NATIONAL TRANSPORTATION SAFETY BOARD

Office of Aviation Safety Aviation Engineering Division Washington, DC 20594

November 6, 2014

AIRWORTHINESS GROUP CHAIRMAN'S ADDENDUM

A. INCIDENT: DCA13IA037

Location:	Boston, MA
Date:	January 7, 2013, about 10:23am EST
Aircraft:	Boeing 787-8 (msn 34839), JA829J, Japan Air Lines flight 008

B. GROUP MEMBERS:

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Member:	Takahiro Shizuki GS-Yuasa Kyoto, Japan

Member:	Lori Anglin Boeing Company Seattle, Washington
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C. SUMMARY

On January 7, 2013, about 1021 Eastern Standard Time, smoke was discovered by cleaning personnel in the aft cabin of a Japan Airlines (JAL) Boeing 787, JA829J that was parked at a gate at Logan International Airport, Boston, Massachusetts. At about the same time, a maintenance manager in the cockpit observed that the auxiliary power unit (APU) had automatically shut down. Shortly afterward, a mechanic opened the aft electronic equipment bay and found smoke coming from the GS-Yuasa LVP65-8-402 APU battery.¹ The mechanic also saw two small flames coming from the battery connector. No passengers or crewmembers were aboard the airplane at the time, and none of the maintenance or cleaning personnel aboard the airplane was injured. Aircraft rescue and firefighting responded to the battery fire, and one firefighter received minor injuries. The airplane had arrived from Narita International Airport, Narita, Japan, as a regularly scheduled passenger flight operated as JAL flight 008 and conducted under the provisions of 14 *Code of Federal Regulations* Part 129.

This report documents work performed and information gathered in addition to what is contained in the Airworthiness Group Chairman's Factual Report of February 28, 2013.² The investigation found no evidence of sources of external damage or heat applied to the LVP65-8-401 battery case. Since that report, the Airworthiness investigation has conducted an extensive amount of testing, conducted literature research, and consulted with experts with respect to thermal runaway and overheating of batteries and battery cells. The NTSB is leading the investigation into the thermal

¹ A single battery may be identified by different company part numbers, through involvement of GS-Yuasa, Thales, and Boeing. The GS-Yuasa part numbering is used in this report and based in the LVP cell identification, so the battery is the LVP65-8-402 or -403. This is occasionally shortened to LVP65 when further definition is not required by a passage of text. The equivalent Thales/Boeing part numbering is B3856-901 or -902.

² This report is about the investigation into the battery and airplane involved in the 787 event at Boston on January 7, 2013. The airplane was parked without intent for flight and without a flight crew aboard. This report refers to the Boston and Narita investigations as "events," "thermal runaway," or as "battery failure."

runaway of the battery at Boston JAL 787 with support from the Japanese Transportation Safety Board (JTSB) and other parties.³

This report provides brief references to two subsequent LVP65-8 battery failures in other airplanes, citing only information from sources already made public. These are provided for context regarding work with the JTSB and other groups; plus environmental context. This report also documents a wire found in contact with a metal screw within the flight control electronics battery of the Boston 787. This lithium ion battery was above the APU battery that overheated.

Following the Boston battery failure, a second LVP65-8-402 battery experienced a thermal runaway.⁴ On January 16, 2013, an inflight All Nippon Airways (ANA) 787 made an emergency landing after pilots received a smoke warning in the cockpit after climbing to more than 32,000 feet altitude. The airplane landed at Takamatsu Airport on Shikoku Island and an emergency evacuation was conducted. Subsequent investigation found that the battery had been installed in the main battery position, located beneath the forward galley, and that all eight cells in the battery were found to have thermally overheated.

Boeing altered the battery and the battery installation after the Boston and Takamatsu battery failures and the companies changed the battery part number, so that the GS-Yuasa number changed from LVP65-8-402 to LVP65-8-403. The changes included additional insulation between the battery cells, vents in the side of the blue battery case, placing the battery case within a new stainless steel enclosure, removal of the case ground wire, and addition of an overboard vent to prevent smoke from entering the occupiable space in the airplane.

On January 14, 2014, a JAL 787 experienced an LVP65-8-403 battery failure while the airplane (JA834J) was parked at Narita International Airport. As with the Takamatsu failure, the battery was installed in the main battery position.⁵ Ground personnel reported the event as smoke emanating from the overboard vent. The airplane was parked without intent for flight and the Japan Civil Aviation Bureau (JCAB) has been evaluating the event, with assistance from the JTSB, NTSB, and others. One cell was found to have overheated and vented electrolyte.

In accordance with the International Civil Aviation Organization (ICAO) Annex 13 agreements regarding international aspects about aviation safety investigations, the country in which an incident occurs leads the investigation and other countries may

⁵ This report only cites information obtained from public sources, including NTSB Press Release: <u>http://www.ntsb.gov/news/2014/140115.html</u> and news reports, such as:

http://www.reuters.com/article/2014/01/14/us-japanairlines-787-battery-idUSBREA0D11820140114, http://www.reuters.com/article/2014/01/29/us-japan-787-battery-idUSBREA0S0DP20140129, http://blogs.wsj.com/japanrealtime/2014/02/21/japan-probe-into-787-battery-shows-revamp-stemmeddamage/

³Original details about the LVP65-8-402 battery and 787 involved in the Boston event are contained in the Airworthiness Group Chairman's' Factual Report.

⁴ See the JTSB web-site for details and photos of the ANA JA804A airplane and battery at: <u>http://www.mlit.go.jp/jtsb/flash/JA804A_130116-130327.pdf</u>.

support the leading agency. Because of the close time proximity and technical similarities noted after the battery failures, the NTSB and JTSB investigators have coordinated many of the investigative activities. An extensive number of potential causes for battery failure and thermal runaway have been examined or have been the subject of tests that were conducted at laboratories in the United States, Japan, France, and Taiwan.

The three airplanes had been operating from Tokyo airports where outdoor temperatures had been colder than the freezing temperature of water (0°C/32°F). Boeing requirements for the 787 main and APU lithium ion battery (LIB) include an operational temperature range of $+70^{\circ}$ C ($+158^{\circ}$ F) to -18° C (0.4° F). Each battery is next to an exterior door and there is no recording of battery temperature or when maintenance personnel had the doors open. No control of the battery or cell temperatures is provided and temperature is measured within the battery on two bus bars, not on the cells themselves.

The 787 battery charger is not designed to taper/reduce charge in response to changes in temperature, or in response to electrical changes in cell behavior relating to cold temperatures. The charger is signaled to stop charging when colder than $-15^{\circ}C$ (+/- $1.5^{\circ}C$).

The LVP65 battery cells nominally are at 100% state of charge (SOC) at 4.025 volts direct current. Certification testing did not include failure tests to show how the results of cell internal short circuit would act upon the airplane electrical system.

References are made in this document to Underwriters Laboratories LLC (UL), which is a global independent safety science company offering expertise across seven key strategic businesses. The laboratories include facilities and engineering personnel dedicated to the examination and testing of batteries. The UL facilities have experience which ranges from small consumer-oriented lithium ion cells (LIC), to large format multi-cell lithium ion batteries (LIB) used in vehicles. UL participates in a range of industry groups which develop design, construction, and safety standards. The UL catalogue includes more than 1,000 standards developed by UL.

A portion of the investigation involved information gathering and performance of a contract between the NTSB and UL.⁶ In performance of the contract, UL provided technical expertise, testing of LIC, and testing of LIB. The contract was extended twice to further examine features discovered during the investigation. When the original contract and extension were ending and tests identified areas of potential interest for further effort, UL provided additional services at no cost to the Government through the portion of the UL mission dedicated to non-profit research for public benefit.

Multiple addendums have been created for the UL reports documenting testing performed by UL. The UL tests were performed continuously at the Boeing maximum APU start value for a battery. As noted by Thales on May 7, 2014, except

⁶ Contract NTSB C 13 0004.

for APU start testing, qualification and endurance testing was performed to a Boeing value which was 83% of the power used in the UL testing.

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ACRONYMS:

AD	Airworthiness Directive
APSIF	Airplane Power Systems Integration Facility
ANA	All Nippon Airways
APU	Auxiliary power unit
BCU	Battery charger unit
cP	centipoise, a unit of viscosity measurement
СТ	Computerized tomography
DPA	Destructive Physical Analysis. Also known as a disassembly examination.
EIS	Electro impedence spectroscopy
EV	Electric vehicle
FAA	Federal Aviation Administration
FCE	Flight control electronics
GSY	GS-Yuasa
HEC	Hall Effect Current sensor
HEV	Hybrid electric vehicle
ISC	Internal short circuit
JAL	Japan Airlines
JCAB	Japan Civil Aviation Bureau

JTSB	Japan Transport Safety Board
kHz	Kilohertz, a frequency of 1,000 cycles per second
LIB	Lithium-ion battery
LIM	The GS-Yuasa series of lithium-ion series of industrial batteries
LVP	The GS-Yuasa series of lithium-ion series of aircraft batteries
mS/cm	Millisiemens per centimeter, units of electrolytic conductivity
NREL	National Renewable Energy Laboratory, a principal research laboratory for the U.S. Department of Energy
NRL	U. S. Naval Research Laboratory
NTSB	National Transportation Safety Board
OCV	Open circuit voltage
SEI	Solid electrolyte interphase
SOC	State of charge, typically expressed as a percentage of charge between the operational full charge voltage and the operational discharge/empty charge voltage, as set by a manufacturer.
UL	Underwriters Laboratories, a Limited Liability Corporation

INVESTIGATION PROCESS:

The 787 battery failure at Boston was the first installed (non-cargo and not carry-on) primary lithium ion battery (LIB) known to fail in an airline operation.⁷ Lithium ion battery failure investigations have been conducted in fields other than aviation for more than 20 years.

Literature searches revealed consistent descriptions of cell and battery failure processes that convey simplified versions of the failure processes and paths to investigate. Additionally, on April 22, 2013, the NTSB held a forum on battery safety, in which experts provided presentations about battery design, experience, and failures.⁸ One example was a summary from the National Renewable Energy Laboratory (NREL) that had been created by Dr. Daniel H. Doughty of Battery Safety Consulting, Inc. The Airworthiness investigation examined each of these paths. (See Figure 1 and Figure 2

⁷ No passengers, pilots, or flight attendants were aboard the airplane. The first known installed LIB failure in a transport airplane system was in a Cessna Citation business jet, which led to emergency Airworthiness Directive (AD) 2011-21-51, dated October 6, 2011.

⁸ NTSB forum titled "Lithium Ion Batteries in Transportation" April 11-12, 2013. Presentation materials shown in this report may be found at

http://www.ntsb.gov/news/events/2013/batteryforum/presentations.html



Figure 1. Typical literature search result regarding potential failure causes.⁹ Source: NREL



Figure 2. Cell failure scenario provided by Dr. Daniel H. Doughty, of Battery Safety Consulting, Inc.

⁹ Source: A presentation titled "Addressing the Impact of Temperature Extremes on Large Format Li-Ion Batteries for Vehicle Applications." Ahmad Pesaran, Ph.D. Shriram Santhanagopalan, Gi-Heon Kim National Renewable Energy Laboratory Golden, Colorado, 30TH INTERNATIONAL BATTERY SEMINAR Ft. Lauderdale, Florida, March 11-14, 2013 NREL/PR-5400-58145

Another expert at the NTSB Forum, Dr. Carol Mikolajczak was co-author of a book titled "Lithium-Ion Batteries Hazard and Use Assessment."¹⁰ In addition to consistency with the information above from NREL and Dr. Doughty, the book contained descriptions about both failures and investigations. Text from the book stated that:

Both energetic and non-energetic failures of lithium-ion cells and batteries can occur for a number of reasons including: Poor cell design (electrochemical or mechanical), Cell manufacturing flaws, External abuse of cells (thermal, mechanical, or electrical), Poor battery pack design or manufacture, Poor protection electronics design or manufacture, And poor charger or system design or manufacture. Thus, lithium-ion battery reliability and safety is generally considered a function of the entirety of the cell, pack, system design, and manufacture.

The above sources and others were utilized to guide the investigation into internal and external sources for the initiating battery cell failures.

Surrounding and environmental operational factors were examined. These included high speed data capture during a flight test and subsequent data analysis. For example, the recorded vibration of the 787 was extremely low (values are Boeing proprietary). Other values for the E/E had previously been documented by Boeing, such as humidity values which are specified in proprietary environmental documents that each of the companies had access to.

An extensive number of potential causes for battery failure and thermal runaway were examined or the subject of tests that were conducted at Boeing laboratories. Such potential causes included rapid charge/discharge oscillations, condensation bridging a cell to the battery case, loose electrical terminals, and others. Brief summaries are provided without details in a separate addendum, due to the proprietary nature of the laboratory results that contain the essence of the battery and system design, as well as the system performance and testing.

The previously cited book titled "Lithium-Ion Batteries Hazard and Use Assessment" states that the 11

... ideal lithium-ion battery failure mode is a slow capacity fade and internal impedence increase caused by normal aging of the cells within the battery...

¹⁰ Published by the Fire Protection Research Foundation, written by Mikolajczak, Kahn, White, and Long of Exponent Failure Analysis Associates, Inc. Copyright 2011.

¹¹ Fire Protection Research Foundation report, written by Celina Mikolajczak, P.E., Michael Kahn, Ph.D., Kevin White, Ph.D., and Richard Thomas Long, P.E., Exponents Failure Analysis Associates, Inc. Issued July 2011

The bulk of lithium-ion batteries in the field experience this type of failure mode.

Witnesses and evidence described in the Airworthiness Group Chairman Factual Report related that the LVP65 battery which failed at Boston became hot. Surrounding the battery box were remnants of hot sprayed electrolyte. The book terms this type of failure as an energetic thermal runaway with the following description of the process.

If a typical fully charged (or overcharged), lithium-ion cell undergoes a thermal runaway reaction a number of things occur.

Cell internal temperature increases. Cell internal pressure increases. Cell undergoes venting. Cell vent gases may ignite. Cell contents may be ejected. Cell thermal runaway may propagate to adjacent cells.

BACKGROUND INFORMATION:

NREL VEHICLE BATTERY SAFETY ROADMAP GUIDANCE:

During meetings of June 2013, GS-Yuasa engineering personnel compared the relative properties of various battery types. Aviation applications require a unique set of battery properties, as compared with those made for industrial use. Aviation requirements are high in both power density, which is power for a certain amount of mass and are also high in energy density, which is the total kW-hrs stored in the battery per unit mass, usually expressed in Wh/kg. Electric vehicles (EV) and hybrid electric vehicles (HEV) also utilize large format lithium ion batteries, some of which have lithium ion cobalt oxide (LiCoO₂, also known as LCO) chemistry, and this is the basic chemical combination found in the prismatic cells of the LVP65. (See Figure 3 and Figure 4)



Figure 3. Illustration provided by Western Lithium Corporation compares the relative properties of battery types. Note that the illustration provides rough comparison concepts and not clear performance limits.

The following text was written by Daniel H. Doughty, Ph.D., of Battery Safety Consulting, Inc. for the National Renewable Energy Laboratory (NREL) "Vehicle Battery Safety Roadmap Guidance."¹²

Batteries for EVs and HEVs are fundamentally different from batteries developed for other applications. In addition to the scale difference-EV batteries store up to three orders of magnitude more energy than laptops—the environment that vehicle traction batteries experience during their life is more difficult than in other applications, such as portable computers or cell phones. The demanding environmental conditions include exposure to wide temperature extremes, vibration, high rates of discharge, and high rates of charge. High rates of both discharge and charge can occur at extreme temperatures. To increase an all-electric vehicle's driving range, the vehicle traction application will require high voltage, which in turn requires long strings of cells, long life, and high energy. Finally, because the focus of this study is on EVs and HEVs that are passenger vehicles, fire safety is a primary concern. Batteries with flammable electrolytes present challenges when designing the safety of a vehicle's energy storage device. These safety concerns are especially acute for PHEV and EV applications where vehicles may be charged in confined garage spaces of private residences and commercial businesses.

Safety cannot be determined or evaluated by one criterion or parameter. Rather, enhanced safety is determined by the implementation of several approaches that work synergistically, such as:

¹² U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy Contract No. DE-AC36-08GO28308, October 2012

- *Reducing the probability of a battery failure event*
- Lessening the severity of outcome if an event occurs.

As this safety approach applies to vehicle batteries, thermal stability is perhaps the most important of several parameters that determine safety of Liion cells, modules, and battery packs.

When discussing battery safety, it is important to understand that batteries contain both an oxidizer (cathode) and fuel (anode as well as electrolyte) in a sealed container. Combining fuel and oxidizer is rarely done due to the potential of explosion (other examples include high explosives and rocket propellant), which is why the state of charge (SOC) is a very important variable. Lower SOCs reduce the potential of the cathode oxidizing and the anode reducing. Under normal operation, the fuel and oxidizer convert the stored energy electrochemically (i.e., chemical to electrical energy conversion with minimal heat and negligible gas production). However, if electrode materials are allowed to react chemically in an electrochemical cell, the fuel and oxidizer convert the chemical energy directly into heat and gas. Once started, this chemical reaction will likely proceed to completion because of the intimate contact of fuel and oxidizer, becoming a thermal runaway. Once thermal runaway has begun, the ability to quench or stop it is nil.

The energy content of batteries continues to increase as new electrode materials are developed with increased capacity and higher voltage operation. With these developments, new high-energy cell designs are appearing in the marketplace. Electrode materials represent some of the most reactive materials known and operate at high voltage (4.2 V to 4.6 V).

Different battery chemistries have various failure modes, but several events are common among all types of batteries. A typical response of a cell to abusive conditions is generation of heat and gas. While they may be linked (i.e., gas and heat are produced by the same chemical reactions), there are occasions where heat and gas are produced independently.

Abuse tests are intended to emulate abnormal conditions or environments or when a battery pack is used in a manner outside the design parameters or beyond useful life. Abuse tests can be grouped into three major categories:

- 1. Thermal Abuse (includes thermal stability, simulated fuel fire, elevated temperature storage, rapid charge/discharge, and thermal shock cycling)
- 2. Electrical Abuse (includes overcharge/overvoltage, short circuit, over discharge/voltage reversal, and partial short circuit)
- 3. Mechanical Abuse (includes controlled crush, penetration, drop, immersion, roll-over simulation, vibration, and mechanical shock)

Heat generation within battery cells (termed "self-generated heat") underlies many abuse responses and can make failures more hazardous. For example, a short circuit will heat up a cell because of Joule heating, which depends on the current and resistance of the cell (\vec{I} R). As the temperature increases, the cell begins to produce heat by internal chemical reactions (i.e., above the temperature where onset of self-heating reactions begin). Overcharge can also generate heat within the cell due to other chemical reactions that may trigger thermal runaway. In both of these cases, a comprehensive approach is essential to understand cell response and design of thermal management of the battery pack that incorporate cell thermal environment, heat capacity, and self-heating rate as a function of temperature.

In addition to safety incidents, which can arise when batteries are abused, spontaneous internal failures (called field failures) are observed in batterypowered equipment. Abuse tests in use today cannot predict or screen for field failure, as evidenced by the fact that:

- All battery recalls involve cells that have passed Underwriters Laboratories safety tests.
- Battery companies carry out 100% machine vision X-ray inspection.
- All battery manufacturers use high-potentiometer testing designed to find cells with internal short circuits.

Field failures arising from manufacturing defects that cause internal short circuits have very low probabilities of occurrence (estimates for 18650-size cells that fail catastrophically are 1 in 10 million cells to 1 in 40 million cells). While this may be reassuring for manufacturers of portable electronics, EV and HEV battery packs may have thousands of cells and up to 1,000 times more stored energy, making even this small failure rate unacceptable. The development of an internal short circuit test is an important objective and is being explored by several laboratories. Experimental simulation of internal short circuit field failure is also an important objective in understanding failure mechanisms and mitigation. Several laboratories are pursuing approaches for these purposes and for validation of thermal models of field failure.

To characterize heat and gas generation that might occur during off-normal conditions, cells and packs are exposed to elevated-temperature abusive conditions that resemble conditions that might be seen in the field, if only rarely.

The materials comprising the cell have a profound influence on the safety and abuse tolerance of the cell and battery pack. The choice of cathode has a very significant influence on cell safety. New, high-energy cathodes are being used in commercial cells or are in development. Lithium cobalt oxide (LiCoO2, or LCO) has been the cathode of choice for the majority of consumer-level Li-ion cells produced today. Although it delivers good capacity, it is the most reactive and has poorer thermal stability than other cathodes. Much progress has been made in commercializing safer cathodes. A comparison of the thermal stability of cathodes is shown in Figure S-1. (Airworthiness Addendum Figure 4)



Figure 4. [Doughty Figure S-1.] Self-heating rate of the 18650 full cell as measured by accelerating rate calorimetry (ARC). Improving cathode stability results in a higher thermal runaway temperature (increased stability) and a reduced peak heating rate. Source: E. P. Roth, D. H. Doughty, Proceedings of AABC 15-19 May 2006, Baltimore, MD.

Anode materials are chosen to have a high capacity, high rate capability, and low irreversible loss on formation cycling and stability with respect to cycling and high-temperature exposure. All of these material properties affect the thermal response of the anode under abuse conditions. The relative contribution of the anode and cathode material to the full cell response depends on the specific reactivity of the active materials and the mass loadings of each (the thermal stability of each electrode is important).

Shutdown separators are intended to stop current flow in a cell above a certain temperature limit. An ideal shutdown separator will have a sharp transition to a very high resistance at a relatively low temperature, an ability to block high voltage, and a wide temperature window of stability. Separators generally are classified into three groups: (1) microporous polymer membranes, (2) non-woven fabric mats, and (3) inorganic composite membranes. The separators enhance cell safety by having properties of high mechanical strength (puncture resistance), high thermal stability, and desirable shutdown properties. However, less-than-ideal shutdown separators can be the source of internal shorts and cell failure above the shutdown temperature, especially in high-voltage, series-connected strings. Non-

shutdown separators, even though not offering current-limiting protection, can offer a wider range of temperature stability.

The organic-based electrolytes used in Li-ion batteries have a unique characteristic compared to other electrochemical storage systems. Li-ion electrolytes are almost universally based on combinations of linear and cyclic alkyl carbonates. These electrolytes make possible the use of lithiated graphite (LiC₆) as the anodic active component, resulting in the high power and energy densities characteristic of the Li-ion chemistries. However, organic electrolytes have high volatility and flammability that pose a serious safety issue if the electrolyte is released during an abuse event and begins to burn. Under extreme conditions of voltage and temperature, electrolytes can react with the active materials of both anode and cathode to release significant heat and gas.

LITHIUM ION BATTERY FUNDAMENTALS:

The basic operating principle of LIB cells is that a liquid electrolyte carries lithium ions between the porous active materials (coatings) on two metal foils. The electrochemical process involves movement of the ions in what is known as the rocking chair process, since the ions move back and forth between the positive and negative electrodes during charge and discharge. (See Figure 5 and Figure 6) During charge, the ions move from the micro pores in the active materials (coatings) of the aluminum cathode foil to the micro pores in the coating of the copper anode foil.¹³ The electrochemical process is known as intercalation and reverses during discharge, so that the lithium ions move from negative anode to positive cathode.





¹³ The surface of the negative anode forms a dense shell-like layer upon the initial cell charge and the layer is called the solid electrolyte interphase (SEI). The layer contains the porous materials which the lithium ions enter. The surface is visible in the section concerning dendrites and charge transfer.



between cavities in the graphite cathode and metal oxide complexes in the anode.

Figure 6. More detailed version of Figure 5, showing the lithium ions intercalating into the layers of the anode and cathode. Source: http://www.sneresearch.com/eng/info/show.php?c_id=4932&pg=4&s_sort=2&sub_cat=&s_type=&s_word

A microporous thermoplastic film known as the separator allows movement of the ions while keeping the anode and cathode from making contact, which would short circuit the cell. (See Figure 7 and Figure 8)



Figure 7. Constituents of a LIB cell, beyond what is shown in Figures 5 and 6. The blue color shown to be the electrolyte is a liquid in the LVP65 cells. Source: http://www.mpoweruk.com



Figure 8. Graphic depicting conceptual detail about the porous nature of the electrodes. Source: ROADMAP http://www.nrel.gov/docs/fy13osti/54404.pdf

The lithium ions move between the anode and cathode through a fluid electrolyte in the LVP65 battery cells.

For context in lay terms, the layers shown in Figure 7 and Figure 8 are similar to two layers of kitchen aluminum foil painted flat brown/black when discharged. The color changes to red or gold when charged. The separator material resembles an opaque plastic-wrap between the metal sheets. The electrolyte is similar to light machine oil, clear hydraulic fluid, or thin cooking oil in feel and appearance.

CHARGE RATE FUNDAMENTALS:

The charge and discharge rate of a battery is known as the C-rate. The capacity of a battery is given in ampere-hours (Ah). At a rate of 1C, the battery will charge or discharge the amp-hour (Ah) capacity in one hour. At 0.5C a battery would require 2 hours to completely charge or discharge.¹⁴

The maximum rate for charging and discharging cells has been the subject of extensive research into lithium plating and creation of dendrites which occur when the lithium ions do not intercalate into the carbon of the anode. Metalllic lithium can

¹⁴ Example explanation: http://batteryuniversity.com/learn/article/what_is_the_c_rate

instead build on the surface and potentially short circuit the cell windings. As excerpts from a presentation on the topic:¹⁵

• Li intercalation in graphite occurs $\sim 100 \text{ mV}$, while Li deposition takes place at < 0 v, vs. Li.

• Conditions where Li intercalation kinetics are hindered, the anode potential goes below Li plating potentials

- High rate charge
- $-Low \ temperature$
- Poor interfacial conditions unfavorable for Li intercalation.
- Factors influencing Li plating
- *Nature of electrolyte*
- *Nature anode composite electrode*
- Cathode to anode ratio

• Cell designs are generally cathode limited. However, if anode is sufficiently in excess, it may polarize anode heavily.

• Cathode/anode ratio may change upon cycling/storage, due to more degradation at the anode,

The authors of the above example into research results explained the requirement for "reduced kinetics [charging] for intercalation at low temperatures" as

- Charge acceptance at various rates and temperatures
- Effect of charge voltage
- Effect of charge current and taper current cut-off
- Effect of electrolyte (and corresponding SEI layers formed) Upon charge characteristics
- Identification of conditions which lead to lithium plating

In June 2013, GS-Yuasa engineers described how the limits of a battery's charge and discharge capability would decrease as temperature departed from an optimal range. A similar description was found in a NREL presentation. (See Figure 9)

¹⁵ The work described was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, for the NESC Advanced Battery Technology Program, under contract with the National Aeronautics and Space Administration (NASA). NASA Battery Workshop, Huntsville, Alabama, on November 27-29, 2007, by M. C. Smart, L. D. Whitcanack and B. V. Ratnakumar.



Figure 9. Charge and discharge capabilities are reduced at higher and lower temperatures, as shown in this graphic. Charge is shown in yellow (downward). Note that the temperature values shown are only applicable to the battery model for which this graphic was created.

The GS-Yuasa engineers related that the LVP65 battery was originally designed to charge at 65 amperes. Due to a cooling limitation for the charger, the charger was limited to 46 amperes, resulting in the battery charge rate of 0.7C.

The Securaplane BCU provides a constant current charge mode at a maximum of 46 amperes +/-1 Amperes between -15 to 65 degrees C, then constant voltage when battery voltage reaches 32.2 V. (Changed to 31.9V for the system involved in the January 2014 event.)

AIRPLANE AND BATTERY INVESTIGATION:

DESCRIPTIONS OF SMOKE AND ELECTROLYTE RELEASE:

The mechanic on the scene and his supervisor were interviewed Immediately following the battery failure at Boston by the Airworthiness Group Chairman. The mechanic spoke less English and the supervisor provided translation assistance. Asked about the flames seen, the two worked together to make the following sketch in the Group Chairman's notebook, noting that the flames were at the connector and not from the lid of the battery box. (See Figure 10)



Figure 10. From the Airworthiness Group Chairman's on-scene notebook, this shows a sketch of battery box and flames made by the mechanic and his supervisor. For scale, the height of the original sketch is 1.25 inches.

Both of the 2013 JAL and ANA LVP65-8-402 battery failures resulted in loss of electrolye from cells and each battery had smoke and blackened electrolyte emanate from their blue battery cases. However, in neither case was flame damage found surrounding the positions of the batteries.

In the Boston airplane, little damage was found to systems or secondary structure and there was no impact on primary structure. Burning electrolyte burned the resin out of the fibers of the composite floor panel, without evidence of flame or continuing damage away from where the electrolyte had been.

Smoke was released in all three events. In Boston, the source of ventilation power was not available and the cabin became partially obscured. In the Takamatsu event, the ventilation system was working and only enough smoke reached the cockpit and cabin that occupants reported awareness of a smell.

Smoke emanated from one cell in the LVP65-403 battery during the 2014 JAL event. The change to the mounting design prior to the 2014 event routed material vented from a failed cell out of the battery box that contained the remaining cells. The design concept for the stainless steel case that was added after the 2013 failures provided overboard venting of electrolyte and smoke to prevent entry into the general fuselage environment.

AIRPLANE COMMONALITIES, FLEET DATA, WEATHER EXPOSURE:

The failures involved three separate airplanes and both battery installations with the following descriptions that are based in available information:¹⁶ (See Table 1)

Property	In all three events	In less than three events
Home weather	All three airplanes were	
area	based at separate Tokyo area	
	airports. Narita and Haneda	
	are 47 miles (77 km) apart.	
Time of year	January. JA804A	
	and JA829J events occured	
	in January 2013	
	JA834J occured in January	
	2014	
Cell	The cell electrochemistry is	
electrochemistry	not known to have been	
	changed during the battery	
	and mounting redesign.	
Operator		JA829J and JA834J operated by
		Japan Airlines, JA804A by All
		Nippon Airways.
Age		At the time of failure JA804A had
		flown for about a year, JA834J had
		about seven months; JA829J was
D1 1		less than a month after delivery.
Physical		JA804A and JA834J in forward
location in		E/E, JA829J in aft E/E
airplane		
Installation		JA829J and JA804A had original
		style of battery installation. The
		design of the mounting enclosure
		had been changed before the
		sther changes
		Main and ADL load mofiles are
Electrical load		shown in the soction show
		shown in the section about
		endurance testing.

Table 1. Properties found in the three events.

¹⁶ Information pertaining to the January 14, 2014 event only includes what has been publicly released, or which pertains to the redesigned battery installation that by January 14, 2014 had been installed in all 787 airplanes.

¹⁷ JA804A was built as Boeing Line #9, first flight January 19, 2011. For date of battery replacements see Manufacturing Group Chairman Factual Report. JA829J was built as Boeing Line #84 first flight December 7, 2012. JA834J was built as Boeing Line #98, with the first flight on May 16, 2013.

As of January 16, 2013, the 787 fleet world-wide consisted of 49 airplanes and the region where each was based for operations and maintenance was examined. (See Table 2¹⁸)

Table 2. Airplanes delivered at the time of the Boston and Takamatsu 787 battery failures. The table shows outdoor temperatures at the locations where airlines conducted primary 787 operations and maintenance. Not shown are the identifications of airlines which did not experience battery failures.

Customer Name	Outdoor temperature from first airplane delivery through January 7, 2013 ¹⁹	First Delivery Date	Total
Airline A	3F - 58F -16.1C - 14.4C	09-Nov-2012	2
Japan Airlines	17F - 93F -8.3C - 33.9C	25-Mar-2012	7
All Nippon Airways	19F - 95F -7.2 - 35C	25-Sep-2011	17
Airline B	30F - 92F -1.1 - 33.3C ²⁰	22-Sep-2012	6
Airline C	32F - 90F 0C - 32.2	28-Aug-2012	3
Airline D	33F - 96F 0.6C - 35.6C	05-Sep-2012	5
Airline E	41F - 77F 5C – 25C	14-Aug-2012	4
Airline F	54F - 88F 12.2C - 31.1C	20-Nov-2012	5
TOTAL			49

As of the end of January 2014, Boeing delivered 118 airplanes.

With the exception of where Airline A was located, Tokyo was found to be the coldest of the primary operation and maintenance centers and of the locations listed above. Only the Tokyo area airports had been below 0°C on more than two occasions since delivery. Twice while passing through Narita International Airport in March 2014, the Airworthiness Group Chairman observed 787 airplanes with open E/E (once forward and once aft) doors with nearby ladders. A similar scene is shown in a press photo. (See Figure 11)

¹⁸ Source:

http://active.boeing.com/commercial/orders/index.cfm?content=userdefinedselection.cfm&pageid=m1 5527

¹⁹ Source: Wunderground.com data, which is collected from more than 32,000 weather stations.

²⁰ Combined data for the two cities used for 787 operations and maintenance. The two sub-freezing nights in one city were 31F on December 27 and 30F on December 30, 2012.



Figure 11. AP (press) photo at unidentified airport, showing ladder beneath open forward E/E hatch (AAP) similar to two 787 airplanes seen by NTSB Group Chairman.

Airline A began to operate the airline's first 787 airplane on December 14, 2012, three weeks prior to the Boston battery failure. Discussion with an engineering manager at Airline A revealed that operations and maintenance during cold weather was normal for their maintenance personnel. The 787s in service received most maintenance at night and were generally parked at gates, connected to the terminal and with available ground power. Access to the main battery could be achieved from the ground or from the forward galley. He noted that access from the forward galley did not require a ladder to be brought to the airplane and that the mechanics, parts, and tools would not be exposed to the elements. The APU battery may could be reached through the aft cargo compartment to provide the same beneifts, if the cargo compartment were not in use. A single airplane is rotated out of service each day for maintenance and that airplane has little winter opportunity to cold soak due to occupation by the staff.²¹

As shown in the Airworthiness Group Chairman's Factual Report, each battery is located within an arm's reach of an exterior hatch for maintenance personnel. The JA829J airplane had primarily been parked outdoors and undergoing modifications to enter service between December 22 and December 27, 2012.²²

Two sources of outdoor temperatures were used to document outdoor temperature histories for the dates and approximate locations of the JA829J and JA804A airplanes. There were no recordings to document precisely when the exterior doors next to the batteries may have been open or when the airplanes had been unpowered long enough to cold soak.

²¹ For the purposes of investigation, a four hour period was used as a reference for cold soak. This was based on flight test data form Boeing and separately from JAL.

²² See Appendix A for specific dates and times.

The data from the Japan Meteorological Agency (JMA) is the official temperature for each location shown in Japan and is from a single location at each airport. Some airports had a range of potential conditions due to size or local conditions, such as ramp areas near water. Commercial data was obtained in recognition that the singular sample location reflected in JMA data may not represent temperatures elsewhere in an area. While the data is considered to be best available, Figure 12 illustrates that variations exist for single locaitons. (Values are shown in Appendix A)

The lowest temperature for an approximate location where JA829J transited was -11.1C and for JA804A was -2.6C. The lowest temperature for a location where JA829J stayed for more than four hours was -8.3C and for JA804A was -2.6C.



Figure 12. JAL and ANA 787 coldest daily outdoor temperatures for exposure of the JA829J and JA804A airplanes. Data is from Appendix A with the X-axis representing November 26, 2012, to January 7, 2013. The axis is not labeled to account for two potential separate cold data points in a 24 hour period. For example, one may be a morning data point and the second during the evening.

BOEING 727, 737, 777, AND 787 OPERATIONAL TEMPERATURE RANGES:

Boeing Models 727 and 737 batteries of the nickel-cadmium type of construction are described in a Boeing document that was dated April 5, 1991, which refered to military specifications MS24497-5 and MIL-B-26220. Full charge of the battery was required to be accomplished within 90 minutes and the operating temperature range was -30°C to +71°C.

The Boeing 777 was designed with a nickel cadmium (NiCad) main aircraft battery. The operational temperature range is 0°F to 160°F (-18°C to 71°C). The system was required to fully recharge the battery within 60 minutes.

As noted in the Airworthiness Group Chairman's Factual Report, Boeing specified the 787 operational temperature range to be -18°C to +70°C. The system was required to charge the battery within 75 minutes.

The 787 Airplane Maintenance Manual (AMM) Section 12-33-02-01A limited cold weather operation when cabin or flight deck temperatures drop below -15°C prior to the Boston event and was later changed to 0°C. At lower temperatures the AMM calls for removal of batteries from the airplane, including the main and APU batteries.

ADDITIONAL BATTERY REQUIREMENTS, BOEING 787:

Boeing requirements and compliance findings were examined, with the following extracted for this report. (See Table 3)

Requirement	Compliant analysis based on endurance
	test
The battery shall have service life	The battery is able to operate after 5
corresponding to 5 years under any	years under endurance condition as
combination of operating condition	shown [deleted section numbers], the
specified herein.	result of endurance test of standby system
	operation and endurance test of APU
	start attempt application are shown.
The battery shall operate as defined	The battery is able to operate between -
between	18°C
-0.4°F (-18°C) and +158°F (+70°C).	$(-0.4^{\circ}F)$ and $+70^{\circ}C$ $(+158^{\circ}F)$ as shown
	in [deleted section numbers]. No
	abnormal phenomenon occurred within
	this temperature range.
The Battery shall be capable of accepting	Charging processes below 0°C are
[redacted] [ampere charge] with an	included in endurance test. Although the
internal temperature between -18°C (-	charge acceptance capability becomes
$0.4^{\circ}F)$ and $0^{\circ}C$ (32°F).	low, the it [sic] was clear that the battery

Table 3. Excerpted requirements and findings from a Thales/GS-Yuasa report.

	is able to accept 47 A with an internal temperature between $-18^{\circ}C$ (-0.4°F) and $0^{\circ}C$ (32°E) in endurance test
The battery shall reach [redacted] Ah capacity from full discharged state within 75 minutes at ambient temperature $25^{\circ}C$ +/- $10^{\circ}C$ (77°F +/- $18^{\circ}F$) for 30,000 flight hours.	The battery is able to reach [redacted] Ah capacity from full discharge state within 75 minutes as long as battery capacity has [redacted] Ah. Because it is clear that the battery has the discharge capacity more than [redacted] Ah after 5 operation years as shown in [deleted Figure numbers], battery can comply with this requirement
The battery end of life rated capacity shall be [redacted] Ah or greater.	[a greater number which has been redacted] Ah after 5 years under APU endurance condition [a greater number which has been redacted] Ah after 5 years under APU endurance condition.

BATTERY AND CELL FINDINGS:

The LVP65 cells are a rectangular shape that is termed a prismatic cell shape. (See Figure 13 and Figure 14) The LVP65 has three windings within a metal can that resembles the GS-Yuasa LIM series of industrial batteries in general shape and construction. The LIM series pre-dates the LVP65 series. Cell Model LVP65-8-402 "with improved lithium cobalt dioxide" was the design in the LVP65-8-402 battery aboard the 787 involved in the Boston battery failure of January 7, 2013.



Figure 13. GS-Yuasa Lithium ion individual cell and group of seven cells as a battery.

NOTE: The 787 flight control electronics system (FCE) batteries provide emergency power for the digital flight control electronics systems and each of the shorter LVP10 cells have a single winding. The FCE battery is manufactured by ELDEC for

Honeywell, using GS-Yuasa cells. The following GS-Yuasa photo shows the batteries together and information about the FCE battery assembly is in a later section of this report.



Figure 14. The shape of the eight LVP65 cells used in each main and APU battery.

The anode/separator/cathode foil sets in each are rolled into windings and within each cell are three windings. The external positive and negative terminals at the top of the cell connect internally to the individual winding foils with finger-like collectors. (See Figure 15 and Figure 16).



Figure 15. Exploded view of cell to show current collectors and other cell components.



Figure 16. Major cell components and electrode layering.



During interviews at GS-Yuasa in June 2013, engineering personnel at GS-Yuasa repeatedly stated that the manufacture of the LVP65 cells was similar to the process previously used to make more than 11,000 industrial LIM series of battery cells.²³ During the engineering interviews, GS-Yuasa personnel related that the specification for the maximum charge included a tolerance for manufacturing variations. Also stated during the interview was that none of the LIM series of cells had failed in thermal runaway.

GS-YUASA EXAMINATION OF QUALIFICATION TEST CELLS:

Review of GS-Yuasa test documents from the LVP65 testing found photographs of the unwound cells. The photographs also showed the electrodes as black surfaces and not the gold color that develops during charge and provides a stark contrast of uncharged areas (See Figure 17) GS-Yuasa engineering personnel related that the company did not perform DPA examinations on charged cells, due to the potential danger of cell discharge and combustion during the disassembly.

²³ The chemistry was different for the LVP airplane battery cells and the LIM cells.



Figure 17. Examination of the disassembled LVP65-002 cell windings after the endurance test. (GS-Yuasa)

LITHIUM DENDRITE INFORMATION:

During meetings at GS-Yuasa in June 2013, GS-Yuasa engineering personnel provided the following description about lithium dendrite formation: (See Figure 18)



Figure 18. The above is a GS-Yuasa explanation about dendrites which was provided in meetings of June 2013.

The mechanism of dendrite creation has been extensively documented in LIB research and is available in public literature. The limits of intercalation in a cell include factors such as viscosity resistance to lithium ion movement in the electrolyte, distance between the anode and cathode, anode and cathode coating thicknesses, separator properties, and temperature effects on the anode and cathode coatings. Once all other factors are established, charge current is the controlling function for dendrite formation.

Research into these properties with respect to creation of lithium dendrites and their effects continue, as shown in the following from a research paper titled "Exposing The Roots Of The Lithium Battery Problem," dated December 17, 2013, by DOE/ Lawrence Berkeley National Laboratory.²⁴

Researchers have discovered that the dendrite problem that can cause lithium-ion batteries to short-circuit, overheat and possibly catch fire originates below the surface of the lithium electrode and not at the surface as has been widely believed.

Over the course of several battery charge/discharge cycles, particularly when the battery is cycled at a fast rate, microscopic fibers of lithium, called "dendrites," sprout from the surface of the lithium electrode and spread like kudzu across the electrolyte until they reach the other electrode. An electrical current passing through these dendrites can short-circuit the battery, causing it to rapidly overheat and in some instances catch fire.

Exponent Engineering and Scientific Consulting (Exponent) is one laboratory with extensive LIB experience and authors from Exponent gave a presentation on November 19, 2009 entitled "From Lithium Plating to Lithium-Ion Cell Thermal Runaway."²⁵ The presentation stated that:

In lithium plating, lithium ions deposit as metallic lithium on the negative electrode surface during charging instead of intercalating into graphite.

How exactly does lithium deposit? Current research suggests: Initially, lithium dendrites grow as an extrusion process – lithium deposits at the base of the dendrite and push the tip through a weak spot in the SEI. In later stages, lithium will deposit at dendrite tips and kinks.

Negative effects of plated lithium: Irreversible loss of lithium Dendrites can cause shorting within the cell

²⁴ Source: www.sciencedaily.com/releases/2013/12/131217134710.htm

²⁵ Authors: Celina Mikolajczak, John Harmon, Priya Gopalakrishnan, Ramesh Godithi, Ming Wu, Proceedings, 27th International Battery Seminar & Exhibit for Primary & Secondary Batteries, Small Fuel Cells, and Other Technologies, Ft. Lauderdale, FL., March 15-18, 2010.

A mat of dendrites and dead lithium can increase the likelihood that a minor short will lead to a cell thermal runaway.

Microphotographs of a sectioned dendritic growth may show tree-like rings, as shown by Exponent. (See Figure 19).



Figure 19. A sectioned single dendritic growth, projecting upward from the anode. Ring-like growth patterns are visible. Photo: Quinn Horn, Exponent.

Regarding dendrite creation and as stated by the Purdue School of Materials Engineering:^{26 27}

Dr. David Ely and Prof. R. Edwin Garcia have identified the different ways in which Li-ion batteries can develop dendrites during recharge. The formation of these defects is of great importance because its nucleation precedes internal short-circuiting and even battery ignition.

Fundamentally, the performed research proposes a Universal roadmap to allow experimentalists and theoreticians alike to explore the different regimes of behavior during battery recharging, and enables researchers to identify the charging conditions that will favor complete suppression (or at least minimization) of lithium aggregates. The work readily explains available in situ experimental data and reconciles conflicting existing theories as they were reported during the 1990s and early 2000s. (See Figure 20)

²⁶ https://engineering.purdue.edu/MSE/ResearchFocus/dendrite-suppression-to-curtail-lithiumion-battery-failure

²⁷ http://phys.org/news/2013-03-analytical-theory-lithium-ion-batteries.html



Figure 20. Lithium dendrite formation map developed by Dr. David Ely and Prof. R. Edwin Garcia at Purdue University.

The lithium dendrite formation map above relates to the following Purdue description.

Horizontal axis corresponds to battery charging state, and vertical axis corresponds to the initial size of the (lithium) deposit. Regimes of behavior during the initial stages of nucleation and growth are:

1) Dendrite suppression, below the blue curve (improved battery life);

2) Dendrite growth regime, above the black line (will lead to battery failure and ignition);

3) Long incubation time regime, between the blue curve and the black curve (during battery storage and lasts from days to months); and finally,

4) Short incubation time regime, in the vicinity of where the blue and black curves merge (during fast recharge rates).

Continuous gray curves highlight charging states of constant dendrite incubation time.

Dashed gray curves show the initial growth velocities of the stable nuclei.

Inset (a) exemplifies a lithium dendrite internally short-circuiting a battery. The micrograph is courtesy of Quinn Horn.

By starting from fundamental principles, the heterogeneous nucleation and growth of electrodeposited anode materials is analyzed. Thermodynamically, we show that an overpotential-controlled critical radius has to be overcome in order for dendrite formation to become energetically favorable. Kinetically, surface tension and overpotential driving forces define a critical kinetic radius above which an isolated embryo will grow and below which it will shrink. As a result, five regimes of behavior are identified: nucleation suppression regime, long incubation time regime, short incubation time regime, early growth regime and late growth regime. In the nucleation suppression regime, embryos are thermodynamically unstable and unable to persist. For small overpotentials, below a critical overpotential, $2\eta \circ$, and between the thermodynamic and kinetic critical radius, a metastable regime exists where the local electrochemically enabled Gibbs-Thomson interactions control the coarsening of the embryos, thus defining the long incubation time regime. In addition, very broad nuclei size distributions are favored. For large overpotentials, above 2 °, a short incubation time regime develops as a result of the small energy barrier and large galvanostatic driving forces. In addition, very narrow size distributions of nuclei are favored. In the early growth regime, thermodynamically and kinetically favored nuclei grow to reach an asymptotic growth velocity. Finally, in the late growth regime, morphological instabilities and localized electric fields dominate the morphology and microstructural evolution of the deposit.

DENDRITIC FORMATIONS:

Researchers at the Naval Research Laboratory (NRL) in Washington, DC, have created dendrites in experimental LIB cells under controlled circumstances to isolate variables related to dendritic creation and growth. NRL Principle Researcher Dr. Corey Love provided information about his work in the creation of lithium dendrites at a range of specific temperatures, in part to examine the relation of temperature to dendrite morphology. He reviewed microphotographs and data from this investigation and provided the following text about dendrites and their creation:

Dendrites likely nucleate from areas of surface inhomogeneities or disruptions in the surface layers which lead to non-uniform current distribution during charging. In this case it appears the dendrites are nucleating at locations where there is significant variation in the local stateof-charge originating near the wrinkles seen in the electrode foils. This could induce localized overcharging which would not necessarily be detectable in the cell voltage.

The dendrites originate from areas of full state-of-charge and extend into areas of lesser lithium concentration. Lithium ion is reducing to lithium dendrites at the steep lithium ion concentration gradient between the gold and red-brown sections of the anode. Below is a figure from my data which shows the color change of a carbon anode when it becomes lithiated. The figure at left shows an experimental cell of lithium metal (left) vs. carbon anode (right) before lithiation. The figure at right shows the various stages of lithiation as evident by color changes to the carbon anode. The varying levels of lithium concentration are given by color: high concentration (gold), moderate concentration (red-brown), low concentration (dark blue) and non-lithiated carbon (gray). The dotted lines are provides to aid in the distinction of these regions. (See Figure 21)



Figure 21. Distribution of charge as color change of a lithiated carbon anode. The bubble seen in the electrolyte [of the right microphotograph] formed after charging and impeded ion mobility during the discharge process. The bubble could be thought of as unoccupied free volume within a cell, such as a void left behind by a wrinkle in the electrode foils. Source: Dr. Corey Love, Naval Research Laboratory.

The more wrinkles or free volume within the cell the more likely you will establish this steep lithium concentration gradient during cycling. This could be due to the fact it is difficult for lithium ions to migrate through the "void" areas of the anode materials have become delaminated from the copper current collection. If anode materials was delaminated it would lose electronic contact and become electrochemically inactive. In either case, when the ratio of anode to cathode capacity decreases lithium deposition is likely.

Once the dendrites form, they likely grown quickly with each repeated charge/discharge cycle especially at sub-ambient temperatures where mass transport of lithium ion in the electrolyte is reduced and intercalation kinetics are impeded. During cell discharge it is easier for the lithium intercalated into the carbon anode to shuttle back to the cathode and intercalate into the $LiCoO_2$ than for the lithium dendrite to release Li cation to the cathode. Therefore each charge cycle grown the dendrite more and more. Low temperatures also increase the growth rate.

The steep lithium concentration at the gold/red-brown interface is even more unstable at low temperatures. Slow mass transport of ions and intercalation kinetics at low temperature exacerbates the instability at the interface of lithium concentration mismatch.

Dendrites can induce an internal show by at least 2 mechanisms. First, a single dendrite may grow and ultimately make contact with the opposing electrode surface (this typically involves piercing the polymer separator) causing a "hard" short. Second, some dendrites may form small brittle lithium structures which easily break off and form metallic lithium debris. If these particles are mobile they can form a continuous network initiating a "soft" short.

Typically dendrites formed at low temperature are more "spiky" and appear as micron-scale extruded wires [similar to the UL microphotographs show] rather than mossy porous deposits.

In summary, my observation is the dendrites are forming at the interface between the fully and partially lithiated graphite. Low temperature exposure or sub-ambient thermal excursions will induce uncontrolled dendrite growth.

The electrolyte electrical resistance is measured in terms of distance and the wrinkles found in disassembled cells presented step changes in distance, creating localized variations. Dr. Love and the UL researchers related that uneven charge transfer may result in localized variations in lithiation, leading to lithium dendrite formation at the edges of a wrinkle. The excess localized transfer of lithium ions is known as overlithiation.

LVP65 CELL PERFORMANCE TEST RESULTS:

In meetings of June 2013, GS-Yuasa personnel provided data relating the electrical resistance properties of the LVP65 electrolyte over a range of temperatures. The electrical resistance of the electrolyte did not exhibit a straight relationship to the temperature, becoming increasingly more resistive as the temperature decreased. (See Figure 22)



Plots of ratio of internal DC resistance versus temperature (LVP65 cell)

DC resistance is achieved from the slope of the relationship between cell voltage and discharge current during the discharging. Ambient temperature was set from -18 to 70 degree C.

Figure 22. Electrolyte resistance data pertaining to temperature response, as provided by GS-Yuasa engineering personnel in June 2013.

TESTS WITH ELEVATED TEMPERATURES:

Per Dr. Doughty at the NTSB Battery Forum, the chemical reaction rate approximately doubles for each 10°C of temperature increase.

Mobile devices are tested to elevated temperatures for compliance with IEEE Standard 1625 (2008) for Rechargeable Batteries for Multi-Cell Mobile Computing Devices, and the IEEE Standard 1725 (2011) for Rechargeable Batteries for Cellular Telephones. In response to well publicized battery failures, certification to IEEE 1625 is a requirement for manufacturers supplying cells, batteries, adapters netbooks, and other wireless communication devices to leading telecom providers in the USA. These standards require testing at elevated temperatures.
GS-YUASA NAIL PENETRATION, CELL-LEVEL TEST:

GS-Yuasa documented how a nail penetration test was conducted and the results of the test.²⁸ The test used a single LVP65-002 cell with improved positive active material. The section describing the test objective stated that:

This test is conducted in order to confirm the safety when hard short circuit occurs. Although nail penetration is not authorized method, this method is simple one to make hard short of cell.

The cell was charged to 100% SOC and penetrated at the center of the largest face of the cell by the nail with a diameter of [omitted], while in ambient temperature condition of $15 \pm 10^{\circ}$ C (See Figure 23)



Fig. 5.3-1 Setup of nail penetration test of cell

Figure 23. Setup of GS-Yuasa nail penetration test of cell, as shown in GS-Yuasa test record.

The test report stated that:

Just after the nail penetrated the cell, cell voltage suddenly dropped to 0V, and smoke emitted from the rupture valve of cell. [See Figure 24) Test result was vent, smoke, no fire and no explosion. The cell voltage and temperatures were recorded during the thermal runaway of the cell. (See Figure 25)

²⁸ Thales/GS-Yuasa Battery Verification Report [number redacted]



Fig. 5.3-2 Appearance of cell in nail penetration





Figure 25. GS-Yuasa record of the cell voltage, cell temperatures during nail penetration test.

CELL SMOKE GENERATION AND 787 SMOKE EVACUATION:

GS-Yuasa overcharged a cell to failure and documented the volume of gas emitted from the cell during venting and documented that a fire resulted.²⁹ The GS-Yuasa test report showed that a single cell emitted [omitted] cubic feet of gas and the report stated that "Gases generated from cell catches fire. Therefore, it is impossible to measure the gas volume actually."³⁰ The estimated rate of gas generation was [omitted] cubic feet /s. (See Figure 26)



Figure 26. Temperature and venting of cells during intentional overcharge abuse testing.³¹

Boeing performed flight tests for smoke evacuation in the mid and forward E/E. The smoke generator in the mid E/E was placed almost directly in front of the APU battery. Smoke was generated for 20 and 35 second periods at altitudes of 3,000 to 43,000 feet. A report of November 14, 2011, showed that on October 25, 2010, the environmental control system cleared the smoke in the acceptable time and the smoke did not enter occupied areas.³²

²⁹ Thales/GS-Yuasa Battery Verification Report [number redacted]

³⁰ Boeing personnel noted that their volumetric measurements of gas emitted form a cell were different in post-incident testing.

³¹ Source: Thales/GS-Yuasa Battery Verification Report [number redacted]

³² Boeing Document [number redacted]

In the Takamatsu event, the ventilation system was working and only enough smoke reached the cockpit and cabin that occupants reported awareness of a smell.

BOEING LIFE CYCLE REQUIREMENTS AND GS-YUASA QUALIFICATION:

Boeing, GS-Yuasa, and Thales provided thousands of pages of documentation and test results. GS-Yuasa has also published LVP65 and LVP10 temperature related characteristics. The testing included performance at the temperature limits of +70°C and -18°C.³³ (See examples in Figure 27 through Figure 32. The following section shows the relative amounts of testing conducted at the extremes of temperature.)

The data included life cycle performance at two temperatures and the life cycle test ended at 2,500 cycles.³⁴. (See 30for a partial example) The test plan did not call for full battery and individual cells cycling to failure during charge/discharge cycles at the upper and at the lower limits of the operating temperature range.



Fig. 4 Discharge characteristics at various currents of 10 A (\Box), 30 A (\triangle), and 50 A (\bigcirc) at 25 °C for LVP10 type lithium-ion cells. The cells were discharged to 2.75 V after charged at 10 A to 4.0 V for 3 hours in total at 25 °C.

Figure 2127. GS-Yuasa data conveying LVP10 discharge characteristics at 25°C.

http://www.gs-yuasa.com/us/technic/vol7/pdf/007_01_014.pdf

³³ Thales/GS-Yuasa proprietary documents contain these and extensively more performance data. What is shown was made publicly available by GS-Yuasa and is shown as examples. Source:

³⁴ Source: Thales GS-Yuasa [number redacted]



Fig. 5 Discharge characteristics at various currents of 50 A (\bigcirc), 200 A (\triangle), and 700 A (\square) at 25 °C for LVP65 type lithium-ion cells. Cells were discharged to 2.75 V after charged at 70 A to 4.025 V for 3 hours at 25 °C.

Figure 28. GS-Yuasa data conveying LVP65 discharge characteristics at 25°C.



Fig. 6 Discharge characteristics at 50 A under various temperatures of 25 °C (\bigcirc), 0 °C (\triangle), and -20 °C (\square) for LVP65 type lithium-ion cells. Cells were discharged to 2.75 V after charged at 70 A to 4.025 V for 3 hours at 25 °C.

Figure 29. GS-Yuasa data conveying LVP65 discharge characteristics at three temperatures.



Fig. 7 Charge and discharge cycle life performance for LVP65 type lithium-ion cells with cycling under 25 °C (\bigcirc) and 45 °C (\triangle). The cells were discharged to 2.75 V at 70 A after charged at 70 A to 4.025 V for 3 hours in total at 25 and 45 °C.

Figure 30. GS-Yuasa data conveying charge and discharge cycle life performance at two temperatures.



Fig. 8 Calendar life performance for LVP65 type lithium-ion cells under floating conditions of 4.025 V at 25 °C (\bigcirc) and 45 °C (\triangle). The cells were charged at 70 A to 4.025 V at 25 and 45 °C. Capacity was checked periodically to confirm the retained cell capacity at the discharge condition of 70 A to 2.75 V at 25 °C.

Figure 31. GS-Yuasa data conveying LVP65 calendar life performance at 25°C and 45°C.



Fig.11 Discharge performances of LVP65-8 type lithium-ion batteries for engine start under various temperatures of 25 °C (\bigcirc), 0 °C (\triangle), and -18 °C (\square). Fully charged batteries were discharged at constant power of 15 kW.

Figure 32. GS-Yuasa data conveying LVP65-8 discharge performance for engine start at three temperatures, including -18°C.

NOTE: The following section includes parts of the text and illustrations for requirements found in a Thales/GS-Yuasa document that relate to the temperatures and cycles which battery cells were qualified to. To limit proprietary disclosure, the full requirements and specific test results are not included.

Boeing, Thales, and GS-Yuasa engineering personnel related that Boeing provided a set of requirements which GS-Yuasa used to demonstrate battery life as a repetitive series of temperatures for charge and discharge cycles. These requirements and test results were documented in a Thales GS-Yuasa report.³⁵ An excerpt from the text for this endurance test stated that:

MAIN/APU batteries are installed in *E/E* bay of airplane. Environment condition and operation pattern is defined in SCD. Temperature varies from -18° C to $+70^{\circ}$ C, and charge/discharge cycle is defined as follows.

- Power down followed by power up (standard day case): 41 cycles per year
- Power down followed by power up (worst case): 1 cycle per year

³⁵ GS-Yuasa/Thales Report [number redacted]

• APU start: 34 single start per year, 3 successful 3 consecutive start per year

In 2006, Boeing provided the endurance test plan for MAIN battery and APU battery, which determines the test conditions of the endurance cycle life test. The objective of this test is to accelerate the degradation of the cell by changing the temperature frequently with a short interval and increasing the charge/discharge cycle number. Although the test condition is different from one of NiCad battery, this acceleration cycle life test has been applied to the existing NiCad batteries for aviation use.

This section shows the result of endurance test performed in accordance with the test condition specified by Boeing in June 2006. This test consists of two types of test. One of them is for Main battery (standby system application (section 4.2)), and another one is for APU battery (APU system application (section 4.3)). During the test, fundamental discharge performance was checked to verify the cell performance periodically.

This test result has been reported to Thales and Boeing in past Technical meeting.

The Airworthiness investigation examined documentation pertaining to the tests conducted with respect to performance evaluations and to qualification of the battery and cell components. The following is from a de-identified Thales document:

4.2 TEST CONDITION4.2.1 Test condition of standby system operation

The system shall be operated at the duty cycle and output load requirements of Table 4.2-2. The simulated operational hours shall be accrued by repeated cycling of load cycle A of Table 1030 cycles total, with a rest period of up to two hours after every 5 cycles.

The capacity of the system at standby loading conditions shall be determined by subjecting it to cycle B after every 100 cycles of load cycle A at normal operating temperature. The capacity shall also be verified at the 1C rate after each sequence (step 13). Charging prior to step 13 shall be at $68^{\circ}F(20^{\circ}C)$.

The entire test shall represent 12 months of operation, or 2420 flight hours. The rest periods, the load cycle B conditions and the capacity checks shall not be considered as part of the operational hours. Stabilized battery temperatures shall be as shown in Fig. 4.2-1. Addendum Figure 33.] The detailed sequence of testing shall be as follows: [Addendum Table 4]

[Addendum Table 4] Table 4.2-1 Test condition of standby system				
operation	operation			
Step	Test condition	Test condition		
1				
1	1 ea	Cycle A	70	
2	[redacted] ea	Cycle A	40	
3	2 ea	Cycle A	70	
4	[redacted] ea	Cycle A	30	
5	[redacted] ea	Cycle B	45	
6	lea	Cycle A	-18	
7	[redacted] ea	Cycle A	20	
8	2 ea	Cycle A	-18	
9	[redacted] ea	Cycle A	10	
10	[redacted] ea	Cycle B	0	
11	[redacted] Ah capacity check at the 1C rate		20	
12	Hot soak for 6 hrs		70	
13	Repeat the above	Repeat the above sequence until each step has been		
	performed 5 times.			

This document names the following test period as "1 set". 1set = 5 cycles of step 1 to 12 in Table 4.2-1 = 12 months of operation, or 2420 flight hours

NOTE: The original version of the following table contained proprietary information unrelated to the battery and charge system. It has been synopsized to the following charge/discharge values: [Addendum Table 5]

[Addendum Table 5] Table 4.2-2 Standby system duty cycle and loading

Time (minutes)		
5 75 5	[redacted] [redacted] [redacted]	Amps Amps Amps
10	[redacted]	Kwatts
5	[redacted]	Amps
2	[redacted]	Kwatts
10	[redacted]	Amps
75	[redacted]	Amps
	<i>Time (minutes)</i> 5 75 5 10 5 2 10 75	Time (minutes)5[redacted]75[redacted]5[redacted]10[redacted]5[redacted]2[redacted]10[redacted]75[redacted]



Fig. 4.2-1 Temperature profile of the standby operation of the endurance test

[Addendum Figure 33, Document Figure 4.2-1] According to Thales, "This document was based on Boeing entry information coming from the B777 program and was adjusted for the B787 battery. This cycling profile was discussed and approved by Boeing."

4.2.2 Test condition of APU start application

Tests No. 1 and 2 together represent 6 months of operation and a total of 1210 flight hours. The battery shall be fully charged prior to the start of each test. In this document, test period of 6 months operation (test 1 and test 2) is indicated as 1 set.

a) Test No. 1

The system shall be operated at the duty cycle and output load requirements of Table 4.2-4 [Addendum Table 7] to simulate operational hours. Temperature profile is shown in Fig. 4.2-2. [Addendum 34] The simulated operational hours shall be accrued by repeating cycling of Table 4.2-4 load cycle A and load cycle B (Total 1485 cycles: 1260 cycles of load A and 225 cycles of load B). The rest periods shall not be considered as part of the operational hours. The detailed sequence of testing shall be as follows:

Step	Test	Temperature
1	· 28 ea. Cycle A followed by 5 ea. Cycle B, all	-
	at 23.8°C.	
	• Rest period of up to two hours.	
	• Repeat the above test an additional 4 times	
	for a total of 5 times (140 load cycles A and	
	25 load cycles B total)	
	• Hot soak the battery at $70^{\circ}C$ for 6 hours.	
2	Repeat step 1	[Redacted]°C
3	Repeat step 1	[Redacted]°C
4	Repeat step 1	[Redacted]°C
5	Repeat step 1	[Redacted]°C
6	Repeat step 1	[Redacted]°C
7	Repeat step 1	[Redacted]°C
8	• 28 ea. Cycle A followed by 5 ea. Cycle B, all	-
	at -12.2°C.	
	• Rest period of up to two hours.	
	• Repeat the above test an additional 4 times	
	for a total of 5 times (140 load cycles A and	

[Table 6] *Table 4.2-3 Duty cycle and output load requirement in APU endurance test.*

unrelated to the battery and charge system. It has been synopsized to the following charge/discharge values: [Addendum Table 7]

NOTE: The original version of the following table contained proprietary information

-17.8°C

25 load cycles B total) Hot soak the battery at 70°C for 6 hours.

9

Repeat step 8

[Addendum Table 7] *Table 4.2-4 APU start system duty cycle and loading (Test 1)*

Load Cycle A:	Time (minutes)	
A1 Discharge	0.75 5	[redacted] Kwatt
A2 Charge CCCV	5	[redacted] Amp
Load Cycle B:		
B1 Discharge	0.75	[redacted] Kwatt
B2 Charge CCCV	75	[redacted] Amp



Fig. 4.2-2 Temperature profile of the standby operation of the endurance test

Figure 34. According to Thales, "This document was based on Boeing entry information coming from the B777 program and was adjusted for the B787 battery. This cycling profile was discussed and approved by Boeing."

b) Test No. 2

A sequence of 25 discharge/charge cycles shall be performed 4 times. Detailed load cycle C is shown in Table 4.2-5. [Addendum Table 8] The battery temperatures for these tests shall be $25 \pm -5^{\circ}$ C except as noted. The 25 cycles sequence shall consist of the following:

- Discharge for 15 of the 25 cycles of Load Cycle C5 at 29.4°C +/- 5.6°C
- Discharge for 5 of the 25 cycles of Cycle C3 through C5 at 29.4°C +/- 5.6°C
- Discharge for 3 of the 25 cycles of Cycle C1 through C5 at 29.4°C +/- 5.6°C
- Discharge for 1 of the 25 cycles of Cycle C1 through C5 at 70°C
- Discharge for 1 of the 25 cycles of Cycle C1 through C5 at -18°C
- Following each of the above steps, th ebattery shall be subjected to a battery charge per step C6 of Table 4.2-5.

[Addendum Table 8] *Table 4.2-5 APU start system duty cycle and loading (Test 2)*

Repetitive Charge/Discharge	Time in Minutes	Loading
Load Cycle C		
C1 APU Unsuccessful Start Attempt	0.75	[redacted] Kwatts
C2 Rest Period	1 min	[redacted] Amps

C3 APU Unsuccessful Start Attempt	0.75	[redacted] Kwatts
C4 Rest Period	1 min	[redacted] Amps
C5 APU Unsuccessful Start Attempt	0.75	[redacted] Kwatts
C6 Battery CCCV Charge	75.0	[redacted] Amps

Cells were disassembled at the end of the endurance test. GS-Yuasa examinations found "No abnormal points (such as dent of current collectors or peal pf [sic] welded portions, etc.)" (See Figure 35)



Figure 35. Disassembly of LVP65-002 cell and examination results that followed the endurance test. (GS-Yuasa)

The cells windings were unwrapped to examine for condition, including for lithium dendrites. GS-Yuasa engineering staff in June 2013 interviews related that any dendrites would appear as "gray paste" on the black anode and that no gray paste was observed. (See Figure 17)

HIGH TEMPERATURE STORAGE TEST

GS-Yuasa performed a hot storage test, in which the battery was heated to 85°C for a period of 18 hours.³⁶ [Plots of data and other test details have been redacted]

Excerpts from the test summary included the following:

³⁶ GS-Yuasa/Thales Report [number redacted]

During the test, battery maintained the safe temperature. And no electrolyte leakage, no smoke and no fire observed. Battery case didn't have any damage after the test. "Checksum of inhibition 1" and "Inhibition of charging 1"shut off, when the battery temperature was higher than 70°C.

7.9.6 Summary of the high temperature storage test

... it was verified that the battery was able to maintain the safe temperature and safe pressure even after the battery was stored in the high temperature of 85°C. Additionally, no explosion, no electrolyte leakage and no damage of the battery were observed.

EXTERNAL SHORT CIRCUIT TEST

GS-Yuasa performed an external short circuit test with an ungrounded battery.³⁷ The initial battery voltage was 32.11 volts and the test was conducted with pre-heating the battery to 70°C. The short circuit was created with three feet of [diameter ommitted] electrical cable. As a result, peak current was [ommitted] amperes and the duration of the short circuit was 77 ms.

HIGH IMPEDANCE EXTERNAL SHORT CIRCUIT TEST

GS-Yuasa performed a high impedance external short circuit test with a Boeing representative present.³⁸ After the battery vented smoke, teardown found the vent discs intact. As noted in Table 7.13-2, the mass of each cell decreased and the teardown found that at least one plastic rivet seal had visibly melted at the tops of most cells. (See Addendum Figure 48) Excerpts from the report follow.

Preparation and adjustment before test

Before the test, battery voltage was 31.95 V. Short circuit impedance was measured before the test. Total circuit impedance was [ommitted] m-ohm.

Test result

The battery was maintained in the oven at 70 °C, after that performed high impedance external short circuit test. [deleted text] Fig. 7.13-5 showed the battery voltage and short circuit current during the test [Figure 36]. Fig. 7.13-6 showed the battery voltage and temperature profiles during the test Figure 37]. Fig. 7.13-7 showed the profiles of each cell voltage during the test [Figure 38]. [deleted text] Battery behavior was shown in Fig. 7.13-9. [Figures 39 through 46] Smoke or electrolyte fume was observed at 2 minutes after starting the test. After that, maximum amount of smoke or electrolyte fume were observed at 4 minutes after starting the test. At 5 minutes after starting the test, a few smoke or electrolyte were observed. At 7 minutes after

³⁷ GS-Yuasa/Thales Report [number redacted]

³⁸ GS-Yuasa/Thales Report [number redacted]

starting the test, smoke was not emitted from the battery. Table 7.13-1 [Addendum Table 9] summarized the result during and after the high impedance external short circuit test.

Item	Pass / fail criteria	Result	Pass/fail
Battery	- No explosion of the	During the test, smoke and	Pass
appearance	battery case	electrolyte fume was observed,	
during and	- no fire from the battery	however battery was no explosion	
after the test	box	and no fire from the battery box. In	
, , , , , , , , , , , , , , , , , , ,	- No electrolyte dripping	addition, no electrolyte dripping	
	from the battery box onto	from the battery box onto the floor.	
	the floor.		
Battery	-	Peak fault current was 3135 A and	Pass
behavior		average fault current was 1261 A.	
		Short circuit duration was 500 s or	
		more. (until 0 V)	
		Maximum temperature of the	
		battery inside was 287°C.	
		Maximum temperature of BMS	
		wire was 411°C.	
		Surface temperatures of the	
		battery were less than 100°C.	
BMU	During the test, confirm if	"Inhibition of charging 1" and	Pass
operation	the BMU shall operate in	"Checksum of inhibition 1"	
during the	accordance with	signals turned off because battery	
external short	[redacted]	temperature was 70°C or more.	
circuit test		"Inhibition of discharging 1"	
		signal turned off when the cell 3	
		was 2.1 V or less.	
		"Checksum of inhibition 2" turned	
		off when the cell 3 reached to 0 V.	
		(Delay time of the latched low	
		voltage was 10 s.)	
		"Battery fail" signal turned off,	
		when the battery voltage was 16.26	
		V. This indicates the failure of the	
		internal power supply due to the	
		low battery voltage.	
BMS wire	-	BMS wire was not burned after	Pass
		exposing high current, which is	
		high impedance short circuit test.	
		See Fig. 7.13-12	

[Addendum Table 9] *Table 7.13-1 Test results during and after the high impedance external short circuit*

Result of the investigation after the test

Table 7.13-2

[Addendum Table **10**] showed the result of the investigation after the high impedance short circuit test. This investigation was performed in order to check the battery state after the high impedance external short circuit test.

[Addendum Table 10] Table 7.13-2 Result of investigation after the test

Item	Pass / Fail criteria	Result	Pass/fail
BMU	BMU operation	After the external short circuit test,	Pass
operaton	check. BMU shall	battery voltage dropped 0 V. All of	
check and	output the signals in	BMU output signals turn off due to the	
thermistor	accordance with	lost of the power source (battery	
check	[redacted]	voltage)	
Mass	-	[Each cell mass was measured before	Pass
measurement		and after the test, revealing losses of	
		electrolyte from each, for a total of	
		1048 grams]	
Physical	- No electrolyte	No electrolyte dripping from the	Pass
inspection	dripping from the	battery box onto the floor. Battery box	
and leakage	battery box onto the	sealing was prevented from electrolyte	
check	floor.	leakage as shown Fig 7.13-16	
		Battery appearance is shown in Fig.	
		7.13-11 to Fig. 7.13-16	

Summary of the external short circuit test

As indicated in Table 7.13-1 and Table 7.13-2, it was verified that no electrolyte was dripping from the battery box onto the floor even after the battery was exposed to the high impedance external short circuit test. Additionally, no explosion and no fire from the battery were observed.



Fig. 7.13-5 Battery voltage and short circuit current profiles during the external short circuit test

[Figure 36] *Battery voltage and short circuit current profiles during the external short circuit test. (Voltage redacted)*



Fig. 7.13-6 Profiles of the battery voltage and temperature during the test

[Figure 37] *Profiles of the battery voltage and temperature during the test. This figure also lists thermocouple locations.*



Fig. 7.13-7 Profiles of cells during the test

[Figure 38] Profiles of cell voltages during the test.



[Figure 39] Two minutes after start of test.



[Figure 40] Two and a half minutes after start of test.



[Figure 41] Three minutes after start of test.



[Figure 42] Three and a half minutes after start of test.



[Figure 43] Four minutes after start of test.



[Figure 44] Four and a half minutes after start of test.



[Figure 45] Five minutes after start of test.



Fig. 7.13-9 The battery behavior during high impedance external short circuit test.

[Figure 46] Twenty minutes after start of test.



Front side of the battery box



Backside of the battery box



Right side of the battery box

Left side of the battery box

Fig. 7.13-11 Appearance check after high impedance external short Addendum Figure 47. Electrolyte on exterior of battery box. (see arrows)



Fig 7.13-14 Tear down inspection after high impedence short circuit of the battery. Addendum Figure 48. Appearance of the top of the battery after short circuit test.



Fig. 7.13-16 Appearance of the front side of the battery box Addendum Figure 49. Appearance of battery box interior after test.

BATTERY EVOLUTION:

KEY DATES IN EVOLUTION OF THE LVP65 SERIES OF BATTERY:

2002	787 development begins	
May 3, 2004	Thales contracted to build battery and charger sub-system.	
January 2005	Collaborative Boeing/Thales suppliers selection: GS Yuasa for the battery and Securaplane for the battery charger) Securaplane factory fire with LVP65-8-400 battery (B3856-800).	
November 6, 2006		
2007	Contactor added to BMU and BMU3 added.	
June 15, 2009	 Battery modifications: Charger inhibited below -15°C Cell design LVP65-002 finalized "with improved lithium cobalt dioxide" A carbon material was changed and thickness was altered for aging performance. Battery established as the LVP65-8-402 (B3856-802). Electrical system modification: Main battery relay (MBR) added. 	
July 7, 2009	Battery Serial 10 vented cell 2 at the AFSIP laboratory. The battery was a LVP65-8-401 (B3856-801). The battery diode module was subsequently added.	
January 7, 2013	JA829J APU battery serial 396 thermal runaway at Boston	
January 16, 2013	JA804A main battery thermal runaway in flight and diversion to Takamatsu, Japan.	
January – May 2013	Redesign of battery and containment system in response to Boston and Takamatsu events. Battery became LVP65-8-403 (B3856-803).	
April 19, 2013	FAA Redesign approval of battery and containment system in response to Boston and Takamatsu events. Battery became LVP65-8-403 (B3856-803)	
January 14, 2014	Venting of main battery at Narita International Airport.	

EVOLUTIONARY STEPS:

The GS-Yuasa LVP65 battery progressed through three main evolutionary stages prior to the failure in Boston on January 7, 2013.³⁹ No photos were available of the original configuration that was used during development. The battery, cells, and cell constituents underwent additional minor changes between the original developmental design and the Boston event. The final LVP65-8-402 configuration "with improved lithium cobalt dioxide" as installed in the certificated airplanes was established in June 2009.

The original battery configuration was used during a substantial portion of the system development and qualification testing.⁴⁰ It consisted of a BMU, HECS and eight cells, but did not include an internal contactor. This battery was a developmental step in the evolution that followed the initial design. (See Figure 50, Figure 51, and top illustration in Figure 52)



Figure 50. Exterior of LVP65-8-400 battery (B3856-800)



Figure 51. Cell and BMU arrangement in LVP65-8-400 battery (B3856-800). Note early cell numbering reversed to current nomenclature.

³⁹ GS-Yuasa/Thales Report [number redacted].

⁴⁰ Subsequent battery designs also required developmental tests and each was subjected to qualificaiton tests.

Following a fire during development of a battery charger unit (BCU) at Securaplane Industries on November 6, 2006, the battery was redesigned to the LVP65-8-401). (SeeFigure 52, center illustration) The LVP65-8-401 battery included the internal contactor and sub BMU board to interrupt the charging in an abnormal situation. The internal contactor was installed in the BMU area. The cell compartment was the same as in the first generation battery.

A number of changes were implemented after the unintentional venting of a cell in the AFSIP laboratory on July 7, 2009. The LVP65-8-402 battery included a modified BMU4 board to avoid the subsequent charge of the battery after over discharge. The BMU had four levels of overcharge protection. This version of the battery moved from "red label" development and test to "black label" as a certified component in the 787 program. The airplane was modified to include the battery diode module.

The cell compartment was the same as in the LVP65-8-400 battery (B3856-800) type battery. GS-Yuasa engineering personnel explaining the production process in June 2013 said that the internal portion of the eight battery cells are identical. Production lots are divided so that half have the rupture valve near the positive terminal and half have the rupture valve near the negative terminal.



Figure 52. Evolutionary development of the LVP65 series battery from top to bottom.

Following the 2013 battery failures, the battery was redesigned as the LVP65-8-403. (Figure 53). In addition to improving the thermal and electrical isolation of the cells from each other, ports were added to the battery case, adjacent to each cell vent. Venting of cells was no longer contained in the case.



Figure 53. Battery design modifications for LVP65-8-403 configuration. Source: Boeing

Since the cells vented out of the battery case in the LVP65-8-403 configuration, a mounting box was developed for the vented cell products to vent overboard through a tube.⁴¹ The vent tube is normally closed by a rupture disc and the battery remains at cabin altitude unless in a failed configuration. After cell venting, a rupture disc opens the vent tube to the exterior of the airplane. (See Figure 54)



Figure 54. Redesigned battery mounting and enclosure. The hole in the rear of the case is where potential vented cell materials would pass through a rupture disc then a tube to go overboard. Source: Boeing

⁴¹ Other changes were also made, such as deleting the battery case ground. (This refers to the grounding of the blue battery case, not the surrounding enclosure.)

INTERVIEWS RELATED TO BATTERY DEVELOPMENT HISTORY:

During a meeting with Boeing engineering staff on March 12, 2013, Boeing attendees noted that the company may buy new technologies as a product, for topics in which Boeing has limited experience or expertise. Examples given were engines, avionic radios, and lavatory components. Oversight is provided by Boeing, and this was characterized as "paying for specialized expertise."

The following is from interviews at Thales and GS-Yuasa.

Thales responded to a Boeing request for information (RFI) for the power conversion system. The potential tier one vendors for this system would be responsible for preintegration, checking all interface control between the battery and charger. Thales only prior experience in system integration at the airplane level was the ATR42 power system. For the ATR42 system, Thales had subcontracted the ATR testing and system certification documentation for the power sub system to Alenia. As of March 12, 2013, Thales had obtained no power system TSO approvals from the FAA. (Thales had obtained avionics system TSO.) This was Thales first experience in lithium-ion battery design for civil aircraft applications. Thales had designed and built NiCad charging systems for an unspecified military application. The prototypes for the Boeing 787 lithium-ion charging system were made with a representative battery and not the design which was later certificated. For the Airbus A380, Thales builds a generator system.

Thales evaluated multiple companies as potential second tier suppliers. Securaplane and GS-Yuasa were potential vendors for the battery charger and battery. The Thales staff in May 2013 believed that during the RFI for the charger, Boeing introduced Securaplane (STI) to the RFI process as a potential candidate. GS-Yuasa became involved through a response to a Thales RFI. Thales provided all of the battery and battery charger RFI responses to Boeing. Following initial designs, feasibility demonstrations, Boeing selected Thales to provide the system in May 2004.

Thales had and still has no knowledge of the airplane electrical loads like Boeing does, and has no control of environment around/between the battery and charger. At Boeing's request, Thales examined both nickel cadmium (NiCad) and Li-ion battery systems and then provided a cost-benefit analysis of each to Boeing. Thales constructed proof of concept prototypes of each system prior to their selection as a vendor. There were several different lithium-ion technologies available at the time: lithium-nickel, lithium-manganese, and lithium-cobalt. Li-cobalt was the recommendation by more than one company due to performance. Lithium ion was selected as the format for the airplane main and APU batteries in September 2004. Thales selected GS-Yuasa with Boeing approval in January 2005.

In the cell and battery design and specifications, the BMU was required to monitor each cell and be able to prevent over-charge with maximum reliability. Installing the BMU in the box was felt to best assure these requirements. The protection concept was to separate the monitoring and have redundancy to stop charging, so this capability is present in both the charger and in the battery box. The charging channel can only access the cells through the BCU, not directly from aircraft generators.

In the battery charging system, Boeing developed the basic architectural concept and designs to functionally put the battery on the bus, as opposed to the BCU powering the battery, which in turn powered the bus. Thales filled the Boeing architectural concept with equipment. The first charger could recognize whether a NiCad or LIB was installed, per a Boeing request.

Thales personnel worked in Seattle to discuss and write the first drafts of specification control and other documents and had input into the system development and design coordination. Each component has a specification control document (SCD) and there is not a system-level SCD.

The FAA's only contact was with Boeing, not Thales. The FAA/Boeing 787 lithiumion battery Issue Paper was developed by FAA and Boeing in 2006 with support from Thales and vendors GS-Yuasa & Securaplane. The Special Conditions followed in 2007.⁴² Following an overcharge failure of a battery in a system-level simulation, Thales learned an airplane transformer rectifier unit (TRU) had been connected electrically parallel to the battery. (See section about the 2009 APSIF battery failure)

Once Boeing decided upon use of a lithium-cobalt battery system, technical coordination meetings occurred between people from GS-Yuasa, Securaplane, and Thales to define system details. Thales was the facilitator/interface to make sure definitions were clear between GS-Yuasa and Securaplane. Questions that arose between GS-Yuasa and Securaplane were resolved by Thales, and then Thales would forward amended ICDs to Boeing for review. Responsibility for defining signals between the system components was defiend by an SCD which required Boeing approval. The Boeing Wire Diagram Manual and Boeing hardware selection criteria defined what hardware should be used in design of the system.

Securaplane and GS-Yuasa drawing approvals and documents were provided by Thales, then again from Boeing. The design documents were the implementation of the Boeing SCD, which was written in coordination with the vendors. At Preliminary Design Review (PDR), Thales provided design info to Boeing, and again at Critical Design Review (CDR). The FAA never met with Thales during those reviews. [While this paragraph describes interviews with Thales personnel, according to Boeing personnel, there were numerous meetings between Securaplane and GS-Yuasa with Boeing personnel at the time.]

In safety requirements for the implementation of the SCD, such as allowing no electrolyte leakage, Thales forwarded the requirements to GS-Yuasa. GS-Yuasa

⁴² The Issue Paper and Special Conditions are described in depth in the System Safety Group Chairman's Factual Report.

decided on how to meet the requirements and created the design, which was then reviewed and approved by Thales and subsequently by Boeing.

The development test plan for the battery and charger subsystem was first developed by Thales; this was based on Boeing requirements and included a qualification test plan. The certification test plan was a Boeing responsibility. These plans specified how the components and the system would function individually and together, as well as how to validate the requirements. Some tests were performed at GS-Yuasa and some at Securaplane. For example, development of a cell required a set of tests, as did the development of BMU, development of charger, development of battery, and preintegration of the integrated system.

When developing the system and engineering abuse tests for the LIB cells, Thales had no prior experience. GS-Yuasa had experience which then became the basis for the development and testing of the cells and battery. At the cell level, Thales relied on GS-Yuasa experience for which types of abuse test to perform and then passed that information to Boeing. Boeing also had input in the design, according to Thales personnel. For example, the decision to only use analog circuitry in the BMU came from Boeing. Thales performed tests on individual protective BMU circuits physically to ensure that failures functioned as intended. It also was done to verify portions of the FMEA.

As examples of GS-Yuasa input in the design process, cell balancing was part of the GS-Yuasa design that GS-Yuasa had experience in and Thales did not. Thales engineering staff had regular meetings at GS-Yuasa during the design and qualification testing and checked the design of the electronic hardware as a circuit. The functionality was designed and reviewed by GS-Yuasa engineers. In testing conducted at Thales laboratories, company personnel performed pre-integration tests and monitored signals between battery and the BCU without monitoring of the individual cells.

The GS-Yuasa development test plan was initially provided to Thales, then was part of coordination meetings with Boeing. The Boeing engineers were present during the later qualification tests.

After review of the above, Boeing provided the following text:

Boeing believes that these paragraphs do not fully or accurately describe the selection process for Thales, GS Yuasa, or the manner in which Li-Co was selected as the battery's chemistry. In particular, like all Beoing suppliers, Thales was selected through an exhaustive process. Thales and several other suppliers worked on-site with Boeing for two years on the preliminary development work for the 787's Electrical Power System ("EPS"). Based on the first-hand knowledge Boeing gained during that time, Thales and one other supplier were then selected to build a prototype component for the EPS. After careful analysis of both suppliers and their prototypes, Boeing selected Thales.

When Thales was competing to become a supplier, a Nickel Cadmium ("Ni-Cd") battery, like those used in most airplanes, was the baseline for the design, with Li-ion as an option. After selecting Thales as a supplier, Boeing and Thales conducted a trade study that showed Li-ion batteries could be used safely and had many advantages over Ni-Cd batteries. From that point onward Li-ion became the baseline for the design. However, Ni-Cd remained an option for much of the EPS's development, as Boeing and its suppliers worked to design a Li-ion battery that could meet safety and performance requirements. Having determined that a Li-ion battery was the best choice, Thales and Boeing began to look for a supplier. Thales selected GS Yuasa, in part, based on its reputation as a worldwide leader in Li-ion batteries. Before GS Yuasa was selected, Boeing and Thales toured GS Yuasa's facilities and evaluated its designs and manufacturing capabilities. Boeing concurred with the selection of GS Yuasa.

After selecting GS Yuasa, Boeing and Thales worked closely with them to determine which Li-ion chemistry was the right choice for the battery. Lithium Cobalt ("Li-Co") was the only chemistry that provided the necessary power density. And Li-Co had a proven track record of safety in other applications. For example, Li-Co had been used by GS Yuasa in satellite batteries. Throughout the development and testing process, Boeing, Thales, GS Yuasa continued to re-evaluate Li-Co against other chemistries. All of its performance characteristics were evaluated and at each step of the analysis and development process it was determined that with the proper layers of safety features included in the battery system and at the airplane level design, Li-Co provided a safe and effective choice for the 787 Main/APU battery. If further explanation is needed, Boeing would refer and incorporate the testimony from Panels 1 and 2, in particular, from the NTSB's investigative hearing.

AIRCRAFT LEVEL EFFECT:

The area of the APU battery was examined for aircraft vulnerability to heat and flame. Above the APU battery was the Flight Control Electronic System (FCES) backup battery and a metal avionics rack. Above the rack were electrical components for the APU system. To the (aircraft) left of the APU battery was a vertical metal wall of an avionics rack. To the right was a box of circuit cards for the anti-ice system. Behind the APU battery was wiring for the battery and APU system. An air gap existed between the battery case and the secondary floor structure beneath the battery, which was aluminum and carbon fiber composite. The main airplane electrical power distribution panels in the compartment were separate from each other and located on opposite sides of the compartment, each about 10 feet laterally from the APU battery.

ELECTRICAL RESULTS OF THERMAL RUNAWAY:

Electromagnetic interference (EMI) qualification tests had been performed to show that the battery was not susceptible to EMI from the airplane and would not generate EMI into the airplane systems.⁴³ A condition not tested for was the extent of how much EMI could be introduced to the digital computers and other avionics by an internal short circuit within a battery cell.

Potential EMI was identified in the APSIF failure data as large voltage and current transients at rapid frequency. [See Figure 59] Data from GS-YUASA testing also showed large transients at an unmeasured frequency during an internal short circuit test. (See Figure 36)

OTHER BATTERIES:

Documentation about prior battery failures was examined. The two prior events involving the LVP65 batteries were not the versions certified for use the 787. Both of the failed batteries were predecessor designs with similarities in the cells and major differences in the battery monitoring units (BMUs), as described in the battery history and evolution sections, above.

SECURAPLANE:

At least four versions exist about the fire and what initiated it. These included ones from Exponent (which conducted an investigation for Boeing), GS-Yuasa, various Government records, and the technician involved. Three of the accounts attribute the fire to variations on the test setup. The technician attributed the failure to company management, test equipment, and instructions provided to him.

All accounts agree to that at about 9 am, on November 6, 2006, a fire broke out and destroyed the main Securaplane building when a B3856-800 battery (LVP-8-400) was being charged for test. The Securaplane fire involved a developmental battery in a manufacturing facility and the battery had been in use for about 14 months, since delivery in September 2005. (See Figure 55) The building had furniture and other potentially flammable materials not present in the 787 E/E compartment. (See Figure 56) The technician working with the battery was the sole injury and refused medical assistance at the scene.

⁴³ GS-Yuasa/Thales Report [number redacted]



Figure 55. Arizona Star news photo of flames at Securaplane factory. 44

The technician related afterward that he had been charging and discharging cells between 30 and 32.2 volts to test the BMU. The BMU was connected to the battery through test equipment that had pins which could be reconfigured. The BCU was in front of him on a work bench and the battery was to his right.



Figure 56. Work station and destroyed battery.

 $^{^{44}} Source: http://azstarnet.com/news/local/multicell-battery-causes--alarm-fire/article_f82af55f-30d9-5998-8ba9-f9acf6bc87fa.html$

He stated that he turned off power to the BCU, noticed that the battery temperature of 74.4°C was more than the allowable maximum temperature of 70°C, and after a period of time heard a pop and hissing sound. A jet of flame from the battery came toward him in his chair. He made two attempts to put out the fire with a Halon fire extenguisher and as the fire continued, exited the building.

Exponent investigated the fire with assistance from GS-Yuasa and Thales. While the work station had been destroyed by the fire, the remnants of the test in progress remained and the technician was able to describe what he experienced. The recovery of the battery showed that a BMU cable remained attached and the lid had been fastened to the battery. (See Figure 57)



Figure 57. Remnant of battery under test at time of Securaplane fire.

The configuration of the work station provided information about the test setup in use. Following the examinations and interviews, the Exponent documentation indicated investigators agreed that:⁴⁵

- 1. Thermal runaway occurred to the cells in the battery.
- 2. Cell #8 was the first cell to fail, followed by propagation and failure of the other cells.⁴⁶
- 3. The BMU was not connected directly to the BCU. Whether the BMU was connected through the test station and active or not could not be conclusively determined.

⁴⁵ The three summary items on this page and the four points listed on the next page are from the results of the 2006-2007 investigation. During creation of this 2014 Addendum document for the Boston battery failure, GS-Yuasa stated that the company finds the information to be incorrect or misleading.
⁴⁶ The design reference to ordering of the cell numbers was later reversed and in terms of the LVP65-

Investigators also noted that if the BMU was active, and at the mid-level voltages the technician said that he was using, the voltage was less than the 4 volts at which the BMU initiates the cell balancing function.

Note that Thales added that the BMU signal cable was connected to the BCU through test equipment known as a "break-out box." The BCU signal connector wass connected to the "Fixture ATP" that outputs artificially created ("dummy") signals to the BCU.

At this point, four different versions were found to explain how the failure started. These included:

- 1. Cell 3 or 6 experienced a short circuit, followed by overcharge of at least one other cell. It was noted that this would be contradicted by an initial venting of cell #8
- 2. Without the BMU function, a cell imbalance led to overcharge or over discharge of a cell until it experienced a thermal runaway. It was noted that this was type of failure was only possible in a laboratory, as the airplane circuit directly connected the BMU and BCU.
- 3. An internal short circuit led to a thermal runaway.
- 4. The technician claimed that company personnel had altered the battery and that he had been instructed to work with unsafe equipment to test the battery.

In terms of the 2013 Boston 787 investigation, the battery and testing were different from when the 2006 fire happened. The cells had been changed, two redesigns of the BMU were implemented, and the test equipment for the certificated airplane had been developed more than two years after the technician left the company. The Airworthiness investigation into the Boston event found no connection between the claims of the employee involved in the November 2006 fire and the battery which failed in Boston more than six years later.

A finding from the Exponent report about the Securaplane investigation stated that: "Proper implementation of a BMU will not guarantee prevention of thermal runaway failures in the future because the function of BMU is only to send signals and does not actually stop overcharging."
Aerospace Systems Airplane Power Systems Integration Facility (APSIF)

The following is a summary of a proprietary engineering investigation which was performed and omits some details.

On July 7, 2009, a battery failed at the UTC Aerospace Systems Airplane Power Systems Integration Facility (APSIF) and vented electrolyte. The facility is where 787 power system components were tested as an integrated electrical system. The battery was a LVP65-8-401 (B3856-801), serial #10, and cell #2 was later found to have vented.⁴⁷ (See Figure 58)



Figure 58. The leakage of electrolyte from beneath the lid of the battery that failed at the APSIF laboratory.

The battery voltage declined over a period of minutes and the charger stopped providing a charge. (See Figure 59) The laboratory data also revealed deep discharges and high rate charging that reached hundreds of amperes. The anode was not designed to intercalate [accept the charge of] the lithium ions at such high charge rates.

⁴⁷ Cell numbering in the order used in the Boston event battery.



Figure 59. Electrical voltage reduction and fluctuations recorded during the APSIF battery failure. Red and orange depict amperage. Blue depicts voltage.

In addition to the vented cell, the battery internal contactor had been damaged and failed in the open state. The BMU also contained a failed resistor. Both were determined to be caused by high heat generated by the failed cell.

Physical indications of over discharge were found through chemical analysis performed on the failed cell, another good cell in the battery, a fresh cell, and an overdischarged cell from another battery. Each had copper on the positive electrode.

The failed battery had been installed in the main battery configuration at the laboratory. Methods of charging were identified that were unique to the laboratory environment, which would not be in an airplane. The review also found a potential charge path (not high rate) in the airplane power system.

The engineering investigation found that the most likely failure mode was an internal cell short circuit created by repetitive over-discharge and subsequent high rate recharge operations. As a result of the failure and investigation, several aspects of the system design were changed. These included addition of the over-discharge latch-out feature and the main battery diode module (BDM).

LVP10 FLIGHT CONTROL ELECTRONICS BATTERY:

The bottom of the flight control electronics (FCE) battery had been exposed to the APU battery in an open rack and heat had damaged the data plate of the FCE. (See Figure 60) The FCE lid was removed a year after the Boston event. The Honeywell assembly was found to contain battery cells supplied by GS-Yuasa and assembled by the ELDEC Division of Crane Aerospace and Electronics.

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Figure 60. Data plate on FCE battery.

The Honeywell Abbreviated Component Maintenance Manual (27-09-02, Feb 25/2011) provides the following description.

The battery supplies electrical power to the Flight Control Electronics (FCE), if other power sources are not available. The battery is sealed and maintenance-free. The internal components of the battery are not repairable. It is designed to use Lithium-ion (Li-ion) technology. The battery has seven lithium-ion cells that are connected in series.

When the aircraft is in flight, the battery is charged by the PCM [power conditioning module]. The PCM supplies a current-limited constant voltage source. The charge control circuitry gets terminal voltage, cell terminal voltages, charge/discharge current, and temperature data from the battery. While the FCE is powered by primary or secondary inputs, the PCM charges the battery to a flight-ready status.

(1) The PCM uses its Battery Management Function (BMF) electronics to do the functions that follow:

- Battery Cell Balance
- Cell Over-voltage Shutdown
- Battery Temperature Monitor
- Cell Under-voltage Shutdown
- Battery Over-voltage Shutdown
- Battery Current Monitor
- On-Condition Maintenance (OCM)

The BMF electronics monitors the battery when it is charged and discharged.

B.Temperature

The battery is designed to function in the aircraft environmental temperature ranges. Exposure to high temperatures will decrease the charge retention of a stored battery. It is necessary to limit the amount of time that a battery is exposed to high temperatures.

The voltage of the battery one year after removal from the airplane was 27.8 volts. The lid has open corners that are not sealed. The lid was removed and on a plastic insulator sheet was evidence of dried fire extinguishant. (See Figure 61)



Figure 61. Evidence of dried fire extinguishant. (arrow)

The battery monitoring unit functions for the battery are contained in the flight control computer and not inside the battery case. As with the LVP65, the LVP10 has two temperature sensors mounted on bus bars, but none on the battery cells themselves. The heavy gauge wiring inside the case had been sleeved for chafe protection. A chafe point was found between a battery monitoring wire and a case screw. (See Figure 62)



Figure 62. Chafe of wire on screw head found in FCE battery. (yellow arrow from right). Two temperature sensors. (Two arrows from top)

ELECTRIC VEHICLES:

Records from lithium ion battery use and failures in electric vehicles was examined. Every automobile currently sold was found to have heating and cooling through use of air, oil, coolant, or a combination.

The only model in production known to use the lithium cobalt oxide battery chemistry is the Tesla Motors Model S. Tesla started building the Model S on June 22, 2012, delivered 22, 477 cars in 2013, and expects to deliver 35,000 in 2014.⁴⁸ Of those delivered by the end of 2013, only 4 have been known to be involved in vehicle fires, for a rate of 0.0222% ending in fire.⁴⁹ Each of the fires was preceded by enough damage to penetrate the quarter-inch thick metal plate that houses the battery. The pack is mounted below the bumper crush line.

Comparing the rate of fires in this model of electric vehicle to the total number of vehicle fires, the U.S. Fire Administration's (USFA's) National Fire Incident Reporting System (NFIRS) data shows that overall:⁵⁰

⁴⁸ http://ir.teslamotors.com/secfiling.cfm?filingID=1193125-14-58778&CIK=1318605

⁴⁹ The 2012 reocrds are unclear regarding how many were delivered to customers. The fires were on October 1, 2013, Kent, Washington; Struck metal debris; October 18, 2013, Merida, Mexico, High speed crash; November 6, 2013, Smyrna, Tennessee, Struck metal debris (tow hitch); February 1, 2014, Toronto, Canada, Parked after driving. A fire at the wall charger and not in the vehicle took place November 2013, Irvine, California. Other Tesla information from Tesla and http://en.wikipedia.org/wiki/Tesla Model S

⁵⁰ http://www.usfa.fema.gov/downloads/pdf/statistics/v13i11.pdf

Approximately one in seven fires responded to by fire departments across the nation is a highway vehicle fire. This does not include the tens of thousands of fire department responses to highway vehicle accident sites.

Sixty-one percent of highway vehicle fires and 35 percent of fatal highway vehicle fires originated in the engine, running gear, or wheel area of the vehicle.

Insulation around electrical wiring (28 percent) and flammable liquids in the engine area (18 percent) were the most common items first ignited in highway vehicle fires.

Within the quarter-inch thick battery housing, Tesla automobiles have two available batteries, to provide normal or extended range. The design of the Tesla battery incorporates liquid heating/cooling loops that pass by each of up to 7,104 individual cells.⁵¹ (See Figure 63) Each cell in the illustration below is slightly larger than the typical AA battery cell used in flashlights and other devices. The battery management unit monitors each of the cells and can lock out individual cells exceeding preset parameters.



Figure 63. Cooling tubes pass each cell in this automotive battery.

⁵¹ Publicly accessible illustration from Patent Application: 20100025006. Publication date: 2010-02-04. Inventor: Peng Zhou, Assignee: Tesla Motors.