**NATIONAL TRANSPORTATION SAFETY BOARD**
**OFFICE OF AVIATION SAFETY**
**WASHINGTON, D.C. 20594**

**March 7, 2013**

# SYSTEM SAFETY AND CERTIFICATION GROUP CHAIRMAN'S FACTUAL REPORT

**NTSB ID No.: DCA13IA037**

## A. INCCIDENT:

| | |
|---|---|
| Location: | Logan International Airport, Boston, Massachusetts |
| Date: | January 7, 2013 |
| Time: | About 1021 Eastern Standard Time (EST) |
| Aircraft: | Boeing 787-8 |
| Registration: | JA829J |

## B. GROUP MEMBERS:

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| Chairman: | Mike Hauf<br>National Transportation Safety Board<br>Washington, D.C. |
| Member: | Dana Schulze<br>National Transportation Safety Board<br>Washington, D.C. |

## 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 787-8, JA829J that was parked at a gate at Logan International Airport, Boston, Massachusetts. About the same time, a maintenance manager in the cockpit observed that the auxiliary power unit (APU) had automatically shut down. Shortly afterward, a mechanic opened the aft electronic equipment bay and found smoke and flames coming from the APU battery. 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.

## D. DETAILS OF THE INVESTIGATION:

As part of the NTSB investigation, a review was conducted of the Federal Aviation Regulations (FARs) and special conditions (requirements) applicable to the 787-8 Main and Auxiliary Power Unit (APU) Lithium-Ion Battery and Battery Charger system as well as the corresponding certification plan developed by Boeing and approved by the Federal Aviation Administration (FAA) that defined the agreed upon methods to be used to demonstrate that the battery and battery charger system met applicable FAA and European Aviation Safety Agency (EASA) requirements. This factual report documents the relevant FARs, special conditions, and portions of the certification plan that pertain to the APU and Main battery and battery charger system, specifically identifying those analyses, tests, and inspections that were required to demonstrate compliance.

In addition to documentation of the regulatory requirements and the certification plan, this report also documents pertinent sections of the 787-8 Electrical Power System (EPS) safety assessment that pertain to the 787-8 Main and APU battery systems, which was developed by Boeing to evaluate the design of the EPS for compliance with safety requirements defined by the FAA and EASA.

This System Safety and Certification Group Chairman factual report is intended to supplement the NTSB Battery and Airworthiness Group Chairman factual reports.

### D.1 Systems Descriptions:

#### D.1.1 Airplane and Power Conversion System (PCS):

The Boeing 787-8 is a twin-engine, wide body, commercial airplane. The Main Battery/Battery Charger located in the forward Electronic Equipment (E/E) Bay and the APU Battery/Battery Charger located in the Aft E/E Bay are part of the Power Conversion System (PCS), which is an element of the 787-8 Electrical Power System.

The Main Battery provides power to selected electrical/electronic equipment for both normal and non-normal conditions. Conditions include but are not limited to normal power-up and power-down of the airplane, backup power to critical loads, full support of critical 28V loads when all active power is lost, and support of battery only braking conditions for normal towing and parking as well as emergency operation.

The APU Battery system provides power to start the APU during both ground and flight operations. In addition, the APU provides momentary 28 V hold-up to some essential equipment and power to open the APU Door and the APU controller.

The battery design and part number is identical for both the main and APU positions and these units are interchangeable.

### D.1.2 Lithium Ion Battery and Battery Charger (Main and APU) Description:

The Li-ion battery that is used for the Main and the APU battery contain 8 sealed lithium ion cells that are connected together in series with thermal conductive plates and packaged within an aluminum battery box. The battery also includes the battery monitoring unit (BMU), Hall Effect current sensor (HECS), temperature sensors, internal non-latching contactor, battery failure detection and diode module failure detection (detection of high rate charge current). The BMU, which is installed within the battery, incorporates redundant circuits that generate battery status, balance cell voltages, and makes battery Built In Test Equipment (BITE) and failure annunciation to the battery charger. These protection circuits are designed to protect against overcharge, over-discharge, overheating, and ensure proper cell balancing.

Each battery is charged by a dedicated Battery Charger Unit (BCU). All Battery signal and failure information are provided to the aircraft system through the BCU. If an internal battery failure is detected by the BMU, an inhibition signal is relayed to the BCU and it will stop all charging of the battery and shall annunciate the battery failure at the aircraft level.

1. The main battery system also includes a Battery, BCU, and Battery Diode Module (BDM). The Bus Power Control Unit (BPCU) monitors for failure indications from the Main Battery/Battery Charger and reports any failures. The BDM includes a large power diode and a battery side interface for the battery charger. The BDM protects the battery against high charge current when the Hot Battery Bus is paralleled with another 28 V Dc source via the Main Battery Relay (MBR), Electric Brake Power Supply Unit (EBPSU) contactors, or other equipment isolation failure.

2. The APU battery system also includes a Battery, BCU, and a Starter Power Unit (SPU[1]), a BDM is not included or necessary for the APU Battery System. The Remote Data Concentrator (RDC) monitors for failure indication from the APU Battery/Battery Charger and reports any failures to the BPCU.

The baseline Li-ion battery is a 50 ampere-hour (end-of-life) lithium-ion (Li-ion) chemistry battery. The main and APU batteries are identical, but provide electrical power sources to two distinct functional areas. The nominal voltage of the battery is about 29.6 volts and when it is fully charged, the voltage is 32.2 volts.

According to Boeing's System Safety Assessment document for the 787-8 Electrical Power System, Li-ion batteries are primarily made up of non-flammable components, however, the electrolyte and active material coatings on the negative and positive electrodes contain flammable components.

[1] The starter power unit is used during APU starts only.

Over-charge[2] of a Li-ion cell can result in the cell entering thermal runaway, which could result in the battery cell venting[3] and the generation of smoke and fire. Cell venting with a fire is distinct from venting with smoke only; outside of an additional ignition source, over-charge is the only known failure condition that can result in venting with fire according to Boeing's System safety Assessment. Cell venting with smoke, however, can be initiated by several failure modes, including external overheat, external short circuit of appropriate impedance, internal short circuit, recharging a battery that has been discharged to a state-of-charge that is too low, high rate charging at greater than a 1C (one times the capacity Amp hour rating of the cell), or charging at cold temperatures. Each cell has a safety vent[4] that opens when the cells internal pressure reaches unsafe levels to eliminate unsafe conditions.

Each battery charger takes unregulated 28VDC power on its input and converts it to regulated DC power output. The output voltage level varies depending on battery state of charge (SOC), to between 22VDC at 0% SOC and 32.2V when fully charged. For all voltages, the charger current is limited to a maximum output current of 46A.

The battery charger receives inputs from the BMU such as temperature, cell balance, inhibition of discharge and inhibition of charge, etc, and regulates charging accordingly. The battery charger, via the Bus Power Control Unit (BPCU) for the main battery and a Remote Data Concentrator (RDC) for the APU battery, provide the battery parameters (such as battery current and battery voltage) to support the Electrical Flight Synoptic Page and the battery-charger failure indications (such as battery state of charge indication for dispatch) to the Engine Indication Crew Alerting System (EICAS).

## D.2 Certification Aspects of the Investigation:

### D.2.1 787-8 Type Certification Process and Overview:

The FAA is responsible for prescribing minimum standards required in the interest of safety for the design, material, construction, quality of work, and performance of aircraft, aircraft engines, and propellers (Ref. 49USC44701). Product certification is a regulatory process administered by the FAA to ensure that aircraft manufacturer's products comply with Federal Airworthiness Regulations. Successful completion of the certification process enables the FAA to issue a type certificate (TC). To obtain a TC, the manufacturer must demonstrate to the FAA that the aircraft or product being submitted for approval complies with all applicable FARs. The FAA determines whether or not the applicant has met its responsibility to show compliance to the applicable FARs. According to 14 CFR 21.21, an applicant is entitled to a type certificate for an aircraft, if:

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[2] Charging above the manufacturer's high voltage specification is referred to as overcharge, (reference Lithium-Ion Batteries Hazard and Use Assessment Final Report prepared by Exponent Failure Analysis Associates, Inc., dated July 2011.)

[3] Vents are usually formed by including a burst disk in the cell design by including a score mark on the cell (typical in prismatic designs), or by adjusting weld strength to allow failure of weld closures at safe venting pressures. (Reference Lithium-Ion Batteries Hazard and Use Assessment Final Report prepared by Exponent Failure Analysis Associates, Inc., dated July 2011.)

[4] According to Boeing's System Safety Assessment document

(a) The product qualifies under Sec. 21.27; or
(b) The applicant submits the type design, test reports, and computations necessary to show that the product to be certificated meets the applicable airworthiness requirements of the Federal Aviation Regulations and any special conditions prescribed by the Administrator, and the Administrator finds that upon examination of the type design, and after completing all tests and inspections, that the type design and the product meet the applicable requirements of the Federal Aviation Regulations, and further finds that they meet the applicable airworthiness requirements of the Federal Aviation Regulations.

The Federal regulations that apply to type certification of transport-category airplanes are 14 CFR Part 21, 25, 26, 33, 34, and 36. The Part 25 regulations are those concerned with the airworthiness standards for transport-category airplanes and are organized into subparts A through G. According to 14 CFR 21.21 and FAA Order 8110.4C[5], the Federal regulations that apply to a specific transport-category airplane are contained in the type certification basis that is established by the FAA effective on the date of application per 14 CFR 21.17 a (1). These regulations represent the minimum standards for airworthiness; an applicant's design may exceed these standards and the applicant's tests and analyses may be more extensive than required by regulation. The specific applicable regulatory requirements and how compliance will be demonstrated is documented in an FAA approved certification plan.

The FAA has 10 Aircraft Certification Offices (ACOs) which are responsible for approving the design certification of aircraft, aircraft engines, propellers, and replacement parts for those products. The certification oversight and approval for the 787-8 was conducted by the Seattle ACO.

### D.2.2 Certification History and Basis for the 787-8 Airplane:

On March 28, 2003, Boeing applied for an FAA type certificate for its new Boeing Model 787-8 passenger airplane.

According to the Boeing Model 787-8 Type Certificate Data Sheet[6] (TCDS), the 787-8 airplane was granted transport category approval on August 26, 2011. The applicable certification basis was the 14 Code of Federal Regulations (CFR) Part 25 Airworthiness Standards, through Amendment 25-119 and amendments 25-120, 25-124, 25-125 and 25-128 with some exceptions and special conditions (SC) as noted in the 787-8 TCDS[7] including 25-359-SC for the Lithium Ion battery installation.

The 787-8 FAA certification was also validated by the European Aviation Safety Agency (EASA) with the approval granted on August 26, 2011. Their applicable certification basis was

[5] In June of 2010, this guidance was moved to Order 8110.112.
[6] The Type Certificate Data Sheet (TCDS) is a formal description of the aircraft, engine or propeller. It lists limitations and information required for type certification including airspeed limits, weight limits, thrust limitations, etc.
[7] Reference Federal Aviation Administration Type Certificate Data Sheet T00021SE, Revision 5, dated January 2, 2013.

Certification Specification (CS) 25, Amendment 1, effective as of December 12, 2005[8] with some Certification Review Items[9] (CRI's) including F-24 for Lithium Ion batteries.

### D.2.3 Roles and Responsibilities in Li-ion Battery Certification:

Historically, the FAA has relied on a variety of organizational or individual designee programs to meet its responsibility to hold the aviation industry accountable to its safety standards. The FAA utilizes designees across its scope of responsibilities, such as pilot licensing, mechanic certification, pilot medical examinations and aircraft design certification.

When Congress created the FAA in 1958 to promote the safety of civil aviation, it recognized the practical necessity of FAA utilizing private sector expertise to keep pace with the growing aviation industry and explicitly gave the agency the authority to delegate certain certification activities, as the agency deems necessary, to qualified persons. The designee program itself has roots as far back as 1927, and the Federal Aviation Act continued and allowed for the expansion of delegations of authority.

Typical individual designees involved in aircraft design, certification and manufacturing include Designated Engineering Representatives (DERs), Designated Manufacturing Inspection Representatives (DMIRs), and Designated Airworthiness Representatives (DARs). Delegation Option Authorization (DOA), Organizational Designated Airworthiness Representative (ODAR) and Designated Alteration Stations (DAS) are examples of organizational delegation programs that have been utilized for many years-, or in the case of DOA, for several decades. Recognizing the need to expand the scope of approved tasks available to organizational designees; and establish a more comprehensive, systems-based approach to managing designated organizations, FAA issued a final rule (70 Federal Register 59932) that established the Organization Designation Authorization (ODA) program in October 2005. The FAA oversees designee activities and any authorized compliance finding made by a designee or delegated organization is, in effect, an FAA finding. By November 2009, all companies that had applied for ODA had completed the transition as required by the FAA.

On August 18, 2009, Boeing received ODA approval from the FAA. Boeing transitioned from the previous delegated authorizations, Design Organization Approval (DOA) and Organizational Delegated Airworthiness Representative (ODAR), during the following weeks. The ODA approval included Production Certificate (PC), Type Certificate (TC), and Major Repair, Alteration, and Airworthiness (MRA) for current production models and development programs. As defined by regulation and FAA procedures, Boeing as the ODA Holder is responsible for showing compliance to the regulations. Within Boeing, a team of appointed individuals known as the ODA Unit performs limited duties on behalf of the FAA. The processes and authority for the ODA Unit are approved by the FAA. A TC ODA unit may make discreet findings as authorized by FAA for certain reports or tests in support of type certification programs. However, issuance of a type certificate cannot be delegated and is only done by the FAA.

[8] Reference EASA Type Certificate Data Sheet Number EASA.IMA.115 for the Boeing 787-8, Issue 3, dated May 10, 2012.

[9] Certification Review Items issued by EASA may include requirements similar to FAA Special Conditions.

Figure's 1 and 2 below provide a high level illustration of the 787-8 Main and APU battery certification process including reference to the process steps and certification tasks for which approval was retained by the FAA and those that were delegated to the Boeing ODA (approvals and findings of compliance determined by Boeing's ODA Unit).

## Figure 1 Timeline of the 787-8 Certification Process

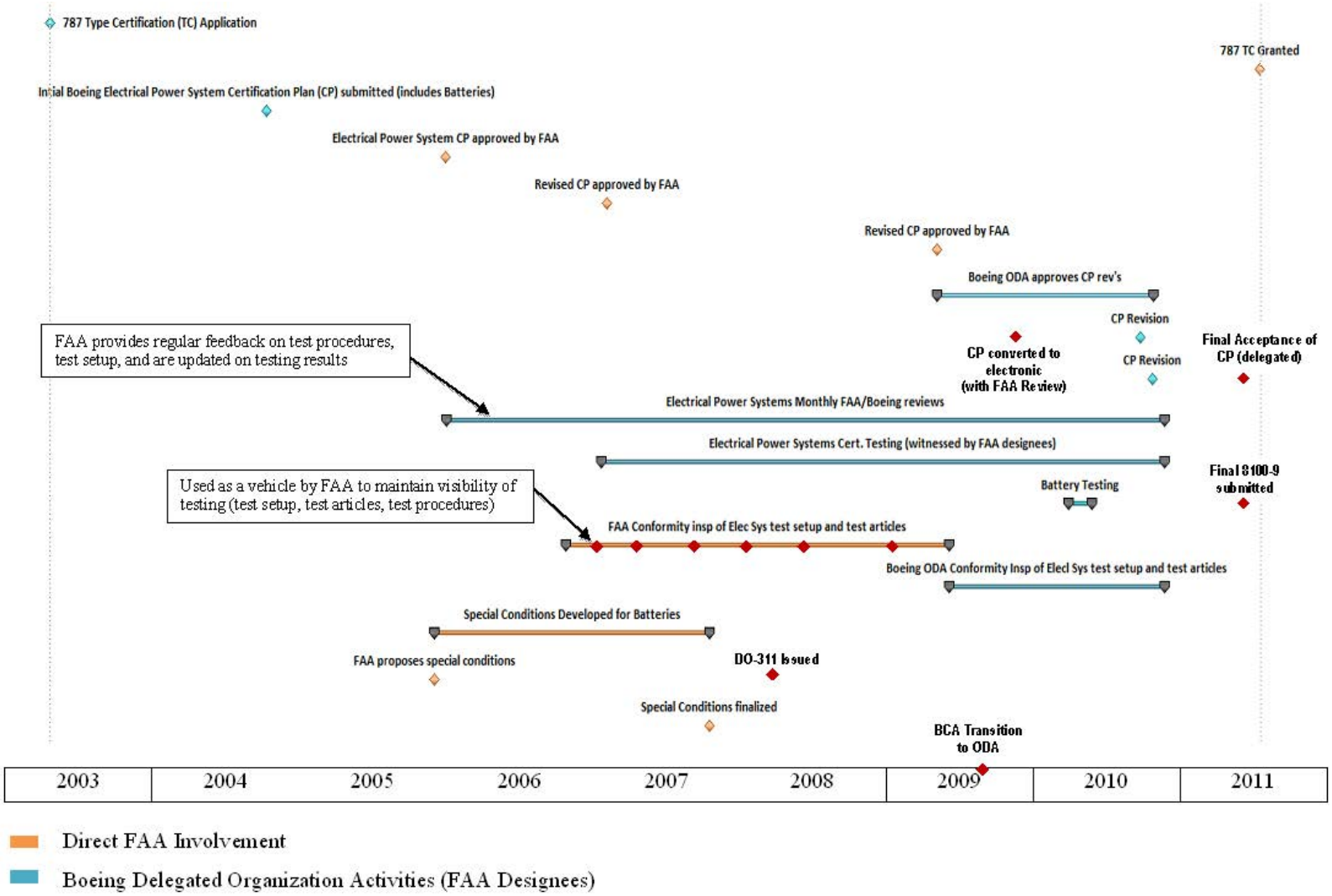
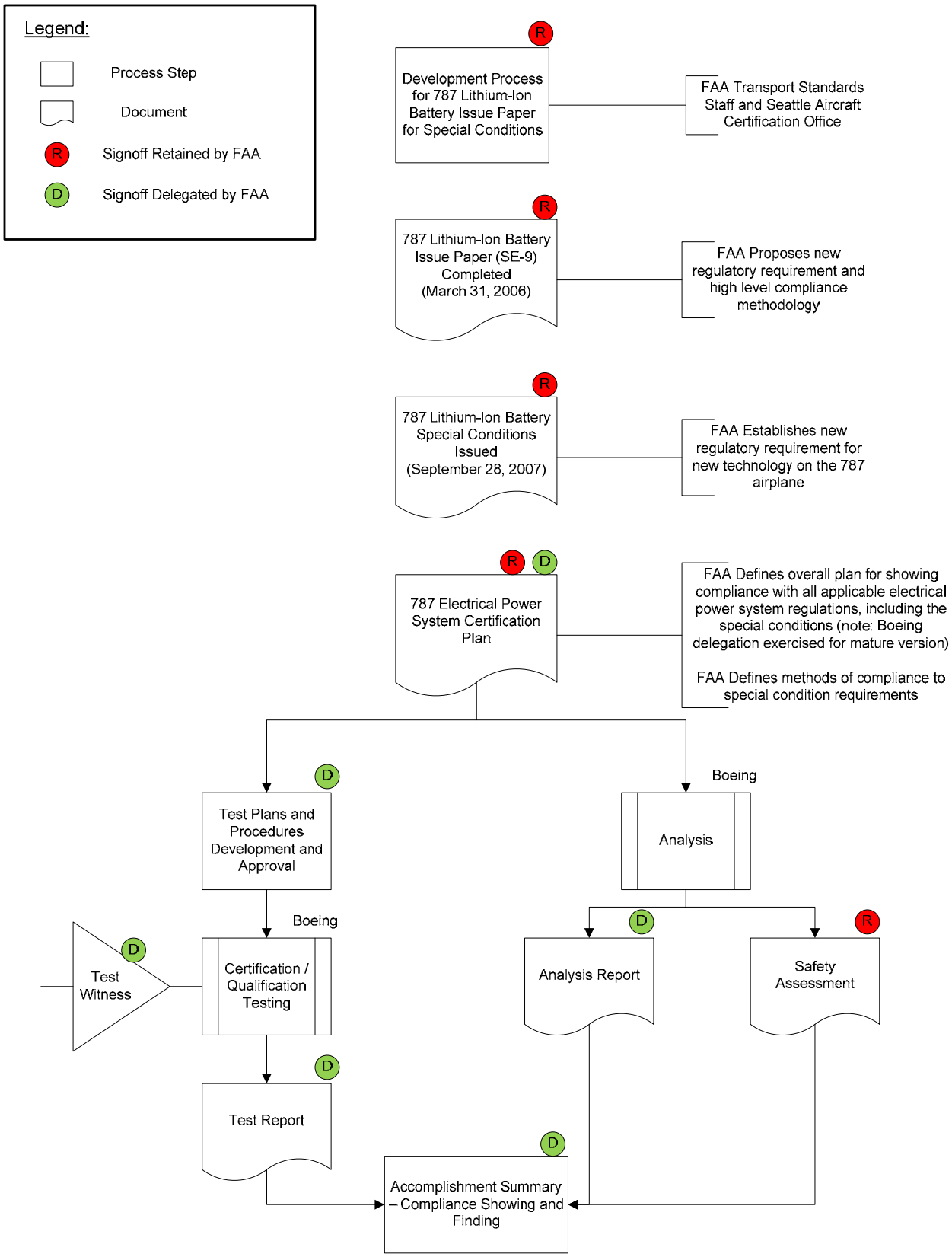


**Figure 2 Certification Tasks and Delegations for the Certification of the 787-8**



### D.2.4 Special Conditions for Lithium Ion Battery and Battery Charger:

If, during the conceptual design phase, the FAA determines that existing regulations or safety standards applicable to the design feature being certified are inadequate or inappropriate, it can determine that special conditions are necessary. Title 14 CFR 21.16 states that if "the airworthiness regulations of this subchapter do not contain adequate or appropriate safety standards for an aircraft, aircraft engine, or propeller because of a novel or unusual design feature of the aircraft, aircraft engine or propeller," the FAA can initiate rulemaking to produce standards that establish a level of safety equivalent to existing regulations. Novel or Unusual features are unique to a specific certification project, are judged relative to the existing standards, and are treated on a case-by-case basis. Special conditions begin with an issue paper and are developed by the ACO, with full participation by the applicant and other relevant participants. Once developed, the proposed special condition is forwarded to the appropriate directorate, which reviews it and coordinates review, approval, and publication of the rule change in the *Federal Register*. The Boeing Model 787-8 airplane would be the first large transport category airplane to utilize Li-ion main and auxiliary power unit (APU) start batteries[10]. Because rechargeable lithium ion batteries were considered a novel and unusual design feature in transport category airplanes, this proposed use of Li-ion batteries on the Model 787-8 airplane prompted the FAA to review the adequacy of the existing battery regulations. To facilitate this review and corresponding special conditions that would likely be required to address inadequacies in the current battery regulations, the FAA developed an Issue Paper, SE-9, "Special Condition: Lithium-Ion Battery Installations," to provide a structured means to track the resolution of the relevant technical, regulatory, and administrative issues that would arise in working with Boeing to certify the Main and APU Li-ion battery installations.

The Issue Paper noted that increased use of nickel-cadmium batteries in small airplanes had resulted in increased incidents of battery fires and failures, which led to additional rulemaking affecting large transport category airplanes as well as small airplanes[11]. At the time of the FAA's review of the proposed 787-8 design, there was limited experience with the use of rechargeable lithium ion batteries in applications involving commercial aviation. However, the FAA noted that other users of this technology, ranging from wireless telephone manufacturing to the electric vehicle industry, have noted safety problems with lithium ion batteries, which included overcharging, over-discharging, and flammability of cell components. The FAA cited the following issues in its Issue Paper:

**(1)** <u>Overcharging</u>

In general, lithium ion batteries are significantly more susceptible to internal failures that can result in self-sustaining increases in temperature and pressure than their nickel-cadmium or lead-acid counterparts. This is especially true for overcharging, which causes heating and destabilization of the components of the cell, leading to formation (by plating) of highly unstable metallic lithium. The metallic lithium can

[10] According to the FAA's notice of final Special Conditions, the 787-8 design included planned use of lithium ion batteries for the following applications: Main and Auxiliary Power Unit (APU) Battery/Battery Charger System, Flight Control Electronics, Emergency Lighting System, and Recorder Independent Power Supply.

[11] On September 1, 1977, and March 1, 1978, respectively, the FAA issued 14 CFR 25.1353 c(5) and c(6), governing nickel-cadmium battery installations on large transport category airplanes.

ignite, resulting in a self-sustaining fire or explosion. Finally, the severity of thermal runaway from overcharging increases with increasing battery capacity, in part because of the greater quantity of electrolytes in large batteries and partly as a result of the greater energy storage capacity of the larger batteries.

**(2)** Over-discharging
Discharge of some types of lithium ion batteries beyond a certain voltage (which is determined by many technical factors including cell electrolyte chemistry, discharge rate, time spent below that voltage, temperature) can cause corrosion of the electrodes of the cell, resulting in loss of battery capacity that cannot be reversed by recharging. This loss of capacity may not be detected by the simple voltage measurements commonly available to flight crews as a means of checking battery status. This is a problem shared with nickel-cadmium batteries.

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

The FAA's review found that the existing airworthiness regulations did not contain adequate or appropriate safety standards for lithium-ion batteries. In particular, the FAA noted that, in general, lithium ion batteries are "significantly more susceptible to internal failures that can result in self-sustaining increases in temperature and pressure (thermal runaway)" than nickel-cadmium or lead-acid batteries. Also, unlike nickel-cadmium and lead-acid batteries, some types of lithium-ion batteries use liquid electrolytes that are flammable. As a result, the FAA issued a notice of proposed special conditions (72 Federal Register 21162, April 30, 2007), which detailed the issues of concern from the issue paper and solicited public comment on the proposed special conditions. Responding to public comments received, on October 11, 2007, the FAA published nine special conditions for the 787-8 lithium-ion battery installation (72 *Federal Register* 57842) to mitigate safety problems caused by overcharging, over discharging, and flammability of cell components. The intent of the nine special conditions was to establish appropriate airworthiness standards for lithium ion battery installations in the 787-8 and to ensure, as required by 14 CFR 25.601, that the battery installations were not hazardous or unreliable. To address these concerns, the special conditions adopted the following requirements:

- Those sections of 14 CFR 25.1353 applicable to lithium ion batteries.
- The flammable fluid fire protection requirements of 14 CFR 25.863. In the past, this rule was not applied to batteries of transport category airplanes, since the electrolytes used in lead-acid and nickel-cadmium batteries were not flammable.
- New requirements to address the hazards of overcharging and over-discharging that are unique to lithium ion batteries.
- New maintenance requirements to ensure that batteries used as spares are maintained in an appropriate state of charge.

Accordingly, "Special Conditions: Boeing Model 787-8 Airplane; Lithium-Ion Battery Installation," 25-359-SC, became effective on November 13, 2007 as part of the type certification basis for the Boeing Model 787-8 airplane. 25-359-SC states:

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

(1) Safe cell temperatures and pressures must be maintained during any foreseeable charging or discharging condition and during any failure of the charging or battery monitoring system not shown to be extremely remote. The lithium ion battery installation must preclude explosion in the event of those failures.

(2) Design of the lithium ion batteries must preclude the occurrence of self-sustaining, uncontrolled increases in temperature or pressure.

(3) No explosive or toxic gases emitted by any lithium ion battery in normal operation, or as the result of any failure of the battery charging system, monitoring system, or battery installation not shown to be extremely remote, may accumulate in hazardous quantities within the airplane.

(4) Installations of lithium ion batteries must meet the requirements of 14 CFR 25.863(a) through (d).

(5) No corrosive fluids or gases that may escape from any lithium-ion battery may damage surrounding structure or any adjacent systems, equipment, or electrical wiring of the airplane in such a way as to cause a major or more severe failure condition, in accordance with 14 CFR 25.1309 (b) and applicable regulatory guidance.

(6) Each lithium ion battery installation must have provisions to prevent any hazardous effect on structure or essential systems caused by the maximum amount of heat the battery can generate during a short circuit of the battery or of its individual cells.

(7) Lithium ion battery installations must have a system to control the charging rate of the battery automatically, so as to prevent battery overheating or overcharging, and,
   (i) A battery temperature sensing and over-temperature warning system with a means for automatically disconnecting the battery from its charging source in the event of an over-temperature condition, or,
   (ii) A battery failure sensing and warning system with a means for automatically disconnecting the battery from its charging source in the event of battery failure.

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

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

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

### D.2.5 Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems DO-311:

DO-311, "Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems," which was developed by RTCA Special Committee SC-211, was issued March 13, 2008. This document contains Minimum Operational Performance Standards (MOPS) for rechargeable Lithium battery systems to be used as permanently installed power sources on aircraft. Compliance with these standards is of one approach to assure that the Lithium battery will perform its intended function(s) safely, under conditions normally encountered in aeronautical operations. These standards apply to the chemical composition, cell size, cell construction, cell interconnection methods within batteries, venting provisions, operational and storage environments, packaging, handling, test, storage and disposal of rechargeable Lithium batteries, installed separately or in avionics equipment aboard aircraft. The standard was developed by SC-211, which included representatives from industry and government, including representatives from Boeing and the FAA.

The FAA indicated that because this standard was released after the effective date of their Special Conditions on Li-Ion batteries, 25-359-SC, it did not become a requirement for the 787-8 Main and APU battery certification.

### D.2.6 Boeing Certification Plan for Demonstrating Compliance to Regulatory Requirements:

A review of the Boeing 787 Electrical Power Systems Certification Plan (CP), which includes the power conversion system, was conducted during this investigation. The original CP was approved by the FAA on December 22, 2005. This CP presents a high level system description of the electrical power systems, which includes the battery and battery charger system, and defines the methods that are to be used to show compliance to applicable FAA and EASA requirements. . After the FAA approved the Certification Plan, reviewed the qualification test procedures and subsequently approved the requests

for qualification test conformity inspections, final approval of several test reports and the associated finding, was delegated for the Boeing ARs to perform on behalf of the FAA. ARs exercise their authority and responsibility by signing FAA Form 8100-9, Statement of Compliance with Airworthiness Standard.

According to the CP, the Lithium Ion Battery, Boeing part number B3856-901R, was to be supplied by GS Yuasa in Kyoto, Japan, and the battery charger unit, Boeing part number C3808-900R, was to be supplied by Securaplane in Tucson Arizona.

Table 1 below provides a list of the pertinent tests and analyses presented by Boeing, approved by a Boeing AR, and accepted by FAA to demonstrate compliance to various certification requirements (both FAA and EASA) as part of the certification plan.

**Table 1 Certification Deliverables, 787-8 Battery and Battery Charger**

| Test/Analysis | Applicable FARs | Applicable CSs |
|---|---|---|
| Qualification Test, Battery/BCU Subsystem | 25.601, 25.1301(a), 25.1301(d), 25.1309(a), 25.1309(g), 25.1351(a)(2), 25.1351(b)(4), 25.1431(a), 25.1431(d), 25App-K25.1.1 | 25.601, 25.1301(a), 25.1309(a)(1), 25.1351(a)(2), 25.1351(b)(4), 25.1360(a), 25.1431(a), 25.1431(d) |
| Qualification Test, Mechanical Battery with Contactor | 25.601, 25.1301(a), 25.1301(d), 25.1309(a), 25.1309(g), 25.1431(a), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.601, 25.1301(a), 25.1309(a)(1), 25.1431(a), EASA/787/SC-CRI_F-24 |
| Qualification Test, Electromagnetic Interference (EMI), Battery with Contactor | 25.1301(d), 25.1309(a), 25.1309(g), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.1309(a)(1), EASA/787/SC-CRI_F-24 |
| Qualification Test, Climatical, Battery with Contactor | 25.601, 25.1301(a), 25.1301(d), 25.1309(a), 25.1309(g), 25.1431(a), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.601, 25.1301(a), 25.1309(a)(1), 25.1431(a), EASA/787/SC-CRI_F-24 |
| Personnel Hazard Justification for Main/APU Battery | N/A | 25.1360(a) |
| Qualification Analysis, Red Label to Production Configuration for Main/APU Battery | 25.1301(a), 25.1301(d), 25.1309(a), 25.1309(g), 25.1431(a), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.1301(a), 25.1309(a)(1), 25.1431(a), EASA/787/SC-CRI_F-24 |
| BCU Q2 Qualification Test, Electrical Performance, Battery Charger Unit | 25.601, 25.1301(a), 25.1301(d), 25.1309(a), 25.1309(g), 25.1351(a)(2), 25.1351(b)(4), 25.1431(a), 25.1431(d), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.601, 25.1301(a), 25.1309(a)(1), 25.1351(a)(2), 25.1351(b)(4), 25.1360(a), 25.1431(a), 25.1431(d), EASA/787/SC-CRI_F-24 |
| BCU Q2 Qualification Test, Climatic, Battery Charger Unit | 25.601, 25.1301(a), 25.1301(d), 25.1309(a), 25.1309(g), 25.1431(a), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.601, 25.1301(a), 25.1309(a)(1), 25.1431(a), EASA/787/SC-CRI_F-24 |
| BCU Q2 Qualification Test, Mechanical, Battery Charger Unit | 25.601, 25.1301(a), 25.1301(d), 25.1309(a), 25.1309(g), 25.1431(a), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.601, 25.1301(a), 25.1309(a)(1), 25.1431(a), EASA/787/SC-CRI_F-24 |
| BCU Q2 Qualification Test, Electromagnetic Interference (EMI)/Electromagnetic Conductivity (EMC), BCU | 25.1301(d), 25.1309(a), 25.1309(g), 25App-K25.1.1, FAA/787/SC/25-359-SC | 25.1309(a)(1), EASA/787/SC-CRI_F-24 |

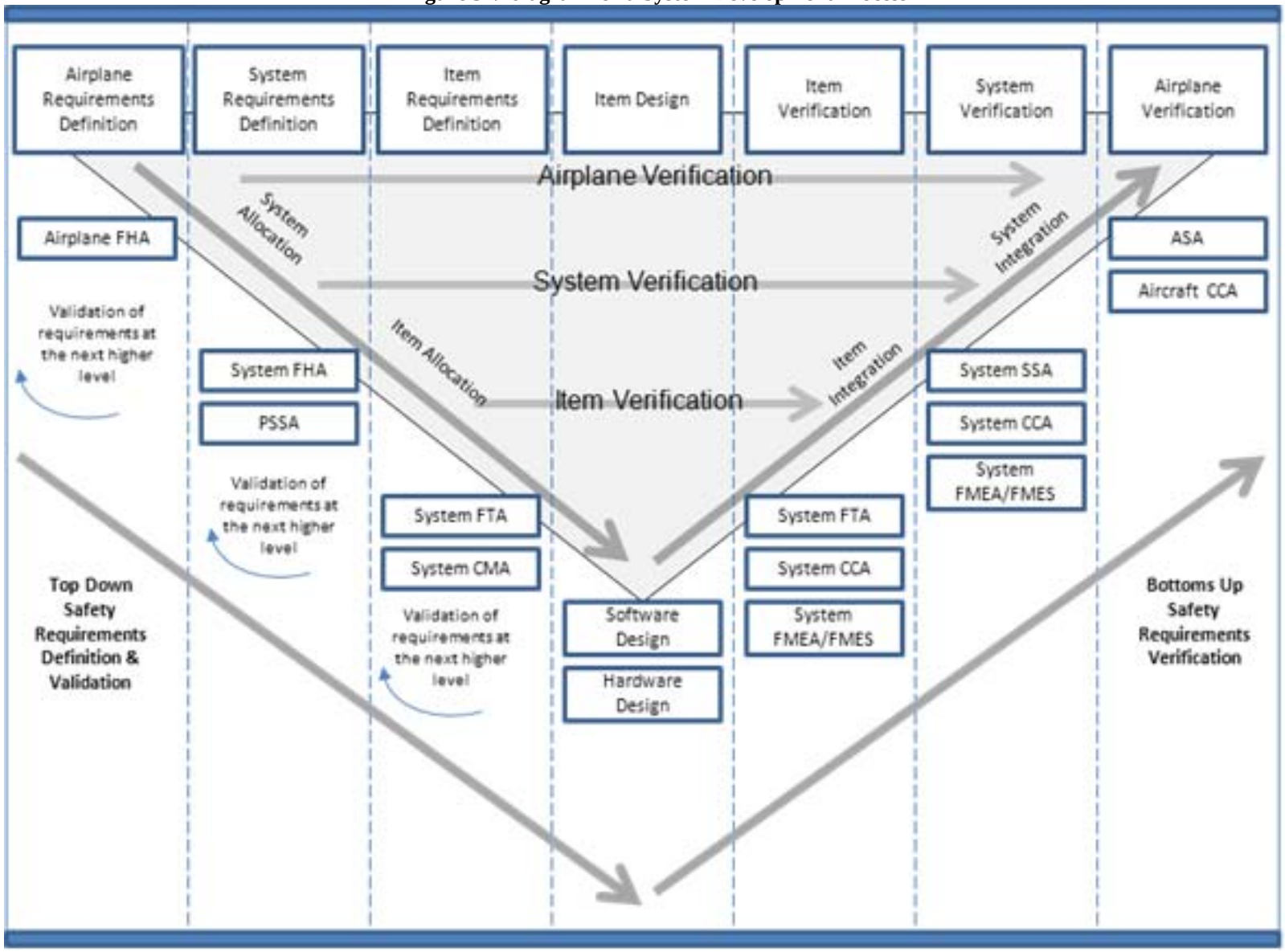
## D.3 787-8 Lithium-Ion Battery System Safety Assessment:

### D.3.1 Overview of System Safety Assessment Process Description:

The process for developing and certifying a safety-critical system must provide assurance that all significant single failure conditions have been identified and that all combinations of failures which lead to hazardous or catastrophic airplane level effects have been considered and appropriately mitigated. Aircraft manufacturers provide this assurance through their safety assessment processes.

The basic structure of a system development process can be represented by a V-diagram, where time is represented horizontally (left to right) and system hierarchy is represented vertically (Reference Figure 3). Initially (top left), the top level design requirements (payload, range, passenger capacity, performance, etc) for the aircraft are selected. The airplane requirements are then broken down into airplane-level functions (e.g. provide power generation and distribution); airplane-level functions to system functions (e.g. provide electrical power to user systems); system-level functions to systems (e.g. provide backup electrical power); systems to subsystems (e.g. provide battery charging) in a top-down process. Following this system development process requirements for each part item or piece of equipment are identified with each level providing validation of the level above. Validation is the process of ensuring that the requirements are sufficiently correct and complete. The right side of the V diagram involves a series of bottom-up evaluation activities to ensure the requirements are verified as met at each level in integration of the final product. Verification is the process of ensuring that the final product meets the design requirements. Verification activities may include analysis and testing the individual item of equipment (e.g. battery and/or battery charger) and then progressively integrating the equipment into a complete system and even flight testing for verification of a fully integrated system on the aircraft.

**Figure 3 V-diagram for a System Development Process**



Safety assessments are a primary means of compliance for *systems* (as opposed to identifying structures or airplane performance characteristics) that are critical to safe flight and operation. Safety assessments proceed in a stepwise, data-driven fashion, analogous to the system development process described above. Starting with airplane functions, functional hazard assessments are performed to identify the failure conditions associated with each function. Systems functional hazard analyses are performed for system level functions. Preliminary safety assessments are performed as the system is developed adding more specific design and implementation detail to address specific hazards The bottom-up verification by safety analysis starts with an analysis of the components of a system to ensure single failures do not result in significant effects. Combinations of failures are logically combined to develop probability of a failure and checked to ensure they are commensurate with the criticality of the failure condition. Thus, the final definition and characterization of a safety-critical system is verified by the result of the analyses conducted during a safety assessment.

Safety assessments are conducted by the applicant, and its suppliers, and are reviewed and accepted by the FAA. The safety assessment process is outlined in AC 25.1309-1A and described in detail in SAE ARP4761. Although the safety assessment process outlined in the AC is not mandatory, applicants who choose not to conduct safety assessments must demonstrate compliance in another, FAA-approved way (for example, by conducting ground or flight tests).

A functional hazard assessment (FHA) is a systematic examination of a system's functions and purpose, and it typically provides the initial, top-level assessment of a design and addresses the operational vulnerabilities of the system function. The FHA is therefore used to establish the safety requirements that guide system architecture design decisions. Performed independently of any specific design, an FHA evaluates what would occur if the function under question was lost or malfunctioned and classifies that effect to prioritize focus on the most serious outcomes. An FHA is conducted early in the design and development cycle to identify failure conditions and classify them by severity, beginning at the airplane level and working down to individual systems. The latest draft of the upcoming revision to AC 25.1309-1A includes five severity classes that are used to classify the effect of loss or malfunction as part of an FHA. These classes are: no safety effect, and minor, major, hazardous, and catastrophic. The differences among the classes are associated with effects on the airplane, occupants, and crew.

Once the hazard classification of a system is established, the applicant conducts system-specific analyses to identify and evaluate failure conditions and identify ways either to eliminate the adverse effects of a failure or to ensure that a failure probability is inversely proportional to its hazard classification. Analytic and qualitative methods for conducting safety assessments include functional hazard assessments, preliminary system safety assessments, and system safety assessments. Techniques that may be used to conduct the safety assessments include fault tree analyses and failure modes and effects analyses.

The FHA may be incorporated in the certification plan for FAA review early in the development process. The safety requirements derived from the FHA and the Preliminary Systems Safety Analysis are used as input for system safety assessments.

A system safety assessment is a systematic evaluation of a design solution and implemented system and can be accomplished using a number of different techniques: qualitative and

quantitative fault tree analysis (FTA), failure modes and effects analysis (FMEA), failure modes and effects summary. An FTA is a structured, deductive, top-down graphical analysis that depicts the logical relationships between each failure condition and its primary causes and uses the results of the FMEA as the basic events in the FTA analysis. A FMEA provides a qualitative and quantitative way to identify the effects of a single function or system failure at the next-higher level of a system.

### D.3.2 Functional Hazard Assessment:

Boeing performed a functional hazard assessment (FHA) as part of their evaluation of the 787-8 Electrical Power System Safety. The FHA was performed to determine the potential hazards that various failuresof electrical system components could introduce to the airplane and its occupants. The functional hazard assessment identified and classified, pursuant to the guidance in AC 25.1309-1A, two hazards associated with the main and APU lithium-ion battery: "battery vents smoke/fire," which was classified as catastrophic,[12] and "battery vent and/or smoke (without fire)," which was classified as hazardous.[13]

On the basis of the results of the functional hazard assessment, Boeing defined failure and mitigation requirements for the main and APU lithium-ion battery; three of the requirements related to smoke, gas, and electrolyte release are shown in table 2.

**Table 2 Battery/Battery Charger Failure Detection/Mitigation Requirements**

| Requirement | Description of Requirement |
|---|---|
| 1 | The battery shall have a probability of less than 1 x $10^{-7}$ for gas emission. |
| 2 | The battery shall have a probability of less than 1 x $10^{-7}$ for smoke emission. |
| 3 | Battery shall be designed to prevent spilling flammable fluid, a hazardous event with occurrence with a probability of less than $10^{-9}$. |

### D.3.3 System Safety Assessment of the Main and APU Li-ion Battery Systems:

Boeing's 787-8 System Safety Assessment (SSA) presents the overall safety analysis of the 787-8 Electrical Power System (EPS), which was used to evaluate the design of the EPS for compliance with safety requirements derived from Federal Aviation (CFR 14 Part 25), EASA Certification Specifications (CS) and accompanying advisory material. Included in their SSA are sections that provide a description of the Main and APU battery and their battery charger, the Lithium-Ion battery failure modes, the batteries design and qualification, applicable special condition (25-359-SC), Functional Hazard Assessment (FHA) that was performed as part of the 787-8 Electrical Power System Safety Analysis, fault tree documentation, and an airplane level safety assessment.

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

Boeing's 787-8 electrical power system safety assessment also included an analysis of lithium-ion battery failure modes. This analysis determined that overcharging was the only known failure mode that could result in cell venting with fire. As a result, Boeing established additional design requirements to ensure that the likelihood of occurrence of an overcharge event was extremely improbable[16]. Boeing further determined that cell venting without fire could be initiated by several different failure modes, including external overheating, external short circuit of appropriate impedance, internal short circuit, recharging a battery that has been over discharged, a high rate of charging at greater than a 1C (one times the capacity Ahr rating of the cell), or charging at cold temperatures. To evaluate the effect of cell venting resulting from an internal short circuit, Boeing performed testing that involved puncturing a cell with a nail to induce an internal short circuit. This test resulted in venting with smoke but no fire. In addition to this testing and to assess the likelihood of occurrence of cell venting, Boeing acquired information from other companies about their experience with the use of similar lithium battery cells. Based on this information, Boeing assessed that the likelihood of occurrence of cell venting would be about one in ten million flight hours.

On the basis of these analyses and tests, Boeing incorporated several safety features inside and outside of the battery that were designed to prevent the conditions of cell venting and cell venting with fire. These features include:

- A dedicated battery charger that charges within very precise voltage and current limits.
- Cell balancing circuits to ensure all the cells in a battery are charged up equally and are within safe voltage limits.
- Battery circuits that monitor cell and battery voltages and temperatures and control the battery charger accordingly.
- An internal safety contactor to disconnect the battery in case of any high voltage conditions.
- A battery diode module (Main battery only, the APU battery has no other possible charge sources) that prevents charging of the battery from any other sources other than the dedicated battery charger.
- Cell assembly processes that prevent, detect, and eliminate contamination as a source of cell internal short circuiting.
- Operation in a suitable thermal environment including protection from cargo fire threats via an insulating liner.
- Cell designed to be tolerant to external short circuit conditions, by either fusing internally if the current is too high or able to withstand discharging fully into a fault without generating fire. Additionally, airplane wiring is routed and protected to minimize the probability of an external short circuit occurring.

Overall compliance with applicable 787-8 main and APU lithium-ion battery safety requirements was shown through formal analyses and tests. In addition to those noted above, theses analyses and tests were performed by Thales/GS-Yuasa and reviewed by Boeing project engineering, Safety Group, Reliability and Maintainability engineering, and the Boeing Authorized Representatives. Formal analyses included the Battery Functional Hazard

[16] The risk of fire was addressed through overcharge protections. For example, Boeing required that the battery monitoring unit when combined with the overall battery protection subsystem shall prevent undetected over-charge (over-voltage) a catastrophic event with a probability of occurrence of less than $1 \times 10^{-9}$.

assessment (FHA)[17], Fault Tree Analysis (FTA[18]), Failure Mode and Effects Analysis (FMEA[19]) and the Battery/Battery Charger System Safety Assessment (SSA[20]).

Battery testing consisted of full-performance, environmental qualification, and destructive tests. The destructive tests included external short circuit (low and moderate impedance shorts at battery terminals), overcharge (charge battery at 36 volts for 25 hours), high temperature storage (185º F for 18 hours), and over discharge (discharge battery to zero volts) tests. Boeing noted that they found no evidence of cell-to-cell propagation failures or fire resulting in these tests.

Boeing's safety assessment report noted that endurance testing, during which the battery is cycled and exposed to various operating temperatures over time, was also performed[21]. At the conclusion of its testing and safety assessment process, Boeing prepared documented compliance data supporting each of the nine items of Special Condition, 25-359-SC.
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Mike Hauf

Aircraft System Safety Engineer

[17] The FHA was conducted by Thales Avionics Electrical Systems.
[18] The FTA was conducted by Thales Avionics Electrical Systems and GS-Yuasa.
[19] The FMEA was conducted by Thales Avionics Electrical Systems. and GS-Yuasa
[20] The BCU and battery SSA was conducted by Thales Avionics Electrical Systems.
[21] Endurance testing was not a certification requirement, but was performed at Boeing's option.