltage during discharging

Tests conducted by Boeing revealed that BIT operation during discharge is accompanied with high transient voltage applied to each cell. On-board test also confirmed the same contactor BIT. With these facts, it is possible that the serious incident airplane experienced high transient voltage applied to each cell.
(Section 3.9.2)

e. Causes of heat generation

Possible major causes for battery heat generation are overcharging, over-discharging, external short circuit, cell case short circuit, and internal short circuit. The FDR records and battery damage suggest that the possible cause of battery heat generation is, among other things, internal short circuit. (Section 3.10)

f. Causes of internal short circuit

(1) Metal object in a cell

The discovery of metal pieces in two cells probably makes it difficult to completely deny the metal contamination.
(Section 3.11.1)

(2) Separator damage

Possible separator damage is caused by cracks generated by tensile stress when a set of winding is rolled and by charging and discharging, and heat-driven melting and shrinkage. In regard to the heat-driven separator melting and shrinkage, as the heat generation in the serious incident occurred in the main battery, the possibility of resistive heating leading to heat generation which consequently results in separator melting and shrinkage is low. (Section 3.11.2)

(3) Lithium metal deposition

(a) Effects of low-temperature conditions

The fact that all similar incidents occurred in cold season, it is probably difficult to deny the effects of cold conditions on internal short circuit.

It is possible that repeated irregular charging and discharging were conducted with low cell core

temperatures during the cold season, which derived from service destinations and accompanying routes.
(Section 3.11.3 a.)

(b) Flexural deformation and wrinkles on the anode

There are possibilities that non-uniform winding formation such as flexural deformations and wrinkles produced non-uniform distance between the electrodes accelerating lithium metal deposition.

It is also possible that battery charging and discharging or cell manufacturing process is responsible for wrinkle formation. (Section 3.11.3 b.)

(c) Degradation of cell interior

In the case of the serious incident main battery, the possibility of cell interior degradation associated with service duration may be remote.

However, the small fluctuations of BCU charging currents which deemed to pose negative effects on battery life indicates that it degraded cell interior, lead to non-uniformity of anode active material, and affected the battery performance. (Section 3.11.3 c.)

(d) Lithium metal deposition in the serious incident main battery

Although lithium metal was not identified in the testing, the following findings suggest that the lithium metal had probably deposited in the serious incident main battery:

- Effects of cold temperature environment on charging.
- Wrinkles discovered on anode in the same type LIB.
- Possibility of non-uniform anode active material due to degraded anode active material.

(Section 3.11.3 e)

(e) Possibility of internal short circuit caused by lithium metal deposition

If an LIB is used under proper conditions, internal short circuit deriving solely from lithium metal deposition is very unlikely.

The fluctuating charging currents and high transient voltage are observed on 787 battery system, it is possible that these electric transient or other factors combined may have affected the lithium metal deposition leading to an internal short circuit. (Section 3.11.3. f.)

(4) Cause of internal short circuit

From the analyses of internal short circuit, three possible candidates for interior short circuit remain: lithium metal deposition in the cell, metal piece contamination, and damaged separator. Given the fact that all similar battery incidents occurred in the cold season, lithium metal deposition deriving from charging under cold conditions could have existed. However, it is unlikely that lithium metal deposition was the sole causal factor of the internal short circuit leading to venting. It is possible that electric transient or other factors combined may have affected the lithium metal deposition leading to an internal short circuit.

As no mechanism of internal short circuit was conclusively identified, we are unable to exclude the possible involvement of other factors associated with design and manufacturing. (Section 3.11.4)

g. Type certificate

(1) Applicability of type certificate

(a) Issue paper

The FAA noted safety problems with lithium-ion batteries, which only included overcharging, over-discharging, and flammability of cell components. The FAA probably underestimated the risk of internal short circuit during special condition study. (Section 3.12.1.1)

(b) Special conditions 25-359-SC

At the time of the serious incident, the global 787 fleet accumulated flight time of approximately 50,000 hr. This meant the actual statistical probability for the event "Battery vent and/or smoke (without fire)" to become 4 x 10^{-5} per flight hour, well above the estimated 1 x 10^{-7} per flight hour. (Section 3.12.1.2)

(c) Probability of cell failure

The cell failure rate was calculated based on the industrial LIB cell failure record, whose cell ingredients are different from the 787 batteries. For the calculation, expected confidence level was 60%. For general statistical analysis, confidence level of 95% or 99% is used; however, confidence level 60% that is stipulated in JIS C 5003 was possibly used. (Section 3.12.1.3)

(2) Handling of internal short circuit test

Kakuda tests, which simulated actual on-board configuration, replicated thermal runaways. The internal short circuit test conducted by GYT during developmental phase not simulating the actual on-board configuration did not develop into a thermal runaway.

It was inappropriate to exclude the internal short circuit from the TC tests based on the test which was conducted not simulating the actual airplane configuration. (Section 3.12.2)

(3) Latest LIB airworthiness standards (TSO-179a/RTCA DO-311)

RTCA/DO-311, which is referred to by the latest version of LIB airworthiness standard TSO-179a, does not stipulate test procedures to properly simulate internal short circuit. It should be amended to mandate internal short circuit tests simulating proper on-board environment. (Section 3.12.3)

4.2 Probable Causes

The emergency evacuation was executed on Takamatsu Airport taxiway in the serious incident, which was a consequence of emergency landing deriving from the main battery thermal runaway during the airplane's takeoff climb.

Internal heat generation in cell 6 very likely developed into venting, making it the initiating cell, resulting in cell-to-cell propagation and subsequent failure of the main battery. It is very likely that cell 6 internal heat generation and increased internal pressure caused it to swell, melt the surrounding insulation material and contact the brace bar creating a grounding path that allowed high currents to flow through the battery box. The currents generated arcing internal to the battery that contributed to cell-to-cell propagation consequently destroying the battery.

Cell 6 heat generation was probably caused by internal short circuit; however, the conclusive mechanism thereof was not identified.

In the serious incident, the internal short circuit of a cell developed into cell heat generation, thermal propagation to other cells, and consequently damaged the whole battery. The possible contributing factors to the thermal propagation are that the test conducted during the developmental phase did not appropriately simulate the on-board configuration, and the effects of internal short circuit were underestimated.

5. SAFETY ACTIONS

5.1 Safety Actions Taken by Boeing and Approved by the FAA

5.1.1 Safety Actions Taken by Boeing

a. Elimination of potential cell failure causes

(1) Improved busbar fastening nuts

(2) Reduced electrical stress to electrolyte

- Improved cell insulation
- Increased insulation for the battery case bottom
- Improved cell-to-cell/cell-to-battery case isolation
- Increased insulation for the battery top cover
- Improved insulation for the brace bars
- New drain holes for the bottom fixation frame and the battery box against liquid condensation
- Reduced BCU output voltage
- Stabilized battery charging current

(3) Measures against over-discharging

- Improved BMU

(4) Improved manufacturing practice

- More rigid ATP
- Improved quality control

b. Measures against cell-to-cell propagation

(1) Improved cell-to-cell/cell-to-battery case isolation

(2) New drain holes for the bottom fixation frame

(3) Improved internal wiring against heat

(4) Installation of tubing for vented gas to escape overboard.

c. Measures against battery venting

(1) Installation of an enclosure box (A battery is electrically floating in this box, while the box is grounded to the CRN.)

(2) Installation of tubing for vented gas to escape overboard.

5.1.2 Effectiveness of the Safety Actions

As described in the section 2.13.2, b., JAL's 787 parked at Narita International Airport experienced a cell 5 venting while it was under preparation for the next flight.

The JCAB is investigating this event. So far it is known: one cell vented; there was no thermal propagation; electrolyte and other interior materials were trapped in the battery box; and no arcing between the cell case and the brace bar occurred. The vented gas was exhausted overboard through the dedicated tubing.

5.2 Safety Actions Taken by the FAA and JCAB

5.2.1 Safety Actions Taken by the FAA

On January 16, 2015 (Eastern Standard Time) the FAA issued the airworthiness directive (AD) 2013-02-51 ordering the battery system to be modified or other actions be taken in accordance with a method approved by the FAA before further flight. At this time the global 787 fleet accumulated total of about 51,000 flight hours.

On April 22, 2015, the FAA issued the AD 2013-08-12[11] on the battery system modifications, which allowed grounded 787s to become flyable upon finishing the necessary modifications.

5.2.2 Safety Actions Taken by the JCAB

The JCAB issued the airworthiness directive (Koku-ko-ki No. 92) based on the above mentioned FAA AD. It requested domestic 787 operators to take utmost measures for equipment inspection and maintenance, and pilot training while releasing safety information to customers. In response, the airlines took the additional measures listed below:

a. Flight test after the modification
b. Confirmation of battery safety
    - In-flight battery monitoring
    - Random inspection of the batteries in use
c. Familiarization flights by flight crew
d. Information release to the public

---

[11] The AD incorporated Boeing Service Bulletin B-787-81205-SB 500003-00, Issue 001, dated April 19, 2013.

6 SAFETY RECCOMMENDATIONS

6.1 Actions to be taken by the FAA

The internal short circuit test by nail penetration method under the simulated on-board configuration with the battery ground wire demonstrated a thermal runaway, while the test without the ground wire did not.

Given the facts and analyses of other tests combined, in the serious incident the very likely sequence of scenario for the main battery thermal runaway is as follows:

- Cell 6 was the initiator of the thermal propagation;
- Cell 6 and the brace bar contacted with each other allowing high currents to flow through the battery box to cause arcing; and
- Arcing bolstered the thermal propagation leading to the thermal runaway.

It is very likely that the engineering test conducted during the developmental phase did not develop into thermal runaway because the battery box was not grounded with the ground wire. This demonstrates that it was inappropriate to exclude the internal short circuit test from the safety assessment based on the test result which was not conducted simulating the actual airplane configuration.

There is a possibility that present standards for airplane LIB do not appropriately address the electric environment although they stipulate environmental conditions such as temperature, humidity, inertia, and so on. In addition, the FTA in the safety assessment provided to the JTSB lacked the assessment of the thermal propagation risk.

The probability of LIB vent with smoke was estimated to be less than one out of ten million flight hours in the type certification; however, in reality three events of cell heat generation have occurred in less than 250,000 flight hours, resulting in the rate far exceeding the estimate. The calculation of failure rate in the type certification, which was done based on the failure records of similar LIB, was probably inappropriate.

In addition, contactor opening not expected in the design is very likely associated with cell venting; therefore, the necessity for risk reassessment on the loss of all electric power should be examined.

The JTSB, in light of the serious incident investigation, makes the following safety recommendations that the Federal Aviation Administration of the United States of America should take the following mitigation actions.

The FAA should:

a. Provide instruction to airplane manufactures and equipment manufactures to perform equipment tests simulating actual flight operations.

b. Review the technical standards for LIB to ensure that the electric environment is appropriately simulated, and if necessary, amend the standards.

c. Review the LIB failure rate estimated during the 787 type certification, and if necessary, based on its result, review the LIB safety assessment.

d. Review the TC for its appropriateness on heat propagation risk.
e. Assess the impact of contactor opening after the cell vent on the flight operation and take appropriate actions, if necessary.

6.2 Measures to be Taken to Instruct The Boeing Company as a Designer and Manufacturer of the 787

Although this investigation could not conclusively identify the mechanism of the internal short circuit, low temperature during overnight stay possibly contributed to the internal short circuit as the three battery incidents (this serious incident inclusive) occurred in the midst of cold January and low temperature is said to be favorable for lithium metal deposition. In addition, there are reports of cell contamination deriving from manufacturing, which may be related to the cause of the battery event. Furthermore, this investigation found the unexpected BCU operation and contactor opening which are outside the design envelope in relation to the charging control.

In light of these facts, the Federal Aviation Administration should supervise Boeing to:

a. Continue the study of internal short circuit mechanism considering the effects of non-uniform winding formation and other factors deriving from manufacturing process; and continue efforts to improve LIB quality and its reliability, reviewing the LIB operational conditions, such as temperature.
b. Improve BCU and contactor operations which are not intended in the design envelop.

Figure 1: Estimated Flight Route

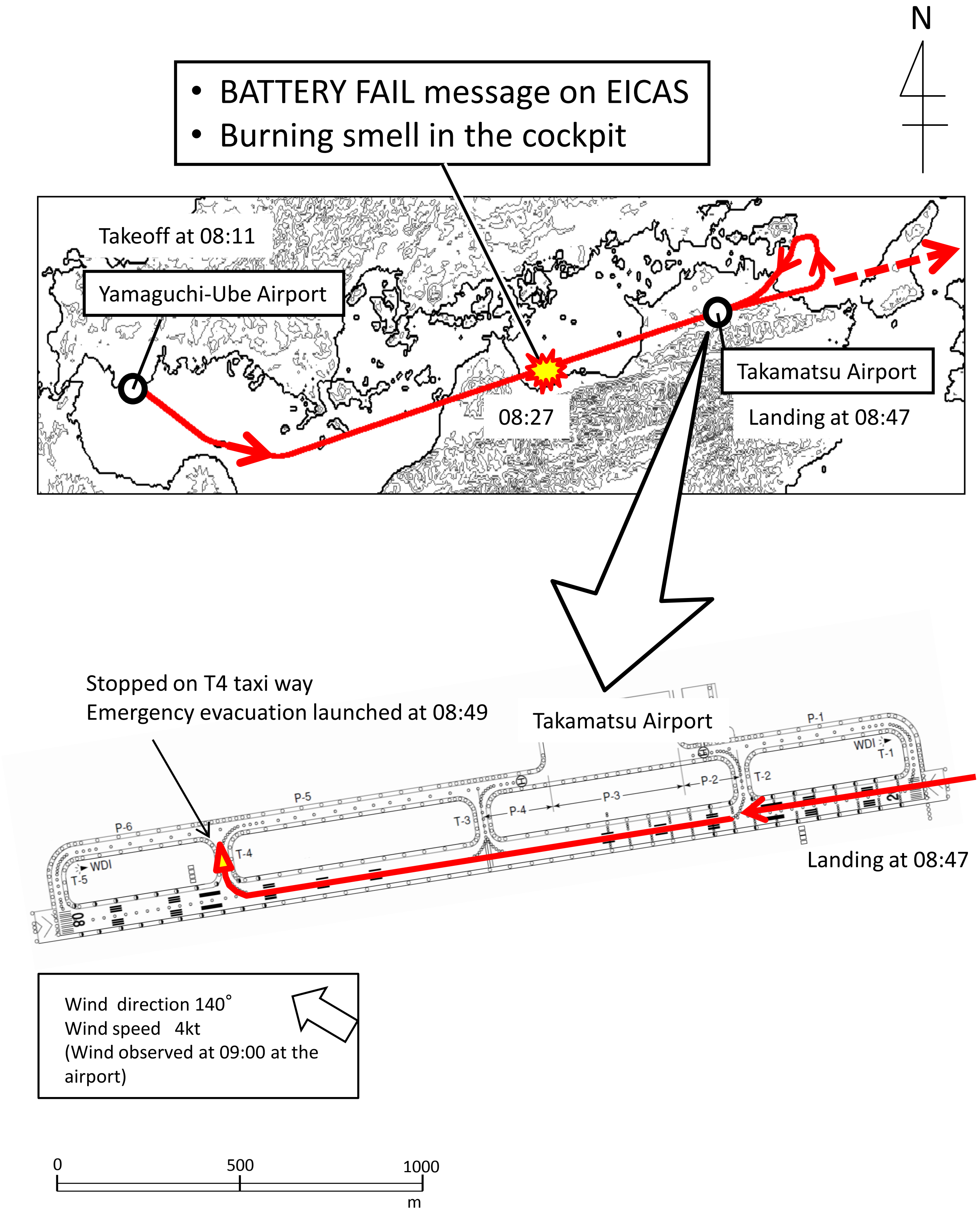


Figure 2: FDR Records

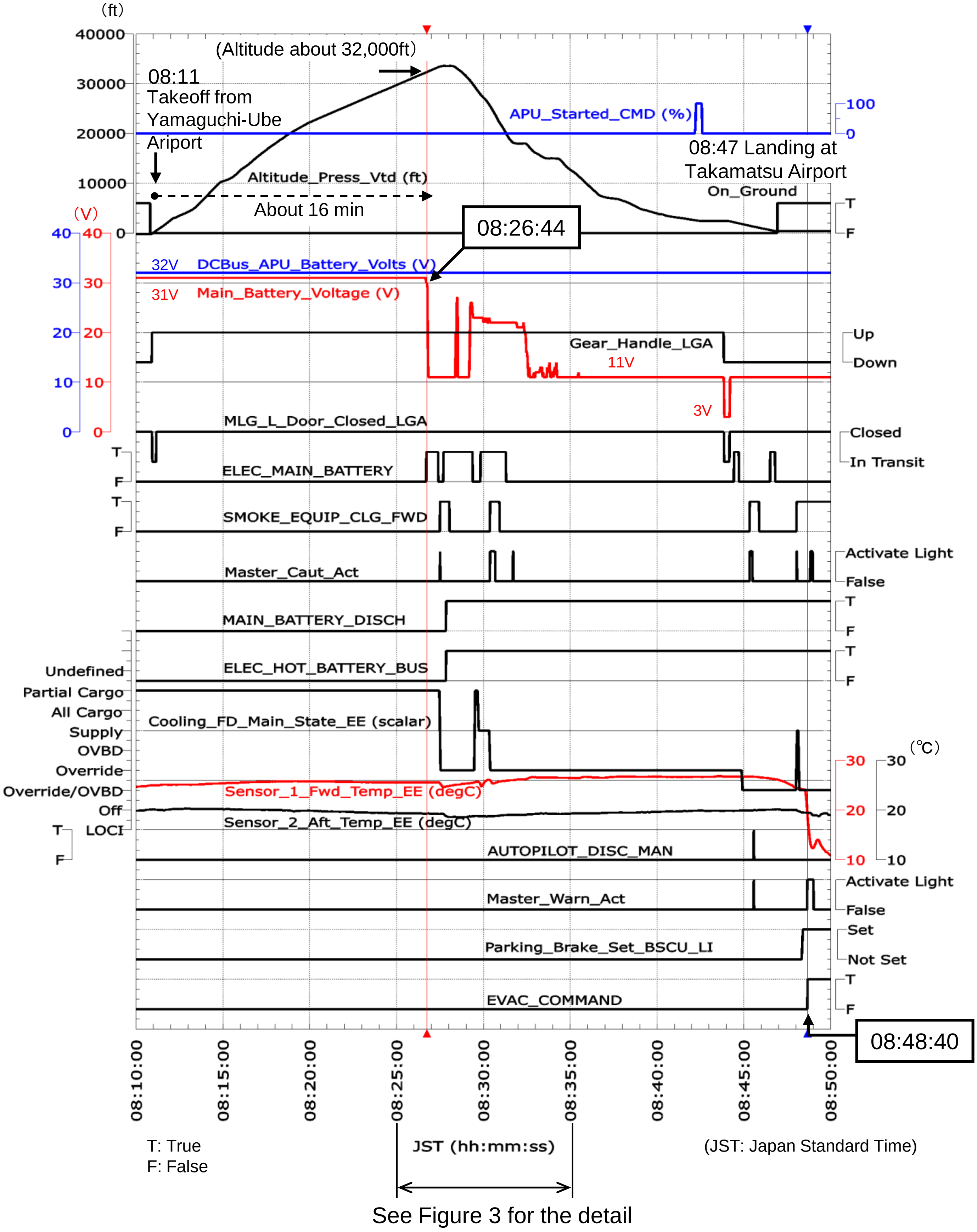
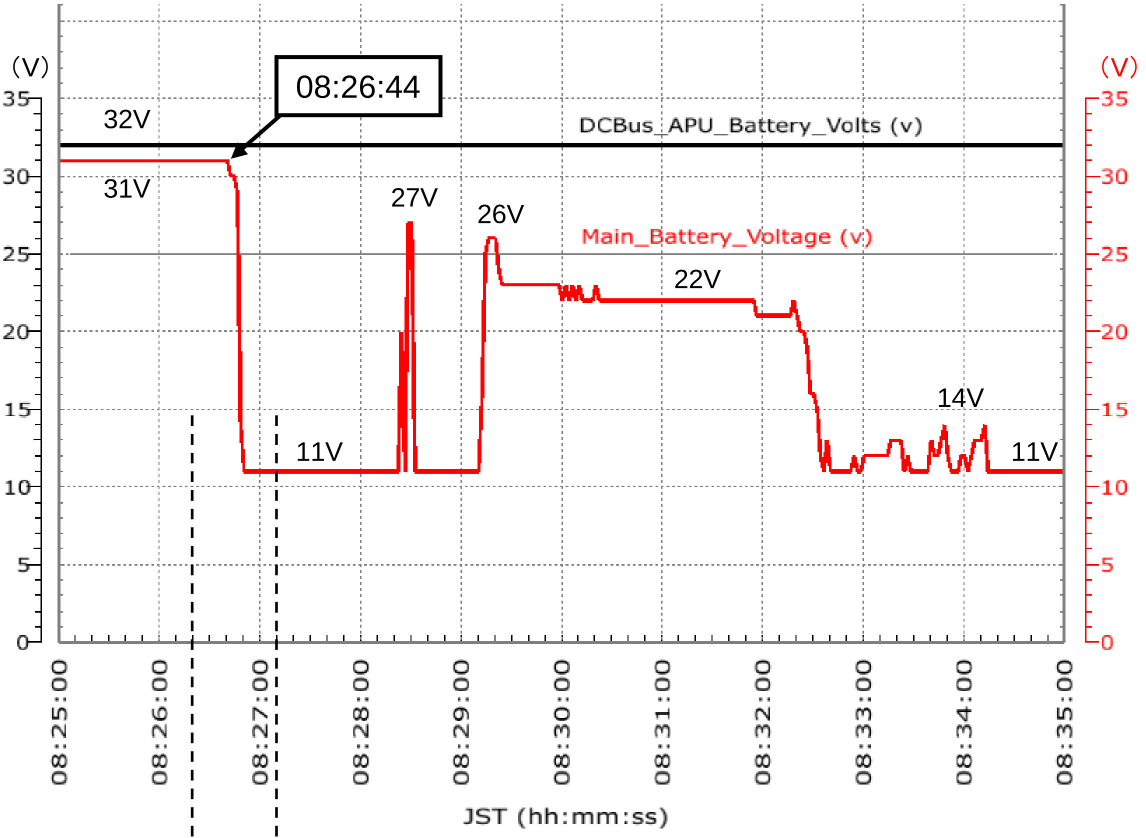
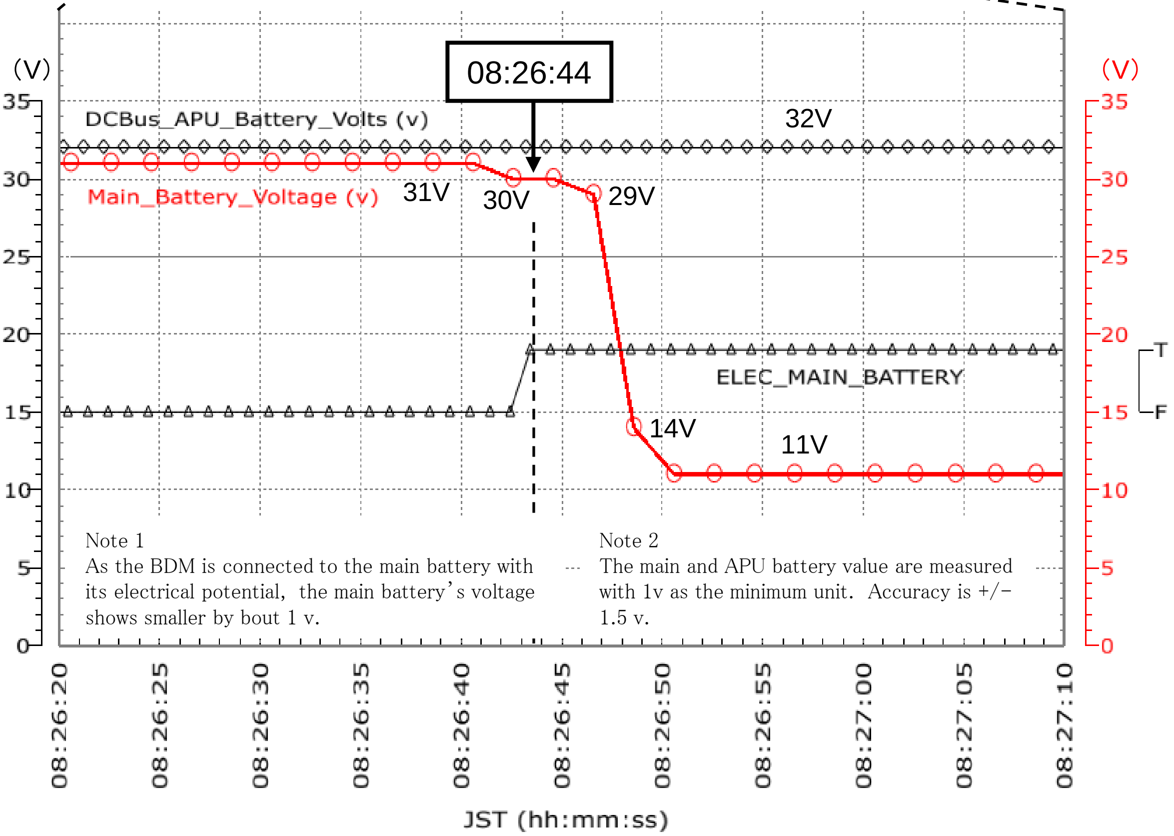


Figure 3: Battery Voltage Fluctuation



Blow-up

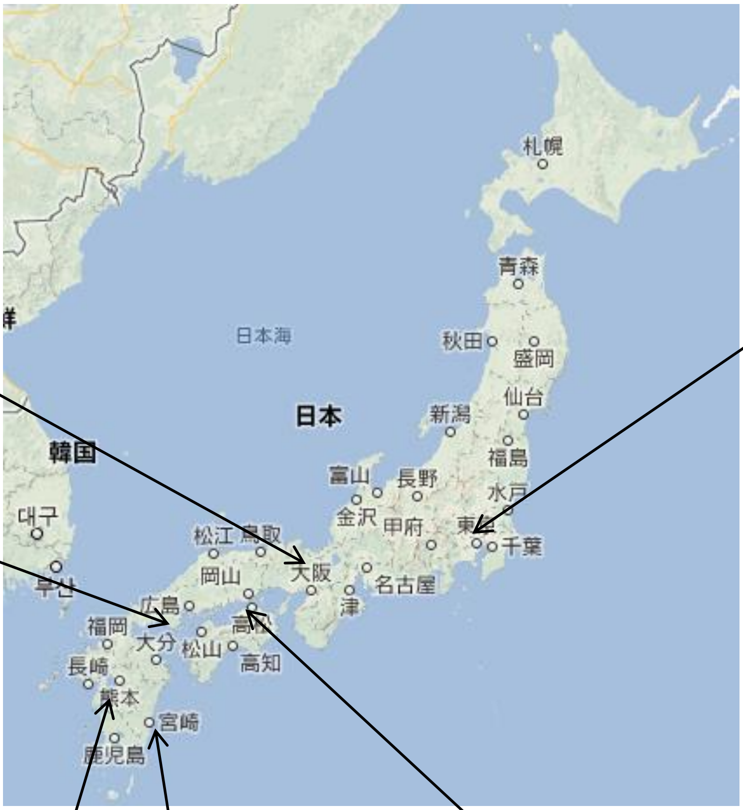


Note 1
As the BDM is connected to the main battery with its electrical potential, the main battery's voltage shows smaller by bout 1 v.

Note 2
The main and APU battery value are measured with 1v as the minimum unit. Accuracy is +/− 1.5 v.

Figure 4: Lowest Temperature at Overnight Stay Airport
（Dec. 1, 2012 – Jan. 15, 2013）

Unit: ℃



Osaka International Airport

Date	OAT
1/14	2.3

Yamaguchi-Ube Airport

Date	OAT
12/3	7.5
12/17	5.4
12/24	1.6
1/3	−1.0
1/9	1.3
1/13	3.8
1/15	−1.5

Kumamoto Airport

Date	OAT
12/14	11.0

Miyazaki Airport

Date	OAT
12/6	3.1
12/7	10.3
12/9	0.5
12/15	12.4
12/19	1.0
12/21	10.7
1/7	7.3
1/10	−2.1

Takamatsu Airport

Date	OAT
12/2	1.3
12/13	−0.4
12/22	3.7
12/23	−2.6
1/5	−0.8
1/12	−0.2

Tokyo International Airport

Date	OAT
12/1	3.7
12/4	4.6
12/5	9.3
12/8	3.4
12/10	0.5
12/11	1.4
12/12	2.6
12/16	6.8
12/18	4.7
12/20	1.6
12/25	3.1
12/26	0.8
12/27	0.3
12/28	3.7
12/29	6.3
12/30	7.6
12/31	2.9
1/1	4.8
1/2	5.3
1/4	1.5
1/6	3.2
1/8	5.1
1/11	0.6

Red letter : In hanger

Figure 5: Airplane Exterior

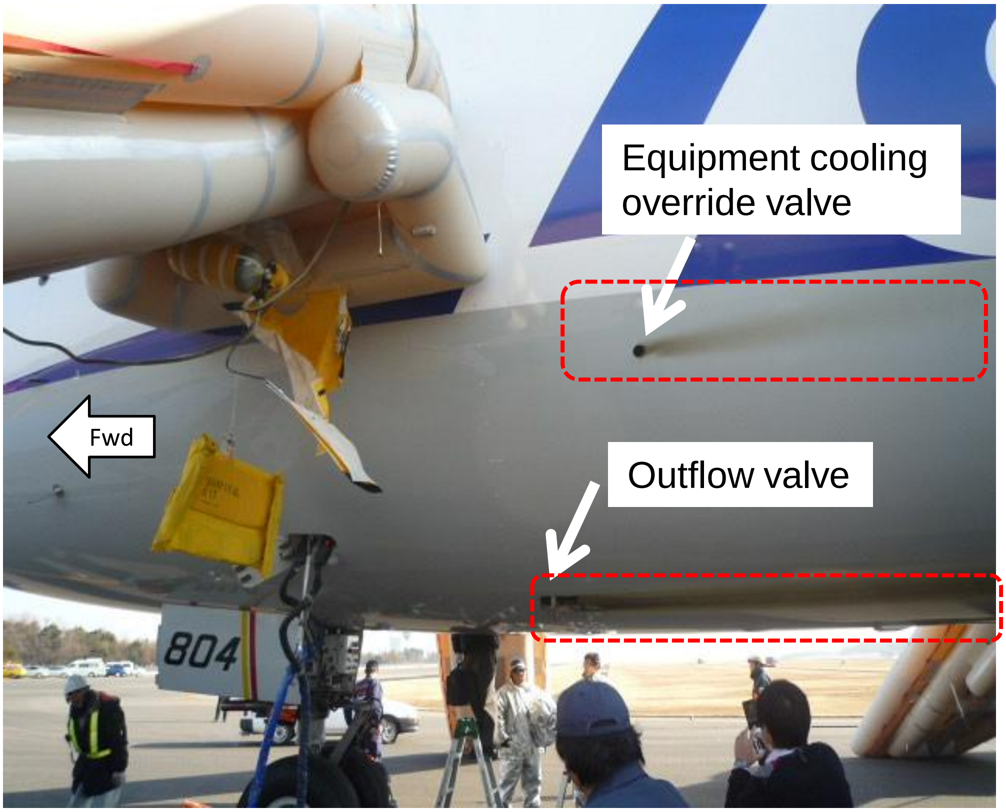


Figure 6: Main Battery

Exterior

Interior

Figure 7: Battery Top Surface

- Positive terminal of cell 3 was missing.
- The nut and washer remained.
- The busbar which connect s cells 3 and 4 was meltd.

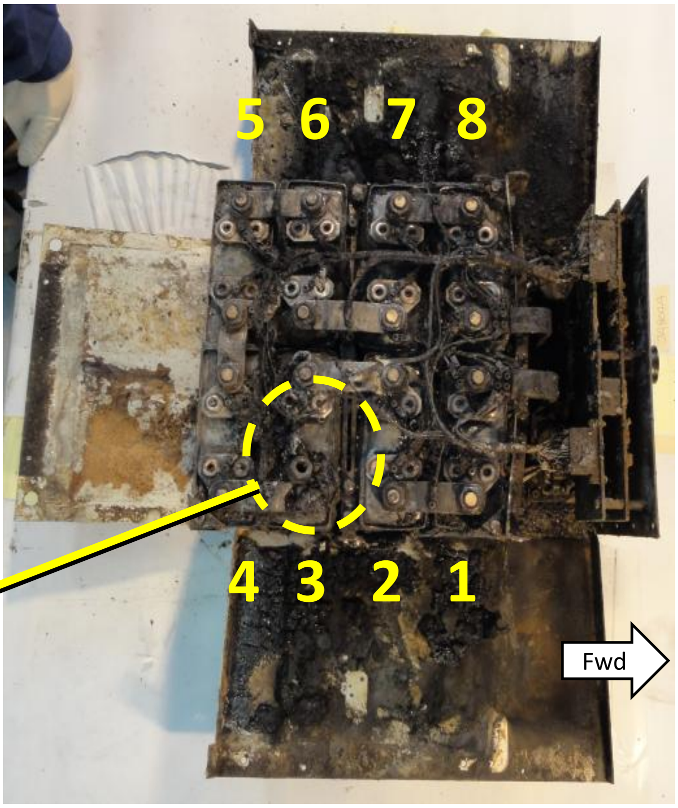


Figure 8: CT Scan Image

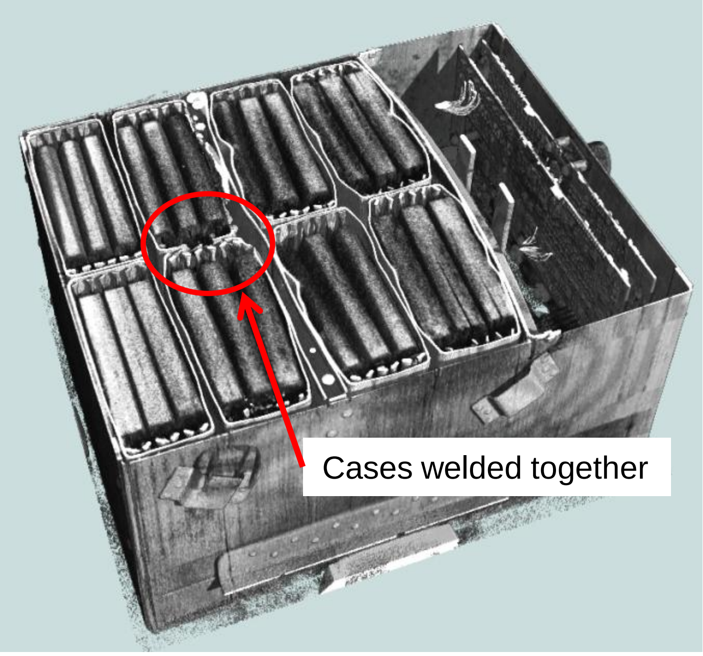


Figure 9: Damage of Each Cell


Cell 1


Cell 2


Cell 3

Cell 6

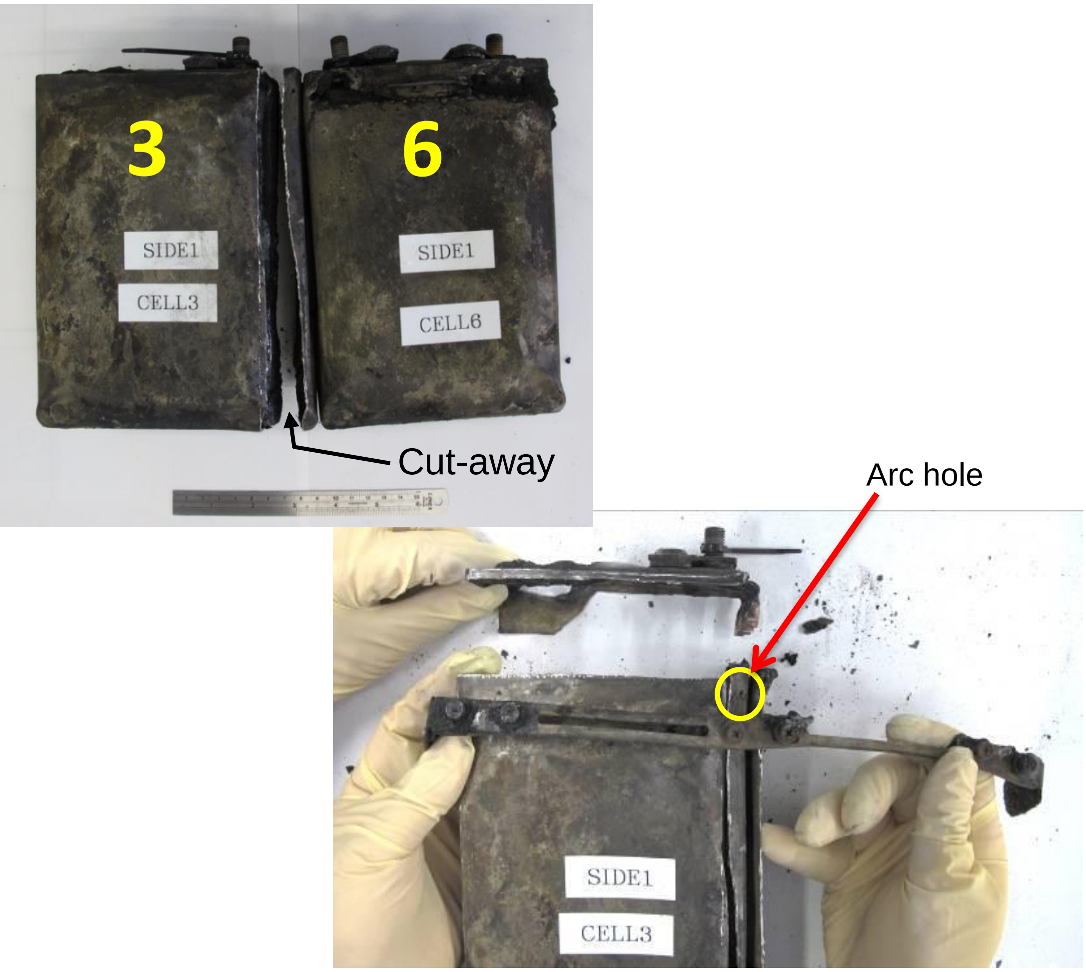

Cell 5

Cell 4


Cell 7


Cell 8

Figure 10: Cell 3



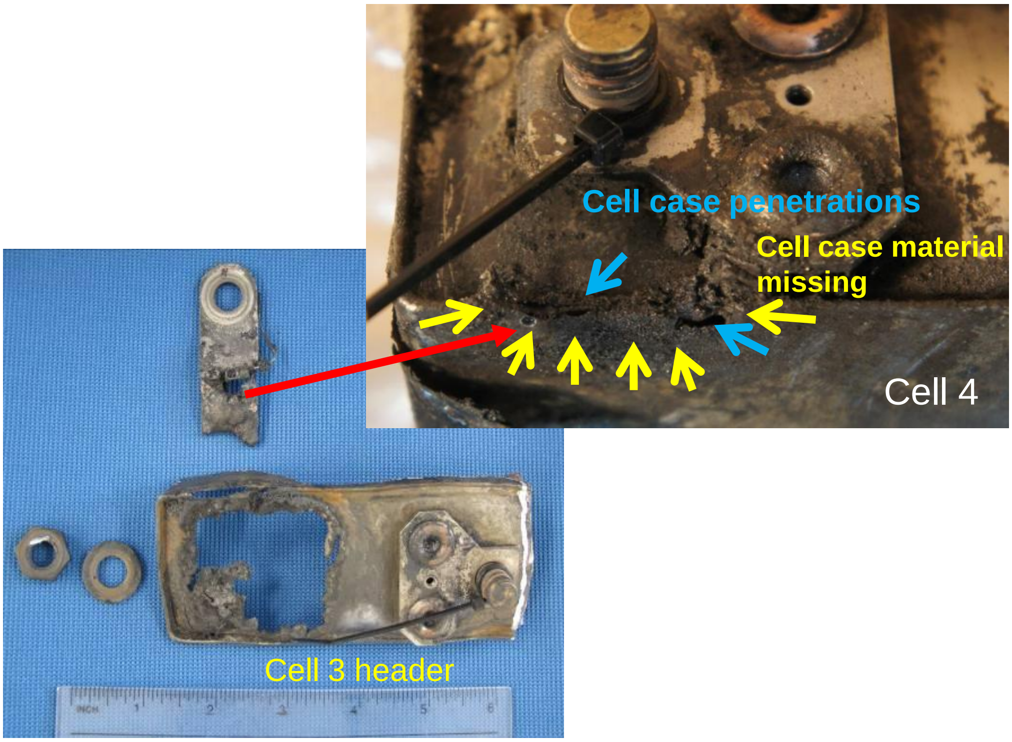


Figure 11: Cell 4 Interior

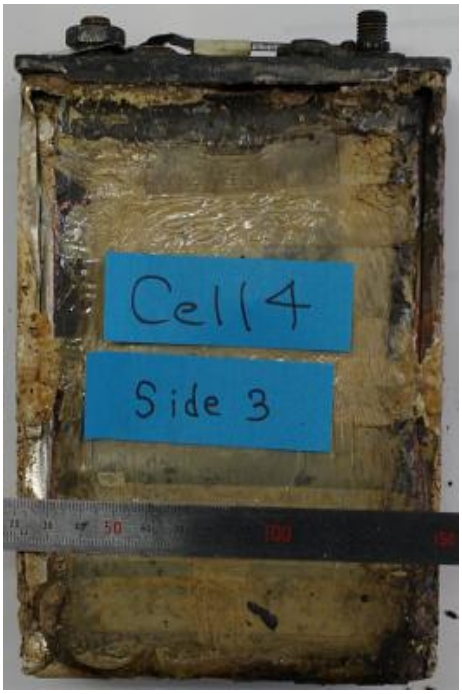


Figure 12: Damage to Cell 5

S1

W1

Figure 13: Cell 6 and Brace Bar

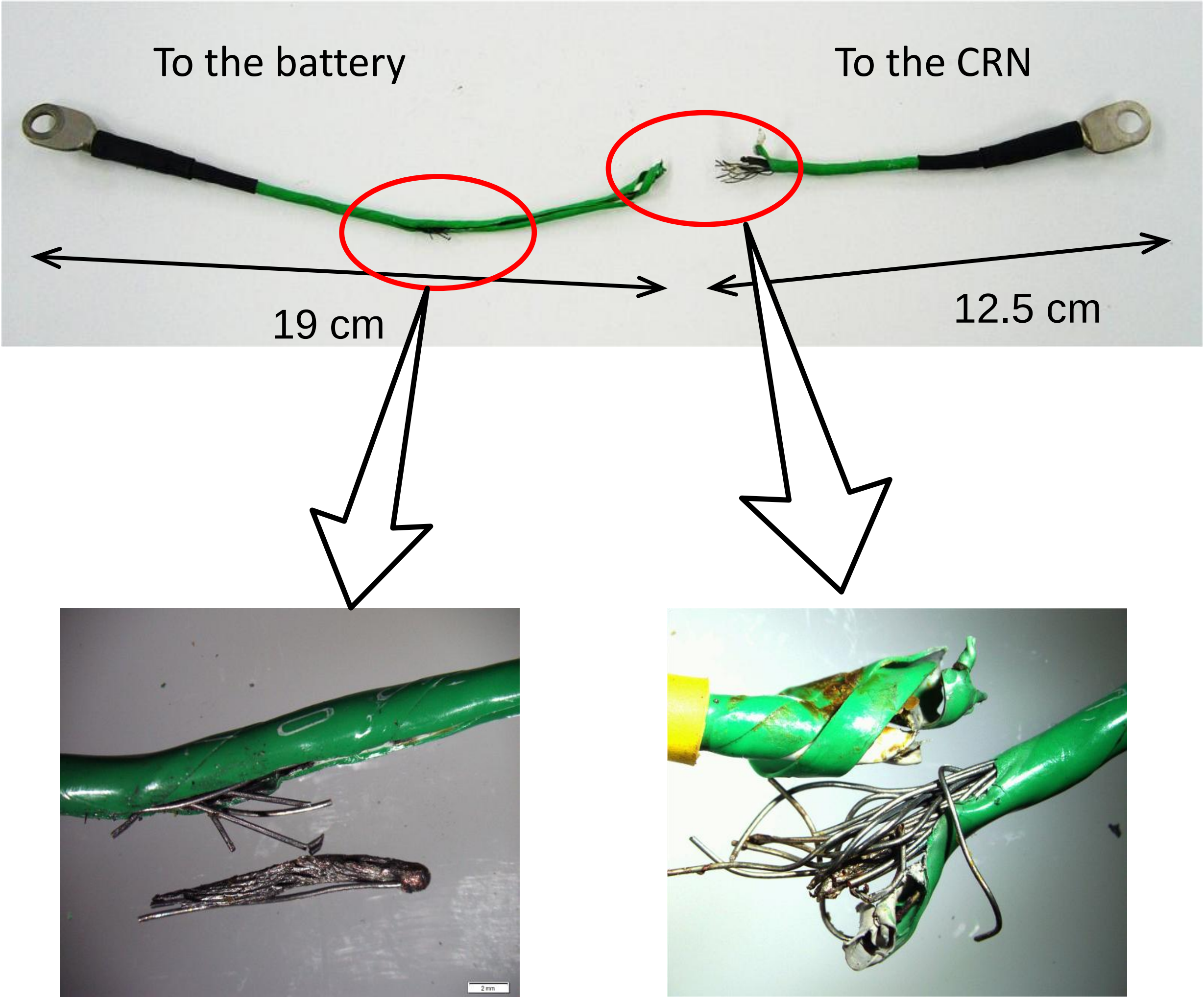
Part of this portion was welded to the cell case.

Figure 14: Safety Valve

Cell 1: Open Cell 2: Open Cell 3: Open Cell 4: Close

Cell 8: Open Cell 7: Open Cell 6: Open Cell 5: Close

Figure 15: Ground Wire



Appendix 1

Response on the Ground

08:31 Kansai Approach informed Takamatsu Tower that the airplane had requested to divert to Takamatsu Airport due to an emergency situation. At the airport, this information was forwarded to the Air Traffic Controllers' Office, the Airport Administrator and Airport Security Officer via Director of General Affairs Division.

08:37 Tokyo Rescue Coordination Center informed Air Traffic Services Flight Information Officer (hereinafter referred to as "information officer") that the airplane had declared emergency due to cockpit smoke and intended to divert there.

08:41 A security officer issued the level 2 mobilization to Takamatsu Firefighting Office, Air Safety Foundation. The Tower, using the crash horn, informed Kansai Approach, operations officer, and security officer that the airplane was flying at 3,200 ft, 15 nm NE of Kagawa VOR with ETA at the Airport 08:46. The security officer, using the dedicated telephone, informed Takamatsu City Fire Brigade of the expected diversion.

08:42 Fire engines No.1,2 and 5 departed towards the stand-by position: Fire engine No.1 and 5 occupied T3 taxiway; Fire engine No.2 at T1 taxiway. The security officer informed Prefectural Police Headquarters of the expected diversion.

08:45 A command vehicle departed towards T3 taxiway and stood at stand-by.

08:47 The airplane landed and Fire Engines No.1, 2, 3 and the command vehicle followed the airplane. The TWR, using a crash horn, informed Kansai Approach, information officer and security officer of the landing at 08:47.

08:48 The airplane came to a stop on T4 taxiway. The security officer who observed the spewing smoke around nose gear relayed his observation to the Tower over multi channel radio. The Tower relayed this message to the captain. The Tower informed the information officer to the effect that it confirmed the smoke.

08:49 The airplane's doors 1R to 4R and 1L to 3L were opened. Passengers began to slide for emergency evacuation. The security officer made public announcements to stay away from the airplane and ordered Takamatsu Firefighting Office to activate Emergency Information Forwarding System.

08:50 The Emergency Information Forwarding System was activated. The Tower informed the information officer that the airplane stopped on T4 taxiway and passengers started emergency evacuation. The information officer informed that the runway would be closed.

08:52 All the passengers and crewmembers were evacuated.

08:56 The security officer asked the PIC to check for the number of occupants and their safety. AT 09:05 he received the verbal report from the PIC.

09:05 Airplane occupants started to walk towards the terminal building.

09:25 The security officer, ANA mechanics, City Fire Brigade personnel started site inspection.

09:35 The City Fire Brigade informed the information officer that a male passenger who suffered hip bruise (light injury) had been taken to the city hospital.

09:49 The City Fire Brigade informed the information officer that the airplane was confirmed safe.

10:04 Vehicles from Takamatsu City Fire Brigade began leaving the site and at 10:25 all of them left the site.

10:34 The Security officer ordered the fire engines' withdrawal from the site and this completed at 10:40.

Thermal Propagation Testing at Kakuda Space Center

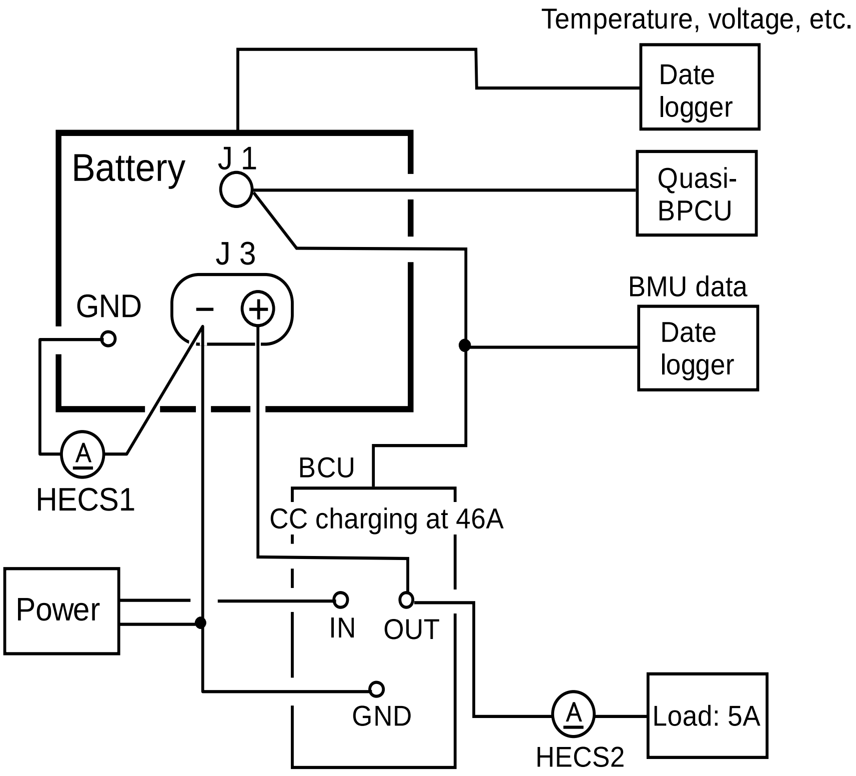
1. Purpose

To examine the cell-to-cell thermal propagation originating from cell 6 under simulated on-board conditions.

2. Test Configurations

No.	Batt. S/N	Configuration	Cell S/N
1	S/N 463	Nail penetration Incubated to 70℃ Charging amps: 46A Load: 5A	Cell1: 53800299 A Cell2: 53800318 B Cell3: 53800245 A Cell4: 53800320 B Cell5: 53800363 A Cell6: 53800346 B Cell7: 53800362 A Cell8: 53800386 B
2	S/N 413	Nail penetration Incubated to 30℃ Charging amps: 46A Load: 5A	Cell1: 53780258 A Cell2: 53780147 B Cell3: 53780253 A Cell4: 53780237 B Cell5: 53780215 A Cell6: 53780143 B Cell7: 53780140 A Cell8: 53780142 B
3	S/N 189	Nail penetration Incubated to 30℃ J1, J3 and ground wire: open	Cell1: 53300208 A Cell2: 53300234 B Cell3: 53300209 A Cell4: 53300235 B Cell5: 53300210 A Cell6: 53300236 B Cell7: 53300212 A Cell8: 53300237 B

Figure 1: Test Set-up



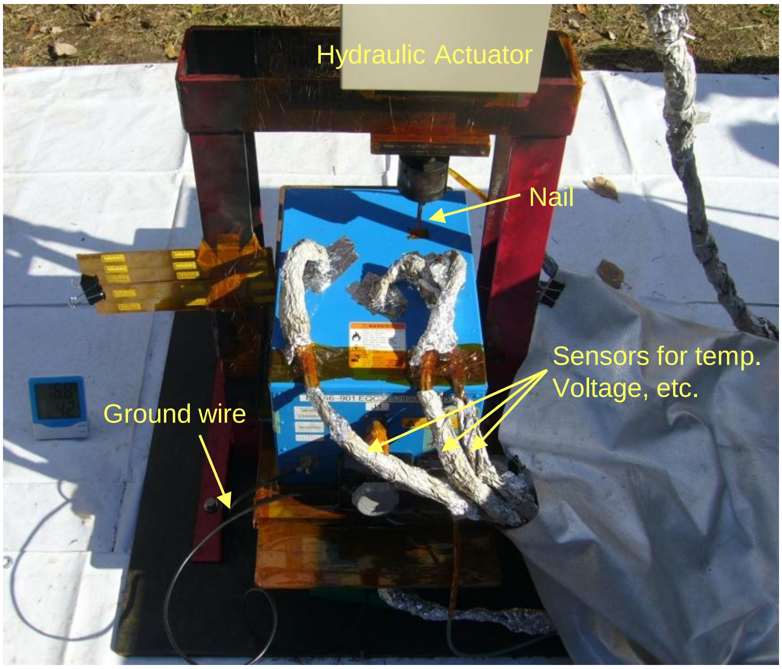
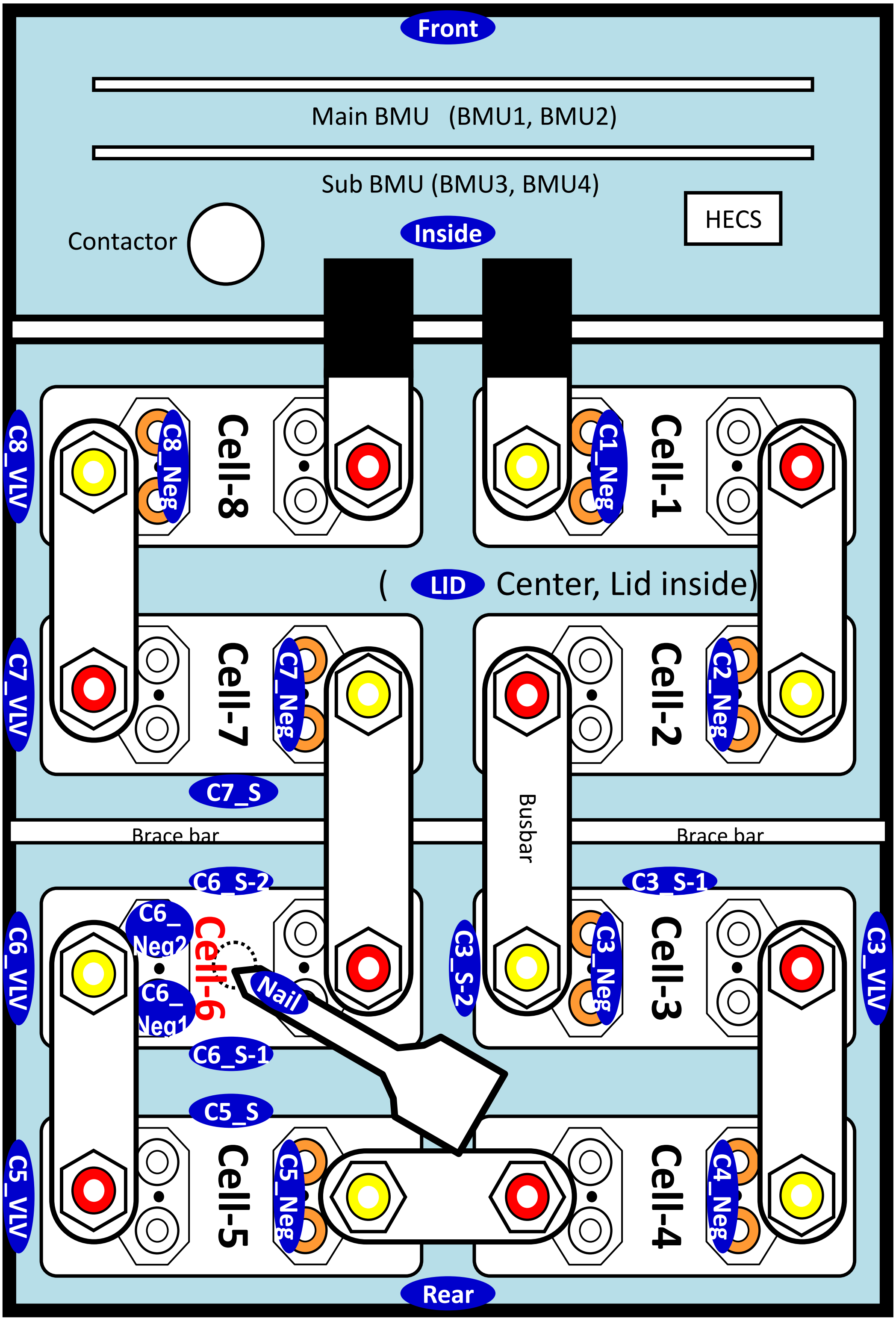


Figure 2: Thermo-Couple Location



Th : Thermo-sensor

🔴 : Positive terminal

🟡 : Negative terminal

Neg : Cell negative terminal

S : Cell case outer surface, center

VLV : Battery case inside, near safety valve

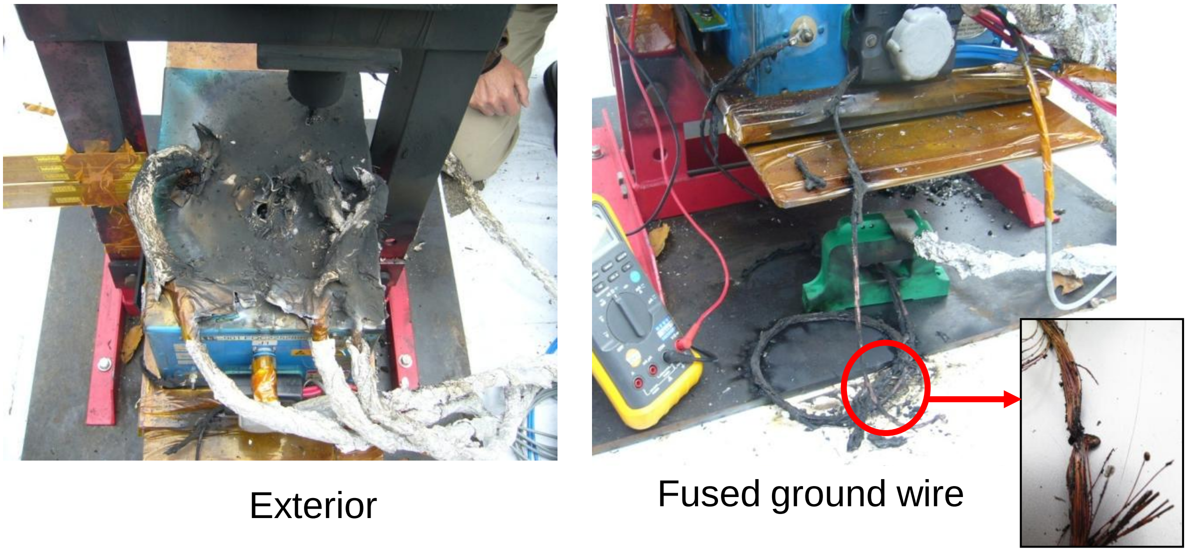
Nail : Nail with thermo-couple

Figure 3: Test Results

The tests simulating the on-board conditions (configuration 1 and 2) demonstrated the occurrence of thermal runaway with a fused ground wire deriving from a cell internal short circuit; however, floating battery (configuration 3) did not generate the same result.

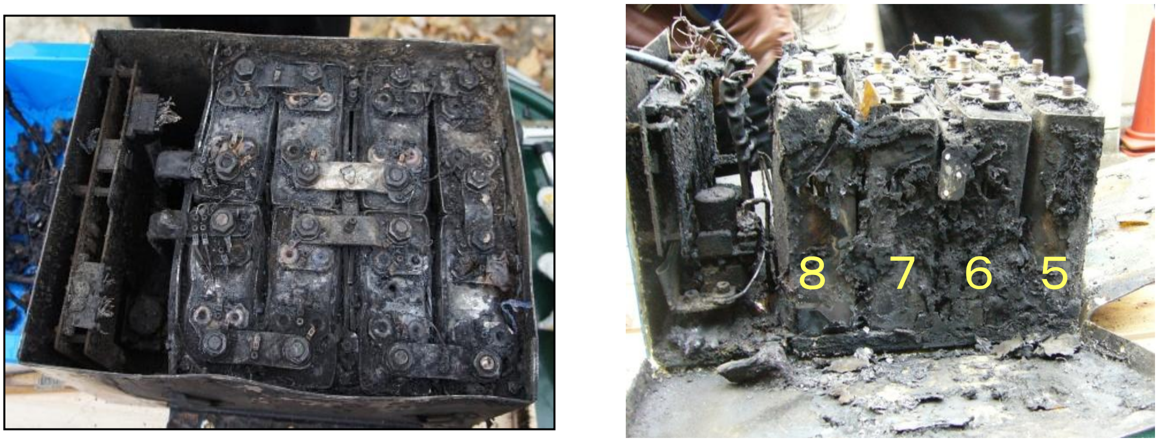
No.	Battery S/N	Configuration	Cell S/N	Result
1	S/N 463	Nail penetration Incubated to 70℃ Charging at 46A Load 5A	Cell1: 53800299 A Cell2: 53800318 B Cell3: 53800245 A Cell4: 53800320 B Cell5: 53800363 A Cell6: 53800346 B Cell7: 53800362 A Cell8: 53800386 B	11:27 Nail penetration. Cell 6 vented. 11:32 Cell 5 vented 200–600A of current ran through the ground wire（for 30 sec）. 11:34 Cell(?) vented. 11:35 Cell(?) vented. Cells 5–8 vented.
2	S/N 413	Nail penetration Incubated to 30℃ Charging at 46A Load 5A	Cell1: 53780258 A Cell2: 53780147 B Cell3: 53780253 A Cell4: 53780237 B Cell5: 53780215 A Cell6: 53780143 B Cell7: 53780140 A Cell8: 53780142 B	10:36 Nail penetration, **Cell 6** vented. 10:50 **Cell 7,** then **Cell 5** vented. 10:56 **Cell 8** vented. 11:07 Cell3(?) vented. 11:08 Cell(?) vented. 11:11 Cell(?) vented. 11:22 Cell(?) vented.
3	S/N 189	Nail penetration Incubated to 30℃ J1 and J3 and ground wire: Open	Cell1: 53300208 A Cell2: 53300234 B Cell3: 53300209 A Cell4: 53300235 B Cell5: 53300210 A Cell6: 53300236 B Cell7: 53300212 A Cell8: 53300237 B	11:40 Nail penetration. **Cell 6** vented. 12:46 Cell 6 temporary temp. increase No thermal propagation was observed.

Figure 4: Post-test Conditions (Configuration 2)



Exterior

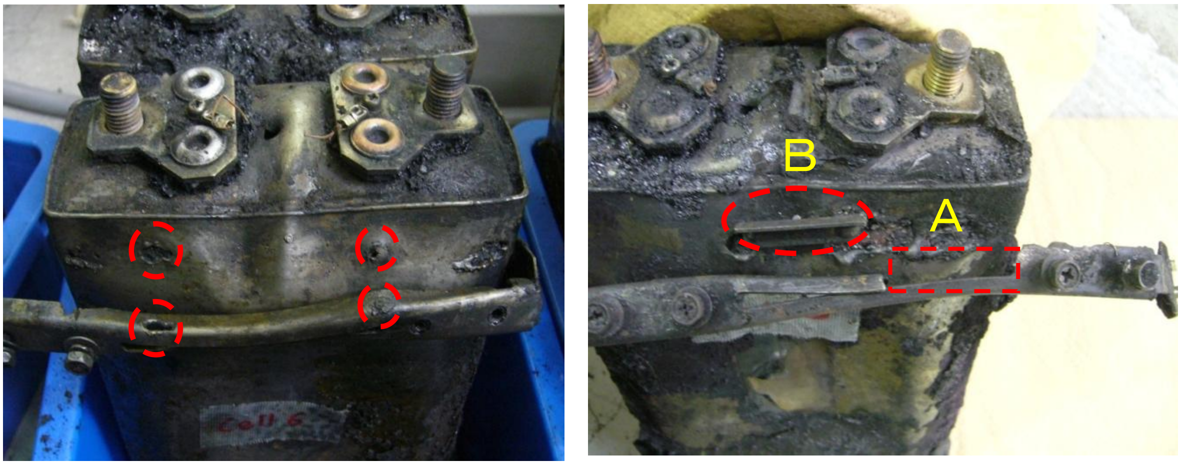
Fused ground wire



Battery Top

Battery Side (S3)

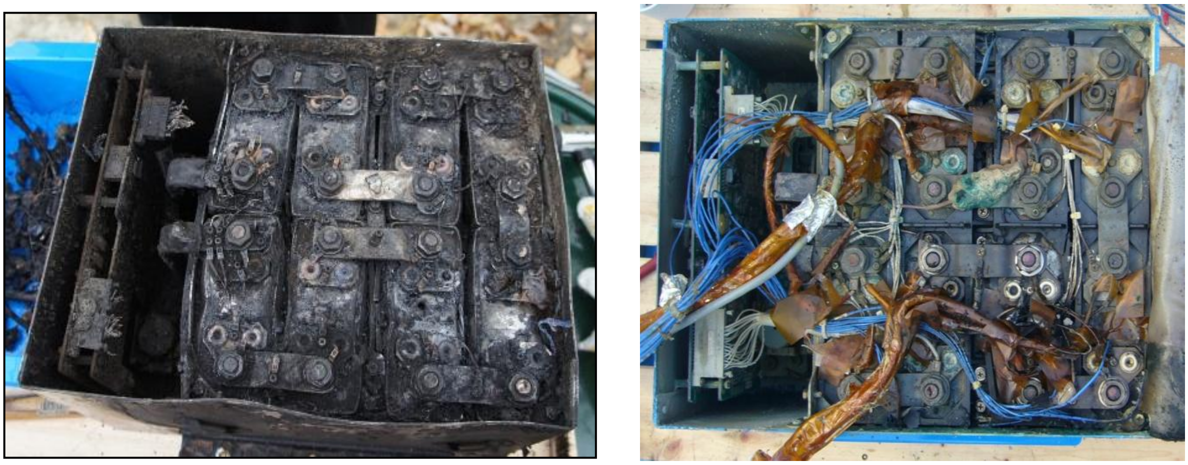
Figure 5: Cell 6 and Brace Bar (Configurations 1 and 2)



Config. 1 (Two arcing pits)

Config. 2 (Part of the brace bar is fused to the cell case(from A to B))

Figure 6: Comparison between Configurations 2 and 3



Config. 2

Config. 3

Figure 7: Damage to Current Collectors

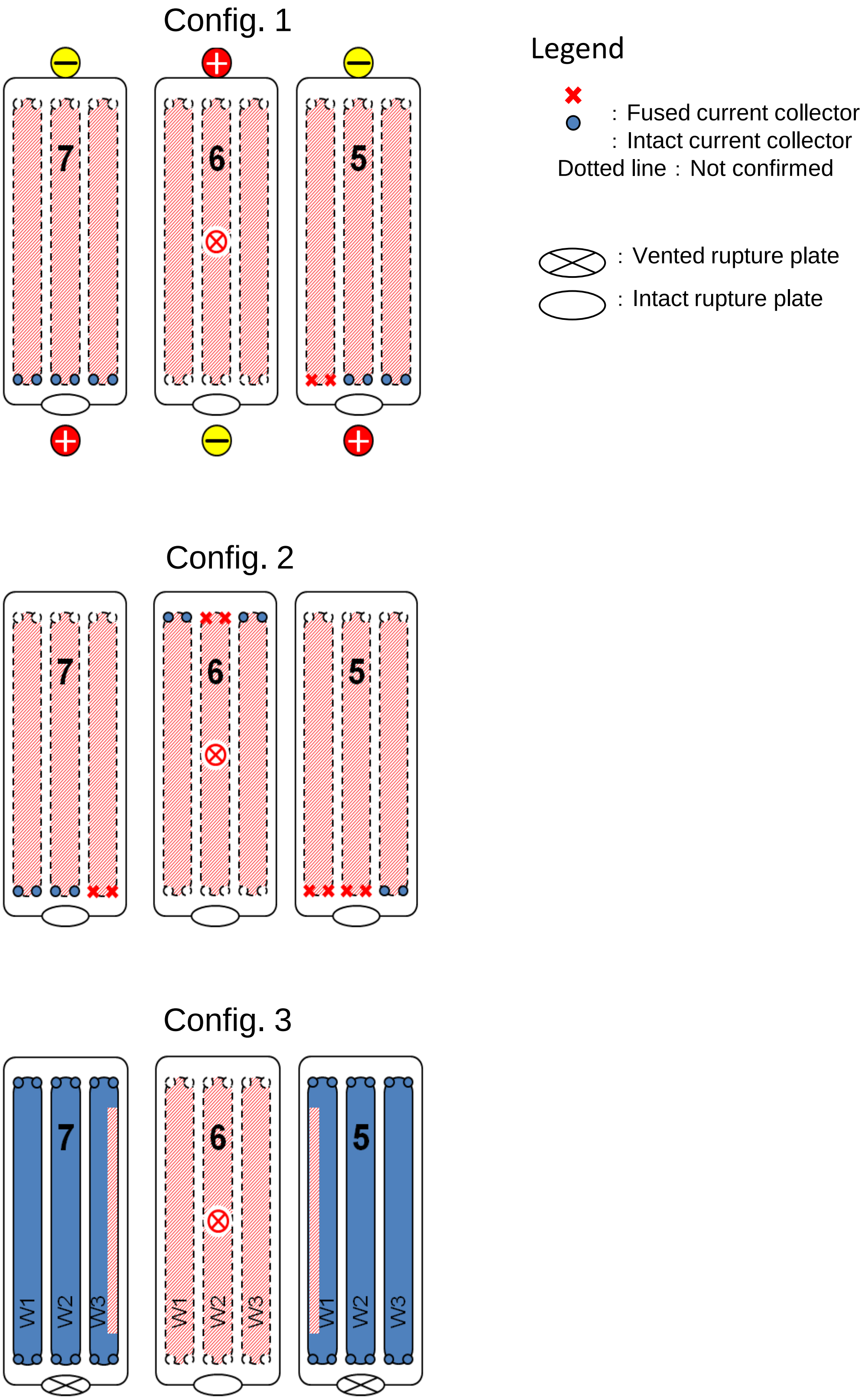


Figure 8: Battery Voltage Fluctuation (Configuration 2)

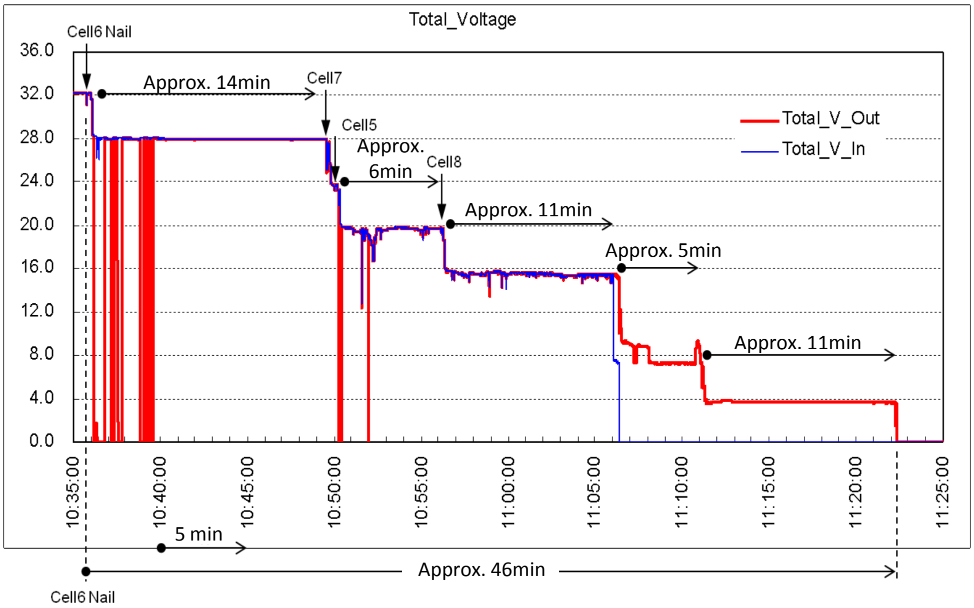


Figure 9: Cell Temperature (Configuration 2)

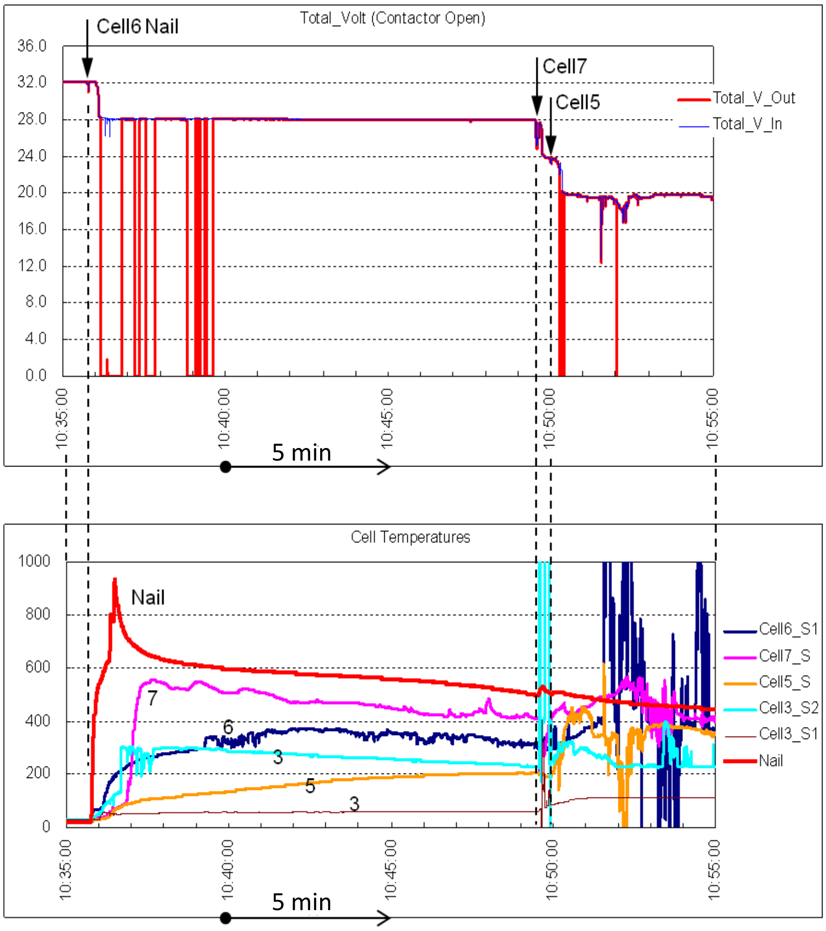
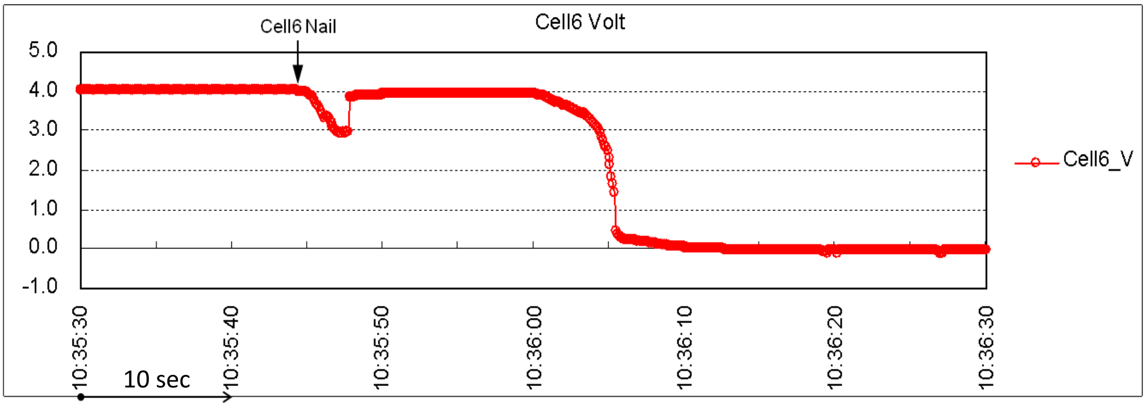


Figure 10: Detailed Cell Voltage Fluctuation (Configuration 2)



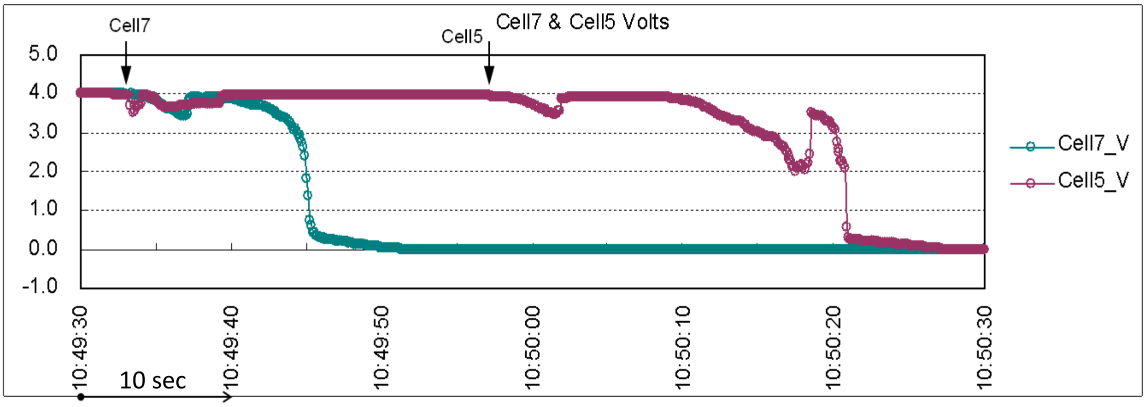
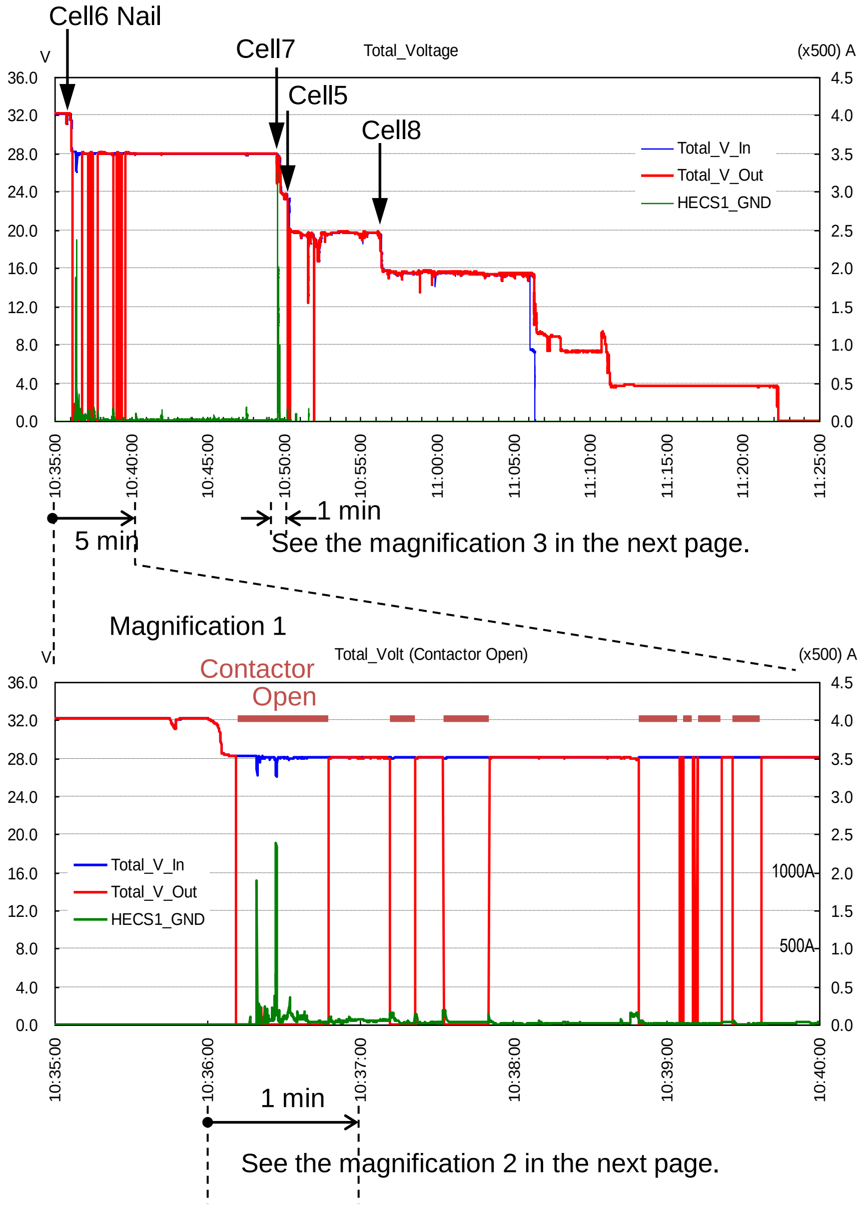


Figure 11-1: Fluctuations of Cell Voltage and Ground Wire Current (Configuration 2)

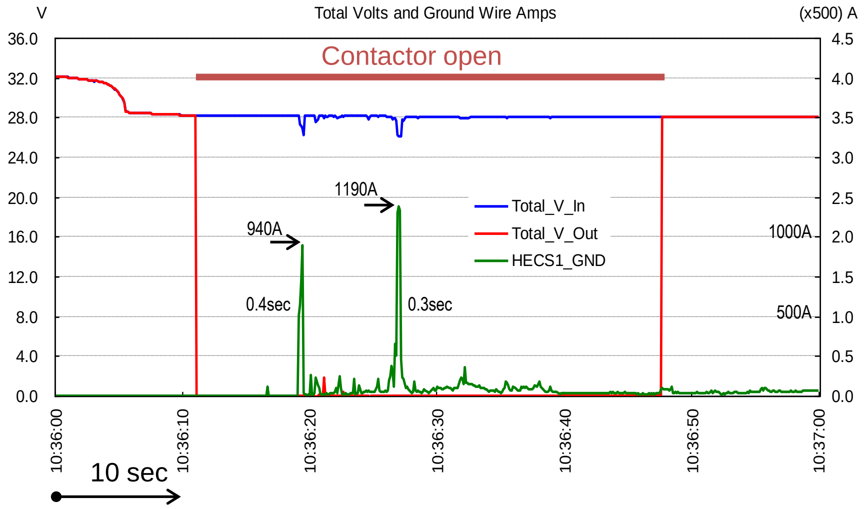


See the magnification 3 in the next page.

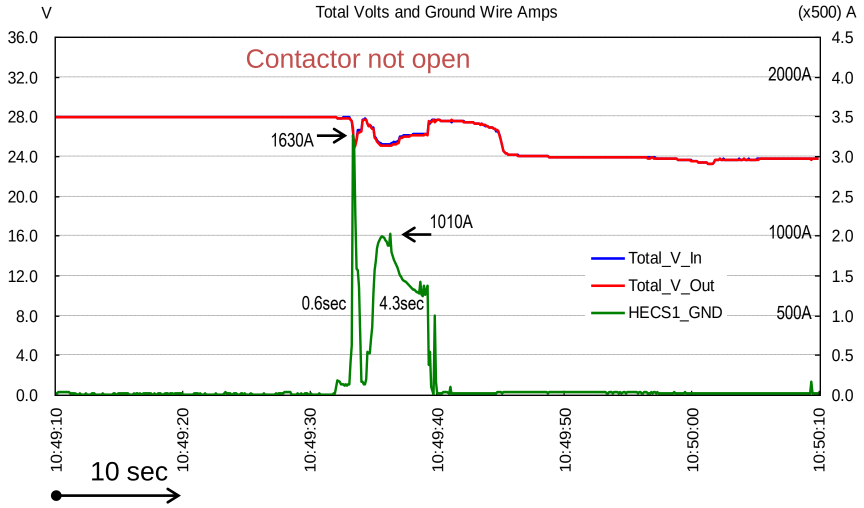
See the magnification 2 in the next page.

Figure 11-2: Cell Voltage, Ground Wire Current (Configuration 2)

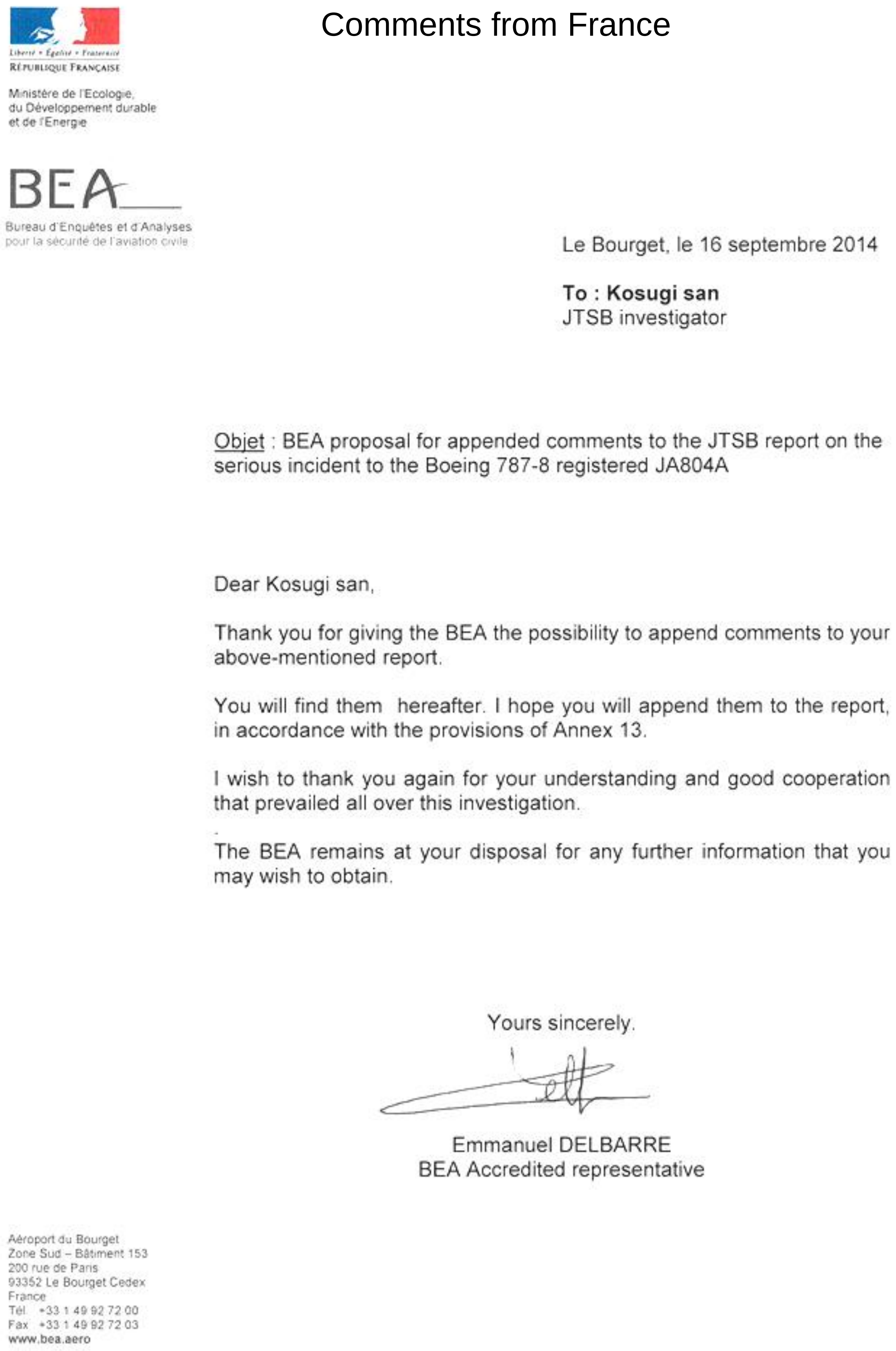
Magnification 2



Magnification 3



Comments from France



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RÉPUBLIQUE FRANÇAISE

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 16 septembre 2014

To : Kosugi san
JTSB investigator

Objet : BEA proposal for appended comments to the JTSB report on the serious incident to the Boeing 787-8 registered JA804A

Dear Kosugi san,

Thank you for giving the BEA the possibility to append comments to your above-mentioned report.

You will find them hereafter. I hope you will append them to the report, in accordance with the provisions of Annex 13.

I wish to thank you again for your understanding and good cooperation that prevailed all over this investigation.

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

Yours sincerely,

Emmanuel DELBARRE
BEA Accredited representative

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Proposed comments to append

Charging at low temperature

The coldest temperature outside the airplane during grounding was only minus 2.6 degree Celsius.

Experimentation on electrolyte viscosity and performances demonstrate that these condition do not affect this battery in the operating Temperature range (-18°C to +70°C).

External laboratories performed numerous tests to attempt to create lithium metal in the LVP65 cells with harsh constraints more severe than those recorded in the three incident without any conclusive results.

Oscillation of charging current

The BEA considers that the oscillations observed are due to the pre-load circuit of the BCU equipment. This phenomenon occurs at the end of the charging phase when BCU is in Constant Voltage (CV) mode.

External independent laboratories performed similar tests in order to investigate on this phenomenon. The test results clearly demonstrate that such "noisy" oscillations have no effect on the battery or on a cell safety and performances. The magnitude of current measured is smaller and doesn't induce heat or any negative effect on battery.

The BEA concurs to this conclusion that oscillations have no negative effect on the safety or on the performance of the battery or cell.

Wrinkles or gaps in anode caused by manufacturing or by repeated charging/discharging

GS YUASA performed 125 charging/discharging tests, using cold temperature at -23°C, charge voltage rate at 4.2V and charge current rate at 70 Amperes on LVP65 cells without any evidence of creation of lithium metal deposit and with no conclusive result on an internal short, heat generation and venting.

The BEA concurs to the fact that wrinkles are a very unlikely contributing factor to the incident.

Proposed safety recommendations

1

The BEA suggests to take into account the various reports established during the battery investigations and the Thales testing and to modify the recommendation towards FAA and Boeing as follows :
"Although this investigation could not identify the mechanism of the internal short circuit, the Federal Aviation Administration should instruct The Boeing Company to:

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- Continue studies of the internal short circuit mechanisms considering the effects of internal and external phenomenon that potentially impact the lithium-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 the lithium-ion batteries quality and its reliability".

2

- In addition, the BEA suggests another safety recommendation:

During the investigation it appeared that the Digital Flight Data Recorder didn't record the Main Battery Current as it is done for the APU battery. As this information would be of help for the contributing factors determination, the BEA proposes to the JTSB to add, in the chapter 6.2 (Measures to be Taken to Supervise The Boeing Company as a Designer and Manufacturer of the 787), a recommendation as follows :

"The Federal Aviation Administration should instruct The Boeing Company to:

- add the recording of the Main Battery current by the DFDR with an appropriate current range".